Design of Gibe III Dam Middle Level Outlets

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1 - Introduction

This paper describes the design of the Middle Level Outlets of Gibe 3 dam.

Gibe III is a 250 m high gravity dam, the world's highest built with RCC technology, located in Ethiopia, The middle outlet system is foreseen to control the impounding, to release an artificial flood for environmental purposes and for exceptional maintenance of the power waterways.

The design of these outlets, which was led by the authors, has been particularly challenging since they operate with high heads, over 140 m of water column, and with a total discharge capacity of about 1600 m^3/s.

Minimize the risk of cavitation and erosion during operation was a major design achievement. Moreover, since the construction of the MLOs was on the critical path, a major design issues was minimize interferences of their construction with RCC placement for the dam.

The hydraulic and structural design of these Middle Level Outlets required uncommon technical solutions, described in this paper.

Two physical models were used to understand the hydraulic behaviour. The second, in scale 1:20 and entirely dedicate to these structures, was used to analyse accurately the hydraulic behaviour of the inlet, of the conduit and outlet sections.

The middle outlets operate since 2015, when the first impounding of the reservoir was carried out.

Fig. 1: Right MLO operating, October 2016

2 – The optimum layout

The middle outlets are designed for several uses. During the first impounding, they controlled the raise of the water levels in the reservoir. During operation, they release an artificial flood of about 1500 m^3/s, for about two weeks during the wet season, reproducing a natural flood for environmental and social purposes. They might also be used for maintenance purposes, lowering the reservoir during the dry season to inspect the power waterways.

Therefore these outlets are designed for a wide range of operating conditions:

- Water levels in the reservoir from 770 to 892 m a.s.l (i.e. 20 to 142 m above the inlet sill)
- Discharge up to 800 m^3/s each.

The selected layout includes two middle outlets, symmetrically disposed in the dam body under the spillway, at the two sides of the structure, as shown in the figure below.

