GIBE III DAM, DESIGN OF RCC ZONING

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Introduction

Gibe III hydroelectric project, located in the Southern Nations, Nationalities and Peoples' Region of Ethiopia, is the third plant of the Gibe-Omo cascade comprising Gilgel Gibe (IP=200 MW) and Gibe II (IP=420 MW), both operating, Koysha (under construction) and Gibe V (planned). The plant, with its 1'870 MW of installed power and 6'400 GWh of annual energy production, is one of the most important projects in the Ethiopian Government's commitment. The dam is the world's tallest (250 m high) and one of largest (6.2 Mm^3) Roller Compacted Concrete (RCC) dam. The Ethiopian Electric Power company (EEP) is the employer, Salini-Impregilo SpA the EPC general contractor and Studio Pietrangeli Srl the designer. The project commenced in 2006, impounding started at the beginning of 2015; at present dam construction is completed and the plant in full operation.

Fig. 1. Gibe III plant in operation (April 2017)

This paper is focused on the design of the dam RCC zoning and in particular it describes the evolution of the RCC zoning during the different design phases.

The paper, written by the persons directly committed in the dam design, presents key features and design criteria adopted for the RCC zoning, it illustrates the most important results of calculations (such as 2D and 3D static and dynamic analysis of the dam and thermal analysis) and also briefly summarises the main results of the dam monitoring system at date.

1. Level 1 design, Dam RCC zoning

The dam main section of Level 1 design stage is illustrated in Fig 2. The maximum dam height is 235 m (from 660 to 896 m a.s.l.); the upstream and downstream face has a slope respectively equal to 0.1:1 (H:V) and 0.65:1 (H:V).

As shown in the figure, at the level 1 design the zoning is horizontal with classes of increasing strength of RCC from the crest to the base. In particular the dam body is divided into four main zones with the following characteristic strength requirements:

- Elevation from foundation to 730 m a.s.l.: $f_{ck} > 15$ MPa
- Elevation from 730 to 760 m a.s.l.: $f_{ck} > 12$ MPa
- Elevation from 760 to 800 m a.s.l.: $f_{ck} > 10$ MPa
- Elevation from 800 to 850 m a.s.l.: $f_{ck} > 7$ MPa
- Elevation > 850 m a.s.l.: $f_{ck} > 12$ MPa

Moreover the extreme upstream face uses grout enriched RCC (GERCC); convention concrete is foreseen at the spillway sill and chute.

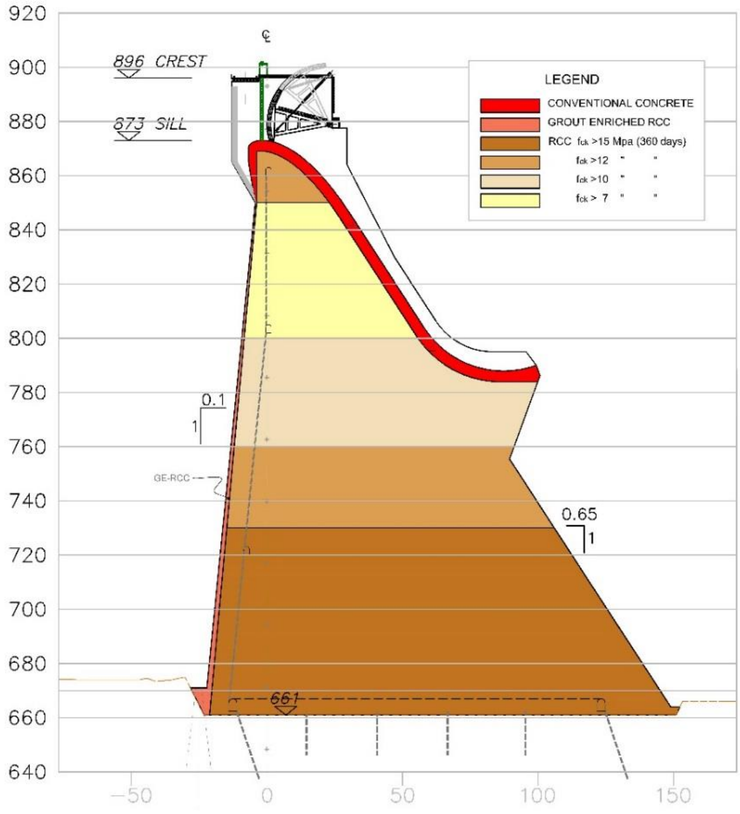


Fig. 2. Gibe III main section (geometry and zoning) at Level 1 design.

2. Level 2 design, Dam RCC zoning

2.1 General

During the final stage design, in accordance with the results of the extensive tests campaign performed on RCC mixes and the results of more sophisticated static and dynamic analyses, some critical issues and potential optimization were found about the following main aspects:

- compressive strength requirements during normal operation condition in the lower zone of the dam;
- tensile strength requirements in the upper zone during seismic events;
- permeability requirements on the upstream zone;
- thermal constrains in the dam central zone;
- upstream face and downstream toe geometry.

