Mathematical modelling of hydro energetic plants providing support to business decisions

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Introduction

The HPP Soteska is a small power plant with two generating units. It is located on the right bank of the Sava Bohinjka River in Soteska, exploiting the fall of the crib dam across the Sava Bohinjka River bed. The two generating units have been built as self-supporting units within different time-frames. The design flow of the first generating unit HPP Soteska 1 is Q_i=6,0m^3/s, its gross head is H_b=4,5m, and its installed capacity on the sill is N_i=218kW. The second generating unit with the design flow of Q_i=18,0m^3/s, the gross head of H_b=7,5m, and the installed capacity on the sill of N_i=743kW, was built by the end of the nineties in the extension of the headrace canal HES1. Together with the construction of the new generating unit the reconstruction of the intake of the headrace canal was carried out; however, during the operation of the HPP it has been proven that the intake plant was under-designed and consequently the intake flow capability into the headrace canal was not sufficient even for the providing of the design flow of the new engine itself, and neither for the joint operation of the complete power station. This was the reason for the undertaking of the flow gauging and the water level course recording alongside the headrace canal, realized at the plant in the year 2000 and providing the base for the conclusion that the hydraulic conditions at the intake have not been normal at all, and that the intake flow capacity into the headrace canal is too small. A rather sharply designed left wing wall was the cause for the fall in water level and the detaching of stream lines, which were oriented towards the middle of the canal, and a little farther downstream crashed into the central retailing wall of the coarse trash-rakes. For this reason the water stream has partially dispensed into two chambers of the coarse trash-rakes, and only the right part of the profile was active. This lack of symmetry of the water stream was perceivable on the longer part of the canal, what was established also by the hydraulic measurements alongside the canal. The above findings and the hydraulic measurements offered the base for the definition of the issue of the intake plant, as well as for the proposition of the intake reconstruction. The solving of the issue of the intake plant was realized in two phases. Within the first phase the provisional proposition was set out, foreseeing the reconstruction of the left intake wing wall and the partial removal of the submerged old floor sill in its extension, what assured more regular flowing around and consequently more uniform distribution of the water stream along the profile of the coarse trash-rake, yet it was still impossible to achieve, in the whole, the design flow and the designed capacities of the HPP Soteska. The second phase was meant to provide a permanent solution, meaning a radical intervention into the existing intake structure following the previously drawn up reconstruction documents. The design solutions of the intake plant reconstruction should be defined more in detail only after the performed hydraulic model research of the intake, either by the application of the physical model, or the three-dimensional mathematical model.

A study of variants of the reconstruction by means of the three-dimensional commercial mathematical model Flow 3d was drawn up in the year 2006 in order to enable to the owner of the plant to reach a decision about the most adequate type and scope of the required reconstruction works of the intake and the headrace canal.

1. Objective of research

The objective of the research was the establishment of the impact of the individual measure for the optimisation of the shape and dimensions of the intake into the headrace canal with the purpose of reducing the hydraulic losses and achieving the designed operating capacity of the HPP Soteska.

The following intake optimisation variants were treated by means of the mathematic model:

- the original shape of the intake into the headrace canal as per the project design, elaborated by the company IBE in the year 1998 – figure 1, designation 1,

- the existing condition of the intake, realized as per the project design, elaborated by the company IBE in the year 2004 – figure 1, designation 2,
- existing condition of the intake, realized as per the project design, elaborated by the company IBE in the year 2004 by means of the removal of the concrete pier in the profile of the coarse trash-rake – figure 1, designation 3,
- variant with the remodelled left intake wing wall – figure 1, designation 4
- variant with the remodelled left intake wing wall and the removed concrete pier – figure 1, designation 5
- variant with the remodelled right intake wing wall – figure 1, designation 6.

