TRANSIENT THERMAL ANALYSIS OF A CONCRETE SPILLWAY

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Abstract: This paper presents a feasibility study of casting with 4.7 m concrete lift height as well as casting along the entire length of a chute of a concrete spillway. To this end, a detailed transient thermal analysis was carried out based on concrete heat of hydration and site conditions (wind, ambient temperature, etc.). Using this analysis, a representative temperature profile was determined and, in a subsequent mechanical analysis, was combined with other types of loads in the analyses made for steel reinforcement design. The transient thermal analysis was conducted based on a realistic construction scenario. Moreover, a detailed 3D finite element model was prepared and analysis was conducted taking into account thermal concrete-rock contact. Two scenarios corresponding to two concrete lift heights were examined : (i) the standard height of 2.3 m (current practice), and (ii) the desired 4.7 m height which significantly enables the reduction of casting time and associated work. Results obtained from the two scenarios are presented and compared.

1 INTRODUCTION

In the frame of optimizing the hydro-electric concrete mass structures, this study is conducted to validate the feasibility of concrete casting considering, on one hand, a lift height of 4.7m for the piers of the spillway, and considering, on the other hand, a length over the whole spillway chute. To validate this lift height of 4.7m, a detailed thermal analysis should be conducted first to provide the temperature distribution profiles of the spillway considering the heat of hydration of concrete. These temperature profiles should be combined with other types of loads in order to estimate the required amount of steel reinforcement for the spillway concrete structure.

A thermal study, based on a realistic scenario of construction, was conducted using the tridimensional finite element (FE) program Abaqus (Dassaut-Simulia, 2011). For this reason, two scenarios of construction were examined. The first considered a standard lift height of 2.3m and the second considered the desired lift height of 4.7m. This lift height of 4.7 m will allow a substantial reduction of the duration of concrete casting work. Results of this study demonstrate the benefits of the advanced numerical tools for rational design of strategic hydraulic structures.

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The transient thermal analyses were conducted using Abaqus standard solver. Modeling details and input data are summarized hereafter.

2.1 Geometry of the structure

As shown in Figure 1, the geometry of the spillway is prepared using Simulia-Catia software. In this study, a part of the rock was also included in the model to account for the concrete-rock thermal interaction.

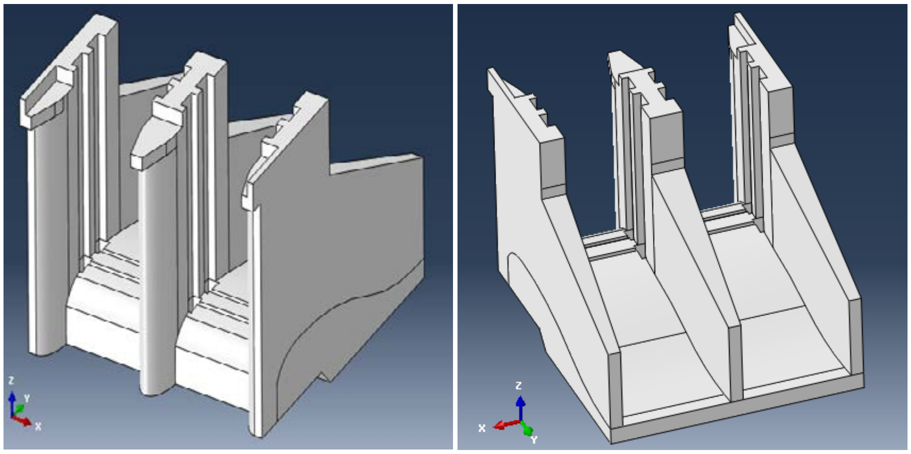
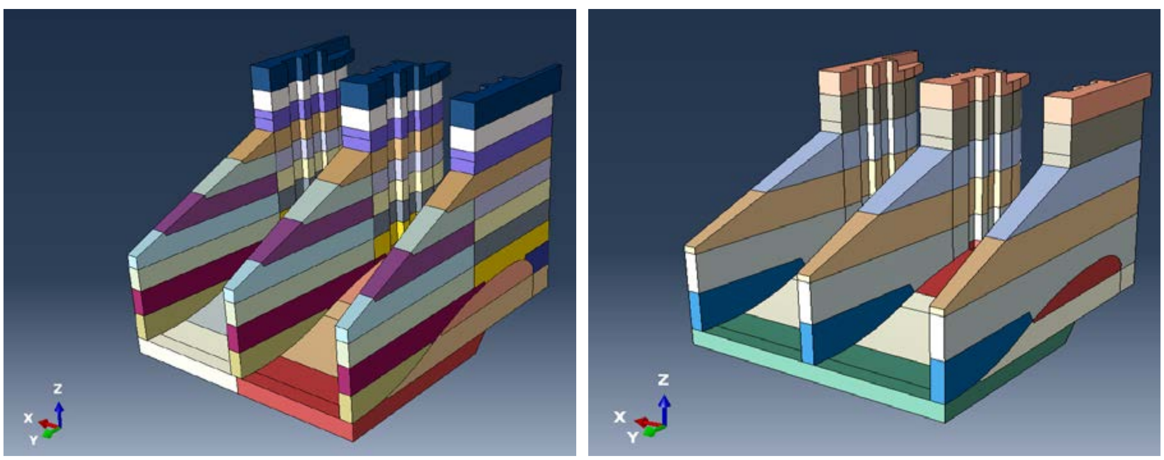


