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S. Erpicum
Liege University, s.erpicum@ulg.ac.be

M. Lodomez
University of Liege, m.lodomez@ulg.ac.be

J. Savatier
ISL Ingenierie

P. Archambeau
Liege University

B. J. Dewals
Liege University

See next page for additional authors

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Author Information

S. Erpicum, M. Lodomez, J. Savatier, P. Archambeau, B. J. Dewals, and M. Pirotton

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Physical Modeling of an Aerating Stepped Spillway

S. Erpicum[1], M. Lodomez[1], J. Savatier[2], P. Archambeau[1], B. J. Dewals[1], M. Pirotton[1]
[1]Dept. of Architecture, Geology, Environment and Constructions (ArGEnCo)
Liege University
Liege, 4000
Belgium
[2]ISL Ingénierie
Saint Jean de Luz, 64500
France
E-mail: S.Erpicum@ulg.ac.be

ABSTRACT

To mitigate the negative effects on the water quality in the downstream river of a projected large dam, and in particular to increase the dissolved oxygen concentration during low flow periods within the first 10 years of dam operation, an aerating weir has been designed and tested on a physical model at the Laboratory of Engineering Hydraulics (HECE) of the Liege University. The design of the structure considers data from the literature. The selected solution is a 3 m high stepped spillway designed to operate in nappe flow conditions within the range of design discharges (25 – 100 m³/s). To validate the design, a physical model representing a section of the weir at a 1:1 scale has been built and operated in the laboratory. A chemical dissolved oxygen removal technique has been applied upstream of the model to be able to measure the weir aerating efficiency. The physical model results show that the proposed structure is able to maintain, in the range of discharge in the river from 25 to 100 m³/s, a minimum 5 mg/l oxygen concentration downstream, whatever the upstream oxygen concentration. The paper presents the design process of the weir, the scale model features and the results of the validation tests on the physical model. The prototype construction will take place in 2017 and the water quality will be monitored.

Keywords: *Physical modeling, aeration, water quality, oxygen deficiency, aerating weir*

1. INTRODUCTION

Vegetation decomposition taking place in artificial reservoirs of tropical regions may significantly alter the water quality by consuming dissolved oxygen and producing methane. If released without sufficient aeration, for instance through the turbines of a power plant, this poor quality water is likely to have a significant impact on the downstream river life. This phenomenon is particularly important during the first years following the first filling of large reservoirs, when flooded vegetation volume is important and the reservoir water renewal limited.

A few dams are known to experience this problem and specific structures have been built downstream to increase the dissolved oxygen concentration (aeration) while degassing methane. Two examples include

- Petit Saut dam in French Guiana, where a steel weir with two successive chutes have been placed (Gosse and Grégoire, 1997);
- Nam Theun 2 project, where various specific structures such as a hollow jet valve, concrete tooth and an aerating weir have been designed (Descloux et al. 2015).

Several systems, using labyrinth weirs, have also been designed and tested by the Tennessee Valley Authority (Hauser and Morris, 1995).

Generally, hydraulic structures such as weirs and stepped spillways may be very effective in increasing the oxygen concentration and degassing methane. This efficiency may be characterized by the deficit ratio r or the aeration efficiency E. These parameters depend on the temperature T and are defined as

$$E_T = 1 - \frac{1}{r_T} = \frac{C_d - C_u}{C_s - C_u} \quad (1)$$

where C_d is the downstream dissolved oxygen concentration, C_u is the upstream dissolved oxygen concentration and C_s is the saturation oxygen concentration.

