DESIGN OPTIMIZATION OF EXISTING VERTICAL SLOT FISHWAYS BY CYLINDER ADJUNCTION

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Abstract

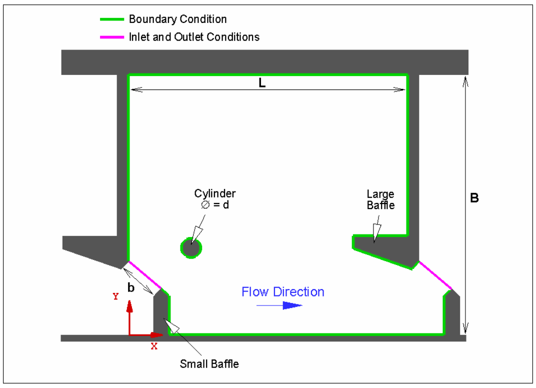
Vertical slot fishways are commonly used and are effective in ensuring unhindered passage of the species of large size fishes. Nerveless the species with small sizes have some difficulties to upstream migrate because the kinematic energy and the velocity are too large for them. One of strategies to answer at this ecohydraulic problem is to determine how the design of existing fishways might be affected by obstacles addition within the pool. This article presents a method to find the optimal cylinder location from numerical simulations of the flow in vertical slot fishway. The modification effect on the main hydraulics parameters of the flow is substantial and allows having a positive impact on biological efficiency of the device.

Introduction

The characteristics of the flow in vertical slot fishways depend mainly to the specific pool design, i.e., the geometry of the pool. The requirements of the fish species for which the fishways is intended, will dictate its appropriate design. However, for the existing vertical slot fishways, it could be unachievable to optimize the geometry for local opposition, financial or technical reason. Consequently, one of strategies is to determine how the design of existing fishways might be affected by minor modification, like artificial roughness or obstacles addition within the pool. The objective of those adaptations is to manage the flow and modify the turbulence activity in order to facilitate the passage of small species and juveniles (length between 10 and 25 cm). This paper presents the numerical simulation of the flow in vertical slot fishways modified by cylinder. The flow field is studied using a numerical Reynolds Average Navier-Stokes model which solves conservation of mass, of momentum, of fluid energy equations with finite volumes discretization and implicit methods, coupled with k-ε Low Reynolds model. To find the best location of cylinder, optimization procedure is performed as regard of turbulence features of the flow. A multivariate conjugate gradient method is used to find the coordinates X_i, Y_i of the center of a cylinder with geometric constraints. Several target turbulence parameters are used as objective functions: the maximum velocity in pool, turbulence kinetic energy, vorticity and global dissipation of the total kinetic energy rate and multi-objective functions combining all of those quantities. Based on both the CFD results and the optimization procedure, it appears that the ideal cylinder position affects the flow in the fishways. The main hydraulics parameters of the flow as turbulence intensity, vorticity and velocity amplitude are significantly modified by one cylinder introduced inside the vertical slot fishways. The modification effect seems to increase the impact on biological efficiency of the device by reducing and modifying these quantities. The optimization algorithm has been validated and allows us to determine the ideal position of obstacle placed within vertical slot fishways pool. The present method is the first stage to define practical indicators for optimizing the biological efficiency of existing vertical slot fishways by cylinder adjunction.

Numerical procedure

The dimensions of the vertical slot fishways model are shown Figure 1. This fishway is defined by a slot with a dimension of b=0.3m. For this study, the width B has limited to 2.7m and a length of L=3m. The slope and the discharge are fixed to 10% and 826 l/s, respectively. The Reynolds number, based on the slot width b and the flow velocity in the slot V_d=2.12 m/s, is fixed to 636000. The circular cylinder, with a diameter d equal to half of the slot width, will be placed at its optimal position. In order to decrease the number of simulated pools and the size of the geometry to be modeled, periodic conditions of the flow are imposed in entry and exit of the pool (Figure 2). The pool is defined by non dimensioned parameters based over the slot's width.



