THERMAL ANALYSIS OF AN RCC GRAVITY DAM DURING CONSTRUCTION : BI-DIMENSIONAL SOLUTION PROPOSED BY STUCKY – COMSA [1]

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SUMMARY : With the help of a 2D Finite Elements software, the assessment of the dam body behaviour due to the concrete heat emission has been performed. The concrete temperatures at several locations of the dam body have been computed, in particular at the exact position of the thermometers at levels 35.0 masl and 50.7 masl. The maximal temperature reached in the centre of the dam body is around 41°C. The significant effect of the air temperature acting on the top of the dam and on the upstream and downstream faces has been observed with temperatures along the faces closely linked to the air temperature. As well, the thermal stresses within the concrete triggered by the heat emission have been assessed. A maximal tensile stress value ranging between 0.7 MPa and 1.0 MPa develops in the vicinity of both faces.

RÉSUMÉ : Au moyen d'un programme bi-dimensionnel d'Eléments Finis, le comportement du barrage dû au dégagement de chaleur du béton durant la construction a été estimé. La température du béton en plusieurs points particuliers du barrage a été calculée, en particulier à l'emplacement des thermomètres aux niveaux 35.0 msm et 50.7 msm. La température maximale atteinte vaut environ 41°C au centre du barrage. L'effet important de la température de l'air a été constaté à proximité des parements amont et aval du barrage, avec des températures de béton réagissant fortement aux conditions ambiantes. Egalement, les contraintes thermiques dans le béton engendrées par le dégagement de chaleur du béton lors de sa prise ont été calculées. La valeur maximale de la contrainte de traction est relevée à proximité des parements et varie entre 0.7 MPa et 1.0 MPa.

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[1] Analyse thermique d'un barrage-poids BCR durant sa construction : solution bidimensionnelle proposée par STUCKY – ComSA

1. INTRODUCTION

In the framework of the 7th Benchmark Workshop on Numerical Analysis of Dams held in Bucharest in September 2003, the study of the thermal behaviour of an RCC gravity dam during construction is proposed to the participants.

As requested, emphasis is put in this paper on the temperature development within the dam body. But the computation of stresses due to temperature has also been performed and is shortly presented at the end of the study[2].

The method used in this analysis relies on a bi-dimensional Finite Elements modelling of the dam and the successive construction steps by means of the software Z_SOIL. This versatile software allows to take into account the influence of all determinant parameters playing a role in the long-term temperature and stress fields inside the concrete dam body.

Section 2 recalls the main data of the problem, whereas Section 3 introduces briefly the characteristics of the software used to solve the problem. Then Section 4 describes the main assumptions made for the purpose of the computation, leading to Section 5 addressing the results of the problem in terms of temperature and stresses. Finally Section 6 summarises in a conclusion the main results and lessons learned with this exercise.

2. MAIN DATA

Only the main features of the project are mentioned below. The reader interested in the complete data of the problem, in particular the common cross-section of the dam, the construction schedule and the tables/curves with the properties of the RCC material and the temperatures monitored on site will refer to the information of the problem provided by the formulator.

The gravity dam to be studied is 92 m high (between elevation 20.0 and 112.0 masl), with a 8 m large crest, a vertical upstream face and a 0.8:1.0 downstream face. The lower part of the upstream face between elevations 20.0 and 55.0 masl is inclined with a 0.4:1.0 slope.

The dam is essentially composed of RCC, which is placed in 0.30 m thick layers with a rate of placement of approximately 1 lift per day. Typically 10 layers are placed at this rate and then a standby is observed locally, during which RCC is placed in other sections.

Both dam faces are made up of conventional vibrated concrete (CVC) which is placed against the formwork and carefully vibrated in order to ensure the best possible bond with the RCC.

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[2] With the quantity of information available for the case study, it was decided from the beginning to stick to a maximum of 60 hours of work. The results presented could actually be obtained within that time frame.

The cementitious content of RCC is composed of 100 kg/m^3 of Portland cement and 90 kg/m^3 of pouzzolanic fly ashes (PFA). On the other hand the CVC used along the faces is made of 350 kg/m^3 of Portland cement.

3. DESCRIPTION OF THE SOFTWARE

Z_SOIL software provides an attractive alternative to traditional approaches to geotechnical and structural problems. It uses recent advances in non linear finite element techniques and plastic modelling of soils and rocks to solve stability, load carrying capacity, deformation and creep issues, including consolidation of two-phase media and transient flow, with excavation/construction sequences, in an unified, cost-effective way. Thermal effects and moisture migration are also included in the software. Z_SOIL exists in 2D and 3D versions.

In the framework of this present study, the 2D version has been used (Z_SOIL V.6.11; for further details, see the web site : www.zace.com). As the problem raised is mainly a thermal issue, the modules of the software linked to rock and soil mechanics have not been used. For the purpose of this study, mainly the possibilities of modelling taking into account the time and construction sequences as well as the thermal effects developing within the concrete mass have been used.

4. MAIN ASSUMPTIONS

4.1 DAM GEOMETRICAL DEFINITION

The model of the gravity dam reflects the exact dimensions and geometry as given in the general information of the problem. Figure 1 shows the model, which is composed of 5’784 nodes and 5’577 elements.

For the sake of simplicity, both CVC strips along the upstream and downstream faces have been discarded.

The use of a 2D Finite Elements model to assess the temperature development within the dam body implies that no heat transmission takes place in the third dimension. This assumption is particularly sensible as the method of RCC placement in successive layers makes the problem essentially bi-dimensional.