Among the works published to date, Nakasone (1987) proposed design equations to predict the deficit ratio r from side to side of a chute depending on the chute height D, the specific discharge q, the critical depth h_c and the tailwater depth h_d. For specific discharges higher than 0.0653 m²/s, they are

$$\ln r_{20} = 5.39\left(D + 1.5h_c\right)^{1.31} q^{-0.363} h_d^{0.310} \text{ for } D + 1.5h_c \leq 1.2m \quad (2a)$$

$$\ln r_{20} = 5.92\left(D + 1.5h_c\right)^{0.816} q^{-0.363} h_d^{0.310} \text{ for } D + 1.5h_c > 1.2m \quad (2b)$$

Nakasone formula is based on laboratory tests and has been validated regarding other researchers' results and field measurements, as detailed in Nakasone (1987). Essery et al. (1978) and more recently Bayar et al. (2007) studied the aeration efficiency of stepped spillways. Using data from experimental tests considering 1 and 2 m high chutes with steps .05 to .5 m high, slope from 11.3 to 45°, and discharge ranging from 0.0116 m²/s to 0.1447 m²/s, Essery et al. (1978) equation writes

$$\ln r_{20} = \frac{D}{\sqrt{gh_s}}\left(0.427 - 0.310 \ln \frac{h_c}{h_s}\right) \quad (3)$$

with h_s as the step height. This equation does not depend on the flow regime. On the contrary, Bayar et al. (2007) equations depend on the flow regime. Also set up from experimental results (2.5 and 1.25 m high chutes, steps .05, 0.1 and 0.15 m high, slope from 14.48 to 50°, and discharge from 0.0167 m²/s to 0.1667 m²/s), Bayar et al. (2007) equation for nappe flow regime writes

$$\ln r_{20} = \left(1 - 0.265\left(\sin\theta\right)^{-2.661}\left(\frac{h_c}{h_s}\right)^{0.007} L_a^{-2.057}\right)^{1.575} \quad (4)$$

with θ the chute angle and $L_a = \frac{D}{\sin\theta} - 6.834 h_s^{0.749} q^{0.205}\left(\cos\theta\right)^{0.915}$.

In this paper, the solution designed to aerate the flow from a large dam reservoir under first filling is presented in details. In particular, the solution has been validated using laboratory tests on a 1:1 physical model of a section of the aerating structure. Section 2 presents the project constraints and the preliminary design of the solution. The physical model used for validation and the methodology of the tests are depicted in section 3, while the results and their discussion are given in section 4.

2. PROJECT CONSTRAINTS AND PRELIMINARY DESIGN

2.1. Project Features

The target oxygen concentration in the river downstream of the aerating structure is 5 mg/l for discharges up to 100 m³/s. It is expected to reach a zero concentration of dissolved oxygen in the water released through the turbines during the first years of reservoir operation. The water temperature in the river varies from 20 to 30°C along the year. At 20°C and atmospheric pressure, oxygen saturation concentration is equal to 9.09 mg/l. The objective of the structure is thus to reach aeration efficiency at 20°C E_{20} equal to 0.55.

It has been verified that the water in the river doesn't contain any specific element which could act against oxygen transfer. Only "natural" oxygen consumption is thus present. In addition, high methane concentrations are expected. The aerating structure has to release this dissolved gas in the atmosphere.

Because of economic and time constraints as well as a difficult access to the construction site (natural reserve), the aeration structure has to be simple and made as much as possible from materials available on site. It has also to be easily dismantled as it will impact the operation of the dam's powerplant while the quality of the reservoir water is expected to become "good" after some years of operation. In particular, a specific first filling plan lasting over several years will be applied to control and mitigate negative impact on the water quality. The requested life time of the structure is thus around 10 years. Regarding the planned operation of the dam during the first years following first filling, key discharges are 25 and 50 m³/s.

A river survey suggested locating the aerating structure at a place where rocks show on the surface (natural chute), a few kilometers downstream of the dam. The river width at this place is around 160 m. Depending on the operation of the upstream powerplant, the chute can be 3 m high.

2.2. Preliminary design

Regarding the river width and the prototype discharge range, the aerating structure has to be effective in the range of specific discharges from 0.159 to 0.637 m³/s/m. The maximum chute height is 3 m. In this context, two main solutions for the aeration structure have been analyzed:

- One or two successive overflow chutes with a downstream basin, where aeration occurs in the downstream basin thanks to the air entrained by the jet at impact;
- A stepped spillway, where aeration occurs on each step along the structure, depending on the flow regime.

Considering the equations available in the literature, and in particular the ones mentioned in section 1, it is possible to propose a structure geometry able to provide enough aeration in the whole range of project discharge, while not exceeding the maximum chute height for both solutions.

