Thermal-Transient Analysis of Dams Using the Finite Element Method: Case Study Block A-7 (Spillway) of the ITAIPU Hydroelectric Plant

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Abstract. The structural behavior of a concrete dam due to thermal variation is an important topic studied in the literature because high thermal gradients influence the performance, strength and structural stability of the dam. Currently, there are several methods to estimate the behavior of concrete structures in the early ages and also during their useful life. Due to the complexity of structural analysis, it is necessary to implement a methodology using programs based on the Finite Element Methods (FEM). A case study was developed in a block of the ITAIPU Hydroelectric Power Plant. A thermal-transient analysis was performed in block A-7 of the Spillway during the years 1982 to 1985. The surface thermometers data were used to determine the boundary conditions in thermal simulations. Solar incidence was also considered on each side of the block. In order to calibrate, the temperatures recorded by the internal thermometers were used and compared with the results simulations performed in the ANSYS program. The results were validated through the percentage difference, which is less than 10%, justifying the use of the thermal model presented.

Keywords: Thermal-transient, FEM, Thermal Distribution.

1 Introduction

Dams are structural elements positioned transversely towards the watercourse flow, permanently or temporarily, whose objective is the containment and accumulation of water, liquid, solid substances or a combination of both [1]. This type of structure can be built with different materials such as: concrete, generally used for gravity dams, arch and buttress; as well as earth and rockfill, used in the construction of conventional dams [2].

According to Veiga [3], structures of great magnitude such as concrete dams have a long heating process that causes an increase in temperature inside the structure in the early ages. Due to the great thicknesses and the low thermal conductivity of the concrete that make up the dams, they present a slow process of heat dissipation, causing high thermal gradients that can generate differential deformations due to the thermal tensile stresses in the concrete.

Due to the concrete behavior, it is important to make an adequate forecast of the temperature distribution in the dams over time, allowing the appropriate calculation models. The numerical models most used today are based on the Finite Element Method, which allows to make a good forecast of the temperature distribution and to determine the effects resulting from thermal variations such as displacements and stresses (CASTILHO [4]).

Considering the complexity of thermal-transient analysis, this work presents a methodology for determining the temperature distribution in Block A-7, located in the central spillway of the ITAIPU Hydroelectric Power Plant. The analyzes were performed using the computational tool ANSYS, based on the Finite Element Method and the results was satisfactory.

2 Thermal Phenomena Analysis

The purpose of a thermal analysis is to calculate the temperature distribution and heat flow. Thermal simulations are normally used for studies of material performance by comparing the strength of the material and the thermal stresses generated due to temperature variation. [5].

The numerical model for thermal analysis in the ANSYS program, is based on a thermal balance equation, obtained through the energy conservation principle. In this program, the calculation is performed from the use of finite elements, where the temperatures in each nodes are determined.

In this type of analysis, three types of heat transfer are studied, such as: convection, conduction and radiation (Figure 1).

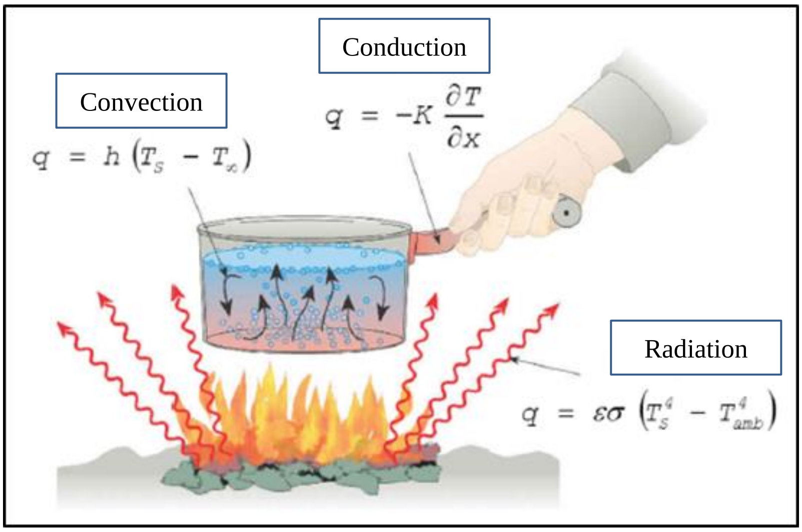


Figure 1. Heat transfer forms (**Source**: Adapted <https://storage.googleapis.com/site.esss.co/2017/01/Imagem-1-esp.png>. *Access in: 23/04/2020)*

In this work, the temperatures of the surface thermometers were used as edge temperatures of the numerical model. Thus, they were not considered heat transfer by convection and radiation, since the temperatures presented in these thermometers are the result of the combination of these three forms of heat transfer that occur on the surface of the dam. In addition, when using equations to estimate heat transfer by radiation and convection, more variables would be inserted in the model that cannot be validated. Thus, working with instrument data, although it be simple, but a measured data increase accuracy in the border conditions.

