DESIGN OF ROCK RAMPS FOR ENSURING FISH MIGRATION

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In many European countries, hydropower production is one of the main factors affecting the quality of river ecosystems, and altering connectivity in rivers. Many fish species depend on an intact longitudinal connectivity to be able to migrate. Given the characteristics of small hydropower sites in Romania and the species that perform migrations, the high roughness channels solution represents a good choice for fish passage. This paper presents some aspects regarding the rock ramps which are simple solutions for fish passage over low obstacles such as culvert outlets and small weirs. In Romania many existing culverts or weirs were designed without fish passage in mind and others are no longer fish-friendly because they have deteriorated over time. In this regard we propose the study of such ramps and also to analyze different constructive options depending on the rockfill configuration and flow rates through these facilities. Different scenarios will be analyzed: rectangular, trapezoidal or semicircular section of the channel, various stair shapes, and the optimum solution, both hydraulic and biological, will be identified.

Keywords: fish passes, fish ladders, rock ramp, rivers longitudinal connectivity.

1. Introduction

Providing free passage of migratory fish is an imperious requirement of Water Framework Directive (WFD), and, in the same time used as an indicator for assessing the potential and ecological status of water bodies. As the hydropower production is one of the main technologies influencing the river water quality, the researchers have this concern regarding the environmental impact mainly due to ecological aspects but also to water flow regimes [1, 2]. Fish passes can contribute to achieve WFD objectives by ensuring the free movement of fish and other mobile aquatic species (invertebrates and plankton) for breeding or feeding [3].

Many types of technologies are available for passing fish upstream or downstream dams. Fish pass designs vary in form, function and complexity depending on the site and the target species, so they were classified in six categories: pool and weir passes, baffled passes, fish locks, pre-barrages, rock

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ramp passes and bypass channels [4]. This study is limited to rock ramps, as part of the hydro energetic micro potential planning and design.

The rock ramps are in fact channels with high roughness, constant slope and without large structural bedforms. They are suitable to be used below culverts or as substitute for steep concrete weirs up to about 1.5 m in height. Boulders are placed on the stream bed in such a manner that a zig-zag stairway to be attained, thus assuring a slow water flow. Also, small pockets of still water appear in which fish can rest. In order to assure the proper water depths for fish at a variety of flows, the cross section from bank to bank should form a shallow "v". The fish ramp design follows primarily to simulate the natural rapids river or streams. Rock ramps represent the best solution for elevation differences less than 1.5 m and the slopes must be below 4%. The focus of fish ramp design is to simulate the structural variety of natural rivers with more or less steep slopes. Larger rock ramps structures have the potential of becoming unstable since the water velocities in the downstream are higher. Furthermore, as the ramp length increases, the risk of forming an exhaustion barrier to fish appears. Thus, for higher elevation differences, rock ramps are usually combined with large pools, forming a system of chutes or with small pools scattered within rock ramps.

2. Design and dimensions principle of fish ramps

For the bottom sills the most used construction types are: rockfill construction; block-stone construction or dispersed construction.

Usually, the substructure contains crushed rockfill placed in layers accordingly with the rules for base layers. It can also be built up on geotextile material or even on a sealing layer [5]. The use of solid material for the entire ramp body may be needed for stability reasons. The surface layer of the concrete ramp body must be roughened, which is usually done by inserting a layer of gravel or rubble into the concrete before it sets.

Regarding the bypass channels, the next may be used with fish ramps also:

- single, large, perturbation boulders, placed in the channel, which increase the roughness of the ramp and provides resting places and shelters for fish;
- irregular boulder bars, which form pool structures, and water can flow either through or over these bars.

For weirs, the necessity of controlling of water levels and the available adequate discharge must be considered. Usually, a portion of the weir is converted to a rough ramp of reduced width (a so-called fish ramp), assuring thus the migration of the aquatic fauna [6].

Fish ramps are usually combined with the weirs for concentrating the discharge available at low and mean water level. The water depth and velocity is attained by placing the boulders so as cascades appear. The discharge from upstream migration period defines the width of the ramp. The average speed in open channels is given by [7]:

$$v_m = \frac{1}{\sqrt{\lambda}} \sqrt{8 \cdot g \cdot R \cdot I} \tag{1}$$

where λ is the total resistance coefficient, R is the hydraulic radius, I is the ramp slope and g is the gravitational acceleration [8].