2.2 2D Static analysis

At the Level 2 Design stage, more accurate static analyses were performed in order to confirm the final dimensions of the dam and define a more reliable and complete stress distribution within the dam body. The following methodologies are adopted:

- FEM with Linear Elastic Static Analysis: to estimate the stresses into the dam body and to assess the stability against sliding of the structure
- FEM with NON Linear Elastic Static Analysis: to study the possibility of cracks propagating from the upstream face of the dam. This analysis allowed to establish the optimum position of the drainage lines.

The Fig. 3 illustrates the contours of minimum required compressive strength into the dam body at the end of construction and during normal operating condition.

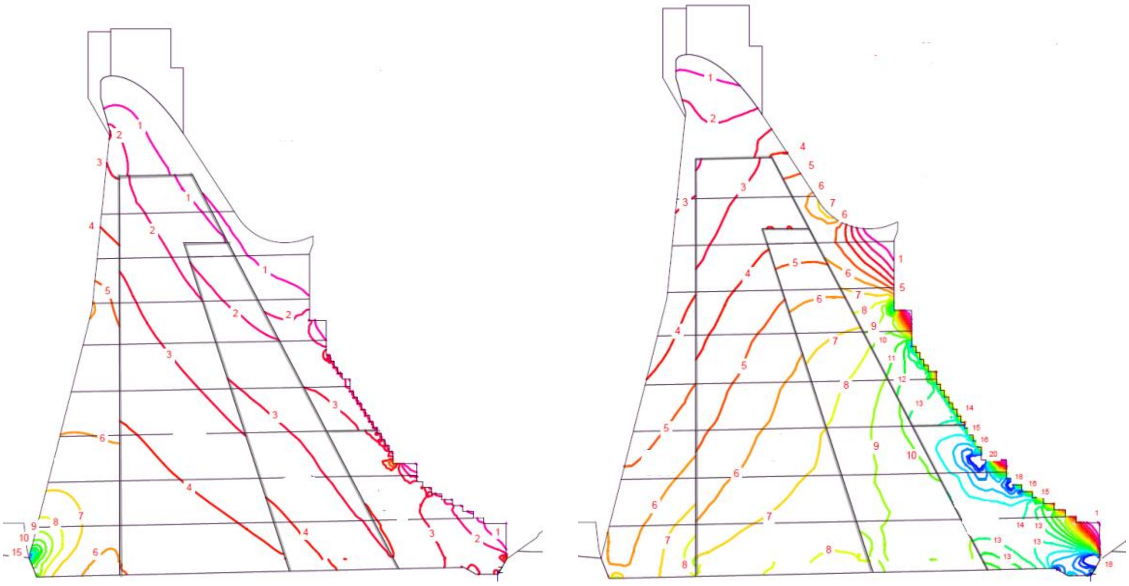


Fig. 3. Minimum required compressive strength; Left: End of construction, Right: Normal operating condition

As shown in the figure the maximum required compressive strength is equal to about 15 MPa at the upstream toe, at end of construction, and 18 MPa at downstream nail, during normal operating conditions. The required compressive strength at the bottom of central zone is always less than 10 MPa.

2.3 2D Dynamic analysis

Dynamic analysis was carried out in order to assess the global stability of the dam body and to determine the damage induced by two different levels of earthquakes (Operating Base and Maximum Credible Earthquakes).
The dynamic behaviour was evaluated by means of linear time history procedure, which involves the direct integration of the equations of motion.
The behaviour of tension zones in the dam body has been evaluated with the "Demand Capacity Ratio" approach (for OBE loads), analysing linear transient dynamic results.
To evaluate permanent displacements and the crack evolution during the MCE events, a non linear analysis has been performed, assuming the presence of a single or multiple weak joints where a crack can open and propagate.
The performed analyses have shown that:

- for Unusual earthquake loading (i.e. Operating Base Earthquake – OBE), no damage occurs, so that the project is compatible with serviceability requirements (see Fig. 4);
- for Super-Extreme earthquake events (i.e. Maximum Credible Earthquake – MCE), the structure undergoes to a certain damage, but it does not collapse (see Fig. 5).

In general, all dynamic calculations have highlighted the most critical situations in the highest part of the dam; the higher tensile strength requirements is located in the upper zone of upstream and downstream faces.
The performed analyses show that sliding displacements and rotational demands are sufficiently small not to jeopardize safety during the main events. Moreover, the evaluated damage level induced by minor seismic events is compatible with serviceability conditions.