Figure 1. Geometry of the concrete spillway.

As indicated earlier, the current feasibility study was conducted considering two lift heights; namely, the standard height of 2.3 (mean value) which represents the current practice for typical mass concrete structures (SN26.1, 2011), and the desired height of 4.7 m (mean value). This latter will result in a significant reduction of concrete casting time. As illustrated in Figure 2, two separate finite element models, including the rock, were prepared using Abaqus software. The figure depicts, using color sets, the different lift heights for each model for the two scenarios (2.3 m and 4.7 m).



a. 2.3 m scenario. b. 4.7 m scenario.

Figure 2. Spillway lifts description.

2.2 Finite Element Mesh

The structure of the spillway and the rock were modelled using 3D solid elements (Figure 3). Tetrahedral 10 nodes elements were used in the simulation of the thermal field for the spillway and the rock (DC3D10: A 10-node quadratic heat transfer tetrahedron). A Tetrahedral 10 node element allows a quadratic representation of the nodal temperature within the element.

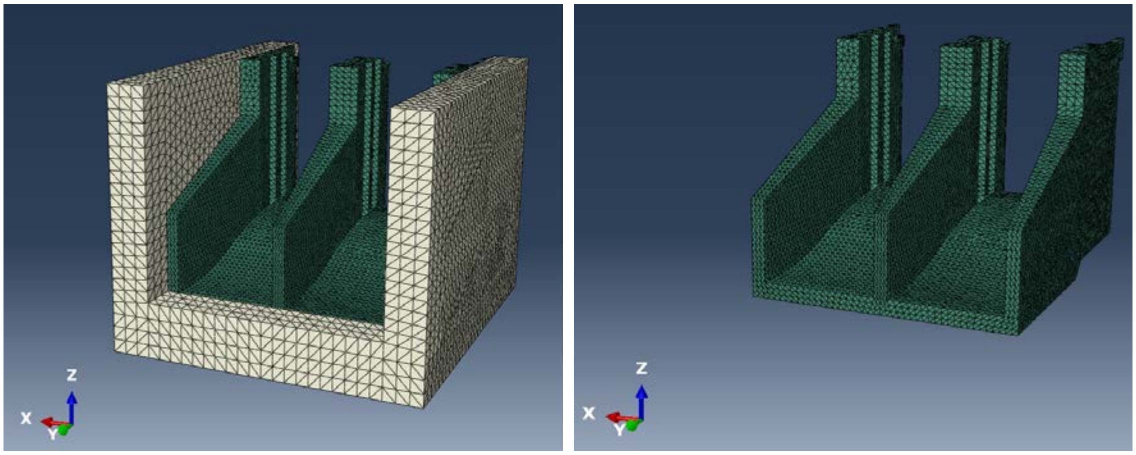


Figure 3. Mesh of the rock-spillway FE model.