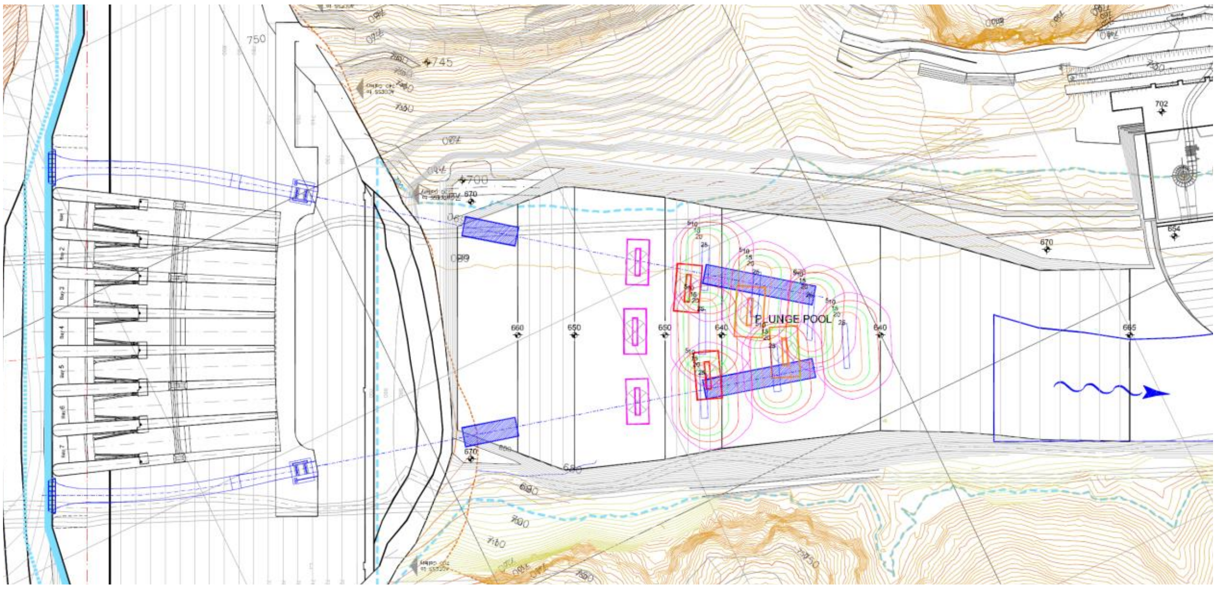

Fig. 2: MO general layout. Two conduits in the dam body and jet impacts in the plunge pool.
(in magenta the impact areas of the spillway jets, in blue those of the two middle level outlets).

The main components of each outlet are:

- a rectangular bulkhead gate, for maintenance (10 x 13m)
- a rectangular inlet (9 x 12 m), with sill at 750 m a.s.l.
- the main circular conduit (d = 6 m, L = 67.5 m), mostly curved in plan with a straight final trunk
- the ring follower emergency guard gate (d = 5.4 m)
- the ring seal service gate (d = 4.8 m)
- a circolar outlet
- transitions and contractions, from the inlet section to the main conduit and to the gates

Each device is equipped with three gates:

- an upstream bulkhead gate, for inspection and maintenance of the middle outlet waterway. A dedicated gantry crane raises the gate from the dam crest.
- the ring follower emergency gate, normally fully opened, that might be closed in case of extraordinary maintenance of the ring seal gate.
- the ring seal control gate, located downstream of the ring follower, that works fully closed or fully opened.

The ring seal, normally closed, can be opened and closed in unbalanced conditions, as needed to control the outlet. The ring follower gate is normally operated in balanced conditions. However, if a sudden closure is needed (for instance if the ring seal is blocked in open position), the gate is designed also to work unbalanced.
The water velocities, in a range from 4 to 48 m/s, are acceptable since the conduit is entirely steel lined, always under pressure and not always in operation.
The following figure shows the plan and section of the left middle outlet.