Considering technical reasons including availability of materials on the dam work site and easier decommissioning, the stepped spillway solution has been preferred by the Designer (ISL Ingénierie). In such a case, nappe flow is the flow regime providing most effective aeration (Baylar et al., 2007). Different criteria can be found in the literature to get such a flow regime. Ohtsu et al. (2001), cited by Baylar et al. (2007), propose the following limit

$$\frac{h_s}{h_c} > 0.57\left(\tan\alpha\right)^3 + 1.3 \quad \text{for } 5.7° < \alpha < 55° \tag{5}$$

while André et al. (2008) propose

$$\frac{h_s}{h_c} > 1.356\left(\tan\alpha\right)^{0.244} \quad \text{for } 18.6° < \alpha < 30° \tag{6}$$

Application of the most restrictive of these two formulae to the discharge range of the project and considering a 15° slope compatible with construction and stability constraints leads to choose 50 cm high steps.

Given these geometric and flow parameters, the aeration efficiency E_{20} of the system has been assessed using equations 3 and 4. E_{20} values predicted by Essery et al. (1978) equation range from 0.67 to 0.52, with increasing discharge. An almost constant value of 0.75 is predicted by Baylar et al. (2007) equation, whatever the discharge. These values are better or close to the target E_{20} value of the project. It has to be noticed that some of the present project characteristics fall outside the range of parameters considered in the researches by Essery et al. (1978) and Baylar et al. (2007).

2.3. Aerating Structure Geometry

Based on the above-mentioned considerations, the aeration structure geometry has been defined as follows: 3 m high and 157 m wide weir with a smooth upstream face inclined by 26.5°, a 3-m long horizontal broad crest and a downstream face made of six 50-cm high and 1.87 m long steps (15° slope). The weir will be built on an existing rock bar using rubble masonry (CIDB, 2015).

3. PHYSICAL MODELING

3.1. Model Features

In order to validate the design of the aerating weir, a physical model has been built and operated at the Laboratory of Engineering Hydraulics (HECE) of the University of Liege.

To avoid scale effects on the oxygen transfer mechanisms and thanks to the limited chute of the prototype, the model has been built at prototype scale (1:1 scale factor). Indeed, even with large scale factors, it has been shown (Chanson, 2009; Felder and Chanson, 2015) that bubbles size is not properly scaled on hydraulic scale models. The bubbles size, and thus the surface of oxygen exchange between water and air, is a key parameter in the aeration process.

