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COMPARISON BETWEEN CROSSBAR BLOCK RAMP AND VERTICAL SLOT FISH PASS VIA NUMERICAL 3D CFD SIMULATION

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ABSTRACT

Due to the European Water Framework Directive (EU-WFD, 2000) all water bodies have to be restored into "good" ecological conditions. To fulfil these requirements in order to hydro-morphological conditions the river's patency may not be interrupted and may allow aquatic organisms to pass the river upstream. Therefore, technical fish passes are built to overcome large river bottom differences, which allow fish to migrate freely. Fish passes can be constructed in various ways. To overcome the height difference a number of stepped pools separated by walls are built, whereby the construction of the walls can vary. As a nature-like solution (rough channel) so called crossbar block ramps with small, shifted openings for the water discharge and fish passing can be constructed. Vertical slot passes represent a technical fish pass solution. Both variations can be found in practical applications. The present paper analyses two types of fish passes as a practical solution between the rivers Wakenitz and Trave in Lübeck, Germany, via numerical 3D CFD simulation. Both, Wakenitz and Trave, are anthropogenic modified since more than one century. Currently, the flow from Wakenitz to Trave conducts through a culvert system and patency is not given. Hence, a solution is necessary to guarantee a fish climb capability. Therefore, a 3D numerical CFD model of a crossbar block ramp and a vertical slot pass will be compared to analyse hydraulic boundary conditions and the possibilities for fish to pass. Indicators like water depths, flow velocities and flow structures are in the focus of interest.

Keywords: fish pass, crossbar block ramp, vertical slot pass, numerical simulation

1. INTRODUCTION

Fish passes allow aquatic organisms to migrate upstream if the water body's patency is interrupted. Next to fish, also other aquatic and benthic organism, e. g. morays, should be able to pass the structure. Thereby, the construction itself has an influence on the fish climb capability. Every organism and every fish has got different demands on patency, shelters, water depths, velocities, geometry etc., which are parameters for finding and overcoming the fish pass without injury, delay or stress. Therefore, multiple construction kinds of technical fish passes have been developed during the last decades. In the present paper two variations of pool passes, a crossbar block ramp and a vertical slot pass, will be analysed. The hydraulic system as well as the fish climb capability will be compared for these two designed structures. For both structures the river's bottom level difference will be divided into multiple small steps by a number of rectangular pools which are generated by laterally installed walls. Openings within these walls (vertical for the slot pass, lower openings within the crossbars for the block ramp) enable the upstream migration of aquatic organisms. The main advantage of pool passes can be found in reduced velocities within the formed basins – higher velocities only occur at selective areas downstream the openings (DWA-M 509). Hence, rest areas will be formed within the basins.

Crossbar block ramps features a number of stepped pools, which are separated by either massive boulder walls forming a lateral crossbar. Smaller stones will form crest openings (notches) within the crossbars – openings will be arranged shifted to avoid circuit flow. Small caps between the rocks provide an additional migration corridor for small fish and benthic organisms. The length of the narrow is longer due to the size of the rocks with large diameters. These nature like constructions are usually accepted by the publicity. For designing a crossbar block ramp Oertel and Schlenkhoff (2012) or Oertel (2012) can be used. DWA-M 509 (2014) gives additional recommendations.

Generally, the vertical slot pass is placed within a rectangular channel with a continuously sloped bottom. Cross walls with either one or two slots extending over the entire height form pools. They allow a continuous water jet through the pools while dissipating energy in each basin (Environment Agency 2010, DWA-M 509 2014). It is common that cross walls have additional flow guiding elements (see Figure 2b), which can have various forms and positions. A number of investigations for vertical slot fish passes have been made e. g. by Rajaratnam et al. (1986), Rajaratnam et al. (1992), Wu et al. (1999) and Heimerl (2008). Additionally, the German guideline DWA-M 509 gives basic design formulas for vertical slot fish passes.

The advantage of vertical slot passes is the deep opening down to the bottom of the channel. This opening allows benthic organisms as well as fish to migrate through the fish pass and a higher flow rate can be guaranteed due to a large flow area. Hence, vertical slot passes are suitable for a wide range of species and also a wide range of water levels. Also less space is necessary in comparison with crossbar block ramps (Environment Agency 2010, DWA-M 509 2014).

DWA-M 509 (2014) gives a large number of different constructions for fish passing and several design guidelines and recommendations are included. Generally a one-dimensional analytical approach is used to determine flow velocities and flow depths on the structure. But particularities of the flow due to velocities, eddies and turbulences will affect the fish climb capability majorly. Especially turbulences influence the possibility for fish to conquer the fish pass. In the present paper fish passes are design based on DWA-M 509 (2014). The hydraulic system will be analysed due to critical values for fish climbing. 3D CFD analysis are arranged to identify fish pass trails and resting areas in detail.