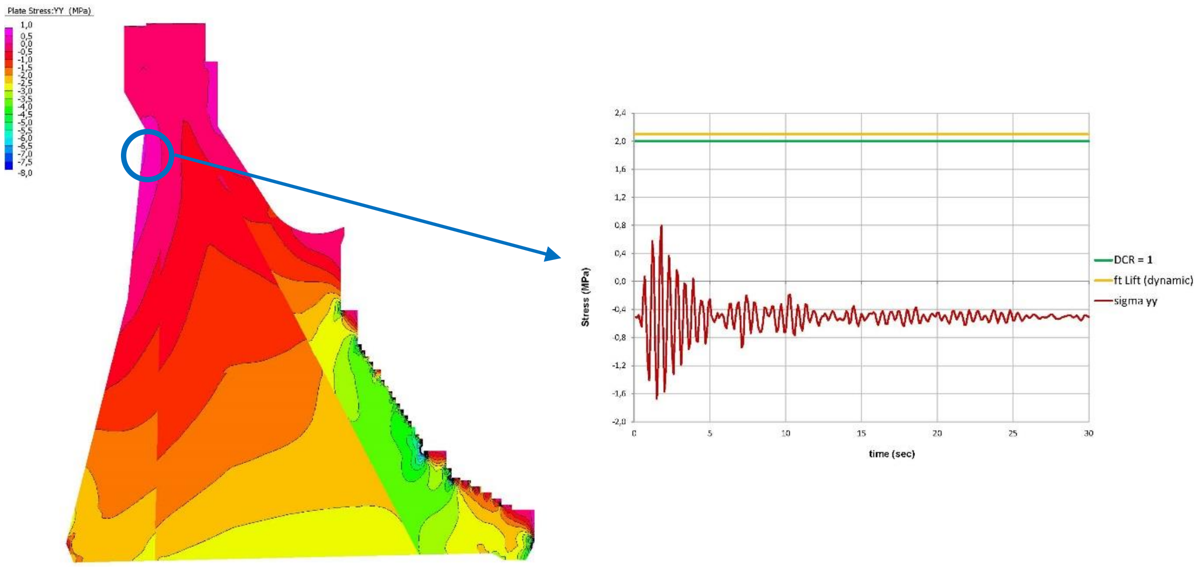


Fig. 4. Dynamic analysis, OBE, Left: maximum vertical tensile stress contour, Right: Tensile stress vs. time (DCR approach)

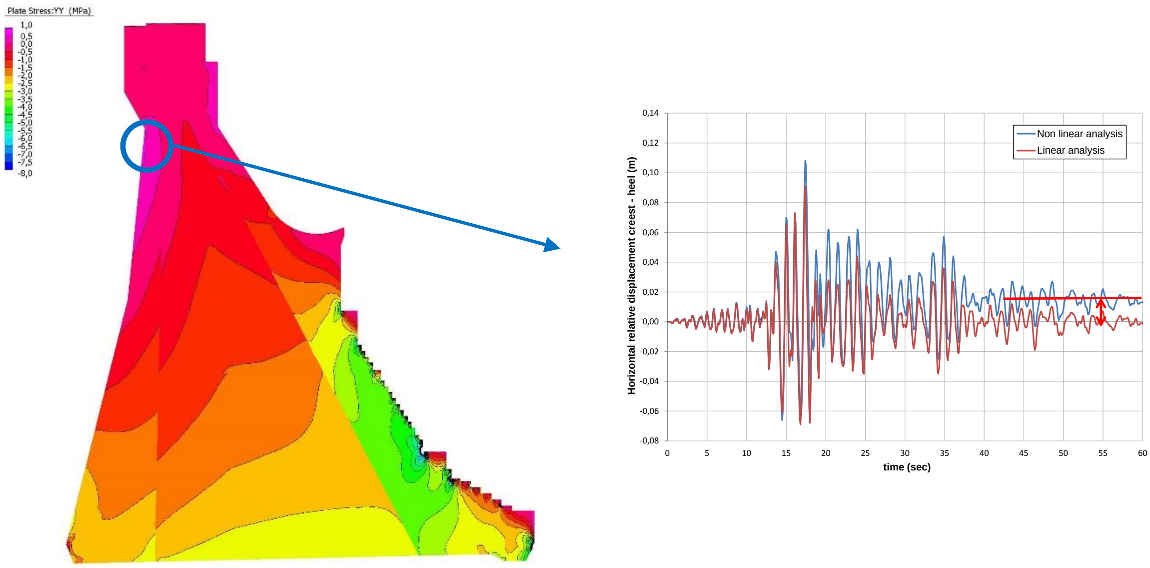


Fig. 5. Dynamic analysis, MCE, Left: maximum verticaltensile stress contour, Right: Displacements vs. time (non linear analysis with multi-cracks approach)

