Characterization of turbulence in pool-type fishways with submerged orifices

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1 Introduction

As in many other countries, the construction of dams in Portugal has greatly altered rivers. Fish movement blockage by dams and weirs has resulted in drastic range reductions of all migratory species in Iberian rivers **(Santos *et al*, 2002)**. In order to reduce their negative impact, in many dams and weirs fishways are installed to allow the upstream migration of fish.

The fishway that has been most commonly used is the pool-type fishway. This basically consists of a series of pools in steps leading from the river at the bottom of the obstruction to the river above. The walls separating the pools can be equipped with notches, vertical slots or submerged orifices which control the water level in the pool and the discharge in the fish pass. The pools have double function: they ensure a proper dissipation of the energy of water flowing through the fish pass, and provide resting areas for the fish **(Larinier, 2002[a])**.

In order to make a fishway effective it must be designed according to the species that will use the fish passage. Therefore, to build an effective fishway, it is necessary to take into account the type of fish species which the fishway will be made for, since there are significant differences between morphological and physiological characteristics among the species, and some characteristics of the fishways can be adequate for some species while inappropriate for others **(Pinheiro *et al*, 2004)**.

The most common fish species in Portuguese rivers are cyprinid species, in particular, the barbell (*Barbus sp.*) and the nase (*Chondostroma sp.*). Nevertheless, studies on their behaviour regarding the obstacles and transposition devices are scarce **(Pinheiro *et al*, 2004)**.

Therefore, Portuguese fishways are designed according to the criteria based on the swimming abilities of salmonid species, which are very different from the cyprinid species swimming abilities. This may explain, in part, the inefficiency observed in Portuguese fishways, and the need to develop design criteria aiming cyprinid species.

The present work continues the research carried out by **Sanagiotto (2007)** and by **Silva (-)**, who studied the characteristics of the flow in passages for fish through successive pools intending to establish a dimensioning criteria for this type of devices adapted to the preferences of the more frequent fishes in Portuguese water courses.

The ratio between flow power and the volume of water in the pool (P_V) is commonly used to characterize the flow turbulence on a pool (**Larinier, 2002[b])**. The increase of this parameter means more difficulty for the fishes to swim or jump from pool to pool. Although **Larinier (2002[b])** recommends a maximum volumetric dissipated power of 200 and 150 W/m^3 for salmonids and cyprinids, respectively, **Sanagiotto (2007)** refers that, for volumetric dissipated power of 100 W/m^3, barbells and nases may present difficulties in progressing along the fishway.

Silva (-) verified that, equipping the cross-walls that divide the several pools of the channel only with aligned bottom orifices, the flow does not present identical characteristics in all of the pools. That occurs because great part of the kinetic height of the jet that leaves the upstream orifice does not dissipate in the pool, thus not occurring the intended dissipation of energy in each pool.

Since the arrangement of the bottom orifices in a straight line can promote the migration of the fish upstream, facilitating their continuous progression **(Kim, 2001)**, it was intended to mitigate the problem observed by **Silva (-)** disposing a baffle bar of small width on the longitudinal wall of the channel, so that the jet that leaves the upstream orifice is deflected. Therefore, in each pool, an energy loss that equals the channel bottom descent occurs, guaranteeing the occurrence of a regime of similar flow in all of the pools.

In the present study, the flows presenting identical characteristics in all of the pools, except the upstream and downstream ones, it is designated as uniform.

The objective of this paper is the characterization of turbulence in pool-type fishways with submerged orifices aligned, through an experimental study. For this study, within each pool, a baffle bar was installed on the side wall adjacent to the orifices. It is also intended to determine which geometries and locations of this bar induce flow patterns with similar characteristics in all intermediate pools.

2 Fishway facility and experimental procedure

The pool-type fishway model is installed in the Water Resources and Hydraulic Structures Division (NRE) of the National Laboratory of Civil Engineering (LNEC), in Lisbon.

The fishway flume is 10 m long, 1,00 m wide and 1,20 m high and is equipped with a tilting system to enable slopes between 0 and 17,5% (Figure 1), though all the tests were performed with a 8,7% slope. The flume walls are made with fibreglass. Upstream, a tank, with an area of 4 m^2, is used to smooth the flow entering the flume. Downstream, a wider tank, with an area of 12 m^2, can be used as the departure pool for the fish, if biological tests are performed.

