State of the Art Thermal Analysis for Neckartal Dam

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1. Introduction

The Neckartal Dam Project is currently under construction on the Fish River near Keetmanshoop in Namibia. The main purpose of the dam is to form an impoundment of 857 million m^3 that will supply irrigation water to 5000 ha of agricultural development in the Karas Region. The outlet works at the dam is also equipped with a mini hydropower facility (3MW), which generates from the ecological releases made.

The dam wall is a 78,5m high mass gravity structure, aligned on a curved upstream axis and constructed using a zoned roller compacted concrete (RCC) mix. The crest length measures approximately 520m from abutment to abutment. The dam is equipped with a 395m long uncontrolled ogee spillway crest, which is divided into two segments. The main spillway defining full supply level (FSL) at 787,5 mASL is 290m long, and caters for flood peaks between the 5 to 10-year AEP (Annual Exceedance Probability) flood event. The raised spillway segment at 789,9 mASL is 105m long, positioned on the right flank for passage up to the SED (Safety Evaluation Discharge) and was specifically designed to reduce flow down the abutment that caused circulating flow downstream of the apron.

The dams structural section is a conventional gravity profile with sloped upstream face, 1:0,2 (V:H) and a stepped downstream face, defined on a slope of 1:0,75 (V:H). The dam is presently under construction by Salini Impregilo and will contain some 900 000 m^3 of RCC upon construction completion.

The project site is located in a semi-arid region, known for its hot desert climate with long, very hot summers and moderate to warm winters. Average monthly temperatures vary over approximately 14ºC throughout the year between winter and summer. Considering this temperature variation and owing to the size and significance of the structure, strict temperature controls are being enforced, achieved by restricting the allowable RCC placement temperature to 28ºC by means of a dedicated aggregate chilling plant.

In this paper, the authors present a summary of the related thermal analyses applied for the design of Neckartal Dam, undertaken to determine the magnitude of the anticipated thermal stresses that will develop and ultimately, to evaluate the potential for cracking within the RCC dam. In this manner, the typical approach and techniques required for a transient thermal and stress analysis of a major RCC dam is demonstrated.

2. Background

For large RCC dams, it is necessary to evaluate the impacts of heat development and dissipation associated with hydration of the cementitious materials applied in the design mix. As stated in U S Army Corps of Engineers (1997)(8), concrete thermal analyses must be performed for any significant mass concrete structure where a potential for thermal cracking exists. In the case of large RCC dams, temperature rise due to internal hydration heat development will generally peak within the first couple of weeks following placement but, once it has developed, it takes several years to dissipate to a steady state seasonal equilibrium temperature internally. The degree of temperature rise and final rate of subsequent dissipation varies- depending to the thermal properties of the mix, the construction procedure adopted, the overall geometry of the section and the external environmental exposure conditions.

Trapped heat progressively dissipates into the atmosphere through convection and the dam foundations via conduction. Volumetric changes thus continuously occur within the RCC dam during the temperature cycle. Differential thermal expansion and the thermal gradients established in this process often result in tensions that have potential to cause cracking, and is influenced by the degree of creep of the mass placement.

Shrinkage associated with long-term cooling must be accommodated to prevent uncontrolled cracking perpendicular to the dam axis. To this end, two distinct thermal effects that significantly influence the development of temperature-related shrinkage/expansion cracking in large RCC dams are evaluated;

- Surface Gradient Cracking

Surface gradient cracking develops due to short term differential shrinkage of the exterior surface of the dam with respect to the core. Soon after placement, heat loss quickly reduces surface temperatures to ambient, whilst the internal core becomes significantly warmer due to hydration heat gain. The resulting swelling of the core and shrinkage of the skin develops compressions within the expanded core and tensions across the surface, with a potential to cause exterior cracking (see Figure 2for illustration).

- Mass Gradient Cracking

As the body of the dam cools over time, two longer term processes give rise to thermal stresses. The first occurs as a result of the core shrinking more than the external zones as a consequence of greater creep and a greater cooling range. This develops compression in the surface and tension in the core, which can result in internal cracking.

The second effect arises as a result of physical restraint, primarily induced by the dam foundation, but also as a result of restraint induced by older underlying RCC lift surfaces. The restraining surface prevents the free volume change of the new concrete layer and tensile strains can develop. Generally, the cracking potential decreases with increasing distance from the restraining surface. Both can, however, lead to mass gradient cracking in the dam (see Figure 1 for illustration).

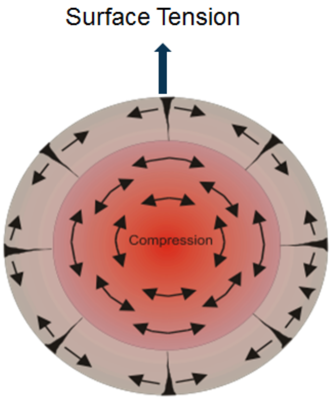

Figure 2: Surface Gradient Cracking Illustration

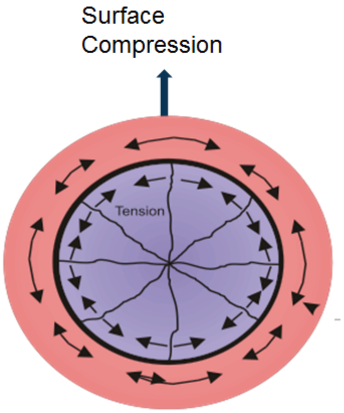

Figure 1: Mass Gradient Cracking Illustration

In order to ensure that a dam is confidently designed, the structural impacts associated with the effects of hydration heat generation must be comprehensively determined and carefully evaluated in the dam structure.

