Evaluation of the flow velocity distribution in the intake structure of a small hydropower plant

Lucia Bytčanková, Ján Rumann, Peter Dušička

Faculty of Civil Engineering, Slovak University of Technology in Bratislava, Radlinského 11, 810 05 Bratislava, Slovakia
lucia.bytcankova@stuba.sk

Abstract. Intake structures are an important part of small hydropower plants, which affect the water flow, turbine operation and total power of power plant. The flow quality is significantly influenced by the flow homogeneity in the intakes, as the inhomogeneous flow velocity distribution has a negative impact to the operation of the hydropower plants, such as uneven load on the mechanical parts which leads to decrease in efficiency and faster aging of turbine parts. The paper describes the flow assessment in the intake structures of a low-pressure small hydropower plant (the Stará Ľubovňa small hydropower plant) with respect to the flow homogeneity. The River2D, 2D numerical modelling software, has been used for evaluation of flow in the intakes. Flow simulations for the current state of operation have been modelled. In assessing the current situation of intake structure, scenarios were modelled. The boundary conditions were changed to approximate the various variants of hydropower plant operation. The simulations proved the negative impact of the construction solution for the flow conditions in the intakes. This appears mostly in profiles of coarse racks and screenings where is a significant unequal distribution of flow and significant deviation in flow velocities from the recommended values. The simulations results were evaluated in turbine intake profiles (profile of screenings), where the distribution of flow velocities was evaluated. The flow velocities in this profile were compared with the average flow velocity in the turbine intake profile. In order to optimize the velocity distribution in the intake structure, the modification of the intake shapes has been proposed. The subject of the proposal was to improve flow parameters. Simulations were created for the modification that were subsequently reviewed. The modification was compared to the current situation of the intakes.

1. Introduction

One of the most important parts of Small HydroPower Plants (SHPP) are the intakes, that directly relate to the entire power plant function. Many authors dealt with the flow in the intake structures [1]. The intakes are connected to a storage reservoir and take water to the power plant. A hydraulically appropriate design of the inlets is linked to achieving the required hydropower parameters. Proper design of the intake ensures sufficient water flow and should provide minimal pressure losses [2], [3]. Non-uniform influx causes irregular load on the turbine runner producing additional radial forces acting on the rotor [4].

A great influence on the flow quality has the homogeneity of the flow velocity field at the turbine intake. An inhomogeneous flow velocity field causes negative effects to the turbine performance, decreasing of its efficiency and it causes uneven mechanical load to turbine unit parts resulting in
decreasing of its lifetime. Due to reduction of the costs of the project, the shapes of intake structures of SHPP with bulb turbines are often not correctly hydraulically designed. This fact results in operational problems of SHPP [5].

Flow in intakes can be solved by physical models, 2D or 3D modeling. Developing measurement capabilities have allowed the emergence of objective criteria that evaluate the interaction between objects of hydropower plant and turbine. The methodology of flow under low pressure SHHP is based on the starting points of the authors Fisher and Franke [6]. Their issues related to flow conditions are mostly dealing with low-pressure hydropower plants with bulb turbines. This method is significantly applied to the results of numerical models.

The paper describes the evaluation of flow in the intake of a low pressure SHPP. To assess the flow, a 2D numerical model of flow was created, which should prove the suitability and possible problems of intake structures and their construction solutions using 2D modeling tools.

2. Materials and methods
The object of analysis of the suitability of intake structure design for homogeneous flow conditions was the Stará ľubovňa SHPP, a small hydropower plant with bulb turbines. The SHPP is located near Stará ľubovňa on the Poprad River. The project consists of a weir (2 weir fields with control flaps), a low-head small hydropower plant with bulb turbines and a fish pass. The small hydropower plant and weir control system maintains operating water level at 520.54 m for which the gates are designed. The control is carried out by the left field of the weir, through which a flow of up to 150 m$^3$.s$^{-1}$ can be released. When larger flow rates occur, both weirs’ fields are used [7].

The power house and structures of the SHPP are located on the left bank of the river. The design flow of the SHPP is 18.2 m$^3$.s$^{-1}$ and the design head is 3.16 m. The turbines have a diameter of 1 290 mm and a maximum power is 510 kW for the design flow [7] (Figure 1).