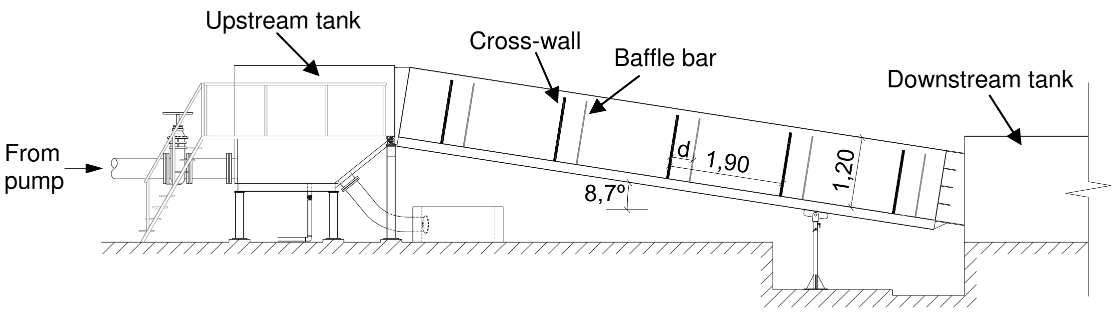


Figure 1 – Fishway facility. Longitudinal section.

The pools are created by cross-walls equipped with quadrangular orifices in a straight configuration. The experiments were conducted with five cross-walls, spaced at 1,90 m intervals, which causes a 16,5 cm drop between consecutive pools. Within each pool, a baffle bar was installed on the side wall adjacent to the orifices (Figure 2).

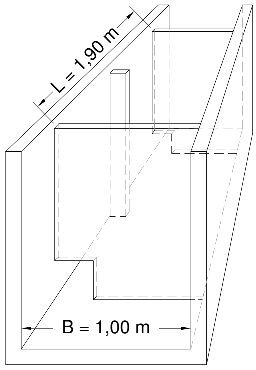


Figure 2 – Fishway facility. Sketch of one pool.

Twelve designs were analysed, differing from each other in the width of the bottom orifice and in the baffle bar. The main characteristics of the designs are presented in Table 1.

Table 1 – Tested designs. Main characteristics.

Design	**b_o (cm)**	**d (m)**	**e_b (mm)**	**Q (l/s)**	**h_m (m)**	**$\mathcal{V}$ (m^3)**	**P_V (W/m^3)**
1	18	0,38	45	36,8	0,883	1,68	35,4
2	18	0,38	90				
3	18	0,76	45				
4	18	0,76	90				
5	18	1,14	45				
6	18	1,14	90				
7	23	0,38	58	60,0	0,845	1,61	60,3
8	23	0,38	115				
9	23	0,76	58				
10	23	0,76	115				
11	23	1,14	58				
12	23	1,14	115				

b_o - width of the orifice; d - distance between the upstream orifice and the baffle bar; e_b - width of the baffle bar; h_m - mean flow depth at the pool; Q - flow discharge; $\mathcal{V}$ - volume of water in the pool; P_V - volumetric dissipated power.

For each design, the flow height on the upstream and downstream sections of each pool was measured. Velocity measurements were performed with an Acoustic Doppler Velocimeter (ADV), from NORTEK AS, in the pool comprised within the third and the fourth cross-wall, which is representative of the flow in all the pools, except for the first and the last one, affected by downstream and upstream boundary conditions.

A 3D mesh of measuring points was defined, considering three planes parallel to the flume bottom located at 25, 50 and 80% of the pool mean depth above of the bottom. 48 velocity measurements were performed in each of these depth planes, which implied 144 measurements for each design. The mesh was not uniformly distributed, being denser in the areas where larger velocities and fluctuations were expected. The discharges were measured with a magnetic flow meter.

3 Analysis of experimental results

3.1 Water depth

As it was already referred, measurements of the flow height were made in the upstream and downstream sections of each pool. In order to accomplish the measurements of the flow height in an expeditious way, these were made through the channel wall that is on the opposite side of the bottom orifices. Thus, the heights of the flow that were measured cannot be taken as the medium height of flow in the upstream and downstream sections. Its only purpose is to evaluate in which design the flow can be assumed as uniform flow.

