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Study on flow characteristics in vertical slot fishways regarding slot layout optimization

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ABSTRACT

Design of effective fishways is becoming increasingly important. This paper focuses on the effect of the angle of deflection (α) between small and large baffles in a vertical slot fishway (VSF). A reliable depth-averaged two-dimensional numerical model PCFLOW2D was used to perform simulations of various VSF configurations, including six angles of deflection, two slot sizes, two large baffle sizes and four water level differences between adjacent pools. The results showed the important influence of α on depth-discharge curves and maximum velocities at the slot which both strongly affect the fishway efficiency. With larger α, up to 42% smaller discharges and up to 33% smaller maximum velocities were calculated. In cases with small α and larger slot sizes much greater maximum velocities than theoretically calculated using over simplified formula were modeled (up to 62%). The important effect of transverse displacement of the slot on discharge and maximum velocity was evaluated. As expected, the most important parameter that determines the discharge and maximum velocity in the fishway is water level difference between adjacent pools. With slot layout optimization it is possible to achieve the same discharge and maximum velocity even at larger water level differences between adjacent pools which obviously reduce fishway construction costs.

1. Introduction

The purpose of fish migration is to reach suitable spawning areas, find food, avoid adverse conditions, or simply to spread the habitat of certain species. These migration routes become interrupted with the construction of a river dam. Effective fishways bridge the interruption and thus greatly improve natural wildlife corridors and biodiversity in the river.

Designers of fishways are confronted with contrary demands of European directives dealing with preservation of wildlife corridors and biodiversity on one hand, and renewable energy on the other hand. EU Water Frame Directive (RL 2000/60/EC) aim is to restore water bodies to reach the good ecological status. Operation of any fishway bypass system means a reduction of the usable water for power production and therefore a long lasting negative economical effect to the producer. Therefore the aim is to design a biologically effective fishway while reducing the flow required for its operation.

The literature lists several different types of fishways, including nature-like fishways and technical fishways, such as weir, Denil, culvert and vertical slot fishway (VSF) type (Larinier et al., 2002; Maddock et al., 2013). The subject of this paper is the VSF type with one vertical slot, similar to VSF types studied by Rajaratnam et al. (1986,1992), which proved to be very effective for fish migration in many cases (Bermúdez et al., 2010; Marriner et al., 2016; Puertas et al., 2012; Rodriguez et al., 2006). A VSF is constructed in a sloping rectangular, usually concrete channel, which is divided into a series of pools by vertical baffles. Water travels from one pool to the next through a vertical slot between two baffles. In the slot region a water jet with maximum velocity is formed, which also creates recirculation regions in the pool with much smaller velocity where the fish can rest before their way up through the next slot. The slot opening extends from surface to the channel bed enabling fish and other aquatic organisms to choose their favorable migration course.

The first VSF was constructed in Canada in 1961 (Wu et al., 1999). The first systematic study of flow in VSF was performed by Rajaratnam et al. (1986, 1992), who investigated a total of 18 pool designs with different pool width and length. They found the linear correlation between water depth and discharge. The equation for the maximum velocity at the slot $v_{\max} = (2g\Delta h)^{1/2}$ was proposed (Rajaratnam et al., 1986). This relation was repeated in a number of recent design manuals (Larinier, 2002; Maddock et al., 2013), and studies (Calluaud et al., 2014; Liu et al., 2006; Puertas et al., 2004). However, extensive field measurements and numer-

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Nomenclature

Notation

b_0	Slot width [m]
C_q	Discharge coefficient [−]
d_x	Short baffle pier width [m]
d_y	Short baffle pier length [m]
D_y	Large baffle pier length [m]
g	Gravity acceleration [ms^{-2}]
h	Water depth [m]
k	Mean flow kinetic energy per unit mass [m^2 s^{-2}]
k'	Turbulent kinetic energy per unit mass [m^2 s^{-2}]
L	Pool length [m]
n_g	Manning's roughness coefficient [sm$^{-1/3}$]
Q	Discharge [m^3 s^{-1}]
Q_{spec}	Discharge per unit width [m^2 s^{-1}]
S_0	Longitudinal slope [−]
$v_{\max}$	Maximum velocity in the slot of a VSF [ms^{-1}]
v_x	Mean longitudinal velocity component [ms^{-1}]
W	Pool width [m]
x	Longitudinal coordinate [m]
y	Transverse coordinate [m]
α	Angle of deflection between small and large baffle [°]
Δh	Head difference between two adjacent pools [m]
Δs_y	Transverse displacement of slot [m]
Δt	Time step [s]
Δx	Cell size in longitudinal direction [m]
Δy	Dell size in transverse direction [m]
ε	Dissipation rate per unit mass [m^2 s^{-3}]

ical simulations by Bombač et al. (2015) showed this equation is based on a somewhat unrealistic assumption that the velocity in the upstream pool is negligible (Bermúdez et al., 2010), and presented results indicating the actual maximum flow velocity at the slot can reach up to values which are 50% higher from those obtained from $v_{\max} = (2g\Delta h)^{1/2}$ equation. Velocities which are greater than assumed during the design process can cause several problems: the weakest swimmers which present the velocity-decisive fish cannot migrate upstream, the discharge in the VSF is uneconomically higher, and finally some other fishway elements such as intake structure are non-optimal.

In this paper a detailed hydraulic study of several different slot geometries shows the effect of the angle of deflection α between small and large baffles on the maximum velocity in the slot region and also on the flow field in the pool.

There is a number of researches dealing with the hydraulics of a VSF in terms of different parameters such as pool dimensions, slope and slot size (Bermúdez et al., 2010; Cea et al., 2007; Liu et al., 2006; Marriner et al., 2014, 2016; Rajaratnam et al., 1986, 1992; Rodriguez et al., 2006; Tarrade et al., 2008, 2011), but none of these focused on the angle of deflection α between small and large baffles. To provide some insight into this important parameter and thus enable optimization of a VSF design, the present study considers six angles of deflection, two slot sizes, two large baffle sizes and four water level differences between adjacent pools.

2. Material and methods

2.1. Numerical model

Numerical simulations were performed using the PCFLOW2D model (Četina, 1988, 2000) which solves the depth-averaged shallow water equations coupled with a turbulence model, as presented in Bombač et al. (2015). In accordance with previous research by Bombač et al. (2014) the depth averaged $k - \varepsilon$ turbulence model of Rastogi and Rodi (1978) was used.

The same basic geometric data of the numerical model as in research by Bombač et al. (2015) was used. Modeled VSF is a 2.2 m wide channel with longitudinal slope S_0 = 1.67% which is separated by vertical baffles into pools of length L = 3.0 m with slots between them (slot width b_0 = 0.59 m). Numerical model of VSF consisted of nine active pools (each with length L = 3.00 m), an inlet reach (0.5 x L) and an outlet reach (3.2 × L), as shown in Fig. 1. Such model dimensions ensure uniform flow in the central pools, with no potential effects of the model inlet and outlet boundary conditions (Chorda et al., 2010; Liu et al., 2006). Comparison of flow fields in adjacent central pools showed no differences. Therefore, all presented numerical results refer to the fifth (middle) pool. Investigated configurations were variants of the geometry of the VSF at the hydropower plant (HPP) Arto-Blanca, Slovenia (Fig. 1).

A relatively dense and uniform numerical mesh was used (Δx = 0.01 m; Δy = 0.02 m). Such a dense mesh had to be used in order to ensure results without any significant effect of numerical diffusion (Bombač et al., 2014). To ensure numerical stability and convergence, the time step was set to Δt = 0.1 s. All simulations were calculated to the final time of 3600 s.

