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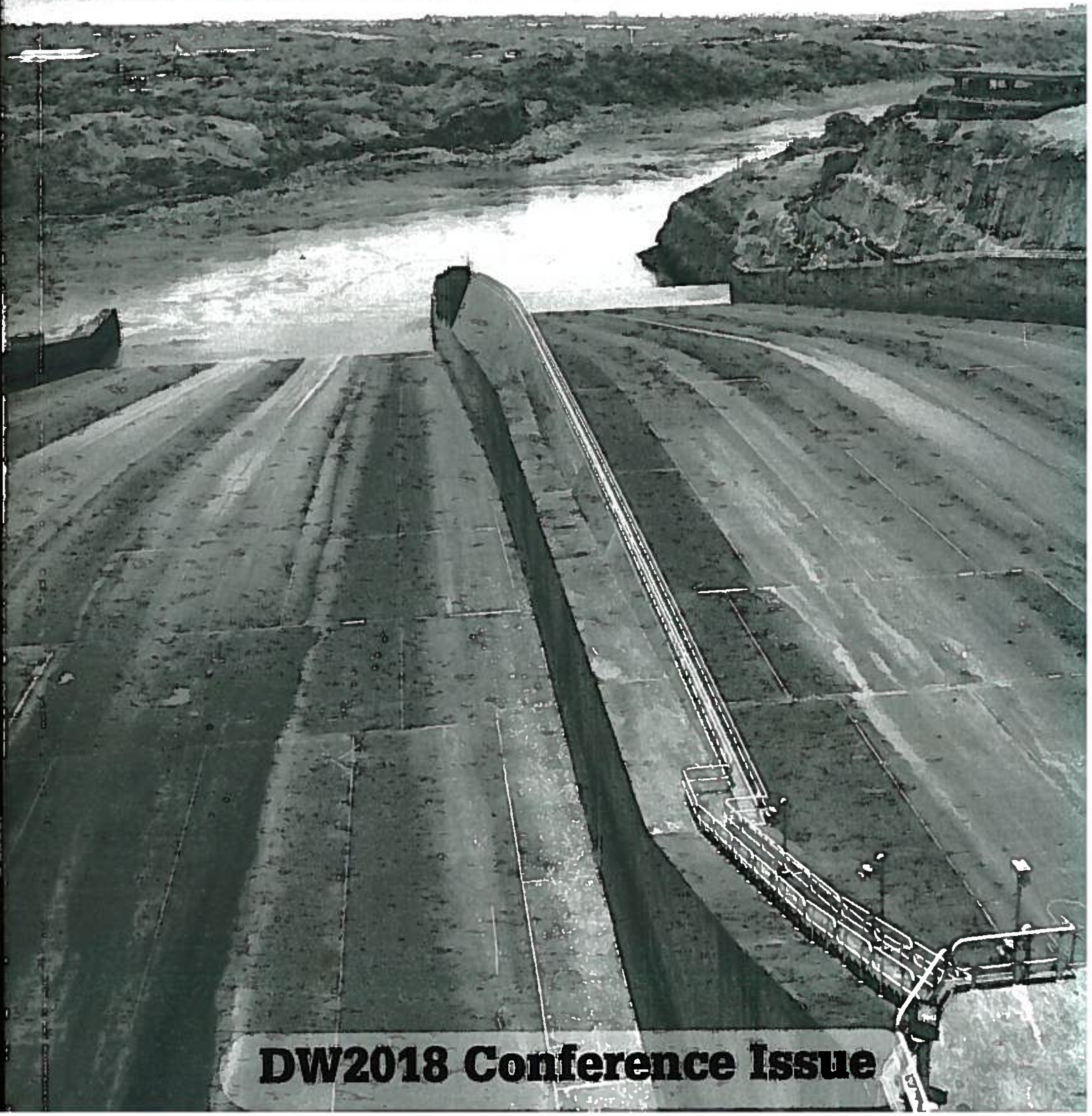

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Design of the Second Stage of Cambambe HPP Project

Marcos C Palu[*], Rafael P G Salles[†] & Diego D Baptista de Souza[†]