In a pool-type fishway, when the flow occurs in a uniform regime, the difference of the water level upstream and downstream the cross-walls should be constant and equal to the channel bottom descent in a pool. For the tested design, this descent is of 16,5 cm. Furthermore, the flow height must be identical in all of the pools.

As it was observed by **Silva (-)**, when the baffle bar is not installed, the water level difference between two adjacent pools is lower than 16,5 cm (Figure 3). That occurs because great part of the kinetic height of the jet that leaves the upstream orifice does not dissipate in the pool, not happening the intended dissipation of energy in each pool.

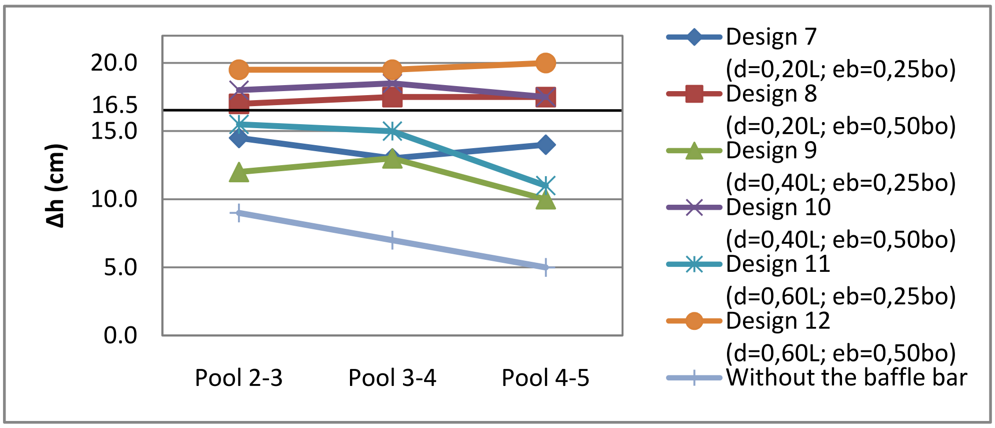


Figure 3 – Water level difference between two adjacent pools (b_o = 23 cm).

It is also verified that, for baffle bars $0,25b_o$ wide (designs 1, 3, 5, 7, 9 and 11), the water level differences are lower than the expected ones (Δh = 16,5 cm) yet higher than the ones observed when the baffle bars are not installed, independently of the width of the bottom orifice and of the distance from the baffle bar to the upstream orifice (Figure 3). Consequently, we can conclude that, with such a baffle bar width, there is some deflexion of the jet originating from the upstream orifice and that some of the kinetic height associated to this jet is dissipated in the pool. However, the width of $0,25b_o$ is insufficient to originate a uniform flow.

When baffle bars $0,50b_o$ wide and with distances of 0,60L from the baffle bar (design 6 and 12) to the upstream orifice are used, it is verified that the water level differences are higher than 16,5 cm (Figure 3). Moreover, it was also noticed that, for design 12 (b_o = 23 cm; e_b = $0,50b_o$; d = 0,60L), the mean flow depth in the pools suffers an accentuated decrease between the upstream and the downstream pool (Figure 4). In this way, we can conclude that with this design a uniform regime does not occur.

Although in design 6 (b_o = 23 cm; e_b = $0,50b_o$; d = 0,60L) this is not evident, as the baffle bar is in the same location and the same flow pattern occurs in the pool (see section 3.2), it was considered that in this design a uniform flow does not occur.