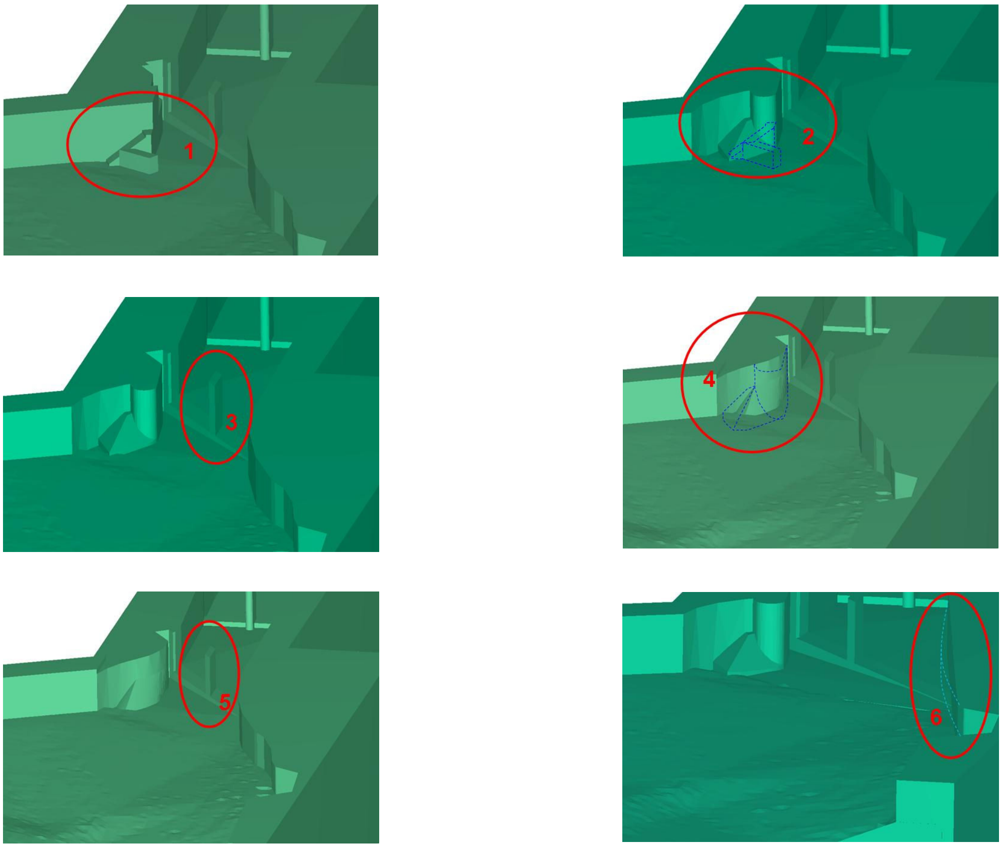

Fig. 1. Treated variants of intake optimisation.

2. Mathematical model Flow 3D

2.1 Model description

The mathematical model 3D of the intake into the headrace canal of the HPP Soteska comprised a part of the Sava Bohinjka River bed, rubber weir, intake to the canal, and approximately 110m of the headrace canal. The complete geometry of the relevant zone was made in the graphic environment ACAD and imported into the finite volume grid as STL file. Due to the different types of geometry shapes the modelled zone is divided in two separate computational blocks (figure 2), within which the grids of various density have been applied. The grid in the block 1, presenting a part of the natural bed of the Sava Bohinjka River is composed of 407487 cells, with the size of the individual cell $\Delta x = \Delta y = 0.35$ m, $\Delta z = 0.25$ m. The grid in the block 2 presents the headrace canal of the two HPP Soteska 1 and Soteska 2. It is composed of 642960 cells, with the size of the individual cell $\Delta x = \Delta y = 0.5$ m, $\Delta z = 0.2$ m.

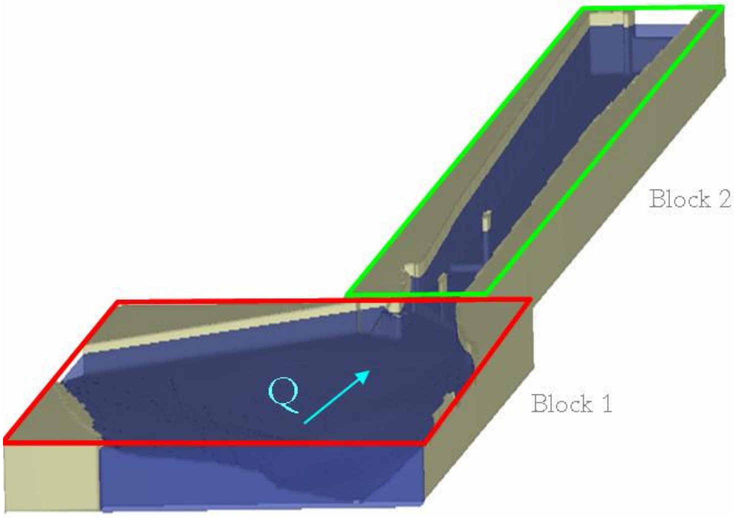

Fig. 2. Mathematical model of the modelled zone

2.2 Boundary conditions

The computations with the mathematical model were carried out in the following boundary conditions:

- At the flow through the HPP Soteska 2 Q_{S2}=18,3m^3/s – for which the model has been calibrated, the downstream boundary condition was the water level in the canal at the elevation Z=474,64mn.m.
- At the flow through the HPP Soteska 1 and HPP Soteska 2 Q_{S1+S2}=24m^3/s – that is, at the joint designed flow of both generating units, the downstream boundary condition was the water level in the canal at the elevation Z=474,56mn.m.

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 u, v, w 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.

2.4 Calibration of mathematical model

The calibration of the mathematical model was performed by applying the water level recording alongside the headrace canal, performed by the Institute for Hydraulic Research in the course of the operation of the HPP Soteska 2 at the flow Q_{S2}=18,3m^3/s in May 2000 . Then, the plant was built in compliance with the initial project design (figure 1, designation 1).

2.5 Verification of mathematical model

The verification of the model was realized by means of the water level recordings, which were performed in the year 2006 at the time of high water of the Sava Bohinjka River. The assessed total flow of the Sava River at the time of recording was approximately 50 m^3/s, the total flow through the HPP Soteska 1 and HPP Soteska 2 being Q_{S1+S2} =21,5m^3/s – computed from the shell curves of both machines. The remaining flow was overflowing across the rubber weir, which, at that time, was elevated that much, that the water level elevation in the Sava Bohinjka River by the right river bank, 10m upstream from the coarse trash-rake, amounted to 475,39mn.m.

3. Results of mathematical model

3.1 Initial shape of intake

The initial variant of the intake into the headrace canal was treated, first of all, as the reference data, meant for the calibration of the mathematic model, since the sufficiently exhaustive measurements in the nature existed only for this shape. Till the commencement of the modelling, the similar measurements could not be performed at the existing condition of the intake, due to the too low river stages of the Sava Bohinjka River.

This variant is distinctive of the low extension of the left wing wall, removed in the year 2004, however, presenting a very marked disturbance in the stream, above all in the left half of the intake. The stream through the left half of the intake is almost disabled, owing to of the above mentioned wall, what causes the well-marked stream velocity rise in the right half (figure 5). The stream from behind the coarse trash-rake even exchanges regime and passes over into the critical flow with velocities, exceeding 4m/s. Due to the contracted active part of the flow profile the hydraulic conductivity of the intake decreases to that extend, that the intake is no more able to conduct the designed flow, and therefore the HPP Soteska can not operate with full power.

