Verification of a Flow 3D mathematical model by a physical hydraulic model of a turbine intake structure of a small hydropower plant and the practical use of the mathematical model

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Introduction

The Drava Power Plants Utility Company is the owner of all hydropower plants on the Drava River, Slovenia. On the flood waves relief structure of the Zlatoličje HPP headrace channel the construction of a turbine intake structure for the Melje small hydropower plant is planned. The Melje small HPP shall exploit the biological minimum discharge for electricity production. Since the structure shall be small, the price of a physical hydraulic model research, in comparison with the price of the structure itself, would be too high. Consequently, the client decided to test the designed structure in the cheapest possible way and ordered a 3D mathematical model of the turbine intake structure. By this mathematical model the designed form of the intake structure should be verified, or, in case of non-compliance, a modified form of such structure which would meet the required modes of the SHPP operation should be proposed. Since such a 3D mathematical model hasn't been used for a hydraulic modelling of this type yet, the project performers were slightly mistrustful of the results obtained by it. Regarding our long years' experiences with physical modelling we decided to construct also a physical hydraulic model in order to be able to verify the designed form of the intake structure and then to use the results for the 3D mathematical model calibration.

1.Physical hydraulic model

1.1 Model description

The partial physical model of the headrace channel and the turbine intake structure of the Small Power Plant Melje (SHPP Melje), set out in figure 1**,** was constructed in the undistorted scale 1:20 in the laboratory of the Institute for Hydraulic Research. A part of the headrace channel of the HPP Zlatoličje is constructed in this model scale, in the width of 20 m and the length of 120 m, 39 m upstream and 54 m downstream the turbine intake structure of the SHPP Melje, namely, the turbine intake structure with the transient piece, where the free surface flow passes into the pressure flow. In the height, the model is constructed from the elevation of 247.5 m above sea level, what forms a bottom of the headrace channel of the HPP Zlatoličje, to the elevation of 254.5 m above sea level.

Fig. 1. Hydraulic intake model in the scale 1:20.

1.2 Boundary conditions

The researches on the physical hydraulic model were performed considering the following boundary conditions:

- the total discharge through the HPP Zlatoličje is constant and comes to $Q_{ZLAT} = 530\ m^3/s$
- the minimum discharge through the SHPP Melje at the elevation in the headrace channel is $H_{CHANNEL}$ = 252.90 m above sea level and comes to $Q_{SHPP} = 20\ m_3/s$
- the maximum discharge through the SHPP Melje at the elevation in the headrace channel is $H_{CHANNEL}$ = 253.30 m above sea level and comes to $Q_{SHPP} = 20\ m_3/s$
- In order to ensure the model similitude of the physical model, such discharge conditions have been provided in the headrace channel of the HPP Zlatoličje immediately in front of the intake in the SHPP Melje, as they were obtained by the result 2D of the mathematical model SMS-RMA2 of the wider zone of the headrace channel, namely, 150 m upstream the river Drava and 230 m downstream the headrace channel. The data for the establishment of the mathematical model 2D have been acquired by the site measurements of surfaces of the steady and the unsteady flow in the headrace channel of the HPP Zlatoličje in the year 2003.

1.3 Objectives of research

The research of the hydraulic efficiency needed the examination of the designed form of the intake structure in the SHPP and the performance the hydraulic optimisation of the project. The surface measurements, the velocity measurements, and the total head measurements were performed on the physical model in the intake zone. The fundamental criterion presented the default elevation of the energy line in the profile of the beginning of the transient piece of the penstock, enabling the capture of the total impact of the intake, including the transient piece, where the free surface flow passes into the pressure flow. In that way the results of the research are directly related to the results of the turbine tract project of the SHPP.

The following intake elements were examined as parameters that could enable the implementation of the intake optimisation:

- upstream intake corner, representing the connection of the spillway wall and the intake, figure 2, designation 1
- downstream intake corner, representing the connection of the spillway wall and the intake, figure 2, designation 3
- orientation of piers, figure 2, designation 2
- intake bottom after the intake trashrack, figure 2, designation 4.

1.4 Methods

The water supply was arranged through the Thompson's triangular flow gauging weir and the feed pipe. The dividing of the discharge into the outflow through the headrace channel and the outflow through the turbine plant was carried out with the regulating gate at the end of the headrace channel and with the regulating valve and the solenoid flow-meter on the penstock downstream of the intake, by means of which the required surface in the headrace channel and in the turbine intake was set, as well as the prescribed discharges.

The water surfaces on the physical model were measured in the intake zone by point gauges in glass cylinders, connected according to the principle of the communicating vessels with the individual survey points on the model. The water flow velocities were realized with the 3d Acoustic Doppler Velocimeter (ADV) in four individual intake profiles. The stream lines inside the headrace channel were monitored by means of the colour tracer.

