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Pool-type Fishway with Orifices: 3D Numerical Simulation of the Flow

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***Abstract* — This study evaluated the flow in a pool-type fishway with submerged orifices, installed on alternate sides in consecutive transversal deflectors. Data obtained from a physical model were used to validate a three-dimensional hydrodynamic model. The fishway geometry used in the validation (Design 1) is composed by pools with 1.90 m long, 1.00 width, orifices with 0.2 m x 0.2 m, bottom slope of 8.7% and deflector thickness of 1 cm. Modifications were made in the initial geometry: the orifice size was increased (Design 2), it was transformed into a vertical slot fishway (Design 3) and the deflector thickness was increased (Designs 4 and 5). Results indicated that for designs 2, 3, 4 and 5, to maintain the same mean depth of flow, discharges 50%, 250%, 1% and 5% higher than the one used in design 1 were required, respectively. The volumetric dissipated power was 173 W/m³ for design 3 and less than 70 W/m³ for the other geometries. For all designs the maximum velocities are lower than 2 m/s that is considered a limit for neotropical fish. For the design 1 the maximum value of turbulence kinetic energy (k) is 0.17 m²/s². The increase in the aperture between pools (Designs 2 and 3) resulted in values of k 35% and 65% greater than the one verified in the Design 1, respectively. The increase in the deflector thickness reduced the maximum values of k. The validated numerical model can also be used to assess flow patterns for other modifications in the design of pool-type fishways.**

Keywords — fish passes; fish passage; CFD; ecohydraulic; hydraulic structures.

I. Introduction

The fragmentation of watercourses by the construction of dams avoid the free movement of aquatic organisms in the environment, which may need to move for reproduction and feeding. In an attempt to help species progress upstream, in some cases fishways can be constructed to help species maintain their life cycles. Fishways can be of various types according to the obstacle height, fish species whose migration must be reestablished and the available discharges. An effective fishway should quickly attract migratory fish and allow them to enter, pass through the pools and leave safely with minimal costs in terms of time and energy. If the velocity and turbulence kinetic energy in the pools are very high, or if the water depth is too low, the fish will be unable to swim through the structure [1].

Among the various types of fishways, the pool-type fishway equipped with submerged orifices is an option usually used in combination with superficial weirs. Submerged orifice type fishways are rarely used because they are difficult to maintain and the fish may have difficulty in locating the orifice at the bottom [2]. On the other hand, pool-type fishway with submerged orifices are usually economical considering water flow rates. For pool-type fishway equipped with submerged orifices, the flow characteristics are influenced mainly by bottom slope, size of the orifice, length and width of the pool. So, it may be useful to investigate modifications in the geometry of this kind of fishway in order to adequate the flow to fish capabilities.

Analysis of flow conditions in fishways can be performed using computational fluid dynamics (CFD) resources. During validation of numerical models is used data from experimental studies. If the model represents correctly the most important aspect of the flow patterns, then it could be used to assess the flow characteristics in new designs. In this study we validate a numerical model for a pool-type fishway with submerged orifices. Then, modifications in the reference design are done including possible situations in future designs, as a larger area of passage between two pools and the increase in the deflector thickness between adjacent pools, considering constructive aspects

II. Materials and Methods

A. Geometry

This study evaluated the flow in a pool-type fishway with submerged orifices, installed on alternate sides in consecutive transversal deflectors. Data obtained from a physical model [3] were used to validate a three-dimensional hydrodynamic model. The fishway geometry used in the validation (Design 1, *Fig. 1*) is composed by pools with 1.90 m long, 1.00 m width, orifices with 0.2 m x 0.2 m, bottom slope equal to 8.7% and deflector thickness of 1 cm. Simulation in the Design 1 was conducted with the same dimensions of the physical model for the purpose of direct comparison of the results without additional scale effects. The structure of the present study has five consecutive pool, an inlet region and an outlet region, with a total length of approximately 13.5 m.