The total resistance coefficient in bypass channels and fish ramps equipped with boulders (figure 1) is determined with Rouvé formula, since the flow resistance of the boulders conceals the influence of the bottom roughness. The Rouvé formula is:

$$\lambda = \frac{\lambda_s + \lambda_0 \cdot (1 - \varepsilon_0)}{(1 - \varepsilon_v)} \tag{2}$$

where ε_0 is ratio between the immersed volume of perturbation boulders and total volume, ε_v is the ratio between the surface area of perturbation boulders and total basal area, λ_s is resistance coefficient of perturbation boulders and λ_0 is resistance coefficient for running waters with a rough bottom, under normal flow conditions.

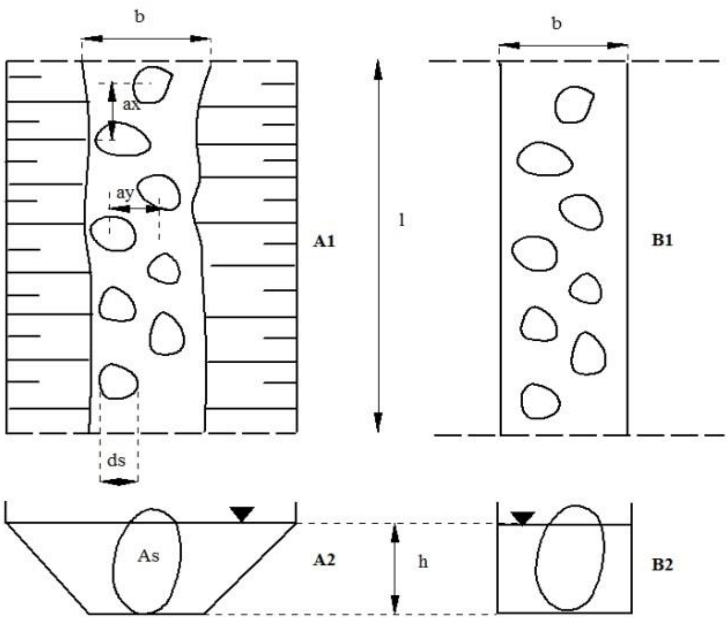

Fig. 1. Bypass channel with perturbation boulders (A1 and A2 – trapezoidal section, B1 and B2 rectangular section).

The resistance coefficient for running waters, λ_0 is computed with the formula:

$$\frac{1}{\sqrt{\lambda_0}} = -2\log\frac{k_s/R}{14.84} \tag{3}$$

which is valid for $k_s < 0.45\ R$, where the equivalent sand roughness diameter, k_s, is replaced for rockfill bottom, by the average rock diameter d_s, and, in the case of a mixed bottom substrate, by grain size diameter d_{90} [9].

The resistance coefficient of perturbation boulders λ_s is given by:

$$\lambda_s = 4 \cdot c_w \frac{\sum A_s}{A_{tot}} \tag{4}$$

where A_s is wetted areas of the perturbation boulders, A_{tot} is the unobstructed flow cross-section and c_w is the form drag coefficient (≅1.5).

The maximum flow velocities in the cross-sections between the boulders are:

$$v_{max} = \frac{v_m}{1 - \sum A_s / A_{tot}} \tag{5}$$

with ΣA_s is sum of the wetted areas of all the boulders within an extremely constricted cross-section [10].

The selected slopes, boulder spacing and boulder diameters should be such that, on average, subcritical flow appears. Changes in the flow pattern must only be allowed in the narrow gaps between the boulders if at all.

3. Fish ladders: sizing and discussion

The most common migrating fish species in Romania are trout, grayling, chub and roach. Therefore, in the following we intend to determine the hydraulic characteristics for a fish ramp appropriate to this situation. Thus, we analyzed a ramp with 26 m longer and 1.3 m width in two particularly case, with trapezoidal and rectangular cross-sections. The body of the ramp is to be built of quarry-stones, whose roughness is estimated at 0.14 m. The water depth is 0.35 m and the flow velocity was reduced and fish shelters created by perturbation boulders that have an edge length of d_s = 0.6 m. The clear distance between the big boulders was 0.4 m.

Firstly, the hydraulic parameters of the two ramp types, as a function of the channel slope were determined. The channel slope values were varied between

(1:20 - 1:30) and the mean and maximum speed values (figures 2 and 3), the width related discharge and the flow regime (based on the Froude number) were computed (figures 4 and 5).

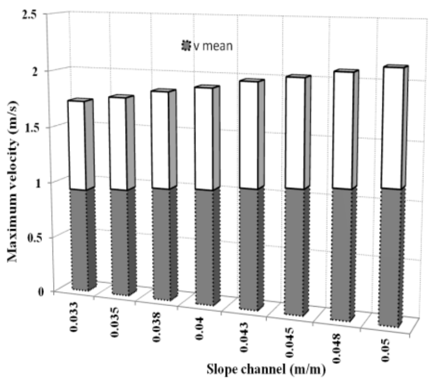

Fig. 2. Velocity for rectangular channel.

