STRESS-STRAIN CHARATERIZATION OF RCC MIXES AT GERD PROJECT AND THERMAL - SEISMIC DAM BEHAVIOR ANALYSES

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1. INTRODUCTION

The Grand Ethiopian Renaissance Dam (GERD) Project is located along the Blue Nile (Abbai) almost at Ethiopian-Sudanese border, few kilometers upstream of Roseires Dam in Sudan and 700 km NE of Addis Ababa, in the Benishangul – Gumaz region.

The plant, with its 5'150 MW of installed power and 15.7 TWh of annual energy production, is one the most important projects in the Ethiopian Government's commitment to meet the country's present and future power requirements.

The whole project includes a roller compacted concrete (RCC) Main Dam (175 m high, 10.2 Mm^3 of RCC volume) and a concrete faced rockfill (CFRD) Saddle Dam (65 m high, 5 km long, 15 Mm^3 of embankment volume). The 5,150 MW installed power will be generated by 13 Francis turbines in two outdoor power-houses located at the Main Dam toe on the right and left riverside. The project also includes a nine-bay gated-spillway, an un-gated auxiliary spillway, an emergency spillway, and two middle outlets to allow the control of the reservoir impounding. The dam is at date under construction; when completed, GERD will feature the largest dam in Africa.

The Project is being implemented by the Ethiopian Electric Power company (EEP), with Webuild S.p.A (ex Salini-Impregilo) as EPC Contractor and Studio Pietrangeli as Designer.

This paper describes the extensive tests campaign carried out at GERD Project on the RCC mixes to investigate the stress-strain curve showing a non-linear behaviour, as well as the correlation between horizontal and vertical direct tensile strength for the same portion of RCC and between tensile modulus and compressive moduli.

The results of above tests have been used for a proper evaluation of thermal strain capacity, and to justify less expensive mixes with lower cementitious content and less heat for areas of high stress.

The dynamic and thermal analyses are discussed along with the methodology adopted for thermal monitoring and control measures.

2. KEY CHARACTERISTICS OF THE RCC DAM

2.1. GENERAL LAYOUT

The general layout of GER Main Dam is illustrated in Fig. 1. The key components of the project are:

- the river diversion system, including 4 culverts for the dry season discharge up to 2700 m3/s (December to June) and a temporary stepped spillway located in the central part of the dam (see Fig. 2), for dam overtopping during the wet season up to 14’700 m3/s ;
- a roller compacted concrete (RCC) Main Dam with a maximum height of 175 m and a total volume of RCC of about 10.2 million cubic meters;
- a free-flow crest stepped spillway located on the overflow section of the main dam which is auxiliary to the main service gated spillway, located on a saddle area to the immediate left of the main dam;
- two steel-lined bottom outlets (6 m diameter), embedded in the dam body, which allow the control of reservoir level and the discharge during plant outage periods;
- thirteen penstocks (8 m diameter), embedded in the dam body. 2 penstocks at lower elevation are dedicated to early generation during reservoir impounding;

- two outdoor power houses located at the Main Dam toe on the right and left riverside housing 7 Francis turbine units and 6 Francis turbine units respectively, totalling 5’150 MW installed capacity;
- one 500 kV switchyard on right bank.

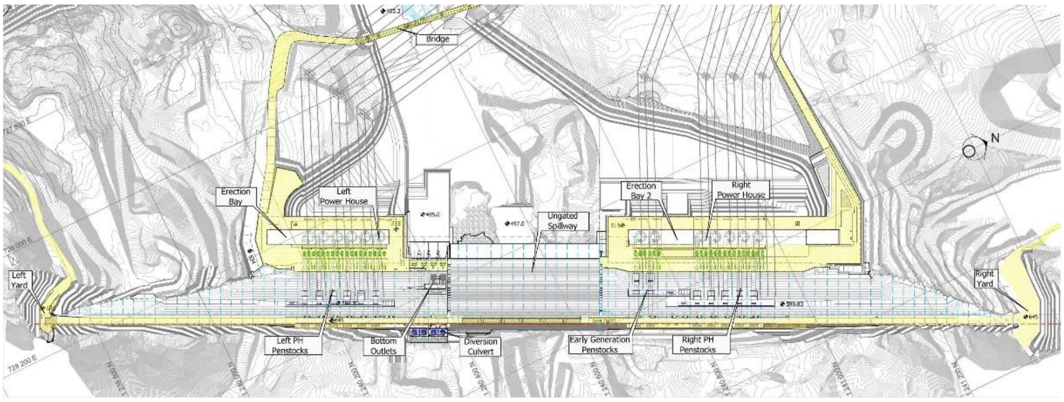


Figure 1 – GERdp hydroelectric project, Main Dam general layout plan view.