2.3 Input data for the transient thermal analyses

The transient thermal analyses require the preparation of the flowing input data:

- Thermal properties of rock and concrete. These properties are summarised in Table 1.

Table 1. Thermal properties for concrete and rock.

	Concrete	Rock
Density (kg/m^3)	2400	2760
Conductivity kJ/(day m ^{o}C)	196	230
Specific heat kJ/(kg ^{o}C)	1.006	0.67

- Setting of a casting scenario as well as the starting date of the first lift. For this purpose, two different construction scenarios, corresponding to the two lift heights, were prepared and validated. Then, these two scenarios were simulated into Abaqus, considering the construction stages, by using the "Model Change" option available in the interaction module of Abaqus. In this context, 202 days and 156 days are necessary to complete the casting of concrete for the two scenarios (2.3 m and 4.7 m), respectively. Moreover, the transient thermal analyses for these two scenarios were conducted considering a time step of 0.25 day for the period of construction and 1 day for the remaining period of the year.

- Constructing a heat release curve in order to model the adiabatic temperature rise in accordance with the type of cement used in building the concrete spillway (Figure 4). This curve was established to be consistent with the LH-HQ-20M concrete (SN26.1, 2011) with cement having a reference value of 270 kJ/kg at 7 days and an amount of 223 kg/m^3 (Qualitas, 2013). As shown in Figure 5, the heat release curve is constructed considering only one FE cube in adiabatic conditions. The heat release curve is incorporated into the analysis and, as shown in Figure 5, the obtained results, in terms of temperature at the centre of the cube, is in perfect accordance with the temperature-rise-curve of this type of concrete.

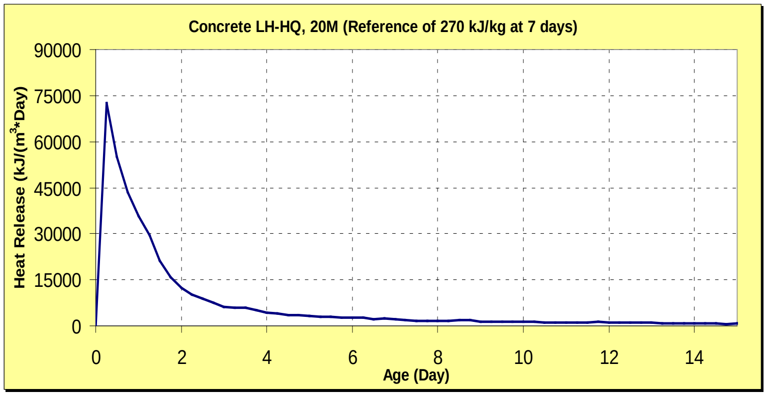


Figure 4. Heat release curve.

- Determining the ambient temperature during the one year period at the site of the study. For this reason, a curve constructed, using the daily mean values for a five-year period, for the site of Havre Saint-Pierre station (data were provided by Environment Canada) was adopted in the study. This station was selected because it is close to site of the study (Figure 6). However, as stipulated in the US-Army ETL1110-2-542 (1997) document, the ambient temperature was increased by 1 ^{o}C to account for solar radiation.

