GIBE III DAM MONITORING SYSTEM

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1 - 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 (200 MW) and Gibe II (420 MW), both in operation, 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 to meet the country's present and future power requirements. The Ethiopian Electric Power company (EEP) is the employer, Salini-Impregilo SpA the EPC general contractor and Studio Pietrangeli Srl the designer.
The dam is the world's tallest (250 m) and one of largest (6.2 Mm^3) Roller Compacted Concrete (RCC) dams. It is built with a rather low cement content, varying from 70 to 120 kg/m^3. A sprayed membrane improves, in the lower part of the dam, the water tightness of the upstream face (GE-RCC).
Impounding of the dam started at the beginning of 2015 in order to anticipate the start of energy production to Autumn 2015, while the dam was still under completion.
By now the dam is almost completed: only the upper portion of the central spillway is still under construction. At the end of the 2016 rainy season the reservoir level had reached elevation 865 m a.s.l., corresponding to a maximum head of about 215 m over the dam foundation.

Monitoring of dam performance (temperatures, leakages, deformations and displacements) during impounding is currently ongoing by means of the extensive instrumentation system installed, while the dam was still under construction and reservoir filling is still under completion, allowing easier and timely reactions in case of need.

This paper focuses on the description of the Gibe III monitoring system, as far as its design, construction and implementation aspects are concerned, and the key parameters being monitored.

Fig. 1: Gibe III plant in operation, while spillway construction is under completion, October 2016

2 – Key Characteristics of the Project

The Gibe III project includes several outstanding key elements, some of which have guided the design and implementation of the monitoring system (reference is made to other papers [1], [2], [3], [4], [5] which illustrate the characteristics of the design mix, the main challenges faced during construction of the dam and the design of the main project components):

- it is the world's tallest (250 m high) and one of the largest (6.2 Mm^3) Roller Compacted Concrete (RCC) gravity dams, creating a reservoir with a length of about 150 km and a volume of about 15'000 Mm^3;
- a world record for the RCC placed in 24 hours (18'519 m^3) was achieved in December 2014;
- the dam is being built with a rather low cement content, varying from 70 to 120 kg/m^3;
- it includes two middle outlets in the dam body, which can lower the reservoir down to about 760 m a.s.l., but no bottom outlets. This means that the lower 100 m of the dam will be permanently underwater;
- a sprayed membrane improves, in the lower part of the dam, the water tightness of the upstream face (GE-RCC);
- the design allows impounding to commence before completion of construction, thereby bringing forward power production;
- the spillway, on the dam crest, will discharge up to 18'000 m^3/s through 7 radial gates measuring 12 x 17.5 m;
- the powerhouse, fed by two power-tunnels with a diameter of 11 m and approximately 1 km long, with its ten Francis turbines (1'870 MW), will be one of Africa's largest hydropower plants.

Trachyte, a fine-grained, medium-strong to strong volcanic rock is the main rock type at the dam foundations. The rock mass is mostly fresh, or slightly weathered, and fractured. However, especially in the riverbed, some zones of intensely fractured/highly weathered trachyte rock were found. Hot water springs were encountered at riverbed elevation, in hydraulic connection with a deep aquifer lying about 100 m below the foundation of the dam. Columnar and vacuolar basalt flows, inter-bedded by metric series of pyroclastic rocks and continental erosional deposits constituted of heterogenic pebbles, are found above the trachytic body, in the upper portion of the dam abutments.

Vertical construction joints, equipped with upstream water-stops and drains, divide the dam into 35 blocks. These joints are obtained by cutting the fresh RCC with a blade which crosses most of the 40 cm thickness of the RCC lifts. The spacing of the joints varies from 11 to 24 m, with an average of 20 m.

The dam body houses longitudinal galleries, one every 40 m of height, located close to the upstream face, extended about 40 m inside the abutments and conceived for drainage/grouting works and monitoring purposes.

3 – Instrumentation System

The extensive instrumentation installed inside and outside the dam body, includes piezometers, extensometers, direct and inverted pendula, manual and automatic joint deformometers, thermocouples and optic fiber sensors, collimators etc.. Leakages inside the dam body are measured locally in correspondence to each drain hole (foundation drains, dam contraction joints drains, dam U/S face drains, springs on dam foundation footprint) and, for broad areas, by means of V-notches installed in the gutters of the longitudinal and transversal inspection galleries.