3. Study Objectives

The suite of thermal analyses addressed in this paper was initiated soon after the commencement of RCC placement at Neckartal Dam. The RCC batch plant includes an aggregate chiller and controls are in place to ensure that the RCC placement temperature does not exceed 28˚C. RCC placement is undertaken year-round and the analysis presented accordingly investigated the temperature and stress impacts of a construction programme without seasonal placement restriction, but having a limiting maximum placement temperature of 28 ˚C.

In essence, the key objectives for the thermal study were to confirm the adequacy of the specified maximum placement temperature by:

- Investigating the thermal stress conditions within the dam body, from first placement until full dissipation of the hydration heat.
- Investigating the thermal impact of faster and slower RCC placement scenarios.
- Confirming the adequacy of the applied 19,4 m induced contraction joint spacing.

4. Study Approach

The thermal study was principally completed in two parts. Initially, a transient thermal analysis was undertaken to obtain the time-dependent temperature distributions within the dam section. Thereafter, the respective temperature data was mapped on a structural mesh to determine the resulting thermal stresses, which were correspondingly interpreted to evaluate the potential for crack initiation within the RCC.

The suite of analyses were undertaken using Marc Mentat Finite Element modelling package and comprised both 2D quadrilateral and 3D solid finite element modelling.

The transient thermal analysis was used to determine the evolution of the temperature distributions across critical sections of Neckartal Dam structure at a number of intervals, extending from 2 weeks to over 50 years. The same distributions were subsequently analysed for associated strain and stress distributions and these were evaluated for the potential development of cracks.

In order to confirm the applicability of the designated 19,4 m joint spacing, a quasi 3D model was applied. In this way, the lateral stress state in the centre of the block could be computed and an estimate of the total long term joint opening at the surfaces could be made.

In summary, the analyses were structured to address the following:

- Develop the anticipated temperature history profiles during construction.
- Compute long-term temperature histories until the trapped hydration heat is fully dissipated and thereby predict the stable seasonal temperature distribution.
- Analyse the initial temperature histories for associated stress and consequential surface gradient cracking.
- Analyse long-term temperature histories for associated stress and consequential mass gradient cracking.
- Predict the expected contraction joint opening and obtain the lateral stress distribution in the center of the RCC block.
- Evaluate suitable provisions that can be applied to counteract associated thermal cracking.

5. Climatic Data

A transient thermal analysis requires input of principal environmental conditions to which the structure will be exposed. Depending on the time step applied, this typically includes ambient temperatures, average wind speed, solar radiation and reservoir temperature/depth relationships upon filling.

The climatic data applied for the study was attained from the Namibian Meteorological Station- 04191829 – Keetmanshoop Airport, which is located approximately 40 km north-east of Neckartal Dam site. The record extended over a period of 40 years. The mean monthly temperature data and corresponding wind speed was applied as summarized in Table 1.

Table 1: Neckartal Dam Average Ambient Temperature (Degrees Celsius)

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Average Temperature (˚C)	27,1	26,9	25,3	21,8	17,9	14,5	14,1	15,6	19	22,1	24,2	26,2
Ave Monthly Wind Speed (km/h)	2,7	2,2	2,2	2,3	2,6	2,2	2,9	2,6	2,6	3	3,3	2,6

The exterior faces of the modelled sections were subjected to the ambient temperatures applied as a convection boundary condition. The time curve applied assumes the monthly average temperature across a daily cycle.

Solar radiation estimates were obtained for Keetmanshoop. The solar radiation energy was converted to an applicable surface temperature rise and applied to the exposed surfaces during RCC placement.

6. Heat Transfer Coefficients

a. Atmospheric Convection

As described in US Army Corps of Engineers (1997) (8), wind speed (V) affects the rate of heat transfer from the convection boundary condition by influencing the Surface Heat Transfer Coefficient (h). The relationship of the wind speed to the Surface Heat Transfer Coefficient is described as:

$$\text{For } V < 17.5 \text{ km/h}$$

$$h = 5.622 + 1.086(V) \text{ W/m}^2\text{.K}$$

Based on the wind speeds indicated above, monthly surface heat transfer coefficients varying between 8,0 and 9,2 W/m^2.K, were applied in the analyses.

b. Gallery Convection

The dam galleries play an important role in internal heat dissipation within the structure body. In the short term, during the hydration heating cycle, temperatures within the galleries tend to be warmer than ambient, but cooler than the adjacent concrete. As the RCC mass cools down, the temperatures within the galleries tend to be partially insulated from the ambient extremes.

