Variant proposal of the fish passage using technical and close to nature approach

Alexandra Vidova[1]*, and *Lea* Cubanova[1]

[1]Faculty of Civil Engineering STU, Department of Hydraulic Engineering, Radlinského 2766/11, 810 05 Bratislava, Slovakia

Abstract. Passing barriers on streams is nowadays an important activity for the protection and restoration of water ecosystems, and one of the goals of the European Union in the field of water habitat protection, that means barriers on waterways should be made suitable for the migration of aquatic fauna. The design and hydraulic parameters of these structures are fundamental in their design process, determining the effectiveness of fish passes in facilitating safe and efficient fish migration. These parameters should consider the specific needs and behaviours of the target fish species. It should provide suitable water depths, velocities, and facilitate fish movement upstream or downstream. The choice between technical fish passes, such as slot pass, and nature-like ones, such as rock ramps, is crucial. The selection of the right type also depends on various factors including the topography, hydrology and the species of fish being targeted. However, it is easier to achieve the parameters by technical fish pass. The proposed fish pass and its parameters were simulated by 1D mathematical model HEC-RAS. It was very difficult to design and fulfil all parameters according to the legislation. For more accurate results is recommended use of 2D or 3D models, or physical models.

1 Introduction

Fish passes serve as infrastructure for facilitating fish migration past anthropogenic barriers in river systems, thereby promoting ecological connectivity and sustaining aquatic biodiversity. This introduction delineates the comparative advantages of integrating technical and nature-inspired designs within fish pass construction and evaluates their efficacy through one-dimensional hydraulic modelling using HEC-RAS software [1]. Traditional fish pass structures often prioritize technical efficiency over ecological compatibility, resulting in suboptimal passage conditions for various fish species [2]. Conversely, nature-inspired designs seek to emulate natural stream environments, utilizing features such as riffles, pools, and meandering channels to enhance hydraulic complexity and promote fish passage. Through the utilization of HEC-RAS, a widely employed tool for hydraulic modelling, the hydraulic performance of both traditional and nature-inspired fish passes can be quantitatively assessed, aiding in the optimization of passage design for different river configurations and flow conditions [3-5]. By synthesizing technical expertise

---

* Correspondng author: alexandra.vidova@stuba.sk

with ecological principles and computational modelling. This study aims to advance the development of fish passes that effectively balance engineering requirements with ecological functionality, thereby contributing to the conservation and restoration of aquatic ecosystems [6, 7].

2 Material and methods

This article employed simulations to compare the effectiveness of technical fish pass and close to nature approach designs. The proposed fish pass is situated near a planned small hydropower plant on the Hornád River in Spišské Vlachy, Slovakia (Fig. 1). The Hornád River exhibits a natural channel morphology in this area. Ichthyological survey and adherence to the Methodological Guidelines for fish pass design classify this specific area of the Hornád River as belonging to the grayling zone, this categorization will influence the selection of target fish species for the fish pass design [8].

Fig. 1. Location of the small hydropower plant on the map.

2.1 Fish ramp

The fish ramp is a nature-like fish pass design that mimics natural streambed characteristics to facilitate fish migration (Fig. 2). It features a low angle sloping channel with a roughened bottom substrate, designed to create gradual water velocities and turbulent flow conditions. This design caters to a broad range of fish species, particularly those with weaker swimming abilities. Compared to technical fishway designs like pool and weir types, fish ramps offer a more ecologically sensitive solution by minimizing habitat disruption and promoting natural migration behaviour.

Fig. 2. Illustration of a fish ramp.

Recommended design parameters of the fish pass [8]:

- maximum cross-sectional flow velocity 1.5 m·s^{-1},
- maximum longitudinal slope: 1:50 (2%),
- minimum water depth in streamline 0.30 m,
- minimum water level width 4,0 m.

A single trapezoidal fish ramp geometry was developed in HEC-RAS software to simulate hydraulic parameters. The channel bottom width was set at 3.0 m, with 1:2 bank slopes (Fig. 3). The lateral slope was designed at a 2% slope as recommended by the Methodological Guidelines [8]. A Manning's roughness coefficient of n = 0.045 was assigned, reflecting the use of quarry stone lining throughout the wetted perimeter [9].