Abstract: *The Cambambe hydroelectric plant is located on the Cuanza River in Angola, about 180km from the capital Luanda. In 2004, after 40 years of operation of the power plant, the owner ENE (National Enterprise of Energy) decided to carry out rehabilitation and expansion works. The rehabilitation project comprised of a change to the original installed capacity from 180MW to 260MW, subject to raising of the reservoir level. The expansion project consisted of heightening the existing arch dam by 20m, construction of a new generation circuit, a new power plant with an installed capacity of 700MW and the building of two new spillways. Finally, this project increased the installed capacity of the Cambambe Dam from 180MW to 960MW, doubling the generation capacity of Angola. This paper describes the development and the challenges that were overcome during the design, which was successfully completed in 2016.*

Keywords: Cambambe Dam, dam heightening, arch dam, HPP, design.

1. Introduction

The Cambambe hydroelectric plant is located near Dondo Village, in the middle section of the Cuanza River, the main river running through Angola, with a drainage area of 115,500km^2. The dam was built in the 1960's by SONEFE (National Society for the Study & Overseas Business Finance) with detailed hydraulic studies by LNEC (National Civil Engineering Laboratory), in Lisbon, Portugal.

The initial project consisted of two stages: the first comprised the building of the 70m high arch dam with a broad crest spillway and a powerhouse with an installed capacity of 180MW (4 Francis turbines, 45MW each). The second stage, at the time planned for the future, considered heightening of the dam by 20m, construction of the seven orifice-type spillways in the dam's body, increase of the installed capacity to 260MW in the existing powerhouse, plus the construction of a new power plant with a new generation circuit. In 1964, the first stage of the Cambambe Dam project was concluded.

After four decades of operation the power plant owner, ENE (National Enterprise of Energy), decided to execute the second stage of the original project in order to increase Angola's power generation. The main

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companies involved in this project were: Engevix Engenharia e Projetos SA and Stucky (Design), Odebrecht (Construction), DAR and Coba (Supervision).

Thus, this paper describes the development of the design of the dam heightening and the challenges overcome in order to execute the second stage of the Cambambe Dam Project.

2. The Cambambe Dam Design

2.1 Original design and layout modifications

The existing dam is a 70m high concrete arch dam with double curvature, with crest elevation of 112.5masl. The dam length is 340m, containing a broad crest spillway 100m long at the centre of the dam with an elevation of 102.15masl, able to spill a discharge of approximately 6500m^3/sec. Figure 1 shows an image from the dam's construction in 1960 and the situation in 2010, just before the beginning of rehabilitation works.

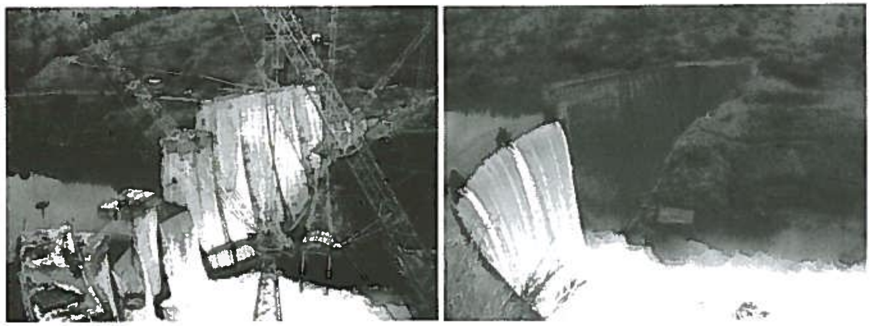

Figure 1. Cambambe Dam construction in 1960, and the dam's situation in 2010

In 2004 the heightening project started, and the initial discussion regarded the new layout. The original Portuguese design planned the construction of seven orifice-type spillways in the dam's body, controlled by sluice gates 9.5m high and 9.0m wide, with a crest elevation of 111.25masl. However, this design had to be changed due to the uncertainties surrounding the condition of the existing plunge pool, located downstream of the dam, after more than 40 years of operation. Furthermore, continuous spilling of the existing spillway hindered the execution of a careful inspection of this plunge pool.

In order to define the location of the new spillway, the design engineers adopted a design flood of 10,000 years of recurrence, which represents a discharge of 9000m^3/sec, according to updated hydrologic studies. After preliminary studies the design engineers, in accordance with the owner, decided to split the design flood between two separate spillways: a main spillway in the left bank and an emergency orifice-type spillway in the body of the dam.

