Design of the Highest RCC dam (Gibe 3, H = 250 m)

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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, and other planned projects downstream.
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.

Construction of the project is under completion while the impounding started a few months ago, to anticipate as much as possible the power production foreseen by the end of this year.

The project includes several outstanding key features:

- the world's tallest (250 m high) and one of largest (6.5 Mm^3) Roller Compacted Concrete (RCC) dam;
- 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;
- a sprayed membrane improves, in the lower part of the dam, the water tightness of the upstream face (GE-rcc);
- a rockfill cofferdam (50 m high) was built in only a few months using a zig-zag geo-membrane core;
- the spillway, on the dam crest, will discharge up to 18'000 m^3/s more than 200 m above river bed;
- the powerhouse with its ten Francis turbines (1'870 MW), will be one of Africa's largest hydropower plants;
- the design allows impounding to commence before completion of construction, thereby bringing forward power production.

Fig.1 - Gibe III dam nearing completion while impounding the reservoir

This paper focuses on the most relevant technical aspects of the dam design.
Reference is made to other papers (ref [1], [2], [3], [4]) which illustrate the characteristics of the design mix, the main challenges faced during construction of the RCC and the design of other project components.

2 – Key Characteristics of the Project

The project is located in a rather narrow gorge of the Omo River, about 150 km downstream of the Gibe II powerhouse. The key components of the project are:

- the river diversion system, designed to discharge up to 5’200 m^3/s, including a 50 m high rockfill cofferdam and three tunnels about 1 km long with diameters from 7 to 14 m;
- the RCC gravity dam, 250 m high, which, when completed, will be the world’s tallest of its kind, creating a reservoir with a volume of 15’000 Mm^3;
- a gated spillway, on the central portion of the dam crest, designed to safely discharge up to 18’000 m^3/s through seven radial gates measuring 12 x 17.5 m;
- a pre-excavated plunge pool, about 300 m long and 100 m wide;
- two middle outlets, embedded in the dam body, which allow the control of the reservoir levels and the discharge of ecological flows (up to 1’600 m^3/s);
- two power tunnels, each one with a diameter of 11 m and about 1 km long, with gate shafts and two large surge shafts with a diameter of 18 m and more than 100 m high;
- two penstocks shafts, 120 m long with a diameter of 8 m;
- an open-air powerhouse located on the left bank of the river, about 500 m downstream of the dam axis, housing 10 Francis turbines generating 1’870 MW and 6’400 GWh/year;
- a switchyard with 15/400 kV step-up transformers;
- a 65 km long 400 kV transmission line.

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 and treated. Hot water springs were found at riverbed elevation, in hydraulic connection with a deep aquifer lying about 100 m below the foundation of the dam.

The dam is a gravity structure. The key geometrical features are as follows:

- 250 m height above foundation
- 670 m crest length
- 0.1:1 H:V basic upstream slope
- 0.65:1 H:V basic downstream slope
- 20 m average vertical joint spacing
- 6.5 Mm^3 RCC volume

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 varies from 11 to 24 m, with an average of 20 m. The distance between the joints is controlled by thermal issues and by the width of the spillway bays, in the central blocks, and by foundations characteristics on the steep abutments.

The basic section of the dam has a classical triangular shape, with a total opening of 0.75:1, adding the upstream and downstream slopes. The slope varies in the lowest portion of the upstream face, below 770 m a.s.l., increased to 0.25:1 (H:V) to improve the sliding stability and reduce tensile stresses especially under dynamic loads. The downstream face is stepped with 2.8 m high steps.

The dam body also houses longitudinal galleries, one every 40 m of height, located close to the upstream face and inside the abutments and conceived for drainage and grouting works. Access to these galleries is gained from the downstream face.

The dam hosts a large gated spillway (Q = 18’000 m^3/s) and two embedded middle outlets (Q = 800 m^3/s each). The spillway sill at the dam crest is controlled by radial gates which will regulate the flows discharged by seven chutes ending with flip buckets. Two middle outlets are embedded in the dam structure at el. 750 m a.s.l. controlled by ring seals and ring follower gates at the downstream end.

Dam zoning is shown in Fig. 2. A higher cement content is used both in the upstream part of the dam (to meet the permeability requirements and the tensile strength under dynamic loads) and at the downstream toe (for the compressive strength requirements).
The various RCC mixes have a rather low cement content, varying from 70 to 120 kg/m^3.

