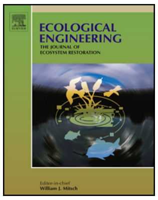
Ecological Engineering 86 (2016) 5–12

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng



Non-uniform hydraulic behavior of pool-weir fishways: A tool to optimize its design and performance

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ARTICLE INFO

Article history:
Received 20 May 2015
Received in revised form 12 October 2015
Accepted 13 October 2015
Available online 31 October 2015

Keywords:
Pool-weir fishways
Water levels
Flow discharges
Hydraulic design
Non-uniform performance

ABSTRACT

Fishways are structures that aim to achieve the free movement of fish through transversal obstacles in rivers. Despite the wide research about their performance, their hydraulic study and characterization has been so far limited to uniform hydraulic conditions which are usually difficult to reach in natural scenarios, either because inaccurate building or simply because the studied situations during the design of the prototypes are never encountered. This study aims to model pool-type fishways with submerged notches and orifices under different regimens, and uniform and non-uniform performances. For this purpose, the classical formulation used in their design has been modified by studying a real-scale fishway under 29 different hydraulic conditions. The proposed new formulation together with a logical bottom-up iterative calculation is able to predict the observed water level distributions. This study demonstrates that orifices and notches can be considered independently when estimating the water level distribution and discharge through the fishway, and the need to modify the classical formulation. The modeling under non-uniform scenarios will allow to enhance and adapt fishways to achieve a greater fish passage during longer time periods.

1. Introduction

Current society needs a large volume of fresh water to keep its present lifestyle, whether for irrigation, to generate electricity or to fulfill industrial, domestic and recreational needs. This, coupled with the exponential population growth, has caused the installation of a great number of infrastructures to collect and use this resource (Nilsson et al., 2005).

These structures are usually cross-sectional to the river, breaking its longitudinal connectivity and blocking the movement of some animals such as fish, which require different environments for some of the most important stages of their life cycle (Porcher and Travade, 2002; Branco et al., 2013). In the best case scenario, the impact of these barriers will cause the diminution in abundance of some species and, in the worst case scenario, their disappearance (Larinier, 2001; Lucas et al., 2001; Branco et al., 2012). It is in this context that fish passes or fishways arise to facilitate the free movement of fish fauna through these obstacles (Clay, 1995; FAO/DVWK, 2002; Larinier, 2002a).

Fish passes are a clear example of ecological engineering, since they are civil engineering devices, which can be natural-like according to their type, with a efficiency, understood as the proportion of fish from a given population that attempt and succeed in surpassing the obstacle, associated to their hydrodynamic variables (discharge, velocity, depth, power, turbulence fields, etc.) and a combination of swimming capacity, behavior, and motivation of fish (Bermúdez et al., 2010; Sanz-Ronda et al., 2015a). In addition, these hydrodynamic variables depend on environmental parameters, such as fluctuation in water levels upstream and downstream of the structure (Fuentes-Pérez et al., 2014).

In Europe, the installation of fishways has increased since the implementation of the Water Framework Directive (European Commission, 2000). However, the efficiency of these structures has been questioned due to the wide diversity of fish species and the great unknowns regarding their swimming abilities, migration periods, and motivation (Bunt et al., 2012; Williams et al., 2012). Therefore, biological and ecological studies are essential, particularly in less studied species, such as potamodromous species (Roscoe and Hinch, 2010; Bunt et al., 2012; Katopodis and Williams, 2012; Silva et al., 2012). In recent years, in the Iberian Peninsula,

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http://dx.doi.org/10.1016/j.ecoleng.2015.10.021
0925-8574/

Notation

The following symbols are used in this paper:

a_o	height of the orifice (m)
B	pool width (m)
b_n	notch width (m)
b_o	orifice width (m)
C_o	discharge coefficient for orifices
C_p	discharge coefficient for the plunging regimen
C_s	discharge coefficient for the streaming regimen
e	thickness of the cross-wall (m)
g	acceleration due to gravity (m/s^2)
h_0	mean water level of the flow in the pool in relation to the center of the pool (m)
h_1	mean water level of the flow in the pool in relation to the upstream of the notch (m)
$h_{1,i}$	mean water level of the flow in the pool in relation to the upstream of the notch in the cross-wall number i (m)
h_2	mean water level of the flow in the pool in relation to the downstream of the notch (m)
$h_{2,i}$	mean water level of the flow in the pool in relation to the downstream of the notch in the cross-wall number i (m)
i	cross-wall number
L	pool length (m)
n	total number of cross-walls
p	sill height (m)
Q	discharge or flow rate ($Q = Q_n + Q_o$ for combined scenarios) (m^3/s)
Q_n	discharge through notches (m^3/s)
Q_o	discharge through orifices (m^3/s)
R^2	determination coefficient
S	slope of the fishway (m/m)
VDP	volumetric dissipation power (W/m^3)
β_0, β_1	dimensionless coefficients for Eq. (4)
ΔH	difference in water level between pools or head drop ($\Delta H = h_1 - h_2$) (m)
ΔZ	topographic difference between cross-walls (m)
ρ	density of water (kg/m^3)
σ^2	variance

this knowledge gap has been addressed by a number of studies (Santos et al., 2012; Silva et al., 2012; Alexandre et al., 2013; Branco et al., 2013; Sanz-Ronda et al., 2015a, among others). From a practical viewpoint, all of these studies should show a correct hydraulic characterization in order to enable the application of the collected knowledge to new designs.