In this analysis, the internal gallery temperature was assumed to be the monthly ambient temperature plus 5˚C for the first year. Afterwards, for two consecutive years, the internal gallery temperature was assumed to be ambient temperature plus 3˚C. Thereafter the internal gallery temperature was assumed to be fairly insulated from the outside ambient climate, and the long term monthly gallery surface temperature was estimated as the difference between mean annual air temperature and the average difference between respective monthly and annual ambient temperatures.

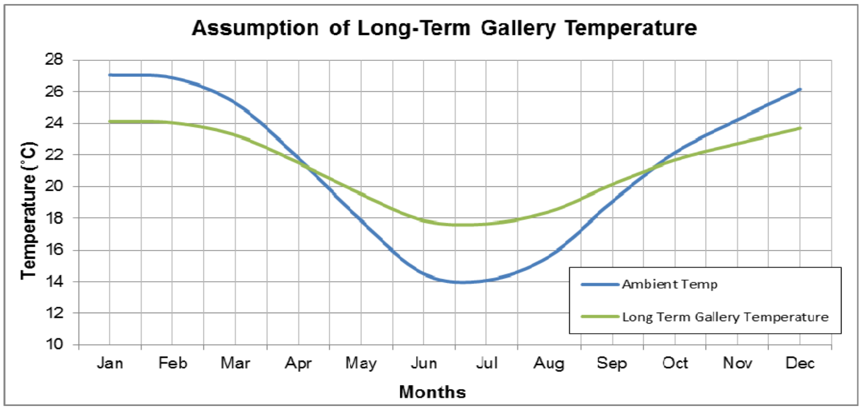

Figure 3: Assumed Long-term Ambient vs. Gallery Temperature Distributions

The assumed long term monthly gallery temperature profile is shown on Figure 3 and compared with the exterior ambient climate. A constant heat transfer coefficient of 7 W/m^2.K was applied to the gallery surfaces.

c. Reservoir Cooling Effect

Upon filling, heat dissipation on the upstream face of the dam will be increased substantially due to the somewhat cooler water and an increased surface heat transfer coefficient.

The temperature vs depth distribution applied was approximated using the equations in Zhu Bofang's paper on the Prediction of Water Temperature in Deep Reservoirs(2), which considers only the water surface and bottom temperatures to define the applicable distribution.

The temperature/depth curves were applied in 10 m increments to the upstream face of the model. For the purpose of analysis, the reservoir level was held constant at the FSL.

d. Radiation

Surface to ambient radiation followed the ambient air temperature cycle. The emissivity value for the RCC was set as 0,92 and a view factor of one.

7. Material Composition & Properties

Due to the remote locality of the site and particularly high cost for procurement and transportation of the cementitious materials, a zoned RCC mix has been applied at Neckartal Dam.

To form the impermeable barrier, an RCC with higher cementitious content is applied from the upstream face to first 6m inside the section, before reverting to a lower cementitious content for the body of the dam, as illustrated in Figure 5 .

Mix 51 RCC contains 65 kg/m^3 of Portland cement, blended with 120 kg/m^3 of fly ash and Mix 52 contains 65 kg/m^3 cement with 20kg fly ash.

Thermal properties for the mix were derived empirically based on the mix constituent ingredients.

From the partial replacement indicated, an adiabatic hydration temperature increase of 16,5˚C was approximated for Mix 51, compared to 13˚C for Mix 52, derived empirically in accordance with Fulton's Concrete Technology (4). The applied evolution of the hydration temperature curve was modelled as illustrated in Figure 4.

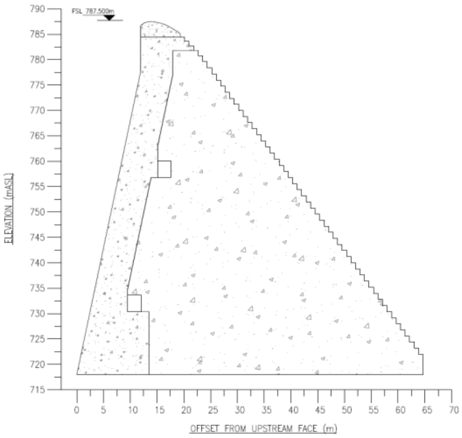

Figure 5: Zoned RCC Mix

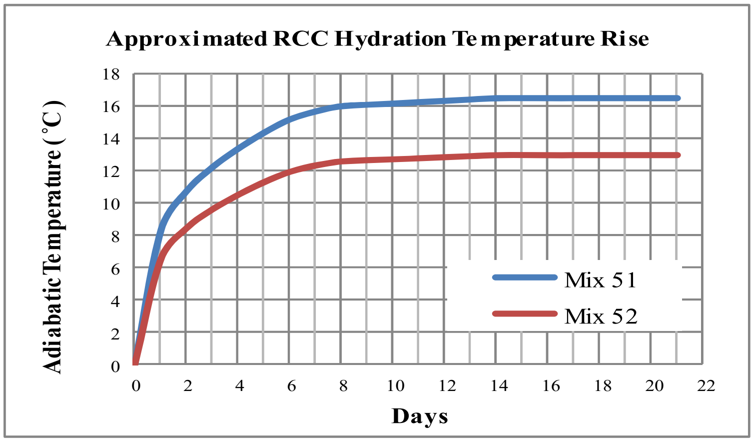

Figure 4: Approximated RCC hydration temperature rise.