At the inlet boundary a constant discharge with uniform velocity distribution normal to the inlet was set. A depth-discharge relation at the outlet boundary was determined iteratively to obtain the same water depth in middle sections of central pools (uniform flow conditions). Influence of bed friction was described using Manning's roughness coefficient n_g. As shown in Bombač et al. (2014), bed friction does not play an important role for this type of flow. A more detailed description of numerical mesh analysis, effect of appropriate turbulence model and Manning's roughness coefficient can be found in Bombač et al. (2014), while a complete description of the numerical model can be found in Četina (1988, 2000).

2.2. Model validation

Numerical model was validated with field measurements of the VSF at the HPP Arto-Blanca (Bombač et al., 2015). Results of simulations were in good agreement with field measurements, demonstrating that PCFLOW2D provides accurate simulations of VSF flow and can be used for the optimization of such fishways.

2.3. Scope of the research

The present paper systematically focuses on various angles between short and large baffles, and demonstrates that these angles govern the flow in a slot. Our research considered three basic groups of geometries. Each group included six variants of angles between baffles, i.e. α = 0°, 10°, 20°, 30°, 40° and 50°. Geometries of the first group had slot width b_0 = 0.59 m and large baffle length D_y = 1.40 m (Fig. 2a). Geometries of the second group had smaller slot width b_0 = 0.30 m (Fig. 2b). Geometries of the third group differed from those in group one by the transverse displacement of slot for Δs_y = 0.20 m to the center of the pool (Fig. 2c). This modification meant shorter large baffle D_y = 1.20 m and for 0.20 m larger small baffle.

In all those cases the head difference between adjacent pools was relatively small, Δh = 0.05 m, with the water surface slope S_0 = 0.0167.

Finally, three additional simulations were conducted to investigate various head differences between pools, including Δh = 0.10, 0.15 and 0.20 m for the basic geometry from group one with α = 20°. All cases are listed in Table 1.

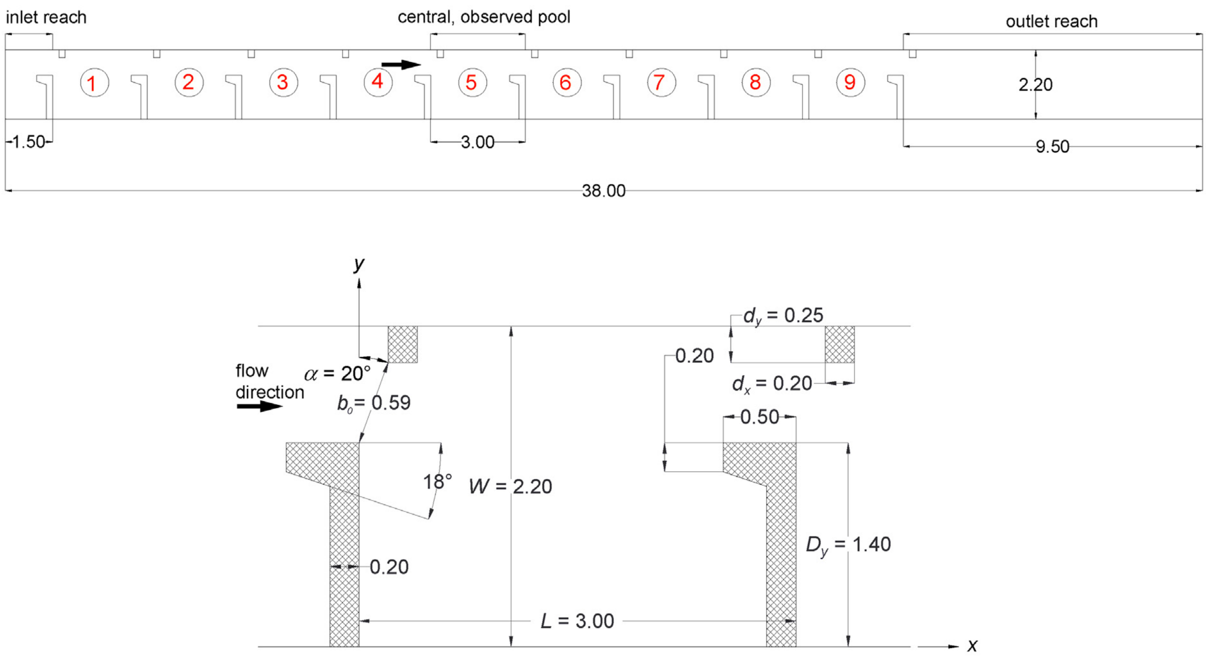

Fig. 1. Plan view of numerical model (above), details of a pool at the HPP Arto–Blanca (below). Dimensions are in meters.

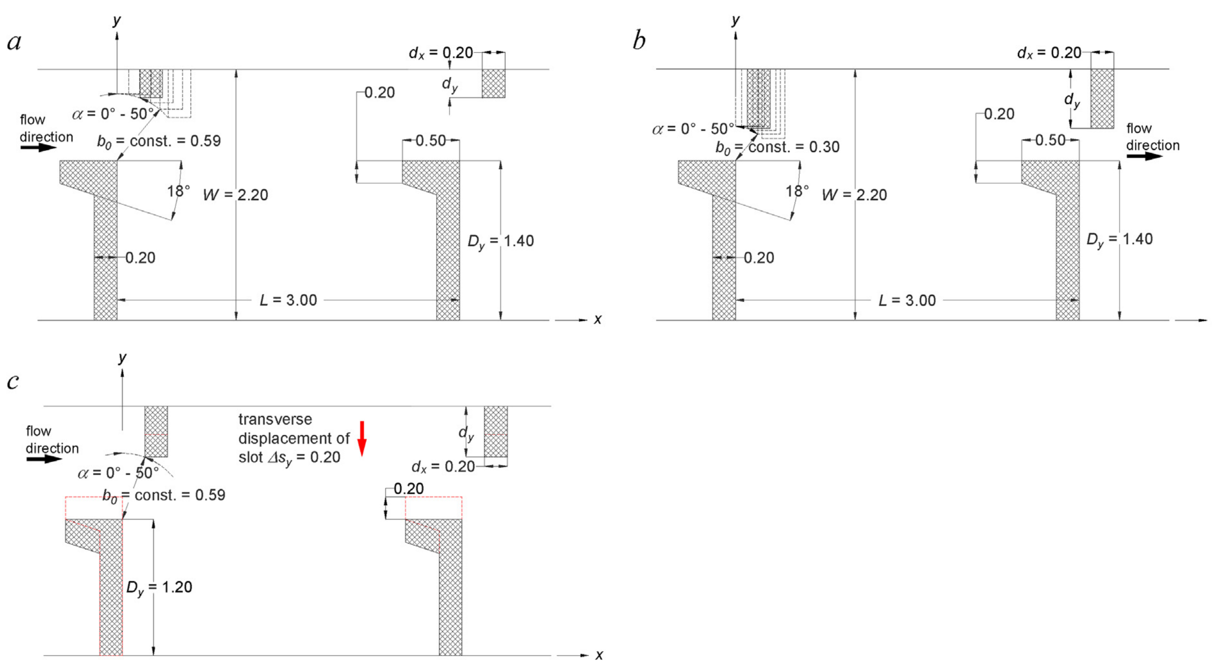

Fig. 2. Geometries of studied groups of variants: (2a) group of base geometries with slot width $b_0 = 0.59$ m; (2b) group of geometries with smaller slot width $b_0 = 0.30$ m; (2c) group of geometries with transverse displacement of the slot for $\Delta s_y = 0.20$ m to the center of the pool and slot width $b_0 = 0.59$ m. Dimensions are in meters.