The most common fishways are pool-type fishways (Clay, 1995; Martínez de Azagra, 1999; FAO/DVWK, 2002; Puertas et al., 2012). They consist of a sloping-floor channel divided by weirs, cross-walls, or baffles into a series of pools, distributing the height to be crossed by the fish (H) into several smaller water drops (ΔH) (Larinier, 2002a). A further classification of pool-type fishways is possible according to the type of connection between pools, being one of the most popular those composed by submerged notch and orifices (SNOF) (Larinier, 2008) (Fig. 1).

This type of fishways can have two different performances or regimes, streaming or plunging, depending on whether the downstream water level (h_2) influences or not, respectively, upstream water level (h_1) (Rajaratnam et al., 1988; Larinier, 2002a). Likewise, it is also possible to define different sub-regimes within these two main performances (Ead et al., 2004).

Pool and weir type fishways have been commonly designed with notches working under plunging conditions (Kim, 2001; Yagci, 2010; Santos et al., 2012). However, in SNOF, the notch is designed to operate in a streaming regimen, which has been shown to enhance the upstream movements of species like Iberian barbel (*Luciobarbus bocagei*), Iberian chub (*Squalius pyrenaicus*) or Iberian nase (*Pseudochondrostoma duriense*), and seems to be more suitable for rivers with fish with wide morpho-ecological traits (Silva et al., 2009; Branco et al., 2013; Sanz-Ronda et al., 2015b). Furthermore, SNOF shows additional benefits such as alternating submerged orifices from side to side. This orifice configuration has shown higher rates of passages than other configurations for the Iberian barbel (Silva et al., 2012).

Previous reports have widely studied similar type of designs using either classical weir-discharge equations (Martínez de Azagra, 1999; Kim, 2001; FAO/DVWK, 2002; Larinier, 2002a; Boiten and Dommerholt, 2006; Santos et al., 2012) or dimensionless relationships (Rajaratnam et al., 1989; Ead et al., 2004; Yagci, 2010); however, these studies were always performed under uniform operational conditions (same mean water level (h_0) and ΔH in all pools). This simplification limits the interpretation of their behavior once they are installed because fishways will work under changing non-uniform conditions which may decrease their efficiency (Fuentes-Pérez et al., 2014), due to large variations in the hydrological regime of rivers, as it is the case in the Mediterranean regions (Gasith and Resh, 1999), or due to an inaccurate execution. That is to say, the boundary conditions and its geometry will determine not only the regimen of the fishway (plunging, streaming or mixed) but also the water level distributions (non-uniform or uniform profiles), which may modify the observed efficiency in laboratory models.

In order to solve the above mentioned issues, this study aims to define the operational conditions of submerged notch and orifice fishways both under different regimens and uniform and non-uniform performances, modifying the classical formulation that has widely been used to describe their behavior. This will allow to describe and predict their functioning, i.e. the hydraulic variables, under natural scenarios, and evaluate the influence of modifications in the design of the fishways regarding the necessities of the target species, making possible the improvement of fishways efficiency. The above is summarized in the main following contributions: (i) new definition of calculus equations for SNOF under uniform and non-uniform performance; (ii) evaluation and validation of predictability of water levels of the proposed equations; (iii) theoretical demonstration of the use of the defined equations and algorithm to improve the fishway efficiency.

2. Materials and methods

2.1. Fishway description

The experiments were conducted in a real-scale SNOF with a design discharge of 0.278 m^3/s (Fig. 1). This structure is located in the Tormes River near the village of La Flecha (Salamanca, Spain) and it is characterized by small deviances from design parameters (±0.010 m) (Sanz-Ronda et al., 2010). The average topographic difference between cross-walls ($\Delta\bar{Z}$) is 0.247 m, that is to say, it has an average slope [$\bar{S} = \Delta\bar{Z}/(\bar{L} + \bar{e})$, where $\bar{L}$ stands for the length of the pool and $\bar{e}$ for the thickness of the cross-wall] of 0.088 m/m (Fig. 2). Cross-walls consist on an alternative succession of submerged hydrodynamic notches [mean width ($\bar{b}_n$) of 0.310 m and mean height of the sill ($\bar{p}$) of 0.917 m] and bottom orifices [mean width ($\bar{b}_o$) of 0.197 m and mean height ($\bar{a}_o$) of 0.191 m].

The geometrical parameters were measured by topographic surveying with a total station Leica TC307 to a precision of 0.001 m.