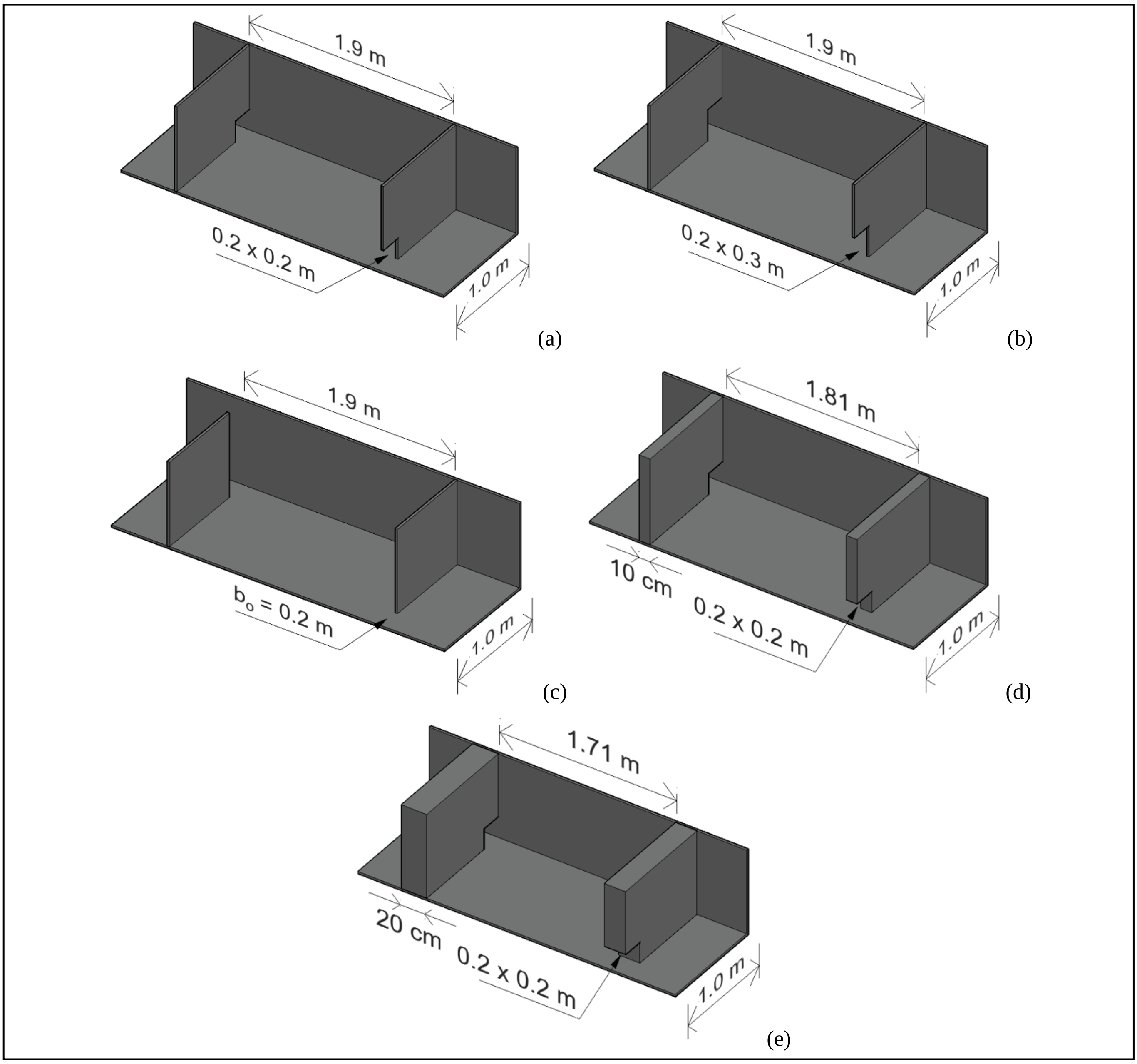

Fig. 1. *Designs of fishway pools: (a) Design 1 - reference; (b) Design 2; (c) Design 3; (d) Design 4 and (e) Design 5.*

The reference design presents limitations to the fish use related to: size of the fish and swimming close to the bottom. The notches must be at least 0.20 m for small fish and to prevent them from being blocked by trash [2]. Increasing the area of passage and type of this opening between consecutive pools may benefit larger fish and also to fishes that swim far from the bottom. Modifications were made in the initial geometry, keeping constant the bottom slope, the width of the pools and the position of the openings between pools. The area of passage between consecutive pools were increased: the orifice size was modified to 0.2 m x 0.3 m (Design 2, Figure 1b) and the orifice was transformed into a vertical slot fishway with 0.20m wide (Design 3, Figure 1c). Two other geometries were tested by changing the deflector thickness between pools: 10 cm (Design 4, Figure 1d) and 20 cm (Design 5, Figure 1e). The increase in the deflector thickness is proposed considering constructive aspects.