2. INVESTIGATION AREA

The planned fish pass is located in Lübeck, Germany within an urban area. This is the reason why the layout of the fish pass is highly restricted due to surrounding buildings and infrastructure. Only a public green area is available to build a fish pass to connect the rivers Trave (Figure 1, left) and channel (Figure 1, right). The height difference between Wakenitz and Trave is approx. 3.1 m for mean discharge events. Currently Wakenitz and Trave are connected via culverts and no fish passing is available, hence patency is not given.

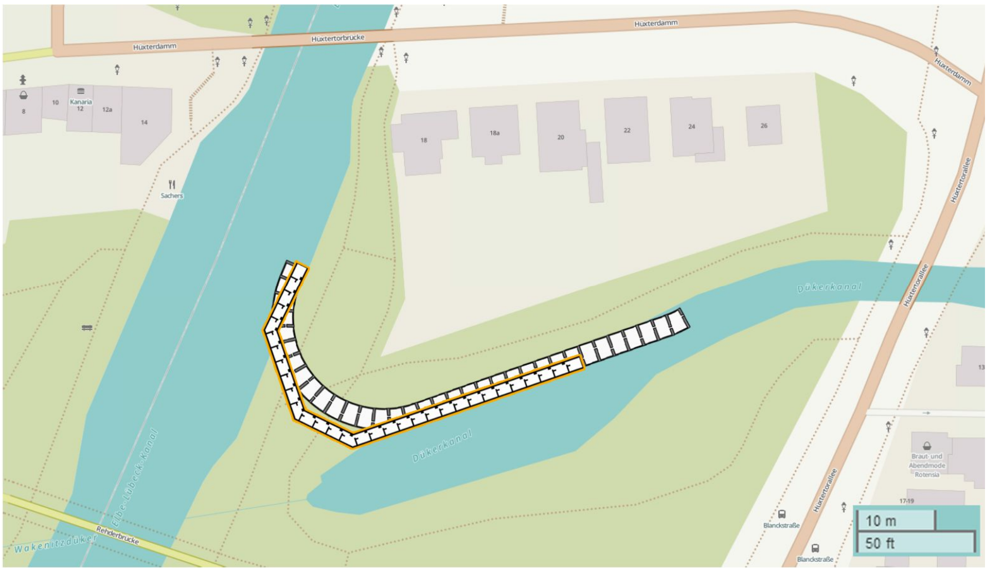


Figure 1. Location of the planned fish pass, black: crossbar block ramp, orange: vertical slot pass (map source: OpenStreetMaps)

The Trave is an estuary of the Baltic Sea with low bottom slopes at the investigation area and hence small flow velocities. The Trave is classified as ruffe-flounder-region due to fish fauna. Relevant fish species that would immigrate upstream to the Wakenitz are pike, carp and catfish (Bremer, 2014). The dimensioning was chosen with a slightly selective effectiveness caused by the adult catfish length, which could not be taken into account due to the restricted plan field. Table 1 shows the chosen geometric boundary conditions based on fish demands given by DWA-M 509 (2014).

Maximum flow velocities that fish can overcome can be set due to the fish region. For Lübeck, as ruffe-flounder-region, the maximum velocity vmax at flow constrictions is 1.45 m/s with a high difference of 3 m. Minimum flow velocities of 0.2 m/s are necessary for fish to find and follow the migration corridor.

Up to the stated geometric boundary conditions and based on the fish needs, DWA-M 509 gives recommendations for the design of the structure concerning the hydraulic processes. The comparable dimensions of both investigated types of fish passes (crossbar block ramp and vertical slot pass) are given in Table 2. A sketch can be found in Figure 2.

Cross walls of the vertical slot pass are flow guiding elements formed like a hammer and a block adjusted (specific angle) to influence the main flow direction. The position of the slots are set at the inner side of the bend, leading to a better hydraulic flow situation with less influence of the bend on flow conditions (Heimerl et al. 2008).

The basins bottom roughness, which is built by aggregate to achieve a better acceptance of fish due to the natural bed, will be neglected within the present investigation.