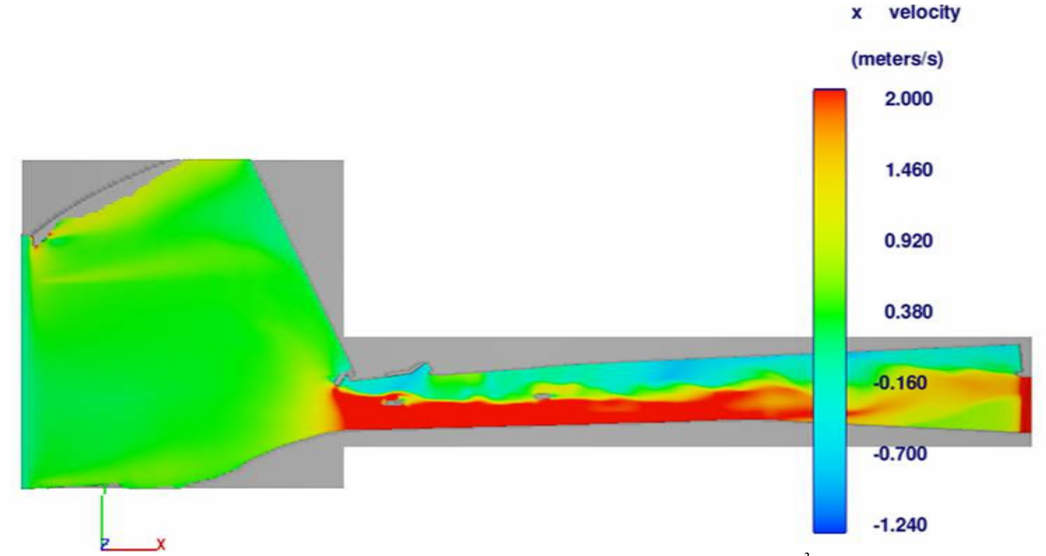

Fig. 5. Initial conditio of the intake at the flow Q_{S2} = 18.3 m^3/s

3.2 Existing condition of intake

Due to the difficulties, described in the point 3.1, the project of the HPP Soteska was elaborated in the year 2004 – the reconstruction of the left wing wall at the intake, following to which the left wing wall of the intake was adequately reconstructed. After the reconstruction of the wing wall the stream condition in the headrace canal improved essentially, yet, the difference between the left and the right half of the intake is still noticeable. The difference in the direction of stream lines, as well as in the stream velocity between the extreme left fourth part of the cross-section of the intake and the part, immediately by the concrete pier in the profile of the coarse trash-rake, can be observed in the left half of the intake. The figures 5 and 6 provide a good view of the difference between the flow pattern at the intake of the initial shape and the flow pattern of the existing intake at the flow Q_{S2}=18,3m3/s.

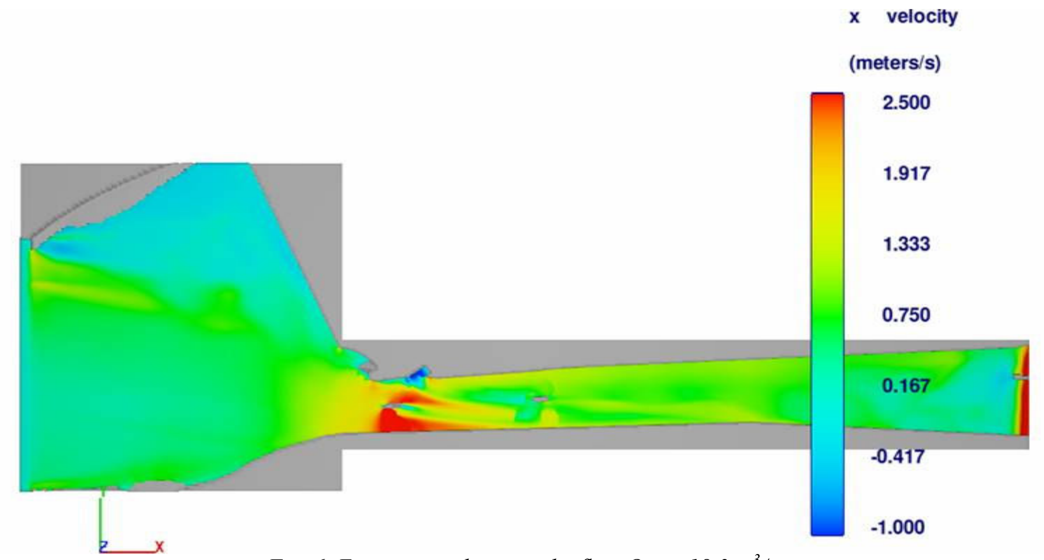

Fig. 6. Existing condition at the flow Q_{S2} = 18.3 m^3/s

3.3 Existing condition of the intake with the removal of the concrete pier in the profile of the coarse trash-rake

The variant, comprising the removal of the concrete pier in the coarse trash rake profile, supporting the bridge across the canal, was tested as one of the least costly possibilities of the improvement of the flow conditions and reduction of the hydraulic losses at the intake into the headrace canal of the HPP Soteska. The pier of considerable dimensions presents obstacle in the stream. We have carried out the simulation of the stream through the intake without the pier for the existing condition of the intake and for the variant, comprising the remodelling of the left intake wing wall. We have tested the situations at the flow Q_{S2}=18,3m^3/s and the flow Q_{S1+S2}=24m^3/s.

The flow pattern at the narrower zone of the intake zone into the headrace canal at the existing condition of the left wing wall and the removed pier is much better in both cases, so at the flow Q_{S2}=18,3m^3/s, as at the flow Q_{S1+S2}=24m^3/s, than in the case of the existing pier. On the contrary, in the case of the existing intake without pier, especially at the flow Q_{S1+S2}=24m^3/s, and partially at the flow Q_{S2}=18,3m^3, we can observe the asymmetry of stream in the profile of the gate and downstream the headrace canal. As the turbulent viscosity has been incorporated into the mathematical model, we believe that this could be the result of the turbulence, caused by the shape of the left intake wing wall in the stream, what can be transferred downstream through the eddies by the stream in the headrace canal. The final result of such a condition are also higher line losses alongside the canal, although the local losses at the intake can be weaker than at the existing condition of the intake due to the increase of the cross-section after the removal of the pier.