In all the designs it was simulated a fishway with five pools, plus an inlet and an outlet region. The central pool of the fishway in each design has uniform flow.

B. Governing Equations

The Ansys-CFX [4] was used for 3D numerical simulation of the flow. The model uses the finite volume method to solve the flow equations. Turbulence was modeled using the Reynolds decomposition, Reynolds Averaged Navier-Stokes (RANS) in 3D.

The equations of continuity and momentum solved by the program are, respectively:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}(\rho V_j) = 0 \quad (1)$$

$$\frac{\partial \rho V_i}{\partial t} + \frac{\partial}{\partial x_j}(\rho V_i V_j) = -\frac{\partial p'}{\partial x_i} + \frac{\partial}{\partial x_j}\left[(\mu + \mu_t)\left(\frac{\partial V_i}{\partial x_j} + \frac{\partial V_j}{\partial x_i}\right)\right] + S_M \quad (2)$$

where ρ is the fluid density; V_i represents the velocity time series, which can be divided into an average component and a time-varying component; μ is the molecular viscosity of fluid; μ_t is the turbulent viscosity of fluid; p' is the modified pressure and S_M is the sum of the body forces. The k-ε turbulence model was used. In this model, the turbulent viscosity (μ_t) is related to the turbulence kinetic energy (k) and turbulence dissipation rate (ε) by the equation:

$$\mu_t = C_\mu . \rho . \frac{k^2}{\varepsilon} \quad (3)$$

where C_μ is a dimensionless constant and equal to 0.09. The values of k and ε are taken directly from the differential transport equations. More details can be found in [4].

The free surface between air and water was modeled using the volume of fluid (VOF) method, where each computational cell is composed of fractions of each of the two phases (water and air). The VOF method solves the set of momentum equations in the domain, while storing the volume of the two phases in each computational cell.

C. Boundary Conditions and Discretization

The non-slip boundary condition was applied to all walls (bottom, lateral walls, and deflectors). The roughness of the walls was considered null in all situations. At the inlet, the mass flow of water and atmospheric pressure to the part corresponding to the air were used. A high turbulence intensity (10%) was applied at the inlet to specify the turbulence kinetic energy and the energy dissipation rate of the flow. At the outlet of the domain, the hydrostatic pressure distribution for the water fluid and atmospheric pressure for air were considered. The top surface of air was defined as an open boundary with atmospheric pressure and zero gradient. The simulation considered the flow in an incompressible isothermal condition, maintaining constant physical properties of the water.

All simulations were performed in steady state. Numerical flow simulation was performed, for each design, with one discharge. For the design 1, the same discharge rate evaluated experimentally by [3]: 0.036 m^3/s, was used. For designs 2 to 5, the discharges were adjusted to obtain the same mean depth of the pool flow as that observed in the design 1, with a maximum variation of 4.7%.

A preliminary analysis was performed to evaluate the mesh independence in the results. Three meshes were tested for the same geometry and discharge. The number of elements in each mesh was 1.2 × 10^6 (coarse mesh), 2.7 × 10^6 (medium mesh), and 6.3 × 10^6 (fine mesh), at the beginning of the simulation (the final number of elements is greater due to mesh adaptation). To check grid independence, we used the grid convergence index – GCI [5], [6]. The refinement ratio between the fine and medium meshes was 1.33, and it was equal to 1.30 between the medium and coarse meshes. The GCI was calculated for velocities in 141 points in the central pool of the fishway. The $GCI_{medium/fine}$ was 3.6% and the $GCI_{coarse/medium}$ was 3.7%. We selected the medium mesh with at least 2.7 × 10^6 elements in the beginning of the simulation. We considered that the meshes used in the simulations have an appropriate balance between accuracy and computational cost.

D. Data Analysis

Values of velocity, mean flow depth, turbulence kinetic energy and turbulence dissipation rate were obtained during the flow simulation and are direct output variables of the process.

Some other variables were calculated in order to compare flow patterns between fishway designs, as presented below.

The discharge coefficients (C_D) is evaluated by:

$$C_D = \frac{Q}{A.\sqrt{2.g.\Delta h}} \quad (4)$$

where Q is the water discharge, A is the area of passage between pools (orifice or vertical slot), g is the gravitational acceleration and Δh is the hydraulic drop per pool.