(a)


(b)

Figure 1: Example of vertical slot fishways (Vichy-France) (a) and pool configuration (b)

The software Star-CD is used to make calculations in two dimensions (2D) of the turbulent flow. The turbulence's model used is k-ε Low Reynolds model, which allows us to acquire a good accuracy close to the boundaries but requires complex mesh and high time of calculation (Goldberg & Apsley, 2009). The calculated grid is designed with two parts: closed to the boundaries with refined structured mesh and, inside the pool with a tetrahedric grid (Figure 2). The differential equations governing the conservation of mass, of momentum, of fluid energy are discretized by the finite volume method and implicit methods are applied to solve them. RANS model ("Reynolds Average Navier-Stokes") is employed, i.e. only the equations of the average movement were solved.

Figure 3 shows the results of calculation in two dimensions of the turbulent flow in the fishway (mean flow velocity). This result will be compared to that obtained for the configuration with cylinder (Tarrade & al. 2005).

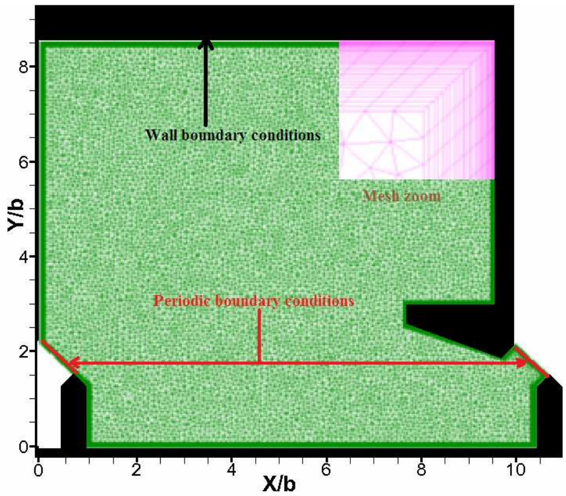


Figure 2: Mesh and boundary conditions used in numerical calculations

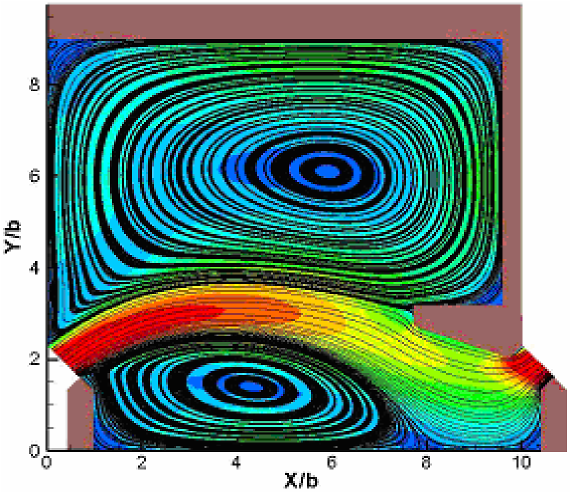


Figure 3: Isocontour of the mean flow velocity norm and streamlines in configuration without cylinder

Optimization strategy

Determining a parametric model in order to locating ideally cylinder within fishway pools requires the implantation and application of an optimization technique.

An optimization problem can be formulated as follows: find the combination of parameters that optimize a given quantity which can be subject to some limitations. The quantity to optimize is called objective function, the parameters used to search the optimum are called optimization variables and the restrictions on the parameter values are known limitations, (Tse & Chan, 1999).

In this optimization study applied to the control of the flow in the fishways, the objective function is defined by the physical quantities characterizing the flow ; it is a stationary, discrete and spatial mean function. The purpose of this study is to determine the coordinates of the positions X_i and Y_i (the optimization variables) of the obstacle placed in the fishway to improve upstream migration of small species.

These local mean variables are extracted using numerical simulations for a fishway configuration defined by B / b = 9 and cylinder diameter of D_c=b/2.