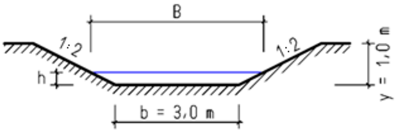

Fig. 3. Cross section of the fish ramp.

In the geometry file, fifty-two profiles were designated along a 156 m ramp length, with a spacing of 3.0 m between each profile. A 5.0 m long resting pool was inserted after an elevation gains of 2.0 m. To create flow obstructions within the fish pass, boulders were strategically placed using HEC-RAS's Obstructions function. An alternating pattern was inserted in geometry profiles featuring either two or three boulders (Fig. 4). The boulder dimensions were set alternately: 75 cm width for profiles with two boulders and 50 cm for those with three. Their height was designed to protrude slightly above the water level. The expansion and contraction coefficients were set up to 0.5 and 0.3 to account for the variation in geometry caused by the boulders. These coefficients are commonly used in bridge construction practices and were deemed appropriate to represent the expanding and constricting flow patterns caused by the boulders within the fish pass [10, 11]. Boundary conditions were set using various discharge values (0.8 m³·s^{-1}, 1.0 m³·s^{-1}, 1.5 m³·s^{-1}, 2.0 m³·s^{-1}) and normal depths specified at both fish ramp edges, specified via longitudinal bed slope of 0.02. Due to the variations in channel geometry, non-uniform steady flow was expected during simulations.

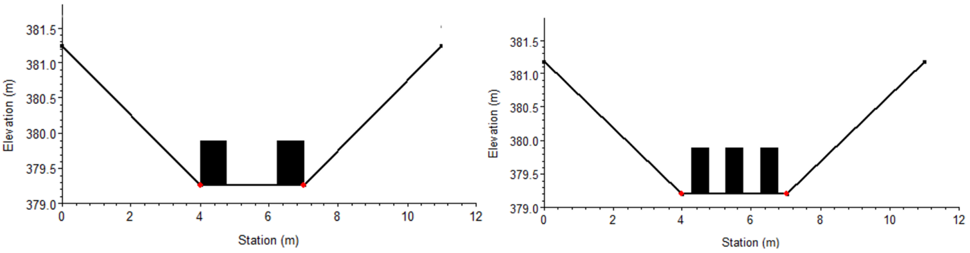

Fig. 4. An alternating pattern of two and three boulders in ramp cross section.

2.2 Vertical slot fish pass

Vertical slot fish passes represent a technical design of fish pass. They function by utilizing a series of vertical slots within a steeply inclined channel. Water flows through these slots, creating a stepped series of high-velocity zones interspersed with low-velocity pools. This alternating flow pattern allows fish to exploit the slower water areas for resting and utilize burst swimming to navigate the higher velocity zones. Vertical slot fishways are particularly well-suited for situations with limited space constraints due to their compact design. However, their efficiency can be lower for some fish species, particularly those with weaker swimming abilities, compared to nature-like designs like fish ramps.

Recommended design parameters of the vertical slot fish pass [8]:

- maximum vertical flow velocity in the slot between pools 1.8 $m \cdot s^{-1}$,
- maximum difference in water levels of neighbouring pools 17 cm,
- minimum width of the flow slot 50 cm,
- minimum water depth in the slot 40 cm,
- minimum water level width 4.0 m,
- length of water pools (minimum cross-walls spacing): 2.0 to 3.0 m,
- recommended pool water volume over 4.0 m^3,
- maximum water energy after dissipation in the fish pass pool 200 $W.m^{-3}$.

Formula for energy dissipation calculation:

$$P_b = \frac{\rho g Q \Delta h}{V_b} \tag{1}$$

where:

Q – flow ($m^3 \cdot s^{-1}$),
g – gravity of Earth (9.81 $m \cdot s^{-1}$),
ρ – water density (1000 $kg \cdot m^{-3}$),
Δh – difference in water levels of neighbouring pools (m),
V_b – pool water volume (m^3).