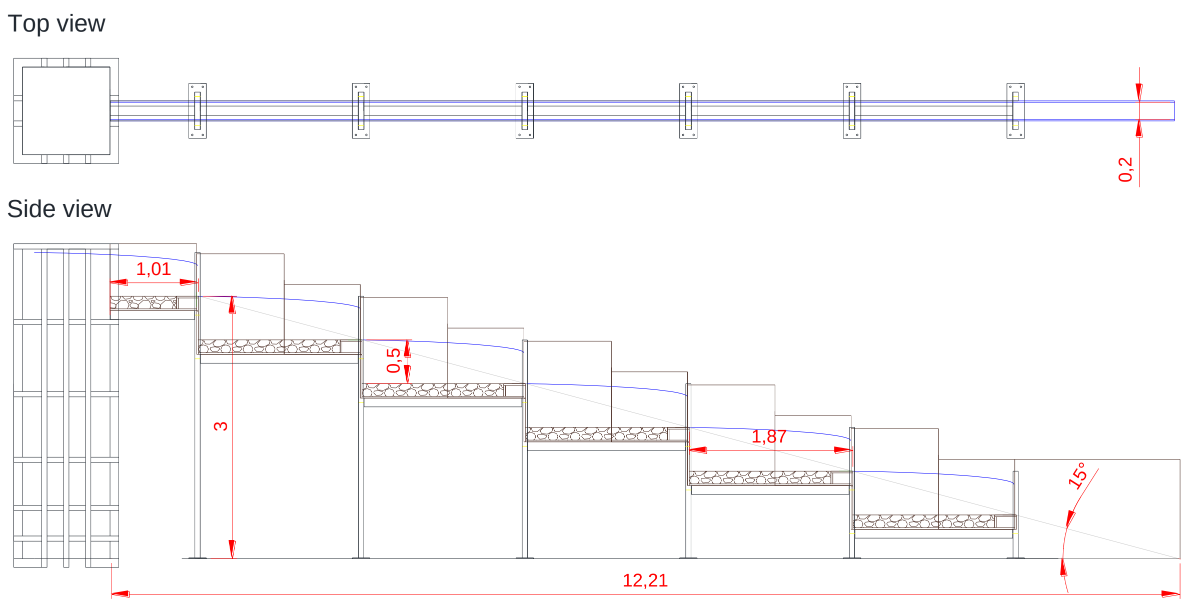

Figure 1. Sketch of the physical model – Dimensions in m

With a 1:1 scale factor, the discharge is a limiting parameter for the tests. As the aerating weir will be horizontal and built perpendicular to the main river reach, the discharge will most probably be uniformly distributed over the weir width. Therefore, the physical model focused on a limited section of the weir (2D vertical model – Fig. 1). The model width has been chosen considering available water volume and discharge considerations. Indeed, to study the aeration process on the weir, it is necessary to remove the oxygen from the upstream water. As the water supply system of the laboratory is a closed loop with pumps, pressurized conduits and an underground reservoir, it is necessary to remove the dissolved oxygen from the water stored in the reservoir. As a consequence, the duration of a test is directly linked to the available water volume and to the discharge. To enable tens of minutes long tests with 4 discharge levels (25, 50, 75 and 100 m³/s on the prototype), a 20 cm wide physical model has been built. Resulting maximum discharge in the physical model is 127.5 l/s.

With such a limited width, strong wall effects may affect the physical model results. In order to limit side friction effects, the model side walls have been made of Plexiglas and PVC (smooth materials). In addition, all the measurements have been done along the model centerline. Finally, air entrainment and aeration will probably be less in the 2D model than in the 3D prototype flow, especially because transverse flow fluctuations development will be limited by the side walls. It is thus believed that the model is conservative in terms of aeration efficiency.

The physical model represents the weir crest and the whole downstream face. The crest and steps bottom are made of rubble masonry, as on the prototype (Fig. 2 - left). Steps face is made of PVC on the physical model (formed concrete on the prototype).

During the test, the upstream discharge has been measured using an electromagnetic discharge meter on the supply pipe (accuracy of 0.5% FS). Dissolved oxygen concentration has been measured continuously in the upstream reservoir, in the downstream collecting channel and on several steps using 6 optical oximeters. On the steps, the oximeters have been placed along the channel centerline and just upstream of the jet impact area, in order to try to avoid perturbations of the measurement by the high air bubbles content at the impact and downstream (Fig. 2 - right). In addition, some Winkler tests have been done to validate the measures from the oximeters.

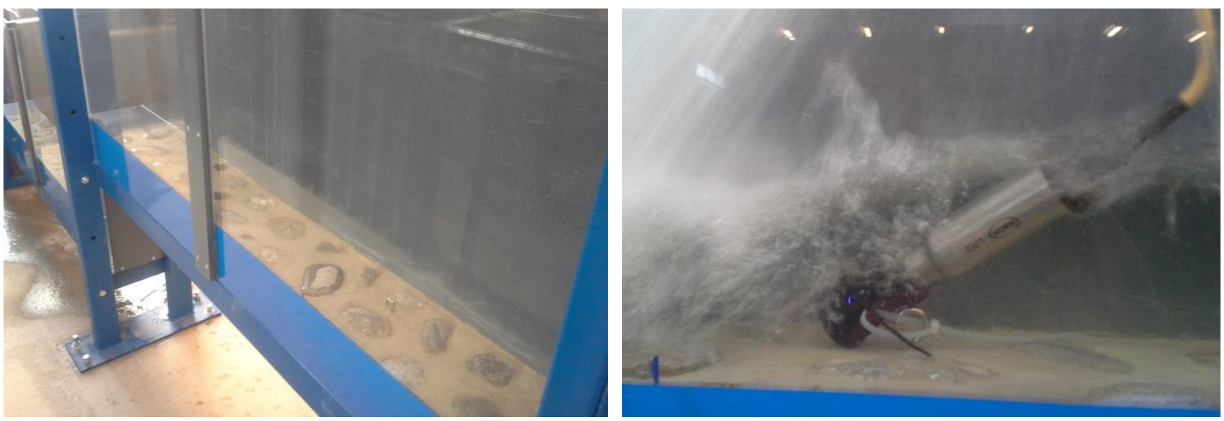

Figure 2. Rubble masonry on the steps (left) and oximeter (right)