The left bank spillway was designed to discharge at 4500m^3/sec, which refers to the 50 years of recurring floods. This spillway is controlled by two radial gates, each 15m high and 19.5m wide, with the ogee crest at elevation 115masl. Since this has become the main spillway, the orifice-type spillway (emergency spillway) is expected to operate only for floods exceeding the 50 years recurrence floods. In this situation the flow from the left bank spillway would provide a water cushion to mitigate the impact of the falling jet of the orifices in the existing plunge pool.

Consequently, the design resulted in five orifice-type spillways controlled by sluice gates 5.2m high and 9.5m wide each, with a crest elevation of 107.29masl. Figure 2 illustrates the definitive layout of the Cambambe Dam with the spillway locations.

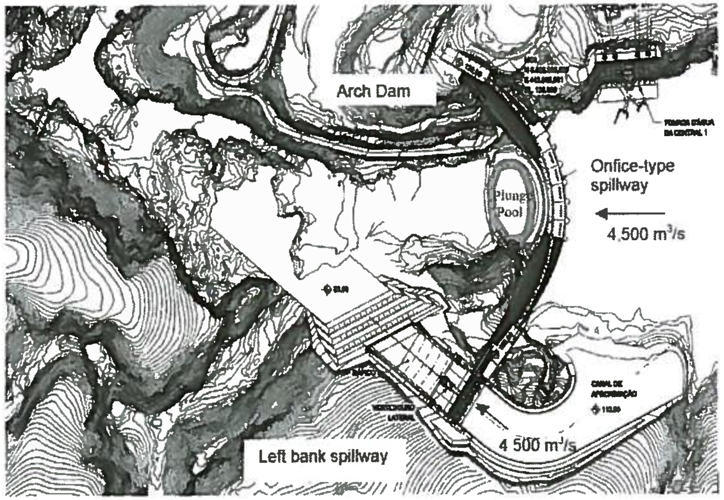

Figure 2. Cambambe Dam layout

In addition, the new water intake would be located on the right bank. Figure 3 shows an aerial image from Google Earth taken after the beginning of construction on 27th July 2014, where it is possible to visualize the location of the main structures.

Figure 3. Cambambe Dam aerial view (Google Earth)

2.2 Dam heightening

The dam heightening design considered the rise of the existing arch dam by 19.50m, changing the original crest from elevation 112.5masl to the new elevation of 132masl, thus the initial reservoir level elevation of 103masl was changed to 130masl. Figure 4 provides an upstream view of the design and location of the spillways.

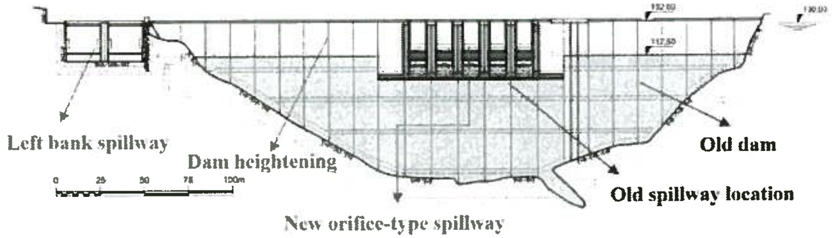

Figure 4. Cambambe Dam heightening project, upstream view

After definition of the layout construction started. The main issue was the building of the orifice-type spillway over the old spillway, due to the unceasing flow. The solution to carrying out construction of this new spillway was to divert the flow to the existing bottom outlet during the dry period (June-November). However, a repair on the bottom outlet was needed first, as described in the next section.

In addition, another issue was the occurrence of floods during construction of the orifice-type spillway. This particular load case had to be taken into account in the structural design in order to assure the stability of the structure during construction. Figure 5 illustrates the start of the dam heightening process, and a flood situation just after construction of the spillway began.

