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# DESIGN OF THE CAMBAMBE DAM HEIGHTENING

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

## 1 INTRODUCTION

The Cambambe hydroelectric is located near the Dondo Village, in the middle section of the Cuanza River, the main river of Angola, with a drainage area of 115,500 km$^2$. The dam was built in the 60's by SONEFE (National Society for the Study and Overseas Business Finance) with detailed hydraulic studies by LNEC (National Civil Engineering Laboratory), in Lisbon.

The initial project consisted in two stages: the first one comprised the building of 70 m high arch dam with a broad crest spillway and a powerhouse of 180 MW of installed capacity (4 Francis turbines of 45 MW each). The second stage, at that time planned for the future, considered the heightening of the dam in 20 m, the construction of seven orifice-type spillways in the dam's body, the increase of the installed capacity to 260 MW 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 the Angola's power generation. The main companies involved in this project were: Engevix Engenharia e Projetos S.A and Stucky (Design), Odebrecht (Construction), DAR and Coba (Supervision).

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

## 2 THE CAMBAMBE DAM DESIGN

### 2.1 Original Design and Layout Modifications

The existing dam is a 70 m high concrete arch dam with double curvature, with the crest in the elevation 112.50 m.a.s.l. The dam length is 340 m, containing a broad crest spillway 100 m long at the center of the dam in the elevation 102.15 m.a.s.l, able to spill a discharge of approximately 6,500 $m^3/s$. The Figure 1 shows an image from the dam construction in 1960 and the situation in 2010, just before the beginning of *rehabilitation works.*

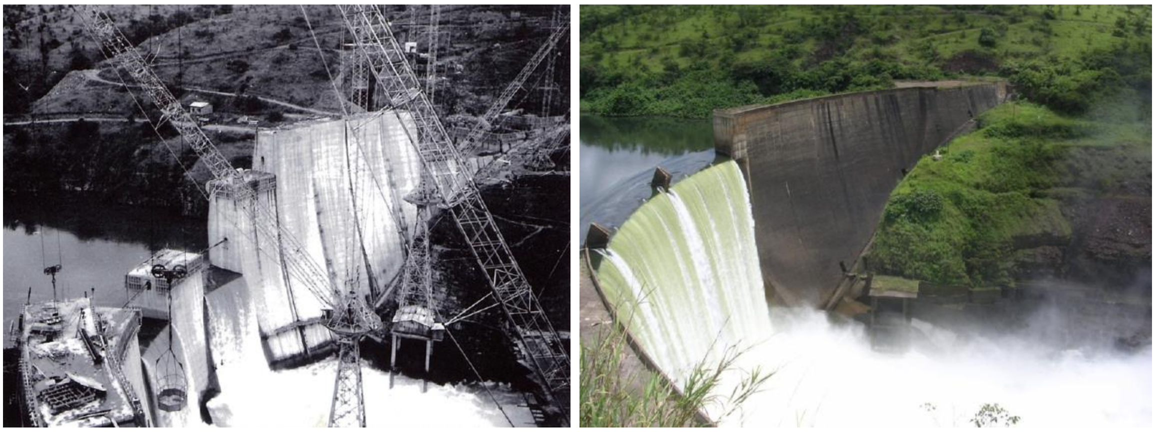

Figure 1: Cambambe Dam construction in 1960 and the dam situation in 2010

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

In order to define the location of the new spillway, the design engineers adopted the design flood of 10,000 years of recurrence, which represents a discharge of 9,000 $m^3/s$, according with the updated hydrologic studies. After the preliminary studies, the design engineers in accordance with the owner decided to split the design flood in two different 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 for 4,500 $m^3/s$, which refers to the 50 years recurrence flood. This spillway is controlled by two radial gates 15 m high and 19.50 m wide each, with the ogee crest in the elevation 115.00 m.a.s.l. 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 flood. 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 orifices-type spillways controlled by sluice gates 5.20 m high and 9.50 m wide each, with the crest in the elevation 107.29 m.a.s.l. The Figure 2 illustrates the definitive layout of the Cambambe Dam with the spillways location.