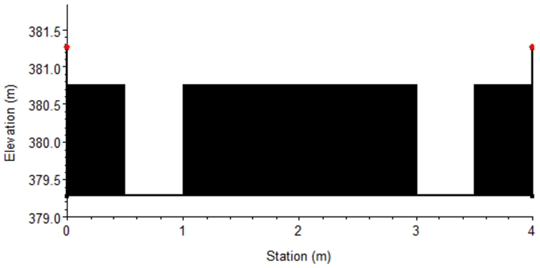

Fig. 5. Two vertical slots in cross section of the designed vertical slot fish pass.

The simulated vertical slot fish pass included 17 pools, each 3.0 m long and separated by 0.2 m thick vertical slots. This geometry contained 19 profiles and a total fish pass length of 59.8 m. To facilitate fish migration after a 2.0 m elevation gain, a 5.0 m long resting pool was designed. The slope was determined as the head (3.2 m) divided by the fish pass length excluding the resting pool (54.6 m), resulting in a 5.53 % longitudinal slope. A vertical slot pass design was conceived as a rectangular channel, measuring 4.0 m wide and 2.0 m height. A Manning's roughness coefficient of n = 0.040 was determined to represent the channel lining, consisting of rough materials like quarry stone. The Obstructions function was utilized to strategically place two vertical slots with a width of 0.5 m within each vertical cross wall (Fig. 5). To improve the model's accuracy in capturing the channel geometry, a clean profile (without obstructions) was inserted behind each vertical cross wall. This approach ensures that HEC-RAS considers the temporary widening of the channel before the next partition during flow calculations. To account for the variations in channel geometry caused by the obstructions, expansion and contraction coefficients were set to 0.5 and 0.3 [10]. Additionally, to promote flow complexity and potentially reduce water velocity within the pools, a boulder was placed 0.3 m downstream from each slot within the respective pool. Boundary conditions were same as in the previous fish pass and set using various discharge values (0.8 $m^3 \cdot s^{-1}$, 1.0 $m^3 \cdot s^{-1}$, 1.5 $m^3 \cdot s^{-1}$, 2.0 $m^3 \cdot s^{-1}$) and normal depths specified at both fish ramp edges, specified via longitudinal river bed bottom slope of 0.0553. Non-uniform steady flow was designated as the anticipated flow regime within the fish pass during simulations.

3 Results and discussion

The analysis of the fish ramp design revealed a critical discrepancy in water velocities. Simulated velocities exceeded the legislative limit of 1.5 $m \cdot s^{-1}$ for all simulated flow rates (Table 1). This poses a potential barrier to fish pass, as excessive velocities can hinder or even prevent upstream migration. While water depth met the design criterion of minimum water depth of 0.3 m for most discharges, a single case at the lowest discharge (0.8 $m^3 \cdot s^{-1}$) fell below this limit. However, the minimum water level width remained within acceptable limits for all simulated scenarios (Fig. 6, Fig. 7). These findings highlight the need for further optimization of the fish ramp design to ensure velocities comply with guideline´s recommendations and water depth remains sufficient for fish passage across the entire range of expected flow conditions.

Table 1. Resulting values for the fish ramp (in red are values out of limit).

Discharge	**Maximum Flow Velocity**	**Minimum Water Depth**	**Minimum Water Level Width**
Q	v_{max}	h_{min}	B_{min}
$[m^3 \cdot s^{-1}]$	$[m \cdot s^{-1}]$	[m]	[m]
0.8	1.63	0.29	4.16
1.0	1.74	0.33	4.32
1.5	1.94	0.43	4.72
2.0	2.1	0.51	5.04

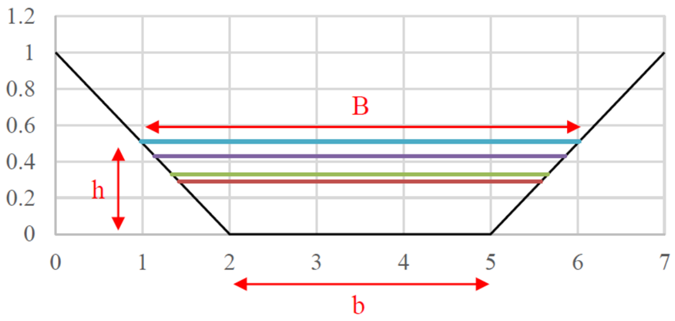

Fig. 6. Water levels in the fish ramp for different dopped discharges.