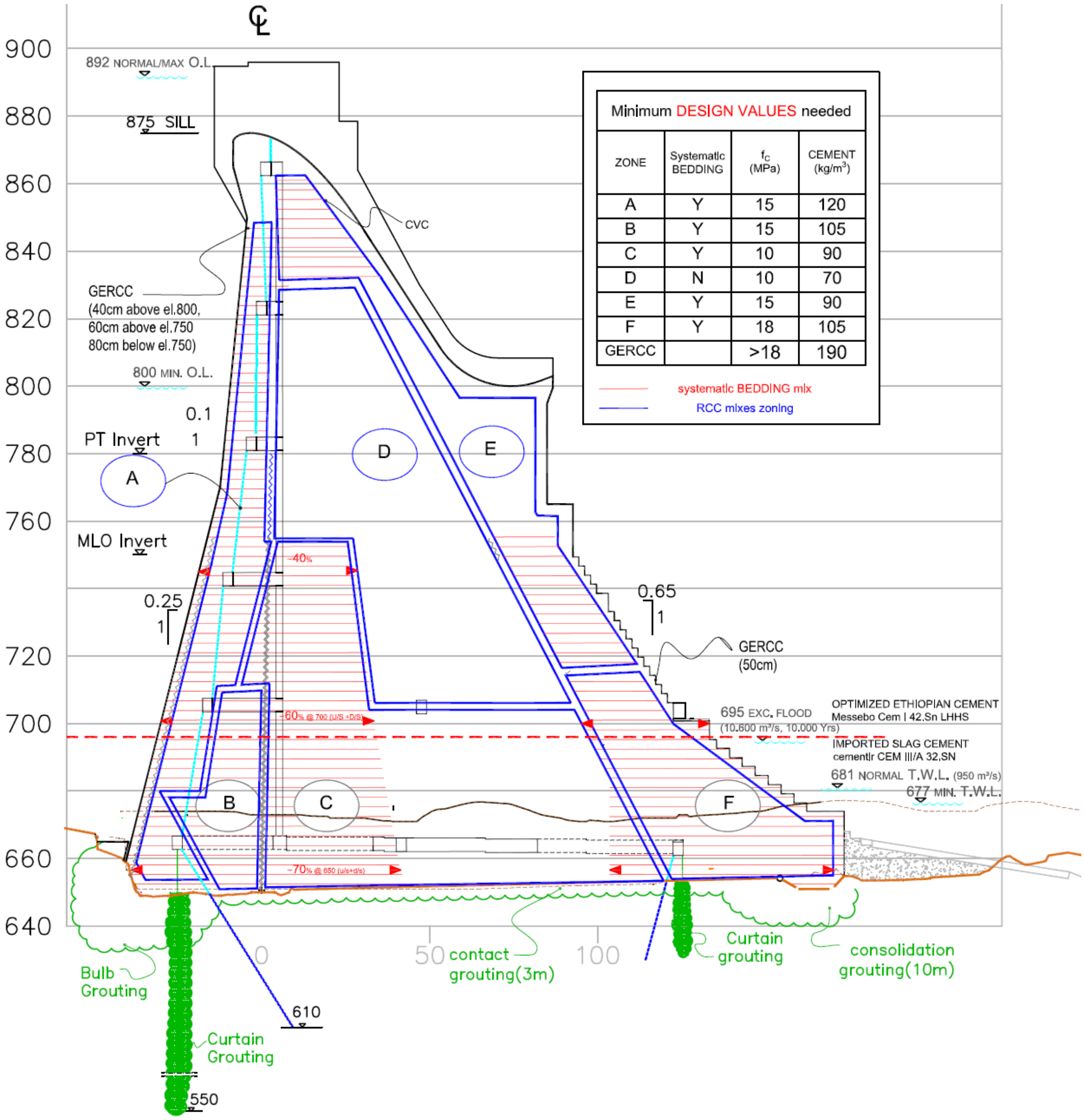

Fig. 2 Dam – Main Section with RCC Zoning

The extent of the bedding mix indicated in the figure is mainly controlled, in the upstream portion of the dam, by the impermeability requirements at lift joints. In the downstream portion of the dam, the bedding mix increases the sliding strength where the compressive stresses are higher, improving the stability of the dam.

The design thickness of the lift is 40 cm. Most of the lifts are inclined slightly downstream by 1%. Although this is not in favour of dam stability, it allows the lift surfaces to be cleaned more effectively, especially in the upstream zone.