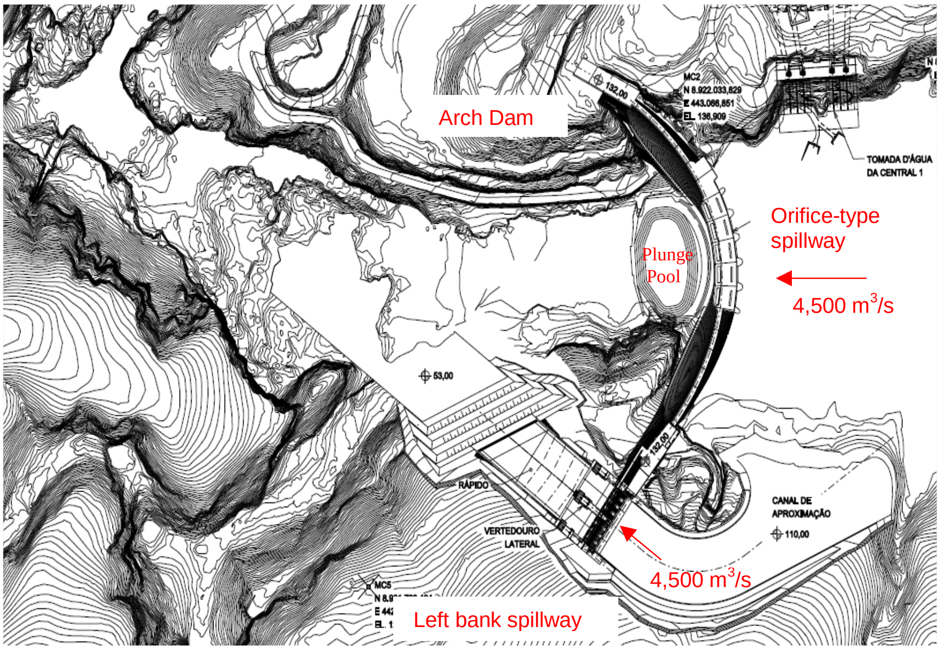


Figure 2: Cambambe Dam layout

In addition, the new water intake would be located in the right bank. The Figure 3 shows an aerial image from *Google Earth* taken after the beginning of construction in 27/07/2014, where is possible to visualize the location of the main structures.