Data from the instrumentation system is collected following the guidelines reported in the First Impounding Report and presented in dedicated factual reports issued on a monthly basis by the site Technical Office.
Data is periodically analysed by the Designer in order to assess the dam behaviour and identify the presence of routine or alert conditions for the dam monitoring activities.

The following paragraphs report the results, updated to the end of November 2016, of the dam monitoring assessment for the main components of the instrumentation system.

In general terms, the performance and behaviour of the whole project has been fully satisfactory until now and routine monitoring conditions are applied for all the parameters:

- foundation uplifts are well below the design values;
- leakages are very low (i.e., less than 60 l/sec) and well below the discharge capacity of the pumping system installed in the lower galleries;
- no significant dam settlements and displacements have been observed (it is worthwhile recalling that the expected displacements from FEM models made at design level were of some centimeters in the horizontal direction, but they were consequent to the assumption that the dam would have been entirely built before impounding, which is far from the reality in which impounding started during dam construction);
- measured temperatures are close to those predicted by the thermal analysis model which proved to be effective and reliable.

Since the beginning, monitoring of the dam was referred to the water levels in the reservoir, on which most of the parameters under observation depend. In order to better understand the behaviour of the dam and the data reported in the subsequent paragraphs, key-dates and definitions are indicated hereunder:

- pre-impounding (i.e., filling of the volume between U/S cofferdam and RCC dam from el. 670 up to el. 720 m a.s.l.) started in-mid July 2014 and was completed in October 2014;
- impounding started on 19th January 2015 with the closure of the Right Diversion Tunnel;
- the reservoir level overtopped the U/S cofferdam (surpassing pre-impounding level) at the beginning of May 2015;
- the first Temporary Ecological Valves, located inside the Right Diversion Tunnel, were closed at the end of June 2015. At this date, the reservoir level had reached el. 765 m a.s.l.;
- the second Temporary Ecological Valves, located inside the Right Diversion Tunnel, were closed in mid-August 2015. The Powerhouse ecological valve was opened on the same date; the reservoir level reached el. 805 m a.s.l.
- closure of the Powerhouse ecological discharge valve and the start of energy generation by the First Unit occurred on 10th October 2015. At this date, the reservoir level had reached el. 841 m a.s.l.;
- RCC placement was completed on 31st October 2015;
- the reservoir level reached el. 850 m a.s.l. at the end of January 2016, corresponding to a head of about 200 m on the dam foundation level (about 80% of the maximum hydrostatic load);
- commissioning of all 10 Units was completed by August 2016;
- the reservoir level reached el. 865 m a.s.l. at the end of October 2016, corresponding to a head of about 215 m on the dam foundation level (approximately 85% of the maximum hydrostatic load);
- by the end of November 2016 the reservoir level had reached el. 862 m a.s.l.

4 – Uplift on Dam Foundation

Following the progress of RCC and grouting activities 109 piezometers (91 vibrating wire piezometers + 18 open pipe piezometers) have been installed inside the dam body, roughly aligned along sections in order to allow the drafting of uplift profiles in the U/S – D/S direction.
A typical example of uplift profile is reported in the following figure, which shows:

- RCC dam profile;
- reservoir level;
- position of piezometer sensors;
- alignment of grouting and drainage curtains;
- measured uplift for each sensor and piezometric line (line connecting the uplifts recorded in the various sensors);
- deep aquifer piezometer and relevant pressure (red line);
- "scaled uplift indicative reference line" (dotted red line) obtained by scaling the uplift diagram considered in the stability calculations according to the actual reservoir level (this procedure is indicative only being very conservative for the purpose of dam stability verification).