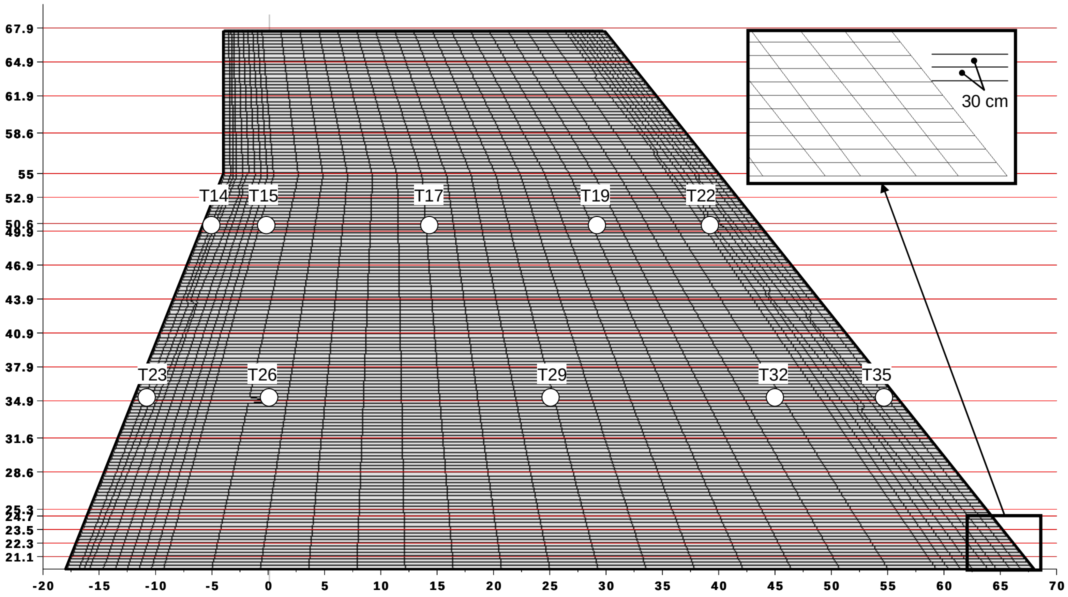

Figure 1 : General View of the 2D FE Model

4.2 CONSTRUCTION PROCEDURES AND SCHEDULE

The schedule of RCC placement as given by the instruction of the formulator has been carefully followed. In particular, every 30 cm thick RCC layer has been introduced in the model and placed successively according to the schedule.

The upstream and downstream formworks have been maintained in position during three days after the RCC placement. Then the formwork is released and installed at its new, higher position. The concrete starts diffusing heat 5 hours after placing (dormant period). From 5 hours to 72 hours, the diffusion occurs through the formwork, whereas from 72 hours onwards, the formwork is removed and the diffusion takes place in the air.

The computation has been run with a selected time step of 12 hours.

4.3 CHARACTERISTICS OF MATERIALS

All properties of RCC material given in the directive have been used for the computation. To model the heat emission of RCC, the “Shrinkage Core Model” developed by Bazant has been used. Of particular interest is the formulation of the heat source H as a function of the maturity M :

$$H(t,T)=H_{\infty}\frac{aM}{1+aM} \qquad (1)$$

The maturity M is a function of the absolute temperature T and time t :

$$M(t,T)=\int_{t_d}^{t}\exp\left[\frac{Q}{R}\left(\frac{1}{T_1}-\frac{1}{T}\right)dt\right] \qquad (2)$$

Where :		
	H_∞	Total value of concrete hydration heat per unit volume [kJ/m^3]
	a	Heat source parameter [1/day]
	Q/R	Activation energy / universal gas constant [°K]
	T_1	Reference temperature, normally 20°C = 293 °K
	t_d	Dormant period [day]

For this exercise the values adopted are the following :

H_∞	265 kJ/kg x 190 kg/m^3 = 50’350 kJ/m^3
a	0.125 1/day
Q/R	4’000 °K
T_1	20°C = 293°K
t_d	5 hours = 0.2083 day

This set of parameters (in particular the parameter a) has been selected according to the own experience of the authors and in order to fit in an acceptable way the hydration heat curve given by the formulator.

4.4 INITIAL AND BOUNDARY CONDITIONS

The ambient temperature at site has been chosen equal on both upstream and downstream faces as well as on the upper face of the dam. Even though it might be considered somewhat rough, the average temperature given by the formulator has been selected for the case study. As the average temperature data provided cover approximately 12 months and the problem extends on 22 months, the data have been assumed equivalent cyclically from one year to the next.

Furthermore, the RCC temperature at placement has been assumed constant throughout the year at the value of 24°C. Given that this temperature ranges during the year from 23°C up to 27°C, this assumption is deemed acceptable.

The convection & radiation surface coefficient has been selected as α=100 kJ/m^2/h/°C, as suggested in the directive. During the first three days after RCC placement (when the formwork is still in position), this coefficient has been selected at the value of α=28.8 kJ/m^2/h/°C (=8 W/m^2/°K). No correction of both parameters has been made owing to the sunshine effect.

Finally the rock foundation of the dam has been selected as providing adiabatic thermal conditions, that is, no heat dissipation of concrete occurs through the foundation.

5. RESULTS

5.1 TEMPERATURE

5.1.1 Temperature Versus Time

The temperature development at levels 35.0 masl and 50.7 masl is shown in Figures 2 (Level 35.0 masl) and 3 (Level 50.7 masl).