The 2D numerical model of flow of the SHPP Stará ľubovňa was created in the River2D program. River2D is free software, 2D model solve the basic mass conservation equation and two (horizontal) components of momentum conservation [8].

The model geometry was created from the altitude data of the SHPP. The bed of the stream was considered at a uniform level, the intake structure of the SHPP was modeled to the real situation. The model used Manning’s roughness coefficient of 0.025, which describes a straight regular gravel bottom trough [2].

![Figure 1. The small hydropower plant Stará ľubovňa](image_url)
The inlet boundary condition (upstream boundary condition) was determined by the flow that flows into the modeled area. The outflow boundary condition (downstream boundary condition) was determined by the water level elevation (Figure 2).

![Model mesh and boundary condition](image)

**Figure 2.** Modelling mesh and boundary condition

In the simulations, the boundary conditions were changed to approximate the various variants of the hydropower plant operation. The upstream boundary condition is tagged $Q_p$ and the flow rates of 18.2 m$^3$.s$^{-1}$ and 32.7 m$^3$.s$^{-1}$ were used in the calculations. The downstream boundary condition determines the operating level of 520.54 m, which was changed, based on the selected scenario. The bulb turbine TG1, the bulb turbine TG2, determined the downstream boundary condition and the left flap of weir called *WEIR*. Overall, 8 different operational scenarios have been simulated (Table 1).

The simulation results were evaluated in turbine intake profiles (profile of screenings), where the distribution of flow velocities was evaluated. The flow velocities in this profile were compared with the average flow velocity in the turbine intake profile. The comparison is expressed by the percentage relative deviation of flow rates from the average flow velocity.

| Scenario | $Q_p$ [m$^3$.s$^{-1}$] | $TG1$ [m] | $TG2$ [m] | $WEIR$ [m] | $TG1$ [m] | $TG2$ [m] | $WEIR$ [m] |
|----------|------------------------|-----------|-----------|------------|-----------|-----------|------------|
| A        | 18.2                   | 520.54    | 520.54    | -          | 10.7      | 7.5       | -          |
| B        | 18.2                   | 520.54    | 520.524   | -          | 9.1       | 9.1       | -          |
| C        | 32.7                   | 520.54    | -         | 520.54     | 4.3       | -         | 28.4       |
| D        | 32.7                   | 520.54    | -         | 520.566    | 9.1       | -         | 23.6       |
| E        | 32.7                   | -         | 520.54    | 520.54     | -         | 6.4       | 26.3       |
| F        | 32.7                   | -         | 520.54    | 520.557    | -         | 9.1       | 23.6       |
| G        | 32.7                   | 520.54    | 520.54    | 520.54     | 4.7       | 5.3       | 22.7       |
| H        | 32.7                   | 520.549   | 520.54    | 520.574    | 9.1       | 9.1       | 14.5       |

For assessments, flow rates of 18.2 m$^3$.s$^{-1}$ and 32.7 m$^3$.s$^{-1}$ were selected. A flow 18.2 m$^3$.s$^{-1}$ represents the design discharge of the SHPP. One turbine unit should be able to process a flow 9.1 m$^3$.s$^{-1}$. A flow 32.7 m$^3$.s$^{-1}$ represent 30-day flow. The operational manual determined the operating level 520.54 m. The operating level tolerance is ± 80 mm [7].
In order to optimize the velocity distribution in the intake structure, the modification of the intake shapes has been designed (Figure 3). Current state simulations have shown an improper connection of the inlet structure to the riverbed. The left wall of the inlet is connected to the riverbed at an angle of approximately 60 °, which causes the current to tear from the walls, creation of ‘flow shadows’ and creation of vortexes. These negative effects need to be eliminated to help improve the flow velocity distribution.

In the modification, the original inlet structure was preserved. The modification consists in shifting the riverbank to the level of submerged screen and rounding the wall edges, while the length of submerged screen remained unchanged.