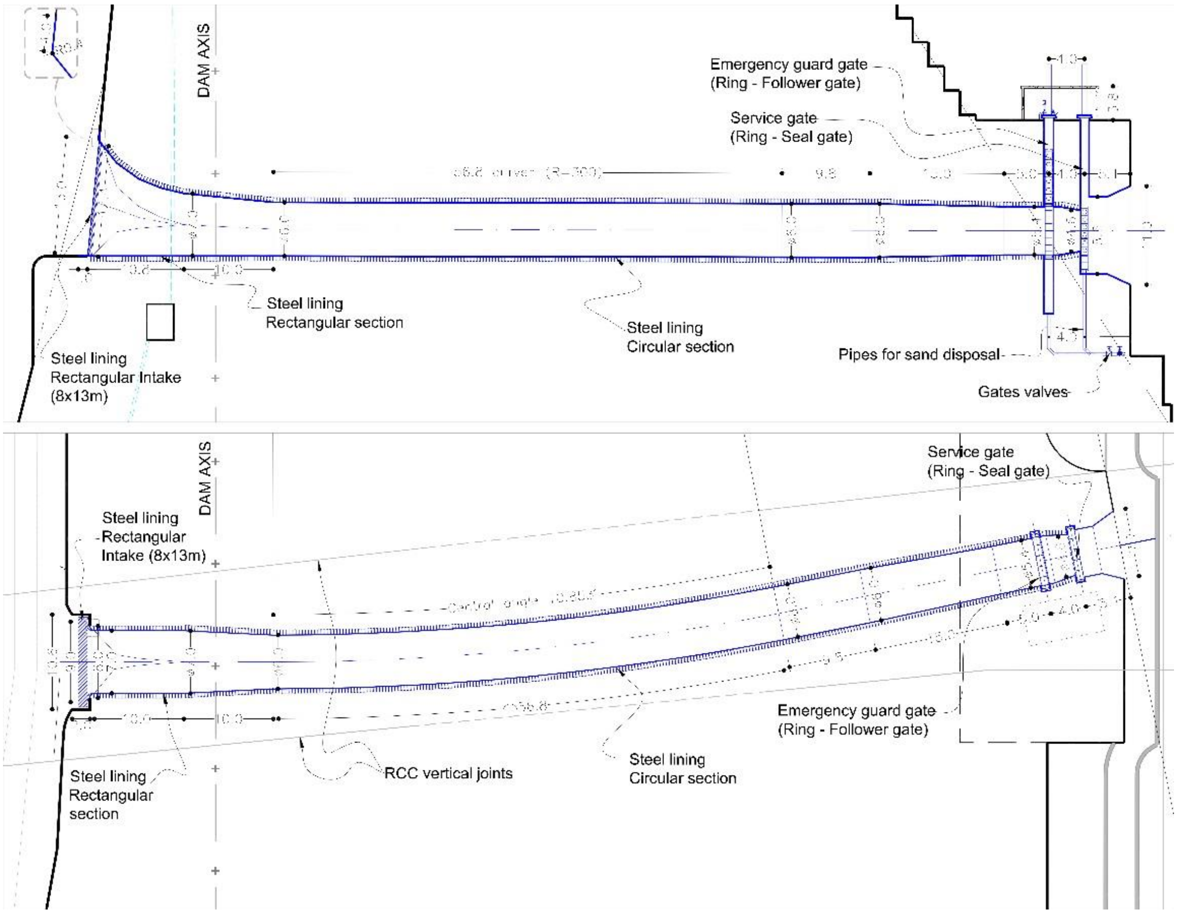

Fig. 3: MLO layout (plan and section)

The jets of the MLO fall into a pre-excavated plunge pool, located between the dam toe and the powerhouse, with a gross head of 70-80 m from the outlet sill to the tail-water level. While the bottom of the plunge pool is mostly unlined, we have added a reinforced concrete block where the impact area of the middle outlet jets if found. This is a further line of defence, especially in case of prolonged operation with low flows (i.e. and a low water cushion) which might scour the pool bottom.