Whereas specific Heat (cp) is temperature dependent, constant value is usually deemed acceptable for the range of temperatures applicable within mass concrete structures such as dams (8).

Thermal conductivity is calculated directly from the product of thermal diffusivity (h^2 - the rate at which temperature change can occur), specific heat capacity (c_p) and density (ρ).

Although no laboratory tested thermal diffusivity values were available, values from mixes on similar projects were applied.

The assumed thermal conductivities were estimated as 1.86 and 1.85 W/m˚C for Mix 51 and Mix 52, respectively

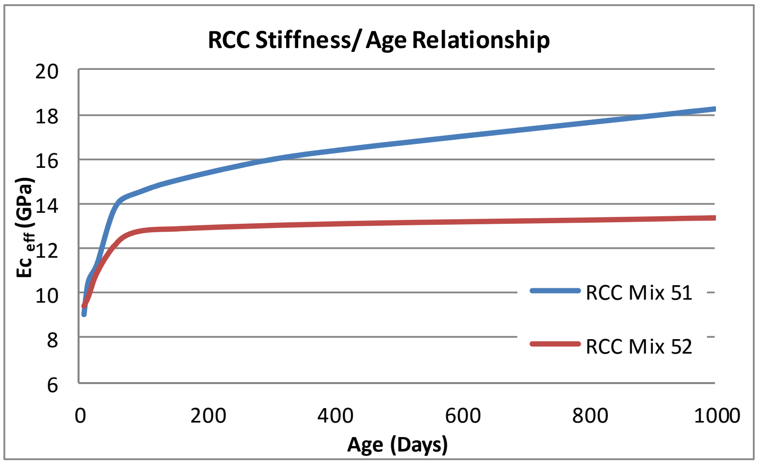

Figure 6: Applied RCC Stiffness/Age Relationship.

A Thermal Expansivity Coefficient (α) for the RCC and CVC was assumed as 9 microstrain/˚C for both Mix 51 and Mix 52. The value of this property is strongly influenced by the type and quantity of coarse aggregate used in the mix and does not vary with age or strength.

The temporal elastic modulus development was approximated on the basis of the age/strength relationship for the RCC, as obtained from the trial test results. As all of the early temperature and stress development processes in RCC are slow, a sustained modulus was applied, taken as 2/3 of the instantaneous value. The resulting Stiffness/Age relationships for the RCC are illustrated in Figure 6**.**

For RCC ages beyond 2 years, a constant long-term sustained elastic moduli of 18,25 GPa and 13,4 GPa were applied for RCC Mix 51 and Mix 52, respectively.

A summary of the basic physical and thermal properties applied in the analyses is shown in Table 2. The temporal development for the tensile- and compressive strengths used for subsequent stress evaluations are listed, as obtained through actual laboratory testing.

Table 2: Materials Properties applied for Neckartal Dam RCC

Description	**Symbol**	**Rockmass**	**RCC Mix Design 51**	**RCC Mix Design 52**	**Unit**
Density	ρ	2950	2703	2705	kg/m^3
Sustained Deformation Modulus (Long term)	E_{mod}	15	18,25	13,4	GPa
Thermal Expansivity	α	8.00E-06	9.00E-06	9.00E-06	/˚C
Specific Heat	c_p	840	993.61	987.55	J/kg˚C
Thermal Conductivity	*k*	1.85	1.86	1.85	W/m˚C
Poissons Ratio	υ	0.3	0.2	0.2	
Direct Tensile Strength (28/365 days)			0,97/1,99	0,61/0,88	MPa
Compressive Strength			16,5/34,0	15,4/22,0	MPa

8. Tensile Strength & Cracking

For stress based evaluations, the direct tensile strength (f_t) of the RCC is used. Computing tensile stresses on the basis of the time-dependent E modulus value, the tensile strength of the parent RCC was applied, as obtained from testing during the full scale trials. For horizontal cracking, a joint tensile strength of 70% parent strength was assumed.

From the work of Raphael as referenced in the Engineering Pamphlet, EP 1110-2-12$^{(7)}$ indicates that linear behaviour in RCC can be anticipated until stresses exceed 60% of the direct tensile strength. From this point, energy is released non-linearly through crack initiation and propagation. The source defines the following key points for subsequent damage interpretation for elastic analysis evaluations:

for $f_t < 0.6 f_t'$, No cracking is expected;
for $0.6 f_{t'} < f_t < 1.25 f_{t'}$, Surface cracking is anticipated;
for $1.25 f_{t'} < f_t < 1.33 f_{t'}$, Macro cracking is expected;
where $f_{t'}$ = Indicated tensile stress & f_t = Peak Tensile Strength.

9. Construction Approach

Figure 7: 3D Illustration of Neckartal Dam.