2.3 3D analysis

In addition to the 2D static and dynamic analysis, above described, a three-dimensional analysis of the gravity dam structure carried out with Non Linear Static Analysis with a staged load application in three main phases: 1) initialization of the foundation stresses, 2) dam construction, 3) reservoir impounding up to normal operating level. The results have confirmed that stress distribution between 2D and 3D analyses are very similar in the Construction load case and it are different in the Normal Operating Condition due to the tri-dimensional effects that consist, as expected, in transfer of horizontal loads from the main sections to the lateral ones. The stress maps resulting from this 3D model were useful tool for the detailed RCC dam zoning.
This since this analysis suggests that, even if locally only, the 3D effect might lead to over seed the compressive stresses obtained from the bi-dimensional modelling.
The analysis of the effective stresses have shown that no tensions appear at the u/s face in terms of effective vertical and maximum principal stress (no cracks are foreseen).
The relative displacement due to impounding have been calculated considering the difference of displacements between the end of construction and Normal Operating Condition. The comparison between the two-dimensional

results to the three-dimensional ones has shown that there is a reduction of displacements in the central section and an increase in the abutment section due to a transfer of loads from central to lateral sections.

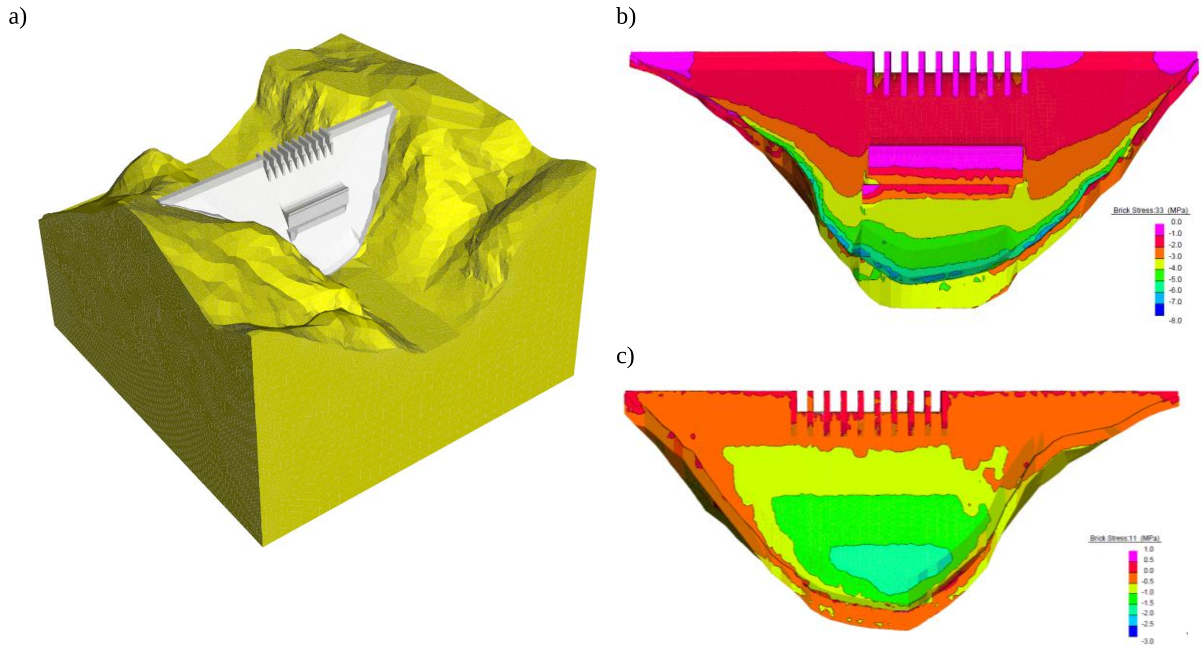


Fig. 6. Dynamic analysis, MCE, a) 3D FEM geometrical model, b) NOC, compressive stress on downstream face, c) NOC, tensile stress on upstream face

2.4 Thermal analysis

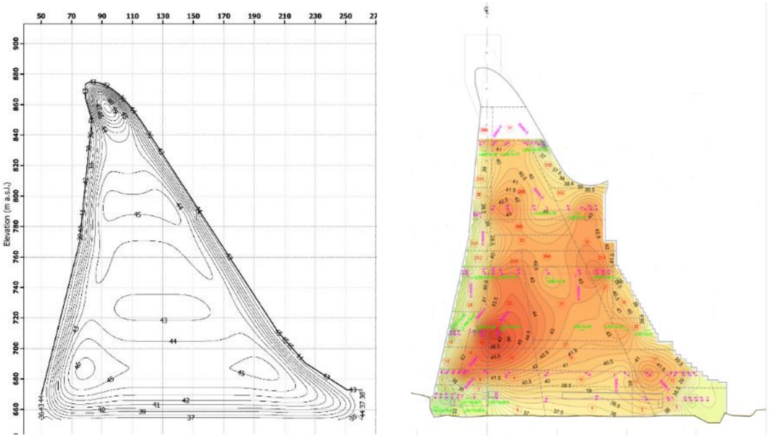
Transient thermal analysis has been conducted by finite differences software developed by Studio Pietrangeli in order to evaluate the temperature distribution histories in the dam. SP's in-house thermal model considers the main parameters that influence thermal behaviour of an RCC dam (i.e. time-dependent ambient conditions, time variation of thermal properties of the RCC/Grout Enriched-RCC mixes and production parameters)
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 main purpose of the study is to establish the maximum allowable placing temperatures for different mixes and locations in the dam to control the RCC peak temperature and the consequent thermal strains so that the tensile strain capacity is not exceeded and cracking is avoided.