2.1 Conduction

Conduction is a process of transferring energy in a medium due to a temperature gradient, physical mechanisms, atomic or molecular activities. The transfer of heat by conduction is calculated by the Fourier law that allows determining the thermal flow, considering the temperature distribution in the core (INCROPERA [6]). The amount of heat (qx) that passes through an area at a given time is calculated by the following eq. (1), based on Fourier's Law:

$$q_x = -\mathrm{k}\,\mathrm{A}\frac{dT}{dX} \tag{1}$$

Where:

k: Thermal conductivity of the material

A: Considered area

$\frac{dT}{dX}$: Thermal gradient

2.2 Transient thermal analysis

Transient thermal analyzes are used primarily to determine temperature or thermal quantities that suffer variation with the time variation. For applications of this type of analysis, the simulation is divided into time steps, called a step, where a different edge temperature is considered for each step [5]. Figure 2 shows an example of subdividing the temperature into time steps.

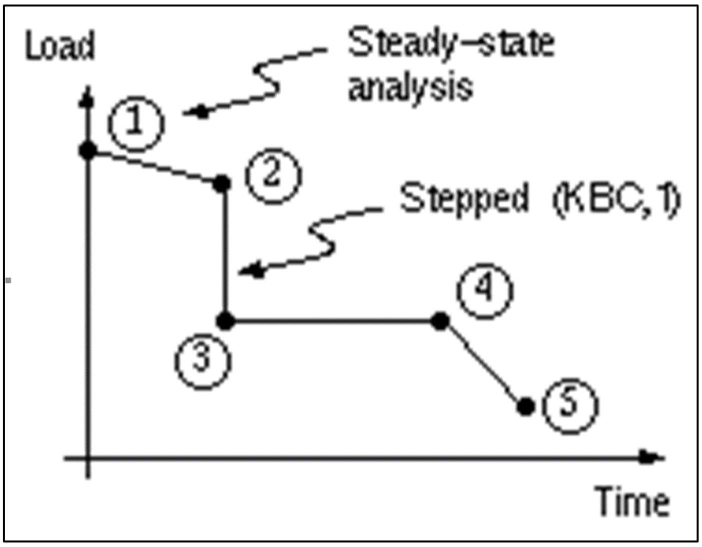


Figure 2. Temperature versus time curve. (**Source**: Adapted ANSYS [5])

3 Case Study of Block A-7 of the Spillway of the ITAIPU Hydroelectric Power Plant

This item describes the procedures carried out for the case study of block A-7 (Figure 3) of the spillway of the ITAIPU Hydroelectric Power Plant, in order to determine the temperature distribution in the block through the use of FEM.

Figure 3. Plan view of the ITAIPU Hydroelectric Power Plant - Location Block A-7 (Google Earth,2020)

3.1 Modeling of structural elements of block A-7

For the three-dimensional modeling of Block (A-7) drawings from the Technical File System (SAT). Figure 4 shows a schematic of the final model of the block based on technical drawings.

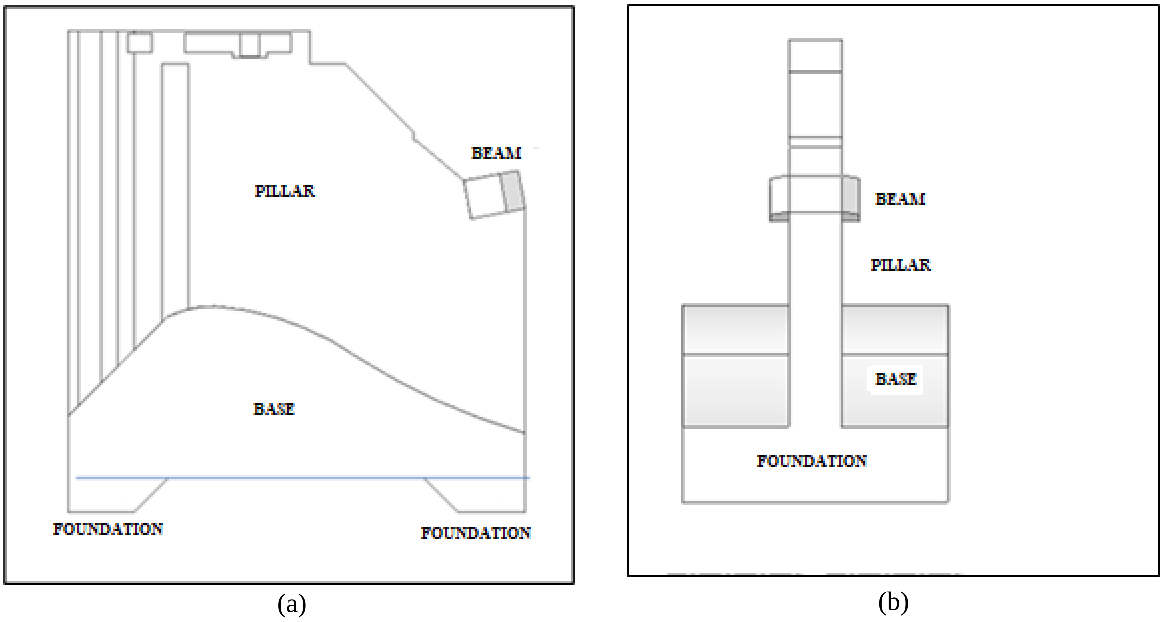
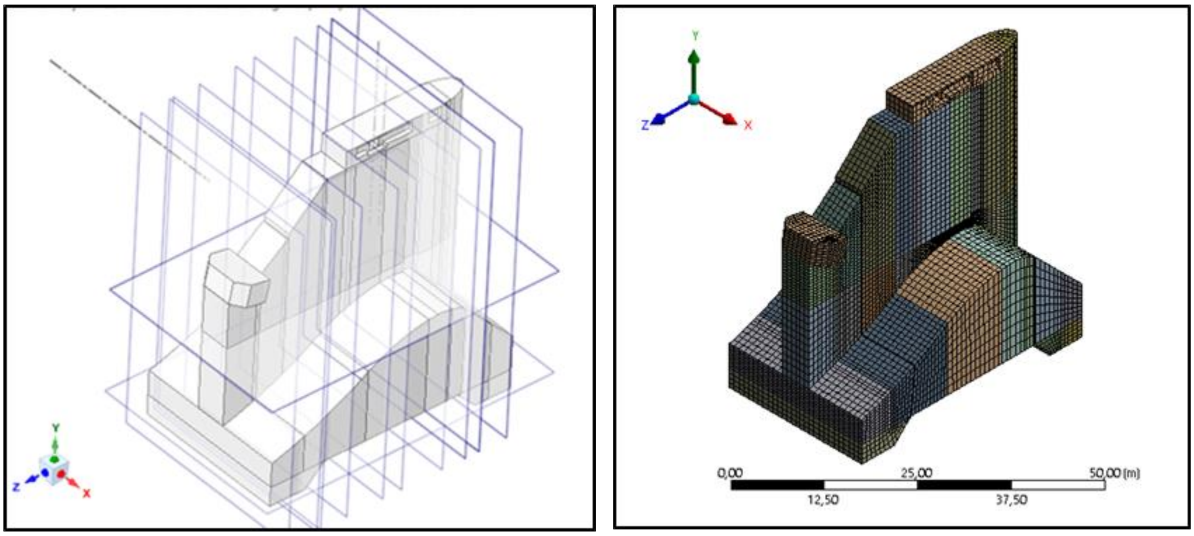