Figure 2 – GERdp hydroelectric project, Main Dam temporary stepped spillway.

2.2. RCC MIXES ZONING

The Main Dam is a roller compacted concrete gravity dam with a maximum height of 175 m and a length of about 2 km at crest elevation (645 m a.s.l.). Two typical sections are designed:

- Overflow Section (stepped spillway)

The upstream face has a 0.14:1 (H:V) slope in the lower portion (below elev. 575 m a.s.l.) and vertical in the upper portion. The stepped downstream face has an average slope ranging from 0.77:1 to 0.95:1 (H:V).

- Non-Overflow Section
  The upstream face has a 0.10:1 (H:V) slope in the lower portion (below elev. 545 m a.s.l.) and vertical in the upper portion. The stepped downstream face has an average slope of 0.77:1 (H:V).

The dam has 85 monolith blocks separated by cutting joints into the freshly RCC after compaction. The vertical contraction joints are equipped in the upstream zone with double waterstops and control drainage. The contraction joint spacing along the dam axis varies from 18 to 27 m.

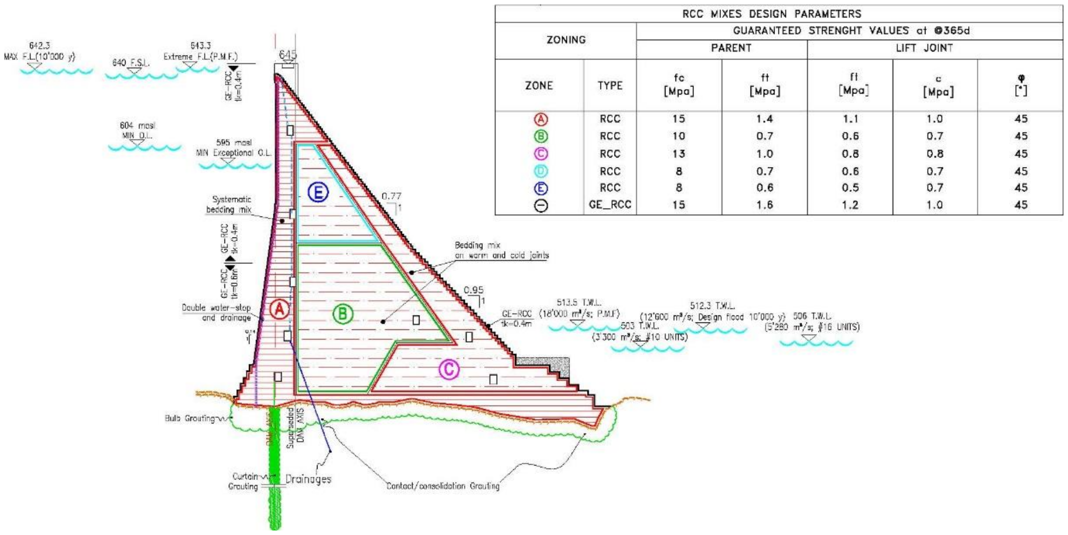
The joints spacing is controlled by thermal issues and by the dimensions of the concrete structures of electro-mechanical equipment (penstocks, culverts and bottom outlets) crossing the dam body.

The dam is equipped with 5 main longitudinal galleries, every 30-40 m of height, located close to the upstream face and sized in order to provide and efficient drainage system aimed at mitigating and control uplift pressure. Transversal (u/s-d/s) galleries are foreseen to allow the access from the downstream face, seepage water monitoring and discharge and additional drainages along weak zones encountered during foundation excavation.

Fig. 3 illustrates the overflow section of the dam with the RCC mixes zoning, including their mechanical characteristics and extent of systematic bedding at lift joints.

Extensive mix designs and testing have been carried out in order to define the specific RCC mixes for different areas of the dam as described in paragraph 2.3 below. Two types of cement are being used: CEM I 42,5 LHHS (Portland Low Heat of Hydration and High Sulfate resistance) for the first 300’000 m3 of RCC production and CEM IV-A 32,5 R (Pozzolanic cement) for the rest of dam body (to date equal to about 7 Mm3). Cement contents vary, through the cross section of the dam, from 75 to 125 kg/m3 where Portland cement is used and from 90 to 140 kg/m3 in case of pozzolanic cement.

A higher cement content is used in both the upstream part of the dam, to meet the tensile strength under extreme seismic load and permeability requirements, and the downstream toe, for compressive strength requirements. Mixes with low cement content are used in the central zone of the dam in order to control the temperature rise and the consequent risk of cracking.