Of all the extracted dimensionless quantities, we have positioned our work on the hydraulic variables that influence significantly the characteristics of the fish swims, (Peña & al, 2004): spatial mean velocity $\|V_{2D}\|^*$, spatial mean turbulent intensities $\|tke_{2D}\|^*$, spatial mean turbulent dissipation ε^* or spatial mean vorticity ω^*, (Tarrade & al. 2008).

$$\left\|V_{(2D)}\right\|^* = \frac{1}{n}\sum_{\vec{x}} \frac{\sqrt{\overline{u_1^2(\vec{x})} + \overline{u_2^2(\vec{x})}}}{V_d} \qquad (1)$$

$$\left\|tke_{(2D)}\right\|^* = \frac{1}{n}\sum_{\vec{x}} \frac{\overline{u'^2_1(\vec{x})} + \overline{u'^2_2(\vec{x})}}{2*V_d^2} \qquad (2)$$

$$\varepsilon^* = \frac{1}{n}\sum_{\vec{x}} \frac{b}{V_d^3} * \overline{\varepsilon(\vec{x})} \qquad (3)$$

$$\omega^* = \frac{1}{n}\sum_{\vec{x}} \frac{b}{V_d} * \overline{\omega(\vec{x})} \qquad (4)$$

where n is the mesh point number.

In order to introduce obstacle in the fishway, geometric constraints must be necessary taken into account to avoid obstacle position unless a slot width from the walls of the fishway. These domain constraints are designed to avoid congestion of the fishway by branches and maintain the proper functioning of the device (Figure 4).

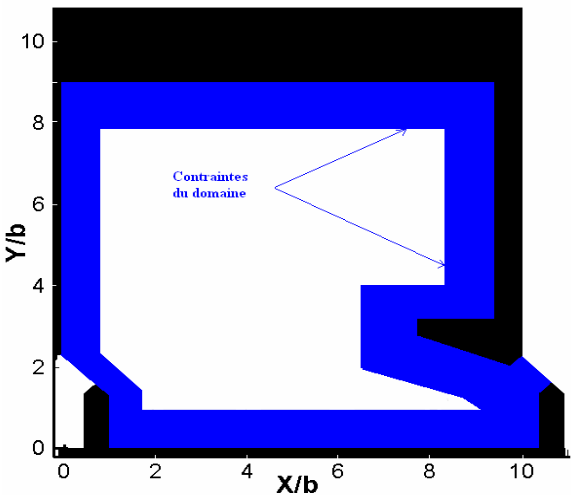


Figure 4: Domain constraints

To obtain the obstacle positions, it was necessary to develop an optimization algorithm. Conventionally, the iterative procedure of optimization algorithms without constraint is given in Figure 5, (Khalil, 2009) and (Luersen, 2004). We choose an initial point, we define the search direction (up for finding a maximum or down to search for a minimum), and then an appropriate step displacement is calculated by proper technique. The process is repeated with the new point found until a local optimum is obtained.

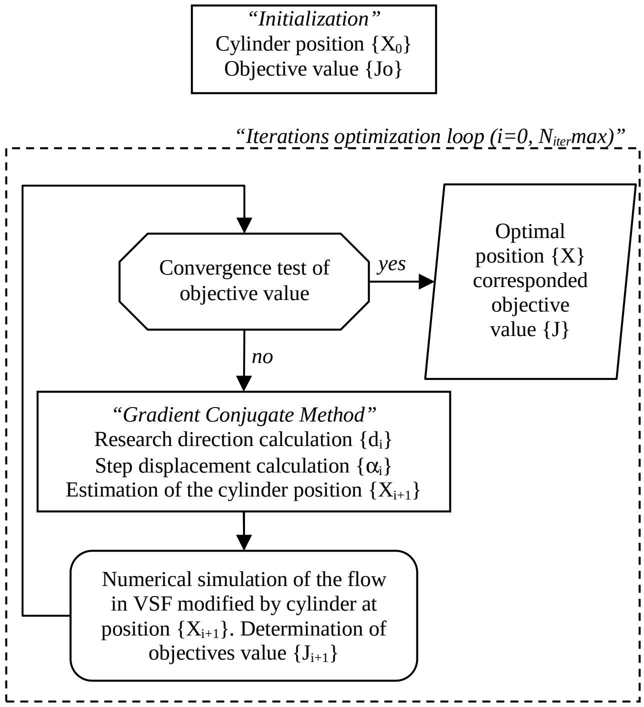


Figure 5: General algorithm for local optimization

The convergence test of the method is based on two stopping criteria. The first is a convergence criterion of the objective function between two successive iterations. The second test is a convergence criterion of the optimization variables between two successive iterations. Otherwise, the optimization algorithm will be converged when, on the one hand, there is no influence of the change in position of the obstacle on flow values (first criterion) and that; on the other hand, the position of the obstacle remains unchanged (second criterion).

