UPSTREAM FACE PERMEABILITY MONITORING at GIBE III RCC DAM and RESIN INJECTION WORKS

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1 - Introduction

Gibe III is the third plant of the Gibe-Omo cascade comprising Gilgel Gibe (IP=200 MW) and Gibe II (IP=420 MW), both in operation. It includes a 250 m high RCC (Roller Compacted Concrete) dam which, almost completed, is the world's highest of its kind.

Low cementitious-content mixes were used, with a cement dosage ranging from 70 to 120 kg/m^3 having a higher cement content in the lower part of the dam and at the upstream face (to meet the upstream dynamic tensile strength and permeability requirements) and at the downstream toe (for compressive strength requirements). The upstream face used grout enriched RCC (GE-rcc) with widths varying from between 80 cm to 40 cm depending on the dam height.

The project is characterized by the presence of two middle level outlets in the dam body at el. 750 m a.s.l. (*i.e.*, about 100 m above the dam foundation level) designed to control the reservoir levels during impounding, release artificial flood and lower the reservoir down to the power tunnel intake level. This means that, once impounded, it will not be possible to lower the reservoir below the level of the middle outlets and the dam portion between 650 and 750 m a.s.l. will be permanently underwater.

Consequently, in order to identify in advance any possible major anomalies regarding upstream face permeability, an extensive investigation programme (referred to as K-Monitoring) was implemented on site consisting of water-tests through the dam drainage holes, which were drilled upwards from one dam inspection gallery to another (at 40 m vertical intervals) while continuing with the dam construction.

Mapping of the upstream permeability then enabled specific local protection works, such as local resin injections, to be designed prior to commencement of impounding which started before dam completion.

Fig. 1 View of the dam: the spillway is under construction and the reservoir reached 190 m over 250 m (July 2016)

2 - RCC Main Features

The first part of the dam, totalling about 1.25 Mm^3, was built using blast furnace slag cement imported from Italy in order to guarantee a continuous and controlled supply of high quality cement. One of the main advantages of this type of cement is that the low heat of hydration greatly contributes to avoiding thermal cracks in the massive concrete.
The detailed characteristics of the starting design mix, including its thermal and mechanical properties are illustrated in specific papers to which reference is made [2], [3] and [4]. The mix design included:

- cement Cementir CEM III/A 32.5 N slag cement from Italy
- total aggregate (%) 71 = crushed river gravel, 24 = crushed basalt, 5 = crushed ignimbrite
- sizes (mm) sand = 0-6, medium gravel = 6-25, coarse gravel = 25-50
- aggregate fines (%) 6
- filler ignimbrite powder

The remaining part of the dam (about 5 Mm^3) was built using Ordinary Portland Cement (OPC) produced in Ethiopia with low heat of hydration:

- cement Messebo CEM I 42.5N LHHS,

This cement was specifically manufactured after extensive laboratory and field tests carried out by Salini-Impregilo working in co-operation with the major Ethiopian cement producers [2].

In the upstream zone involved in the K-monitoring programme, the cement content is equal to 120 kg/m^3 and systematic bedding mix was applied on every RCC lift joint (with a design thickness of 40 cm). The impervious face includes a grout enriched RCC layer with variable width (from 80 cm to 40 cm) depending on the dam height.

The RCC was delivered to the work areas by means of a single large conveyor system built on the left abutment, with a maximum capacity of about 800 m^3/h. Placing and spreading of the RCC was carried out by dozers equipped with laser control systems that continuously adjusted the blade position in order to guarantee a constant RCC lift thickness.

3 - K-Monitoring

As mentioned previously, the main scope of this investigation campaign was to detect possible defects in the upstream portion of the RCC (in particular in the dam portion below the level of the middle outlets which will be permanently underwater) in order to have the time necessary to intervene from the upstream face prior to impounding, which was planned to start before dam completion.

Upstream RCC permeability was investigated by water-testing the dam drainages holes. One drain hole was selected for each dam block (the average width of the blocks varies between 20 and 25 m) and in every stretch of the dam comprised between two inspection galleries (spaced vertically at 40 m intervals). The drainage hole diameter varies from 200 mm to 150 mm (300 mm in the upper portion of the dam) with a spacing of 3.2 m (reduced to 1.6 m in the lower portion of the dam below el. 700 m a.s.l.).