The thermal study highlights that the critical area in terms of thermal stresses is lower zone of the dam (up to 20 m from the foundation) where the restraint factor due to the foundation is highest (especially in the central zone) and the effect of heat loss from the foundation begins to decrease significantly. In order to avoid thermal cracks in this zone the maximum peak temperature cannot exceed 40-42°C.

The study indicates as best solution to reduce at minimum the risk of thermal crack (i.e. limitation of value of peak temperature into the da body) and avoid complications in the construction methodology (i.e. utilization of post-cooling system, reduction of the production rate) the following suggestions:

- utilization of cement with lower hydration heat;
- RCC mixes with lower cement content in the central zone of the dam, where as shown in the previous paragraph, no stringent strength requirements are necessary;
- pre-cooling of materials (i.e. aggregates, water) up to obtain a maximum placing temperature of RCC in the zone near the foundation not greater than 20-23°C;
- systematic RCC surface protection by curing in order to reduce the increase of RCC temperature due to the solar irradiation and heat transmission from environmental (convection with air).

a)



b)

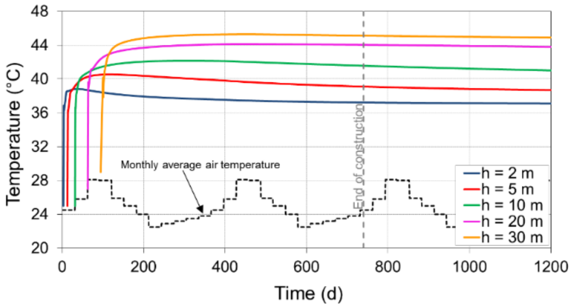


Fig. 7. Thermal analysis, a) Dam temperatures comparison, Design calculation vs. As built; b) RCC temperature history in the dam central zone at different distances from the foundation (h).

2.5 RCC Zoning

At the level 2 design, the RCC zoning was developed up to obtain the configuration illustrated in Fig. 8.