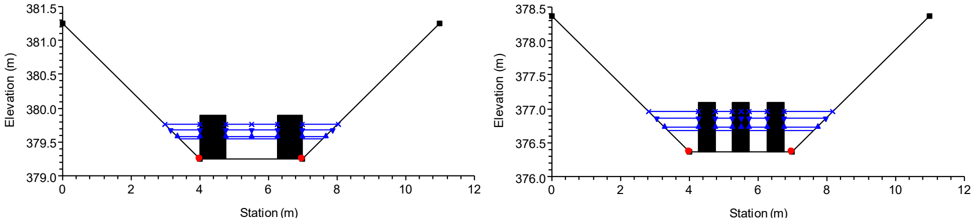

Fig. 7. Water levels for different dopped discharges in cross sections with two and three boulders.

Implementing a milder slope for the ramp would allow for a deeper water column at lower discharge rates (Fig. 8). This would address the concern of insufficient water depth at the lowest discharge and ensure undisturbed passage for fish even under these conditions. An alternative approach might involve using an asymmetrical triangular cross-section for the fish ramp. This design offers greater flexibility compared to a traditional symmetrical profile. By strategically adjusting the bank slopes, it becomes possible to achieve both the required water depth and the width in water level simultaneously. This can potentially improve overall fish migration efficiency by providing a wider zone for fish to navigate while maintaining sufficient depth for safe passage.

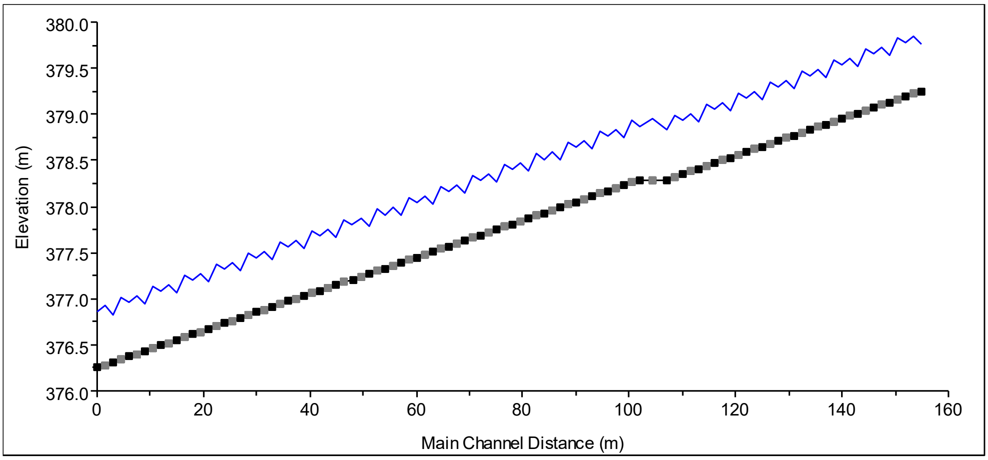

Fig. 8. Longitudinal profile of the fish ramp for discharge 2.0 $m^3 \cdot s^{-1}$.

The evaluation of the vertical slot fish pass model revealed a critical issue with water velocities within the slots. For all simulated discharges, velocities exceeded the legislative limit of 1.8 $m \cdot s^{-1}$ (Table 2). This poses a potential barrier to fish migration, as high velocities within the slots can be difficult for fish to navigate. On the other hand, other parameters displayed adherence to design criteria. Minimum water depth (h_{min}) and the maximum difference in water levels between neighbouring pools (Δh_{max}) met the prescribed values (Fig. 9, Fig. 10). Additionally, the minimum pool water volume remained within acceptable limits. However, a concerning finding was the exceedance of the legislative limit for maximum water energy dissipation (200 $W \cdot m^{-3}$) for all simulated discharges. This elevated dissipation energy level could potentially restrain fish passing through the structure.

Table 2. Resulting values for the vertical slot fish pass.