Two methodologies were adopted:

- Falling-Head Water Tests
  These tests were carried out over the entire length of the drainage hole between two inspection galleries, observing the lowering rate of the water level inside the hole and the presence of any water stains appearing on the upstream face.
  The tested drainage hole was sealed in its lower portion by installing a pneumatic packer above the ceiling of the lower gallery. The hole was saturated for at least 24 hours before starting the readings. A total number of about 60 dam drains, corresponding to an overall length of about 2,400 m; were tested.

- Water-Pressure Tests
  These tests were performed on the same drainage holes previously tested with falling-head methodology.

Double packers were installed inside the drain holes in order to isolate a 2.1 m long stretch (corresponding to 7 to 5 layers of RCC). No. 5 steps of ascending and descending pressure with a duration of 10 to 30 minutes each were applied, monitoring the pressure and volume data in real-time with digital apparatus. The maximum testing pressure was set between 80 to 110% of the local hydrostatic head (a minimum cover of 40 m of RCC was required to proceed with the pressure test).

In some cases, where high permeability was recorded, the pressure test was repeated reducing the length of the tested stage in an attempt to better localize the permeable area.

One example of visual monitoring of the dam upstream face during execution of the falling-head tests is given in the following photo of the left bank between elevation 780 and 740 m a.s.l. Contraction joints are represented with blue dotted lines, the water staining on the upstream face observed during the saturation phase of the drain holes (identified by chainage, offset and elevation) is highlighted with a red circle.

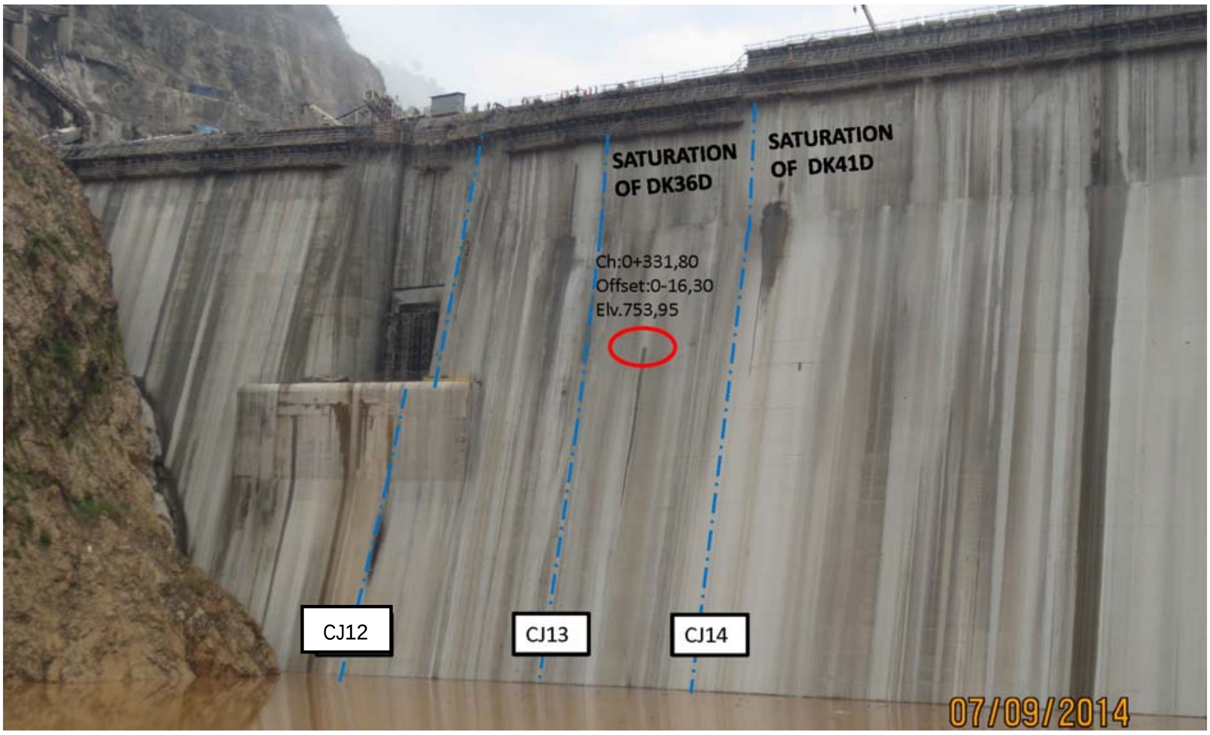

Fig. 2 Visual monitoring of upstream face during water testing of dam drain holes.