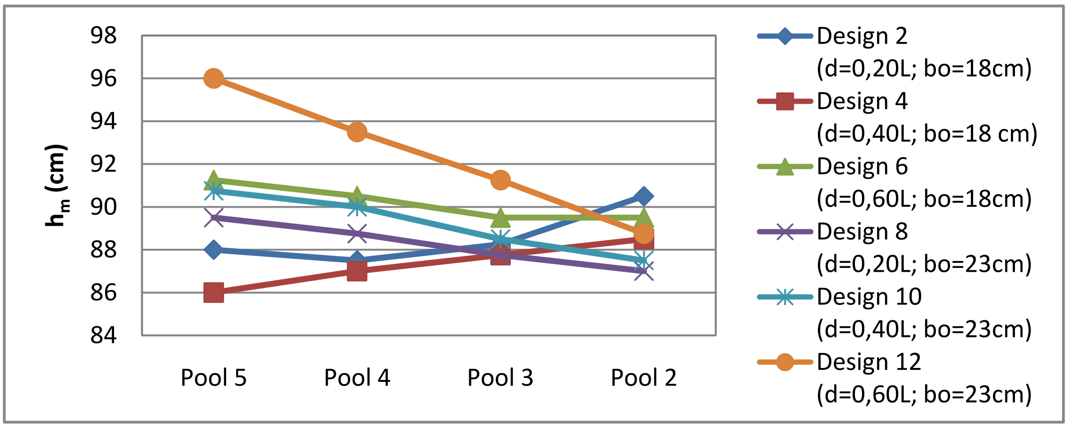


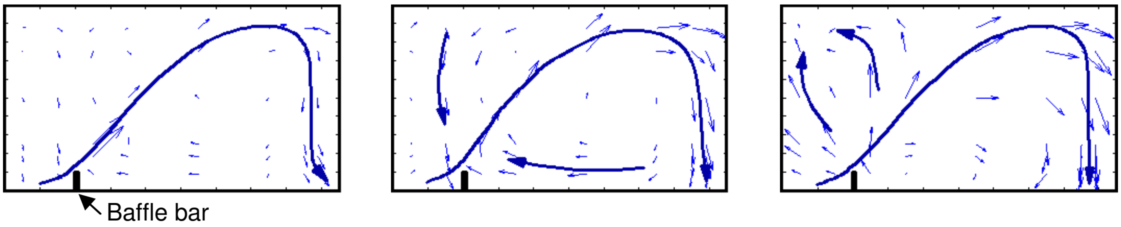
Figure 4 – Mean flow depth at the pools (e_b = $0,50b_o$).

It is verified that when bars $0,50b_o$ wide and with distances of 0,20L or 0,40L (designs 2, 4, 8 and 10) are used, a water level difference of 16,5 cm between adjacent pools are obtained (Figure 3). We can conclude that, in these designs, the jet originating from the upstream orifice is deflected and there is a larger dissipation of energy in the pools. It is also verified that the mean flow depth does not change significantly in these designs (Figure 4). Thus, it is considered that, in the designs 2, 4, 8 and 10, a uniform flow occurs.

3.2 Velocity field

Observing the obtained velocity fields, it was verified that they have several similarities among themselves, being possible to distinguish four flow patterns, designated as Pattern 1, 2, 3 and 4.

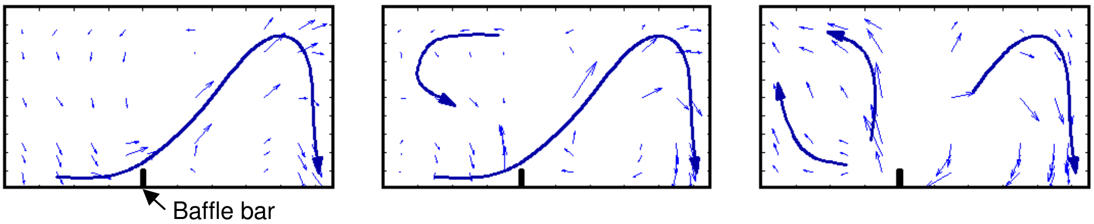
Pattern 1 occurs when the baffle bars are $0,50b_o$ wide and are at a distance of 0,20L from the upstream orifice (design 2 and 8). In this pattern it can be observed, in all plans of measurement, that the jet, which comes out of the upstream orifice, is deflected by the baffle bar, taking the direction to the opposite downstream corner, forming two low velocity regions separated by the jet.



(a) (b) (c)

Figure 5 – Pattern 1 (e_b = 0,50b_o; d = 0,20L): a) z = 0,25h_m; b) z = 0,50h_m; c) z = 0,80h_m.