Neckartal Dam will be constructed in phases, with construction initiating in the left section adjacent to the diversion culvert in the dry season, in preparation for the river diversion to take place. With the river diversion under operation, construction will be advanced on the right section of the dam wall and once the two sections are level, (from approximately 12,4 m height), the dam will be constructed in a conventional manner, placing RCC continuously between abutments.

This approach implied that the RCC surface on the left flank would be constructed to elevation 730,4 mASL and left exposed for up to 3 months.

Furthermore, in the absence of a definitive construction placement schedule, it was necessary to investigate more than one potential scenario. In this regard, a rapid and delayed placement scenario was evaluated, in order to envelope the potential temperature extremes that may have specific influence on the levels of thermal stresses developed in the structure. In summary, Scenario 1 essentially assumed a consistent monthly placement of 141 600 m^3 and Scenario 2 applies a progressive placement which peaks at approximately 60 000 m^3 per month.

10. Transient Thermal Analysis

The transient thermal analysis component was completed using the Transient Heat Flow Module in Marc Mentat. The modelling accounted for the actual construction sequence applied for the RCC placed to the point of study commencement and followed the placement programme scenarios described for the balance. On the spillway section, the analysis also included the construction of the reinforced concrete spillway crest cap placed on top of the RCC.

The simulation process was initiated at a time 10 years prior to the first placement of RCC in order to allow the temperatures in the foundation to stabilise and redistribute realistically.

The RCC placement temperature was assumed to be the average monthly ambient temperature plus the mean solar radiation, which accounts for radiation on aggregate stockpiles, mixing, conveyance and spreading, but limited to 28 ˚C, which is the maximum allowable placement temperature specified.

The surfaces of the structure were modelled in bi-weekly intervals and exposed to the external climatic conditions using surface convection on the basis of the wind speeds indicated. Radiation was applied, together with the estimated heat transfer coefficient for the gallery surfaces and estimated gallery air temperature variations. The simulation procedure continued in this manner, with the successive lifts being simulated at the end of the bi-weekly construction window, until completion in June 2017. After filling, an increased heat transfer coefficient was applied to the upstream face, in conjunction with appropriate seasonal water temperature variations with depth to simulate the presence of the dam reservoir. In order to investigate the long term impacts of temperature loss, the climatic variation cycles were applied to the surfaces of the dam over a period in excess of 50 years.

11. Static Stress Analysis

Linear static analyses were conducted by mapping the temperature distributions attained at specific stages of the construction development on a structural mesh. The thermal gradients acquired from the transient thermal analyses were used to obtain the thermal stresses based on the age dependant modulus of elasticity and an assumed closure temperature, or “zero stress” temperature, which defines the temperature at which no strains exist in the model.

Stress analyses were conducted from November 2015 at half month intervals during the construction period, and at every standing point encountered during the construction programme. Following construction completion, the thermal stresses were computed bi-monthly, specifically targeting winter and summer periods.

The conventional vibrated concrete (CVC) spillway was included in the transient thermal analysis specifically to account for the insulating effect it will have on the underlying RCC.

- **Reference Temperature for Surface Gradient Cracking Evaluations**

Surface tensions will develop whenever the heated core is expanded relative to the surface. For the purpose of conservatism, a reference temperature equal to the assumed placement temperature was applied for early age stress analyses. This assumption implies that the core will expand linearly above the placement temperature with no creep effect under restrained compression, which would otherwise reduce the development of surface tensions under steep thermal gradients. Under this assumption, maximum tensile stress will be indicated at the dam surfaces.

- **Reference Temperature for Surface Gradient Cracking Evaluations**

During the process of hydration heat development, it has traditionally been assumed that the compression stresses experienced in restrained concrete as a result of thermal expansion are largely lost to creep in the fresh material and the "zero stress" temperature is generally equated to the maximum experienced. Research by Shaw(5 &6) has demonstrated that this assumption is not necessarily valid in the case of high quality, high paste RCC and very little creep actually occurs during the hydration heating and subsequent cooling cycle at the core of a large RCC dam.

In the case of Neckartal Dam, however, the cementitious content in the bulk of the placement volume is low and for this reason, mass gradient stress analyses were conducted that assume the traditional approach, such that all the core compression is lost to creep during hydration.

In this regard, the temperature difference between the newly completed dam and the long-term temperature steady state temperature was used to complete the stress analysis with a respective reference temperature of 0˚C.

12. Finite Element Modelling

MSC Apex was used to mesh critical sections for the different cases. These were then exported to Marc Mentat module, where the thermal boundaries and material properties were defined and analysed in the Transient Heat Flow- and the Static Structural Modules.

For the 2D thermal analysis, 8-node quadrilateral shell elements were used, as shown in Figure 8.

The dam was modelled using a very fine mesh density of 300 x 300 mm elements, with up- and downstream sections so that the different RCC mixes can be applied in lifts that reflect the bi-weekly construction progress.

The galleries were included by omitting elements at their designated locations. The foundation was modelled with 300 x 300mm elements at the surface where it connects to the dam wall, before transitioning out to 5 x 5 m elements. The foundation was extended in excess of one dam height in the upstream, downstream and vertical directions.