The volumetric dissipated power (P_V) can be calculated from the following equation:

$$P_V = \frac{\gamma.Q.\Delta h}{B.L.h_m} \quad (5)$$

where γ is the specific weight of water, B and L are the pool size, width and length, respectively, and h_m is the mean depth of the flow in the pool.

The spatial distribution of the dissipated power inside the pool can be evaluated in each position i of the pool by:

$$P_{Vi} = \rho . \varepsilon \quad (6)$$

where ε is the turbulence dissipation rate for the i position inside the pool.

The maximum flow velocities can be performed through analysis of the potential theoretical velocity (7). This relationship considers Bernoulli equation, assuming that velocities within the pools are insignificant and that the difference in water depth between consecutive pools produces the maximum velocity in the region of the passage between consecutive pools [7].

$$V_{max\,theoretical} = \sqrt{2.g.\Delta h} \quad (7)$$

For comparison of simulated and experimental results, two performance measures were used: root mean square error (RMSE) and mean absolute percentage error (MAPE).

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III. Results and Discussion

A. Validation of the numerical model

Fig. 2 shows a comparison between simulated and measured velocity field. The same flow pattern is observed by simulated and measured data: there is a big recirculation inside the pool in all planes parallel to the bottom, with higher velocities in the region close to the orifice and lower values in the center of the pool. A quantitative comparison between experimentally observed and simulated velocity magnitudes indicates a root mean square error (RMSE) of 0.11 m/s. The mean absolute percentage error (MAPE) is -1.83% for the velocity magnitude and of 19.1º for the angle. Considering previous studies (e.g. [8]) these differences are acceptable to evaluate flow characteristics in a fishway. In addition, the same numerical model and assumptions were previously used for the evaluation of the flow in a vertical slot fishway presenting good results [9], [10].

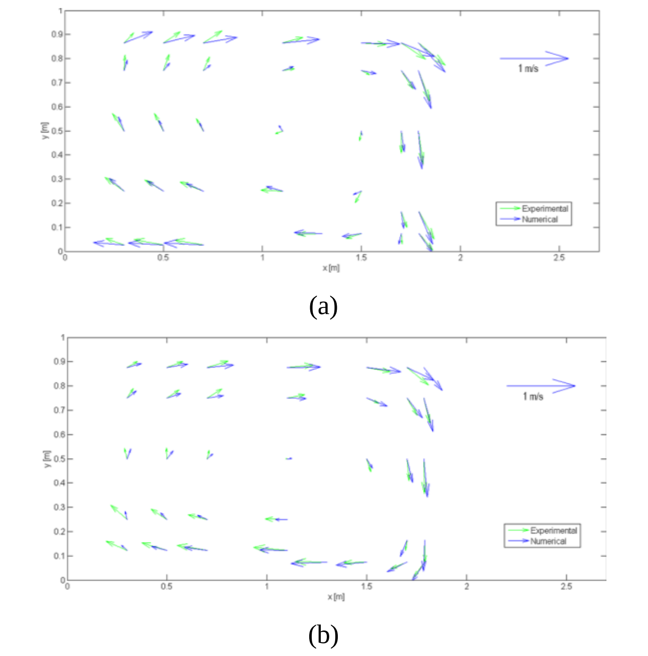

Fig. 2. *Comparison of measured (experimental) and simulated (numerical) velocities for Design 1 in planes parallel to the bottom of the fishway: (a) z/h_m=25% and (b) z/h_m =50%, for the central pool of the structure (z is the distance of the plane to the bottom and hm is the mean depth of the flow).*

B. Main hydraulic characteristics

The main hydraulic characteristics obtained in the simulations are presented in TABLE I. It show the discharges (Q), mean depths of the flow (h_m), discharge coefficients (C_D) and volumetric dissipated power (P_V). Simulation results indicated that for designs 2, 3, 4 and 5, to maintain the same mean depth of flow, with a maximum variation of 4.7%, flow rates 50%, 250%, 1% and 5% higher than the one used in the reference design (Design 1) were required, respectively. The maximum value of the discharge coefficient and volumetric dissipated power were observed in the vertical slot configuration (Design 3). The volumetric dissipated power was 173 W/m³ for Design 3 and less than 70 W/m³ for the other designs. Indeed, the value of this variable in all configurations is compatible with the limits considered adequate by fish literature [2], [11], [12], [13].

TABLE I. Main Hydraulic Characteristics Obtained for all Designs.