3.2. Tests Characteristics

The tests have been carried out with water almost completely deoxygenated (oxygen concentration close to 0 upstream of the model). As the water supply system upstream of the model is completely pressurized (submerged pipe in the model upstream reservoir), the whole water volume of the laboratory reservoir (350 m³) has been deoxygenated.

To remove the dissolved oxygen from the reservoir, Cobalt chloride and sulfite have been mixed with the water. By a careful control of the sulfite volume, the dissolved oxygen concentration in the reservoir has been brought very close to zero. Sulfite excess has to be avoided to not affect the reaeration process on the aerating structure.

During a test, the deoxygenated water is first pumped into the model and upstream oxygen concentration is close to 0. After some minutes, because of mixing of the remaining deoxygenated water with the (aerated) water coming back from the model, oxygen concentration upstream of the model increases slowly. To limit this increase, when this concentration approaches 1 mg/l, sulfite is added in the free surface collecting channel downstream of the model, just before return to the laboratory reservoir. This sulfite, together with the Cobalt chloride still present in the water, consumes the oxygen. To control this sulfite injection during the tests, continuous control of oxygen concentration took place just upstream of the first step (model inlet).

Because of negative effects on the global water quality during the deoxygenation process (in particular, increase of the water conductivity), the number of deoxygenation operations has been limited to three. Each test has been conducted with increasing or decreasing discharge, with stabilization to each of the target discharge values (25, 50, 75 and 100 m³/s at prototype scale).

The experimental conditions and the chronology of the three tests are given in Table 1. Given the discharges considered and the model dimensions, Reynolds number $\mathrm{Re} = q/\nu$, with ν the kinematic viscosity, varies from 1.6 10^5 to 6.4 10^5 while Weber number $We = \rho q^2 / h_c \sigma$, with ρ the water density and σ the water surface tension, varies from 2.5 10^3 to 1.6 10^4.

Table 1. Experimental conditions and tests chronology

	Water temperature [°C]	Atmospheric pressure [hPa]	pH start/end [-]	Conductivity start/end [μS/cm]	Time [min]	Stage duration [min]	Model discharge [l/s]	Prototype discharge [m³/s]
Test 1	20.0	998.0	8.4/8.5	365/480	0	-	0.0	0
					3 to 13	10	31.8	25
					15 to 22	7	63.7	50
					24 to 30	6	95.5	75
					30	-	0.0	0
Test 2	19.0	990.0	8.5/8.5	490/590	0	-	0.0	0
					3 to 13	10	121.0	95
					15 to 27	12	95.5	75
					30 to 40	10	63.7	50
					41 to 65	24	31.8	25
					65	-	0.0	0
Test 3	18.9	984.0	8.6/8.6	590/770	0	-	0.0	0
					3 to 18	15	31.8	25
					28 to 38	10	63.7	50
					41 to 51	10	95.5	75
					53 to 63	10	127.4	100
					65	-	0.0	0

4. RESULTS AND DISCUSSION

4.1. General Flow Features

Instantaneous pictures of the flow are given in Figure 3 for discharges of 25, 50, 75 and 100 m³/s at prototype scale. Nappe flow regime occurs for all discharges on all steps except on step 1 for discharges higher than 25 m³/s. On step 1 and for discharges higher than 25 m³/s, no jet and impact are observed on the downstream step and flow aeration seems consequently very weak compared to what is observed on the same step for smaller discharge (Fig. 4).