RCC MIXES DESIGN PARAMETERS

ZONING		GUARANTEED STRENGHT VALUES at @365d				
		PARENT		LIFT JOINT		
ZONE	TYPE	fc [Mpa]	ft [Mpa]	ft [Mpa]	c [Mpa]	φ [°]
Ⓐ	RCC	15	1.4	1.1	1.0	45
Ⓑ	RCC	10	0.7	0.6	0.7	45
Ⓒ	RCC	13	1.0	0.8	0.8	45
Ⓓ	RCC	8	0.7	0.6	0.7	45
Ⓔ	RCC	8	0.6	0.5	0.7	45
⊖	GE_RCC	15	1.6	1.2	1.0	45

Figure 3 – GERD overflow section (geometry, mechanical characteristics zoning, extension of lift bedding mix).

As shown in the figure a systematic bedding mix is prescribed only in the upstream portion of the dam, in order to meet the impermeability requirements at lift joints, and for the first 3 m above the foundation. In the remaining part of the dam the bedding mix is prescribed only for the warm and cold joints with maturity higher than the initial setting time of the mixes (8-12 hours). The impervious upstream face uses grout enriched RCC (GE-RCC) with a width varying from 40 to 60.

In the overflow section the downstream steps are protected by conventional concrete with Silica Fume; a GE-RCC transition is foreseen between the concrete and the RCC mixes. A GERCC layer, 40 cm wide, is instead used at the downstream slope of non-overflow section to enhance the face appearance and durability.

3. DESCRIPTION OF RCC TESTING CAMPAIGN AT GERD

The testing campaign of tensile and stress-strain analysis described in this paper has been performed at the Grand Ethiopian Renaissance Dam (GERD) Project during different steps of investigation. The testing campaign for RCC included about 500 cores from different zones of the dam body, comparing compressive and tensile strength with accompanying stress-strain curves and modulus values for both horizontal and vertical samples. In addition to testing on site, some cores were also sent to the Mapei laboratory in Milano, Italy, for further verification and comparison.

Results obtained have shown that tensile modulus was significantly lower than the compressive modulus as shown in the table 1.

Table 1: Compressive and tensile modulus at GERDP (avg values)

	Compressive Modulus					Tensile Modulus				
	Ultimate strength	Modul 25%	Modul 50%	Modul 75%	Modul 100%	Ultimate strength	Modul 25%	Modul 50%	Modul 75%	Modul 100%
	MPa	GPa	GPa	GPa	GPa	MPa	GPa	GPa	GPa	GPa
Gerdp	16.5	28	22	16	7	1.1	10.5	9.5	8.5	6.5
				Ratio tensile / Compressive			38%	43%	53%	93%

Typical compressive and tensile stress-strain curves, plotted as a percent of ultimate strength and ultimate strain for the GERD project are shown in Figures 4 and 5.