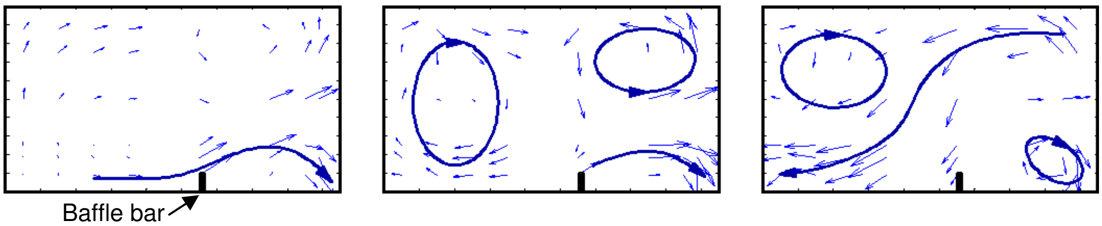
Pattern 2 is observed when the baffle bars are 0,50b_o wide and are at a distance of 0,40L from the upstream orifice (design 4 and 10). In this pattern, it was also verified that the jet originating from the upstream orifice is deflected by the baffle bar, differentiating from Pattern 1, essentially in the plan z = 0,80h_m by the formation of a region upstream the baffle bar, where the flow goes towards the upstream corner opposite to the orifice.



(a) (b) (c)

Figure 6 – Pattern 2 (e_b = 0,50b_o; d = 0,40L): a) z = 0,25h_m; b) z = 0,50h_m; c) z = 0,80h_m.

Pattern 3 occurs when the baffle bars are 0,50b_o wide and are placed at a distance of 0,60L from the upstream orifice (designs 6 and 12). In this pattern, for the depth z = 0,25h_m, low velocities are observed in almost the whole pool, just existing higher velocities near the baffle bar and the downstream orifice. In the plan z = 0,50h_m two recirculation regions appear next to the upstream and the downstream cross walls, whereas the region with higher velocities next to the downstream orifice is still observed. On the plan z = 0,80h_m, a jet going towards the corner on the upstream orifice is formed in the shape of an S, dividing the pool in two recirculation regions.



(a) (b) (c)

Figure 7 – Pattern 3 (e_b = 0,50b_o; d = 0,60L): a) z = 0,25h_m; b) z = 0,50h_m; c) z = 0,80h_m.

Pattern 4 occurs in some designs where the baffle bars used are 0,25b_o wide. In this pattern it was verified that, in the plan z = 0,25h_m, the jet that comes out of the upstream orifice is not deflected by the baffle bar. In the two planes closer to the surface (z = 0,50h_m e z = 0,80h_m), a great recirculation region is observed in all the pool area.

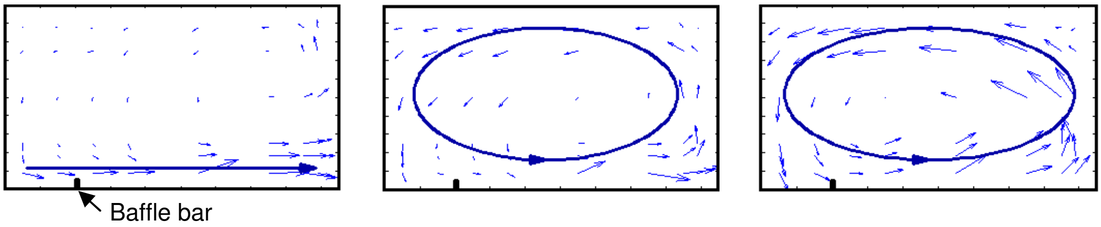


Figure 8 – Pattern 4: a) z = 0,25h_m; b) z = 0,50h_m; c) z = 0,80h_m.

Afterwards, the maximum velocity variation was analysed, based in the ratio between the maximum velocity in each plane parallel to the bottom and the potential velocity ($V_{xy\,máx} / V_p$), being the potential velocity defined as

$$V_p = \sqrt{2g\Delta h} \quad (1)$$

where g is the gravity acceleration and Δh the drop between two adjacent pools. As it was referred before, the drop between two adjacent pools is 16,5 cm, therefore, the potential velocity through the bottom orifices 1,80 m/s.

It was possible to verify that the ratio $V_{xymáx}/V_p$ in the measurement plan z = 0,80h_m does not present a significant variation, being the average value 0,18.

It was verified that the ratio $V_{xymáx}/V_p$ increases with the width of the bottom orifice in all measurement plans. However, this increase is more accentuated closer to the bottom.