1.5 Results of the Physical model

In the course of the research it was established, by means of the monitoring of the flow through the intake, that the zones of the return flow are created at all the operating modes, and that the optimisation of the intake shall be realized.

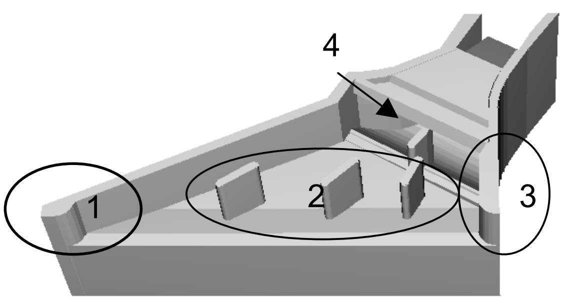

Fig. 2. Designed intake form

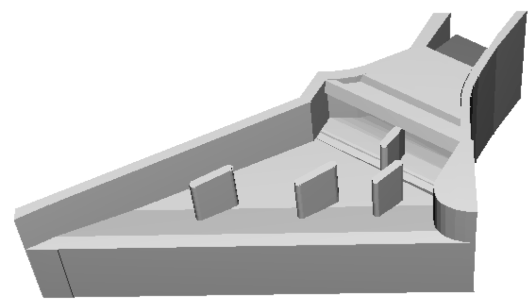

Fig. 3. Proposed intake form

1.5.1 Upstream corner

In all the operating modes the design form of the upstream joint between the spillway wall of the headrace channel of the HPP Zlatoličje and the left lateral wall of the intake into the MHPP Melje causes the apparition of a minor zone of the return flow, reaching approximately till the beginning of the skimming wall. The solution without rounding-off enables the undisturbed flowing around without return flows in all the foreseen operating modes.

1.5.2 Orientation of piers

The physical model served, as well, for the examination of the flowing around piers in the intake. At the design variant the utmost upstream pier is oriented rather parallel to the flow direction, while the medium and the downstream pier are oriented rather too much downstream, causing the turbulence zone after both of them, what could mean, at the more appropriate orientation, minor resistance in the flow. As the piers exert an impact on the direction of stream lines, the model served for the verification of the situation with piers, oriented in the direction of the minimum resistance.

1.5.3 Downstream corner

The downstream joint between the spillway wall of the headrace channel of the HPP Zlatoličje and the right lateral wall of the intake into the Small HPP Melje is realized, in compliance with the project, with the rounding of the rectangular wall of the intake, regarding the headrace spillway wall. The bifurcation of the stream lines immediately before the corner is the same in practically all the operating cases. There is always a calm zone, limited by the rejected stream line. Therefore we suggest the modification of the geometry of the intake right wall, which shall be oriented in accordance with the right lateral wall by the intake trashrack and connected with the spillway wall by two communicating arches of different radiuses. In that way the shape of the downstream corner approaches at most to the course of the rejection stream line and at that does not increase the hydraulic losses of the intake.

1.5.4 Intake bottom after the intake trashrack

The intake project for the intake trashrack foresees the concave over-deepening of the bottom. Due to the said over-deepening a vortex with the horizontal axe is created after the threshold of the trashrack (figure 4). The proposed form of the intake bottom (figure 5) does not provide the return flow and the water jet comes smoothly into the penstock.