3. Results and discussion

This section is divided into six sub-sections. Sections 3.1–3.4 deal with the effect the angle α has on those hydraulic parameters which are most important in terms of VSF design. With this in mind and to provide a clearer picture, these sub-sections consider geometries of the first two groups (denoted S1A0 to S2A5 in Table 1, shown in Fig. 2a and b).

Section 3.5 presents an analysis of the effect of transverse position of the slot. Displacing the slot transversely away from the longitudinal wall of the VSF (i.e. lengthening the short baffle, see Fig. 2c) changes the flow velocity fields significantly.

Cases in Sections 3.1–3.5 are characterized by relatively small Δh between adjacent pools, while Section 3.6 presents cases with greater Δh and its effect on the VSF velocity field. Four variants of Δh are compared for both the same shape and size of baffles.

3.1. Depth-discharge curves

Depth-discharge curves were calculated for all geometries in the first two groups (cases S1A0 to S2A5), and their comparison

Table 1
Cases of pool geometry simulated using PCFLOW2D numerical model.

case	slot width b_0 [m]	slot angle α [°]	large baffle length D_y [m]	head difference between pools Δh [m]	surface slope S_0 []
S1A0	0.59	0	1.40	0.05	0.0167
S1A1	0.59	10	1.40	0.05	0.0167
S1A2	0.59	20	1.40	0.05	0.0167
S1A3	0.59	30	1.40	0.05	0.0167
S1A4	0.59	40	1.40	0.05	0.0167
S1A5	0.59	50	1.40	0.05	0.0167
S2A0	0.30	0	1.40	0.05	0.0167
S2A1	0.30	10	1.40	0.05	0.0167
S2A2	0.30	20	1.40	0.05	0.0167
S2A3	0.30	30	1.40	0.05	0.0167
S2A4	0.30	40	1.40	0.05	0.0167
S2A5	0.30	50	1.40	0.05	0.0167
S3A0	0.59	0	1.20	0.05	0.0167
S3A1	0.59	10	1.20	0.05	0.0167
S3A2	0.59	20	1.20	0.05	0.0167
S3A3	0.59	30	1.20	0.05	0.0167
S3A4	0.59	40	1.20	0.05	0.0167
S3A5	0.59	50	1.20	0.05	0.0167
S1A2H2	0.59	20	1.40	0.10	0.0333
S1A2H3	0.59	20	1.40	0.15	0.0500
S1A2H4	0.59	20	1.40	0.20	0.0667

Denotations S, A and H in Table 1 mean slot, angle and head, respectively.

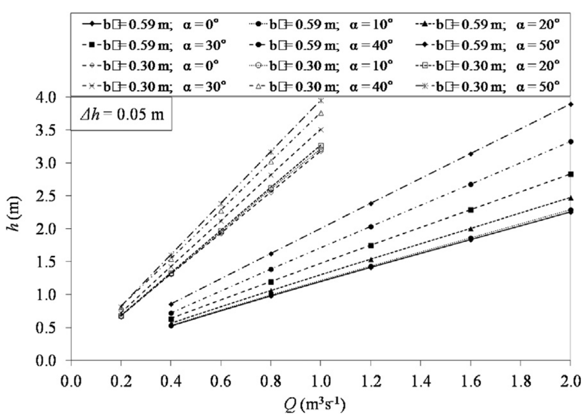

Fig. 3. Depth-discharge relationships for cases S1A0 to S2A5.

Table 2
Values of coefficients x_1, x_2, x_3, x_4 and x_5 for geometry groups *a* and *b*.

coefficient	values for b_0 = 0,59 m	values for b_0 = 0,30 m
x_1	1.39648485	1.00503411
x_2	0.10226141	0.03460622
x_3	−0.00717306	−0.00158651
x_4	−0.01514534	−0.00509518
x_5	−0.00013413	−0.00005663

is given in Fig. 3. The first group with slot size b_0 = 0.59 m conveyed discharges Q = 0.4, 0.8, 1.2, 1.6 and 2.0 m^3s^{-1}, while the second group with smaller slot size b_0 = 0.30 m conveyed smaller discharges Q = 0.2, 0.4, 0.6, 0.8 and 1.0 m^3s^{-1}. This means the results are comparable since the specific discharges (per slot width) are the same for both geometries (S1 and S2 in Table 1). Depth-discharge curves are presented in Fig. 3.

Fig. 3 confirms that discharge Q in a VSF is practically linear to water depth h (Chorda et al., 2010; Rajaratnam et al., 1986, 1992; Wu et al., 1999), and can be described in terms of $Q = k \cdot h$(where k is a coefficient). A more hydraulically suitable equation is:

$$Q = C_q \cdot b_0 \cdot h \cdot \sqrt{2 \cdot g \cdot \Delta h} \tag{1}$$

The coefficient C_q in Eq. (1) depends both on the angle of deflection α and water depth in the pool h, and can be expressed as:

$$C_q = x_1 + x_2 \cdot h + x_3 \cdot \alpha + x_4 \cdot h^2 + x_5 \cdot \alpha^2 \tag{2}$$

A set of values of the coefficients x_1, x_2, x_3, x_4 and x_5 in Eq. (2) changes for each separate group of geometry (i.e. slots *a*, *b* and *c* in Fig. 2), as shown in Fig. 4. A set of coefficients values is given in Table 2.

Figs. 3 and 4 indicate that the flow strongly depends on the angle of deflection α. However, α is not taken into consideration in the theoretical equation $v_{max} = (2g\Delta h)^{1/2}$ and this could be an explanation why this equation is not adequate. Increasing angle α decreases discharge capacity, so that at α = 50° (case S1A5, Table 1) discharge amounts only to 57.6% of the value at α = 0° (case S1A0). It should be noted that in VSF the angle of deflection α should be between 20° (for small fishways, as stated by Gebler (1991)) to 45° (Larinier, 1992; Rajaratnam et al., 1986). In our study the smallest angles α were below that limit, including α = 0° and α = 10°, to allow determination of reference values and trends of hydraulic characteristics.

Flow characteristics are very similar for various discharges or depths. An example for case S1A2 is given in Fig. 5.

It is evident from Fig. 5 that the only significant difference of flow field is the maximum velocity – its value is greater for the cases with greater discharge.

Calculated longitudinal velocity components v_x at cross section x = 0.5 m for discharges Q = 0.4, 0.8, 1.2, 1.6 and 2.0 $m^3\,s^{-1}$ for case S1A2 are shown in Fig. 6. Increasing the discharge for as much as 400% resulted in only 12% higher maximum velocity.

Water surface elevations within VSF are dependent only on the water level at both upstream and downstream end of the VSF. If all slots are the same, than the water surface slope along them is the same. In other words, flow depth depends on the water levels at both ends of the VSF, while the shape of the slots determines the discharge. Therefore, to compare the effect of variants of geometry one has to consider results obtained for cases with equal depth of the flow. We chose to compare cases with h = 1.30 m, as described in the following sections.