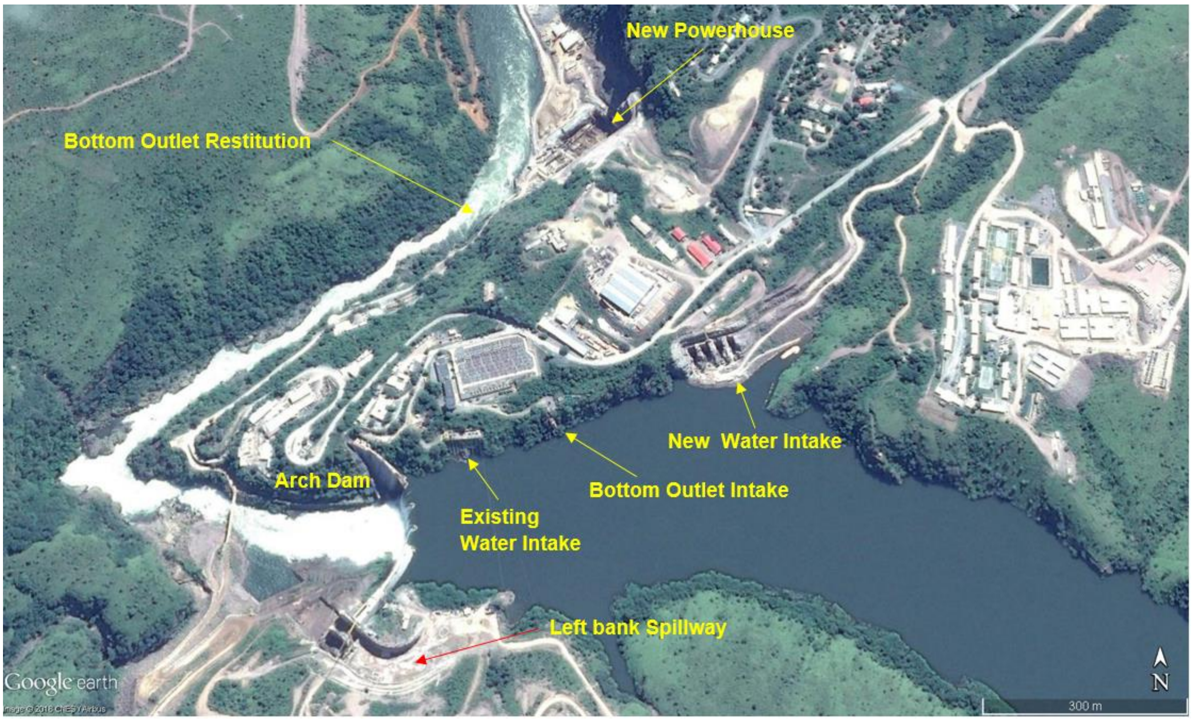


Figure 3: Cambambe Dam aerial view (*Google Earth*)

## 2.2 The Dam Heightening

The dam heightening design considered the rise of the existing arch dam in 19.50 m, changing the original crest from the elevation 112.50 m.a.s.l to the new elevation 132.00 m.a.s.l, thus the initial reservoir level elevation 103.00 m.a.s.l was changed to 130,00 m.a.s.l. The Figure 4 provides an upstream view of the design and the location of the spillways.

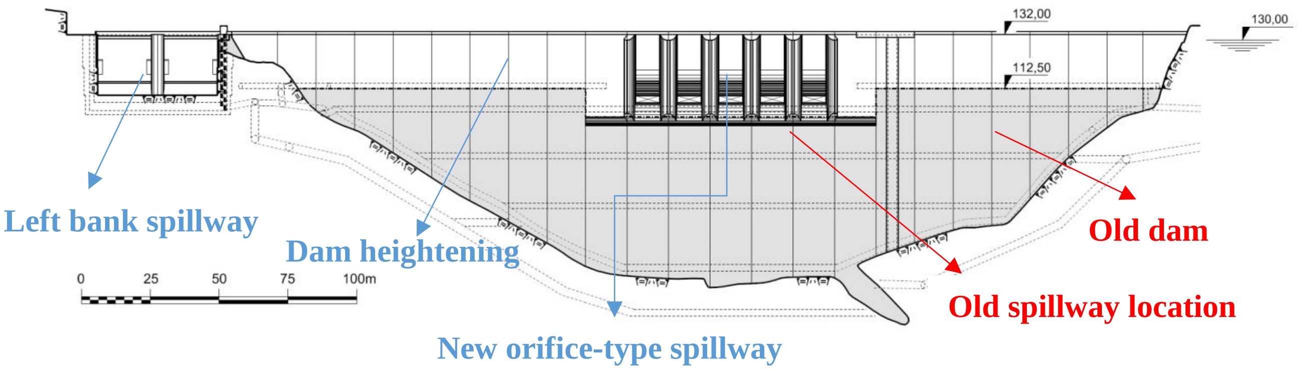


Figure 4: Cambambe Dam Heightening Project, upstream view

After the definition of the layout the construction started, nevertheless the main issue was the building of the orifice-type spillways over the old spillway, due the unceasing flow. The solution to carry out the construction of this new spillway was diverting 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 topic.

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

Figure 5: Pictures from the dam site during the dam heightening

The next item describes the repairs needed in 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 the location in the Figure 3) to divert the flow during the dam 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 in the elevation in 56 m.a.s.l and it is operated by two gates. First, a caterpillar gate 4.5 m wide and 6.7 m high designed for execute repairs along the structure and a radial gate 3.5 m wide and 6.0 m high, to control the flow.