Figure 4. Block A-7 three-dimensional model, **(a)** Side View, **(b)** Front View. (**Source**: the author,2020)

3.2 Discretization of the structural model of block A-7

One of the characteristics of the FEM is to perform the discretization of a geometry in small parts, called finite elements [7]. The three-dimensional discretization of a structural element can be performed, using basically three types of elements, such as: tetrahedral, hexahedral and polyhedral.

Block A-7 is a large structure with several types of structural elements. To achieve satisfactory results, it was necessary to perform a refinement on each of the elements. It was planned to generate a mesh with predominantly hexahedral elements to decrease the number of elements and minimize the error in the results. As a result, a mesh with 141,874 node and 31,794 elements, predominantly hexahedral. Figure 5 shows the subdivision of the block, as well as the mesh and the elements generated.



(a) (b)

Figure 5. **(a)** Geometric model division, **(b)** Mesh. (**Source**: the author,2020)

3.3 Definition of thermal and mechanical properties of concrete

For the initial analyzes, the thermal and mechanical properties of the concrete were defined: the specific heat coefficient, thermal conductivity, specific mass and the modulus of elasticity, as shown in Table 1

Table 1 Thermal and mechanical properties of concrete

Section	**Specific Heat *(c)***	**Thermal Conductivity*(k)***	**Specific Mass *(p)***	**Elasticity Modulus *(E)***
	$J \cdot kg^{-1} \cdot K^{-1}$	$W \cdot m^{-1} \cdot K^{-1}$	$kg \cdot m^{-3}$ (*)	Mpa
Foundation	895,98	1,8492	2400	25600
Base	895,98	1,8492	2650	24440
Pillar	895,98	1,8492	2400	25600
Pre-Stressed Beam	895,98	1,8492	2400	25600

3.4 Interpolation of thermal data (Surface Thermometers)

In Figure 6, it can be seen that block A-7 has an upstream surface thermometer (TS-A-001) and four internal thermometers (TI-A-001, TS-A-002, TS-A-003 e TS-A-004), being the TI-A-004 near of concrete-rock surface.

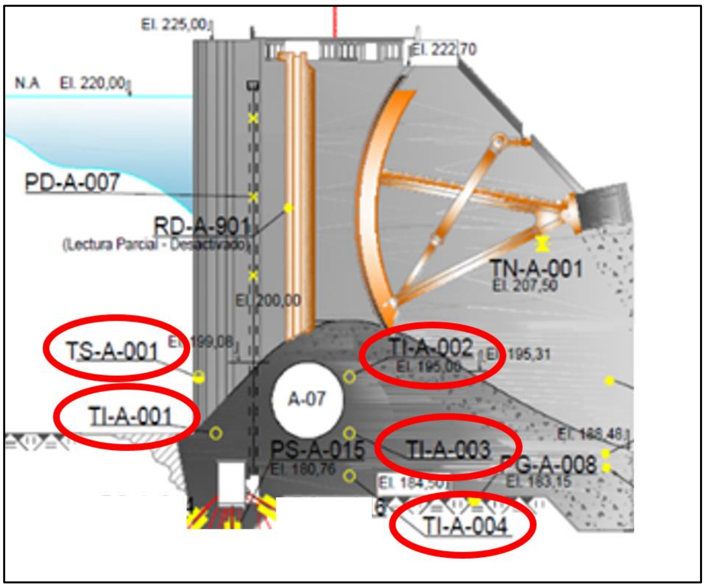


Figure 6. Block A-7 spillway instruments. (**Source**: SAT [8])