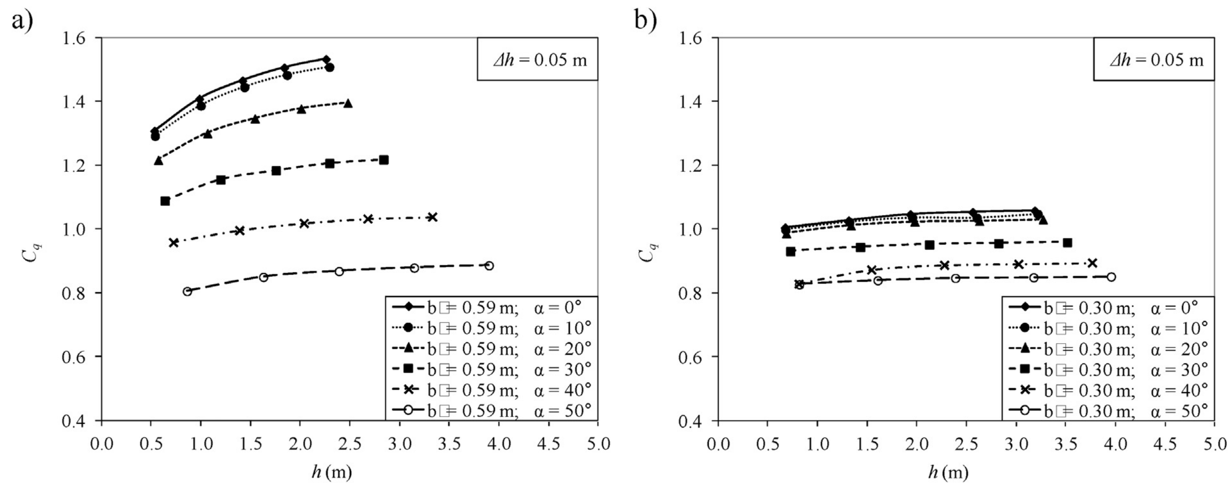

Fig. 4. Discharge coefficient C_q for cases with slot width b_0 = 0.59 m (left) and for cases with slot width b_0 = 0.30 m (right).

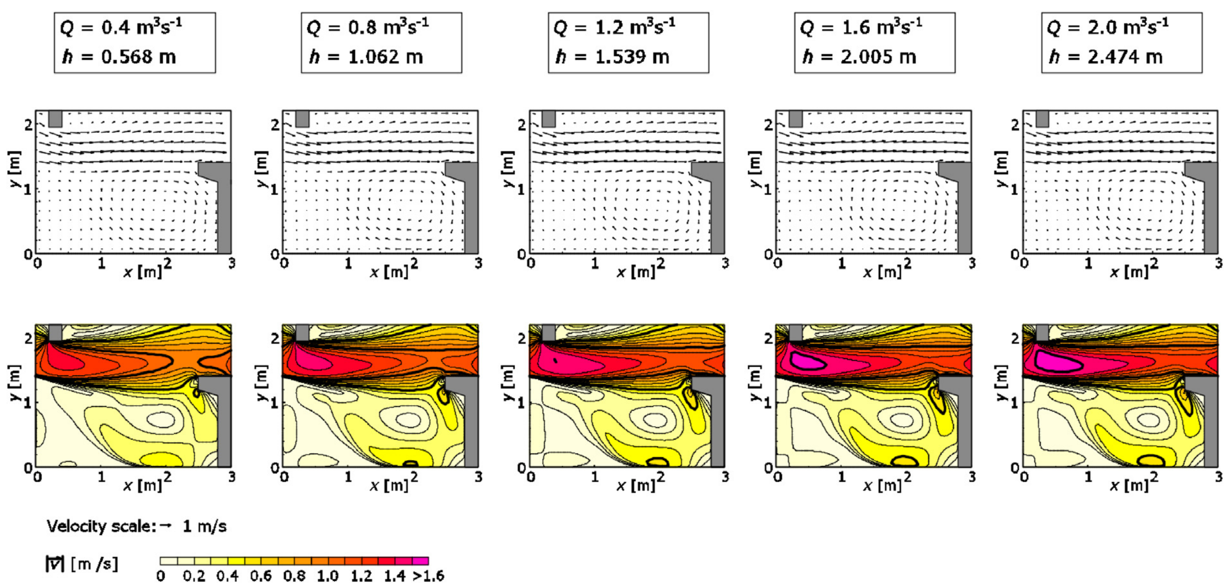

Fig. 5. Velocity vectors and calculated isovels in the central pool of VSF for discharges Q = 0.4, 0.8, 1.2, 1.6 and 2.0 $m^3 s^{-1}$ (case S1A2).

3.2. Effect of angle of deflection between baffles on discharge in VSF

As mentioned, angle of deflection between baffles strongly affects the discharge in VSF. Fig. 7 shows the discharge for variants of α in the normalized relation to the referential case of α = 0°. When α increases, discharge decreases. In cases with b_0 = 0.59 m the increase of α resulted in greater decrease of discharge than in the cases with b_0 = 0.30 m. For both b_0 the increase of α = 0° to α = 10° caused only a fraction smaller discharge. At α = 50° the discharge for case b_0 = 0.59 m (case S1A5) and b_0 = 0.30 m (case S2A5) was 42.4% and 18.6%°, respectively, smaller than at α = 0.

Fig. 8 shows relations $Q(\alpha)$ for b_0 = 0.30 m and 0.59 m, respectively, both relations are given for h = 1.30 m. It is evident that at small angles α discharges in slots with wider opening are almost three-times bigger than in slots with narrower opening. This can be attributed to the contraction of the flow, which has relatively larger effect in smaller openings.

To get a better comparison one needs to consider discharge per unit width of b_0 (Fig. 9). Interestingly,

this specific discharge at α = 0° through narrower opening is 27% smaller than through wider opening, but the difference decreases as α increases, and finally at α = 50° the specific discharge through narrower opening is 3% larger than through wider opening.

Table 3 summarizes discharges and maximum velocities for all cases with h = 1.30 m.

3.3. Effect of angle between baffles on maximum velocity in the slot

One of the most important hydraulic parameters affecting the overall effectiveness of a VSF is the maximum velocity of the flow. It has to be smaller than the burst speed of the weakest fish migrating through VSF. Velocity of the flow reaches its maximum in the opening between slots, and is highly dependent on the angle of deflection between baffles, as the present study indicates. Fig. 10 shows the relation between the maximum velocity and the angle of deflection for geometries type *a* and type *b*. It is evident the value of maximum velocity v_{max} is greater at smaller angle α, and decreases as α increases. Larger angle between baffles directs the flow to circulate into the region between larger baffles, resulting in greater dissipation of energy and thus smaller velocities. At smaller angles this effect is much smaller and the kinetic energy is transported to the next slot almost without dissipation.

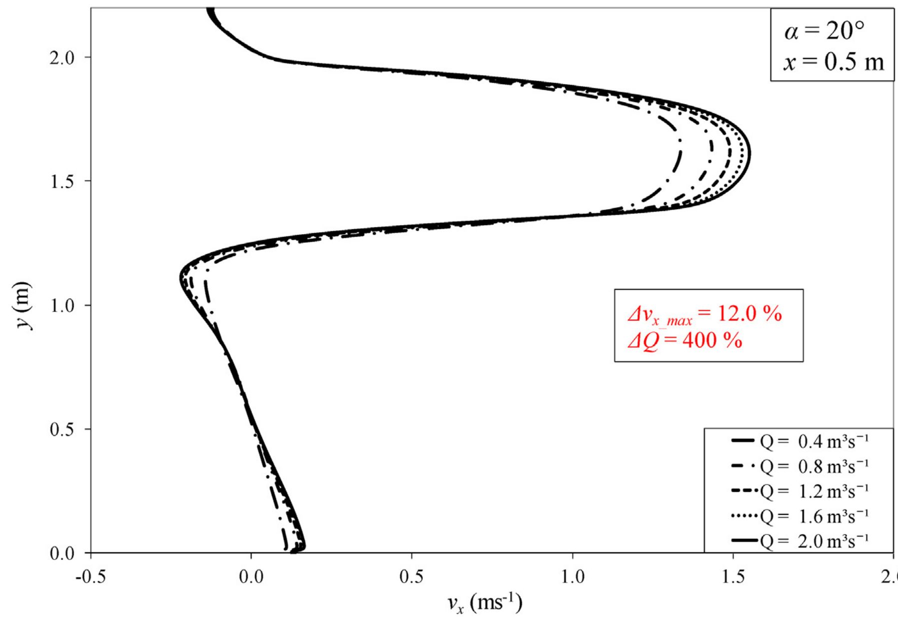

Fig. 6. Calculated longitudinal velocity components v_x at cross section $x = 0.5$ m for discharges $Q = 0.4$, 0.8, 1.2, 1.6 and 2.0 $m^3 s^{-1}$ (case S1A2).