The flow geometry and modeling mesh were created to edit the intake structure. The simulations were calculated for the upstream boundary condition flow rate $Q_P = 18.2$ m$^3$.s$^{-1}$ and 32.7 m$^3$.s$^{-1}$. The downstream boundary condition varied depending on the modeled scenarios. An overview of the simulated scenarios of the modification is given in Table 2.

| Scenario | $Q_P$ [m$^3$.s$^{-1}$] | $TG1$ [m] | $TG2$ [m] | $WEIR$ [m] | $TG1$ [m] | $TG2$ [m] | $WEIR$ [m] |
|----------|-----------------|--------|--------|--------|--------|--------|--------|
| A        | 18.2            | 520.54 | 520.54 | -      | 10.1   | 8.1    | -      |
| B        | 18.2            | 520.54 | 520.528| -      | 9.1    | 9.1    | -      |
| C        | 32.7            | 520.54 | -      | 520.54 | 5.0    | -      | 27.7   |
| D        | 32.7            | 520.54 | -      | 520.566| 9.1    | -      | 23.6   |
| E        | 32.7            | -      | 520.54 | 520.54 | -      | 6.7    | 26.0   |
| F        | 32.7            | -      | 520.54 | 520.555| -      | 9.1    | 23.6   |
| G        | 32.7            | 520.54 | 520.54 | 520.54 | 4.7    | 5.8    | 22.2   |
| H        | 32.7            | 520.543| 520.54 | 520.57 | 9.1    | 9.1    | 14.5   |

3. Results and discussions
Eight scenarios for real geometry were simulated. In the scenarios A, C, E, G the initial model calculations were performed. Based on the flow distribution, the operating levels were adjusted until the
flow distribution was even for turbines with a maximum flow rate of 9.1 m$^3$.s$^{-1}$. The scenarios B, D, F, H represent the resulting distribution of flow. The scenarios B and H have been selected and the resulting flow velocity maps are shown in Figure 4 and Figure 5.

**Real geometry - Scenario B** (Figure 4)
Boundary conditions:
$Q_p = 18.2$ m$^3$.s$^{-1}$ (total inflow);
$TG_1 = 520.54$ m; 9.1 m$^3$.s$^{-1}$ (water level, outflow);
$TG_2 = 520.524$ m; 9.1 m$^3$.s$^{-1}$ (water level, outflow).

![Figure 4. Real geometry - Scenario B - Distribution of flow with vectors](image)

**Real geometry - Scenario H** (Figure 5)
Boundary conditions:
$Q_p = 32.7$ m$^3$.s$^{-1}$ (total inflow);
$TG_1 = 520.549$ m; 9.1 m$^3$.s$^{-1}$ (water level, outflow);
$TG_2 = 520.524$ m; 9.1 m$^3$.s$^{-1}$ (water level, outflow);
$WEIR = 520.574$ m; 14.5 m$^3$.s$^{-1}$ (water level, outflow).

![Figure 5. Real geometry - Scenario H - Distribution of flow with vectors](image)
In order to improve the flow parameters, the modification of the intake shapes has been designed. For the modification, 8 simulations were also created. Adjustment simulations consisted of operating level changes for selected flow rates. Simulations A, C, E, G represent the initial calculations, simulations B, D, F, H represent the final calculations. Figure 6 and Figure 7 show the resulting flow velocity maps for scenarios B and H.

**Modification - Scenario B (Figure 6)**
Boundary conditions: \(Q_P = 18.2 \text{ m}^3\text{s}^{-1}\) (total inflow);
\(TG_1 = 520.54 \text{ m}, 9.1 \text{ m}^3\text{s}^{-1}\) (water level; outflow);
\(TG_2 = 520.528 \text{ m}, 9.1 \text{ m}^3\text{s}^{-1}\) (water level; outflow).

![Figure 6. Modification - Scenario B - Distribution of flow with vectors](image)

**Modification - Scenario H (Figure 7)**
Boundary conditions: \(Q_P = 32.7 \text{ m}^3\text{s}^{-1}\) (total inflow);
\(TG_1 = 520.543 \text{ m}, 9.1 \text{ m}^3\text{s}^{-1}\) (water level; outflow);
\(TG_2 = 520.54 \text{ m}, 9.1 \text{ m}^3\text{s}^{-1}\) (water level; outflow);
\(WEIR = 520.57 \text{ m}, 14.5 \text{ m}^3\text{s}^{-1}\) (water level; outflow).