Finally, it was verified that the ratio $V_{xymáx}/V_p$ decreases with the increase of the distance from the baffle bar to the upstream orifice, for z = 0,25h_m. In the two measurement plans closer to the surface it was verified that the relation $V_{xymáx}/V_p$ does not change with the variation of the distance from the baffle bar to the upstream orifice.

3.3 Turbulence pattern

The difficulty of passage for migrants increases with the turbulence and aeration in the pools. A simple indication of the turbulent levels in the pools is given by the volumetric dissipated power in the pool **(Larinier, 2002[b])**. However, this parameter is one indicator of the global turbulence in the flow.

In order to analyse turbulence variation in the pools, other turbulent parameters, as the turbulent kinetic energy, turbulent intensity and Reynolds shear stress, must be studied. These turbulent parameters were only analysed for the designs in which a uniform flow was obtained.

– **Turbulent kinetic energy**

The instantaneous velocity in one point may be decomposed as

$$V_i = \overline{V} + V_i' \qquad (2)$$

where $\overline{V}$ is the mean velocity in the point during the sampling period and V_i' is the fluctuating component at the sampling time. The turbulent kinetic energy is defined by **(Rodi, 1980 *in* Puertas et al, 2004)**

$$k = \frac{1}{2}\left(u'^{2}_{rms} + v'^{2}_{rms} + w'^{2}_{rms}\right) \qquad (3)$$

where u', v' and w' are the fluctuating components of V_i' on the system coordinates x, y, z and u'_{rms}, v'_{rms} and w'_{rms} the respective root mean square values.

Figure 9 shows the turbulent kinetic energy field for design 2 (b_o = 18 cm; e_b = 0,50b_o; d = 0,20L).

It was found that the turbulent kinetic energy field presents some similarities with the mean velocity field. It was observed that the highest values occur in the same regions where the mean velocity presents high values, meaning near the bottom of the pool and, for each plane, in the jet trajectory. It was also found that the maximum value of turbulent kinetic energy decreases when the distance between the upstream orifice and the baffle bar increases.

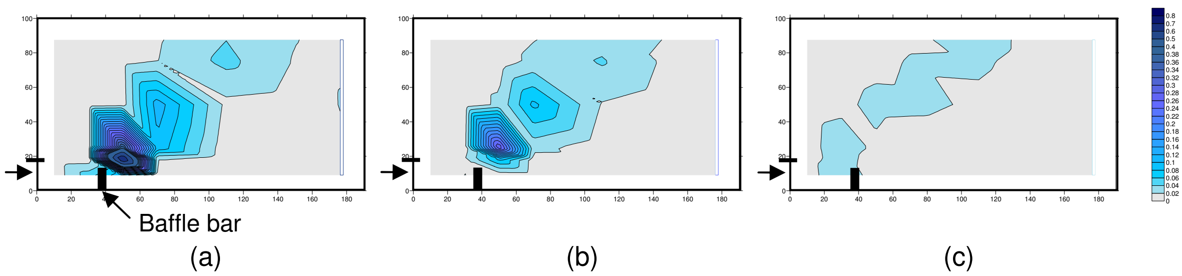


Figure 9 – Isolines of turbulent kinetic energy (m^2/s^2) in planes parallel to the pool bottom, for design 2 (b_o = 18 cm; e_b = 0,50b_o; d = 0,20L): a) z = 0,25h_m; b) z = 0,50h_m; c) z = 0,80h_m.

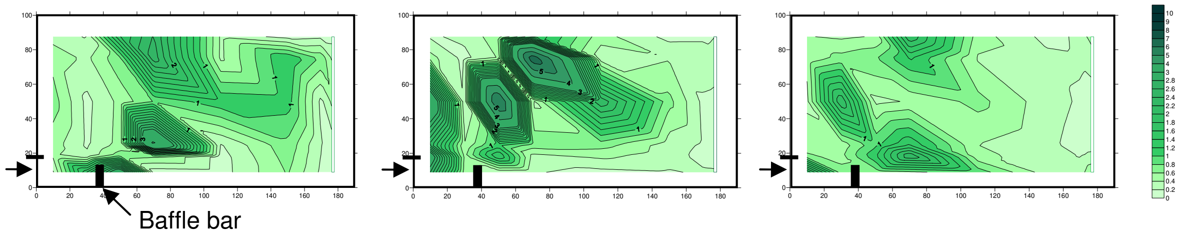
– **Turbulent intensity**

Mosquera (2004) and **Sanagiotto (2007)** use the turbulent intensity,

$$I_t = \frac{k}{\overline{V}^2} \qquad (4)$$

as a measure of turbulence in pools.