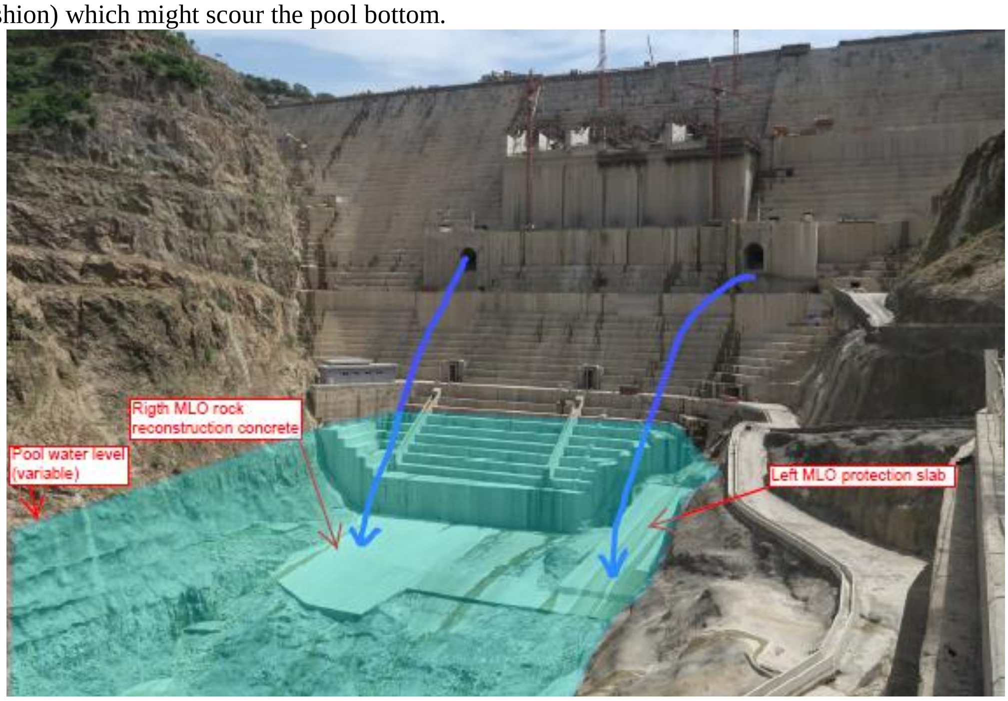

Fig. 4: MLO pool upstream protection, before impounding.

The right protection is a massive concrete reconstruction block to protect the dam toe, since we have found weak rock zone in the river bed. The left protection is a reinforced concrete block, anchored at the corner of the pool.

3 – The optimization process of the design

The basic layout conceived for the MLO included straight conduits, an upstream guard sliding gate, located within a gate chamber inside the dam body, and, downstream, a radial gate to regulate the outflows.

This layout presented the following criticalities:

- The inspection of upstream portion of the conduit was not possible;
- Construction of the gate chamber caused relevant interferences with the placement of the RCC of the dam
- Radial gate vibration under partial opening conditions with high heads.

Therefore, the scheme was upgraded in order to:

- Guarantee the inspection of the entire conduit;
- Minimize interferences with RCC placement;
- Substantially improve the hydraulics, minimizing risks of gates vibrations and cavitation;

We have added an upstream emergency bulkhead gate running on the upstream face of the dam. This gate allows inspecting the entire conduit, eliminating the gate chamber and eliminating all intermediate piers. The hydraulic behaviour, obviously critical because of the high velocities of the flow, is greatly improved. However, also the weight of the upstream bulkhead is increased up to ~400t, thus requiring a large crane at the dam crest.
Consequently, in order to lift the bulkhead gate, we had to relocate the MLO outside of the print of the spillway and introduce a bend in plan to discharge the jets into the rather narrow river bed.

Looking more in detail into the inlet block, the basic design was updated as follows.

The hydraulic shape was optimized. The inlet transition from square to circular section was developed in a stretch of conduit of sufficient length to accommodate a transition providing a constant and smooth variation of the velocity field.

The structural design was also improved as show in the next figure. The construction of the inlet creates a cavity in the RCC body that has to be suitably reinforced and provided with waterstops for water tightness.
However, because of its rectangular shape, the steel lining cannot be self-withstanding against internal and external loads, as happens with the circular section of the conduit. Since the concrete is more rigid than the steel leaf, a large portion of the loads would be transferred to the concrete, substantially increasing its reinforcement and therefore costs and technical complications during constructions.

To mitigate this effect we have designed the steel lining at the inlet, as it can be seen in the photo, with a relevant external stiffening structure. The thickness of steel was increased up to 50mm and more, the added transversal stiffeners increased resistance of inlet section while longitudinal stiffeners acted as load spreaders and shear studs creating composite action between concrete and steel. These solutions reduced deformations and therefore the loads transferred to the concrete, which is therefore not congested of steel bars, improving its quality.

Fig. 5: Inlet block stiffening structure

Looking more in detail into the outlet block, the design was substantially upgraded as follows.

We have replaced the downstream radial gate with gates placed outside of the RCC dam body, in order to minimize interferences with RCC placement during their installation. Furthermore, placing the gates near the outlet cavitation parameters become higher than the incipient cavitation parameters. Thus, aerators that would interfere with RCC dam placement up to the crest can be avoided.

Ring follower and ring seal gates are not commonly used. Their main advantage is the hydraulic behaviour of the conduit. The section does not change (i.e. is always circular) therefore minimizing head losses and avoiding critical edges or points of incipient cavitation that can be caused by a transition from circular to rectangular section, unavoidable with other types of gates.