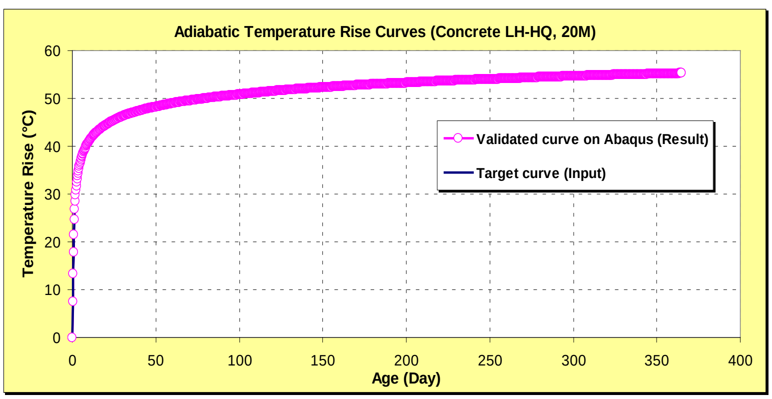


Figure 5. Adiabatic temperature curve.

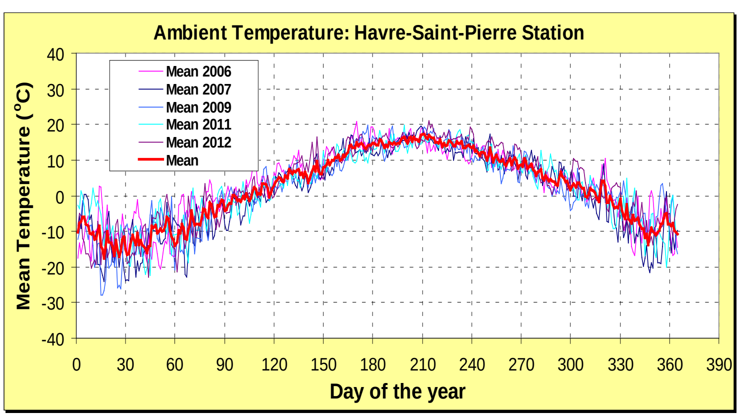


Figure 6. Typical ambient temperature for the site of the spillway (Havre Saint-Pierre, Quebec).

- Establishing the reference wind velocity of the site of study. A reference value of 10 km/h is obtained based on a five-year monthly mean curve (Figure 7) at the location of Havre Saint-Pierre station (data provide by Environment Canada).

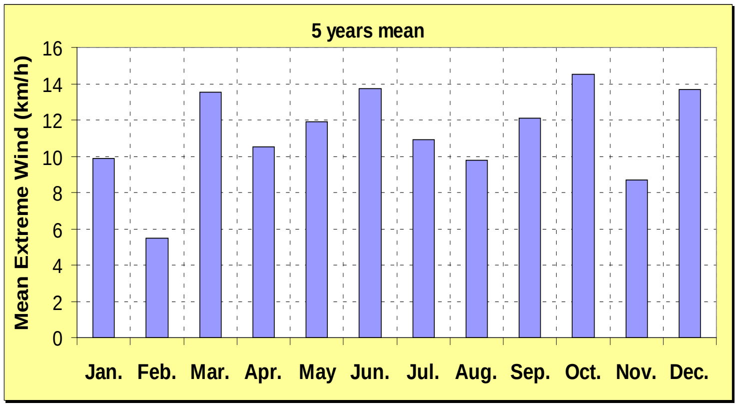


Figure 7. Typical wind velocity for the site of the spillway (Havre Saint-Pierre, Quebec).

- As shown by Figure 8.a, a thermal contact, type conductance, is considered for modeling the physical interface between rock and concrete.