In order to facilitate analysis of the acquired data, pressure test results were transformed into average permeability coefficients of the tested stages by applying the Hoek and Bray (1981) formula:

$$k_e = \frac{Q \cdot ln\left(2 \cdot m \cdot L/D\right)}{2 \cdot \pi \cdot L \cdot H}$$

where:

$$m = \left(k_e / k_p \right)^{0,5}$$

k_e and k_p are the equivalent permeability normal (*i.e.* lift joints permeability) and parallel (*i.e.* parent RCC permeability) to the hole respectively; D is the hole diameter; L is the length of the tested stage and Q is the average flow.

Some authors [1] suggest a value of 2 or higher for the anisotropic ratio k_e/k_p, in consideration of the fact that the permeability is mostly controlled by the lift joints (especially when high average permeability is encountered).

In order to better calibrate/validate this ratio some laboratory tests were carried out on RCC cores drilled in the upstream portion of the dam. These cores were selected in order to be representative of (1) parent RCC well compacted with no signs of segregation, (2) bonded RCC lift joints, (3) parent RCC or lift joints showing some voids/porosity near the surface.

Tests were executed using Matest C-430 permeameter which is conceived to perform water permeability tests on cylinder concrete specimens with a maximum diameter of 160 mm. Specimens are inserted in a cell and subjected to hydrostatic stress for a pre-set period of time. The water permeated through the specimen is directly collected and measured into a graduated cylinder. It is therefore possible to determine the permeability coefficient by the following formula:

$$k = \frac{cc \cdot h}{A \cdot t \cdot P}$$

where:

cc is the volume of permeated water; h and A are the height and surface area of the specimen respectively; t is the duration of the test and P is the hydrostatic pressure.

In order to test the lift joints the RCC cores were re-drilled in the laboratory in a direction parallel to the joint itself and the parent RCC portions above and below the lift joint were isolated by means of epoxy paint.

Fig. 3 Preparation of lift joint specimen.

The number of tests (about 15) is too small to be statistically significant but the following trend was observed: permeability of the bonded joints (E-10 m/s) is slightly lower than that of the parent RCC while a decrease of two orders of magnitude was observed for the poorly bonded joints (E-8 m/s). Therefore a value of 2 for the ratio k_e/k_p was applied to calculate the average permeability of the stretches of the drain hole tested with water-pressure methodology.

An excerpt from the upstream face permeability mapping is shown in Fig. 4 relative to the portion of the dam between contraction joints CJ-15 and CJ-18 and galleries at elevation 660 and 700 m a.s.l.. The figure shows the:

- areas with upstream face leakages observed during execution of falling head tests (cyan);
- areas with upstream face leakages observed during execution of pressure tests (blue);
- mapping of the honeycombs, observed after removal of the formworks (brown);
- values of permeability calculated for the various stretches of the tested drains (higher permeability zones are highlighted by solid red hatch).

It may be observed that:

- upstream face leakages mapped during the execution of falling-head tests match the higher permeability zones determined with the pressure tests, therefore the simpler and faster falling-head test seems capable of identifying major local anomalies in the upstream face permeability;
- in the upper portion of the tested drain the above correspondence is less evident because of the quite rapid drawdown of the water level inside the drain hole; from this point of view a constant-head test would have been more effective;
- no relationship between position of honeycomb and upstream face leakages is observed;