To determine the downstream edge temperature, the D-38 block thermometers was used (TS-D-003), as shown in Figure 7

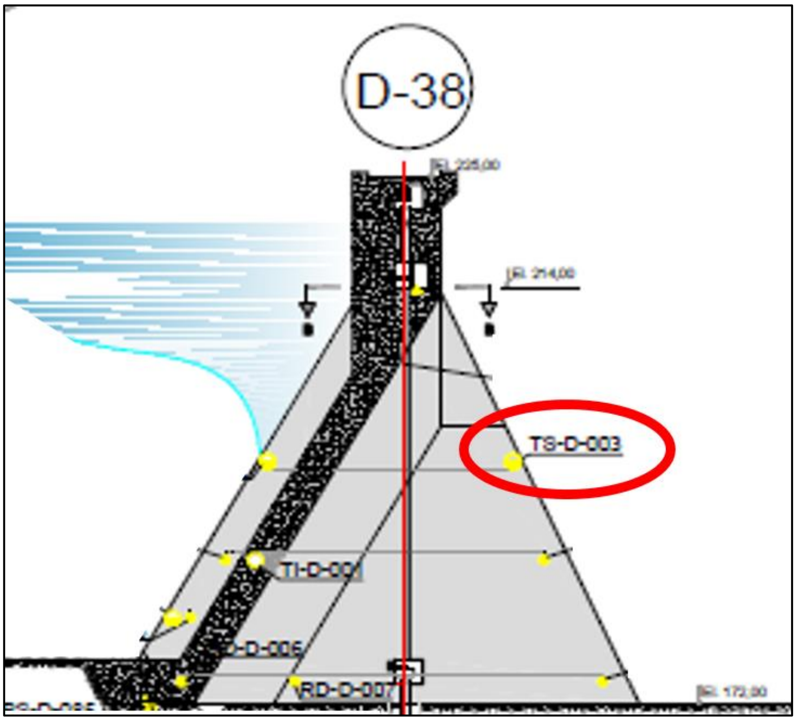


Figure 7. Block D-38 Instruments (**Source**: SAT [8])

Since the temperature measurements recorded on the thermometers are not periodic, it was necessary to perform an interpolation of the data using the cubic spline polynomial interpolation method using the MATLAB program, thus obtaining an daily temperatures for each instrument, from 1982 to 2019. Figures 8 and 9 show the temperature graphs of the interpolated instruments. It is observed that in 1982 the temperatures of the TS-A-001 surface thermometer are higher. This was due to the heat of hydration that was present at the time of concreting and that was dissipating during the first years after construction.

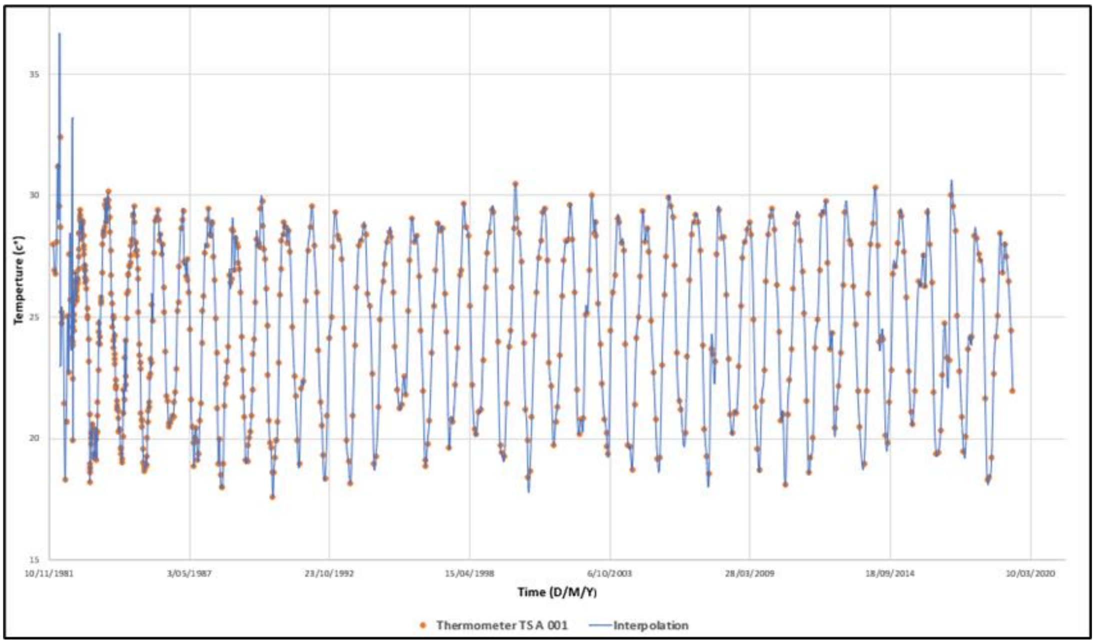


Figure 8. Interpolation of the thermal data of the TS-A-001 thermometer (Block A-7). (**Source**: the author,2020)