Discharge	**Maximum Flow Velocity**	**Minimum WaterDepth in the Slot**	**Maximum Difference of Neighbouring Pools**	**Minimun Pool Water Volume**	**Maximum Water Energy**
Q	v_{max}	h_{min}	Δh_{max}	V_{min}	P_{max}
$[m^3 \cdot s^{-1}]$	$[m \cdot s^{-1}]$	$[m]$	$[m]$	$[m^3]$	$[W \cdot m^{-3}]$
0.8	2.00	0.40	0.17	5.52	241.70
1.0	2.15	0.47	0.17	6.72	248.17
1.5	2.46	0.61	0.17	9.36	267.26
2.0	2.71	0.74	0.17	11.76	283.62

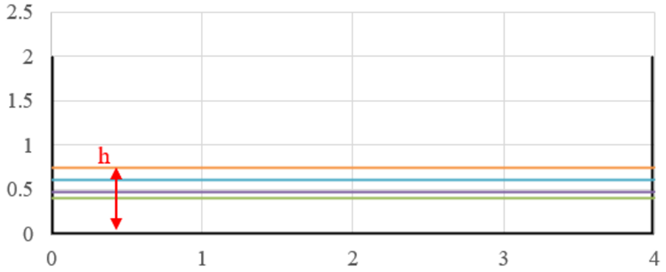

Fig. 9. Water levels for the vertical slot fish pass.

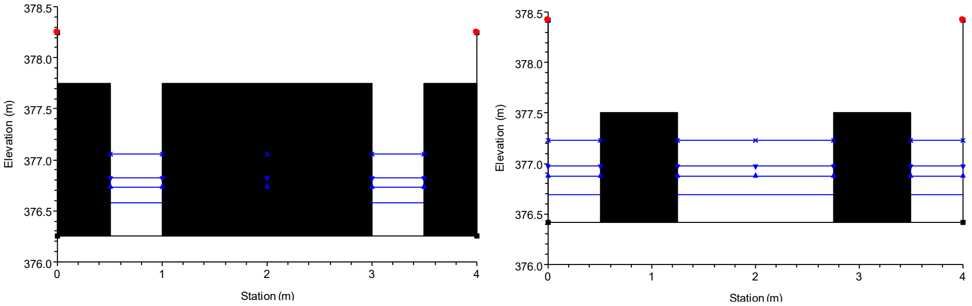

Fig. 10. Water levels in vertical slot fish pass for different dopped discharges (left – vertical cross wall with 2 slots and right – cross section with boulders placed downstream cross wall).

These results highlight the need for design modifications to address excessive velocities within the slots and reduce water energy levels within the pools to ensure safe and efficient fish pass. A reduction in the designed bed slope could potentially address these issues by lowering velocities, consequently increasing water depths and pool volumes (Fig. 11). This, in turn, would lead to lower water energy dissipation values within the pools.

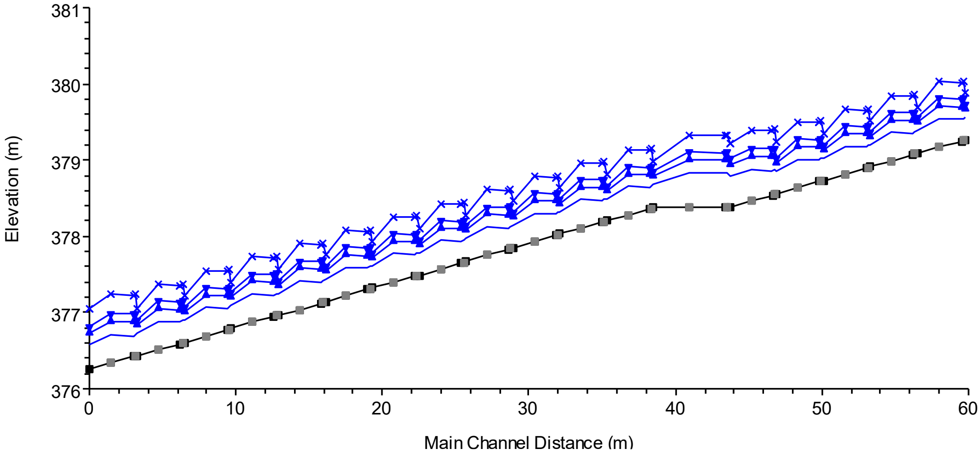

Fig. 11. Longitudinal profile of the vertical slot fish pass for all simulated cases.

