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THE ANALYSIS OF CONSTRUCTION TECHNIQUES AND THERMAL TENSIONS IN GRAVITY DAMS

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Abstract. *Gravity dams are usually built with mass concrete, which has a large volume of concrete. During the process of hydration of the cement particles, there is release of heat, in a process called heat of hydration, raising internally the temperature of the concrete. This phenomenon causes the internal temperature of the concrete to be different from the surface temperature, resulting in a thermal gradient, in addition to a slow cooling in the core of the dams. These temperature changes give rise to thermal stresses, which, if not foreseen and prevented can cause damage to the structures when they exceed the resistive capacity of the concrete. The thermal stresses take into account the phenomenon of intrinsic creep in the concrete, that is, there is variation of the modulus of elasticity over time with the change in temperature. There are a few techniques to try to minimize this problem, such as layered construction, concrete placed at lower temperatures, the use of low heat of cement hydration, among others. An effective way of preventing thermal problems in dams is the numerical simulation, being possible with the mechanism, to predict the most critical regions and to analyze, then the probability of structural damage. Thus, this work shows numerical simulations using the finite element method - MEF, through the ANSYS program, for layered gravitational dams. This article tries to expose some of the most favorable conditions in the construction process, identifying possible cracking sites, through numerical and analytical analyzes, contributing to the dissemination of these studies and showing community interest, constructive methods and methods of analysis that may induce safer construction.*

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1 INTRODUCTION

Gravity dams are used for water storage and power generation, and Brazil is one of the main constructors in this field. Gravity dam structures require special care since they are built of mass concrete, which is any concrete volume at dimensions large enough to require measures to cope with heat generation from cement hydration and with attendant volume changes in order to minimize the possibility of cracking [1].

Cracks in these structures are undesirable, because they affect the permeability, durability, appearance and the internal stress in them. Cracks often result from the developed tensile stress that exceeds the concrete tensile strength. However, temperature changes alter the mass concrete volume and mainly generate hydration heat. Temperature control is crucial to avoid fissures [2].

Temperature increases in the center of bulky pieces due to the exothermicity of cement hydration reactions. The center is practically under adiabatic conditions, when piece-thickness exceeds one meter, because concrete is a low-heat conductor and temperature can rise to 70°C, or more, under such condition. Temperature gradient can be found between the surface and the center of the structure [3].

Temperature increase changes the initial modulus of concrete elasticity. Creep rates increase due to higher temperature, which also increases creep stress Therefore, these properties undergo different local variations inside mass concrete structures due to temperature, which, in its turn, is linked to time [4].

Low hydration heat diffuses from the surface during the construction process due to reduced concrete conductivity. The next layer cannot be released until the previous one reaches the prescribed temperature level. Such process often delays the construction process [5].

Numerical modeling is one way to prevent and avoid damages in mass concrete structures. These models allow temperature and stress to be assessed prior to concrete structure construction. The Finite Element Method - FEM can help predicting the maximum temperature reached by certain concrete types and also simulating constructive methods able to reduce thermal effects.

Many researchers study the thermomechanical effect on mass concrete in different structures, among them: 6, 7, 8, 9, 10 ,11, 12, 13. The Group Dynamics and Fluid Structure of the University of Brasilia - UnB (GDFE), stood out in recent years due to its many researches on this subject [13, 14, 15, 16, 17,18].

The aim of the current study is to collaborate with concrete mass studies, mainly to gravity dam projects, by using analytical methods and MEF, through ANSYS WORKBENCH. The construction methods will be analyzed based on two models applied to the dam in order to verify the best results obtained through numerical simulations.

2 THEORETICAL BACKGROUND

2.1 Heat Equation

Heat Equation deduction was based on [6, 19, 20, 21]. The energy balance equation followed the scheme in Figure 1.