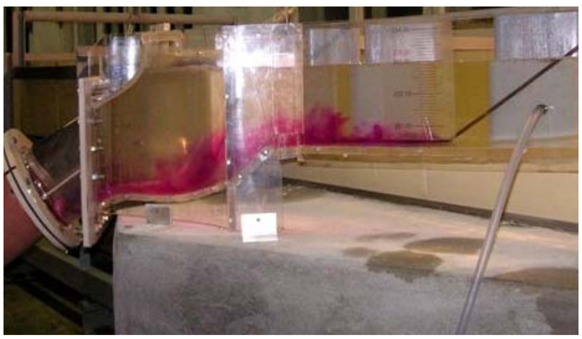

Fig. 4. Designed form of the intake bottom

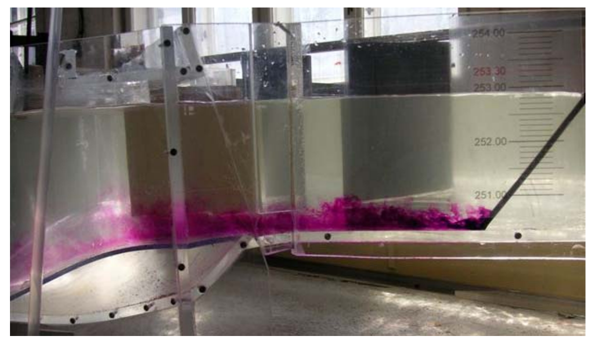

Fig. 5. Proposed form of the intake bottom

2. Mathematical model Flow 3D

2.1 Model description

The geometry of the intake and the headrace channel was elaborated in the graphical tools ACAD and imported into the net of finite volumes as STL file format. The same zone was modelled as the one on the physical model. Due to the optimisation of the design time, as well as to the providing of boundary conditions, the treated zone was divided in three individual blocks, at which differently precise grids have been used. The grid in the block 1 was composed of 15000 cells, and the size of the largest individual cell was ($\Delta x= \Delta y=1$ m, $\Delta z=0.2$ m). The grid in the block 2 was composed of the 480000 cells, and the size of the largest individual cell was ($\Delta x= \Delta y=0.5$ m, $\Delta z=0.2$ m). In the block 3, however, the fine grid was used, composed of the 719200 cells and the size of the largest individual cell was ($\Delta x= \Delta y=0.25$ m, $\Delta z=0.1$ m)

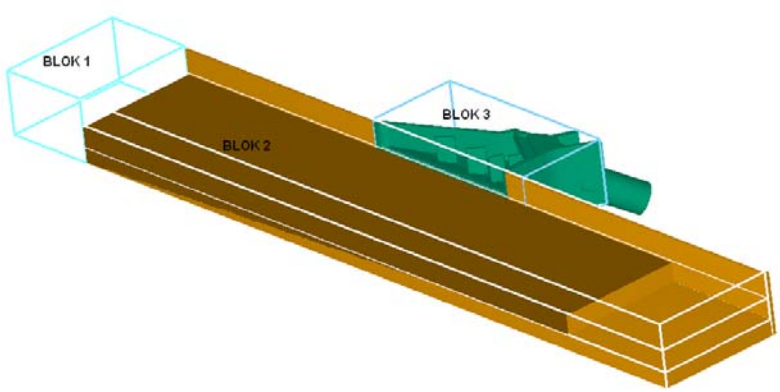

Fig. 6. Mathematical model of the intake and the division into individual design blocks

2.2 Boundary conditions

The same zone has been modelled by means of the mathematical model as it was modelled at the physical model, in order to provide the model similitude of the 3D mathematical model with the physical model. To achieve an easier definition of the boundary conditions, the entire treated zone was divided in three separate design blocks, shown in the figure 6. The following boundary conditions were considered in the Flow 3D:

- The block 1 simulated the discharge, expressed by the flow rate through the plane (rate Vz).
- On the block 2, the right boundary condition was expressed by the water level, measured on the physical model. The water level was obtained by a dam, the height of which was determined by calculation.
- On block 3, the outflow, expressed by a flow rate, was used as the final boundary condition.

2.3 Numerical methodology

The commercially available CFD package Flow-3D uses the finite-volume method to solve Reynolds-averaged Navier-Stokes (RANS) equations. The computational domain is subdivided using Cartesian coordinates into a grid of variable-sized hexahedral cells. For each cell, average values for the flow parameters (pressure and velocity) are computed at discrete times using staggered grid technique (Versteeg and Malalasekera 1995). The staggered grid places all dependent variables at the centre of each cell with the exception of the velocities x, y, z and the fractional areas Ax, Ay and Az. Velocities and fractional areas are located at the centre of each cell faces (not cell centre) normal to their associated direction. The modelling of the free-surface flow over an obstacle with Flow-3D contains the makeup of each cell within the grid to one of five conditions: completely solid, part solid and fluid, completely fluid, part fluid, and completely empty. The intake was defined as an obstacle in the rectangular domain by the implementation of the Fractional Area/Volume Obstacle Representation (FAVOR) method. The free surface was computed using a modified volume-of-fluid (VOF) method (Savage and Johnson, 2001).

2.4 Results of the mathematical model

For the both utmost operating cases, described in the point 1.2, the design form of the intake was examined first by means of the mathematical model, and after that the intake form, which was researched by means of the physical model. The results, obtained by the mathematical model, are comparable with the results of research, performed on the physical model, described in the points 1.4.1-1.4.4.
The figures below demonstrate only the flowing around the bottom after the intake trashrack at the project design of the bottom (figure 7) and at the proposed design of the bottom (figure 8). It is evident that at the project form of the bottom, the zone of the return flow is created, too, after the threshold of the trashrack, which, however, was more expressive on the physical model. At the proposed design, however, the stream lines flow around the bottom correctly.