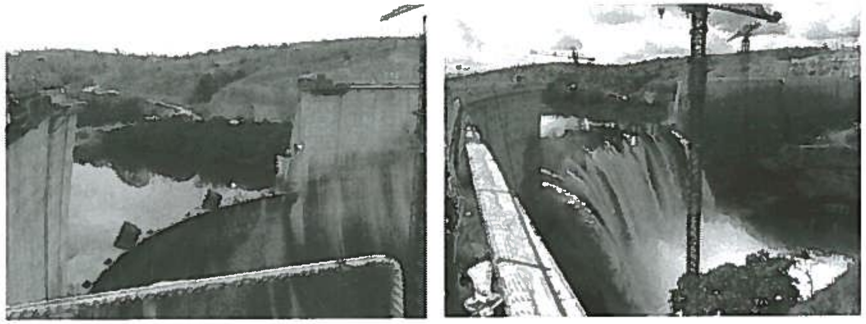

Figure 5. Pictures from the dam site during heightening of the dam

The following section describes the repairs needed to the bottom outlet in order to enable the execution of the orifice-type spillway.

3. The Bottom Outlet

3.1 Existing structure

At the beginning of the Cambambe Hydroelectric project, the Portuguese engineers designed a bottom outlet excavated in the right bank (see location in Figure 3) to divert flow during the dam's construction. After the conclusion of the dam, this structure would be used to evacuate sediment during the reservoir operation. The bottom outlet structure has an intake elevation of 56masl, and is operated by two gates. Firstly, a caterpillar gate 4.5m wide and 6.7m high, designed to allow execution of repairs along the structure, and a radial gate 3.5m wide and 6m high, to control the flow.

Downstream of the radial gate there is a "D" shaped section tunnel, 6.0m wide and 7.5m high, with concrete lining on the bottom and on the walls. The tunnel has an extension of 420m, with a bed slope of 0.0341m/m. Discharge capacity is approximately 650m^3/sec. Figure 6 illustrates the original design of the bottom outlet.

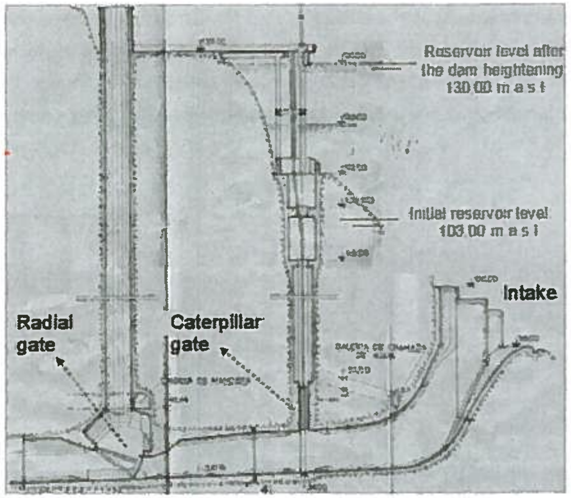

Figure 6. Bottom outlet original design

3.2 Cavitation and aerator design

As reported by Palu *et al*[1], an inspection of the tunnel revealed a huge process of cavitation after more than 40 years of operation. Figure 7 shows a sketch and a picture taken from the cavitation in the bottom outlet.

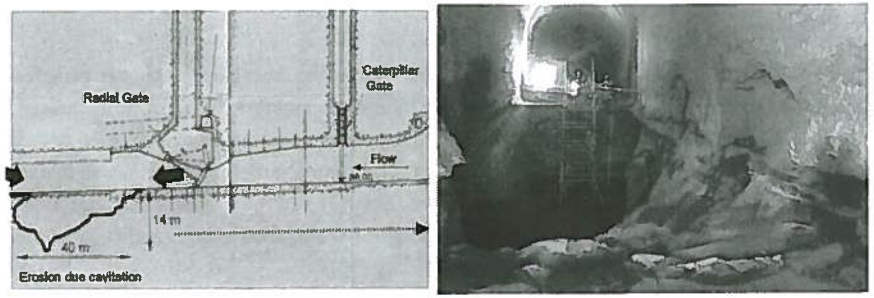

Figure 7. Bottom outlet cavitation[1]

Considering the hydraulic head (≈ 70m) and the resultant velocity in the radial gate section (≈ 35m/sec) it is not surprising to discover the occurrence of this phenomenon.

According to Falvey[2] the experience with flow in spillway tunnels and chutes indicates that damage becomes significant when flow velocities exceed 30m/sec. However, one should note that the effects of the cavitation were not sufficiently known at the time of the conception of the Cambambe Dam design (1960's). After several incidents with cavitation around the world during the 1970's and 1980's, e.g. Yellowtail (US), Bratsk (Russia), Glenn Canyon (US) and Karum (Iran), identification of the causes and the solutions to mitigate such process has greatly advanced.