Table 3
Hydraulic characteristics in VSF slots for simulations with water depth $h = 1.30$ m.

Case	discharge Q [$m^3 s^{-1}$]	max. velocity v_{max} [ms^{-1}]
S1A0	1.094	1.603
S1A1	1.076	1.564
S1A2	1.000	1.479
S1A3	0.874	1.336
S1A4	0.746	1.194
S1A5	0.630	1.066
S2A0	0.397	1.143
S2A1	0.394	1.105
S2A2	0.390	1.070
S2A3	0.364	1.009
S2A4	0.333	0.932
S2A5	0.323	0.918
S3A0	0.915	1.356
S3A1	0.907	1.324
S3A2	0.851	1.252
S3A3	0.770	1.167
S3A4	0.669	1.047
S3A5	0.579	0.944
S1A2H2	1.398	2.080
S1A2H3	1.586	2.532
S1A2H4	1.765	2.937

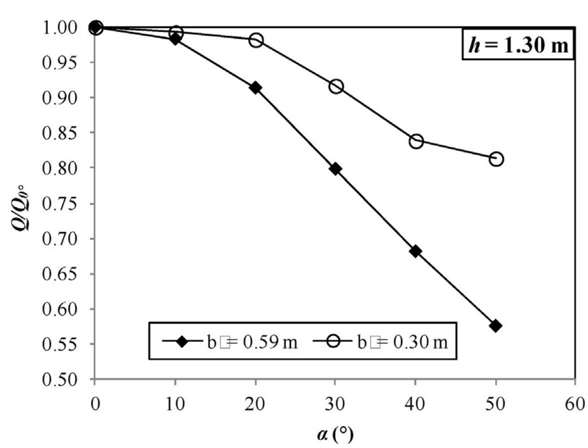

Fig. 7. Normalized discharge Q/Q_0 (where Q_0 means $Q(\alpha = 0^\circ)$ in relation to α.

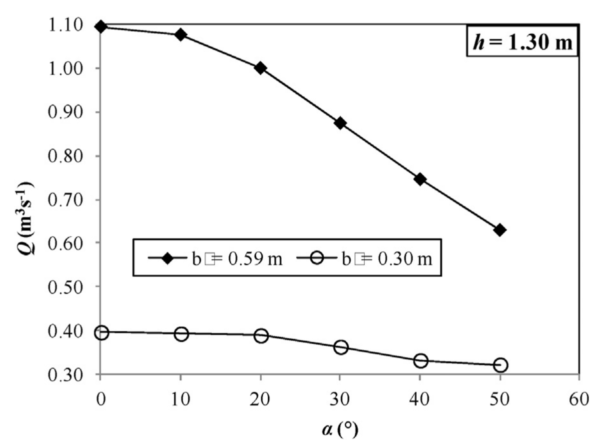

Fig. 8. Relation $Q(\alpha)$ for both variants of b_0, with $h = 1.30$ m.

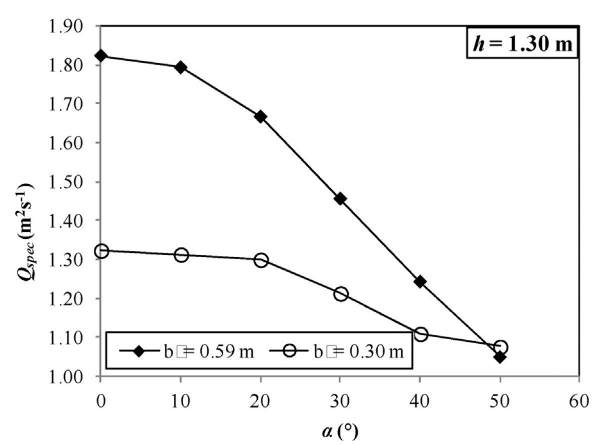

Fig. 9. Relation between discharge per unit width ($Q_{spec.} = Q/b_0$) and α for $h = 1.30$ m.

In all observed cases of the present study the maximum velocity was greater than the theoretical value obtained from equation $v_{max} = (2g\Delta h)^{1/2}$. This can be attributed to the fact that this equation considers neither α nor b_0, although both affect the velocity, as

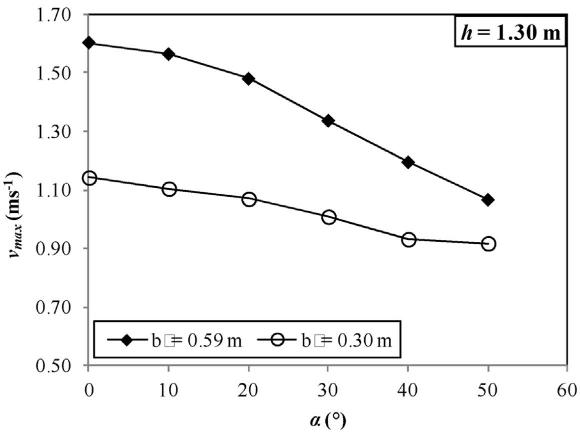

Fig. 10. Maximum velocity v_{max} of the flow with $h = 1.30$ m for both openings b_0 and various angles α.

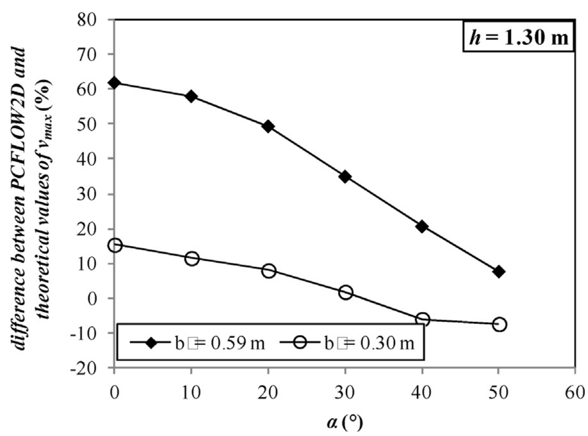

Fig. 11. Difference between PCFLOW2D and theoretical values of v_{max} at $h = 1.30$ m.

Fig. 10 shows. The difference between PCFLOW2D and theoretical values of v_{max} is given in Fig. 11.

In variant S1A0 the difference amounts to as much as 62%. This difference decreases as α increases, finally amounting to 8% at α = 50° (case S1A5). Interestingly, the difference between v_{max} values is significantly smaller for smaller slot sizes (cases S2). In case of S2A0 the PCFLOW2D value of v_{max} is 15% greater than the theoretical, but becomes even 7% smaller than theoretical in case with α = 50° (case S2A5). Results clearly show that the size of the slots affects the dissipation of kinetic energy of the flow and can – combined with smaller angles of deflection – lead to maximum velocities which are significantly larger than theoretical values of $v_{max} = (2g\Delta h)^{1/2}$. This difference underlines the important role of hydraulic modeling at optimizing the design of VSF.