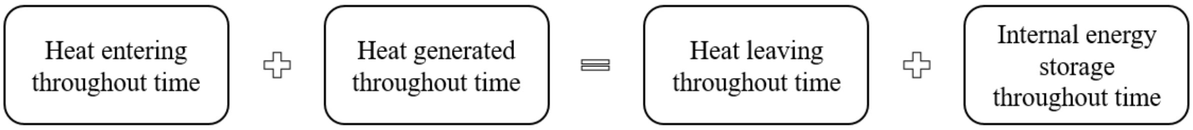

Figure 1– Heat exchange in the elementary infinitesimal volume of matter.

It was usual to represent the Heat Equation when the thermal conductivity was constant throughout the analysis, and it required mathematical treatment:

$$k\nabla T^2 + \dot{q} = \rho c \frac{\partial T}{\partial t} \tag{1}$$

wherein,

- $\dot{q}$ is the heat generated;
- k is the thermal conductivity;
- T is the temperature;
- ρ, c are the specific mass and specific heat, respectively.

2.2 Hydration Heat

$k\nabla^2 T$ Since the heat equation shown in Eq. 2, in the adiabatic test, the term equals zero.Once the rate of internal heat generation ceases after a certain time, the temperature increases continuously while there is heat generation, until it stabilizes at a constant level. Thus, we have:

$$\dot{q} = \rho\, c\left(\Delta\dot{T}^{ad}\right) \tag{2}$$

Wherein,

- T^{ad} is the adiabatic temperature change rate.
- q is the internal heat variation at one point.

2.3 Initial (IC) and boundary conditions (BC):

- Initial temperature (IC): $T(x, y, z, t = 0) = f(x, y, z)$
- Prescribed temperature in the contour (BC) - Dirichlet condition: $T(x, y, z, t) = f(x, y, z, t)$
- Prescribed Boundary flow (BC)- Neumann condition:$k\frac{\partial T}{\partial n}(x, y, z, t) = q_n(x, y, z, t)$

2.5 Mass concrete stress calculation

Stresses are calculated in accordance with [10, 22, 23, 24, 25, 26].

The deformation matrix $[\Delta\varepsilon]$ is given by multiplying the creep matrix $[J]$ by the variation matrix of thermal tensions $[\Delta\sigma]$, due to each thermal variation ($\Delta T = T_i(t) - T_0$ = temperature at the instant of time minus the initial temperature), Eq. 3:

$$[\Delta\varepsilon] = [J][\Delta\sigma] \tag{3}$$

Thus, stress at a certain time is given by summing all stress increments, Eq. 4:

$$\sigma\,(t_n) = \sum \Delta\sigma_i \tag{4}$$

2.6 Fluency Prediction Model

Models adopted to predict creep caused by time follow the same principle: a hyperbolic curve that tends to an asymptotic value. Curve shape and final value will depend on several factors such as curing conditions, loading age, mixing ratio, room temperature and humidity [27]. There are several models to predict fluency, but we will herein present the USBR model.

Bureau Reclamation [28]: a logarithmic expression is used to accurately approximate the normal creep behavior within one year. The function is given by Eq. 5:

$$J(t,\tau) = \frac{1}{E(\tau)} + \emptyset(z)\log(t-\tau+1) \tag{5}$$

Wherein a and b are coefficients and adjustment:

- J is the creep function, which is the function of the modulus of elasticity E (MPa) and the coefficient of creep ϕ (1/10-6 MPa), in 1/10-6 MPa.
- t is time (in days).
- τ is age (in days).

$$\emptyset(z) = a + \frac{b}{\tau} \tag{6}$$

This model is adopted by researchers at Furnas [29].

3 RESULTS AND DISCUSSIONS

The simulations of a structure constructed in layers of concrete were analyzed to investigate some techniques used in gravity dam concreting. The thermal analyses were performed through MEF in the ANSYS WORKBENCH software and the mechanical ones were analytically performed in the MATLAB software.

Dimensions in Figure 2 are algebraically shown based on the study cases. The dam would be defined by B - base, H - height, L – length in three dimensions. Layer names are highlighted; the first layer (C1) was followed by the second one (C2) and so on up to the last layer. Specific mass 2393.0 kg / m³, thermal conductivity 2.6 W/m°C and specific heat 898.5 J/kg°C were used in the modeling process.