4 Conclusions

The construction of fish passes plays an important role in overcoming barriers on streams and restoring longitudinal connectivity for fish and aquatic organisms. This ongoing effort aligns with the ichthyological legislation established by the Slovak Republic's Ministry of the Environment. A key objective in fish pass design and construction is achieving compliance with established regulatory limits. While "nature-like" designs that mimic natural stream characteristics are often preferred, achieving strict adherence to all legislative parameters using these approaches can be challenging. Conversely, technical fish passes offer a more straightforward path to meeting regulatory limits. This study employed a 1D model to evaluate two fish pass designs. While this approach offers valuable insights, it is crucial to acknowledge its limitations. For more precise results, future studies could incorporate 2D or 3D models, or even utilize physical hydraulic models within a hydraulic laboratory. However, it is important to acknowledge the increased time commitment associated with these more complex approaches.

This contribution was developed within the framework and based on the financial support of the APVV-20-0023 project, “Research on hydraulic characteristics of fish passes with regard to ichthyological requirements”.

References

1. M. Hammerling, N. Walczak, Z. Walczak, P. Zawadzki, *The possibilities of using HEC-RAS software for modelling hydraulic conditions of water flow in the fish pass exampled by the Pomiłowo barrage on the Wieprza river,* Journal of Ecological Engineering, **17**, 81 – 89 (2016)
2. B. A. Marriner, A. B. M. Baki, D. Z. Zhu, S. J. Cooke, C. Katopodis, *The hydraulics of a vertical slot fishway: A case study on the multi-species Vianney-Legendre fishway in Quebec, Canada*, Ecological Engineering, **90**, 190 – 202 (2016)
3. J. Puertas, L. Pena, T. Teijeiro, *Experimental approach to the hydraulics of vertical slot fishways*, Journal of Hydraulic Engineering, **130**, 10 – 23 (2004)
4. M. Bombač, M. Četina, G. Novak, *Study on flow characteristics in vertical slot fishways regarding slot layout optimization*, Ecological Engineering, **107**, 126 – 136 (2017)

5. M. Kubrak, B. Smoliński, J. Říha, A. Kodura, P. Popielski, K. Jaboński, *The application of a minimum specific energy concept for a fish ladder design*, Archives of Civil Engineering, **68**, 555-568 (2022)
6. M. Zukal, P. Fošumpaur, T. Kašpar, M. Králík, *Innovative approach to the design of stilling basin: Improvement of fish migration and scour utilization for energy dissipation.* In Proceedings of the River Flow 2020 10th Conference on Fluvial Hydraulics, 7–10 July 2020, Delft, The Netherlands (2011)
7. S. Okhravi, R. Schügerl; Y. Velísková*, Flow Resistance in Lowland Rivers Impacted by Distributed Aquatic Vegetation.* Water Resources Management, **36**, 23 (2020)
8. V. Polák, V. Mužík, V. Druga, D. Abaffy, F. Rebenda, P. Matok, K. Mravcová, R. Hránková, M. Čomaj, D. Joštiaková, *Určenie Vhodných Typov Rybovodov Podľa Typológie Vodných Tokov: Metodické Usmernenie Ministerstva životného prostredia SR*; Výskumný ústav vodného hospodárstva Bratislava, Slovak Republic, 270 (2015)
9. P. Maňák, *Seminární Práce z Předmětu Morfologie a Říční Inženýrství. Manningův Drsnostní Součinitel,* České vysoké učení technické v Praze, Czech Republic, 14 (2017)
10. HEC-RAS River Analysis System, User´s manual, Version 5.0. Davis: US Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center, 538 (2016)
11. C. Goodell, *Coefficients of Contraction/Expansion at Bridges*, In Proceedings of the 1D/2D Modeling with HEC-RAS, 1–3 August 2023, Denver, Colorado (2023)