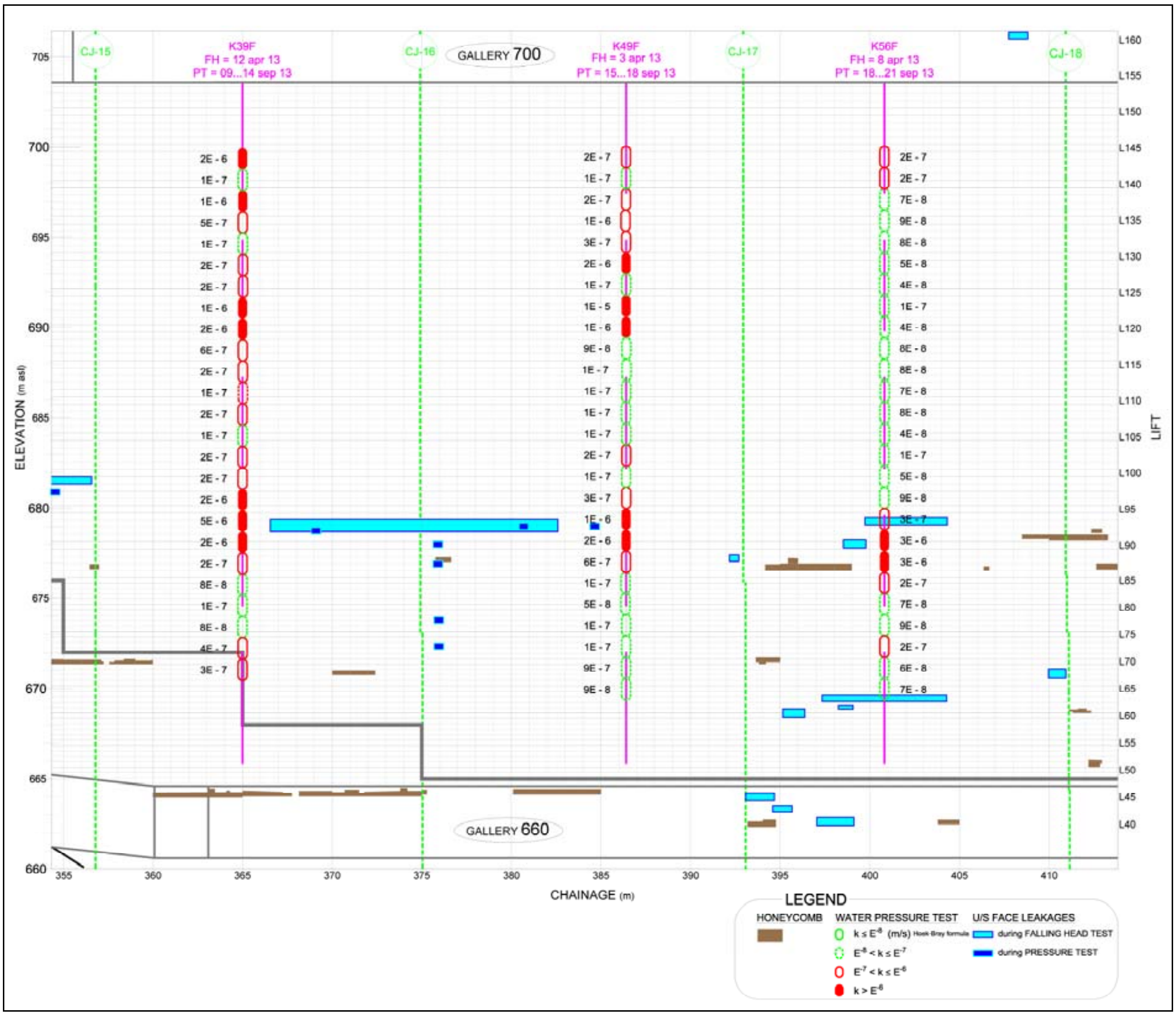

Fig. 4 Upstream face permeability mapping

4 - Resin Injection Works

The leaking lift joints identified during the K-monitoring programme were treated with epoxy resin compound in order to meet the tensile strength and permeability requirements of the upstream face.

Epoxy resin injection works were carried out from the upstream face using either a mobile platform lowered from the dam crest or directly from the dam toe for the lower zones.