Fig. 12 shows the effect of angle of deflection on longitudinal location of the profile with maximum velocity. It is evident that maximum velocity takes place at a more downstream location when α is larger. This follows from the fact that maximum velocity occurs in the region of smaller baffle, which is positioned farther in the downstream direction when α is larger.

3.4. Effect of angle between baffles on flow field in VSF

Angle between baffles and the size of the slot both significantly affect not only discharge and maximum velocity but also flow characteristics such as flow field, recirculating flow region, turbulent kinetic energy k', and dissipation of turbulent kinetic energy ε. Among the characteristics mentioned, this paper focuses only on

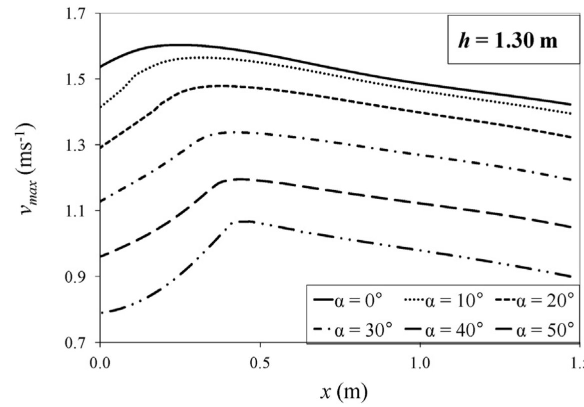

Fig. 12. Location of the profile with maximum velocity for $h = 1.30$ m and $b_0 = 0.59$ m.

the flow field. Calculated isovels in the central pool of the VSF for all geometries with $\Delta h = 0.05$ m are shown in Fig. 13. In this section, only the first two columns of the figure (geometries of group *a* and *b*) will be discussed, while the third column, showing the effect of the displacement of the slot (geometries *c*) will be discussed separately in Section 3.5.

Fig. 13 shows that increasing the angle of deflection changes direction of the flow towards the wall opposite to the smaller baffle, causing recirculation zone between larger baffles to decrease, while the recirculation zone between smaller baffles increases. This effect is more evident in variants with smaller slot width (geometries group *b*) than in those with larger slot width (group *a*). In case S2A5 the recirculation zone between larger baffles almost disappears, but at the same time a larger one appears behind the smaller baffle.

Figs. 14 and 15 shows calculated longitudinal velocity components v_x at different cross sections. In variants with slot width $b_0 = 0.59$ m (Fig. 14) the velocity profiles are similar for all angles. Maximum velocities decrease as the angle between baffles increases. Differences between maximum velocities increase as the angle increases (the difference between variants S1A0 and S1A1 is small).

In variants with slot width $b_0 = 0.30$ m (Fig. 15) the velocity profiles are similar for angles up to α = 30°, but change significantly when α = 40° and α = 50°. The main flow (and with it also the maximum velocities) turns towards the lower (i.e. right-side) wall, especially in the variant with α = 50°.

3.5. Effect of transverse displacement of the slot

To investigate this effect the slot was transversely displaced 0.20 m towards the centerline of the VSF, as shown in Fig. 2c, creating six geometry variants (group *c*) with longer small baffles and shorter large baffles. Resulting discharges and maximum velocities are listed in Table 3 (cases S3A0 to S3A5). The results show that discharge capacity of the VSF decreases as the slot is displaced towards the axis, as shown in Fig. 16.

It is evident that displacement of the slot for 0.20 m towards the centerline of the VSF reduces its discharge capacity for 13% on average. The largest reduction ΔQ takes place at α = 0° amounting to 16%, while larger α causes this reduction to decrease and finally reach 8% at α = 50°.

Comparison of maximum velocities in initial geometries and in variants with transversely displaced slot is given in Fig. 17.

Velocities act similarly to discharges: transverse displacement of the slot for 0.20 m results in an average 14% reduction of maximum velocities. The largest reduction Δv_{max} takes place at α = 0° amounting to 15%, while larger α causes this reduction to decrease and finally reach 11% at α = 50°.

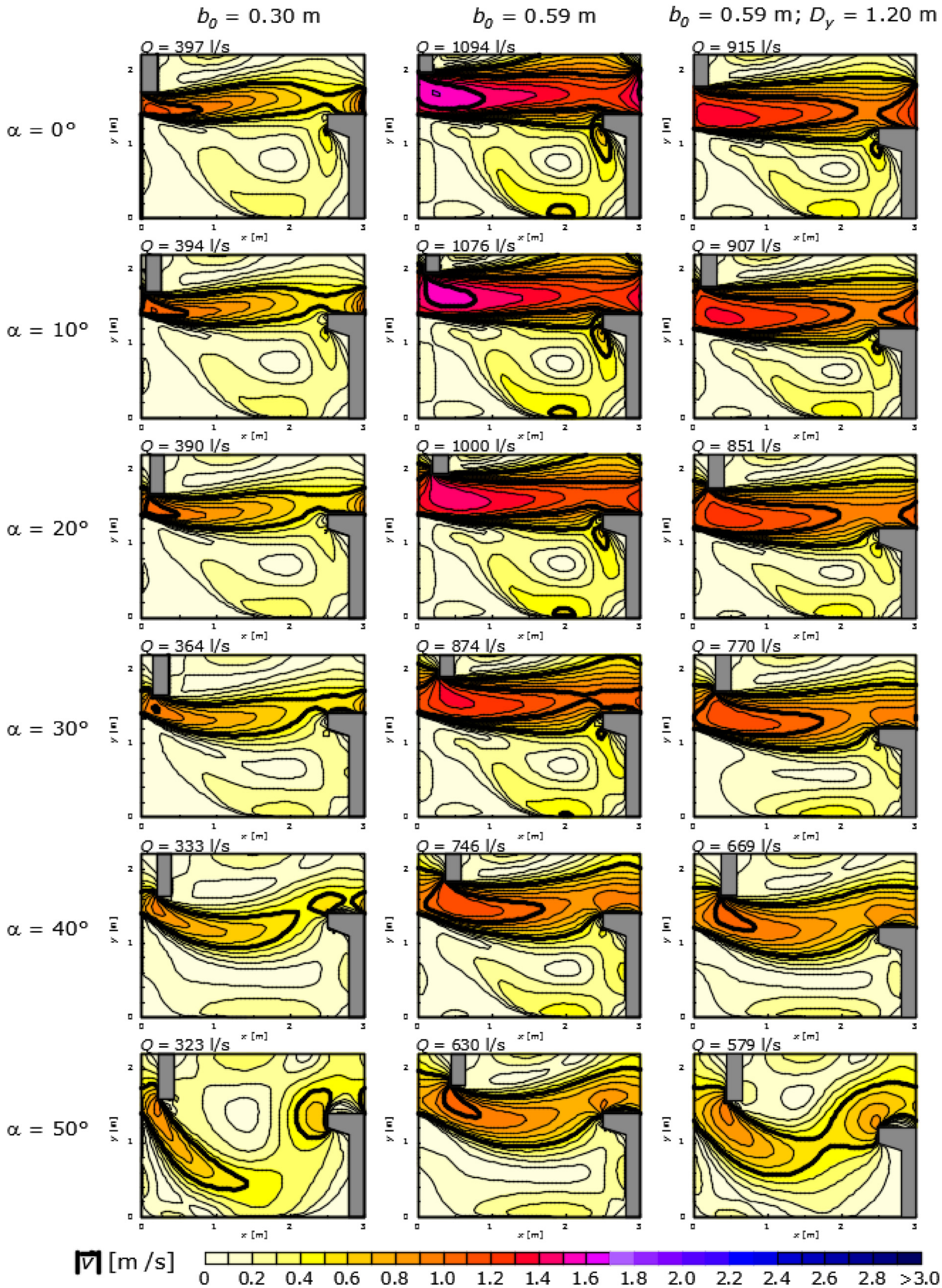

Fig. 13. Calculated isovels in the central pool of the VSF.