The major drawback of this arrangement is the need of a very accurate manufacturing and installation process, to avoid even small misalignment between gate and its frame that, especially with tens of m/s of water velocity such as our case, could be a possible origin of cavitation phenomena.

The ring seal (service) gate discharges in open air and does not require special devices for jet aeration. This is hydraulically favourable but, at the same time, more demanding from structural point of view since such gate discharges the forces only on the lateral sides.

The operating rules have also been improved. The MOL can operate only fully opened or closed, as shown in the figure below, reducing risks of vibrations.

Similarly to the inlet block, we have designed the steel lining of the conduit and the frame of the gates to collaborate as much as possible in transferring on the upstream side the huge forces transmitted by the gates when closed.

The two gate frames were welded and connected through steel beams and stiffeners to the main conduit, in order to transfer the forces in the dam body from the conduit itself (see figure below).

Furthermore, around the zones where the gates transfer the load to the concrete, reinforced concrete block is conceived to spread the load on the lateral sides where tendons retransfer the load in the body of the dam.
Tendons were suitably spaced, and in the reinforced concrete zone equipped with sleeve pipes, to be inserted in a second phase from dam downstream face.

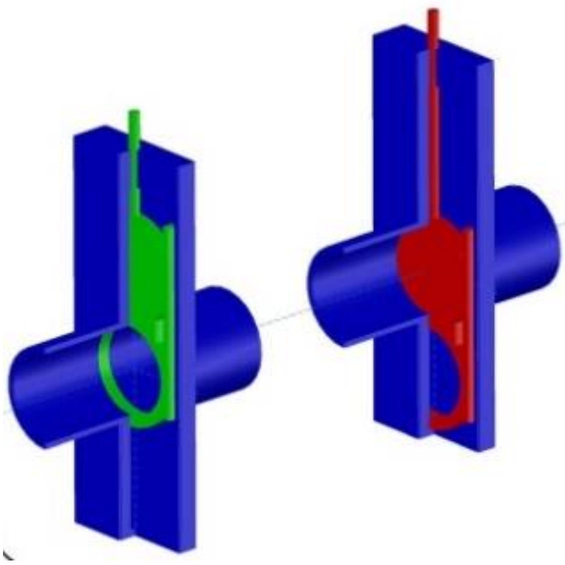

Fig. 6: Ring Follower Gate operation: opened/closed

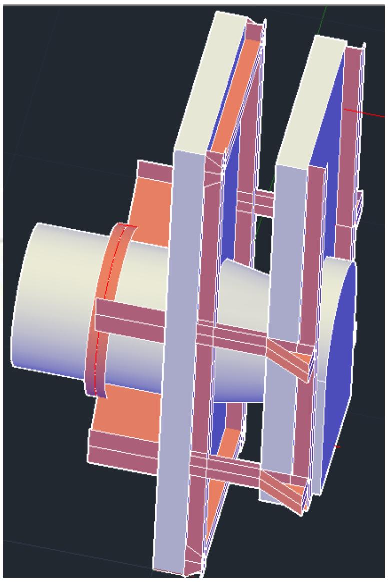

Fig. 7 Downstream block, steel lining reinforcement

4 – Hydraulic Modelling

Two physical hydraulic models were used to understand the hydraulic behaviour, adopting Froude similarities ad different reduced scales.

The first one was in scale 1:60 and reproduces part of the reservoir and of the dam, the entire spillway, the MLO, the plunge pool and the powerhouse. While it was focused on the spillway and plunge pool design, it was used also to optimize jet trajectories in the plunge pool, operating the MLO in conjunction with the spillway.

The second modelling, in scale 1:20, was entirely dedicated to the MLO and was used to verify in detail the hydraulic behaviour of the inlet, conduit and outlet sections. This model was built at the VAW laboratory in Zurich, Switzerland. It includes a pressure tank, reproducing the required pressure head of the reservoir by means of two linked pumps, and the middle outlet pipes made by acrylic glass in order to deeply investigate their hydraulic aspects varying the reservoir water levels.