Design	Q (m³/s)	h_m (m)	C_D	P_V (W/m³)
1	0.0365	0.63	0.51	48.8
2	0.0540	0.66	0.50	69.8
3	0.1300	0.64	0.56	173.4
4	0.0370	0.63	0.51	53.0
5	0.0385	0.61	0.53	60.3

C_D is evaluated by (4) and P_v is calculated by (5).

C. Flow fields

Flow fields of velocity, turbulence kinetic energy and turbulence dissipation rate were used to describe and to compare the flow in all designs.

The velocities in two different planes parallel to the bottom (z/h_m = 25% and 50%) are shown in Fig. 3. It can be observed in the plane z/h_m = 25%, which passes through the orifices (designs 1, 2, 4 and 5), that maximum velocities occur close to the inlet of the pool. In the pools, the highest velocities occur at the upstream orifice line, following until downstream deflector, changing direction and still maintaining high velocities in comparison to other regions of the pool. Part of the flow goes to the downstream orifice and part feeds the flow recirculation within the pools. In the plane z/h_m = 50%, for the designs with orifices (1, 2, 4 and 5), it is observed lower velocities, as this plane does not pass through the orifice. For the Design 3, with a vertical slot instead of an orifice, a main jet is observed in all planes parallel to the bottom.

The flow fields of turbulence kinetic energy (k) and turbulence dissipation rate (ε) present a similar pattern to the velocities field concerning distribution of higher and lower values in the pool. In the TABLE II, the mean and maximum values of velocity, turbulence kinetic energy and dissipated power in the pool are presented for four planes parallel to the bottom for all designs.

The increase in the size of the orifice in 50% (Design 2) resulted in velocities (mean and maximum) up to 20% higher in comparison with the Design 1. The increase in the deflector thickness caused mean velocities up to 17% and 28% higher, for designs 4 and 5, respectively, in comparison to the Design 1. However, the maximum values of velocity were lower for the thicker deflector designs. The vertical slot fishway (Design 3) presents uniform values of velocity, turbulence kinetic energy and dissipated power along the depth, with variations depending on the position in a plan view.