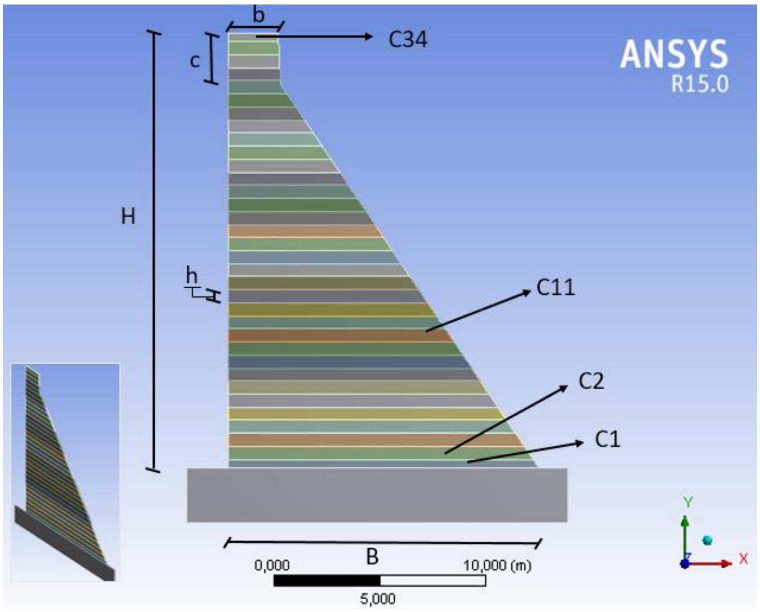

Figure 2 – Geometry of the dam.

Table 1 summarizes the two assessed cases and points out the imposed variations. N is the number of layers; h, H, b, B are the geometric dimensions (Figure 2); Δt (h) is the time the analysis was carried out (in hours); Δt_{lanc} is the layer launch intervals (in hours); $T_{lanç}$ is the layer launch temperature (in Celsius); T_{max} is the layer temperature (in Celsius) and q is the internal heat generation.

CASE	A		B	
N	34		66*	
h (m)	C1	0,4	C1	0,2
	C2 - C34	0,6	C2 - C34	0,4
H (m)	20		16	
B (m)	14,63		12	
b (m)	2,33		1,86	
c (m)	2,37		1,9	
Mesh	C1	0,05	C1	0,025
	C2 - C34	0,08	C2 - C34	0,075
N° nodes	548887		533853*	
N° Elements	230035		222794*	
Δt (h)	10,2		30,26	
Δt_{lanc}	C1	48	C1	48
	C2 - C34	24	C2 - C34	48
$T_{lanç}$ (°C)	C1	20	C1	14
	C2 - C34	20	C2 - C34	15
q	$q1 = 2150000 \times 59{,}44 \times 49032^{2{,}831} \times 2{,}831 \times t^{1{,}831}/(49032^{2{,}831} + t^{2{,}831})^2$		$q2 = 2377945 \times 33{,}94 \times 36288^{2{,}05} \times 2{,}05 \times t^{1{,}05}/(36288^{2{,}05} + t^{2{,}05})^2$	
T_{max} (°C)	67		37,08	

* The analyzes were not performed for all layers or all the time required for the complete solution because it only needed the initial data

Table.1 – Cases of the analyzed dams.

There was layer thicknesses reduction between cases A and B. In both cases, the first layer presented thickness reduction because they were the most critical ones, i.e., they are expected to present more tension due to the imposed restrictions. Layer variations indicate mesh thickness variations and changes in the number of analyzed elements and time. Lower internal heat generation concrete was also used in B, and it led to lower temperatures.

Figures 3 a, b, c show the temperature isotherms in a dam at 34.37 h, 36.86 h and 39.34 h, respectively. We aimed at showing that cooling gets slower in the inner parts close to the gravity center of the model, in the core of the dam. The thermal variation in other models applied to dams can be seen in [15].