Having the maximum water elevation (892 m a.s.l.) high flow velocities into the conduit might lead to cavitation, vibration and high pressure fluctuations acting on the steel structures.
Differently, with the exceptional min. level (760 m a.s.l.) air entraining vortices are likely to occur, turning the fluid into a mixture flow of air and favouring the formation of special phenomena, i.e. air back flow and pulsation.

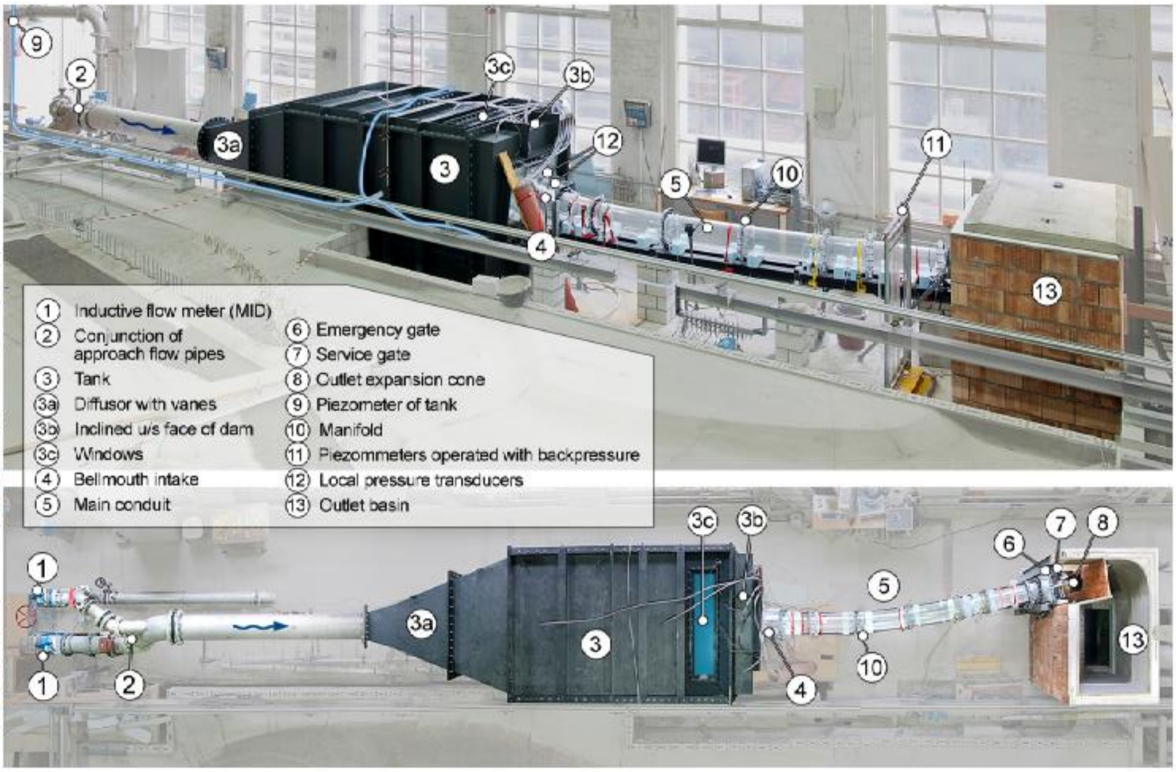

Fig. 8: Physical model (scale 1:20) of the right middle outlet - general overview

After a preliminary analysis of the water flow pattern, and after measuring the pressures and total head at the most critical sections, experiments were conducted to address the following issues:

- flow rating curves;
- static and dynamic pressures acting on the service gate;
- locations where cavitation is expected or possible;
- conduit's flow pattern for the emergency gate closure while the service gate is stuck in half open position;
- critical submergence for air entraining vortices and air-water mixture flow pattern studies.