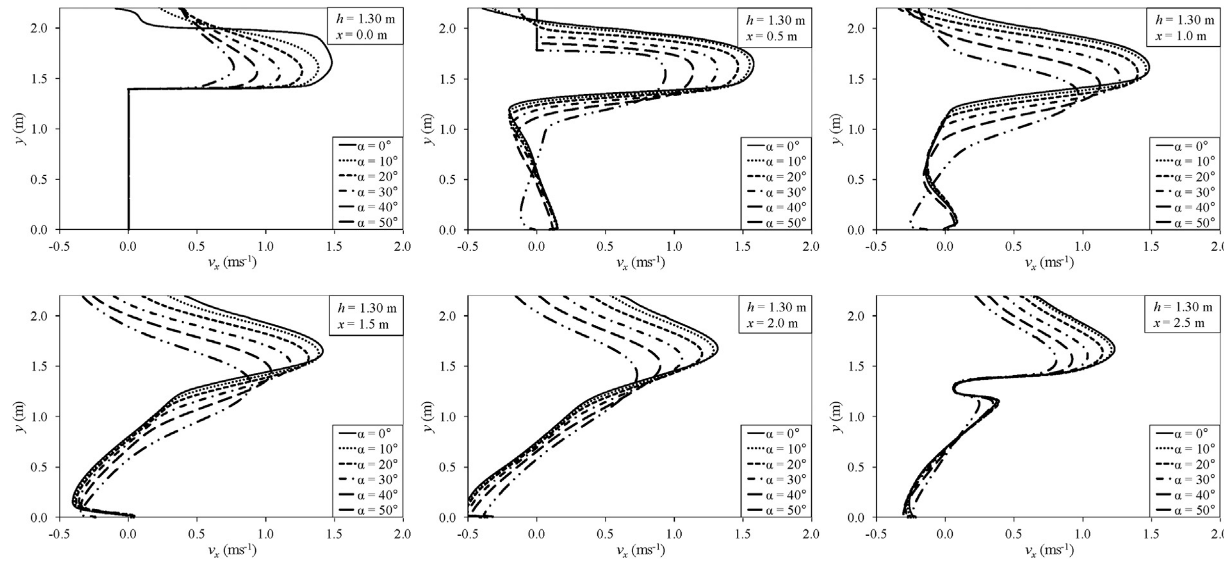

Fig. 14. Calculated longitudinal velocity components v_x at cross sections $x = 0.5$, 1.0, 1.5, 2.0 and 2.5 m for geometries with slot width $b_0 = 0.59$ m and different angle between baffles $\alpha = 0^\circ$, 10°, 20°, 30°, 40° and 50°.

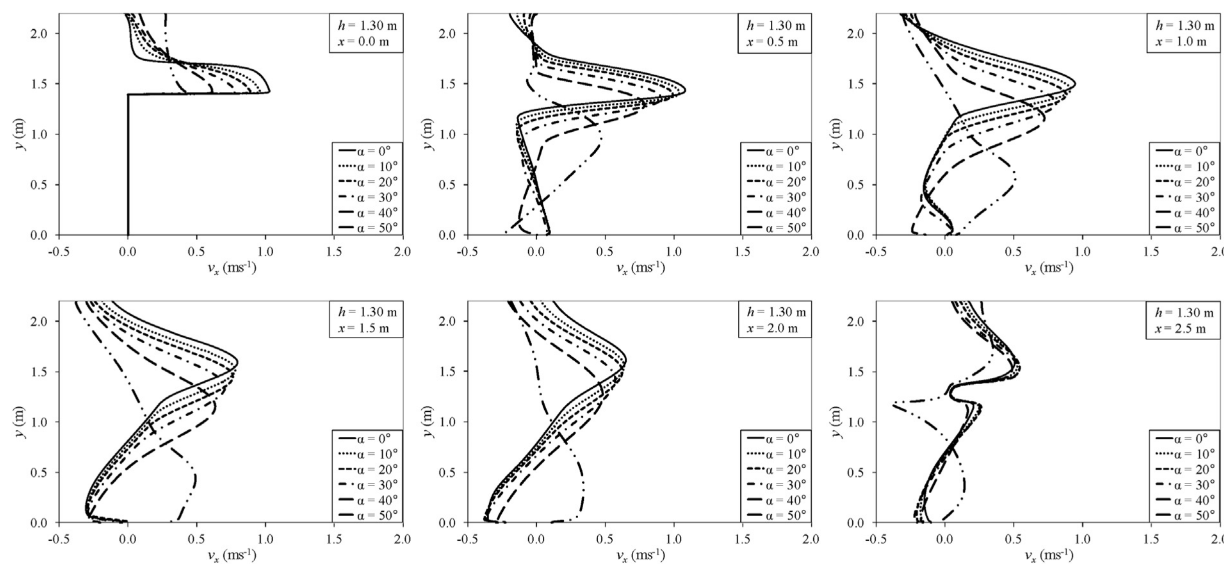

Fig. 15. Calculated longitudinal velocity components v_x at cross sections $x = 0.5$, 1.0, 1.5, 2.0 and 2.5 m for geometries with slot width $b_0 = 0.30$ m and different angle between baffles $\alpha = 0^\circ$, 10°, 20°, 30°, 40° and 50°.

Calculated isovels in the central pool of the VSF are shown in the third column in Fig. 13. Displacing the slot towards the VSF axis changes direction of the flow towards the wall opposite to the smaller baffle, causing recirculation zone between larger baffles to decrease, while the recirculation zone between smaller baffles increases. This effect is the largest when $\alpha = 50^\circ$. In case S3A5 the flow hits the lower (i.e. right-side) wall and interrupts larger recirculation zone between larger baffles, while in case S1A5 the flow moves closer to the left wall, i.e. more in the region between the slots.

3.6. Effect of water level difference between adjacent pools

All cases described in previous sections had relatively small Δh between adjacent pools. Such Δh was chosen on the basis of the referential VSF that operates at HPP Arto-Blanca, and it is this rather small Δh that leads to small velocities and thus allows migration of weaker swimmers. However, also VSFs with larger Δh are being constructed or already are quite common, as larger Δh require fewer slots to achieve a given difference between upstream and downstream elevation (of course, only better swimmers can cope with larger Δh).

Results of simulations with $\Delta h = 0.10$, 0.15 and 0.20 m are presented in Table 3 (cases S1A2H2, S1A2H3, and S1A2H4) and are compared with the case S1A2 where $\Delta h = 0.05$ m. Fig. 18 shows how the discharge increases with Δh.

At the same depth of the flow the discharge at $\Delta h = 0.20$ m is 77% larger than at $\Delta h = 0.05$ m. Even more pronounced is the increase of maximum velocities, as shown in Fig. 19.

It is evident that at $\Delta h = 0.20$ m the maximum velocity is 99% larger than at $\Delta h = 0.05$ m.