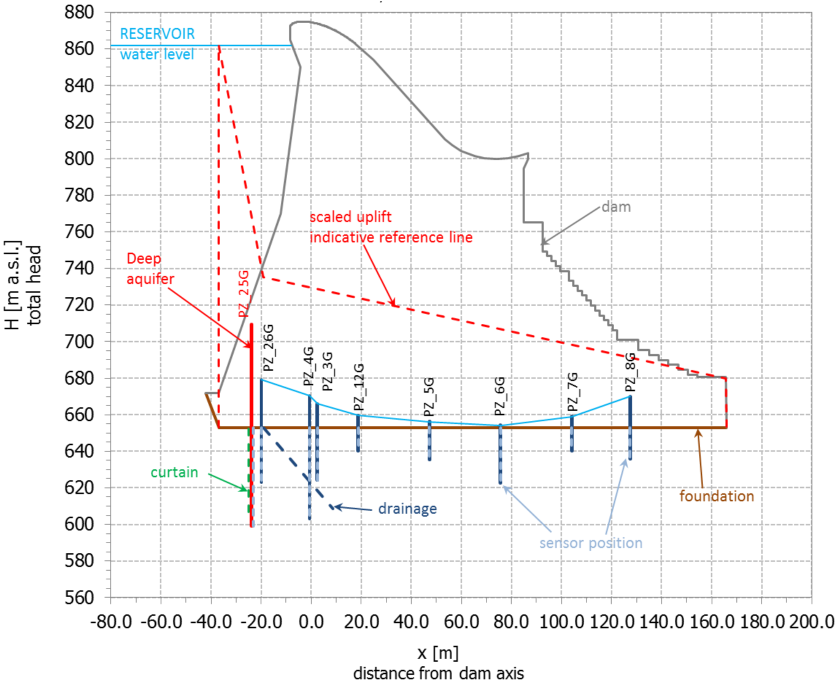

Fig. 2: IS 0+362, Uplift profile @30November2016 ($H_{U/S}$ = 850 m a.s.l.)

The piezometers located in the upper portion of the foundation indicate that, in every instrumented section, the recorded pressure is well below the assumed design value. It is also observed that the piezometric level on the dam foundation is influenced by the valley shape: pressure increase in the abutments is higher than that observed in the sensors installed in the central part at the same elevation).

Moreover the pressure increase in all the piezometers is coherent with the rise of the reservoir water level (see Figure 3).
We mention here that, in the 660/665 m a.s.l. galleries, 3 piezometers installed below or near the roof of the confined aquifer (i.e., pz 25G, 44G and 47G) show a pressure increase which is higher than that measured by the sensors installed at the same chainage and offset by a higher elevation. The observations on the deep-aquifer behaviour are reported in a dedicated paragraph.