Table 1. Geometric boundary conditions demanded by the fish fauna (DWA-M 506 2014)

	POOL LENGTH [m] 3 L_{Fish}	WATER DEPTH [m] 2,5 H_{Fish}	WIDTH MIGRATION CORRIDOR [m] 3 D_{Fish}	WATER DEPTH MIGRATION CORRIDOR [m]
PIKE	**3.00**	0.35	0.30	0.45
CATFISH	4.80	**0.64**	0.72	-
CARP	2.40	0.60	**0.38**	**0.60**

Table 2. Geometrical dimensions of both investigated fish passes

DIMENSIONS [m]		POOL PASS WITH CROSS WALLS	VERTICAL SLOT PASS
CLEAR POOL LENGTH	L_{LB}	3.00	3.25
CLEAR POOL WIDTH	b	4.60	2.45
OPENING WIDTH	s	0.40	0.40
WATER DEPTH	h_u	0.64	0.90
WATER LEVEL DIFFERENCE PER POOL	Δh	0.09	0.10
SLOPE	S	2.5 %	3 %
NUMBER OF POOLS	n	34	30
LENGTH FISH PASS	L_{total}	123	110

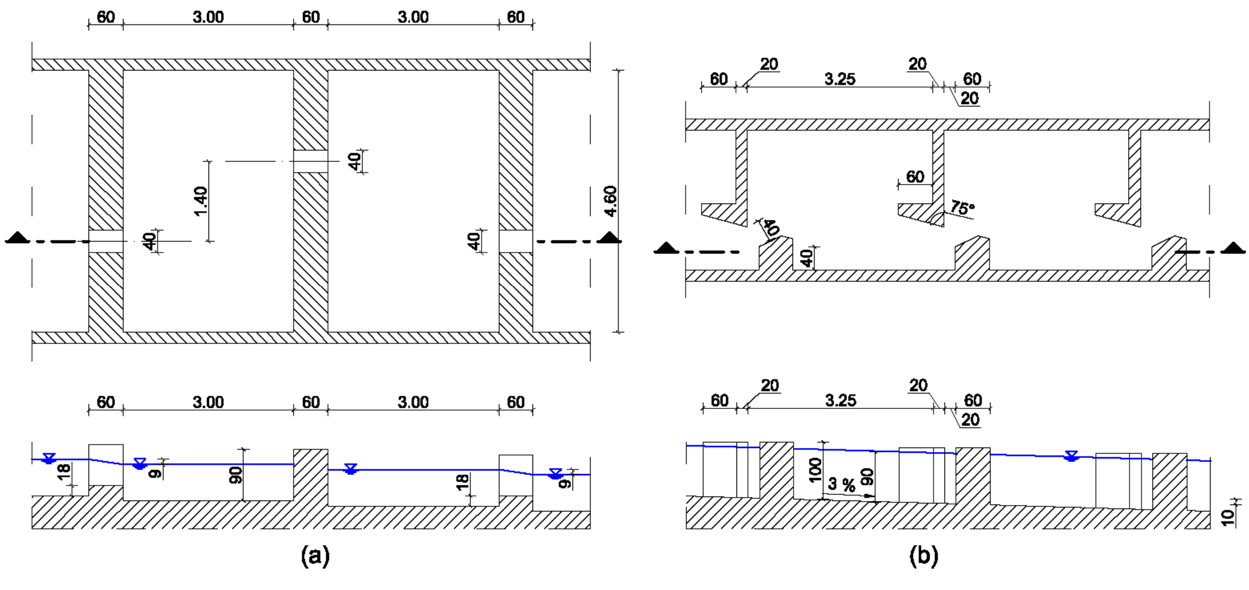


Figure 2. Geometry of designed fish passes, (a) crossbar block ramp, (b) vertical slot pass

3. NUMERICAL MODEL

3.1 General

A 3D numerical CFD simulation provides detailed information about flow structures and thus has become a common instrument to support engineering sciences. Especially complex structures like fish passes induce complex flow regions. A detailed knowledge of flow structures is important to evaluate fish climb capabilities, because not only velocity, water depth etc. are determinant but also turbulent flow and vortex structures. According to Haselbauer (2008) next to velocity and flow depth, turbulent flow is a criterion for successful fish climbing. 3D large-eddy simulations (LES) allow the identification and quantification of additional parameters like turbulent pressure fluctuations or the so called *Q*-criterion (Haselbauer 2008).

LES calculates rather than RANS (Reynolds-Average-Navier-Stokes) an unsteady flow. Thereby large eddies are directly solved without approximations; smaller eddies are solved by approximation (turbulence models). The choice which eddies get solved directly or via approximation is made by the discretization of the computational mesh that consist of a number of interconnected elements or cells to subdivide the model domain into small volumes (FLOW-3D 2014). The finer the mesh is, the more eddy structures are shown, and the closer the results are to the nature.

Numerical simulations are carried out with the commercial CFD software code FLOW-3D (V 11.0.3). LES was chosen for turbulence calculation and the free surface is identified by VOF (volume of fluid) method. Simulations run on a workstation PC with an Intel i7 3.5 GHz CPU and 32 GB RAM main storage.