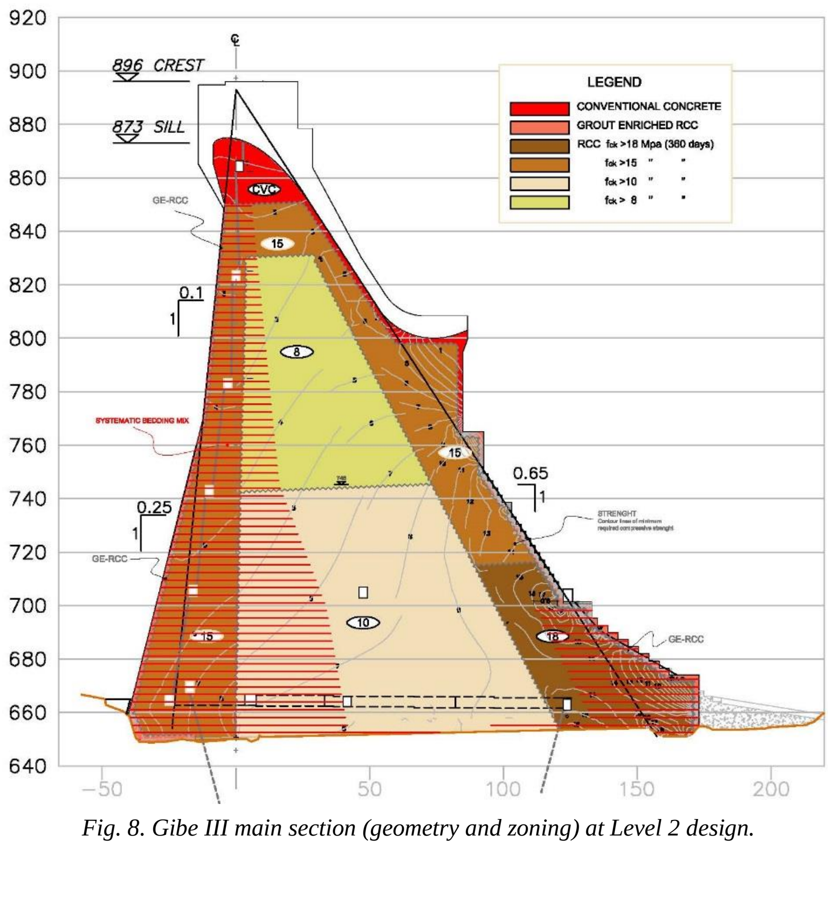
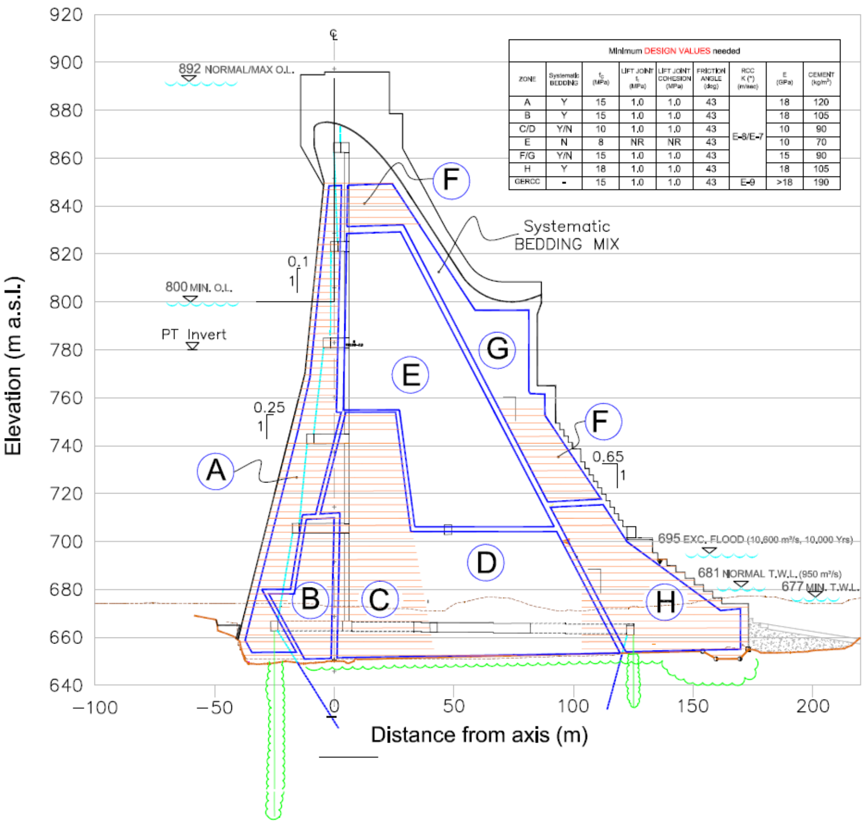


Fig. 8. Gibe III main section (geometry and zoning) at Level 2 design.

The main modification of the dam geometry and RCC zoning in relation to the level 1 design are summarized hereafter:

- the zone with higher strength requirements (f_{ck} > 15 MPa), foreseen in the primary design, for the first 70 m above the foundation level for the whole extension of the section, is limited to the upstream and downstream external zones of the dam. A zone with 18 MPa of required compressive strength is introduced in the downstream toe. This modification is performed in order to:
    - meet the compressive strength requirements at the end of construction, at the upstream toe, and during normal operating condition, at the downstream (ref. paragraph 2.2);
    - meet tensile strength requirements on the upstream and downstream faces during seismic events (ref. paragraph 2.3);
    - improve the waterproofing of the upstream face up to the drainage galleries.
- the zones with lower strength requirements (f_{ck} > 8-10 MPa) is extended in the final stage design up to the whole dam central zone, where there are not stringent strength requirements and especially in order to control the temperature rise and the consequent risk of cracking in accordance with the results of thermal analysis illustrated in the paragraph 2.4.
- a double slope is introduced at the upstream face (0.25:1 slope in the lower portion, below elev. 770 m a.s.l. and 0.1:1 slope in the upper portion) in order to improve the dam behaviour during earthquake;
- local slope decrease at the toe below elev. 700 m a.s.l. is foreseen at the stepped downstream face in order to reduce the compressive stress during normal operating.

Moreover, at level 2 design, the bedding mix zoning is designed. The extent of bedding mix (see Fig. 8) is primarily established by consideration for impermeability at lift joints in the upstream portion of the dam and to assure adequate safety against sliding on any horizontal lifts within the structure during normal and seismic conditions.
Extensive mix designs and testing have been carried out in order to define the specific RCC mixes for different areas of the dam illustrated in the Fig. 8.
The main section of the dam with the cement content zoning and the extent of bedding mix at lift joints for different elevations is shown in Fig. 9.