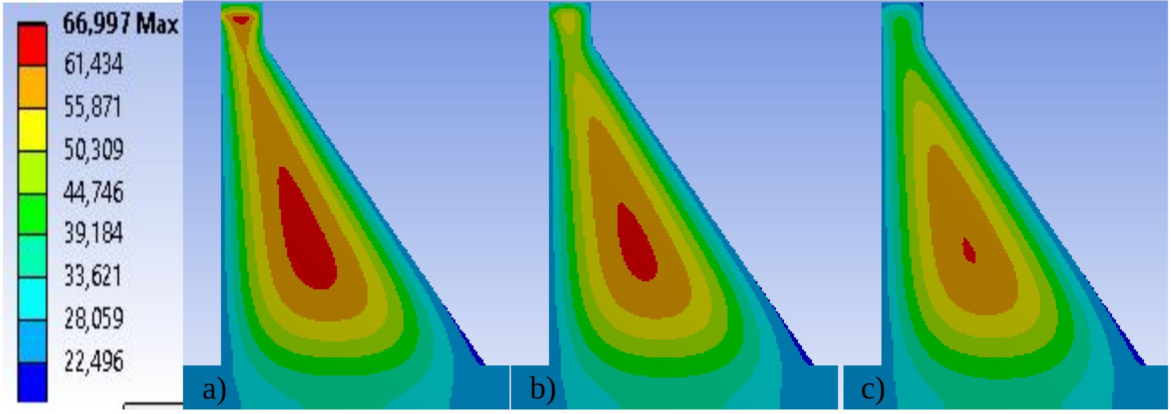

Figure 3 – Temperature isotherms in different ages of the dam: a) 34.37 h; b) 36.86 h; c) 39.34 h.

Figure 3 shows that, even if the structures reach the maximum temperature, layer cooling is faster near the surface. Since the depicted dam has different geometry, the phenomenon repeats itself. Figure 4 presents the temperature profile of all the layers in Case A, always in the central region of the layer. The lower inner figure is a highlight, the layer to eleven TC11 shows slow cooling due to its position, fact that explains why it was one of the assessed layers.