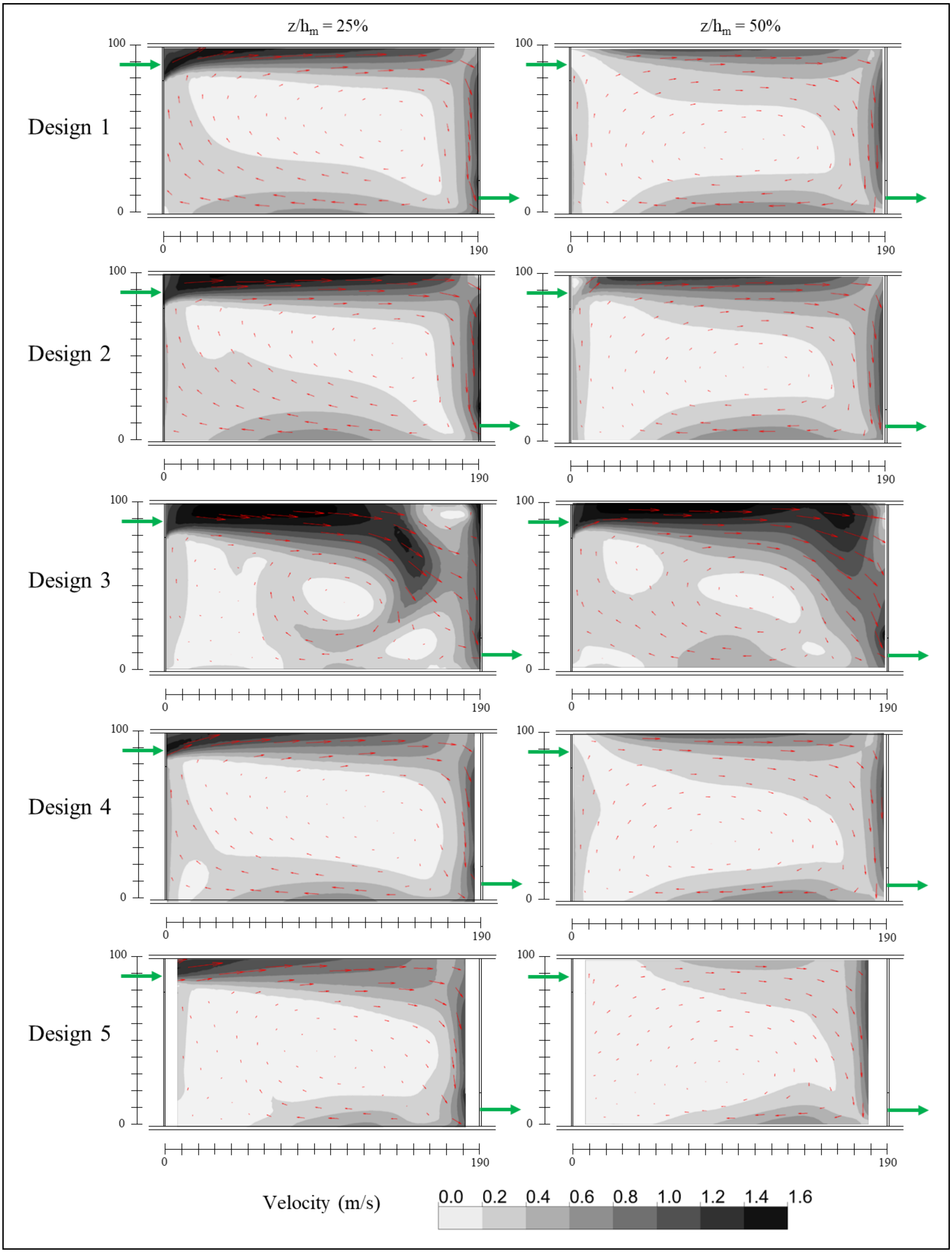

Fig. 3. *Velocity fields in planes parallel to the bottom at a distance from it of z/h_m = 25% and 50%, for the designs 1 to 5.*

TABLE II. MEAN AND MAXIMUM VALUES OF VELOCITIES (V), TURBULENCE KINETIC ENERGY (K) AND DISSIPATED POWER IN THE POOL (PV) IN EACH PLANE PARALLEL TO THE BOTTOM.

Design	z/h_m	V (m/s)		k (m^2/s^2)		P_V (W/m^3) *	
		Mean value	*Maximum value*	*Mean value*	*Maximum value*	*Mean value*	*Maximum value*
1	1%	0.48	1.60	0.01	0.04	71.00	792.00
	10%	0.47	1.59	0.02	0.14	55.00	2316.00
	25%	0.45	1.51	0.03	0.17	71.00	1904.00
	50%	0.37	1.13	0.02	0.04	30.00	522.00
	80%	0.30	0.97	0.01	0.04	23.00	1596.00
2	1%	0.49	1.64	0.01	0.04	79.00	1053.00
	10%	0.50	1.67	0.03	0.16	60.00	1565.00
	25%	0.50	1.61	0.04	0.23	91.00	3277.00
	50%	0.46	1.36	0.03	0.10	64.00	1125.00
	80%	0.35	1.07	0.02	0.04	26.00	424.00
3	1%	0.62	1.65	0.02	0.10	230.00	2255.00
	10%	0.55	1.70	0.05	0.26	137.00	2390.00
	25%	0.60	1.69	0.05	0.28	147.00	2652.00
	50%	0.65	1.76	0.06	0.25	162.00	2700.00
	80%	0.64	1.92	0.07	0.28	215.00	4669.00
4	1%	0.56	1.55	0.01	0.05	87.00	836.00
	10%	0.51	1.53	0.02	0.13	66.00	1999.00
	25%	0.44	1.47	0.03	0.15	80.00	1533.00
	50%	0.35	1.09	0.02	0.04	23.00	332.00
	80%	0.27	0.98	0.01	0.04	20.00	279.00
5	1%	0.61	1.57	0.01	0.04	112.00	1025.00
	10%	0.52	1.55	0.02	0.15	78.00	2245.00
	25%	0.45	1.49	0.03	0.16	108.00	1802.00
	50%	0.26	1.11	0.01	0.05	19.00	353.00
	80%	0.23	1.05	0.02	0.04	33.00	1159.00

* *P_V is evaluated by (6) in each cell. The values of this table represent the mean and maximum values in each plane.*

For the designs with submerged orifices, the mean and maximum values are higher in the planes that pass through the opening between pools (z/h_m = 1%; 10% and 25%), for all evaluated variables: velocity, turbulence kinetic energy and dissipated power in the pool.