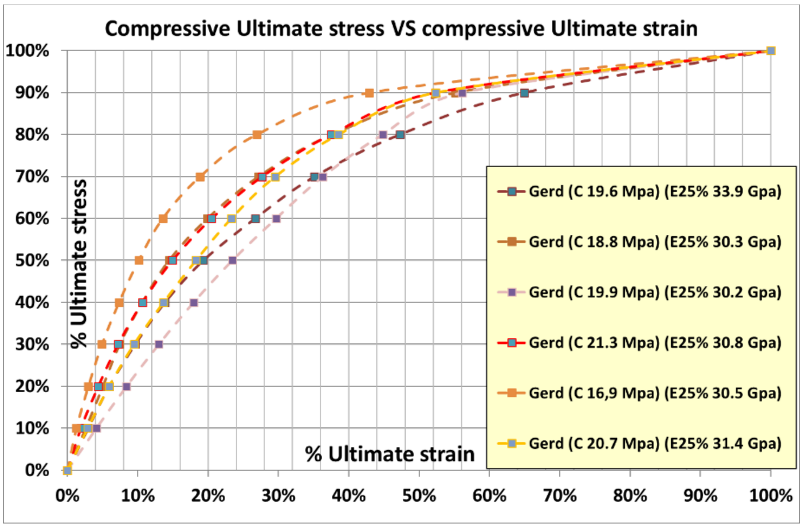


Figure 4: RCC, Typical stress-strain curves for compression at GERD

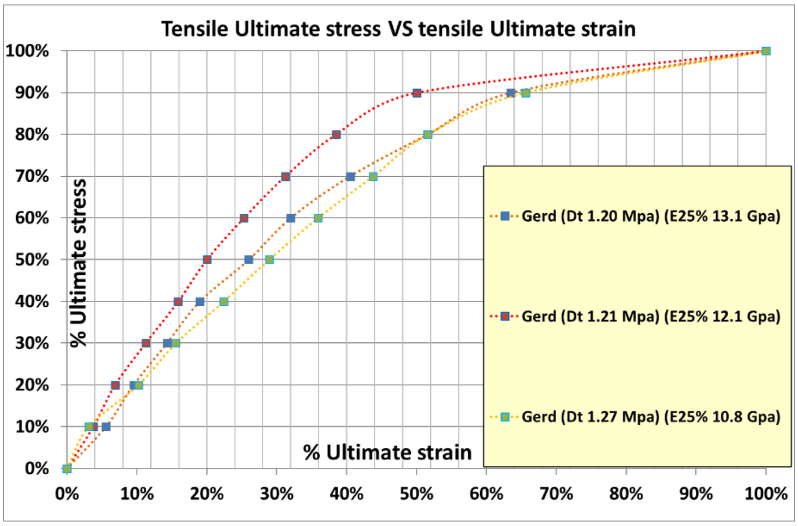


Figure 5: RCC, Typical stress-strain curves for tension at GERD

Figure 6: Direct tensile strength machine used at GERD site laboratory

The properties of concrete for a horizontal core are typically thought to have the same properties as for a vertical core. However, this is not always true for RCC, especially for tensile strength. The authors have found that tensile strength from a horizontal core can be greater than the strength from a vertical core sampled in the same portion of RCC.

At the GERD project, a substantial investigation campaign has been made to establish the difference between properties in the horizontal and vertical directions. This included about 100 adjacent companion cores, that were obtained by first sawing blocks from the floor of the internal gallery or tunnel through the dam. Horizontal and vertical cores were taken from the same material, of the same lift, at the same place after the blocks were removed. Tests have been carried out in each of the three main zones in the dam with cement contents of 130 to 142 kg/m3 (A), 80 to 85 kg/m3 (B), and 110 to 119 kg/m3(C) were tested.

For each zone, the tests have shown a much greater RCC tensile strength and strain capacity in the horizontal direction compared to the vertical direction.

These results were duly considered in the thermal cracking analysis, because thermal stresses develop mainly along horizontal directions. On the contract seismic analysis shows that major tensile stresses are along vertical direction and therefore the lower value of tensile RCC strength shall be considered accordingly. Table 2 summarizes results obtained.

Table 2. Correlation between vertical and horizontal properties for different zones (mixes) at GERD

DT cores results in MPa		**Zone A**			**Zone C**			**Zone B**		
DT$_{VP}$	Direct tensile vertical parent	1.29	1.25	Ratio V/H	1.01	0.97	Ratio V/H	0.96	0.84	Ratio V/H
DT$_{VJ}$	Direct tensile vertical joint	1.27		65%	0.95		52%	0.76		57%
DT$_{HP}$	Direct tensile horizzontal parent	1.91	1.93		1.93	1.85		1.43	1.48	
DT$_{SP}$	Direct tensile by splitting parent	1.96			1.83			1.5		

The overall average horizontal tensile strength was a significant 172% grater than the vertical tensile strength. A close examination of the concrete, including microscopy and petrography did not identify any issue such as trapped air or microscopic horizontal separations under coarse aggregate particles. The overall air voids of the RCC was about 2%. The above assessment is for the RCC.

It should be highlighted that while compressive tests are not particularly difficult and can be done in every RCC project the direct tensile tests with meaningful strain measurements require care, expertise and equipment and need to be carefully verified. This was also the reason for the repetition of some specific tests made also in the Mapei Laboratory in Milan after that hundreds of cores and cylinders have been tested in Gerd site laboratory.

4. DYNAMIC STABILITY ANALYSIS

The stability analyses of the RCC dam were performed following an increasing degree complexity, as usual in engineering practice.

The basic geometry of the dam was preliminarily established by a simple Rigid Body Analysis, verifying the overturning and the sliding stability in accordance with international standards.

At Level One Design, FEM analyses were performed to define a more reliable and complete stress distribution within the dam body, to optimize the shape of the dam and to outline the RCC and bedding mix zoning. The behaviour of the dam under seismic loads was evaluated by means of Response Spectrum Analysis for the calculation of maximum expected tensile and compressive stresses under earthquake, and by means of Equivalent Lateral Force method for the purposes of sliding stability analysis. The dam behaviour was assumed to be essentially two-dimensional, being the height of the dam much smaller than the length of the crest and therefore considering the 3D effects almost negligible. The simplified Equivalent Lateral Force Method proved to be very reliable and it allowed to establish the final geometry of the dam, since all the investigated 2D cross sections respected the requirement that the first vibration mode contributed as much as 80-percent or more to the total seismic response of structure.