ZONE	Systematic BEDDING	f_c (MPa)	LIFT JOINT f_t (MPa)	LIFT JOINT COHESION (MPa)	FRICTION ANGLE (deg)	RCC K (*) (m/sec)	E (GPa)	CEMENT (kg/m³)
A	Y	15	1.0	1.0	43	E-8/E-7	18	120
B	Y	15	1.0	1.0	43		18	105
C/D	Y/N	10	1.0	1.0	43		10	90
E	N	8	NR	NR	43		10	70
F/G	Y/N	15	1.0	1.0	43		15	90
H	Y	18	1.0	1.0	43		18	105
GERCC	-	15	1.0	1.0	43	E-9	>18	190

Fig. 9. Gibe III main section, RCC construction zoning

As shows in the figure the dam is divided in different zones based on the RCC mixes and also the presence (or not) of systematic bedding mix. The cement dosages range from 70 to 120 kg/m^3.

It is highlighted that some minor zoning adjustments was performed during construction in order to optimize the construction procedure.

In conclusion, the zoning and RCC mix design was tailored to achieve direct cost savings (by minimizing the cement content) and indirect ones (by providing a zoning that favours a simple and fast construction, with final benefit on construction time and quality).

3 – Dam performance

Monitoring of dam performance during impounding is currently ongoing by means of the extensive instrumentation system installed, while reservoir filling is still under completion. The maximum reservoir level, from the starting of the impounding (January 2015) to date, is reached at the mid of November 2017 (el. 871 m a.s.l.); the water head at this date was equal to about 220 m on the dam foundation level (about the 90% of the maximum hydrostatic load).

The main results of the dam monitoring assessment for the main components of the instrumentation system (uplift, temperatures, leakages, deformations and displacements), updated at January 2017, is summarized hereafter:

- UPLIFT on Dam foundation

  All 109 piezometers (91 vibrating wire piezometers + 18 open pipe piezometers), installed inside the dam body, indicate that, from January 2015 to January 2017, the recorded pressure was always well below the assumed design value and, moreover, the pressure increase is coherent with the rise of the reservoir water level. Fig. 10 shows the comparison for all the vibrating wire piezometers between the recorded water level at the maximum reservoir water level (el. 871 m a.s.l.) and the one calculated in accordance with the uplift distribution proposed by the USACE manual 1110-2-2200 (utilized in the dam stability calculations).

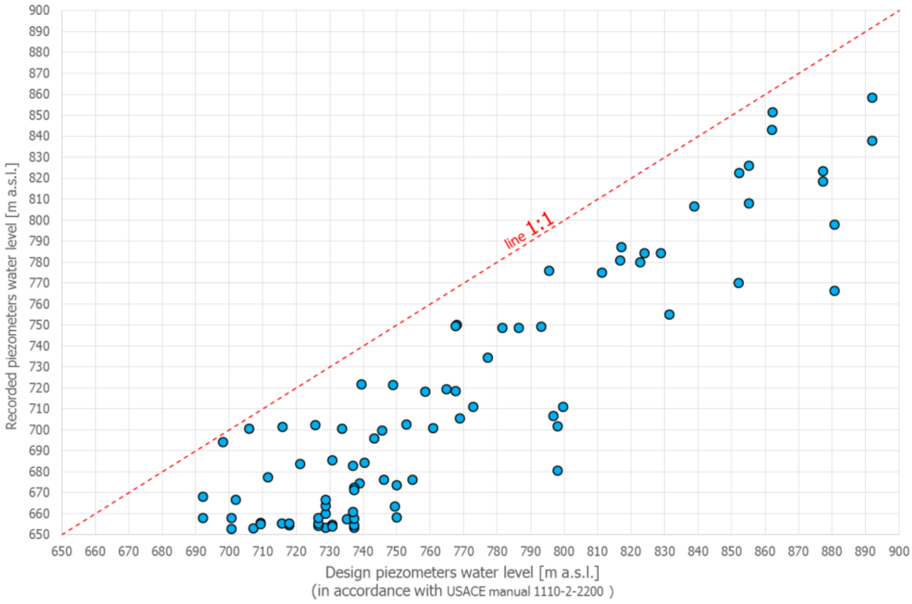


Fig. 10. Piezometers, recorded water level vs. design water level

- LEAKAGES

  The overall flow discharged by the V-notches (at November 2017) installed in the dam galleries is about 64 l/s (Fig. 11), which is very low considering that the impounding water level was at about 90% of maximum operating water level, and compared to the discharge capacity of the pumping system (i.e. about 2’200 l/s). The leakages pertaining to the dam upstream face correspond to only 15 l/s.