The RCC is 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 is being carried out by means of dozers equipped with laser control systems that continuously adjust the blade position in order to guarantee a constant RCC lift thickness.

The impervious upstream face includes a GEV-rcc layer, with a width varying from 0.8 m to 0.4 cm. In the lowest part, below el. 700 m a.s.l., a sprayed membrane, MAPEI Purtop 1000 type, was applied on the entire upstream surface.

Grouting works were carried out from the galleries inside the dam body, extending about 40 m into the abutments. The grouting screen included systematic primary, secondary and tertiary holes, spaced at 3 m intervals, extended in the central part of the gorge up to the roof of the aquifer, 100 m below the foundation of the dam. Control of grouting operations was based on a Grouting Intensity Number (GIN) approach. In correspondence with highly weathered bands, a dedicated treatment consisting in closely spaced holes with high pressure washing and subsequent grouting (HPW&G) was carried out up to a depth of 70 m below the foundation level.

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 by means of v-notches installed in the gutters of the longitudinal and transversal inspection galleries.

3 – Design Mixes

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 a previous specific paper [3]. 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 — sand: 0-6 mm, medium gravel 6-25 mm, coarse gravel 25-50 mm
- aggregate fines — 6 %
- filler — ignimbrite powder

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

- Cement — Messebo CEM I 42.5N LHHS,

This new cement has been specifically manufactured after extensive laboratory and field tests carried out Salini-Impregilo working in co-operation with the major Ethiopian cement producers [3].
Its peculiarity is the use of clay with a high iron ore content to produce the clinker. The iron keeps the heat of hydration under control and the cement acquires a high sulfate resistance and high reactivity. A comparison of the chemical composition of the two cements used is given below.

	Chemical Composition - (%)										
	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Mn_3O_4	P_2O_5	TiO_2	C_3A
CEMENTIR	49.78	28.48	9.04	1.55	5.31	3.12	0.40	0.26	0.03	0.35	-
MESSEBO	62.77	23.46	5.18	3.92	1.18	3.27	0.48	0.13	0.10	0.28	7.08

Table 1 - Cement properties

While the cement was changed, aggregates and filler were confirmed from the starting design mix. The admixture used is the Mapei Mapetard CBS-1 which extends the setting time of the RCC.
The figure below shows the comparison of the adiabatic temperature rise with the two cements, using similar cement content. Differences are less than 4°C

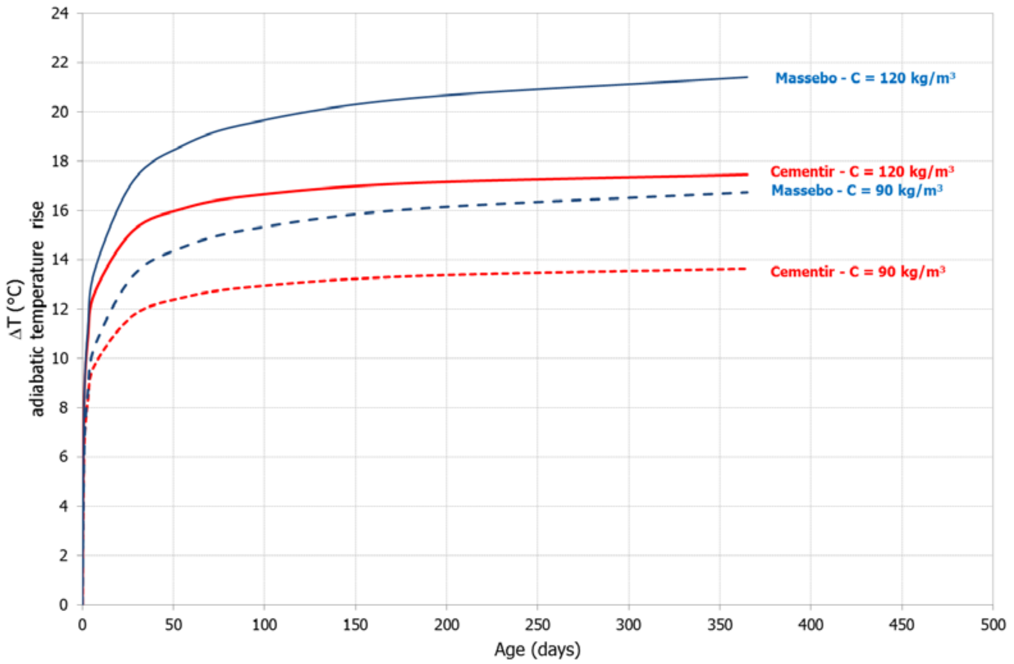

Fig.3 - Adiabatic temperature rise with Cementir and Massebo

4 – Upstream Facing

Most of the existing RCC dams with a low cement content have some form of upstream membrane or impervious layer to ensure water tightness. Since the cement content for Gibe III is quite low, ranging from 70 to 120 kg/m^3, and the dam is the world's tallest, the design of the impervious face was one of the key technical challenges of the dam.
The key design issues adopted for the upstream face basically include:

- a wide upstream RCC zone with systematic bedding mix and higher cement content (120 kg/m^3);
- drainage system, with spacing of the holes reduced to 1.6 m below el. 700;
- two internal waterstops 500 mm wide along vertical joints;
- GEV-rcc layer (0.4 to 0.8 m wide);
- 32 mm rebars, added on each lift (to improve the control of surface cracking);
- anti-evaporation compound Mapei Biblock (to replace curing);
- sprayed membrane, Mapei Purtop 1000, only in the lowest portion of the dam (below el. 700);
- external water-stops 600 mm wide, up to el. 770;
- bulb grouting of the rock mass joints on the u/s dam toe;
- epoxy resins grouting only where required by the extensive permeability test program
- benthonitic plinth and clay+tout venant backfilling the area between the dam and the u/s cofferdam (Fig. 4). This embankment acts as additional protection to clog possible leakages and also facilitated access to the upstream face during construction.

The project includes two middle outlets, which can lower the reservoir down to about 760 m a.s.l., but no bottom outlets.
Therefore, the lowest part of the dam will be permanently underwater. Consequently, an extensive investigation program was implemented to identify possible permeable zones through the upstream face. Water-tests were carried out through the drainage holes, drilled upwards from one inspection gallery to another, while proceeding with the construction. Two tests methodologies were adopted:

- falling-head water tests over the entire length of the drainage holes (40 m), observing the lowering of the water level inside the hole and the presence of any water stains appearing on the upstream face;
- water pressure tests on 5 m long stretches with five stages of ascending and descending pressures, monitoring the pressure and volume data in real time with digital apparatus.

The results showed a substantial concurrence between the two methodologies and that the simpler falling-head test is adequate for most of the project needs.

Finally mapping of the upstream face permeability was used in order to design specific local additional protection works such as:

- reparation of honeycombs;
- injections of the pervious layer with epoxy resins;
- sprayed membrane (Fig. 4).

Fig.4 Application of sprayed membrane and clay backfilling

The GE-rcc layer was placed at the start of the works.
This technique was not always effective and led to local problems such as spot honeycombs, difficult compaction around waterstops and local disbanding on RCC lifts. Consequently, GE-rcc was replaced by Grout Enriched Vibrated Rolled Compacted Concrete (GEV-rcc) for better quality control. The GEV-rcc technique consists in placing the cement water grout under the layer of RCC, and then favouring its return by vibration.

Fig.5 RCC placement: upstream water-stops installation and GEVRCC vibration against rock.

At the end of July 2015 with the water level in the reservoir at el. 790 m a.s.l., the upstream face had experienced only small leakages, in the range of a few litres per second.

4 – Comparison of Design Assumptions with the First Measured Data

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 will still be under completion.

By the end of July 2015 the reservoir had reached el. 790 (144 m of water head).
The middle outlet is being used to control the impounding and release the ecological flows (Fig. 6).

Fig. 6 Wet Commissioning of Left Middle Level Outlet (Q ≈ 300 m³/s)

Monitoring of dam performance during impounding is currently going on by means of the extensive instrumentation system installed. By the end of July 2015 the total amount of leakages collected in the gutters and measured by the v-notches installed in galleries was particularly low, less than 15 l/s.