At the Level Two Design stage, further and more accurate analyses were performed in order to confirm the final dimensions of the dam and to study local effects with the most refined procedures proposed by literature.

In order to ponder the possibility of cracks propagating from the upstream face of the dam, a Non Linear Static Analysis with gap friction elements was performed using Straus 7 finite element code, release 2.4.6. These are linear elements between two nodes; a gap can open and close during the load process and it is active only when in compression. When an element is active, it may have a stiffness contribution both in axial and lateral directions. The axial force is used to model the normal contact force, while the lateral force is used to model the friction between the surfaces on which the nodes lie. The calculations were performed with an iterative process supposing a crack length and the consequent uplift distribution, checking that the computed crack length was almost equal to the assumed value, until convergence was obtained. This further analysis allowed to establish the optimum position of the drainage lines: for the blocks in which a crack could be expected, the drains were moved towards downstream in order not to let the theoretical crack propagate until them.

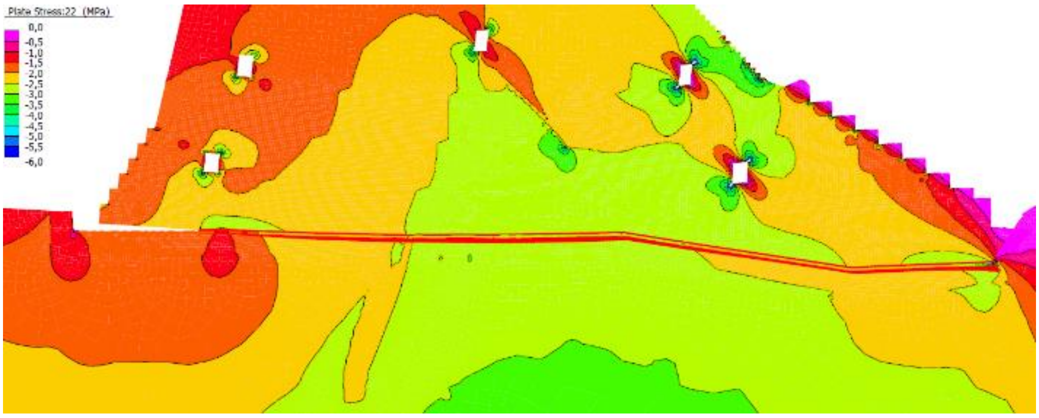


Fig. 7: FEM model theoretical crack propagation in deformed mesh, with gap friction elements (red line)

Seismic behavior was evaluated by means of linear time history procedure. This type of analysis involves the direct integration of the equations of motion and therefore it is the most powerful method available in literature for evaluating the response of structures to earthquakes. The performance evaluation and the assessment of damage level was formulated based on magnitudes of Demand-

Capacity Ratios (DCR), cumulative duration of stress excursions beyond the tensile strength of the RCC. The dam response to the earthquake was considered to be within the linear-elastic range of behavior with little or no possibility of damage, if the computed stress demand-capacity ratios was less than or equal to 1. The dam would exhibit nonlinear response in the form of cracking of the RCC and/or opening of construction joints if the estimated stress demand-capacity ratios exceeded 1.

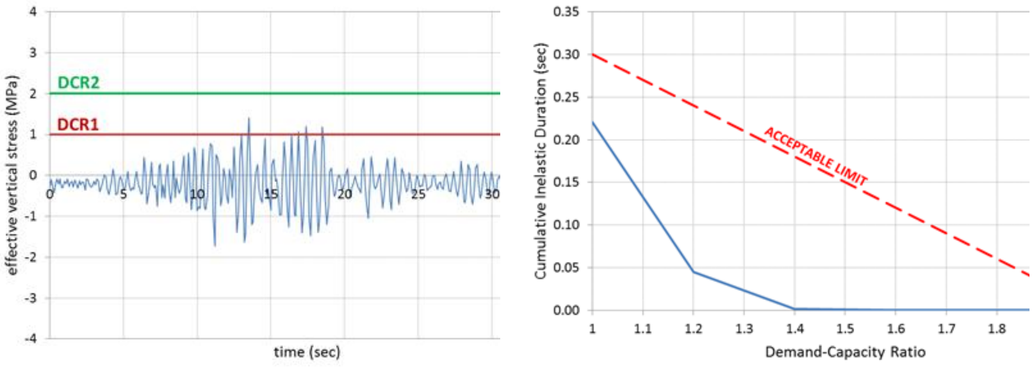


Fig. 8: Time history of vertical stresses under a SEE earthquake (left) and related graph of cumulative inelastic duration (right)

Given the main direction of stress due to earthquake loads, the lower values of RCC tensile strength, corresponding to DT_{VJ} vertical Joint Tensile strength have been assumed. The compressive and tensile modules have been assumed the same but increased of 30 % for dynamic loads in accordance to recommendation of EM 110-2-6051, and Poisson dynamic rations assumed 30% smaller than those used for static analysis (EM 1110-2-6053).