The repair of the bottom outlet was essential to the dam heightening project, since it provided diversion of the flow during dam construction. Since the air injection in the flow is a known solution for cavitation[2], the repair in the bottom outlet included filling of the scour hole, installation of a new steel lining downstream of the gate and construction of aerators along the tunnel. The aerator type chosen was ramp on sidewall type, as illustrated in Figure 8.

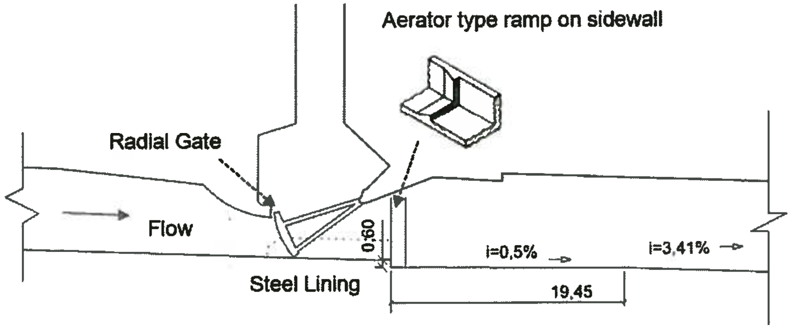

Figure 8. Aerator design

Two similar aerators were built along the tunnel at a distance of 150m and 300m, respectively, downstream of the radial gate. After designing the aerators were tested on a physical model with a scale of 1:30, following the Froude similitude criteria, at the Bardella Laboratory in Brazil. More details regarding the criteria to dimensioning of the aerators can be found in previous studies by Palu *et al*[1].

Construction of the aerators made operation of the bottom outlet possible again. Even though other issues arose due to the condition of the gates, the problem of cavitation was resolved and the heightening project could be resume.

4. The Spillways

4.1 Design criteria and physical model studies

The hydraulic calculations of the spillways followed the well-known Design of Small Dams criteria[3], after which the design was consolidated with physical modelling. The physical model was built in June 2010 at the LACTEC/CEHPAR hydraulic laboratory located in the city of Curitiba, state of Paraná, Brazil. This model was built with a geometric scale of 1:75, following the Froude similitude criteria, reproducing an area of 0.74km^2 in the prototype, which represented an area of 132m^2 in the laboratory. The main tests carried out were: discharge capacity with partial and total gate opening, jet trajectory, pressure in the crest and chute, pressure in the plunge pool and scour depth. Figure 9 illustrates the running of some these tests on the physical model.

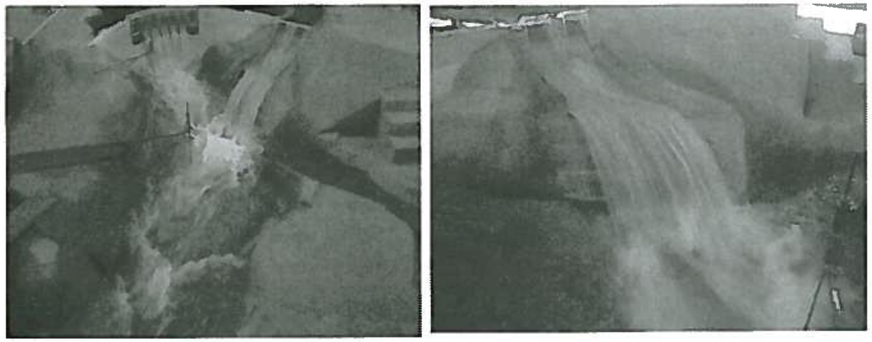

Figure 9. Physical model studies

Overall, the physical model showed satisfactory hydraulic performance of the spillways. However, towards the end of the physical model studies some adaptations were needed to the alignment of the left bank spillway approach channel. However, at this time the physical model studies were almost complete therefore, due to timing and cost, the engineers agreed to test the modifications using numerical model Flow 3D®. The next topic presents the results of this numerical simulation.