In this case the removal of the pier does not provide a favourable result, but it may even increase the total hydraulic losses alongside the complete headrace canal.

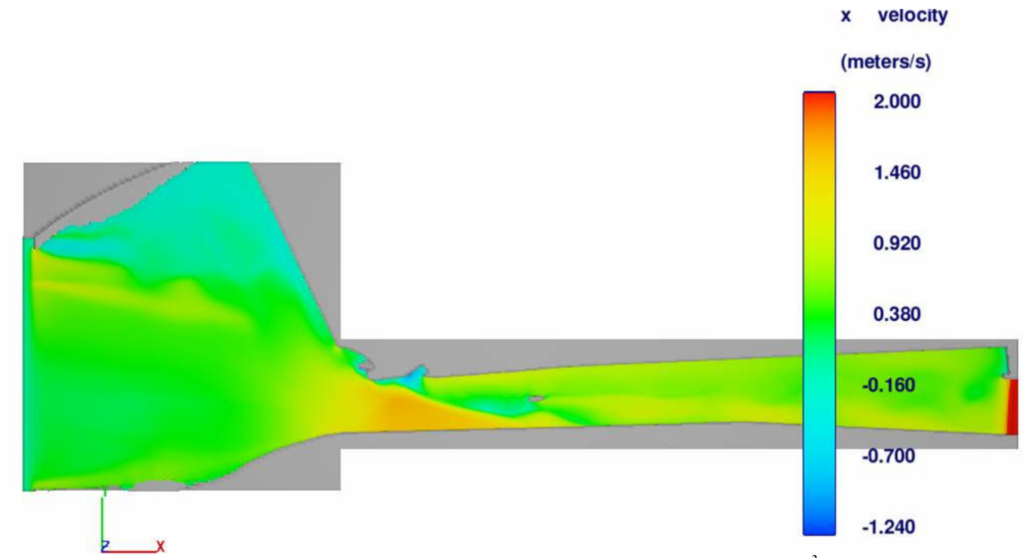

Fig. 7. Existing condition without pier at the flow Q_{S2} = 18.3 m^3/s

3.4 Variant of the remodelling of the right intake wing wall

At the ordinary operating conditions of the HPP Soteska, when the flow of the Sava Bohinjka River is smaller than the designed flow of the HPP (approximately 8 to 9 months per year), the HPP captures practically all the water from the Sava River. Then the priming to the coarse trash-rake is expressively voluminous, and a great deal of stream is coming from the left side round the left wing wall. That is the reason why the existing wing wall still presents a large disturbance in the stream, in spite of the optimisation, which has once already been carried out. The consequence of this is that, at the existing condition, only a half of the left intake half is active (the middle fourth part of the intake), as well as the entire right half of the intake in the coarse trash-rake profile. The extreme left fourth part of the intake is "in the shadow" of the left wing wall. This is, otherwise, much less noticeable than at the initial version.

This was the reason for the simulation of the variant of the remodelling of the left wing wall of the intake. The positive impact of this remodelling is seen, first of all, at the disposition of the stream velocity, shown in the figure 8.