For the cross sections considered representative of the tallest blocks of the RCC dam, where the highest seismic amplification was achieved, Non-Linear Analysis was performed to ensure that collapse could not occur.

On the one hand, these further dynamic analyses confirmed the reliability of the main dimensions of the dam, decided at Level 1 Design and on the other hand, they allowed to refine the RCC zoning.

A Final 3D FEM model was produced, also, using MIDAS GTS NX software. It confirmed the reliability of the assumption of two-dimensional behavior of the dam, especially under static loads, and it allowed us to study with better approximation some aspects including the stability of the banks and the behavior of the dam under bank to bank earthquakes.

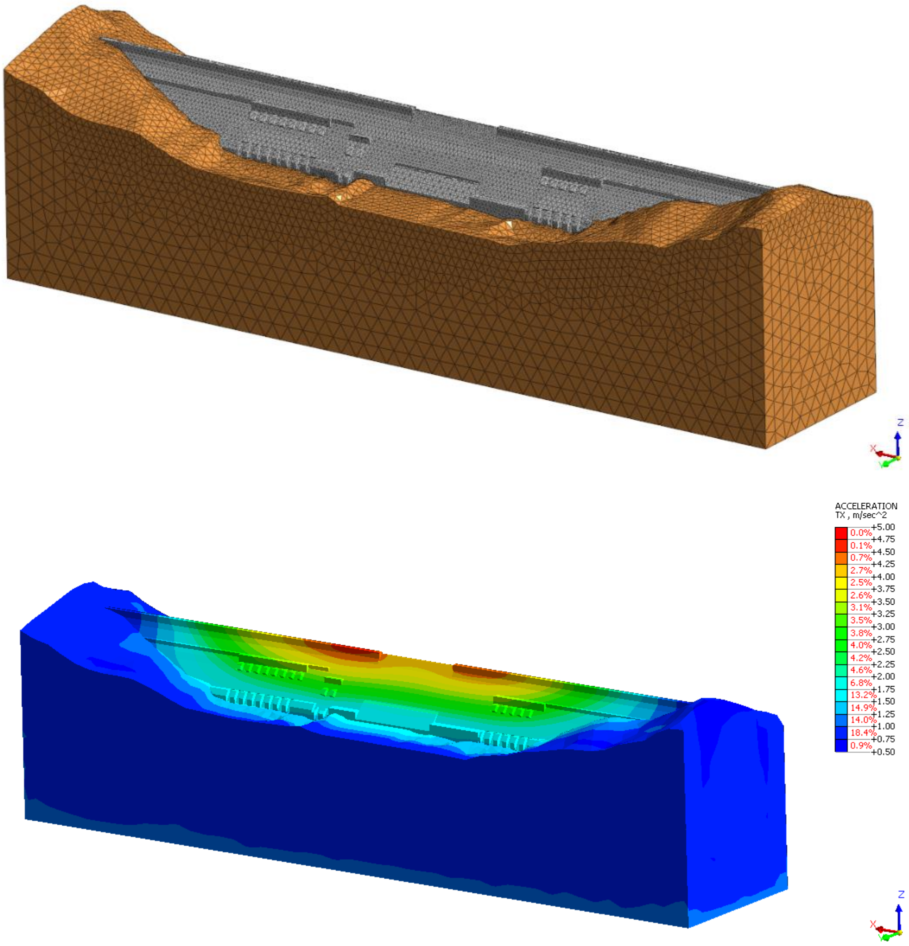


Fig. 9: GERdp – 3D FEM of the whole dam (left) and bank to bank accelerations under a design earthquake (right)

5. THERMAL ANALYSIS AND TEMPERATURE CONTROL

Considering the RCC volume (higher than 10 Mm3) and production rates (up to 370'000 m3/month) of GER Main Dam, temperature control has been one of the most important issues during construction of this project.

The main measures to control temperature rise in the dam consist in: pre-cooling of materials (i.e. aggregates, water), utilization of cement with lower hydration heat, mixes with low cement content, appropriate construction schedule, solar radiation protection by continuous curing.