It was found that the highest values of turbulent intensity occur in the plane z = 0,50h_m, but it was not found any pattern among the isolines maps of turbulent intensity. Figure 10 shows the turbulent intensity field for design 2 (b_o = 18 cm; e_b = 0,50b_o; d = 0,20L).



(a) (b) (c)

Figure 10 – Isolines of turbulent intensity in planes parallel to the pool bottom, for design 2 (b_o = 18 cm; e_b = 0,50b_o; d = 0,20L): (a) z = 0,25h_m; (b) z = 0,50h_m; (c) z = 0,80h_m.

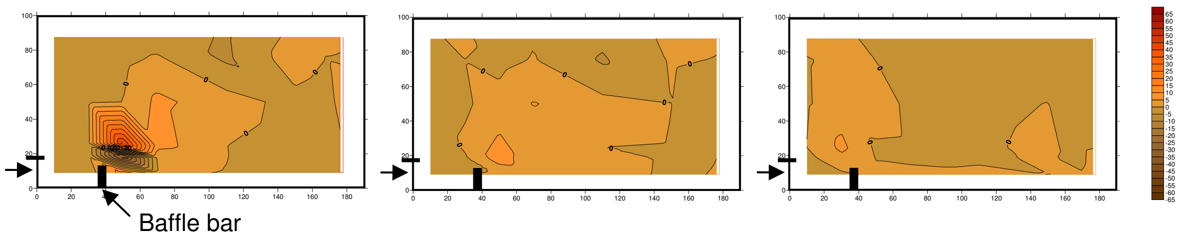
– **Reynolds shear stress**

In turbulent flow, the velocity fluctuations exchange momentum between adjacent layers of fluid, producing shear stresses between those layers, which can be quantified by the Reynolds shear stress, whose mean values in a plane *xy* are

$$\tau_{xy} = -\rho \overline{u'v'} \tag{5}$$

According to **Odeh (2002)**, the Reynolds shear stress is a good measure of turbulent severity when correlating turbulence with fish behaviour.

Figure 11 shows the Reynolds shear stress in planes parallel to the pool bottom for design 2 (b_o = 18 cm; e_b = 0,50b_o; d = 0,20L).



(a) (b) (c)

Figure 11 – Isolines of Reynolds shear stress (N/m^2) in planes parallel to the pool bottom, for design 2 (b_o = 18 cm; e_b = 0,50b_o; d = 0,20L): (a) z = 0,25h_m; (b) z = 0,50h_m; (c) z = 0,80h_m.

For all the designs analysed, maximum values of Reynolds shear stress were obtained near the baffle bar. It was also noticed that, though the Reynolds shear stresses values presented a big variation, most values are between -20 e 20 N/m^2.

4 Conclusions

It was found that, in a pool-type fishway with bottom orifices aligned, it is possible to obtain a uniform flow if a baffle bar with 0,50b_o in width is installed on the side wall adjacent to the orifices at one distance between 0,20L and 0,40L from the upstream orifice.

From the analysis of the velocity fields, 4 flow patterns were identified. It was also analysed the maximum velocity variation for the design in which a uniform flow was obtained (e_b = 0,50b_o and d = 0,20L; 0,40L). It was found that:

– $V_{xymáx}/V_p$ is approximately constant for z = 0,80h_m;

– $V_{xymáx}/V_p$ increases when the bottom orifice width increases;

– $V_{xymáx}/V_p$ decreases when the distance between the baffle bar and the upstream orifice increases for z = 0,25h_m.

The turbulent parameters were only analysed for the designs in which a uniform flow was obtained (e_b = 0,50b_o e d = 0,20L; 0,40L).

It was found that the turbulent kinetic energy field presents some similarities with the mean velocity field. It was observed that the highest values occur in the same regions where the mean velocity presents high values. It was also found that the maximum value of turbulent kinetic energy decreases when the distance between the upstream orifice and the baffle bar increases.

For all the designs analysed, maximum values of Reynolds shear stress were obtained near the baffle bar.

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