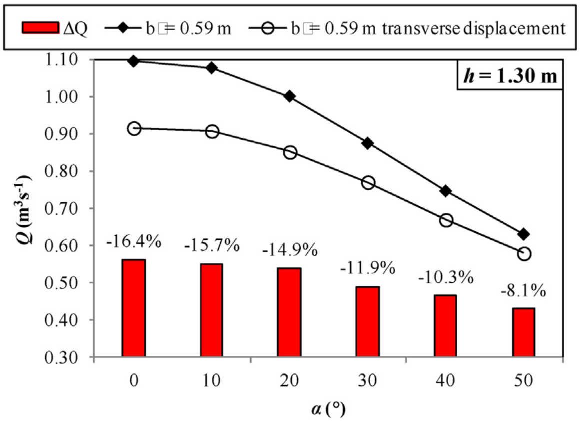

Fig. 16. Discharge at $h = 1.30$ m and $b_0 = 0.59$ m for different transverse positions of the slot.

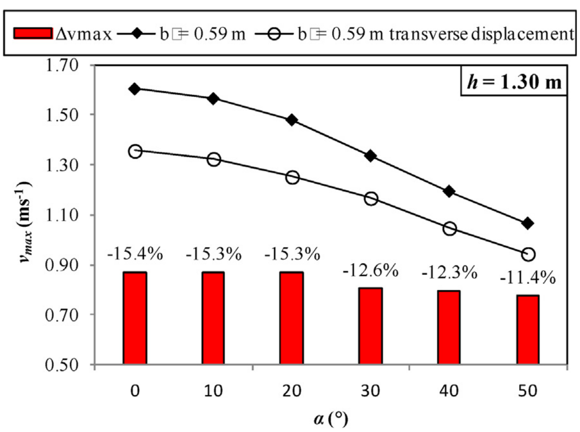

Fig. 17. Maximum velocities v_{max} for $h = 1.30$ m and $b_0 = 0.59$ m with various displacements of the slot.

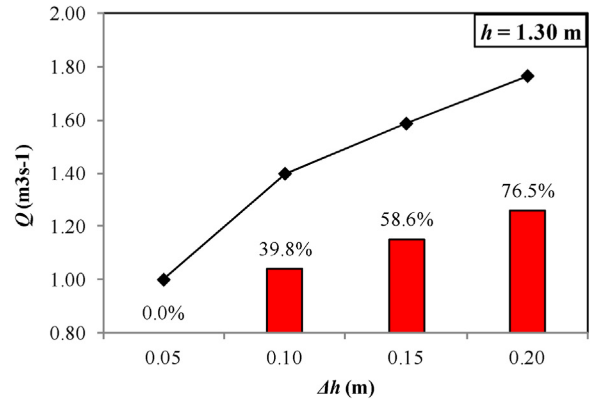

Fig. 18. Discharge at $h = 1.30$ m, $b_0 = 0.59$ m, $\alpha = 20°$ for $\Delta h = 0.05$, 0.10, 0.15 and 0.20 m.

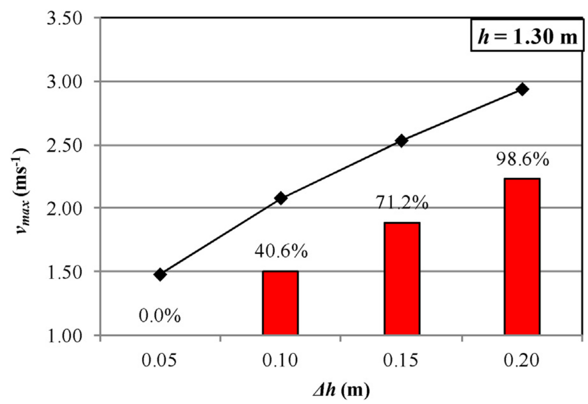

Fig. 19. Maximum velocities v_{max} at $h = 1.30$ m, $b_0 = 0.59$ m, $\alpha = 20°$ for $\Delta h = 0.05$, 0.10, 0.15 and 0.20 m.

4. Conclusions

Fish friendly flow conditions are necessary in an effective fishway. Research presented in this paper underlines the important influence of slot layout on flow characteristics. The following main conclusions can be drawn:

1) Depth discharge curves are strongly affected by the angle of deflection (α) between small and large baffles in a vertical slot fishway. So far – to our best knowledge – this effect has not been examined yet. With larger α up to 42% smaller discharges were obtained. There is also a big difference between specific discharges for two observed slot sizes. At small α discharge is almost three times bigger for the twice as wide slot opening. This is a consequence of side contraction of the jet at the slot which has bigger relative effect at smaller openings and higher

Calculated isovels in the central pool of the VSF are shown in Fig. 20. Increasing Δh between adjacent pools leads to the significant increase of velocities in the zone between slots, while other parts of the flow remain mostly unaffected. This can be attributed to the characteristics of the observed geometry (i.e. case S1A2 with relatively small angle between baffles and relatively large slot width), as water flows practically straight between the slots and there is no major circulation of the main flow. More comprehensive evaluation of the effect of Δh requires additional hydraulic modeling of specific cases of VSFs.

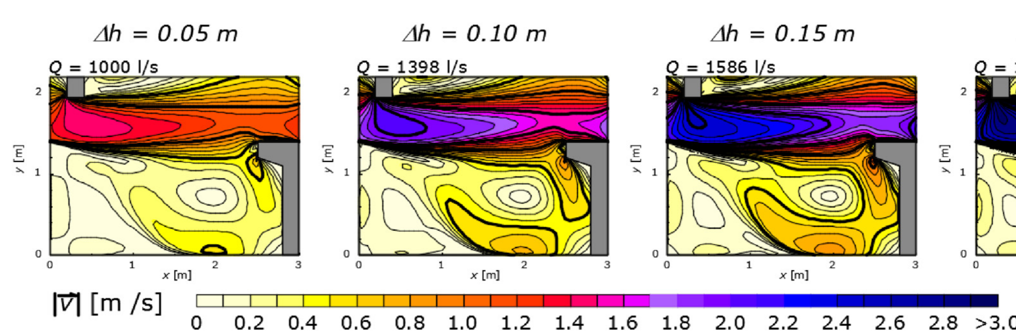

Fig. 20. Calculated isovels in the central pool of the VSF at $h = 1.30$ m, $b_0 = 0.59$ m, $\alpha = 20°$ for $\Delta h = 0.05$, 0.10, 0.15 and 0.20 m.

velocities (which are achieved at smaller α). There is also more energy dissipation in cases with smaller slots. At both geometry groups discharge drops with larger α, but for the wider opening, this effect is twice as large.

2) Angle of deflection strongly influences another important flow characteristic – maximum velocity. Up to 33.5% smaller $v_{\max}$ were obtained with larger α.
3) Maximum velocities calculated with PCFLOW2D model were significantly greater than analytically predicted by the over simplified formula. If velocities greater than predicted occur in the fishway, passage for the weakest swimmers is hindered or even prevented. This demonstrates the importance of hydraulic modeling in the process of an effective fishway design.
4) Even a relatively small change in the slot geometry (e.g. transverse displacement) can have a big impact on flow conditions in a fishway. Transverse displacement of the slot for 0.2 m decreases discharge for 8% to 16% and also decreases maximum velocities for 11% to 15%.
5) As expected the most important parameter that determines the discharge and maximum velocity is the water level difference between two adjacent pools (along with the slot dimension). At the same depth of the flow the discharge at $\Delta h = 0.20$ m is 77% larger than at $\Delta h = 0.05$ m. Even more pronounced is the increase of maximum velocities. At $\Delta h = 0.20$ m the maximum velocity is 99% larger than at $\Delta h = 0.05$ m
6) Optimization of VSF pool layout, especially the slot area, can allow reduction of cost in the construction of fishways, as it can lead to a design resulting in similar flow conditions at larger water level difference between adjacent pools and thus to smaller number of required pools.

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