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

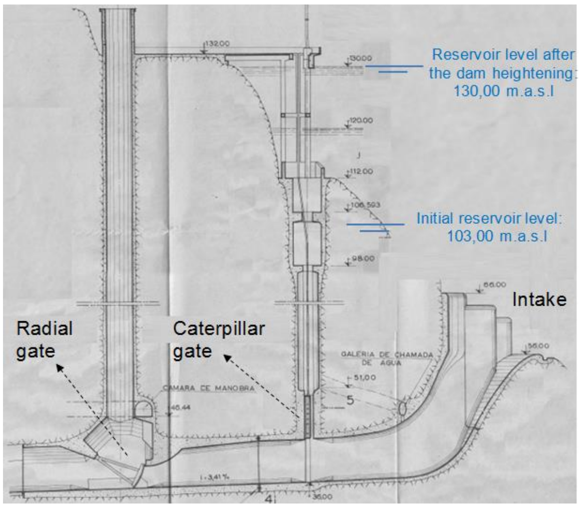


Figure 6: Bottom Outlet original design

## 3.2 Cavitation and Aerators Design

As reported by Palu et al., 2010[1], an inspection in the tunnel revealed a huge process of cavitation after more than 40 years of operation. The Figure 7 shows a sketch and a picture taken from the cavitation in the bottom outlet.

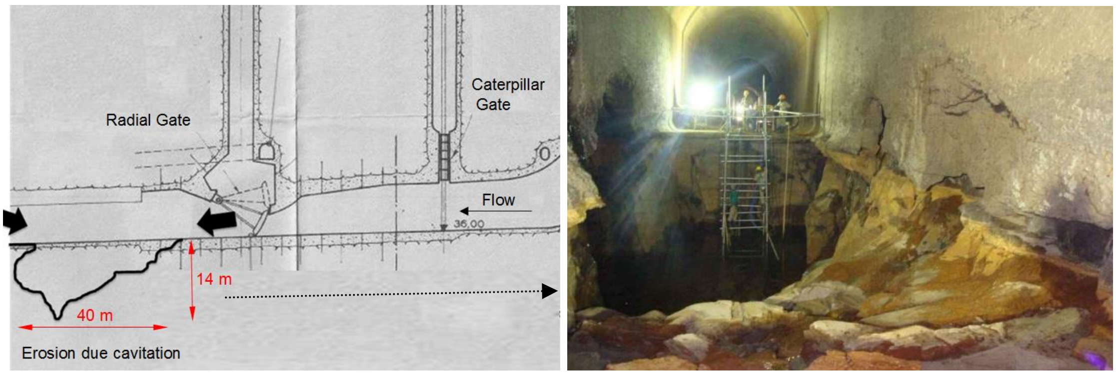


Figure 7: Bottom Outlet cavitation (Palu et al, 2010)

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

According to Falvey, 1990[2] the experience with flow in spillways tunnels and chutes indicates that damage becomes significant when the flow velocities exceed 30 m/s. However, one should note that the effects of cavitation were not sufficiently known at the time of the conception of the Cambambe Dam design (60's). After several incidents with cavitation around the world during the 70's and 80's as Yellowtail-USA, Bratsk-Russia, Glenn Canyon-USA and Karum-Iran for instance, the identification of the causes and the solutions to mitigate such process had great advance.

The repair of the bottom outlet was essential to the dam heightening project, since it provides the diversion the flow during the dam construction. Since the air injection in the flow is a known solution for cavitation (Falvey, 1990)[2], the repair in the bottom outlet included the filling of the scour hole, the installation of a new steel lining at downstream of the gate and the construction of aerators along the tunnel. The aerators type chosen were ramp on sidewall type, as illustrated in the Figure 8.

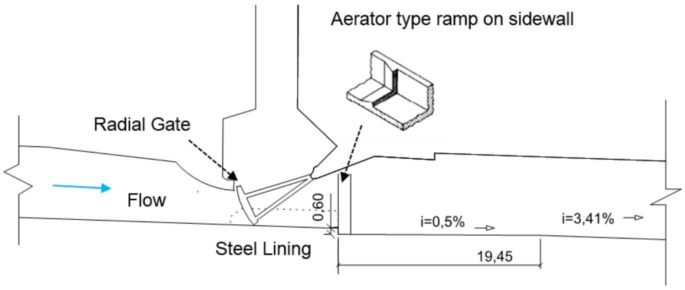


Figure 8: Aerators design

Another two similar aerators were built along the tunnel at the distance of 150 m and 300 m respectively downstream of the radial gate. After the designing, the aerators were tested in a physical model in the scale 1:30 following the Froude similitude criteria at the Bardella Lab (Brazil). More details about the criteria to dimensioning of the aerators can be found at Palu et al., 2010[1].