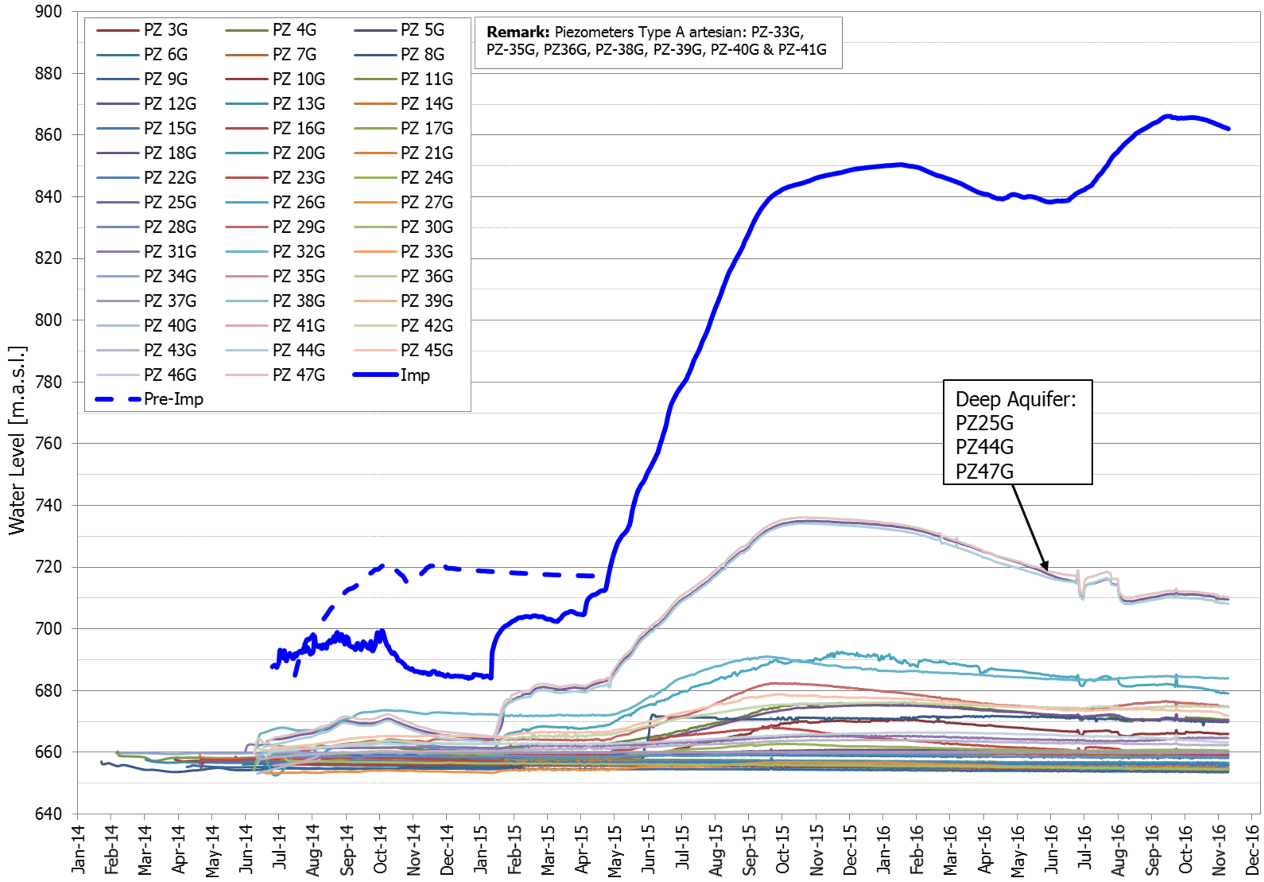

Fig. 3 – Piezometers in the lower dam gallery (660-665 masl): Uplift and Reservoir level vs Time

5 – Leakages

The leakages measurements are conceived in order to separate the waters coming from:

- upstream face drains;
- dam contraction joints drains;
- drains crossing the dam foundations;
- springs on the dam foundation footprint.

Moreover, in addition to punctual measurements, waters coming from broad areas are re-collected in the V-notches installed in the gutters of the dam galleries. It has been observed that, generally, the flow measured in the V-notches is higher than the sum of the individual contributions (foundation drainages, dam body drainages, contraction joint drainages). This is due to the fact that, while the V-notches intercept all the drained waters, the individual spot measurements are carried out only where physically possible (sometimes very small venues or dripping waters are not measurable).

The overall flow discharged by the V-notches installed in the dam galleries is about 58 l/s which is considered very low, considering that the water head on the foundation is about 215 m (about 85% of maximum hydrostatic head), 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 11 l/s.

As shown in the following figure, there is a clear relationship between leakages and reservoir level.