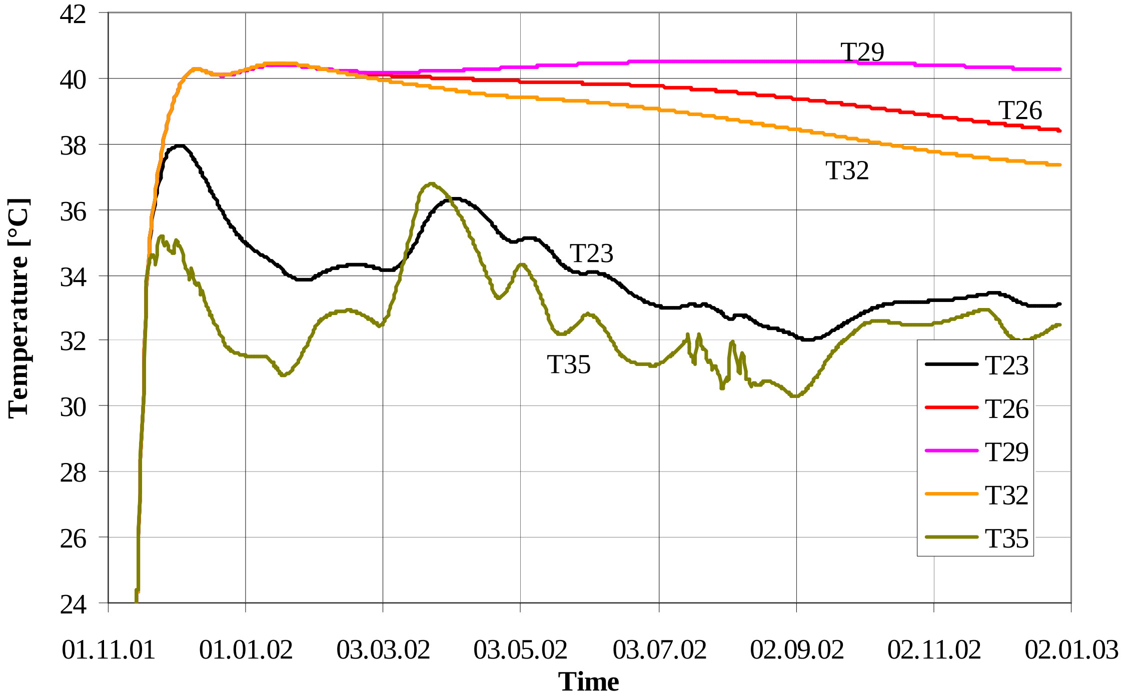

Figure 2 : Elevation 35.0 masl, Temperature Vs. Time

At level 35.0 masl, the temperature at the core of the dam is stable around 40.5°C. Thermometer T29 is located at the centre of the dam, whereas thermometers T26 and T32 are at 12 m and 11 m respectively from the upstream and downstream faces. That is the reason why the temperature at those two points drops faster than in the very centre (T29).

When coming closer to the dam faces, the variations of temperature become similar to the average air temperature. It is interesting to see that thermometer T23, located 2 m behind the upstream face, is less sensitive to air temperature moves than thermometer T35, which is located only 1 m behind the downstream face. The curves for these two thermometers seem somewhat chaotic, because the rough average air temperature curve has been used for boundary conditions. Making that curve smoother by considering seasonal trends rather than daily average air temperature values would have resulted in smoother concrete temperature curves close to the faces (T23 & T35).

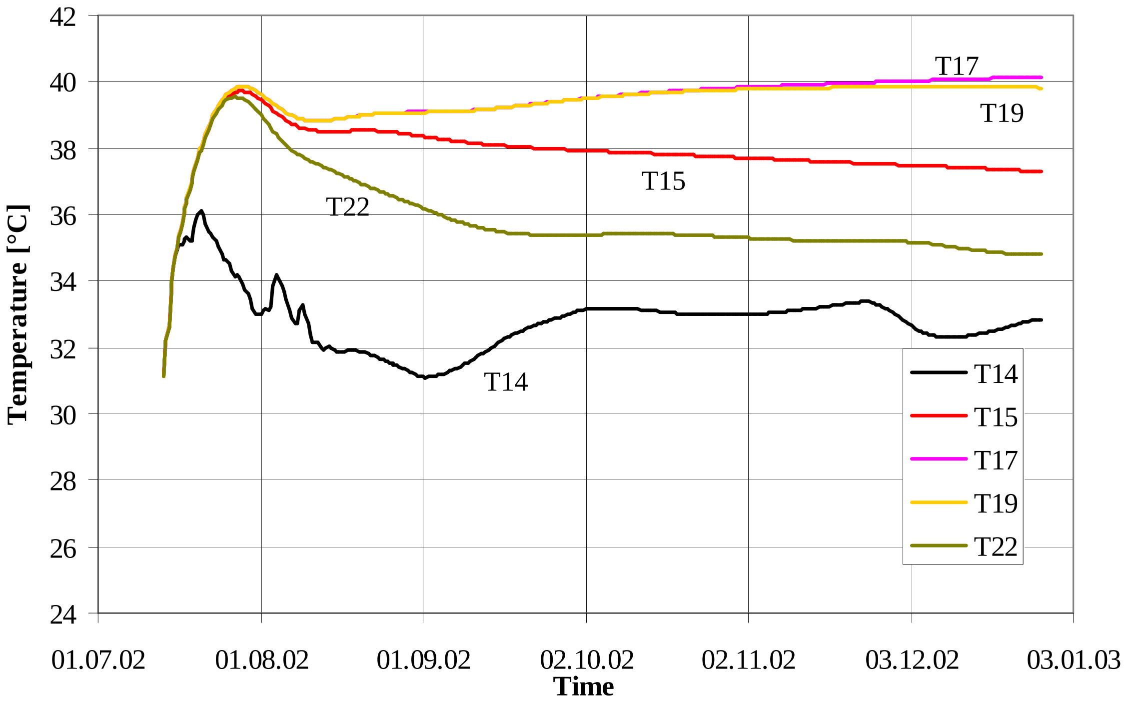

Figure 3 : Elevation 50.7 masl, Temperature Vs. Time

The temperature behaviour described for the elevation 35.0 masl also applies to elevation 50.7 masl (Figure 3). The temperature at the centre of the dam stabilises around 40°C.