The construction of the aerators make possible the operation of the bottom outlet again. Even though other issues have arisen due the condition of the gates, the cavitation problem was solved and the heightening project could be resumed.

# 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 (USBR, 1987)[3], after that the design was consolidated with physical modeling. The physical model was built in June of 2010 at the LACTEC/CEHPAR hydraulic lab located in the city of Curitiba, state of Paraná, Brazil. This model was built in the geometric scale of 1:75, following the Froude similitude criteria and reproducing an area of 0.74 km² in the prototype, which represents an area of 132 m² in the lab. The main tests carried out were: discharge capacity with partial and total gates opening, jet trajectory, pressure in the crest and chute, pressure in the plunge pool and scour depth. The Figure 9 illustrates the running of some tests in the physical model.

Figure 9: Physical model studies

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

### 4.2 Numerical Modeling

The main numerical simulations were performed in the Flow 3D®, which is a numerical model based on the finite volume method. The description of the software features and several hydraulic modeling cases can be found at the website: http://www.flow3d.com/. As described before, 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. The Figure 10 shows the result of the numerical simulation in the Flow 3D®.

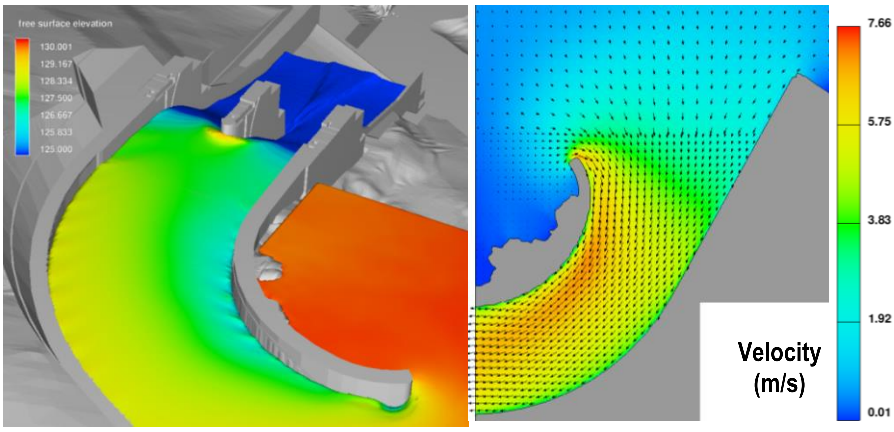


Figure 10: Numerical model studies in Flow3D.

The numerical model confirmed the good hydraulic performance of the spillway after the alteration in the channel alignment. More details about this numerical simulation can be found at Souza et al., 2013[4]. Furthermore, the Flow 3D® was also a powerful tool to help the hydraulic engineers design other structures as well, as described latter in this paper .

### 4.3 Spillway Construction and Operation

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

Figure 11: Spillway test in 2016

## 5 GENERATION CIRCUIT AND THE NEW POWERHOUSE

Finally, the design of the new generation circuit includes 4 new gravity water intakes, 4 new penstocks, a new powerhouse with four units of vertical axis Francis Turbines of 175 MW each, resulting in an installed capacity of 700 MW and a new substation (Salles et al., 2011)[5]. The net head is 109 m and the reference discharge in each turbine is 180 $m^3/s$. The penstock is excavated in rock and the total length is approximately 480 m, being 340 m in concrete lining with a diameter of 7.40 m and a final segment of 140 m in steel lining with a diameter of 6.70 m. The powerhouse is open air excavated with the dimensions 133 m x 36 m. The Figure 12 shows the profile of the new generation circuit.