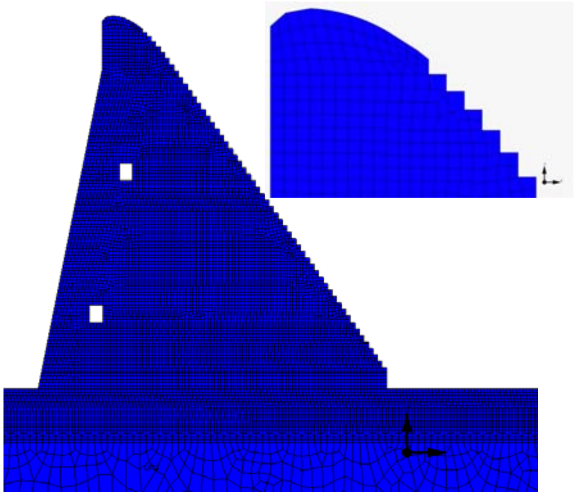

Figure 8: 2D- Finite Element Mesh

The hydration temperature development was converted into an associated daily heat energy value (W/m^2) and this was applied to each element within the mesh individually. In this manner, the hydration heat evolution was allowed to develop concurrently with convection and radiation dissipation at the exposed surfaces, simulating the actual situation in which core temperature rises due to hydration are significantly greater than surface values.

20-node solid Hexahedra elements were used in the 3D model as shown in Figure 9, delineated into lifts that assume the monthly construction progression. The blocks were modeled to reflect joint spacing of 15 m, 19,4 m, 25 m and 30 m, to evaluate the effects. Restraints that prevent out of plane deformation were applied to the foundation and the dam was left unrestrained, and assumed to be rigidly attached to the foundation.

As previously described, the objective of this analysis was to investigate the levels of tension that would develop between transverse induced joints and estimate the joint opening following long term cooling.

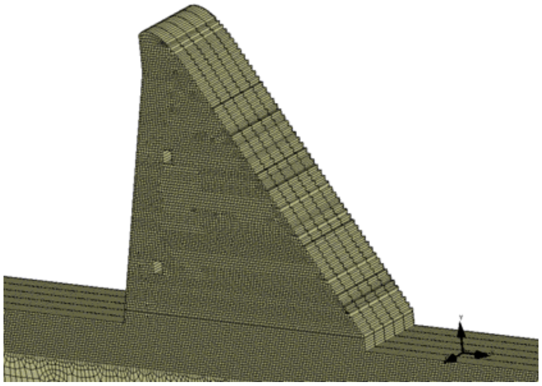

Figure 9: 3D- Finite Element Mesh

13. Results

The resulting thermal behaviour of the dam was reviewed and interpreted through the appraisal of the corresponding temperature histories and the associated temperature distribution contours and stress plots. While it is not possible to fully address all the results obtained, in this paper, the key results of the analyses will accordingly be discussed.

- **Temperature Histories**

Monitor nodes were selected at locations where actual instrumentation will be installed, providing a means to compare measured and predicted temperatures history results in the future to calibrate the model accuracy.

As expected, the surface element temperatures were found to converge relatively quickly to ambient conditions following placement, while the heat built up in the core takes significantly longer to dissipate.

From Figure 10, it is evident that the long term steady state temperature of the core is approximately 23˚C, which is 2 ˚C warmer than the average annual ambient temperature.

This implies an overall heat dissipation of 18˚C to 22˚C from the core, 25 to 30 years after placement.

The period to reach the steady state equilibrium temperature condition increases considerably within the deeper and wider sections.