Thermometer T14 is the most sensitive to average air temperature for it is located only 72 cm behind the upstream face. Thermometer T22, 3.44 m behind the downstream face, is already far less influenced by the air temperature.

With regard to both Figures 2 and 3 above, it can be seen that the main temperature gradient takes place in the first 3 to 5 m behind the dam faces.

5.1.2 Elevation Versus Temperature

For three given dates, Figure 4 shows the evolution of temperature within the concrete mass at different locations and elevations of the dam. For each specific date, two curves are provided that show the temperature in the centre of the dam (bold line) and in the vicinity of the dam face (thin line).

It is to notice that the distance from the face of the curves showing the temperature close to the face is variable with the three different dates : on July 27, 2002 the curve shows the temperature at 2 m from the upstream face, on August 10, 2002 the temperature is monitored at 2 m from the downstream face and on December 28, 2002 the temperature is shown at 4 m from the downstream face. This difference reflects in the curves, with the temperature measured 4 m behind the downstream face (December 28, 2002) clearly with higher temperature than the other two curves measured closer to the face (2 m distance) and thus more sensitive to the air temperature.

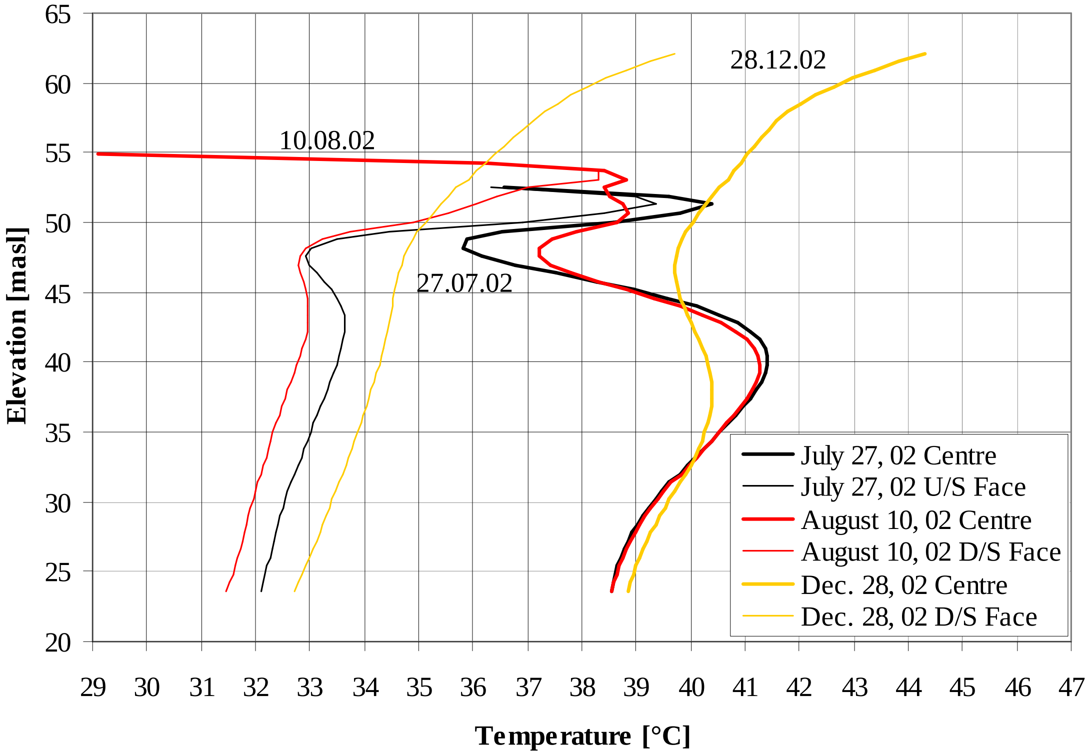

Figure 4 : Elevation Vs. Temperature at Given Dates

In addition it is to note that the temperature value ranging from 39°C to 41°C and prevailing in the core of the dam is clearly visible in Figure 4. When going up and coming closer to the upper, more recently placed RCC layers, the effect of the heat emission and air temperature builds up and becomes increasingly noticeable.

5.1.3 Horizontal Profiles

Figures 5 and 6 show the horizontal temperature profiles at level 35.0 masl and 50.7 masl respectively.

The temperature profile seen at level 35.0 masl is more constant and regular than at level 50.7 masl. This is explained by the distance from the level of measures (35.0 masl and 50.7 masl) up to the level of RCC placement at the date considered : the closer to the upper surface, the closer to the high, ongoing temperature emission and to the effect of air temperature acting of the upper surface. This is clearly noticeable on Figure 6 (level 50.7 masl), where on July 27, 2002 the temperature reaches more than 40°C whereas it has notably started cooling down to approximately 39°C on August 10, 2002.

The strong influence of the air temperature is also remarkable along the dam faces. In particular the very end of the temperature curve is not very relevant and significative, as it is directly influenced by the average air temperature, which has not been smoothed for the purpose of this case study.