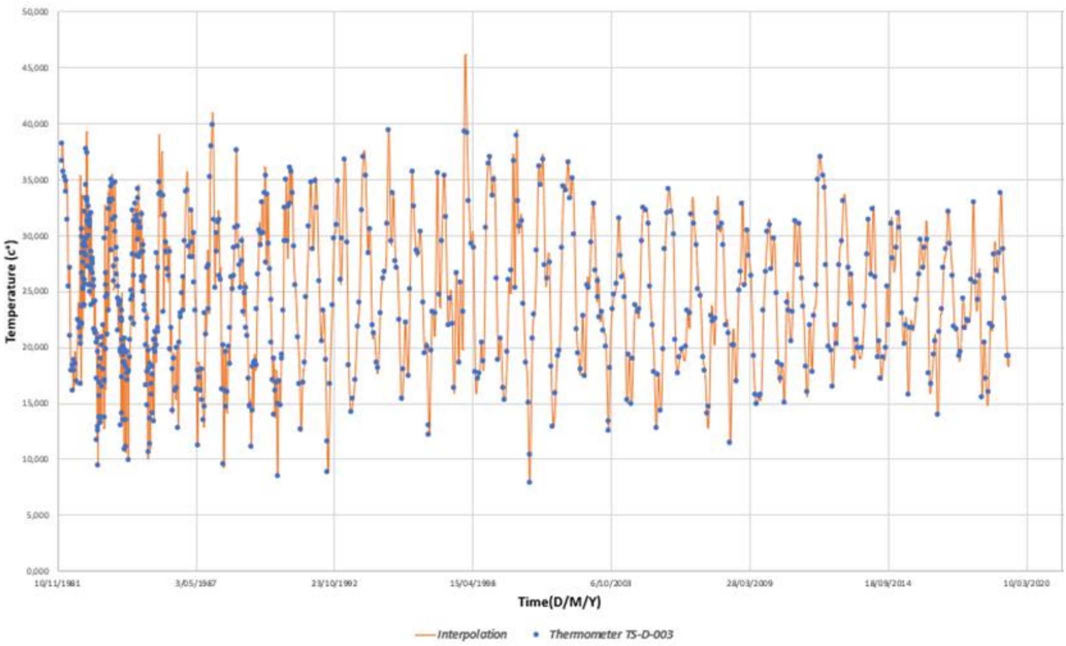
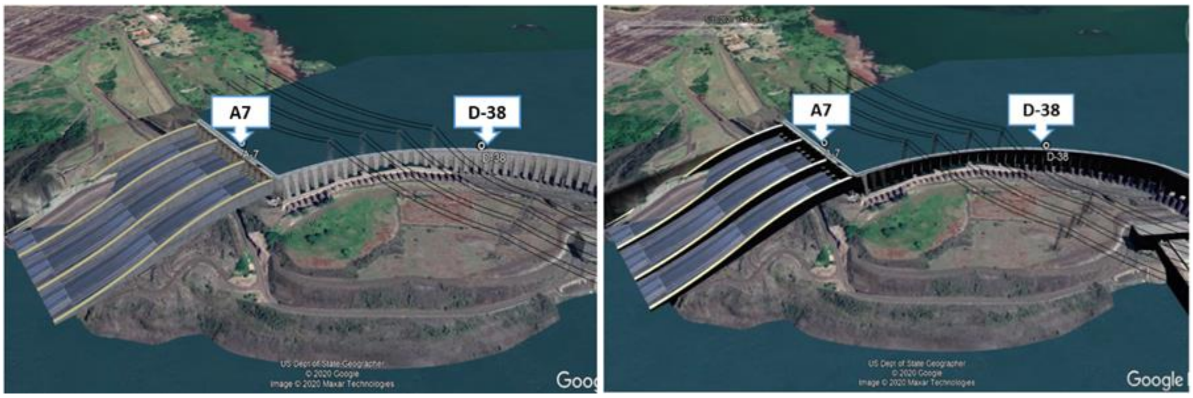


Figure 9. Interpolation of the thermal data of the TS-D-003 thermometer (Block D-38). (**Source**: the author,2020)

3.5 Analysis of the incidence of the sun on the faces of blocks A-7 and D-38.

An analysis of the incidence of the sun was carried out on the face of block D-38, where the surface thermometer used in the analysis is located. The faces irradiated by the sun in these two blocks were verified at the same time. Thus, it was possible to conclude that the temperatures recorded by the surface thermometer on the D-38 block downstream face could be used on the left side of the pillar and base of block A-7, making an extrapolation. Figure 10 shows the incidences of the sun in block A-7 and D-38 in the morning and afternoon.