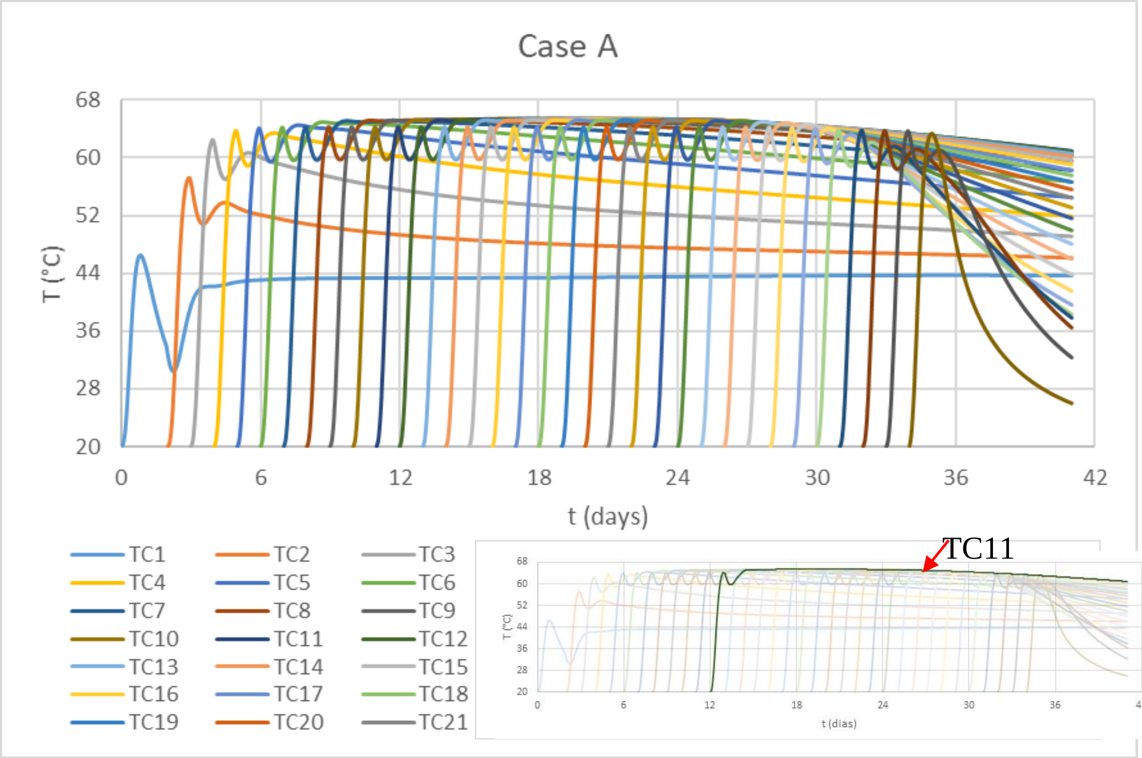

Figure 4 – Temperaturas para o Caso 6-A.

Tensions were analyzed in the first layer in both cases (Figure 5). Simulations disregard structure length (L), which, on the other hand, is taken into consideration in thermal stress analysis conducted through the restriction coefficient [14, 30]. The restriction coefficient were adopted as hypotheses based on information shown in Table 2; the coefficient of restriction (k_r) was defined as the length/height (L/H) through ACI [30]. USBR was the adopted creep method.

Name	L/H	k_r [30]
k_r1	20	0,905
k_r2	10	0,870
k_r3	5	0,685
k_r4	2	0,330

Table.2 – Coefficients of restriction applied to the dam.

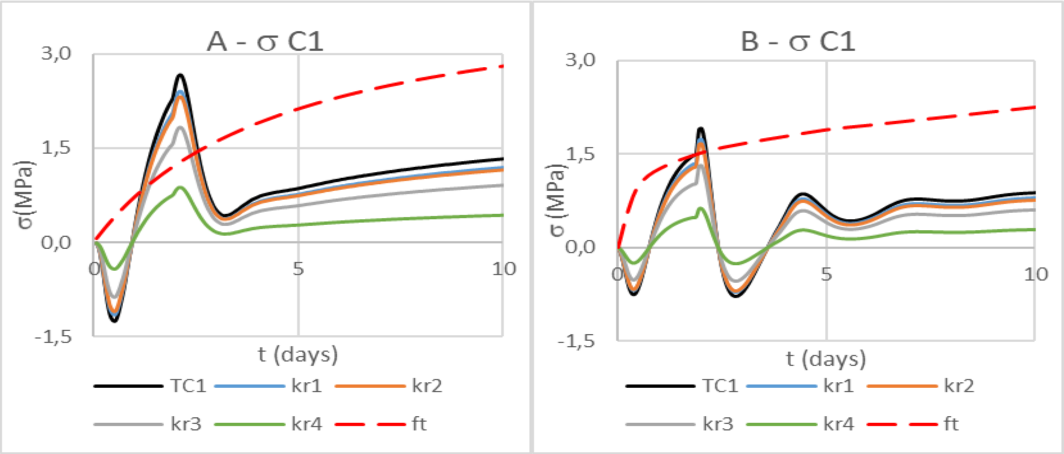

Figure 5 – C1 stress of the analyzed structures.

Based on the analyzed cases and conditions, the first layer emerges as very critical, because it is often built over rigid foundations. Therefore, such construction project requires greater caution throughout its implementation.

Concrete presenting great deformation capacity against restriction and lower thicknesses, smaller aggregates and more paste in the first layers is of customary use. Whenever it is used, the curing water temperature increases depending on concrete temperature.

There was cracking in all cases presenting contraction coefficient k_r1 under the assessed conditions. k_r3 could be used in Case B and only the most favorable situation (k_r4) could be used and adhered in Case A, i.e., maximum length equals to twice the height, which avoided cracking in the layers. Such process shows the coefficient of constraint influence or the relation between structure length and height. The likelihood of cracking is lower when the L/H relation is lower on rigid foundation projects.

There was heat generation curve change between A and B when simulation concerned concrete presenting slight adiabatic temperature raise, layer thickness reduction and layer launch temperature change. The importance of choosing a concrete showing less heat generation, as well as of changes in other characteristics such as the approximate 30°C difference in the maximum temperatures of the layers is noteworthy. It is also possible seeing stress reduction.