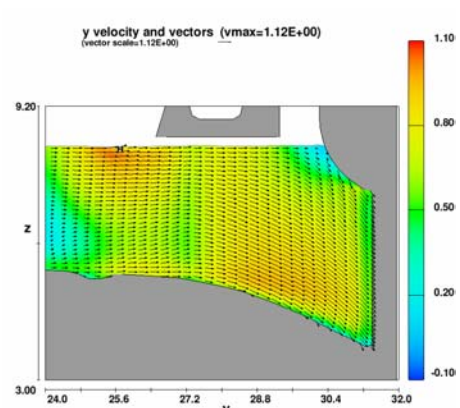

Fig. 7. Designed form of the intake bottom

Fig. 8. Proposed form of the intake bottom

3. Models comparison

The velocity measurements on the physical model were performed in four different profiles, in total in 36 verticals. The velocity measurements on the individual vertical were carried out on different depths of the water.

The figure 6 below demonstrates the comparisons of the velocity components in individual verticals of the selected profile. In the survey points on the individual vertical, situated in different depths, the velocities of the water flow with the 3d Acoustic Doppler Velocimeter (ADV) in the direction of the coordinate axe x, y and z. The triangles indicate the velocity values, measured on the physical model. The lines, however, represent the results of the calculated velocities of the mathematical model Flow-3D. As it is evident from the comparison of the velocity, the values, calculated in individual points of the vertical, wholly match with the measured ones (P1 V11), while in other points a considerable deviation (P1 V1) of measured and calculated values is noticed.

The comparison of velocity shows that the calculated velocities in the direction of the coordinate axe are considerably smaller than the measured velocities in this direction. The disposition of the calculated velocities on the vertical corresponds to the disposition of the velocities, measured on the physical model.

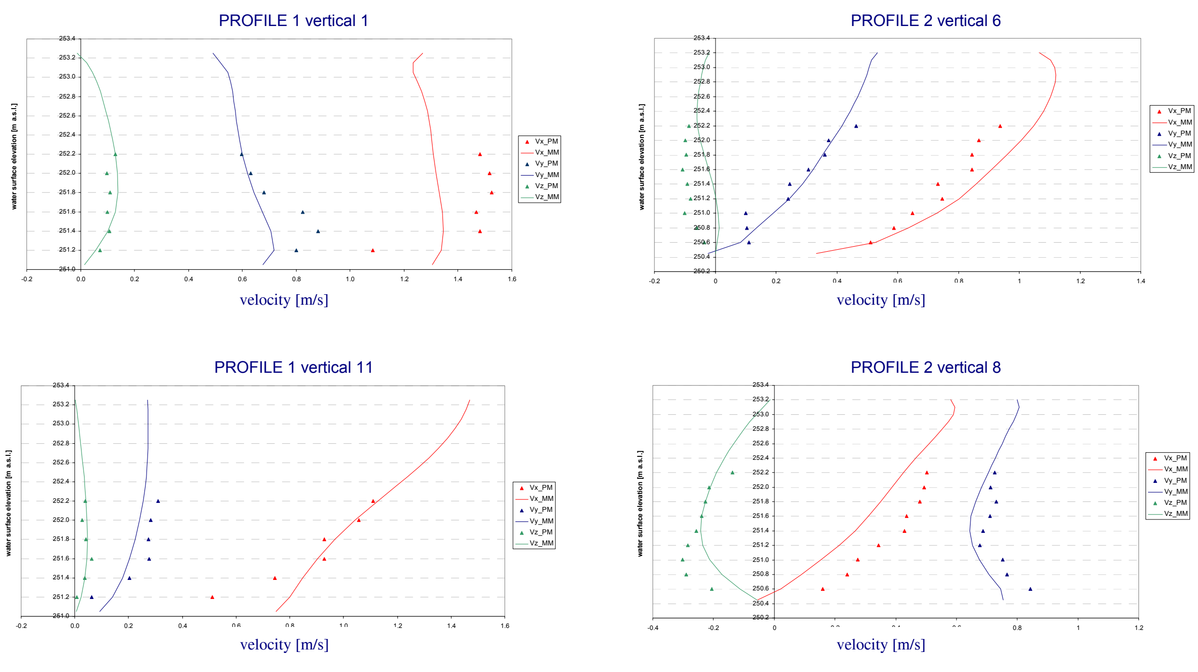

Fig. 6. Comparison of the velocity components in individual verticals

4. Conclusions

The intake element optimisation result brings a more regular water flow pattern in the intake and consequently a reduction of trash accumulation and of energy losses in the intake. In the course of calculations, the following limitations of the Flow-3D have been established:

- in spite of satisfactory computer equipment, a long-lasting calculation and a time-consuming geometry input are required,
- difficult presentation of boundary conditions,
- selection of coordinate system (rectangular or cylindrical); it would be desirable for the programme to enable a curvilinear coordinate system,
- Flow 3D is a useful tool for optimisation of the water flow pattern; however, whenever a fine intake optimisation is required, a physical model shall be used. With a physical model the hydropower plant hydraulic optimisation of the rank under 1% of head can be achieved while with a mathematical model this rank can reach some percents.

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