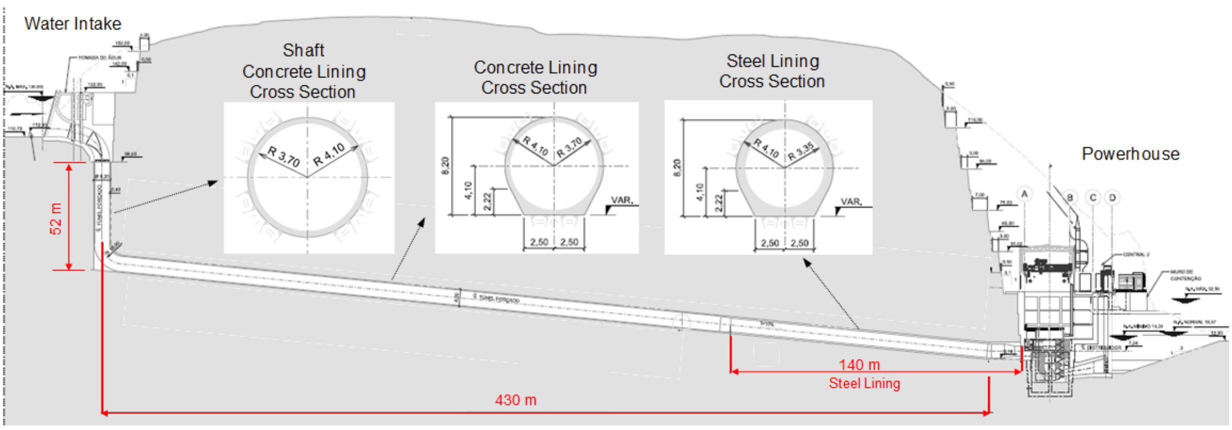


Figure 12: New generation circuit

An issue during the execution of the powerhouse was the proximity of the cofferdam with the jet from the bottom outlet, for this reason the downstream guide walls suffered modifications in order to redirect the jet. In addition, the cofferdam was protected with large size blocks. Another concern was the risk of overtopping of the cofferdam due the river’s narrowness. Thus, a lateral channel 20 m wide and 10 m deep was excavated in the left bank in order to reduce the upstream water levels, enhancing the protection of the powerhouse construction.

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

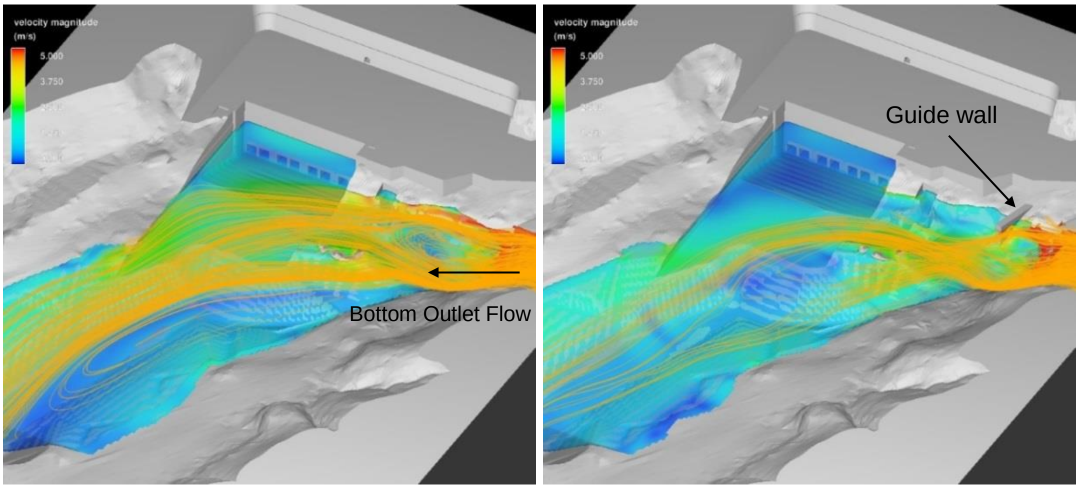


Figure 13: Simulation of flow at tailrace on Flow 3D® before (left) and after (right) the insertion of a guide wall

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

Figure 14: Generation circuit construction stages

## 6 CONCLUSIONS

This paper presented a brief description of the development of the second stage of Cambambe Hydropower design, which included the Dam heightening, new spillways and new generation circuit with a new powerhouse. The challenges found, as 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 the narrowness of the river were all overcome. As the result, the dam was concluded successfully in June of 2016 and nowadays is operating.

Ultimately, the conclusion of this project doubled the Angola's Generation Capacity. The Figure 15 shows an aerial view of the Cambambe Dam after the completion.

Figure 15: Aerial view of the Cambambe Dam concluded.

The reader now is encouraged to check the aerial views from the original dam, some phases of the construction and the dam concluded using the 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.

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