This research procedure of optimal position of obstacles in fishway allows determining the set $\{E_{ideal}\}$ of kinematical quantities $\{\|V_{2D}\|^*_{ideal}, \|tke_{2D}\|^*_{ideal}, \varepsilon^*_{ideal}, \omega^*_{ideal}\}$. However, as this set is obtained separately according to the objective function chosen, four solutions of obstacle positions respectively are obtained giving four physical quantities sets $\{E^{\|V_{2D}\|^*}\}$, $\{E^{\|tke_{2D}\|^*}\}$, $\{E^{\varepsilon^*}\}$ and $\{E^{\omega^*}\}$. To retain a unique position, the four sets of physical quantities $\{E^{\|V_{2D}\|^*}\}$, $\{E^{\|tke_{2D}\|^*}\}$, $\{E^{\varepsilon^*}\}$ and $\{E^{\omega^*}\}$ are compared with the set $\{E_{ideal}\}$.

$\{E_{ideal}\}$ is one of the four sets for which the optimization of all kinematic quantities is better.

The unique solution chosen corresponds to the optimization solution according to $\|V_{2D}\|^*$, $\|tke_{2D}\|^*$, ε^* or ω^* whose all physical quantities are nearest to the ideal set $\{E_{ideal}\}$.

RESULTS

In order to implement the conjugate gradient method, a set of numerical calculations for 16 configurations of cylinder positions in the pool of fishway was performed to optimize the cylinder position. The cylinder positions were uniformly distributed without the prior results in the field of optimization while respecting the geometric constraints imposed.

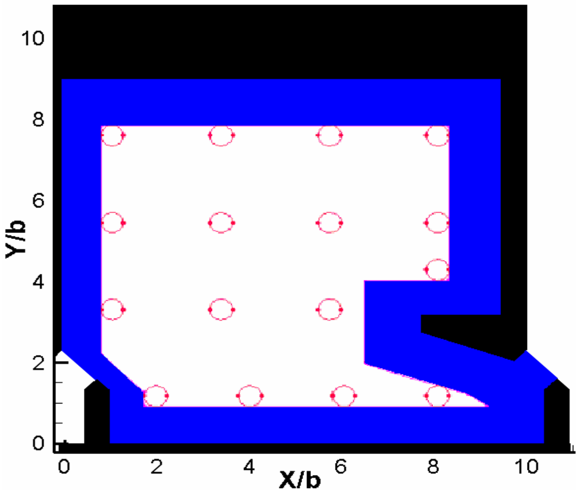


Figure 6: Cylinders positions used as initial dataset to determine the cylinder optimal position in a fishway.

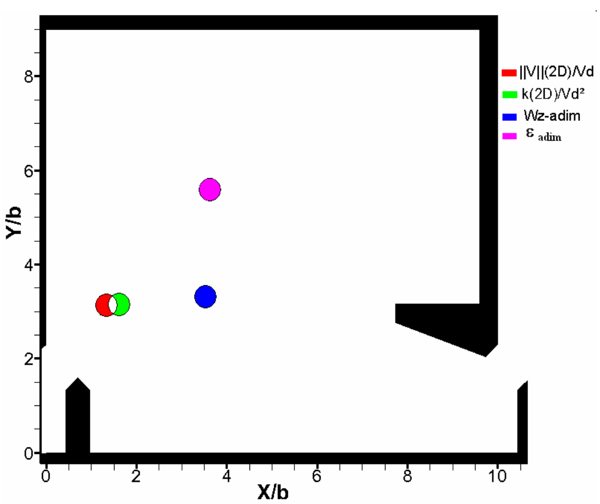


Figure 7: Optimal cylinder positions using optimization for the four objectives functions.

Analysis of this initial database was used to determine the initial solutions required for the implementation of the optimization algorithm. These solutions correspond to the initial position of the cylinder $(\frac{x_0}{b}, \frac{y_0}{b})$ for which the objective function is optimized in this database ensemble.