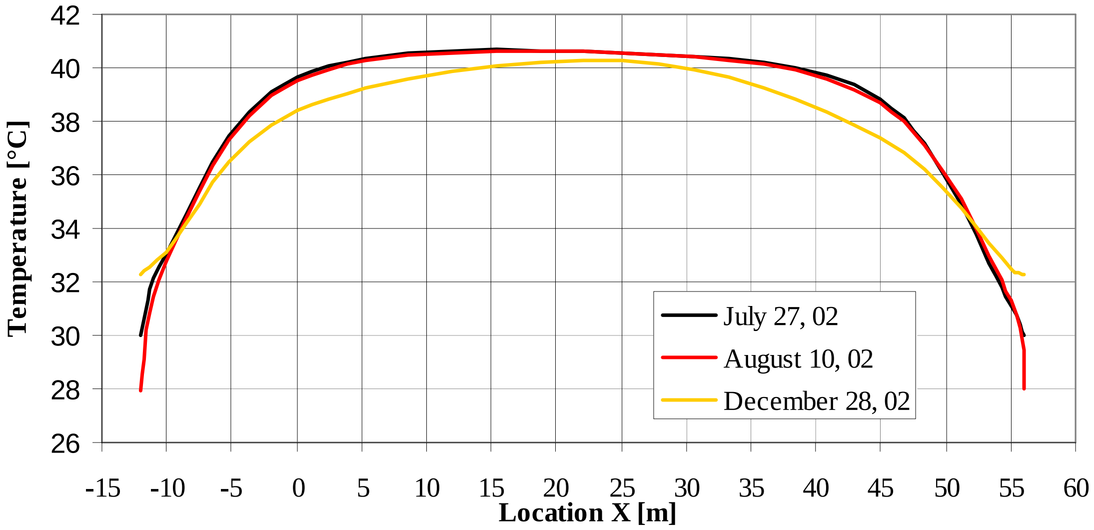

Figure 5 : Horizontal Temperature Profile at Level 35.0 masl

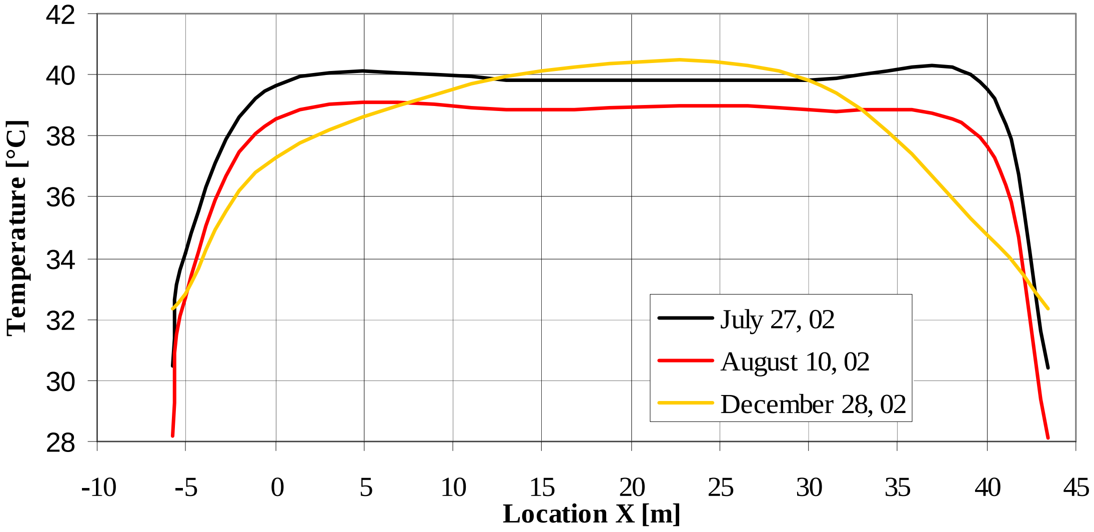

Figure 6 : Horizontal Temperature Profile at Level 50.7 masl

Finally it is interesting to note that the effect of heat dissipation through the dam faces becomes more and more visible in the long-run (see the curves for December 28, 2002); the cooling of the central portion of the dam has not started yet at that date, mainly due to the progress of works (addition of new RCC layers on the top of the dam).

5.1.4 Graphic Outputs

Some 2D graphic outputs are given below (Figures 7 to 10), that show by means of isotherm lines the temperature distribution in the dam body at the date considered.

Two pairs of dates have been selected : (1) August 7, 2001 and November 6, 2001, period during which the concrete works were stopped at level 31.6 masl, and (2) January 31, 2002 and July 11, 2002, when the concrete works were stopped at level 49.9 masl.

Although with black and white pictures only, the process of heat emission and concrete cooling is clearly noticeable in both cases. As well, the adiabatic boundary condition of the foundation is particularly obvious on those figures.