![Figure 7. Modification - Scenario H - Distribution of flow with vectors](image)
For real geometry uneven distribution of the velocity fields in the intake structure is obvious. The shape of the intake structure affects the flow in a way that in a certain section of the inlet a flow with opposing direction as required occurs. Flow simulations in the profile of screenings produced higher velocities in the left part of the flow profile. The flow velocities in the right section dropped sharply. The relative deviations of flow velocity vary from approximately +25% to −50% for both flow rates, which proves great inhomogeneity of the flow conditions in this area (Figure 8, Figure 9).

The modification is compared with the real geometry of the intake structure. In modification, the relative deviations of flow velocity vary from approximately +20% to −45% for flow rate $Q_p = 18.2 \text{ m}^3\text{s}^{-1}$ and approximately +20% to −40% for flow rates $Q_p = 32.7 \text{ m}^3\text{s}^{-1}$.

![Figure 8](image1.png)  
**Figure 8.** Comparison of relative deviation of flow rates from the average flow velocity in the profile of screenings for $Q_p = 18.2 \text{ m}^3\text{s}^{-1}$

![Figure 9](image2.png)  
**Figure 9.** Comparison of relative deviation of flow rates from the average flow velocity in the profile of screenings for $Q_p = 32.7 \text{ m}^3\text{s}^{-1}$
4. Conclusions
The contribution describes the assessment of flow conditions in the intake structure of a small hydropower plant with bulb turbines by the means of a 2D numerical model. Overall, the use of this model shows its suitability for a quick analysis of flow conditions in intake structures of SHPP.

The application of this method on the Stará Ľubovňa SHPP shows that there is a significant uneven distribution of flow velocities in the inlets of the turbine units.

The real geometry is compared with the modification of the intake and the results are evaluated. The results are graphs of relative deviations of flow rates from the average flow velocity in the profile of screenings. Changes in flow homogeneity occurred in the profile of screenings, where modifications help to more evenly distribution of flow velocities. Modifications of intake structure also prevent the current to tear from the walls, creation of ‘flow shadows’ and creations of a vortexes.

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References
[1] Y. M. Shawky, M. B. Ezzat, and M. M. Abdellatif, “Power plant intakes performance in low flow water bodies”, Water Science, vol. 29, no. 1, pp. 54–67, 2015.
[2] T. Hodák, Water power utilization, (in Slovak) University of Technology in Bratislava, Bratislava, 1984.
[3] P. Fošumpaur, and F. Čihák, “Design and optimization of a turbine intake structure”, Acta Polytechnica, Vol. 45, No. 3, pp. 87–91, 2005.
[4] P. Lichtneger, “Intake flow problems at low-head hydropower”, Wasserbaukolloquium 2009, Wasserkraft im Zeichen des Klimawandels, Dresden, Germany, 12-13 March 2009, pp. 259–266, 2009.
[5] M. Angulo, S. Liscia, A. Lopez, and C. Lucino, “Experimental validation of a low-head turbine intake designed by CFD following Fisher and Franke guidelines”, 27th IAHR Symposium on Hydraulic Machinery and Systems, Montreal, Canada, 22-26 September 2014, IOP Conference Series: Earth and Environmental Science, Hydraulic Systems, vol. 22, Paper No. 042014, 2014.
[6] R. K. Jr. Fisher, and G. F. Franke, “The impact of inlet flow characteristics on low head hydro projects”, International conference on hydropower, Portland, Oregon, 19-21 August 1987, pp. 1673–1680, 1987.
[7] J. Lahký, Operational manual for permanent operation of water structure small hydropower plant Stará Lubovňa on the Poprad River (in Slovak) Lahky Design Consulting, Zvolen, 2014.
[8] P. Steffler, and J. Blackburn, “River2D, Two-dimensional depth averaged model of river hydrodynamics and fish habitat”, User Manual, University of Alberta, 2002.