The degree of pre-cooling (i.e. maximum allowable placing temperature of RCC) is defined by accurate thermal study. Transient thermal analysis has been conducted by finite differences software developed by Studio Pietrangeli [2] in order to evaluate the temperature distribution histories in the dam. SP's in-house thermal model considers the main parameters that influence thermal behaviour of an RCC dam, including: time-dependent ambient conditions (fluctuation of air temperature and solar radiation, heat transfer by convection from the external surface of RCC lift); time variation of thermal properties of the RCC/Grout Enriched-RCC mixes and production parameters (placing temperature, construction start, lift height and lift placement rate).

The thermal properties of the mixes, preliminary estimated by conventional laboratory tests, are calibrated by back analysis of the first RCC dam block partially placed and used in the river diversion scheme. This block, measuring approximately 130 x 14 x 20 m (40’000 m3), is on purpose equipped with 31 thermocouples.

The results of transient analysis together with the thermo-mechanical properties and degree of restraint present in the different locations of the dam are used to evaluate mass and surface cracking in the RCC mass and upstream face.

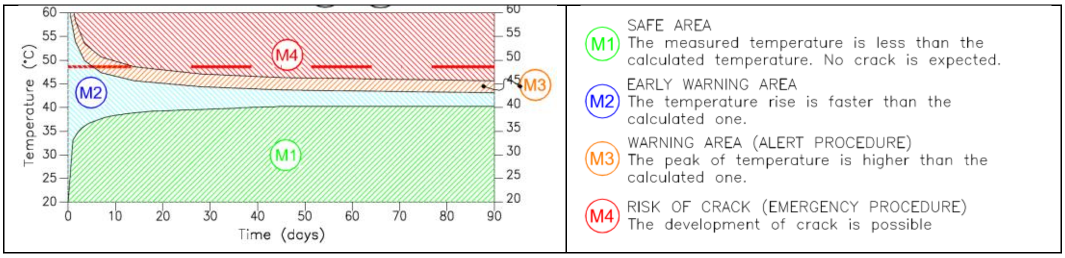
The non-linear behaviour and the related increased strain capacity also has major benefit with regard to thermal stresses and the associated maximum allowed temperature.

During the progress of dam construction, a continuous monitoring of the RCC temperatures at GERD has been implemented, and the measures were periodically compared with the maximum allowable temperatures deduced from thermal studies as a function of dam zone and mechanical characteristics of the RCC mixes.

Hundreds of thermocouples have been installed for this purpose in addition to the basic design instrumentation, and supplemental instrumentation to be installed for long term monitoring.

These temperature limits, together with an indication of prompt actions to be taken in case anomalous temperatures are detected, are included in the temperature monitoring and early warning procedure implemented during the GER Main Dam construction.

The handy tool of early warning procedure is represented by the plot of Fig. 11, which indicate, for each zone of the Dam (different RCC mixes and elevation) the temperature limits and the relevant safety factors against mass cracking. Specific procedures are defined for each warning area M2, M3 and M4.



SAFE AREA
The measured temperature is less than the calculated temperature. No crack is expected.

EARLY WARNING AREA
The temperature rise is faster than the calculated one.

WARNING AREA (ALERT PROCEDURE)
The peak of temperature is higher than the calculated one.

RISK OF CRACK (EMERGENCY PROCEDURE)
The development of crack is possible

Fig. 11 – Temperature early warning zones

An example of comparison between temperatures recorded in the dam body and the threshold limit above described is illustrated in the following figures for each mixes type A, B and C.

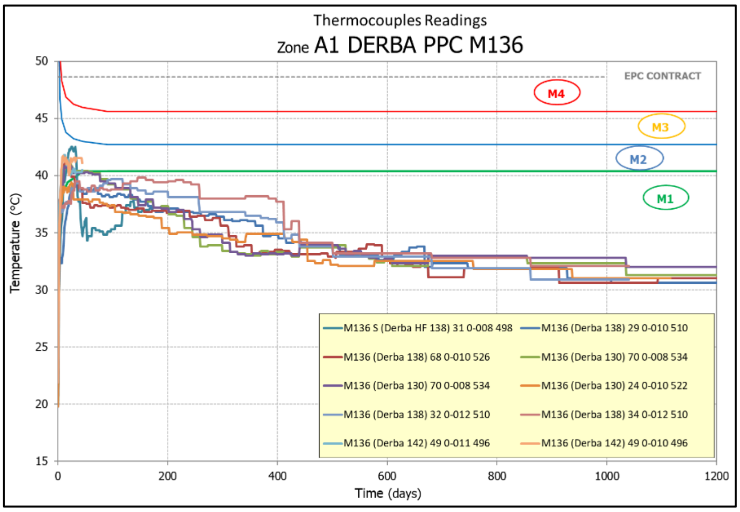


Fig. 12: Temperatures early warning graph (upstream zone A), in the zone A1 at 0-10% of the elevation of the dam from the foundation