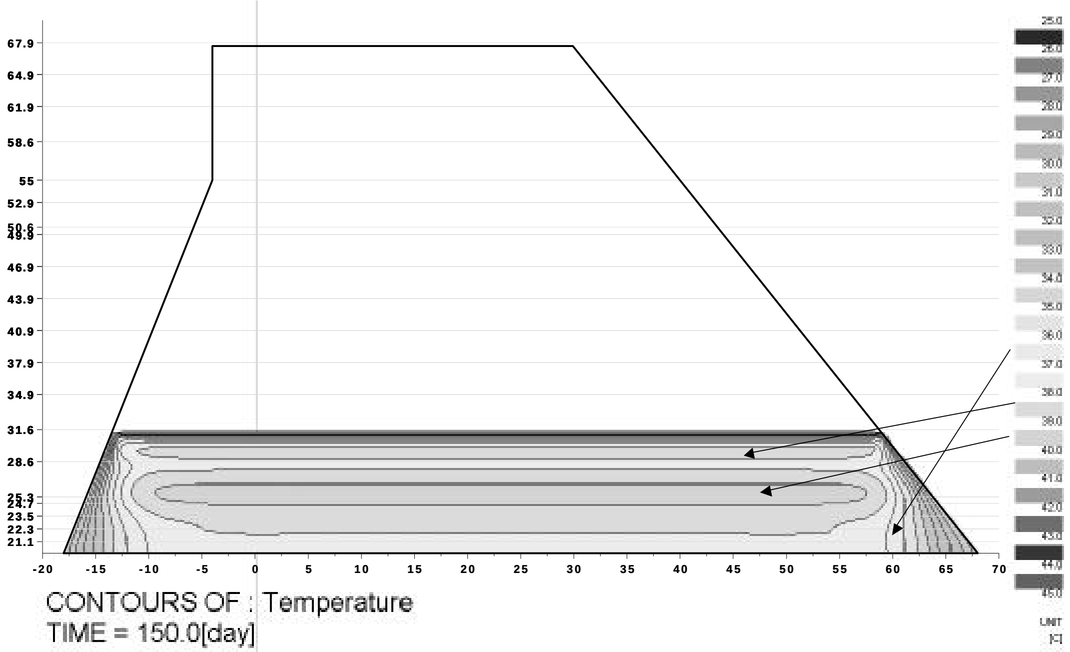

Figure 7 : Temperature Distribution in the Dam Body on August 7, 2001

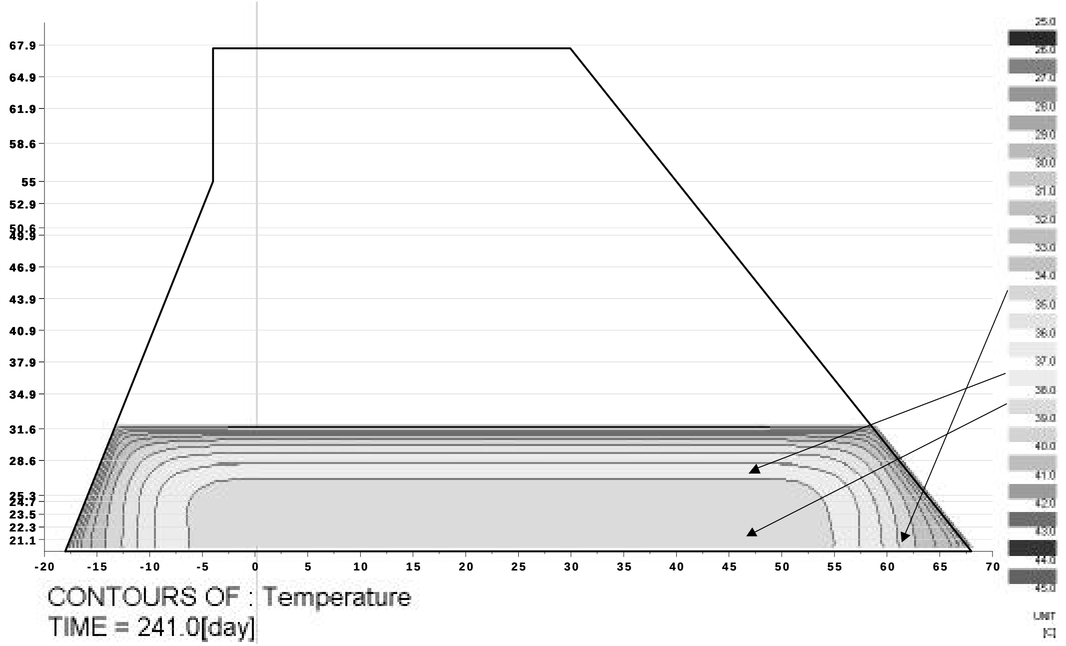

Figure 8 : Temperature Distribution in the Dam Body on November 6, 2001

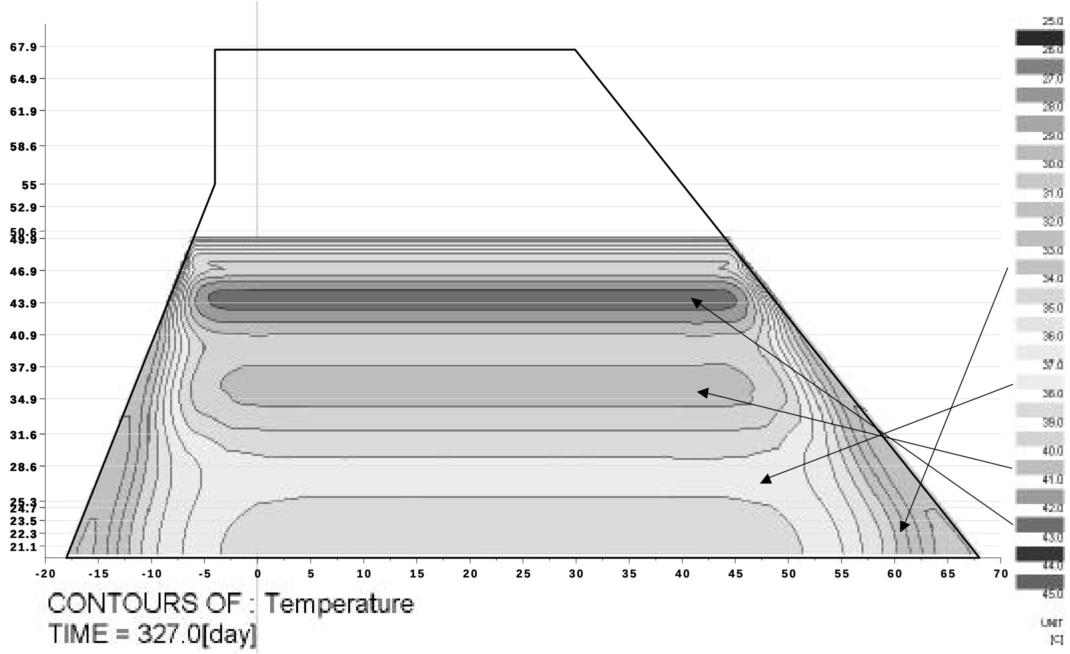

Figure 9 : Temperature Distribution in the Dam Body on January 31, 2002

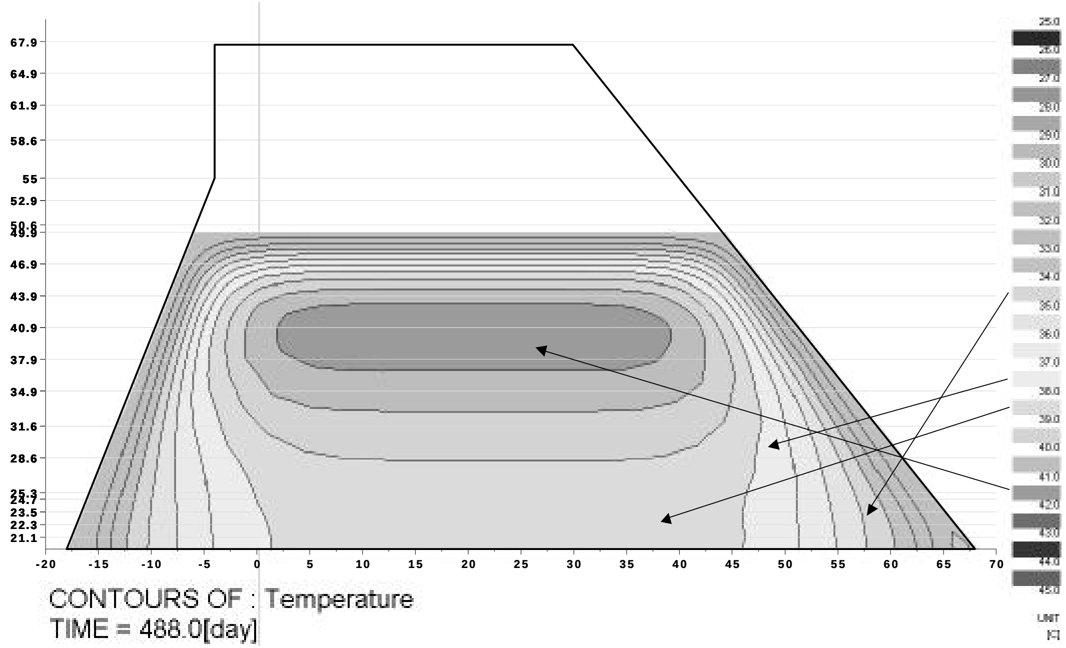

Figure 10 : Temperature Distribution in the Dam Body on July 11, 2002

5.2 STRESSES

The temperature developing within the concrete body induces thermal stresses. More attention is to be paid to tensile stresses, as they may trigger cracks in the concrete mass. Below are given some general considerations about the stress field due to the thermal conditions discussed above (concrete heat emission and air temperature). A more detailed and thorough study on the issue of thermal stresses would require more time and is anyway irrelevant in the context of the current case study.

The computation has been run in elastic conditions. A conventional Elasticity Modulus vs. Time law has been introduced in the model in order to enable the software to compute stresses in the concrete.

The tensile stress field is shown in Figures 11 and 12 for two dates : January 31, 2002 and July 11, 2002. Interestingly these two pictures can be linked to Figures 9 and 10 presenting the temperature field at the same time. Between these two dates no additional RCC layer is placed (the upper surface remains unchanged at elevation 49.9 masl), meaning that the evolution of the temperature and stress fields is only caused by the air temperature changes and the cooling through the upper surface and both upstream and downstream faces of the dam.