No. 22 small areas requiring epoxy resin injection were identified below elevation 750 m a.s.l., corresponding to about 300 linear meters of lift joints.

The main technical features of the selected resin are:

- Type two-component epoxy resin, Draco R.M.3
- Specific weight kg/lt 1.1
- Pot life min 140 (@ 25 °C)
- Final curing days 7 (@ 25 °C)
- Solid content % 100
- UCS MPa 95 (ISO 604)
- Tensile strength MPa 55 (ISO 527-1)
- Flexing resistance MPa 90 (ISO 178)
- Elastic modulus GPa 3 (ISO 604)
- Elongation at break % 4 (ISO 527-1)
- Viscosity A+B cps 200-300
- Suitable to be used in presence of humidity.

Resin was injected in the leaking lift lines through 28 mm diameter, 2.2 m long holes spaced 2 m apart and drilled downwards at 45° in the upstream face by means of pneumatic hammer (leaking lift lines were intercepted at about 1 m distance from the upstream face).

After the blowing and washing of the entire hole series and installation of the packers at the hole-mouth, injection works proceeded from central to external holes with a maximum pressure of about 5 bar measured at the hole-mouth. Hole injection was stopped (and resumed in an adjacent hole) as soon as clean resin was observed from the upstream face leaking lift line or from an adjacent hole.

Particular attention was given to the portions of leaking lift lines close to dam contraction joints, in order to avoid the possible injection of the contraction joint itself.

About 1,300 gross kg of epoxy resin were injected. Therefore the average net take results slightly less than 4 kg of resin per meter of leaking lift line corresponding to an average depth of penetration in the range of 3 - 6 m for a lift opening of 1 to 0.5 mm respectively (*i.e.* less than the distance between dam drain holes and dam upstream face).

Indeed, during the subsequent re-testing phase of the dam drain holes (with falling head methodology) the following observations were made:

- a decrease of water drawdown rate inside the drain holes;
- no evidence of water staining/leaking lift lines on the upstream face.

These observations indicate that, after the resin injection, residual filtration was still present within the RCC lifts but this filtration did not affect the upstream face of the dam. Therefore, the result of the treatment, in terms of improvement of upstream tensile strength and water-tightness, was considered satisfactory.

Further key design elements, in addition to those already mentioned in this paper, were adopted to ensure the required performance of the upstream facing of Gibe III, the world's highest RCC dam [4]:

- two internal waterstops, 500 mm wide, along vertical joints;
- external waterstops, 600 mm wide, up to el. 770 m a.s.l.;
- 32 mm rebars, added on each lift to improve the control of surface cracking;
- Mapei Biblock anti-evaporation compound;
- sprayed Mapei Purtop 1000 polyurea membrane below el. 700 m a.s.l.;
- bentonitic plinth and clay *tout-venant* backfilling the area between the dam and the upstream cofferdam (up to el. 700 m a.s.l..

5 - Conclusions

The results of the K-monitoring programme showed that there is a substantial concurrence between the two methodologies adopted to test the dam drain holes (*i.e.* falling-head on the entire length of the hole between two inspection galleries and pressure tests on 2.1 long stretches): upstream face leakages observed during the execution of falling-head tests match the higher permeability zones determined with the pressure tests. Therefore the simpler and faster falling-head test results are capable of identifying major local anomalies in the upstream face permeability and should be routinely used as real-scale field tests to check the construction quality of RCC upstream zones (paying attention to the upper portion of the tested drain where the drawdown of the water level inside the drain hole may prevent a proper assessment of local upper anomalies).

Resin injection works of the upstream leaking lifts carried out with two-component epoxy resin has proved to be effective in restoring the required watertightness and tensile strength of the upstream face.

The effectiveness of the GE-rcc upstream face and the protection works were tested by filling the volume between dam upstream face and upstream cofferdam (pre-impounding) with water to an elevation of 720 m a.s.l., corresponding to a hydraulic head of about 60 m on the lower dam gallery.