Optimization calculation shows that two kinematic quantities optimized from four give the same cylinder position; we talk about spatial mean velocity $\|V_{2D}\|^*$, and spatial mean turbulent intensities $\|tke_{2D}\|^*$.

Optimization calculation based on spatial mean dissipation ε^* and spatial mean vorticity ω^* give positions which are very far from the first one (Figure 7).

By moving cylinder of their initial position to their optimized position, the gain on the objective function can reach to 66.7%.

The distribution of kinematic quantities isocontours between the initial and the optimized position for each objective function selected shows that the optimization algorithm tends to place the cylinder in the jet axis.

The set $\{E_{ideal}\}$ of kinematic quantities also obtained is : $\{\|V_{2D}\|^*_{ideal}, \|tke_{2D}\|^*_{ideal}, \varepsilon^*_{ideal}, \omega^*_{ideal}\} = \{2.53\ 10^{-1}, 2.21\ 10^{-2}, 6.68\ 10^{-3}, 1.50\ 10^{-4}\}$

$\{E^{\|V_{2D}\|^*}\}$ is the set where the kinematic quantities values are the closest values of the ideal set $\{E_{ideal}\}$. The unique position chosen is the solution for which the spatial mean velocity is minimized. The kinematic quantities isocontours corresponding to the solution selected are shown in Figure 8.

In these figures, we can note the influence of the cylinder compared to configurations without cylinder (Figure 3 and Figure 8-a).

The gain of the cylinder adjunction in its optimized position is obtained by comparing the set $\{E_{\|V_{2D}\|^*}\}$ corresponding to our unique solution to the set $\{E_{WCyl}\}$ corresponding to the physical configuration without cylinder, Table 1.

The Gain is defined by :

$$Gain = \frac{(Q_{1C} - Q_{WC})}{Q_{WC}} * 100 \quad (5)$$

where Q_{1C} and Q_{WC} are, respectively kinematic quantities for configuration with one cylinder and without cylinder.

The gain is the percentage of the kinematic quantity increase or decrease by placing cylinder.

	$\|V_{2D}\|^*$	$\|tke_{2D}\|^*$	ε^*	ω^*	L_m^*
$\{E_{WC}\}$	3.18 $*10^{-1}$	3.47 $*10^{-2}$	6.7 $*10^{-3}$	5.6 $*10^{-4}$	9.65 $*10^{-1}$
$\{E^{\|V_{2D}\|}_{1C}\}$	2.53 $*10^{-1}$	2.22 $*10^{-2}$	5.7 $*10^{-3}$	7.9 $*10^{-4}$	5.80 $*10^{-1}$
Gain %	-20.4	-36.0	14.9	41.1	39.9

Table 1 : Gains related to the optimal cylinder position.

The adjunction of cylinder shows a significant gain on each kinematic quantity. We obtain a significant reduction of spatial mean turbulent intensities greater than 35% and 20% for the flow mean velocity. These two criteria seem crucial in terms of fish swimming capacities influenced by the general agitation of flow.

An increase in the eddy activity is also noted by a gain more than 40% of the total vorticity. However this augmentation is due to the cylinder presence, but it has no influence on the vorticity distribution (Figure 8). Cylinder adjunction influences on turbulent kinetic energy dissipation, however, the physical analysis of this quantity and its impact on fish upstream migration are very difficult to explain because turbulent kinetic energy dissipation is a function of agitation resulted in the turbulent intensity.

This relationship between $\|tke_{2D}\|^*$ and ε^* can be highlighted by determining the turbulent mixing length; L_m^* defined by :

$$L_m^* = \frac{\left(\|tke_{2D}\|^*\right)^{\frac{3}{2}}}{\varepsilon^*} \quad (6)$$

This physical quantity deduced characterized the vortices size due to the turbulent activity creating a physical barrier to the evolution of fish through the fishways.

The presence of a cylinder positioned optimally shows a significant gain reducing 39 % the turbulent eddy activity.