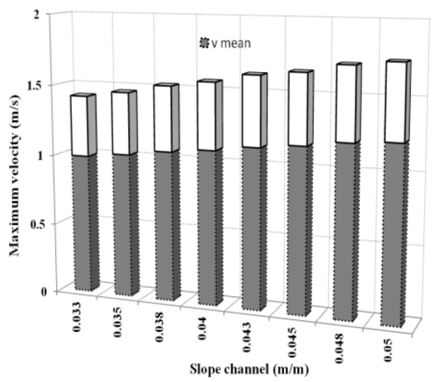

Fig. 3. Velocity for trapezoidal channel.

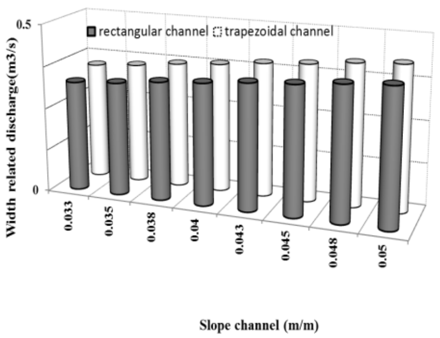

Fig. 4. Width related discharge for rectangular and trapezoidal channel.

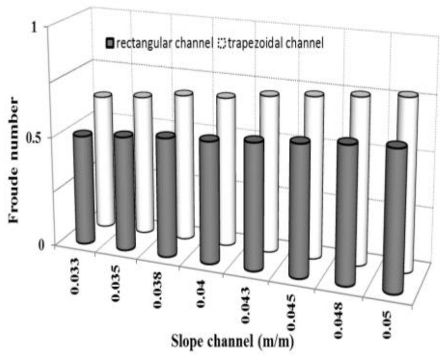

Fig. 5. Froude number for rectangular and trapezoidal channel.

For both channels the increase in slope channel lead to greater values of the maximum and average speeds. However, considering their applicability to low head hydropower, average speeds greater than 0.8 m/s and speeds in the narrow section higher than 2 m/s cannot be accepted. The applicability of these ramps, for the studied geometry, narrows down for thalweg slopes between 1:30 and 1:28.

Analyzing the width related discharge for the two channels, it can be noticed, as expected, that the carrying capacity of the trapezoidal channel is greater than the one of the rectangular channel, for the same bottom width. This is obviously an advantage for this channel, for low water levels and for flooding periods as well.

A final comparative analysis targeted the flow regime in the two types of channels. Thus, for each channel geometry the Froude number was calculated, for the average flow and for the flow in the narrowest section as well. As a result, the Froude number values are mostly subunitary, which indicates a slow flow regime, suitable for a migration channel of fish fauna. The rectangular channels, however, presents the major disadvantage of instability and, as a result, the trapezoidal channels are preferred.

The variations of hydraulic parameters as a function of the thalweg slope were determined. The Froude number corresponding to the narrow sections are almost identical for the two channels, and, for values of thalweg slope less than 1:26, they are subunitary.

For greater slopes however, the flow regime become rapid, and the hydraulic jump may appear, but, since the Froude number is below 1.7, the hydraulic jump is less pronounced. Given the instability and the high flow speed of rectangular channels, the trapezoidal ones were mainly studied hereinafter. Thus, for channels with thalweg slopes between 1:30 and 1:28, different constructive variants, with side slopes between 1:1.5 and 1:3.5, are considered (figure 6).

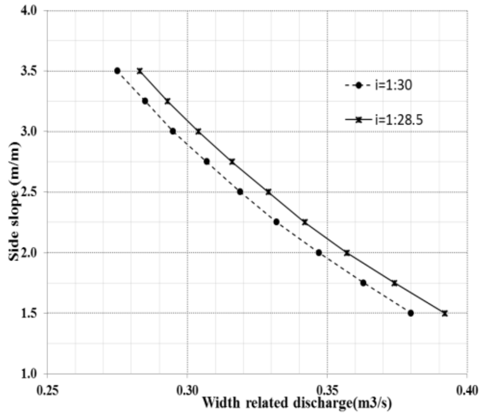

Fig. 6. Dependence between widths related discharge and side slope for trapezoidal channel.