Monitoring of dam performance during impounding is currently on-going by means of the extensive instrumentation system installed. By July 2016 impounding had reached an elevation of about 850 m a.s.l., corresponding to a hydraulic head of about 190 m on the lower dam gallery. The overall behaviour of the dam face in terms of leakages is fully satisfactory. By the end of June 2016 the total amount of leakages collected in the gutters and measured by the v-notches installed in galleries was particularly low, less than 40 l/s (including not only the seepage from the dam body but also from the rock of the foundation).

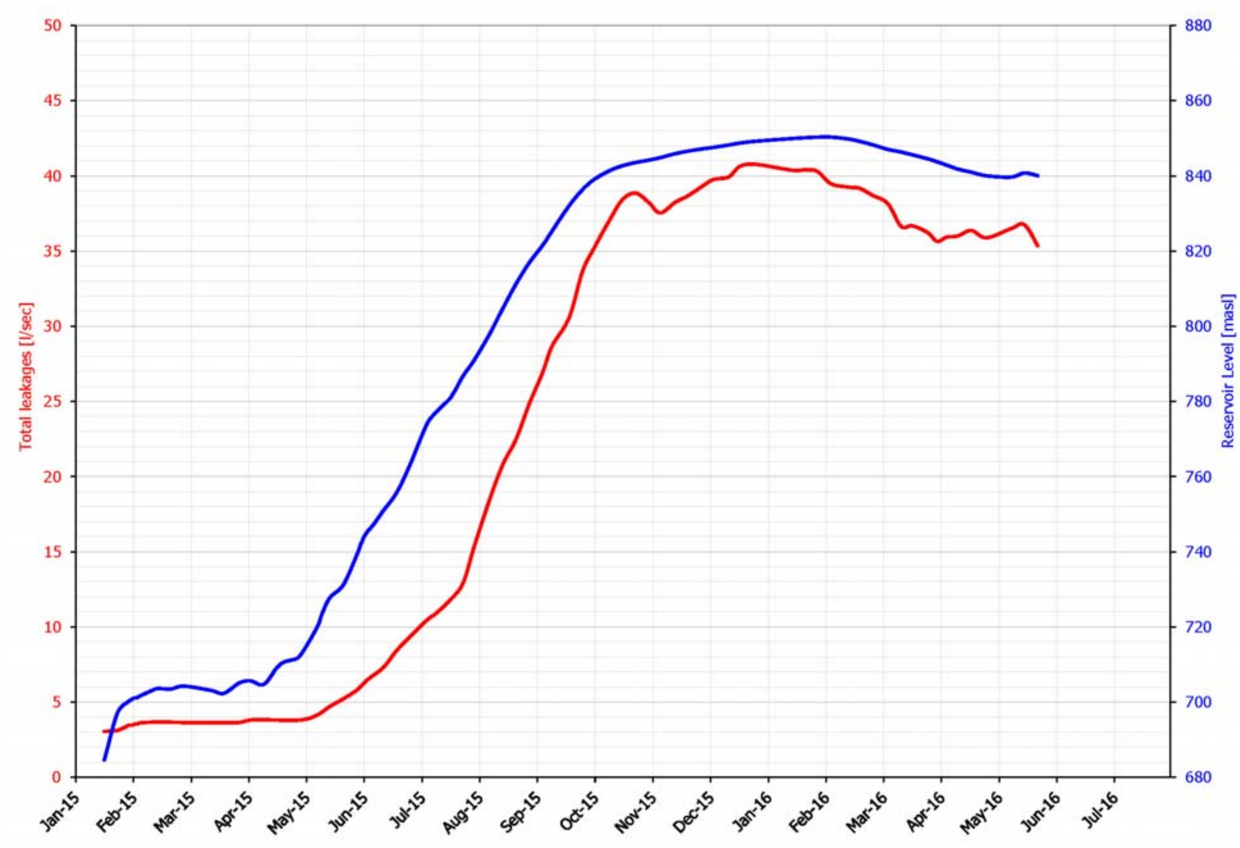

Fig. 4 Overall leakages vs Impounding level

Acknowledgments

The authors wish to express their thanks to: Ethiopian Electric Power (EEP); Eugenio Zoppis (Salini-Impregilo Gibe III Site Manager); Ernest Schrader and Mauro Giovagnoli for their contribution to the development of the RCC mix.

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