Mean values of turbulence kinetic energy (k) are between 0.02 and 0.04 m²/s² for designs 1, 2, 4 and 5 and 0.05 for the Design 3. For Design 1 the maximum value of k is 0.17 m²/s². For designs 2 and 3, where the aperture between pools is bigger, the maximum values are 35% and 65% greater than the one verified in the Design 1, respectively. The increase in the deflector thickness reduced up to 10% the maximum values of k. Previous studies verified that there are values of turbulence kinetic energy associated with the preference of the fish, e.g., k <0.05 m²/s² for Iberial barbel [14], k between 0.02 and 0.035 for silver carp [15].

In the Fig. 4, the mean and maximum velocities in each plane were normalized by the maximum theoretical velocity (7). Regarding the mean flow velocities, for the submerged orifice designs (designs 1, 2, 4 and 5), the values were always below 30% of the maximum theoretical velocity, calculated by (7), ($V_{\max\text{theoretical}} = \sqrt{2.g.\Delta h} = 1.80\ \mathrm{m/s}$). For Design 3, with vertical slot, the mean velocity in the pool was up to 36% of $V_{\max\text{theoretical}}$. Considering maximum velocities obtained in the simulations we found values of 89%, 93%, 107%, 86% and 87% of the theorical maximum values, for designs 1 to 5, respectively. In all situations the velocities are lower than 2 m/s, that is considered a limit for neotropical fish.

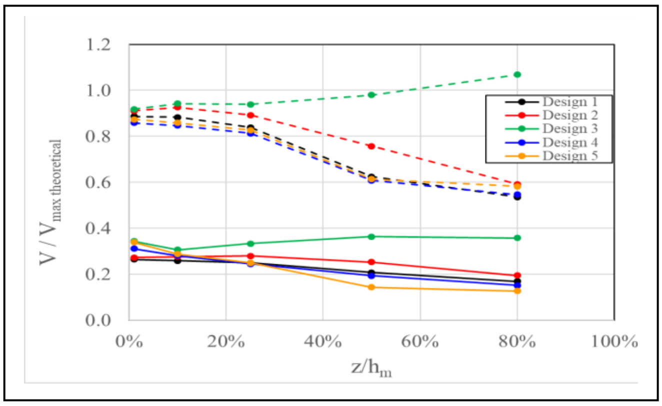

Fig. 4. *Mean (full lines) and maximum (dashed lines) velocities in each plane normalized by $V_{max\ theoretical}$ (7).*

The volumetric dissipated power (P_V) obtained by (5) represent a mean value in the pool. In the TABLE II, it is presented results of P_V for each plane parallel to the bottom, using values obtained by (6) for each element of the domain. The mean values of dissipated power in each plane, as it was observed to velocity and turbulence kinetic energy, are higher in the planes passing through the opening between pools (z/h_m = 1%; 10% and 25%), as shown in Fig. 5. Higher mean values of dissipated power are in the plane close to the bottom for designs 1, 3, 4 and 5. Besides the mean values in each plan and in the pool are within the limits considered acceptable in the literature, it was observed that the maximum values in the pool can reach higher values. Probably it is not a barrier to fish movement, considering that these maximum values occur in a small region of the pool.

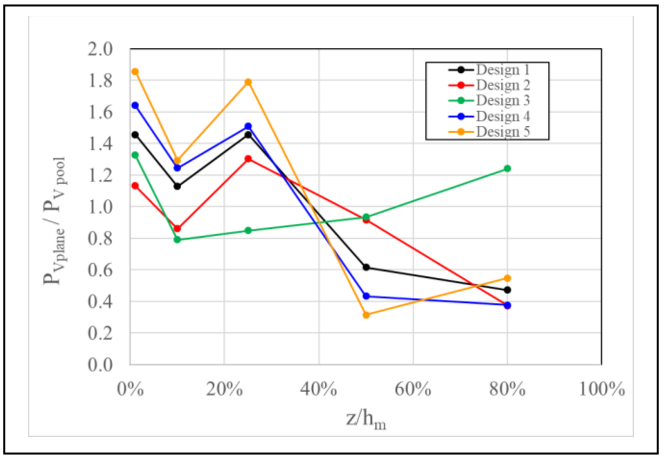

Fig. 5. *Mean dissipated power in each plane (6) in relation to the dissipated power in the pool (5).*

IV. CONCLUSIONS

Considering all aspects evaluated, the pool-type fishway with submerged orifices, installed on alternate sides in consecutive transversal deflectors, may be a good alternative: velocities, turbulence kinetic energy and volumetric dissipated power are lower than the ones verified in a vertical slot fishway. The fishways with submerged orifices are more economical considering water flow rates. To maintain the same mean flow depth, the modification in the design creating a vertical slot fishway resulted in discharges 250% higher than the discharge used in the reference design. On the other hand, the increase in the area of the orifice resulted in an increase in the discharge in the same proportion. Modifications in the deflector thickness do not showed important changes in the flow patterns.

