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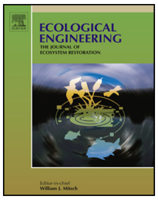

Study on flow characteristics in vertical slot fishways regarding slot layout optimization

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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 [$\mathrm{m}^2\,\mathrm{s}^{-2}$]
k'	Turbulent kinetic energy per unit mass [$\mathrm{m}^2\,\mathrm{s}^{-2}$]
L	Pool length [m]
n_g	Manning's roughness coefficient [$\mathrm{sm}^{-1/3}$]
Q	Discharge [$\mathrm{m}^3\,\mathrm{s}^{-1}$]
Q_{spec}	Discharge per unit width [$\mathrm{m}^2\,\mathrm{s}^{-1}$]
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 [$\mathrm{m}^2\,\mathrm{s}^{-3}$]

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 ($3.2 \times L$), 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 ($\Delta x = 0.01$ m; $\Delta y = 0.02$ 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 $\Delta t = 0.1$ 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. $\alpha = 0°$, 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 $\Delta s_y = 0.20$ 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, $\Delta h = 0.05$ m, with the water surface slope $S_0 = 0.0167$.

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