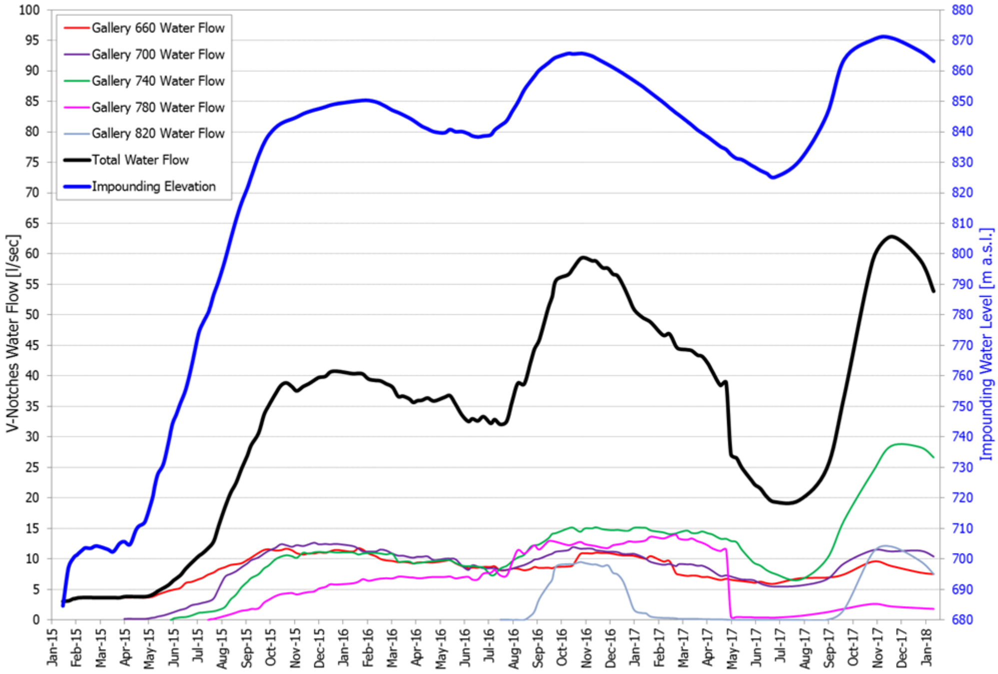


Fig. 11. Overall V-notches discharge and Reservoir Level vs Time

- DAM SETTLEMENTS and DIPLACEMENTS

  The dam foundation settlements are monitored by means of 15 multi-point extensometers, which indicate that the dam foundation settlements in the range of 0-7 millimetres.

  Dam displacements are monitored by means of 5 pendulum (direct and invert), 4 optical alignment collimators at different elevations and 60 contraction joint deformometers installed inside the drain galleries and at the dam crest. Joint deformometers do not show relative displacements of significant magnitude between adjacent monoliths (0-4 mm), while pendula data indicates substantially a stable behaviour of the dam with maximum displacements towards downstream of about 2 cm.

- DAM THERMAL CONDITIONS

  Thermal readings are provided by 226 thermocouples and 388 fibre optic sensors installed in the dam body. Generally, the temperatures recorded are in line with the calculation predictions, with confined differences of some degrees mostly due to local changes in RCC mixes and placement methodology (Fig. 7). Generally the peak temperatures, comprised between 35 and 47°C, is reached in the period from 90 to 730 days from the placing. To date, after about 6 years from the start of RCC placement, the temperatures inside the dam body are substantially constant or slightly decreasing in the central part of the dam. A significant temperature decrease has been observed only in the sensors installed close to the dam upstream face, as expected.

The Authors:

A. Pietrangeli obtained his degree in civil hydraulic engineering from the University of Rome "La Sapienza". In recent years, after becoming managing partner of Studio Pietrangeli, he has been directly responsible for the technical direction and overall management of many of the firm's projects covering more than 40 large dams (up to 250 m high) and 20 large hydroelectric plants (totaling more than 15.000 MW) in Africa, Europe and South America.

A. Cagiano obtained his degree in civil hydraulic engineering from the University of Rome "La Sapienza". He has worked in the field of dams and hydropower engineering for more than fifteen years. He has been project manager for several renowned hydropower projects such as Gibe II, Gibe III, GERDp, Koysha, Batoka and Namakhvani. His expertise includes all the activities of project management, design coordination, contract engineering from the design to supervision of construction for dams and hydropower plants.

G. Pittalis obtained his degree in Civil Engineering from the University of Rome "La Sapienza". He has fifteen years of experience in dams and hydropower engineering working as designer, geotechnical expert and hydraulic specialist. He has gained a remarkable experience during all the phases of the design, from conceptual scheme to monitoring during operation, for several large dams and hydropower plants under construction or recently built such as Gibe III, Grand Ethiopian Renaissance, Koysha, etc.

C. Rossini graduated with honors in civil engineering from the University of Rome "La Sapienza". He has ten years of experience in dams and hydropower engineering, having worked especially in the study and design of the RCC for the large dams of Gibe III and GERdp as well as all the geotechnics aspects of the two projects. He has gained a remarkable experience working closely in the field with major international experts during the construction of Gibe III and GERdp.

A. Masciotta obtained his degree in Civil Engineering from the University of Rome "La Sapienza". He has more than thirty years of experience as civil works designer and structural expert. He has worked for more than fifteen years for Studio Pietrangeli as an independent expert for large dams and hydropower projects. In 2006 he founded Studio Masciotta, a civil engineering firm specialized in civil and structural engineering.