3.2 Model setup

The simulation model contains the entire fish pass (as shown in Figure 1) to investigate and compare the designed geometry for the given hydraulic boundary conditions. Thereby not only the main flow structure can be investigated but also the particularities at the bend area. Also the in- and outlet can be studied. Especially the influence of the bend is of main research interest. The hydraulic boundary conditions in FLOW-3D are set due to the natural situation. The upstream boundary was set as fixed fluid elevation of 3.8 mNN (mean water level in the Wakenitz); the flow rate is 0.3 and 0.5 m³/s. The downstream boundary is set as an outflow with a fixed fluid elevation of 0.74 mNN. Table 3 shows an overview of the performed simulations.

Table 3. Numerical model properties

MODEL	DISCHARGE [m³/s]	GRID WITH [m]	ACTIVE CELLS
POOL PASS WITH CROSS WALLS	0.3	0.1	1,552,211
VERTICAL SLOT PASS	(0.3) 0.5	0.1	1,288,017

4. RESULTS AND DISCUSSION

4.1 Crossbar block ramp

The crossbar block ramp fish pass has an even flow structure through the entire construction. The bend did not influence the flow velocity and flow depth majorly. Only a small increase of water levels at the outer bend can be determined. The flow depths in every pool reach the minimum of 0.74 m and the reduction of height difference between to pools is reaches the required 0.09 m. A flow rate of 0.3 m³/s provides a sufficient environment for fish passing. The flow forms a nearly steady jet through the entire construction (Figure 5) with velocities from 0.8 to 1.2 m/s. The jet is guided from opening to opening. Velocities are reduced towards the surface. The jet is directed almost parallel to the side walls. Till it hits the cross walls where the energy is dissipated, velocities reduce to less than 0.5 m/s and the jet gets split into two parts (Figure 4). One generates an eddy at the side area of the basin, where the distance of the opening is larger towards the side wall, with velocities lower than 0.2 m/s. This zone can present resting areas for fish. The left of the main jet is directed to the next opening and velocities increase again. Suction causes a second eddy on the other side of the pool. The suction can be compared with flow over a weir where discharge is generated due to the height difference. The ground sill also generates a vertical flow from the ground to the opening which could stimulate fish to flow through the opening. Increased velocities of up to approx. 1.5 m/s can influence fish climb capability. But as the local high velocity of 1.5 m/s is only at a short narrow, it should be capable for fish. Once the flow passes the opening the flow pattern will be repeated. In the bend at the end of the fish pass the flow structure is similar except the direction of the main jet changes slightly due to the walls which are arranged at an angle to each other.

Results show that the designed crossbar block ramp should lead to a positive fish climb capability. Maximum flow velocities are slightly exceeded. A short circuit is prevented because the jets hit the downstream crossbar and velocities will be reduced. The bend has only a small influence on the flow system.

4.2 Vertical slot pass

The vertical slot pass can be separated in two main parts to analyse flow depths, flow velocities and flow structures, because the bend has significant influence on the flow system. Flow depths and velocities are shown in Figure 7. The flow depths till the first turn (part 1) couldn’t reach the required value of 0.74 m. This is because the upstream boundary condition with a fixed water level of 3.8 mNN could not be reached, neither with the minimum flow rate of 0.3 m³/s, nor with an increased flow rate of 0.5 m³/s. Flow depths in the first part of the ramp can be found to be 0.69 to 0.80 m (0.75 to 0.85 m in every second pool). Flow depths increase at cross walls and in every second pool. The lowest depth occurs after the flow guiding block. Figure 3 shows a schematic plot of occurring water levels.

After the first bend the influence of the upstream boundary condition will be reduced and hence, flow depths within the pool increase and achieve required depth values. Highest water depths can be found upstream the cross walls with approx. 0.9 m. In the last five basins an influence of the downstream boundary condition represented by lower flow depths can be found.