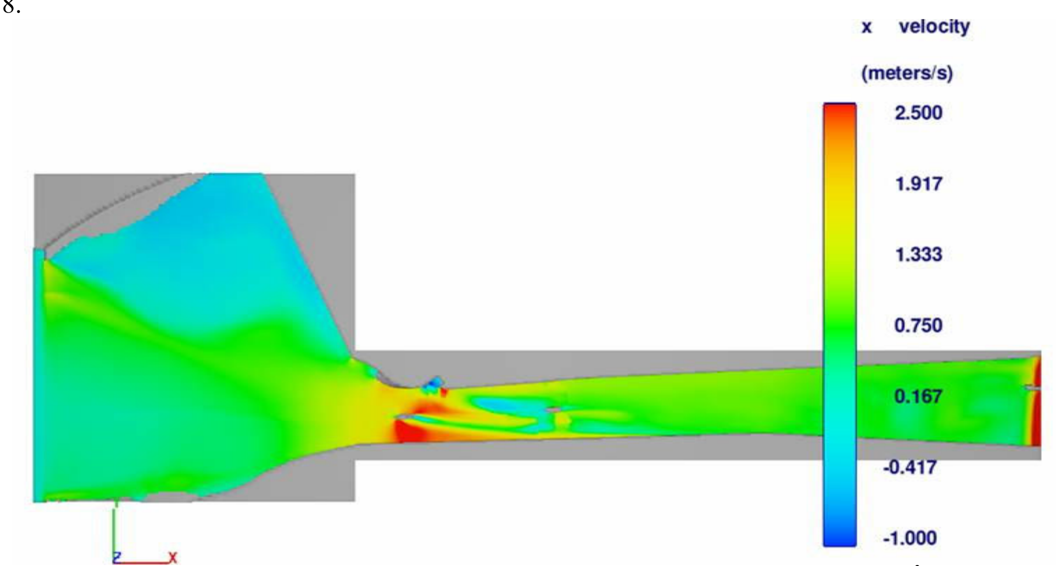

Fig. 8. Modification of the left wing wall of the intake at the flow Q_{S1+S2} = 24 m^3/s

3.5 Variant of the remodelling of the left wing wall of the intake with the removal of the concrete pier in the profile of the coarse trash-rake

Unlike the case, dealing with the removal of the pier in the profile of the coarse trash-rake at the existing condition into the headrace canal, the flow pattern alongside the headrace canal is much more correct in the case of the removal of the pier at the variant with the remodelled left wing wall. In the case of the removed pier the flow pattern at the narrower zone of the intake zone into the headrace canal is much more correct in both cases, so at the flow Q_{S2}=18,3m^3/s, as at the flow Q_{S1+S2}=24m^3/s, than in the case of the existing pier (figure 6). However, in the continuation of the canal, as distinct from the case, described in the point 3.3, there is no noticeable deterioration of stream conditions. In this case there is also no noticeable impact of the turbulent viscosity to the line losses in the headrace canal, resulting in the weaker hydraulic fall from the intake into the canal to the fine trash-rake at the intake into the HPP.

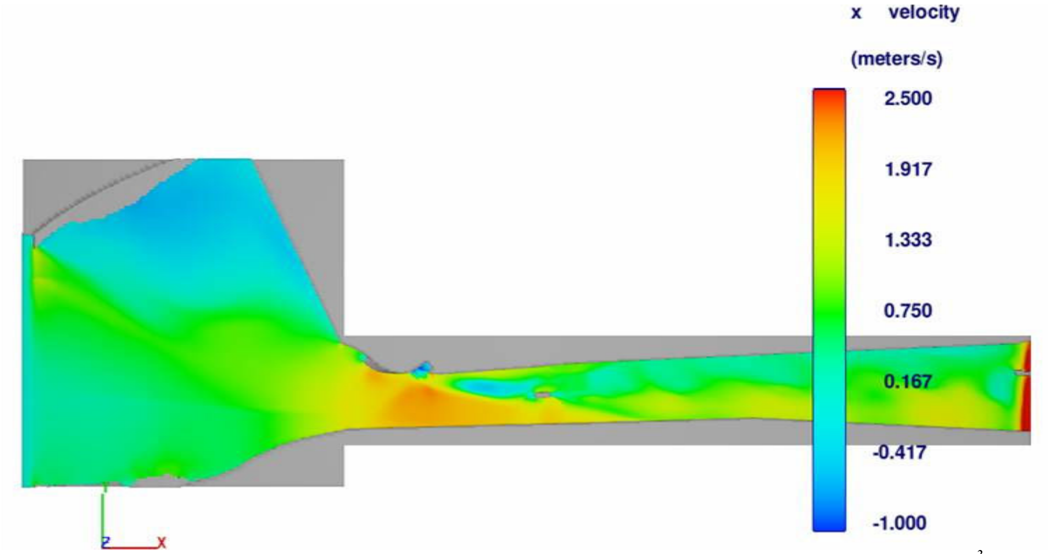

Fig.9. Modification of the left wing wall of the intake without the pier at the flow Q_{S1+S2} = 24 m^3/s

3.6 Variant of the remodelling of the right intake wing wall

One of the principal reasons for the inadequate flow pattern at the intake into the headrace canal is the well-marked asymmetric disposition of the stream prior to the intake, flowing, mainly, from the left side, from the bed of the Sava Bohinjka River. More frontal (head) priming would be hydraulically more favourable, as in this way the impact of the left intake wing wall would be reduced, and the complete cross section of the canal in the coarse trash-rake profile would thus be activated.