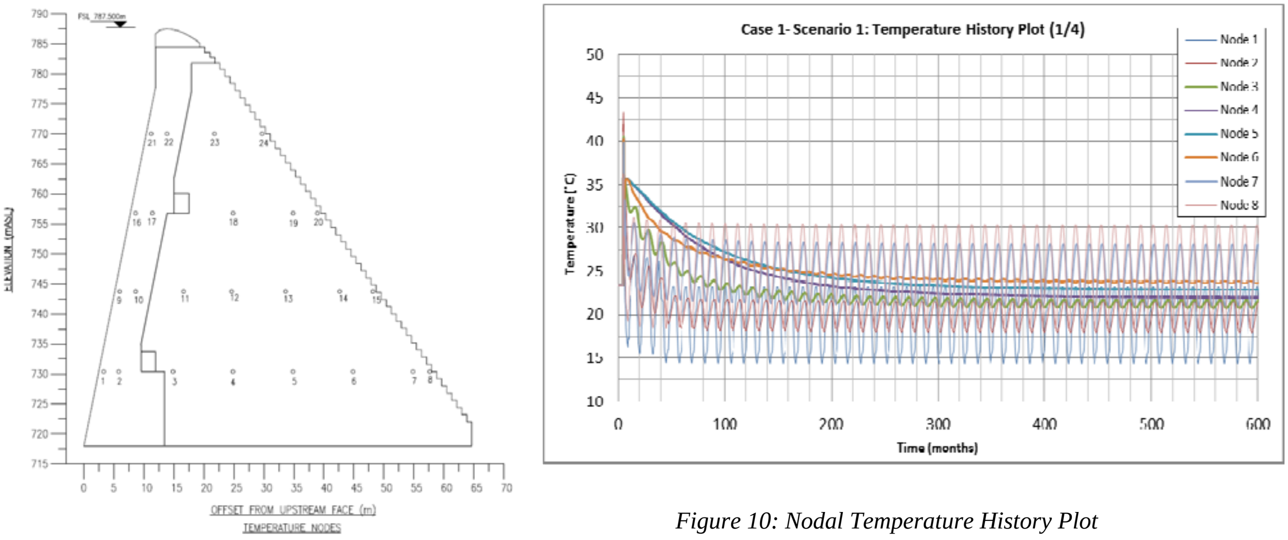

Figure 10: Nodal Temperature History Plot

o Stress Results

Surface Gradient Cracking

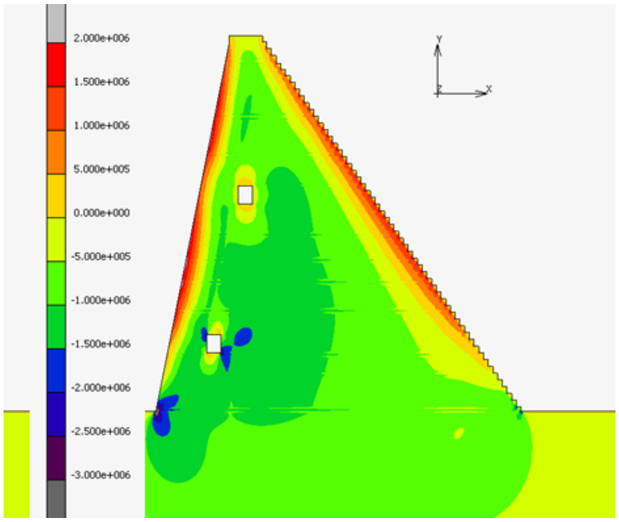

Figure 11: Typical Vertical Tensile Stress Plot

In general, the stress results indicated that surface cracks may occur during construction and within the first few months following the dam completion as a result of steep thermal gradients; particularly on the downstream faces and above the drainage galleries. The results confirmed that if the recommended placement temperature is observed, excessive propagation of the cracks would not occur and no long term impacts will arise. The hydration heat energy of the RCC is significant and considerable cooling would be required to completely eliminate the risk of surface cracking, a condition that is not considered realistic for the climatic conditions and available equipment at the dam site.

Figure 11 graphically illustrates the probable location and extent of horizontal surface cracking that could be expected at the spillway section of the dam.

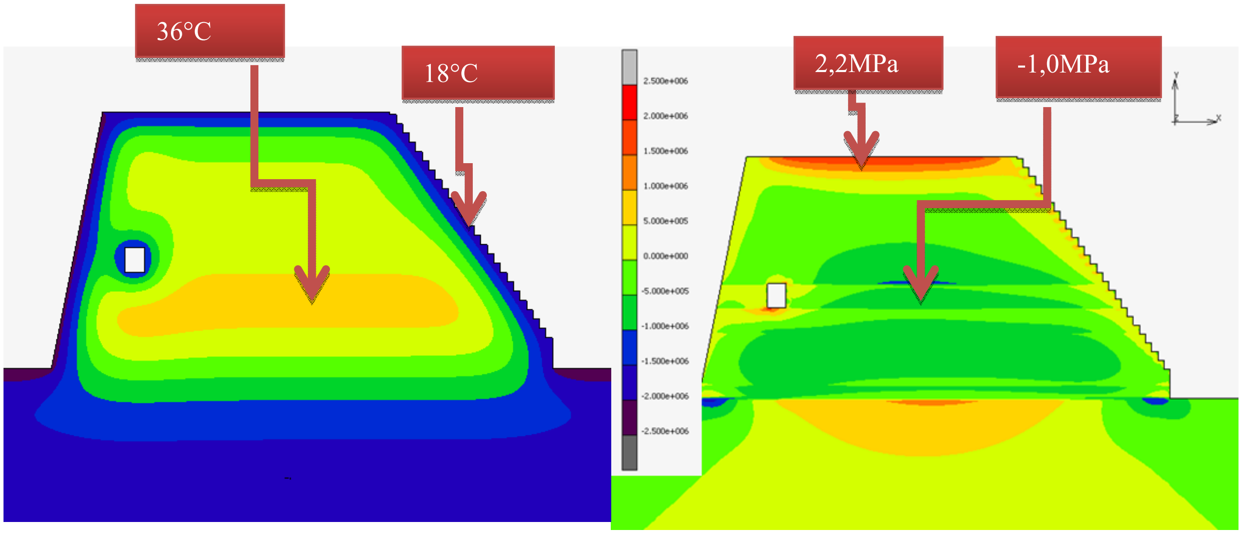

Figure 12: Typical Temperature state and Horizontal Stress Plot following 2 weeks

It was found that during construction, the risk of developing vertical cracks on exposed horizontal lift joint surfaces increased for periods of exposure that generally exceed two weeks in the lower regions, and three weeks for higher elevations. This risk was particularly apparent when the faster placement schedule was followed and then interrupted, since more of the hydration heat was trapped in the core section. Core compressions in the order of 1MPa and surface tensions in excess of 2MPa were computed as illustrated in Figure 12.