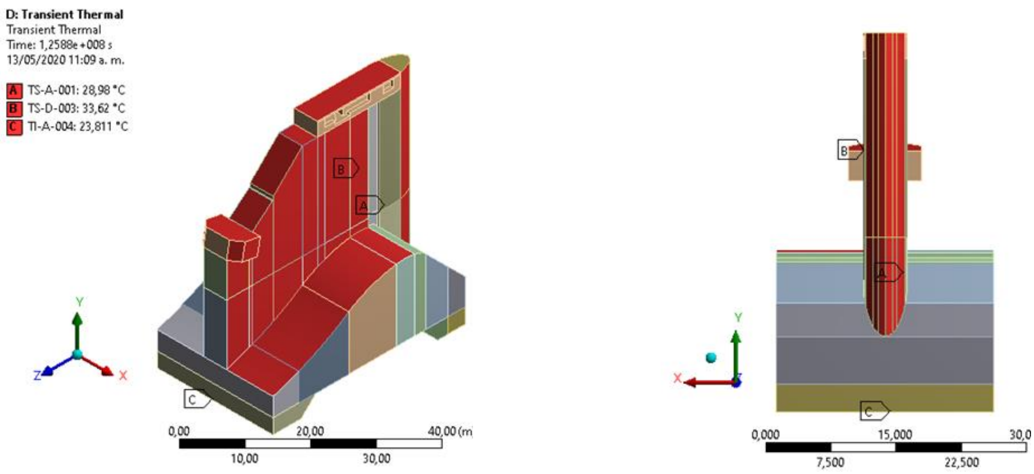


(a) (b)

Figure 10. Incidence of the sun on the dam **(a)** Morning, **(b)**Afternoon. (**Source**: Google Earth, 2020)

3.6 Definition of time step and thermal boundary conditions

The temperatures of the TS-D-003 thermometer were applied to the left side of the pillar and to the base of block A-7, which were defined considering the incidence of the sun in the block. Subsequently, the surface temperatures of the TS-A-001 thermometer were applied to the pillar on the upstream face, from the base of the pillar to the height of 225. It was found that the internal thermometer TI-A-004 is very close to the face between concrete and rock, being possible to use this thermometer as superficial, this in order to be able to simulate the behavior of the block in the foundation. Figure 11 shows the boundary conditions applied to the model, considering the thermal data of the thermometers and their location in the block.



(a) (b)

Figure 11. Thermal boundary conditions **(a)** Isometric View, **(b)** Rear View. (**Source**: the author,2020)

Due to the low thermal conductivity of the concrete, it was necessary to determine a period of the time, which allows the temperatures applied on the surface to be distributed to the core of the block during the summer and dissipated during the winter. A time period of 1460 days is defined, corresponding to 4 years (from 1982 to 1985). Figure 12 shows the temperatures of the surface thermometers inserted in the model, considering 4 years.

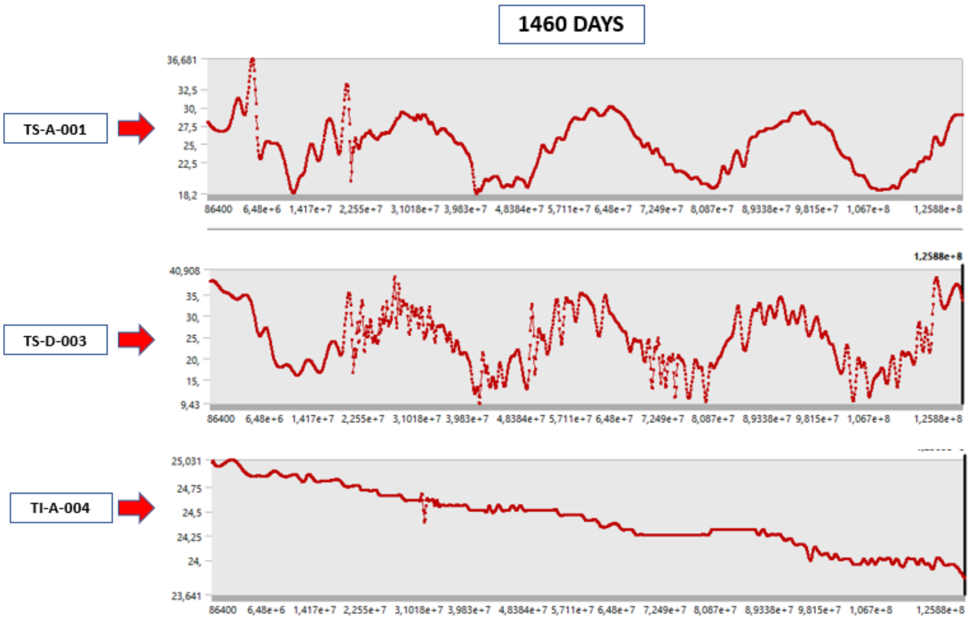


Figure 12. Temperatures entered in the thermal simulation of the block. (**Source**: the author,2020)

3.7 Analysis of the results of the thermal model

Once surface temperatures were applied to the faces, checkpoints were inserted at the internal thermometers position. Block A-7 has 4 internal thermometers (TI-A-001, TI-A-002, TI-A-003, TI-A-004) distributed as shown in Figure 13. It is noteworthy that the TI-A-004 internal thermometer was not used as a checkpoint, since its temperature was used as an edge condition.