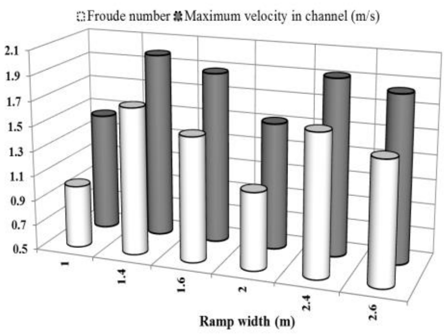

Fig. 7. Maximum velocity and Froude number variation with ramp width for trapezoidal channel for rectangular and trapezoidal channel.

Also, six cases were studied to determine the carrying capacity of channels for diverse values of channel widths and different arrangement of boulders (fig.7):

- one boulder maximum on a row (b = 1m);
- alternative lines, with one boulder and two boulders respectively (b = 1.4; 1.6 meters);

- two interposed boulders on a row (b = 2 m);
- alternative lines, with two and three boulders respectively (b = 2.4; 2.6 m).

It can be noticed that the most advantageous solutions are the ones with an equal number of boulders on consecutive rows. In these situations, the flow regime and the flow rates are proper for fish migration.

4. Conclusions

Fish ramps are vital features in improvement of aquatic ecosystems in surface waters and their function must be faultless in order to restore the free passage in rivers. Those solutions for assuring the migration of the aquatic organisms are adapted to low and very low head hydropower and to the migration abilities of the characteristic fish population.

Placing big boulders lead to an irregular arrangement with increased roughness. The water flows around or slightly over the boulders at low and medium discharge. The water depth rise and the water velocities are reduced. Usually, the values of boulders position are: $a_x = a_y$ = 2 to 3 d_s, and the clear distance should be at least 0.3 to 0.4 m. Their height above the bottom must be one half or two third of their depth. Also, the boulders must have such dimensions and weight which prevents any unauthorized displacement.

Generally, the fish ramps requirements are: mean depth of water: h = 30 to 40 cm; slope: I < 1:20 to 1:30; flow velocity: v_{max} = 1.6 to 2.0 m/s. The bottom substrate, it must be rough, continuous. Also, the fish ramps must have deep zones and resting pools to facilitate upstream migration. For ramps longer than 30m, gentle slopes and deeper resting pools must be used.

The main factor affecting the stability of fish ramps is scour, due to retrogressive erosion. This may be solved by placing multi-layered rock fills, which secure the river bottom just downstream of the ramp.

Analyzing the solution presented in this paper, we can state that for the most common fish species in Romania (trout, grayling, chub, roach and dace) the best fish ramps solution is the trapezoidal one, of 1-2m bottom width, the thalweg slope of 1:30 and a slide slope around 1:2. Such geometry allows maintaining slow flow and flow rates lower than 2 m/s, beneficial for fish movement.

R E F E R E N C E S

[1]. *Diana Maria Bucur, F. Bunea, G. D. Ciocan, G. Băran and E. C. Isbăşoiu*, "Water parameters evolution in a hydroelectric site", in Environmental Engineering and Management Journal**,** **vol. 9**, 2010, pp. 1539-1544.

[2]. *R. Roman, R. G. Iovanel, I. S. Grecu, G. Dunca and D. M. Bucur,* "Experimental evaluation of roughness coefficient of a HPP headrace channel", in U.P.B. Sci. Bull., Series D, **vol. 77**, no. 3, 2015, pp. 233-240.

[3]. *S. Schmutz*, *C. Mielach*, "Measures for ensuring fish migration at transversal structures", in ICPDR – International Commission for the Protection of the Danube River, 2013.

[4]. ***, Hydraulic calculations of running waters – DVWK – Guidelines 220/1991.

[5]. ***, Reclamation – Managing water in the west – Rock ramp design guidelines, U.S. Department of the Interior Bureau of Reclamation Technical Service Center Denver, Colorado, 2007.

[6]. *R. Kapitzke*, Culvert fishway planning and design guidelines. Part H – Rock ramp fishways for open channels, School of Engineering and Physical Sciences, James Cook University, Australia, April 2010.

[7]. ***, Fish passes – Design, dimensions and monitoring, Rome, FAO/DVWK, 2002.

[8]. *A. Ciolac*, "Migration of fishes in Romanian Danube River", in Applied Ecology and Environmental Research, **vol. 2**, no. 1, 2004, pp. 143-163.

[9]. *C. H. Clay*, Design of fishways and other fish facilities, 2nd edition, CRC Press, Boca Raton, Florida, USA, 1995.

[10]. *** Technologies for passing fish at large dams, State of California – The California Natural Resources Agency Department of Water Resources, FloodSAFE Environmental Stewardship and Statewide Resources Office, June 2013.