- Determining the convection film coefficients to model heat exchange between the ambient environment and the rock-concrete system. These films were activated or deactivated during the thermal analysis considering the construction stage process. As shown in Figure 8.b, the films are characterised for the exposed faces of concrete and rock as well as for concrete formwork faces considering the daily mean ambient temperature curve. From the US-Army ETL1110-2-542 document (1997), the convection film coefficients h_a for the faces exposed to air are defined as follow :

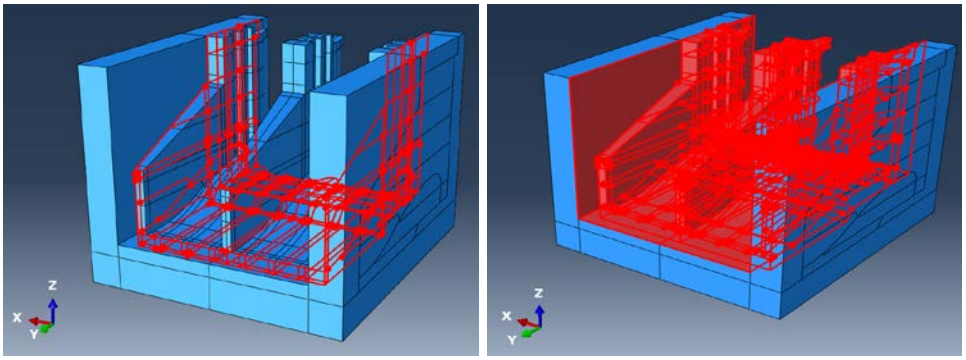
  [1] $h_a = c + a \cdot V \ (\mathrm{W/m^2} \cdot {}^o C)$

  with $a = 1.086$ and $c = 5.622$. Here V stands for wind velocity. As for the formwork faces, the coefficients h_c are expressed by:

  [2] $\frac{1}{h_c} = \frac{e_c}{k_c} + \frac{1}{h_a} \ (\mathrm{W/m^2} \cdot {}^o C)^{-1}$

  Where e_c and k_c stand for the formwork thickness and conductance, respectively. For a wind velocity of 10 km/h, h_a and h_c were selected to be equal to 1425 kJ/m^2 Day ^{o}C and 450 kJ/m^2 Day ^{o}C, respectively.

- Determining the concrete placement temperature in accordance with the specifications of Hydro-Quebec's document SN26.1 (2011). In this document, it is stipulated that the placement temperature for lifts in contact with the base rock should be 7^{o}C and should be 12^{o}C elsewhere. Moreover, and based on sensitivity analyses, the date on which pouring of concrete is critical is estimated around the 1st of July. This date is maintained for subsequent analyses. Furthermore, adiabatic conditions are considered for modelling the physical continuity of the rock.



a. rock-concrete thermal interface   b. convection films (air/formwork)

Figure 8. Surfaces definition for the rock-concrete thermal contact and convection film coefficients.

3 RESULTS AND DISCUSSION

The results obtained from the transient thermal analyses are summarized in Figures 9 to 12. For the 4.7 m scenario, it is observed that the peak temperature for all lifts does not exceed 50^{o}C. This peak value is acceptable according to US-Army ETL1110-2-542 document (1997). Moreover, this rise of temperature does not last for a long period of time. In fact, as shown in Figure 10, the temperature for each lift will follow the ambient temperature within the first year of the heat release. In addition, it can be noticed that the heat release period is relatively important for the spillway chute lifts C2 and C3 compared to piers lifts P1 to P6. This can be explained by the large volume of concrete lift poured in spillway chute which is several times greater than that poured in the concrete lifts piers.