4.2 Numerical modelling

The main numerical simulations were performed in Flow 3D®, which is a numerical model based on the finite volume method. The description of the software features and several hydraulic modelling cases can be found on the website: http://www.flow3d.com. As previously described, the objective of this numerical simulation was the evaluation of the hydraulic performance of the left bank spillway considering adjustments in the approach channel.

In this manner the variables to be checked in the numerical model were: the spillway discharge capacity, the velocity, and the water level along the approach channel. The results of the physical model were used for the calibration of this numerical simulation. Figure 10 shows the result of the numerical simulation in Flow 3D®.

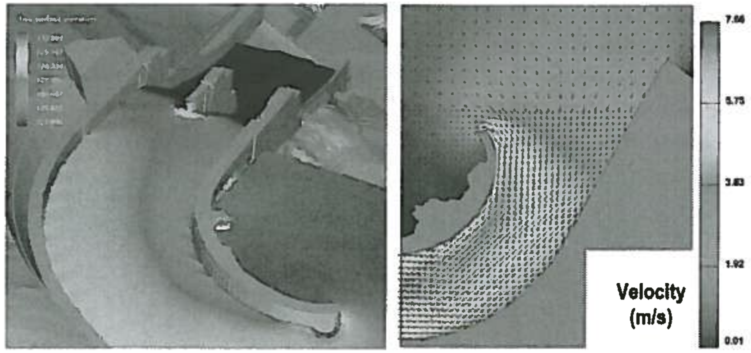

Figure 10. Numerical model studies in Flow3D®

The numerical model confirmed good hydraulic performance of the spillway after the alteration to the channel alignment. More details about this numerical simulation can be found in previous studies by Souza *et al*[4]. Furthermore, Flow 3D® was also a powerful tool in helping the hydraulic engineers design other structures as well, as described later in this paper.

4.3 Spillway construction and operation

After conclusion of the design, the spillways were built, being concluded in June 2016. Following the end of construction both spillways were tested successfully, as shown in Figure 11.

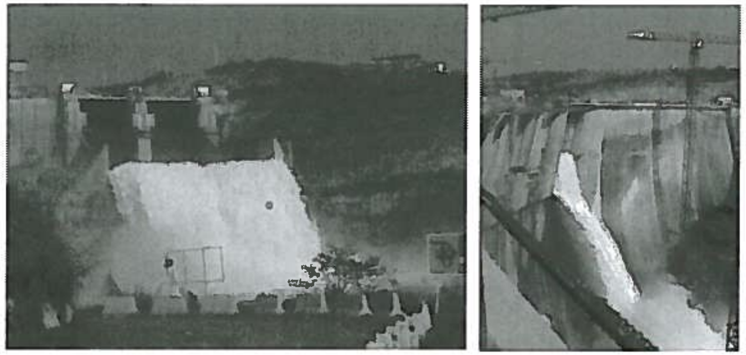

Figure 11. Spillway test in 2016

5. Generation Circuit and New Powerhouse

The design of the new generation circuit includes four gravity water intakes, four penstocks, a new powerhouse with four vertical axis Francis turbines with a capacity of 175MW each, resulting in an installed capacity of 700MW, and a new substation[5]. Net head is 109m, and the reference discharge in each turbine is 180m^3/sec. The penstock is excavated in rock, and the total length is approximately 480m (340m of concrete lining with a diameter of 7.4m, and a final segment of 140m with steel lining with a diameter of 6.7m). The powerhouse is open air excavated with the dimensions 133m x 36m. Figure 12 shows the profile of the new generation circuit.

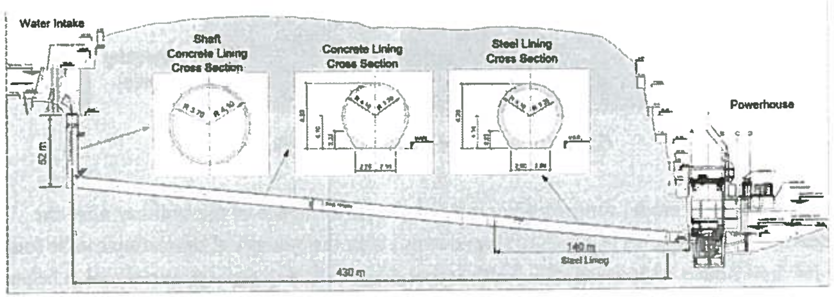

Figure 12. New generation circuit

An issue during execution of the powerhouse was the proximity of the cofferdam to the jet from the bottom outlet. For this reason the downstream guide walls were modified in order to redirect the jet. In addition, the cofferdam was protected with large blocks.