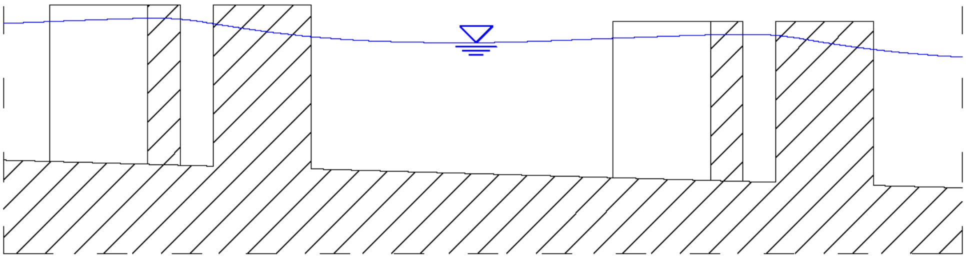
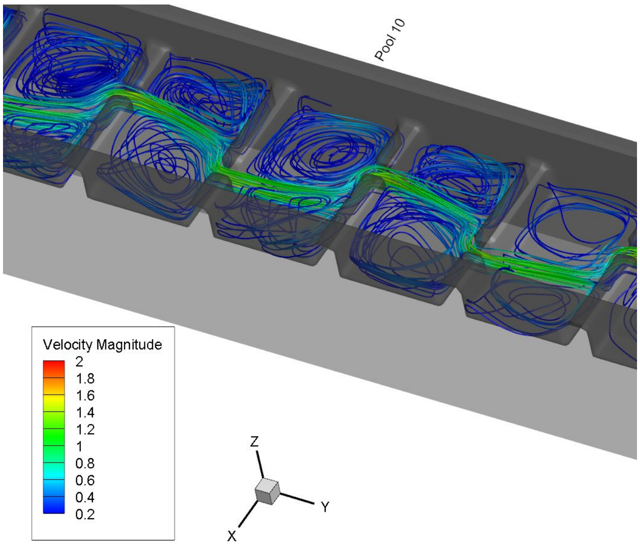


Figure 3. Schematic plot with water level for the vertical slot pass

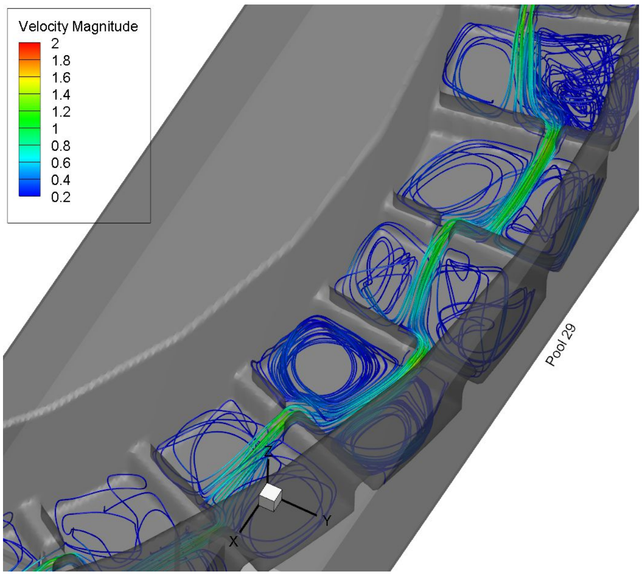
The flow structure and velocities do not vary significantly. In total the flow forms a jet with relatively high velocities through the entire construction and over the entire height. Velocities reach from approx. 0.7 to 1.6 m/s at the outer line of the jet. Decreasing velocities over the height could be assumed if bottom roughness would be taken into account. The jet loses is velocity during the poll resp. the energy is dissipated by mixing in the pool. Due to local effects of the flow guiding block peak velocities with more than 2.0 m/s occur. Velocities are reduced after the first bend and maximum velocities reach 1.6 m/s with smaller local peaks of 2.0 m/s. Nevertheless, velocities are too large to be capable for fish in the entire fish pass. In extreme zones with velocities of more than 2.0 m/s fishes could even get hurt. Also resting areas in every basin with velocities less than 0.2 m/s cannot compensate the exceeding of 1.45 m/s.

Apart from that flow structure the flow is nearly steady in every pool. As shown in Figure 6 the jet flows through the pool losing its velocity and gets split up by the flow guiding hammer element. Thereby, a large eddy is formed, which in some cases flows over the main jet and generates another jet at the opposite side.

Concluding, the simulated vertical slot pass cannot provide the required water depths and exceed the boundary velocity values and, therefore, is not suitable for the local fish population. The same construction would need a higher flow rate to raise water depth, but then velocities would increase once again. The influence of rough bottom material should be analysed to find a practical design with less flow velocities and larger flow depths.