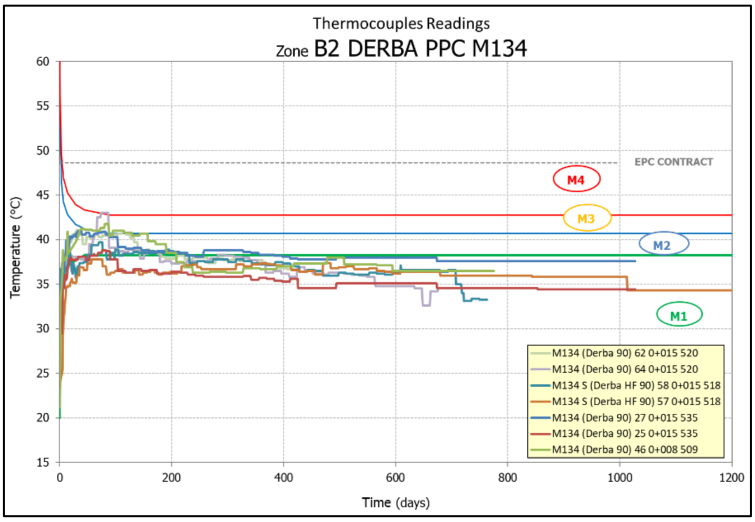


Fig. 13: Temperatures early warning graph (central zone B), at 10-20% of the elevation of the dam from the foundation

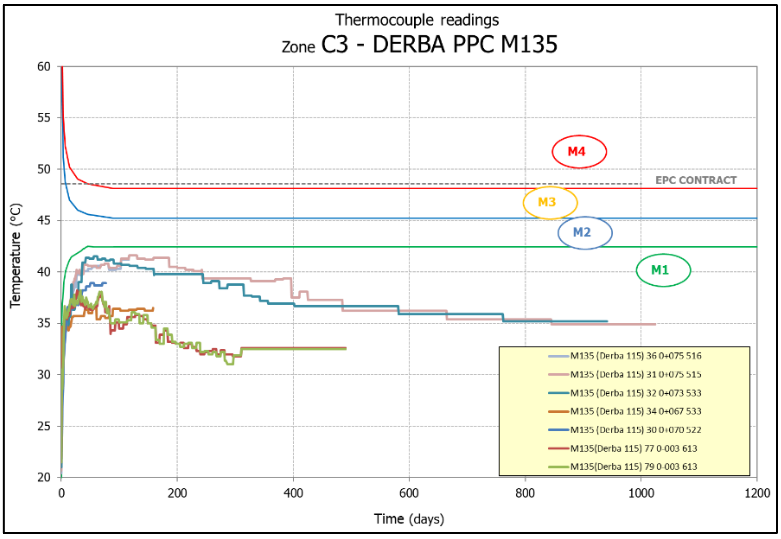


Fig. 14: Temperatures early warning graph (downstream zone C) at 20-40% of the elevation of the dam from the foundation

To date, with about 8.5 Mm3 of RCC placed, temperatures recorded in the dam body are in line with calculation predictions, confirming the good match with the values predicted by the calibrated model.

6. CONCLUSIONS

This paper describes the extensive tests campaign carried out at GERD Project on the RCC mixes to investigate the mechanical characteristics.

Particularly the following main aspects have been investigated in detail:

- The non-linear stress-strain behavior of RCC mixes. A single value for modulus of elasticity can result in erroneous estimate of stresses in the structure, resulting higher than actually occurring.
- The correlation between tensile modulus and compressive modulus. Tensile modulus resulted at least 30 % lower compared with homologue compressive modulus;
- The correlation between horizontal and vertical direct tensile strength for the same portion of RCC. The horizontal stresses resulted averagely 1,6 times greater the the vertical one;

The above results of tests have been used for a proper evaluation of thermal strain capacity, and to justify less expensive mixes with lower cementitious content and less heat for areas of high stress.

The methodologies adopted for dynamic and thermal analyses are discussed in the paper along with the measures for thermal monitoring and control.

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8. SUMMARY AND KEYWORDS

Testo inglese e testo francese

Keywords

Concrete Face rockfill dams, Stress and deformation analysis, External waterstop system, peripheral joint.