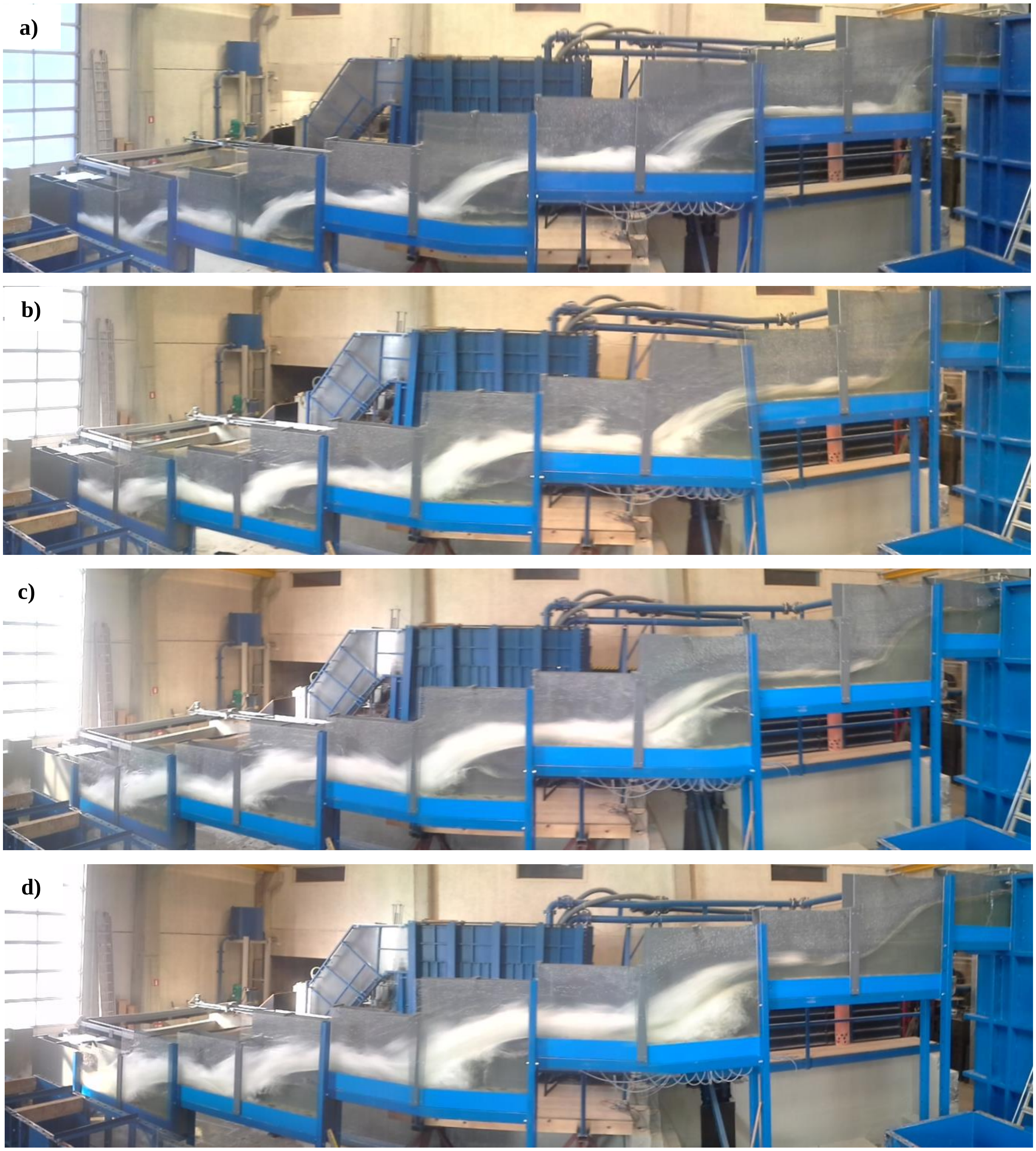

Figure 3. General view of the model – Prototype discharge of a) 25 m³/s, b) 50 m³/s, c) 75 m³/s and d) 100 m³/s