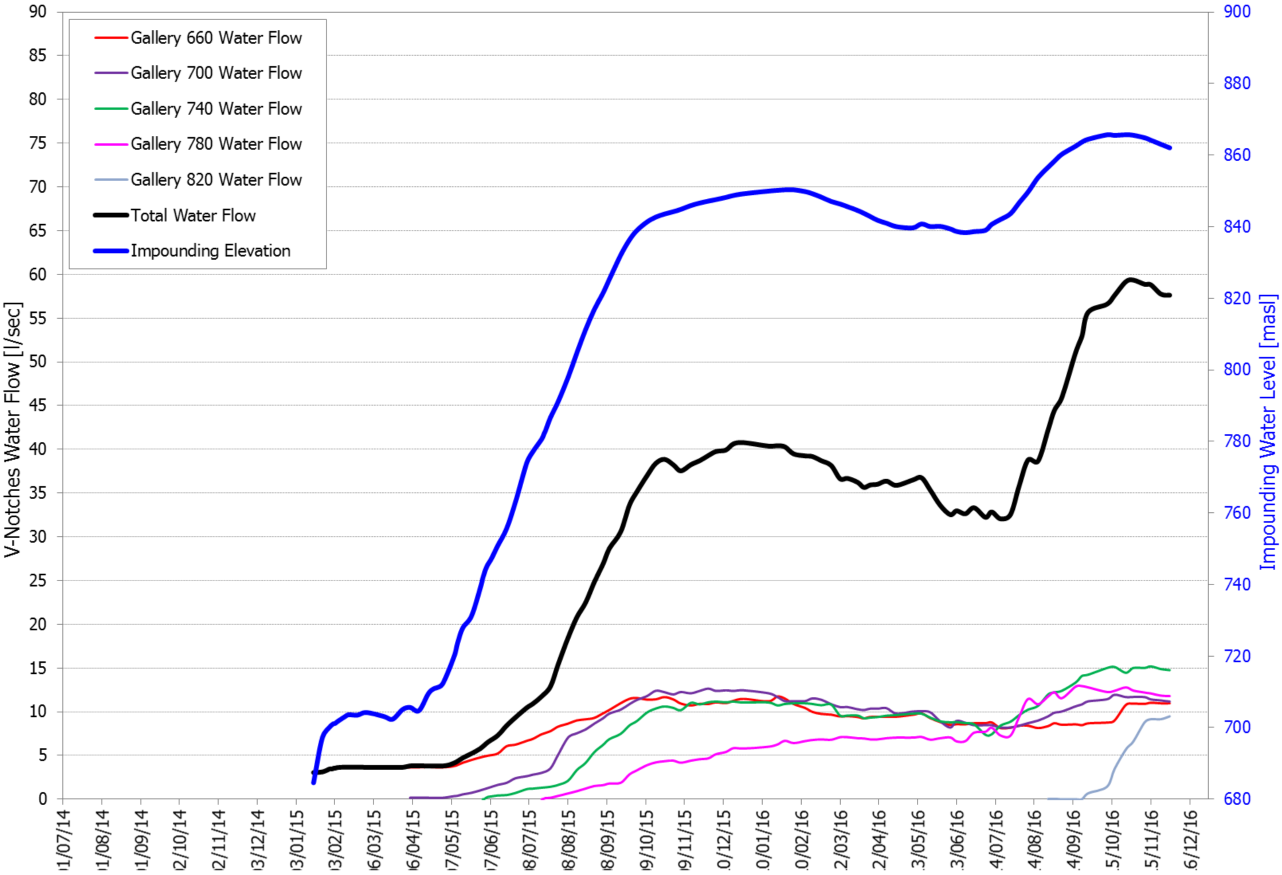

Fig. 4 – Overall V-notches discharge and Reservoir Level vs Time

6 – Deep Aquifer

In the central part, the RCC dam is founded on a dark/light grey trachytic body with a blocky structure and moderately to widely-spaced sub-vertical joints (almost parallel and perpendicular to river alignment). This portion of the rock mass, with a thickness in the range of 100 m, has a very low permeability - generally less than 1 UL (with the exception of the zone 5-10 m below the RCC-rock contact where the permeability increases slightly up to 2-3 UL, due to the disturbance and stress relief induced by the excavation). From about 80 to 130 m below the foundation level, the rock mass appears more fractured and the trachyte gets bleached to light grey while the joint surfaces appear stained with some greenish grey trachyte. In this portion of the foundation the roof of a confined artesian thermal aquifer has been detected. In some boreholes, at the base of the trachytic body, an impervious level of plastic blacky material has been encountered, with the predominant presence of kaolinite besides muscovite and illite.

10 Piezometers have been installed within the deep aquifer:

- 3 Inside the Dam body: PZ25G, PZ44G, PZ47G
- 7 Outside the Dam Body: PZ-DAM02bis, PZ-DP2bis, PZ-DP10, PZ-DP11, PZ-DP12, PZ-DP17, PZ-DP18

From figures 3 and 5 it is possible to observe that:

- there is a correlation between aquifer pressure and the reservoir water level, in particular:
  - this correlation started in January 2015, when the reservoir rose above the U/S cofferdam; the direct connection between the aquifer and the reservoir appeared therefore to be upstream the cofferdam;
  - from May 2015 to January 2016 (reservoir water reached elevation 850 m a.s.l.) this correlation appeared constant and linear, with a coefficient of about 0.4;
  - the pressure is substantially constant in all the deep aquifer, below the dam and the plunge pool area. No significant pressure differences have been observed among the piezometers installed in different zones (slight variations can be attributed to possible local weaker zones and rock mass anisotropy).

    A lower pressure of about 670 m a.s.l. has been observed only in piezometer DP18, 1500 m downstream the dam axis along the Omo river. This piezometer is near the Omo Bridge, some meters upstream the fault limiting the gorge where the dam is located. The level of deep aquifer in this piezometer is not substantially affected by the oscillations of the reservoir. This zone probably acts as a downstream hydraulic boundary.

- Starting from 2016 the first rapid step of reservoir raising was concluded and the reservoir started to oscillate between el. 840 and 865 m a.s.l.. Associated with this reservoir trend, it was observed that:
  - when the reservoir remained substantially constant, the water pressure in the deep aquifer goes down;
  - when the reservoir started to rise again, the water pressure in the deep aquifer also rose again, but with a lower linear coefficient of correlation (a longer period of observation will allow us to better examine and confirm such inferred trend).

This observation may allow us to infer that the closest connection between the reservoir and the deep aquifer is being progressively clogged, with a surely beneficial effect on the gradient of the deep aquifer under the dam and the plunge pool area.