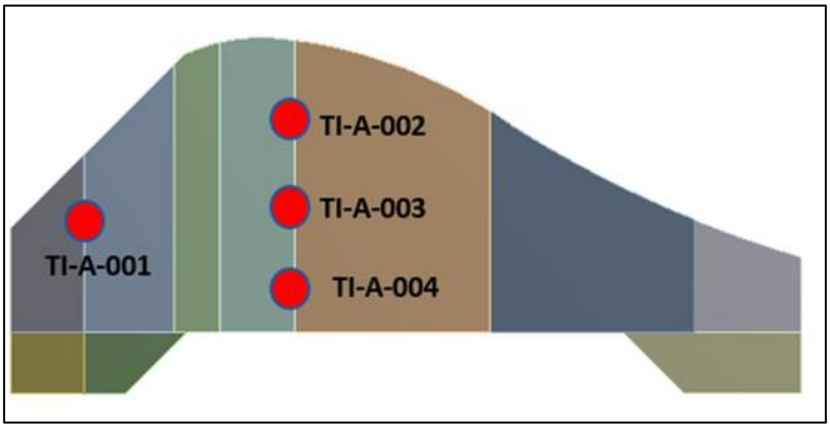


Figure 13. Location of the internal thermometers of block A-7. (**Source**: the author,2020)

The validation of the model was performed by comparing the results obtained in the simulation and the data from the internal thermometers. The verification was performed using the mean of the absolute percentage difference (MAPE), an approximation of 1.71%, 0.94% and 1.16% was obtained for the TI-A-001, TI-A-002 and TI-A-003 thermometers, respectively. The results are shown in Figures 14 and 15

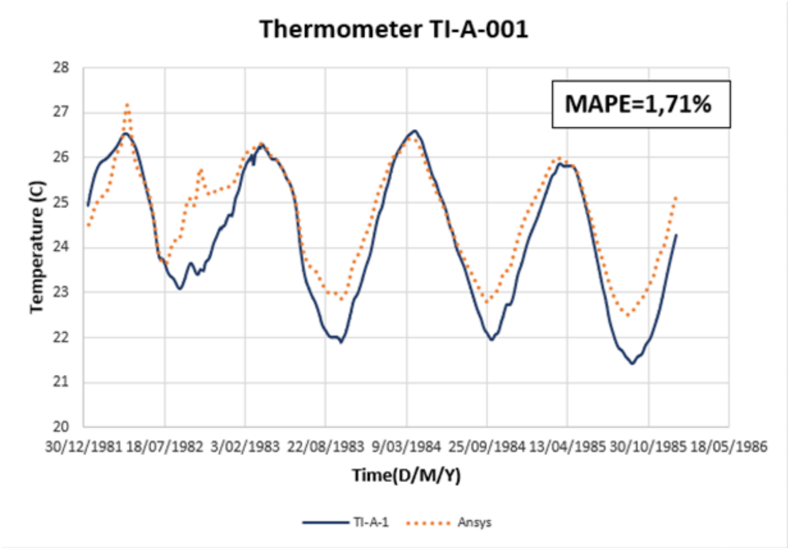
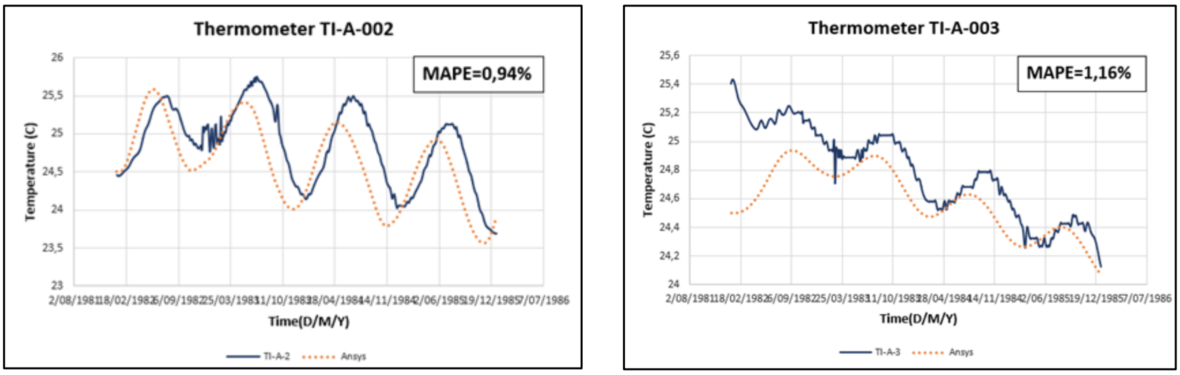


Figure 14. Thermometer Result Comparison TI-A-001. (**Source**: the author,2020)



(a) (b)

Figure 15. Comparison of thermometer results**(a)** TI-A-002, **(b)**TI-A-003. (**Source**: the author,2020)

Once the model was validated, the results of the simulations in the winter and summer periods in each simulated years were analyzed, from 1982 to 1985. It was observed that during the winter the highest temperatures were present in the core of the block. In summer, the highest temperatures are located at the ends (Figure 16). It is also observed that the internal temperature of the block gradually decreases every year. This effect is reproduced by the TI-A-004 internal thermometer, located close to the concrete rock contact in the block foundation and may be a consequence of a slow decrease in the internal temperature of the block caused by the cement hydration heat or/and a water percolation on the rock foundation.