Several tests were carried out varying the water levels through normal and exceptional operating conditions (892, 875, 800 and 778 m a.s.l) together with reservoir impounding conditions (760÷778 m a.s.l.).

The service gate operation was tested for 875 m a.s.l. (spillway sill level) and also the emergency closure with service gate stuck in a position of 50% opening varying the water level from 800 to 875 m a.s.l.
The flows measured are 797, 747, 465, 340 m^3/s respectively for water levels of 892, 875, 800 and 778 m a.s.l..

At normal and exceptional operating conditions both gates can be safely operated fully opened or fully closed. Mean and dynamic water pressures distribution, together with the qualitative analysis of flow conditions, led to conclude that no flow detachment will occur into the conduit, while pressure time series frequency analysis shows no remarkable pressure oscillations.
To prevent the inception of cavitation at the emergency gate section and outlet contraction cone, a high degree of manufacturing precision is necessary to avoid irregularities acting as isolated roughness elements. Moreover, a material with high resistance to cavitation erosion was requested to build this stretch of structure.

With a reservoir water level of 875 m a.s.l. we have varied the service gate opening from 10% to 80%. The pressure distribution at the service gate, for 10% of gate opening, resembled the hydrostatic pressure. For a gate opening of 80%, the flow appears dynamic and turbulent.
In case of emergency gate closure, during the critical closing stage when the control section shift from service gate to emergency gate, we have observed in the model the pressure felling down to vacuum creating sub-atmospheric conditions and oscillating pressures that propagate from the trunk between the gates into the tunnel.
The laboratory staff concluded that the ring follower gate should be used as a guard gate only.

During reservoir impounding, air entraining vortexes occur for water levels between 763 and 776 m a.s.l. With lower water levels, air bubbles were sporadically entrained into the free-surface turbulent shear flow. The mean air entraining ratio was adequate to transport bubbles and air pockets downstream with the flow. No air-backflow was observed, therefore no major concerns were raised with the operation of conduit at low reservoir levels.

5 – Construction Issues

The construction of the MLO was challenging especially because of their size, both for the civil works and hydraulic steel structure, and because of the interferences with the RCC dam construction. Since these works were on the critical path, both for the early generation and for the completion of the project, minimizing the interferences with the RCC placement was a major objective of the optimization process.

The detailed design, as mentioned before, was conceived to minimize construction problems which could have caused delayed, for instance:

- maintaining upstream gate lifting system simple, without special concrete structures along dam upstream face *(see figure aside)*;
- adopting a special construction sequence of the dam blocks to minimize delays on RCC placement,
- avoiding interferences with dam vertical joints;
- strengthening the steel lining structure to avoid excessive reinforcement in the nearby concrete,
- taking advantage of the dam weight to transfer upstream the trust of the downstream gate;
- minimizing reinforcement along the conduit, unless for inlet and outlet blocks which have easier accesses and smaller impact on the construction program;
- allowing adequate space between RCC joints for RCC pouring after steel lining insertion;
- Conceiving downstream block anchors with sleeve pipes in the reinforced concrete part, drilled through the deeper part within the RCC body;

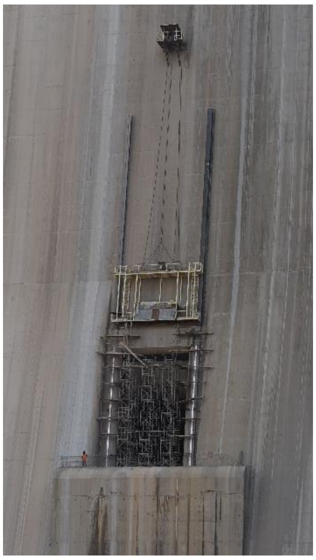

Fig. 9: Upstream bulkhead gate

The placement of the steel lining within the dam body was carried out using Blondin and mobile cranes on the dam, obtaining both easy accessibility and the possibility of working at same time on both conduits. RCC conveyors bridged the steel conduits allowing continuing RCC pouring in between the two MLOs.