So far it remains confirmed that (1) the trend of the deep aquifer pressure rise and (2) the stable and lower pressure measured by the sensors installed at higher elevation (above the aquifer) confirm the substantial water tightness of the upper trachytic body under the dam.

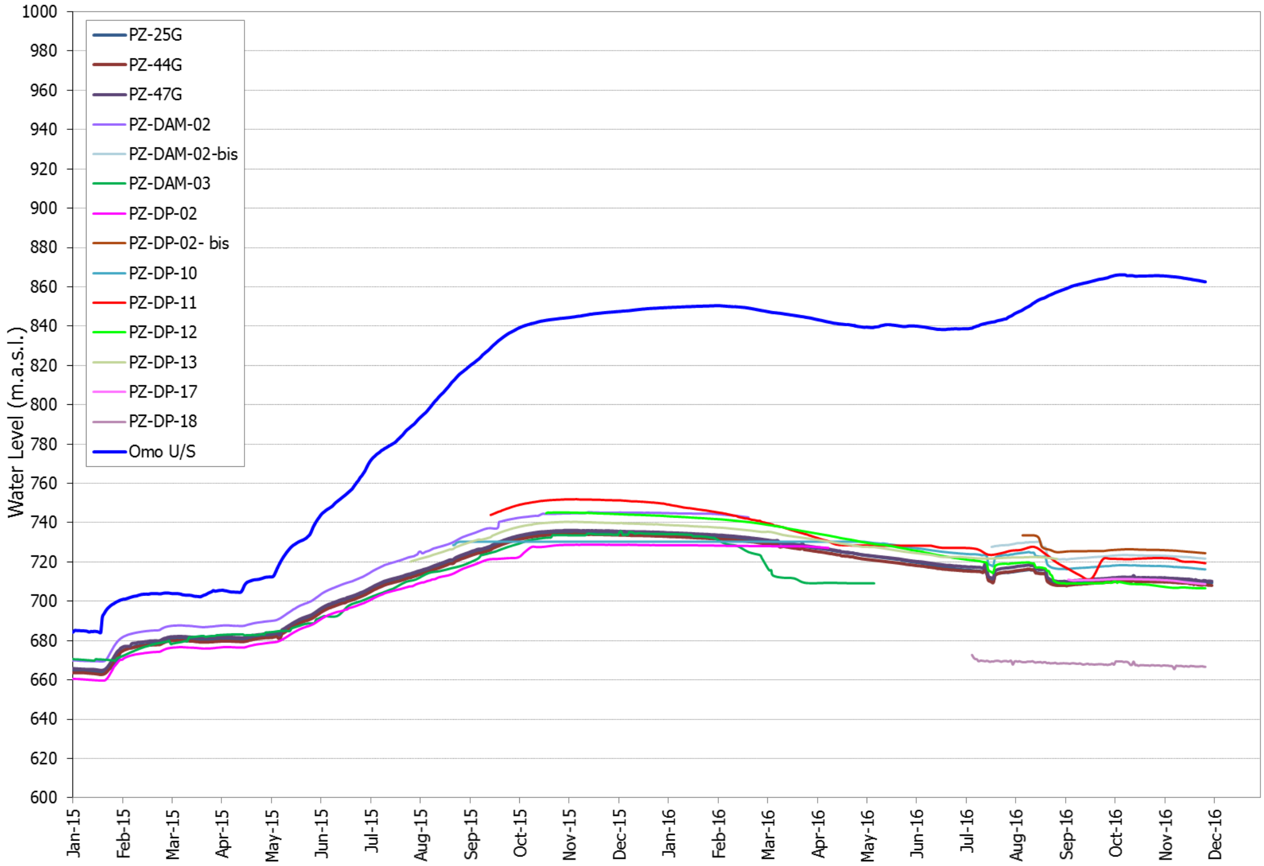

Fig. 5 – Deep aquifer piezometers vs Time

We point out that the hypothetic scenario consisting of the creation of important pore pressures inside the deep aquifer was considered the dam drain system was designed. Drains all along the central part of the dam footprint were in fact purposely drilled as a line of defence to avoid the possible interconnection of the dam foundation with the pressurized deep aquifer through the upper trachytic body that might generate excessive uplift just below the dam, jeopardizing its stability.