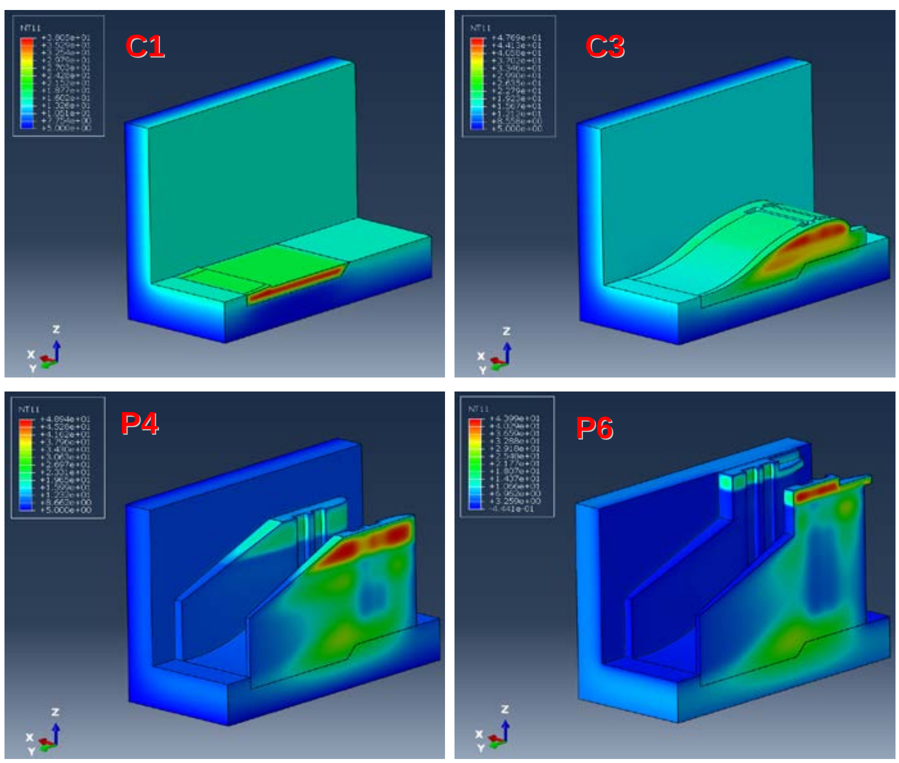


Figure 9. Temperature distribution for the 4.7 m scenario.

However, this study has demonstrated, as shown in Figure 12, that the temperature profiles for the 4.7 m scenario are in the same range as those obtained for the 2.3 m scenario. The small differences in the temperature profiles observed for these two scenarios are attributed to the small thickness of the concrete mass of the piers (ranging from 2 m to 4 m) which can not be compared to the large thickness of the concrete dam structure.

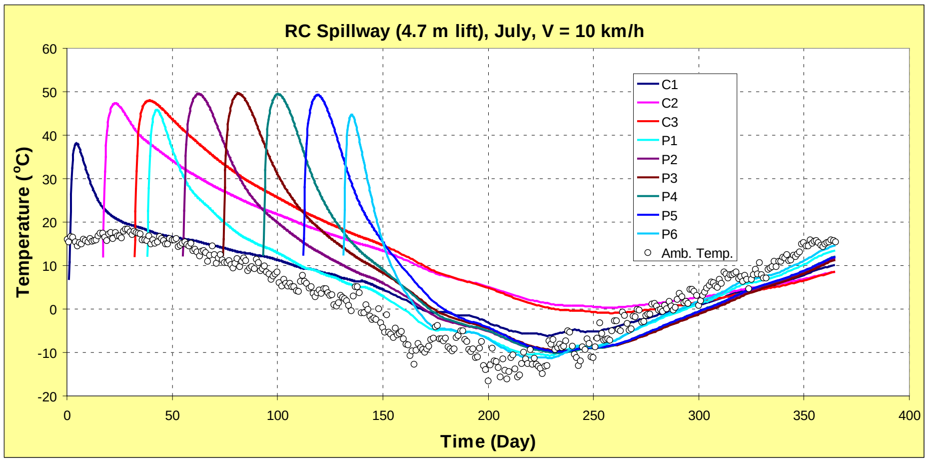


Figure 10. Temperature time history for the 4.7 m scenario.