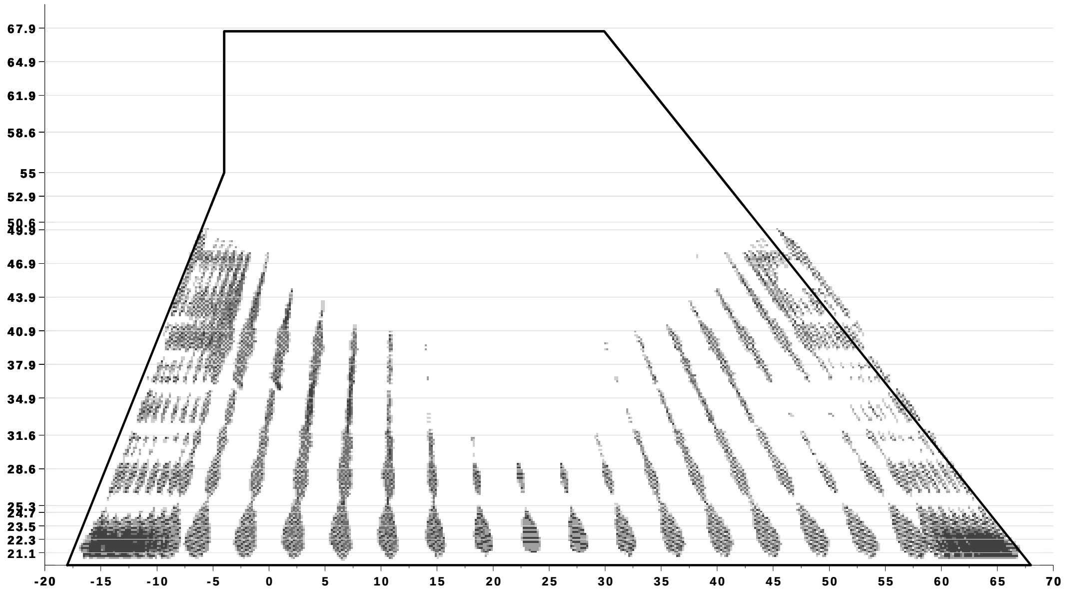

Figure 11 : Tensile Stresses Distribution in the Dam Body on January 31, 2002

It is to notice that both Figures 11 and 12 do not show stresses due to temperature effect only. As the dead weight of the concrete is inseparable from any other load case, it has been included in the computation and is therefore taken into account in the graphic outputs.

Not surprisingly the tensile stresses are the highest close to both faces and reach values ranging between 0.7 MPa and 1.0 MPa, depending on which time is considered. They occur mostly perpendicular to the faces, where the temperature gradient is the highest.

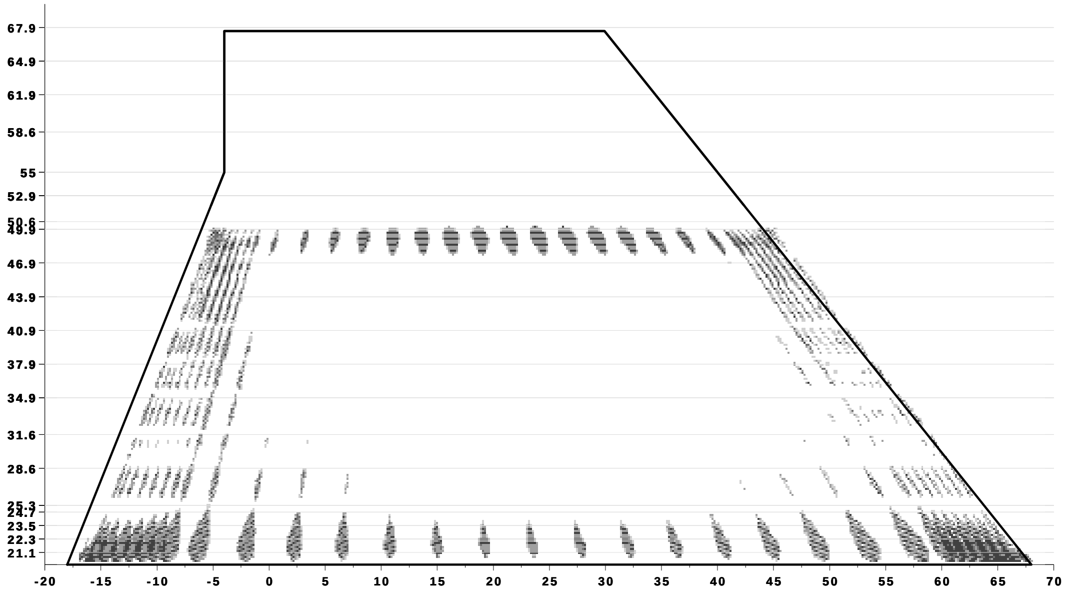

Figure 12 : Tensile Stresses Distribution in the Dam Body on July 11, 2002

When comparing Figures 11 and 12 carefully, it is clearly noticeable that with time going by and the temperature field moving to a more steady state (see Figures 9 and 10), the stress field accordingly moves toward less tensile stresses. The large area without tensile stresses located in the centre of the dam body on Figure 12 illustrates that slow and gradual change.

Finally the effect of the foundation is clearly visible. The tensile stresses prevailing there are due to the FE modelling : the boundary conditions for the foundation have been selected as rigid, thus not allowing any movement of the foundation. This assumption is too pessimistic and explains why the highest tensile stresses are observed in the vicinity of the foundation.

6. CONCLUSION

The analysis of the thermal behaviour of an RCC gravity dam during construction has been presented in this article. Beside the data provided by the formulator of the problem, the study has called for further assumptions. The most crucial ones are the following :

(1) The model is two-dimensional.
(2) The CVC strips located on both the upstream and downstream faces of the dam have not been considered.
(3) The air temperature accounted for in the study is not a smooth annual curve, but the average temperature provided in the instruction of the case.

Assumption (1) can be considered as acceptable, because the RCC placement method is mostly continuous in the third dimension, that is along the dam longitudinal axis (across the valley). On the other hand, assumptions (2) and (3) are more subject to discussion and might well have played a role in the results presented here. However, it has been assumed that both assumptions affect the temperature field developing in the dam body only locally in the vicinity of both dam faces and in an reasonable way for the major portion of the dam.

The temperature field has been presented. The temperature developing in the centre of the dam body reaches approximately 41°C and is very slow to decrease. Conversely the concrete temperature in the first metres behind the upstream and downstream faces is strongly influenced by the air temperature prevailing on the job site. In addition to the various temperature curves asked by the formulator in the context of the case study, some graphic outputs have been given that allow a different outlook onto the temperature development within the dam body.

Finally, some considerations, results and graphic outputs have been provided about the thermal stresses triggered by the concrete heat emission. Those thermal stresses develop mainly along the dam faces, where the temperature gradient is the highest. The maximal stress observed seems to range between 0.7 MPa and 1.0 MPa.