It is necessary to verify if the passage of the fishes by a region close to the bottom of the channel is adequate when compared to the fish species behavior in the related river. As it was observed lower values of velocities, turbulence kinetic energy and volumetric dissipated power in fishways with orifices, it is important to assess if there is a clear preferential flow to orientate the fish during the migration process. The results obtained in the simulations, for the different designs must be compared with fish capabilities, in order to select a good geometry and contribute in the selection of a new design. The developed numerical model showed to be a useful tool to analyze the flow and it can be used to evaluate flow patterns in other designs of pool-type fishways, including different sizes of pools, slopes and area of passage between pools. Future studies should evaluate the pool-type fishway with submerged orifices and superficial weirs.

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REFERENCES

[1] M. Bombač, M. Četina, and G. Novak, "Study on flow characteristics in vertical slot fishways regarding slot layout optimization," Ecol. Eng., 107(2), pp. 126–136, 2017.

[2] M. Larinier, "Pool Fishways, Pre-Barrages and Natural Bypass Channels," in Bulletin Français de la Pêche et de la Pisciculture, 2002, pp. 54–82.

[3] D. G. Sanagiotto, A. Pinheiro, and M. G. Marques, "Caracterização de Velocidades Médias e Padrões de Turbulência do Escoamento em Escadas para Peixes por Bacias Sucessivas com Orifícios de Fundo," vol. 17, no. 2009, pp. 181–192, 2012.

[4] C. F. X. Ansys "C.F.X. Ansys, Solver theory guide." Release 15(November), 209. 2013.

[5] I. Celik, U. Ghia, P. Roache, C. Freitas, H. Coleman, and P. Raad, "Procedure for Estimation and Reporting of Uncertainty Due to Discretization in CFD Applications," J. Fluids Eng., vol. 130, no. 7, p. 078001, 2008.

[6] P. J. Roache, "Perspective: A Method for Uniform Reporting of Grid Refinement Studies," J. Fluids Eng., vol. 116, no. 3, p. 405, 1994.

[7] B. A. Marriner, A. B. M. Baki, D. Z. Zhu, J. D. Thiem, S. J. Cooke, and C. Katopodis, "Field and numerical assessment of turning pool hydraulics in a vertical slot fishway," Ecol. Eng., vol. 63, pp. 88–101, 2014.

[8] T. D. Tran, J. Chorda, P. Laurens, and L. Cassan, "Modelling nature-like fishway flow around unsubmerged obstacles using a 2D shallow water model," Environ. Fluid Mech., vol. 16, no. 2, pp. 413–428, 2016.

[9] D. G. Sanagiotto, J. B. Rossi, and J. M. Bravo, "Applications of computational fluid dynamics in the design and rehabilitation of nonstandard vertical slot fishways," Water (Switzerland), vol. 11, no. 2, 2019.

[10] D. G. Sanagiotto, J. B. Rossi, L. L. Lauffer, and J. M. Bravo, "Three-dimensional numerical simulation of flow in vertical slot fishways : validation of the model and characterization of the flow," 2019.

[11] M. Bell, Fisheries handbook of engineering requirements and biological criteria, Third. Portland, Oregon: Corps of Engineers, North Pacific Division, 1990.

[12] FAO/DVWK, Fish Passes Design, dimensions and monitoring. 2002.

[13] R. W. Wang, L. David, and M. Larinier, "Contribution of experimental fluid mechanics to the design of vertical slot fish passes," Knowl. Manag. Aquat. Ecosyst., no. 396, pp. 1–21, 2010.

[14] A. Silva, J. Santos, M. T. Ferreira, A. Pinheiro, and C. Katopodis, "Effects of water velocity and turbulence on the behaviour of Iberian Barbel (Luciobargus bocagel, Steindachner 1864) in an experimental pool-type fishway," River Res. Appl., vol. 27, pp. 360–373, 2011.

[15] J. Tan, L. Tao, Z. Gao, H. Dai, Z. Yang, and X. Shi, "Modeling fish movement trajectories in relation to hydraulic response relationships in an experimental fishway," Water (Switzerland), vol. 10, no. 11, 2018.