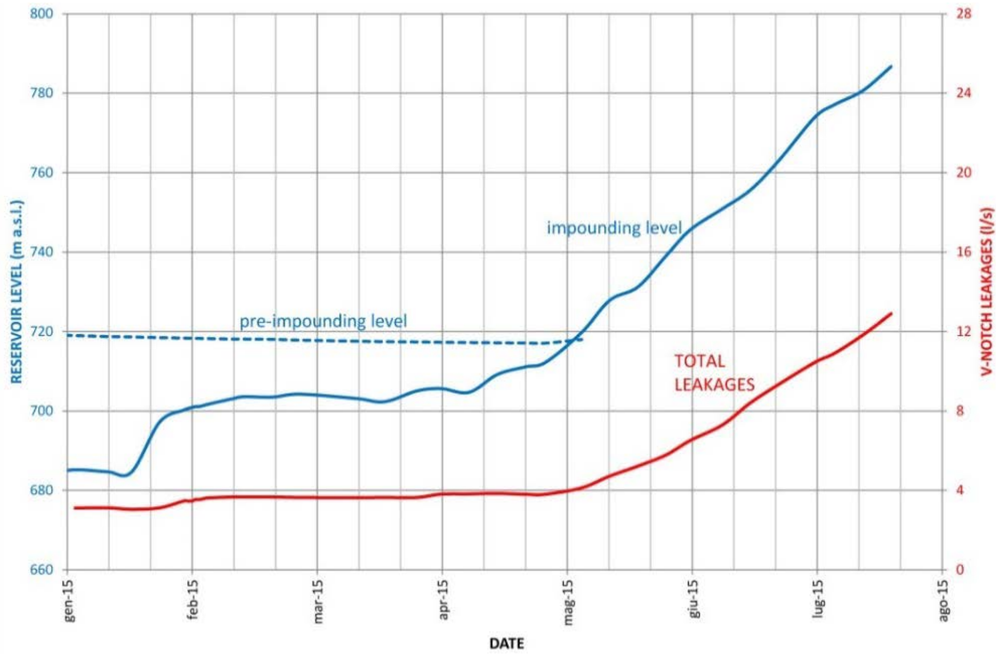

Fig. 7 - Overall leakages VS impounding level

The graph in figure 8. shows the temperatures measured recently in the dam body. The data are similar to those predicted, with local differences of less than 3 degrees mostly due to construction reasons. The model adopted for the thermal analysis described in a previous paper [3] is therefore effective and reliable. 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).

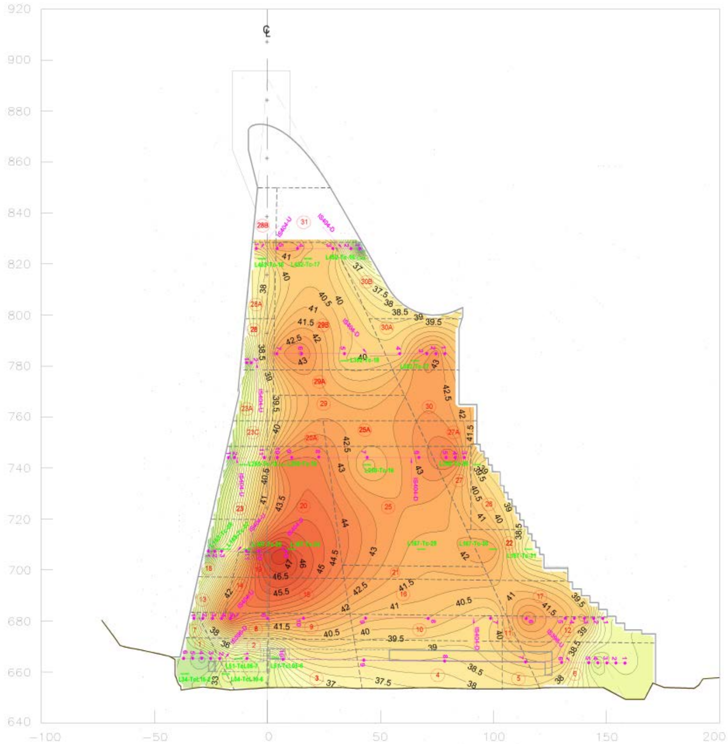

Fig.8 – Temperatures recently measured in the dam body

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References

[1] 2009, G. Pietrangeli , A. Pietrangeli, A. Scuero, G. Vaschetti, "Gibe III: A zigzag geomembrane core for a 50m high rockfill cofferdam in Ethiopia". The 1st International Symposium on Rockfill Dams.

[2] 2013, C. Rossini, E. Schrader, "Gibe III Dam: Project Summary, Mixes, Properties, Thermal Issues and Cores". Water Storage & Hydropower Development for Africa.

[3] 2015, A. Asnake, A. Cagiano, B. Ferraro, E. Zoppis, "Managing unprecedented RCC challenge at Gibe III dam". Water Storage & Hydropower Development for Africa.

[4] 2015, A. Cagiano, A. Masciotta, F. Pianigiani, A. Pietrangeli, "Design and Hydraulic Model of Gibe III Dam Spillway". Hydropower and Dams.

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