(a)



(b)

Figure 4. Simulation results for crossbar block ramp, 3D view, streamlines coloured by velocity magnitude;(a) straight part,(b) bend area

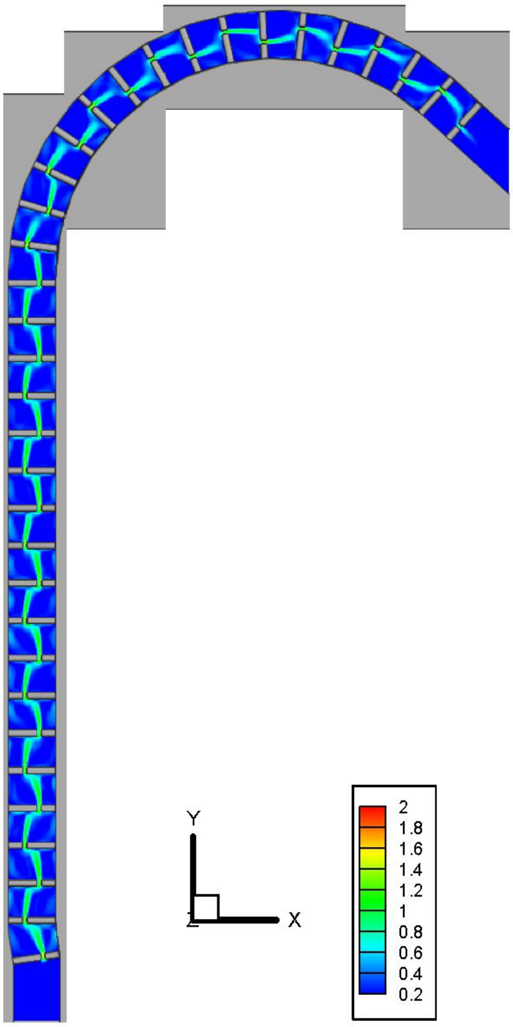
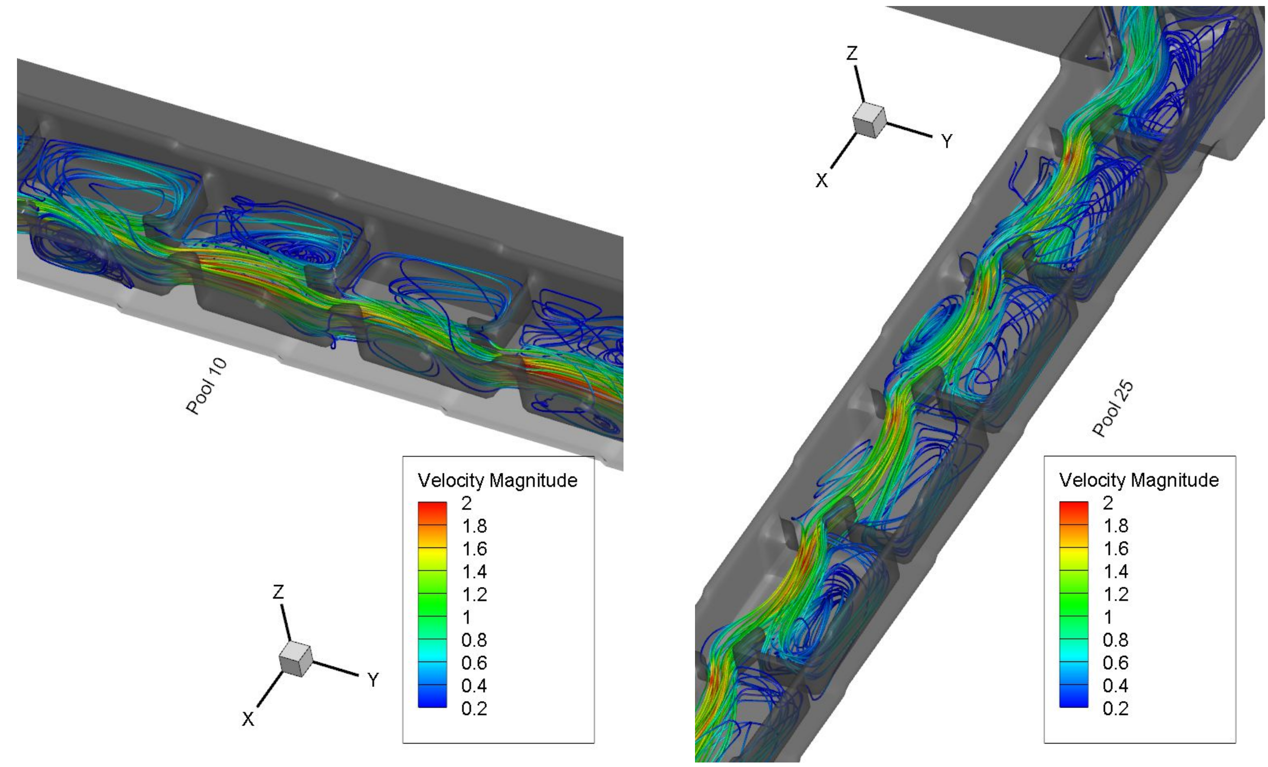
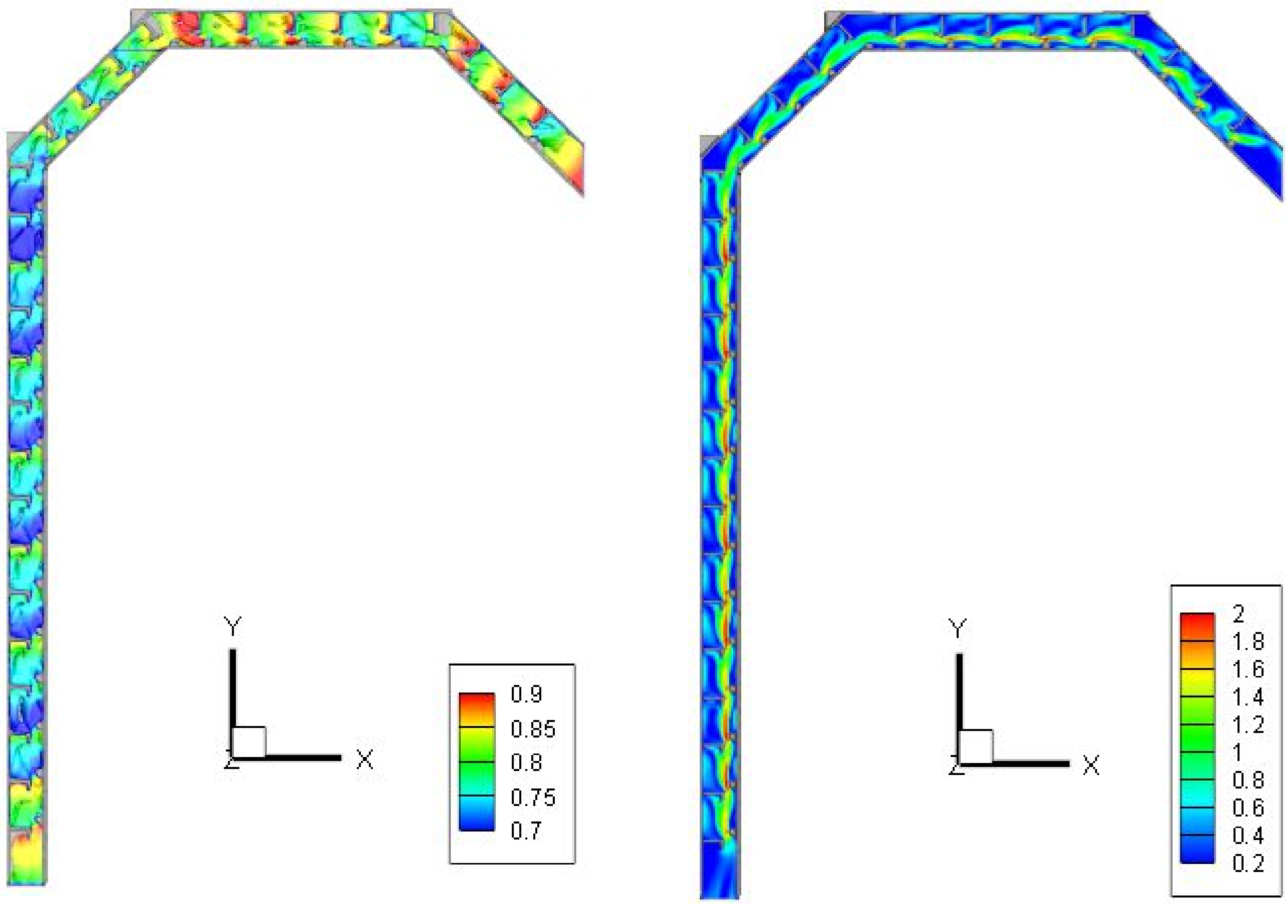