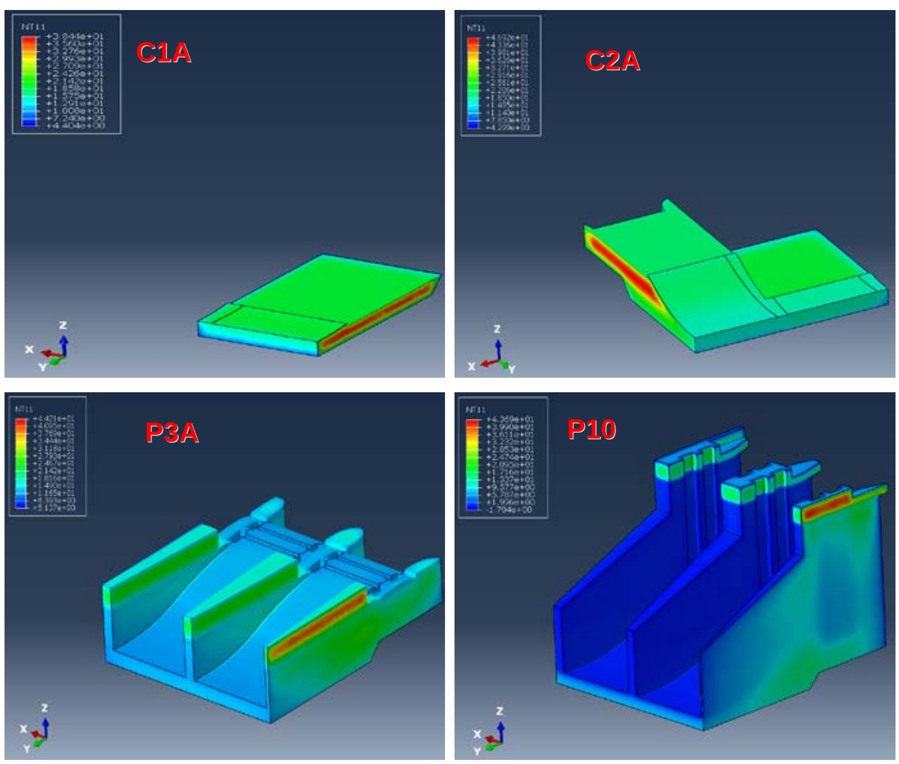


Figure 11. Temperature distribution for the 2.3 m scenario.