Internal Mass Gradient Cracking

For the mass gradient analysis, a maximum joint opening of 4,2 mm was predicted on the model under the assumption of full creep.

Peak internal tensions were computed at the dam foundation contact, where restraint is greatest. The maximum heel tensile stress developed in RCC Mix 51, which has a greater tensile strength. Overall, the internal tensions computed were of sufficient magnitude not to result in internal cracking, thus validating the 19,4 m contraction joint spacing applied.

Figure 13 graphically illustrates predicted joint opening and internal lateral stress state computed in the spillway section block.

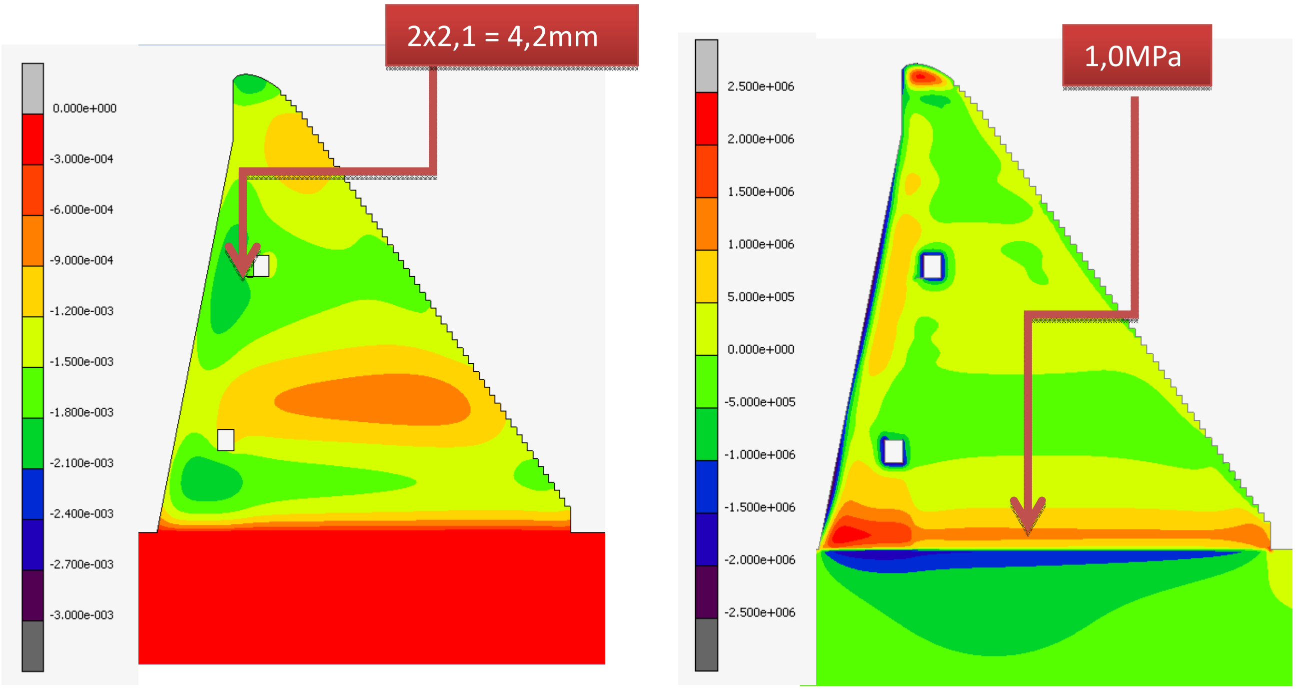

Figure 13: Predicted long-term joint opening and lateral stress state

14. Conclusions

The Thermal Analysis for Neckartal Dam effectively modelled the anticipated temperature development and dissipation cycle. Correlating actual temperature measurement with the predicted values will confirm the accuracy and the applicability of the simulations applied. This will be undertaken as part of the next phase.

On the basis of the dam's geometry, assumed RCC materials properties and applied environmental conditions, the findings of the thermal and stress analyses confirmed that a 28°C RCC maximum placement temperature is quite adequate to restrict any resultant cracking to a manageable level.

A 19,4 m contraction joint spacing is optimal to prevent cracking perpendicular to the dam axis. Under the traditional creep assumptions, a maximum joint opening of 4,2 mm could be anticipated.

In general, only the surface temperature gradients posed any potential risk of cracking.

The principle difficulty of the analyses lies in the correct determination of the thermal parameters and environmental conditions applied. Thermal behaviour at early RCC age contains numerous reservations and any consequential discrepancy between the actual and calculated temperature results can accordingly be attributed to the input parameters, rather than the modelling and computation techniques(1). It is also important to realise that this is a model that can have an indeterminate amount of input variables and realistic assumptions and thorough interpretation is required. However, potentially significant thermal & structural impacts can be reliably predicted using complex thermal studies and these should be undertaken early in the feasibility design phase of a Large RCC Dam

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