Figure 5. Simulation results for crossbar block ramp, plan view, flow velocities in m/s



(a) (b)

Figure 6 Simulation results of the vertical slot pass, 3D view, streamlines coloured by velocity magnitude;(a) first part,(b) after 2nd bend



(a) vertical slot pass water depth in m

(b) vertical slot pass velocities in m/s

Figure 7. Simulation results of the vertical slot pass, plan view, (a) water depth in m, (b) velocities in m/s

4.3 Comparison of fish pass capability

Concerning the capability for fish to migrate upstream towards both designed structures, boundary parameters as velocities, water depths and flow structure were analysed. The numerical simulation results in much higher velocities for the vertical slot pass than for the crossbar block ramp. Velocities of more than 2.0 m/s, as they appear in the vertical slot pass in the present paper, are certainly not capable for fish in the region of Lübeck. The crossbar block ramp lead to more suitable flow conditions with relatively small flow velocities. Hence, a fish climb capability is given. Summarizing, for the investigated location in Lübeck with the examined fish pass structures the crossbar block ramp shows better results.

5. SUMMARY AND CONCLUSION

The present paper gives an overview of the capability for fish passing of (1) a crossbar block ramp and (2) a technical vertical slot pass at a location in Lübeck. The two construction types were modelled numerically and the hydraulic system was simulated using the software FLOW-3D. The numerical simulation of the vertical slot pass showed that it is not capable for local fish in Lübeck. For two investigated discharge events, resulting flow velocities are too high and flow depths are too low. With the same boundary conditions the crossbar block ramp system produces smaller flow velocities which can be capable for local fish population. The low flow rate of 0.3 m^3/s can be implemented and the fish population could migrate upstream despite the large river bottom differences of 3.1 m between Wakenitz and Trave. Nevertheless, both constructions and the numerical flow simulation itself need further investigation. It needs to be clarified why the upstream boundary condition in the slot pass simulation couldn't be reached. To improve the boundary conditions in the simulation it is possible to add short sections of the in- and outflow zones in Trave and Wakenitz to the simulation models. This would stabilize the inflow and represent a more realistic boundary condition. Additionally, the influence of bed roughness was not taken into account in the present simulation. It could be possible that bed roughness will influence flow velocities and flow depths especially for the vertical slot pass, because the highest velocities have been determined at the bottom. Thus, the simulation model needs to be refined in further investigations. Furthermore it is recommended to investigate some parts of the construction like the slope, opening, flow guiding elements etc. It is not yet clear which parameters are the most important for the flow pattern as well as a basic recommendation cannot be made for every case. Therefore, a comprehensive parameter study should be conducted and the simulation results should be verified by observations in physical model tests. However, the dimensioning of fish passes can be as detailed as possible and all boundary parameters can be observed, but there is still no guarantee for the fish's acceptance. The fish's behaviour and preferences are not clarified completely. The behaviour of fish has been monitored in different fish ways for the last years but there is no all-embracing understanding of the capabilities and behaviour of all fish species. Thus, it is questionable if the applied boundary values reflect the fish's preferences.

REFERENCES

Bremer, F. (2014). Entwurf und hydraulischer Nachweis einer Blocksteinrampe in Riegelbauweise zwischen Wakenitz und Trave. Bachelorthesis, *Hydraulic Engineering Section, Civil Engineering Department, Lübeck University of Applied Sciences, Lübeck, Germany.*

DWA-M 509 (2014). Fischaufstiegsanlagen und fischpassierbare Bauwerke – Gestaltung, Bemessung, Qualitätssicherung, DWA-Regelwerk, *Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V., Hennef, Germany*, in German.

EU-WFD (2000) Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy

Environment Agency (2010).Environment Agency Fish Pass Manual – Guidance Notes On The Legislation, Selection and Approval Of Fish Passes In England And Wales, GEHO 0910 BTBP-E-E, *Bristol, United Kingdom.*

FLOW-3D (2014) User's Manual*, Version 11.0.3, Flow Science Deutschland GmbH, Germany.*

Haselbauer, M. A. (2008). Geräuscharme Fischaufstiegsgerinne – Experimentelle und numerische Analyse des Fischpasses vom Typ periodische Schütze. *Dissertation, faculty of civil engineering and surveying, Technical University of Munich, Munich, Germany.*

Heimerl, S., Hagmeyer, M., Echteler, C. (2008). *Numerical flow simulation of pool-type fishways: new ways with well-known tools, Hydrobiologia 609, pp 189-196.*

Oertel, M. (2012). Crossbar block ramps – Flow regimes, flow resistance, energy dissipation, stability. *Habilitation thesis*, University of Wuppertal, Germany.

Oertel, M. and Schlenkhoff, A. (2012). "Crossbar Block Ramps: Flow Regimes, Energy Dissipation, Friction Factors, and Drag Forces." *J. Hydraul. Eng.*, 138(5), 440–448.

Pagliara, S. and Chiavaccini, P. (2006). "Energy Dissipation on Block Ramps." *J. Hydraul. Eng.*, 132(1), 41–48.

Rajaratnam, N., Van der Vinne, G., & Katopodis, C. (1986). Hydraulics of vertical slot fishways. *Journal of Hydraulic Engineering, 112 (10), pp 909-927.*

Rajaratnam, N., Katopodis, C., & Solanki, S. (1992). New designs for vertical slot fishways. *Civil Eng, 19 (3), pp 402-414.*

Wu, S., Rajaratnam, N. & Katopodis, C. (1999). Structure of Flow in Vertical Slot Fishway. *Journal of Hydraulic Engineering*,*125(4), 351–360.*