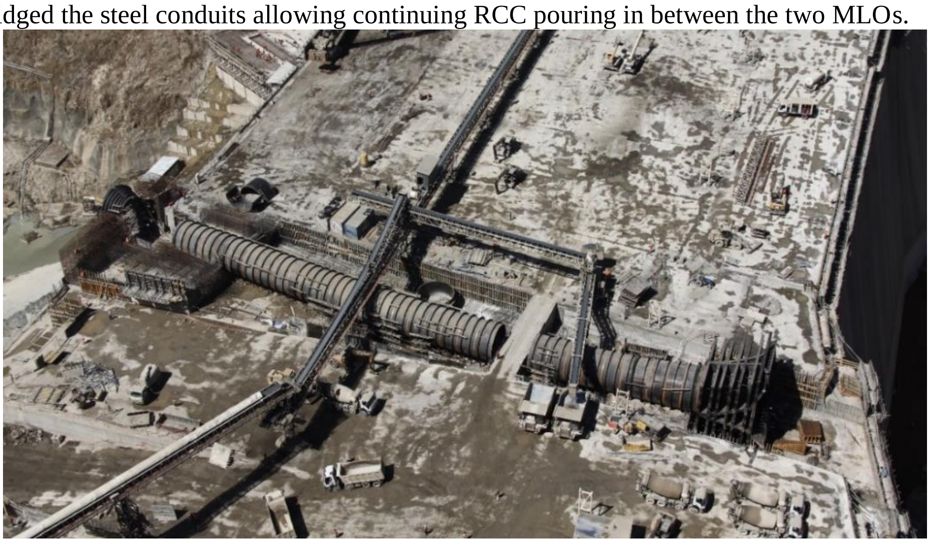

Fig. 10: Right Middle Level Outlet steel lining erection, January 2014

To avoid prolonged suspension of RCC placement, a low block was retained on the right abutment of the dam that was built when proceeding with the steel erection of the MLO.

The trunks of the main conduit were buried with RCC as soon as erected and welded. Differently, trunks of the upstream and especially the downstream gated outlet blocks, outside of the dam body, required a significantly longer construction, while the dam was raised up.

Fig. 11: RCC recess and subsequent pouring around Right Middle Level Outlet, March 2014

Particularly challenging was the accurate alignment of the steel lining elements with the downstream gates casing, fully embedded in dam body.
Within the downstream concrete block, the anchors required to transfer the loads were partly drilled (the portion in RCC) and partly inserted in sleeve pipes (in the reinforced concrete portion), and then tensioned from the outside downstream surface. This allowed to eliminate interferences with RCC.

6 – Conclusions

The design of the MLO has been particularly challenging since they operate with high heads, over 140 m of water column, and flow velocities exceeding 40 m/s.

The hydraulic and structural design therefore required uncommon technical solutions such as:

- add an upstream emergency bulkhead gate;
- select a ring follower emergency gate followed by a ring seal service gate;
- locate the gates outside the dam body;

The selected layout includes two middle outlets, symmetrically disposed within the dam body, at about halfway of the dam height and about 130 m long. The conduits are entirely steel lined and include three main parts:

- an inlet block, with rectangular inlet equipped with a bulkhead gate running on the dam upstream face;
- the main conduit with circular section (d = 6 m), with its transitions;
- an outlet block, located outside the dam body, hosting a ring follower emergency gate followed by a ring seal service gate

Water jets are discharged into a pre-excavated plunge pool, with the impact area protected with concrete blocks.

Several hydraulic and construction issues have been analysed and solved obtain an unusual design well- tailored for the needs of this project.

Nowadays the construction is completed and the MLOs are in operation since 2015.

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