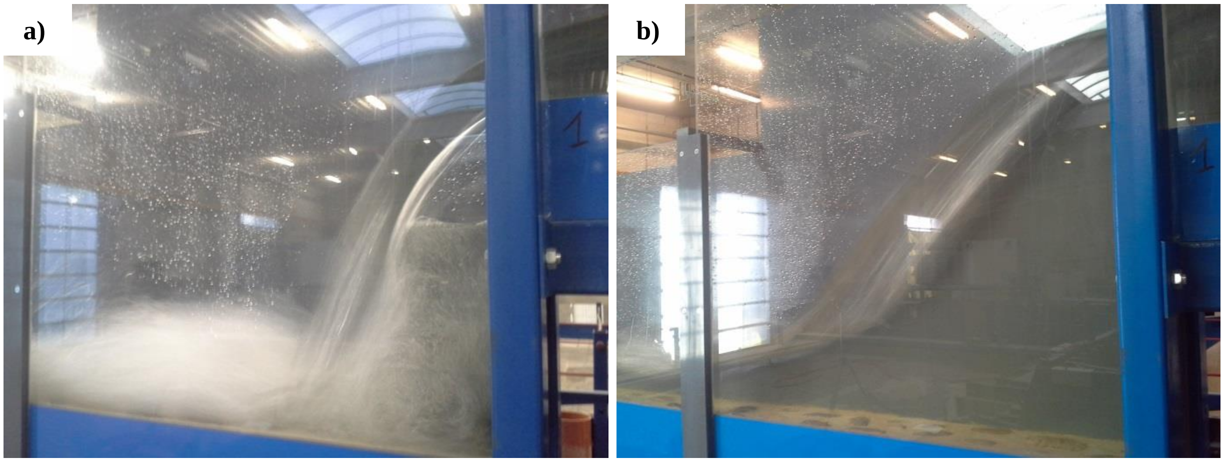

Figure 4. Flow over step 1 - Prototype discharge of a) 25 m³/s and b) 75 m³/s

4.2. Aeration efficiency

The graphs in figure 5 show the evolution of the aeration along the aerating structure depending on the discharge. The results from each test are similar. They show a continuous increase in oxygen concentration along the structure. Each step contributes significantly to the aeration efficiency.