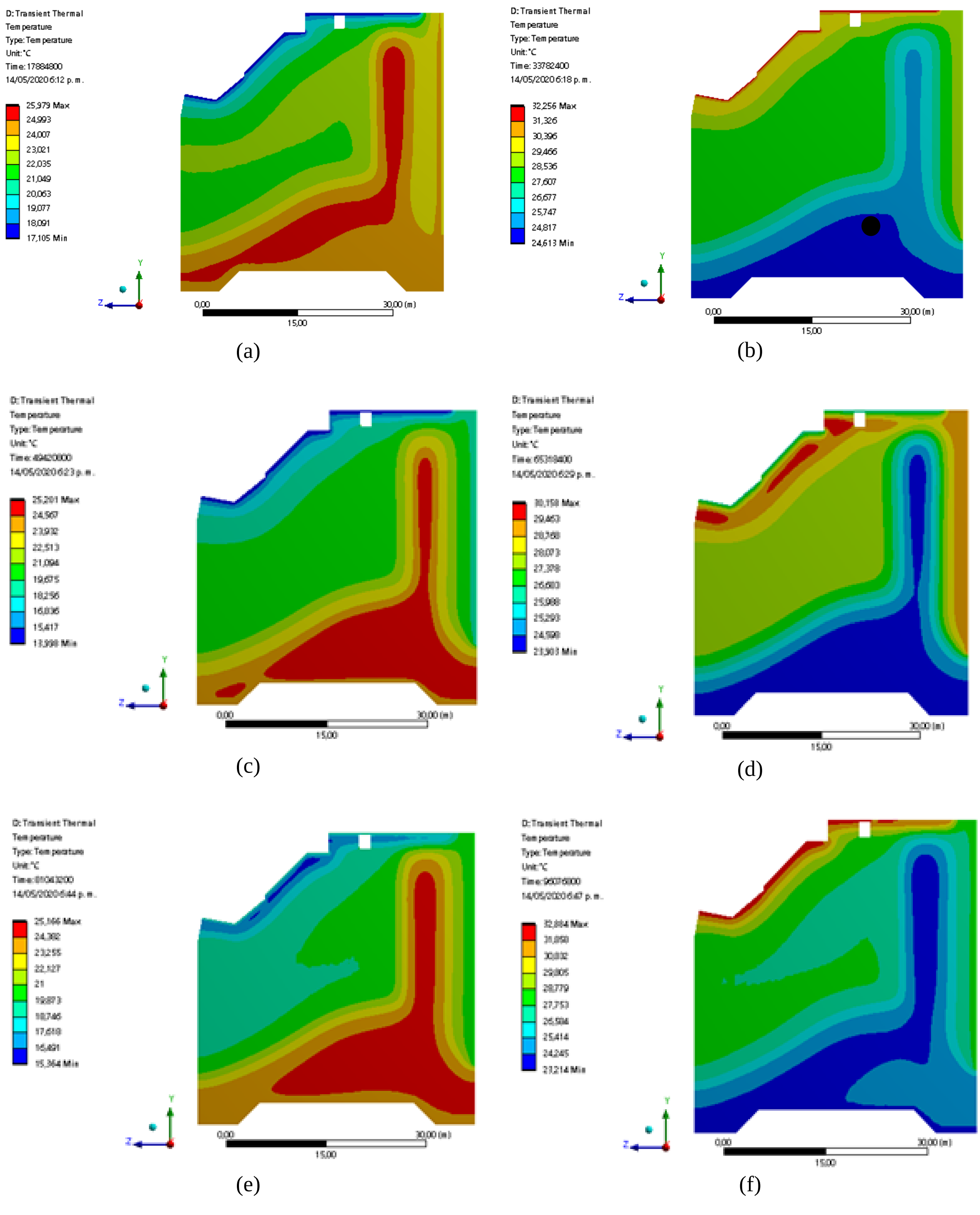


Figure 16. Thermal distribution in block A7 **(a)** 5/08/1982- Winter **(b)** 5/02/1983- Summer **(c)** 5/08/1983- Winter **(d)** 5/02/1984- Summer **(e)** 5/08/1984- Winter**(f)** 5/02/1985- Summer. (**Source**: the author,2020)

4 Conclusions

Due to the lack of surface thermometers downstream, the thermometer from another block was used. However, through analyzes, mainly of the solar incidence in the blocks, it was considered that this extrapolation is representative for block A-07.

Several analyzes were performed considering the lower surface of the block (contact between the concrete of the dam and the rock foundation) an adiabatic region. In these analyzes, the internal temperature values of the simulated block differed from the values of the internal thermometers. Thus, the internal thermometer temperatures were used, very close to the concrete rock contact as an edge temperature condition, resulting in internal numerical values very close to those registered by the internal thermometers taken as a control point. A justification for this phenomenon may be the percolation of water in this region, which ends up removing heat from this surface, so that the edge conditions used previously did not represent reality. Another effect that may also be responsible for the internal temperature variation in addition to the seasonal variation of the ambient temperature is the slow cooling of the concrete due to the hydration heat originated in the construction of the block.

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