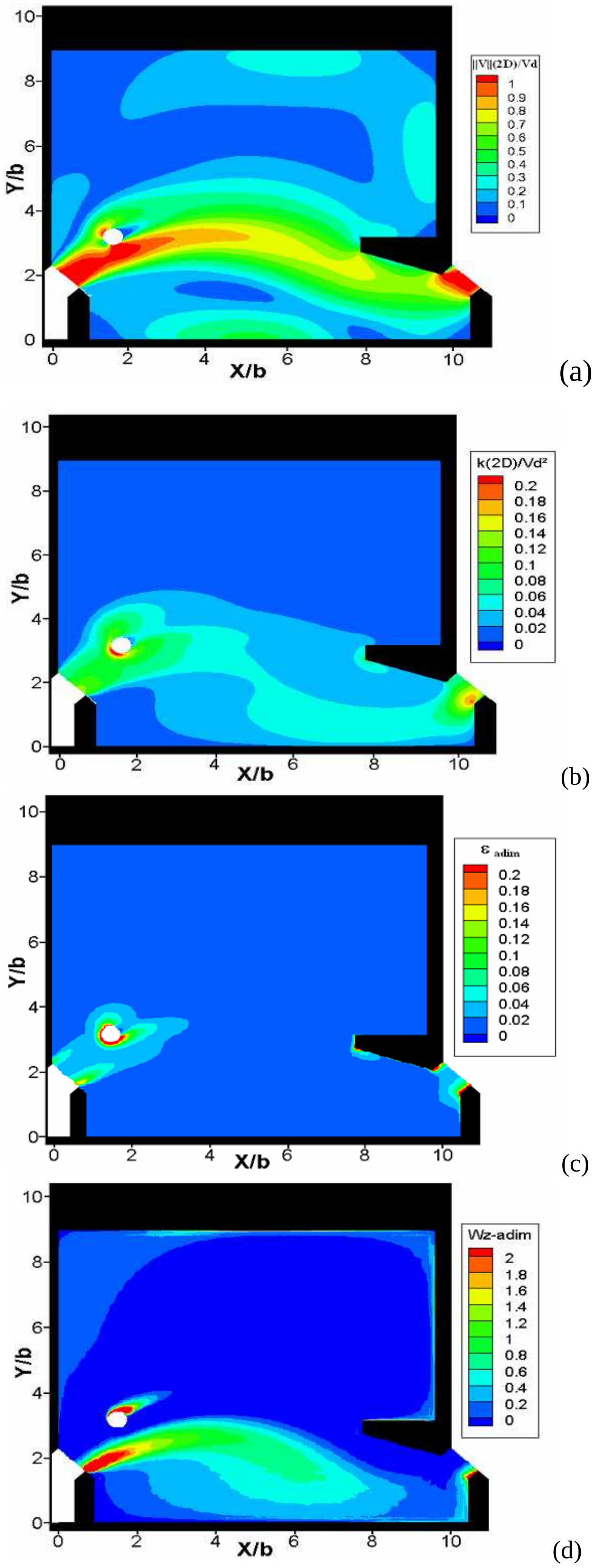


Figure 8: Optimization results for cylinder optimal position ($\|V_{2D}\|^*$ (a), $\|tke_{2D}\|^*$ (b), ε^* (c) and ω^* (d)) for configuration with B/b=9.

Conclusion

The optimization procedure was realized from numerical simulations and was based on flow kinematic quantities inside fishway pool.

The numerical model used is a k-ε model / Low Reynolds which gives a good accuracy in the near wall requiring complex mesh. A mixed mesh (hexahedral in the near wall and tetrahedral elsewhere) is generated to allow a local refinement in order to maintain a reasonable number of cells while ensure high accuracy of calculation and the adjunction of complex geometries, like cylinder.

The optimization results show that the cylinder adjunction modifies the jet pattern that separates into two streams at the approach from cylinder without affecting the two main swirling zones. The cylinder insertion decreases the kinematical quantities ; it reduces the spatial mean turbulent intensities of 36% and 20% for the mean flow velocity. The turbulent mixing length and the dissipation rate increase by inserting cylinder of 40% and 15% respectively. By placing cylinder in its ideal position, the fluid flow is modified to be adapted for small species with weak swimming abilities.

Subsequently, an experimental study (PIV) will be realized in the vertical slot fishway modified by cylinder placed at its ideal position found numerically. Finally, a study with fish will also be carried out in this fishway configuration.

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