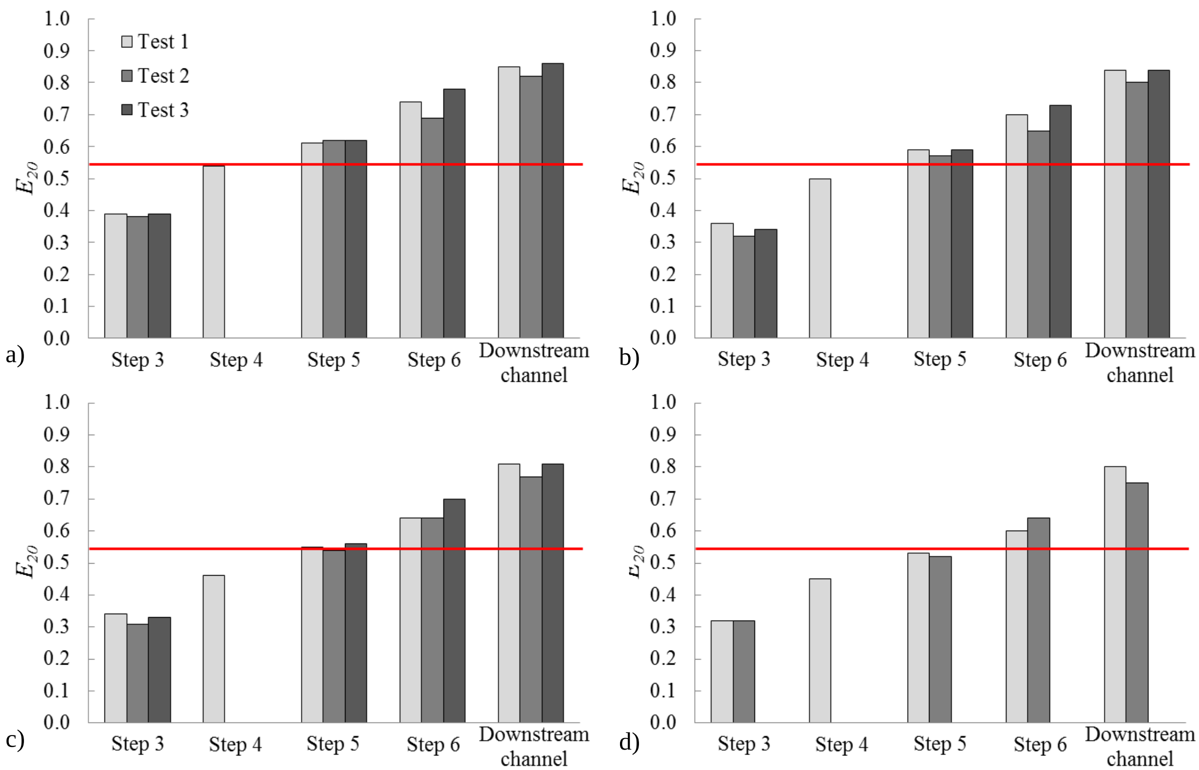

Figure 5. Aeration efficiency at 20°C E_{20} measured along the model for each test – Prototype discharge of a) 25 m³/s, b) 50 m³/s, c) 75 m³/s and d) 100 m³/s

Mean aeration efficiency computed from the results of the 3 tests is displayed in figure 6. Whatever the discharge, the target aeration efficiency is reached after step 6, i.e. a chute of 3 m. For discharges of 25 and 50 m³/s, the target efficiency is reached after step 5. The proposed structure is thus able to meet the project objective.

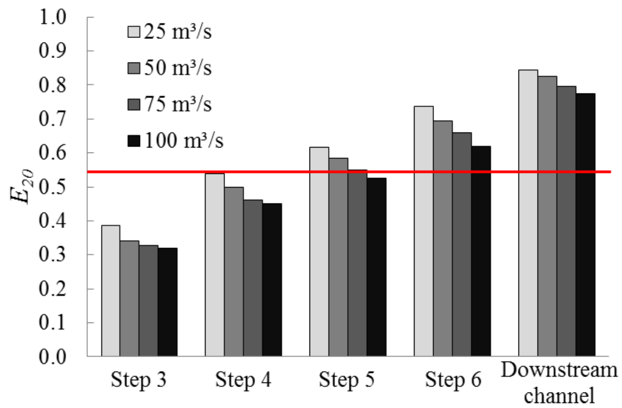

Figure 6. Mean aeration efficiency at 20°C E_{20} measured along the model

Comparison of predicted values from Equations 3 and 4 to measured values given in Table 2 shows similar values, with physical model results bounded by the empirical equations. However, the influence of the discharge is more important in the model than what is predicted by Baylar et al. (2007) formula (Eq. 3), which provides overestimated values. Essery et al. (1978) formula (Eq. 4) predicts well the effect of the discharge variation but provides underestimated aeration efficiencies.

Table 2. Predicted and measured aeration efficiency E_{20} for the structure proposed in this paper

q	h_c	h_c/h_s	E_{20}		
[m³/s/m]	[m]	[-]	Baylar et al. 2007	Essery et al. 1978	Phys model
0.159	0.14	0.27	0.75	0.67	0.74
0.318	0.22	0.44	0.75	0.60	0.69
0.478	0.29	0.57	0.75	0.56	0.66
0.637	0.35	0.69	0.74	0.52	0.62

5. CONCLUSIONS AND PERSPECTIVES

An aerating system using a stepped spillway has been designed to improve the water quality downstream of a large dam. The efficiency of the proposed structure has been validated by means of a 1:1 physical model of a section of the spillway. Experimental results show that target oxygen concentration is reached downstream of the proposed structure in the range of relevant discharges.

Comparison of the measured aeration efficiency with results from the literature shows similarities but also differences. The study is still in progress with

- additional tests on the physical model to increase the reliability of the results and better quantify the gain in oxygen concentration given by each step in order to derive improved design equation;
- a study of scale and geometry effects by building and operation of a scale physical model with a variable width (scaled width or larger width than the one of the physical model presented in this paper).

6. ACKNOWLEDGMENTS

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