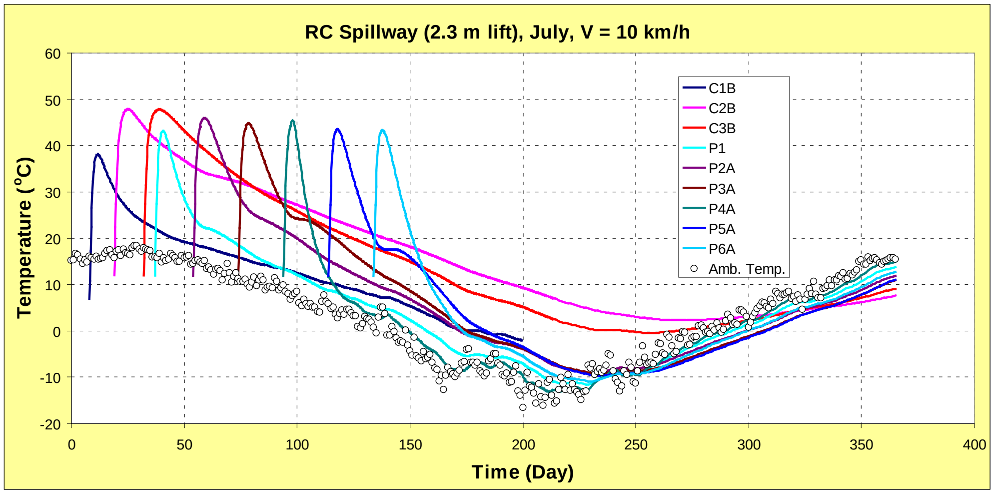
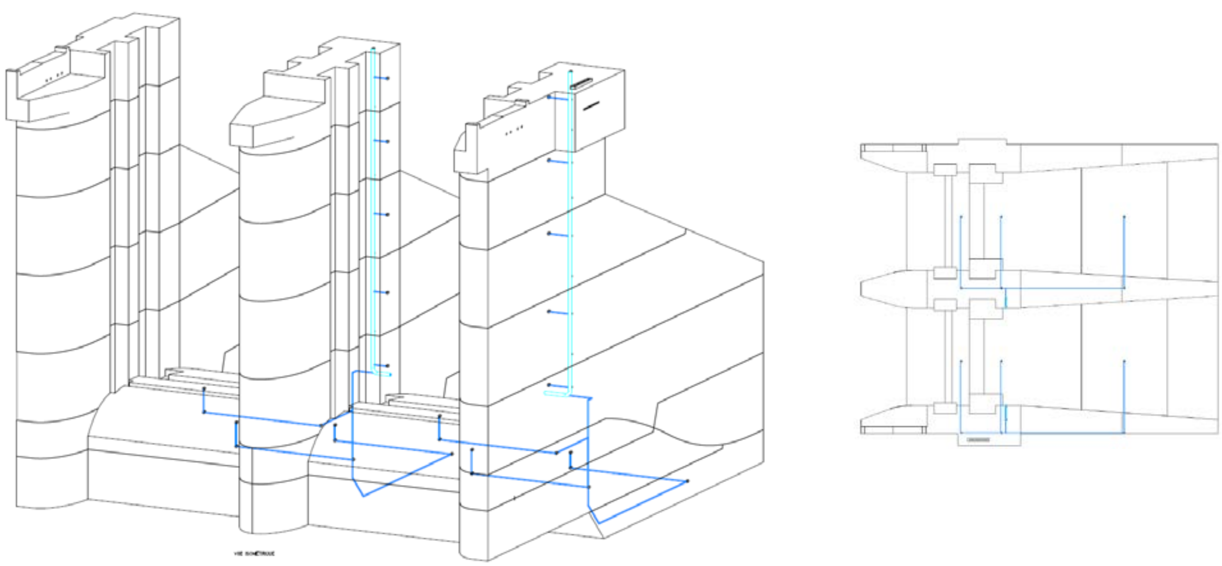


Figure 12. Temperature time history for the 2.3 m scenario.

An important element of this study is to acquire the behavioural data of the thermal distribution in the concrete. This allows the validation of the obtained temperature profiles from the numerical analyses. To this end, as shown in figure 13, instrumentation and monitoring are established and included in the design drawings. Hence, a total of 48 thermocouples type K are deployed for this spillway. The thermocouples wires are hosted in a PVC pipe and are connected to cabinet monitoring post. However, 16 thermocouples are installed in the concrete mass, 16 at the concrete surface (close to the concrete cover), 13 at the concrete interface lifts and 3 at the rock-concrete interface. Without exceeding one year, the minimum frequency of reading in a day is 4 times during the construction phase and 1 time thereafter.



a. Isometric view b. Plan view

Figure 13. Thermocouples deployment.

4 CONCLUSION

In this paper, it is presented the feasibility study of 4.7 m lift height of concrete casting, and casting along the entire length of the chute of the concrete spillway. To this end, a detailed transient thermal analysis is performed based on the concrete heat of hydration and the site conditions. Hence, two scenarios corresponding to two lift heights are examined (2.3 m and 4.7 m). Results obtained from the two lift height scenarios are presented and compared. It is observed that the peak temperature for all the lifts does not exceed 50^{o}C. Moreover, this rise of temperature does not stand for a long period of time and the temperature for each lift will follow the ambient temperature within the first year of the heat release. For the 2.3 m scenario, this study has evidenced, that the temperature profiles are in the same range to those obtained for the 4.7 m scenario. The observed small difference in temperature profiles for these two scenarios is attributed to the small thickness of the mass concrete of the piers (ranging from 2 m to 4 m) which can not be compared to large concrete dam structure thickness. Hence, the 4.7 m lift height is justified and retained as it allows significant reduction of time wok. This study has also demonstrated the benefit of the advanced numerical tools for rational design of strategic hydraulic structures.

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