Other small sites in zones of the banks (river diversion tunnels, main tunnels, manifolds and Power House area) have been observed. Their temperatures indicate that probably the water comes partly from the deep aquifer and partly from water circulation in the rock mass. The total amount of water remains in the range of some tens of litres per second, in terms of volume not critical to the scale of the project.

7 – Dam Settlements and Displacements

The dam foundation settlements are monitored by means of 15 multi-point extensometers installed in boreholes and aligned along 5 section in an U/S to D/S direction.
Dam displacements are monitored by means of:

- 5 pendulum (direct and invert);
- 4 optical alignment collimators at different elevations;
- 60 contraction joint deformometers installed inside the drain galleries and at the dam crest.

The data of multi-point extensometers indicate dam foundation settlements in the range of 0-5 millimetres. The higher displacements, as expected, are recorded in the dam central sections at the downstream toe.

From pendulum and collimator data, it is possible to observe that:

- U/S to D/S direction:
  the dam has had a rotation towards downstream. The horizontal displacements are in the range of some millimetres. The higher displacements, as expected, were recorded in the dam central sections.
- Left to Right direction:
  the dam has moved towards the right in the left abutment and in the central zone and slightly towards the left in the right abutment. The displacements are in the range of some millimetres. The higher displacements are recorded in the central sections, as expected.

The increase in dam settlements and displacements is in line with the reservoir water level, there is no evidence of time dependant behaviour.

Fig. 6 shows the displacements of the dam in an U/S to D/S direction at different elevations and at 8 different dates (different RCC and reservoir water elevations) for one of the pendulums in operation. The plot indicates, as expected, a dam rotation towards upstream during RCC placement when the reservoir level is low and a progressive dam rotation towards downstream with the increase of the reservoir water level.

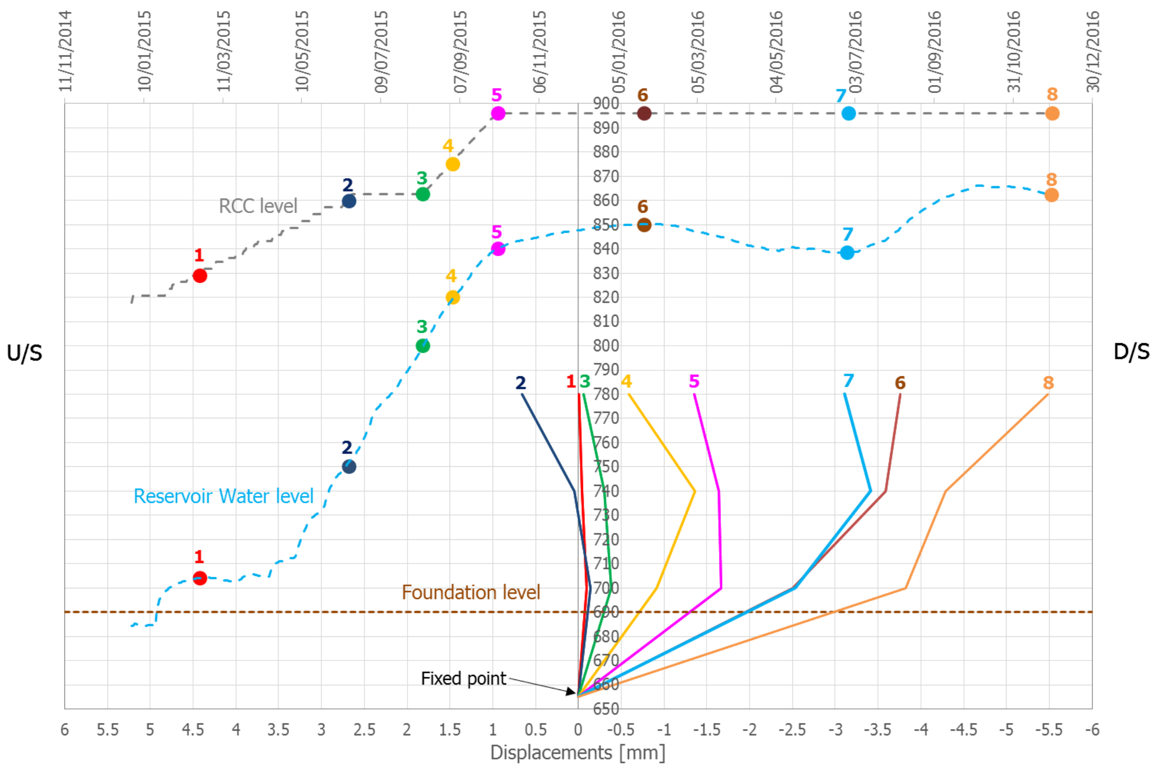

Fig. 6. Pendulum at ch. 0+295 (left abutment), u/s to d/s displacements

Most of the instruments recorded no displacements in any direction. In some contraction joints maximum displacements of 1-2 mm in a left to right direction (opening/closing) have been recorded (especially near the dam crest).