Another concern was the risk of overtopping of the cofferdam due to the river's narrowness. Thus, a 20m wide and 10m deep lateral channel was excavated on the left bank in order to reduce upstream water levels, enhancing the protection of the powerhouse construction.

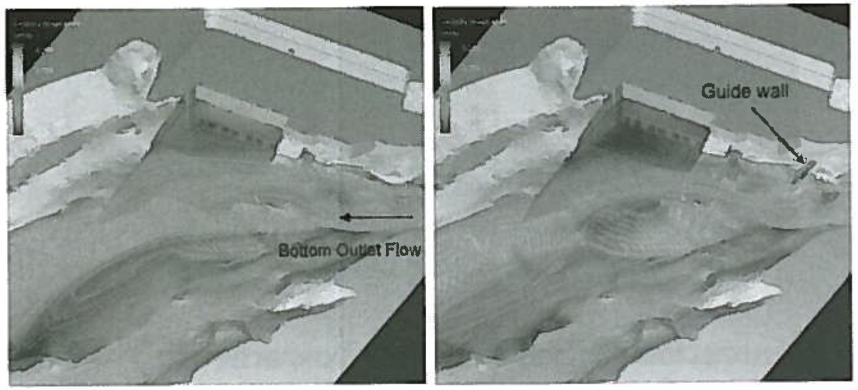

Figure 13. Simulation of flow at tailrace on Flow 3D® before (left) and after (right) the insertion of a guide wall

Moreover, almost at the end of the project, Flow 3D® was used to simulate the interference of the bottom outlet flow in the tailrace of the new powerhouse. With the support of numerical simulation the engineers were able to design a guide wall to deflect the flow, and prevent water recirculation near the turbines. Figure 13 shows some of these simulations.

Finally, the generation circuit was built and concluded successfully in May 2016. In order to illustrate some of the construction stages, Figure 14 (left) shows the execution of the water intake in June 2014 and the excavation of the powerhouse, protected by the cofferdam, in November 2013 (right).

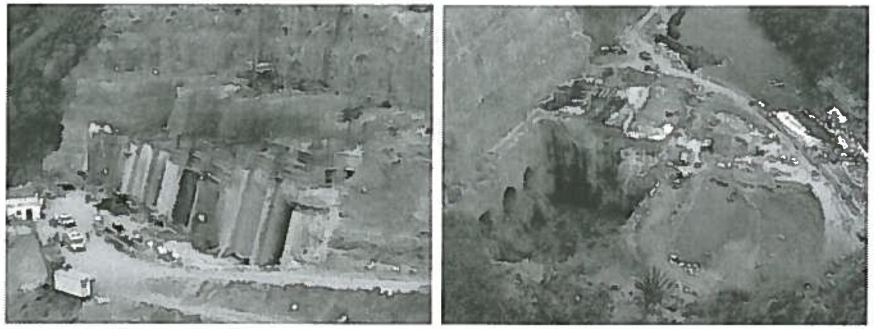

Figure 14. Generation circuit construction stages

6. Conclusions

The paper presented provides a brief description of the development of the second stage of the Cambambe Hydropower design, which included dam heightening, new spillways and a new generation circuit with powerhouse. The challenges faced, i.e. the cavitation in the bottom outlet, the execution of the orifice spillways in the dam's body considering floods, and the protection the powerhouse construction due to the narrowness of the river, were all overcome. As a result the dam project was successfully concluded in June 2016 and is now operating.

Ultimately, the conclusion of this project has doubled Angola's generation capacity. Figure 15 shows an aerial view of the Cambambe Dam after project completion.

The reader is encouraged to check the aerial views of the original dam, some phases of construction, and the completed dam using historical imagery resource in the free software Google Earth (www.google.com/earth/). The geographic coordinates of the dam are latitude: 9°45'7.87"S, and longitude: 14°28'52.35"E.

Figure 15. Aerial view of the completed Cambambe Dam

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