With regard to C1 thickness variations, thicker C1 increased the tensile stress and easily reached the concrete capacity. Reducing concrete casting temperature also results in lower stresses and to less risk of cracking.

The layer launch interval changes the traction conditions, because the layer accelerates the cooling process with time and reduces the risk of reaching high tensile stress.

In addition to C1, the C11 layers were also examined; C11 was chosen because it was located in the most critical region of the structure and because of the slow cooling (Figure 4). Moreover, these characteristics have contributed to higher tensile stress in the body of concrete.

Stress in C2 also was found by multiplying the coefficient of foundation, which was considered flexible. C2 stress was lower than in C11, so it was not investigated.

When layer 11 was 0.6 m at launch temperature 20°C, there was cracking trend at the age of 30 days in Case A (Figure 6). Layer thickness went down to 0.4 m in Case B, along with the other properties, there was no risk of cracking in it.

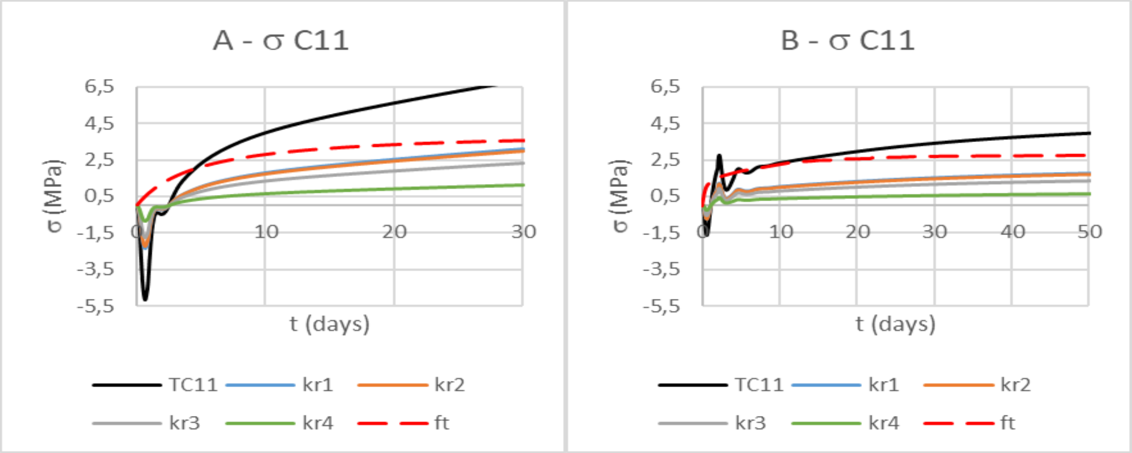

Figure 6 – Thermomechanical stresses to the dam in C11.

Other results of thermal simulations in dams can be found in [14].

4 CONCLUSIONS

The structures of dams built of mass concrete should be carefully analyzed due to the possibility of stress emergence, which leads to cracking. Cracks can occur in the body due to the imposed structural constraints and to the thermal gradient resulting from temperature differences caused by heat generation. Therefore, it is interesting conducting simulations to verify the probability of having these phenomena occurring before the construction of mass concrete.

The effect of the layer launch interval, and of the respective layer heights in the simulation of layered constructions on the temperature profiles was evidenced. Layer cooling and the subsequent layer heating, due to the thermal influence of the overlapping layer, formed corrugations that were followed by the stress curves.

Tensile tensions reduced by approximately 50% in layers overlapped in other concrete layers. This result complies with the coefficient of foundation given by [29]. Stress changes depending on layer position and they can be reduced by L/H ratio reduction. Therefore, length changes and the construction of a shorter first layer can be efficient measures to avoid structure deterioration.

Layers capable of keeping high temperatures for longer have higher tensile tension and are often located in the central regions of the body, near the center of gravity. Overall, the FEM analysis along with the analytical solutions for tension issues are efficient and contribute to efficient simulations before the construction project is implemented in the field.

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