In conclusion, the data from joint deformometers and collimators seem to exclude relative displacements of significant magnitude between adjacent monoliths while data from pendulum and extensometers indicate a substantially stable behaviour of the dam and its foundation.

8 – Dam Thermal Conditions

Thermal readings are provided by 226 thermocouples and 388 fibre optic sensors installed in the dam body between elevation 660 and 860 m a.s.l.

Recorded peak temperatures are compared with EPC contract values (i.e., 47° = average annual temperature + 20°) and maximum allowable temperatures deduced from dam thermal analysis as a function of dam zone [1].
As shown in Fig. 7, 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. The complex shape of iso-thermal contours is due mainly to the zoning of the dam and to the change in cement type (Cementir in the bottom and Messebo in the rest of the dam).

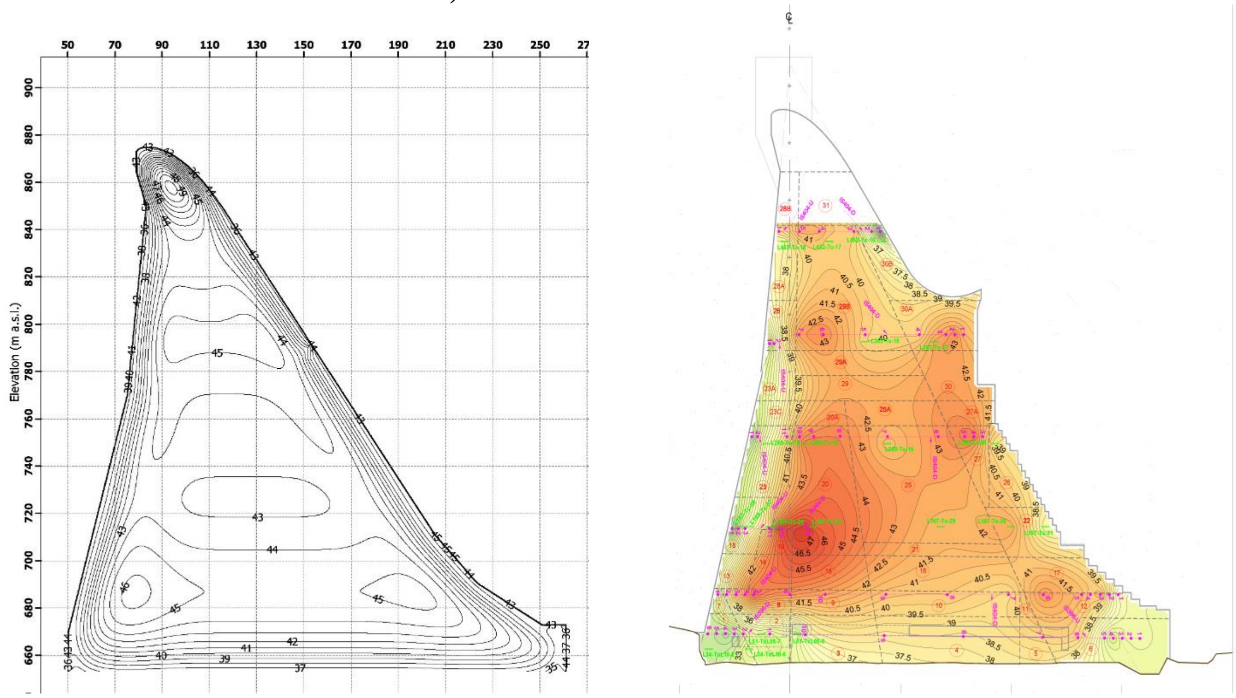

Fig. 7. Dam temperatures comparison, Design calculation vs. As built

To date, after 5 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.

Acknowledgments

The authors wish to express their thanks to: Ethiopian Electric Power (EEP); Eugenio Zoppis (Salini-Impregilo, Gibe III Site Manager); Paolo Bianciardi and Valerio Budano (Salini-Impregilo, Gibe III Laboratory Section).

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