This variant was simulated only as an independent remodelling without the removal of the pier. The flow pattern at the flow Q_{S1+S2}=24m^3/s is the most favourable among all modelled variants. The consequence of so favourable flow conditions are also smaller line losses in the headrace canal, contributing to an even weaker hydraulic fall from the intake into the canal to the fine trash-rake at the intake into the HPP.

The additional advantage of this variant presents the extension of the coarse trash-rake profile, resulting in the weaker velocities of the stream through the trash-rake. This means, weaker hydraulic losses at the coarse trash-rake, as well as easier removal of the floating debris, caught at the trash-rake, otherwise reducing the flow profile and increasing losses.

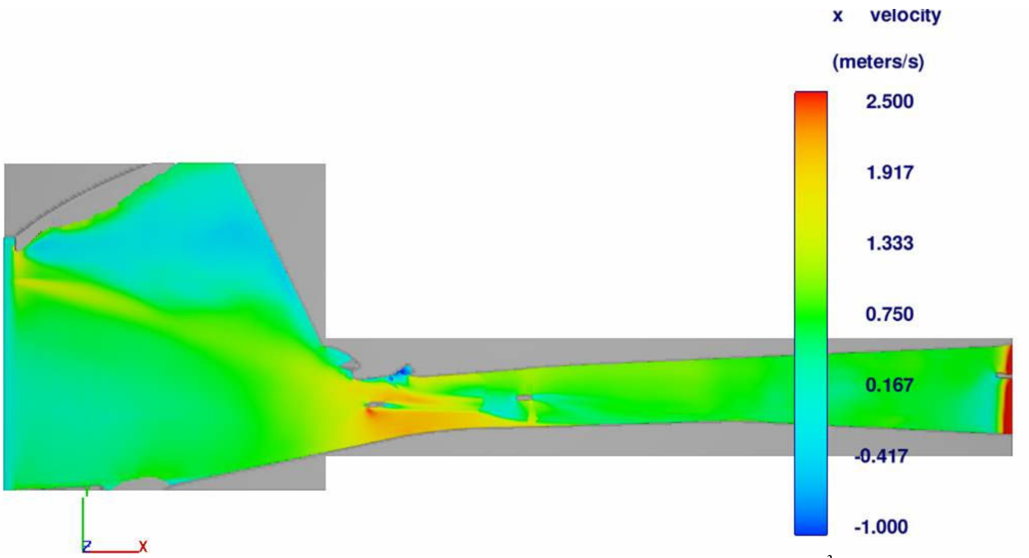

Fig.10. Widening of the right intake bank at the flowf $Q_{S1+S2} = 24\ m^3/s$

4. Conclusions

The main result of the model presents the direct comparison of energy losses, which could occur at the respective variants of the intake optimisation into the canal, and the losses of the existing intake shape. Considering the fact that all the computations were performed for the water levels, which are approximately 20 to 50 cm lower than the feasible operating water levels, the losses in the case of the operation at the maximal water levels would be even lower than the computed ones.

Considering the size of energy losses alongside the intake and the headrace canal, the variant of the simultaneous reconstruction of the left wing and the removal of the concrete pier in the axis of the coarse trash-rake proved to be the most favourable one, which could, compared to the current condition, diminish the losses for approximately 0,09m.

The variant, comprising the widening of the right bank of the intake, provides only a little bit weaker effect, however, in the case of the implementation of this variant, the profile of the coarse trash-rake would be lengthened for good 7 m, what would exert an additional positive effect to the reduction of losses.
Otherwise, at normal operating conditions the coarse trash-rake does not present a source of high energy losses, yet only on the condition of the sufficiently high operating water level, when the flow velocities through the trash-rake are in the class 1,0 to 2,0m/s. Therefore the operation shall be run as close as possible to the elevation of the Sava Bohinjka River, 474,90mn.m, or higher.
The choking with the floating debris at the coarse trash-rake, however, presents bigger problem, as at present, a long lasting and hard manual removal of the floating debris is required at the occurrence of the stoppage of the power plant. The technical measures, providing the simplification of the removal of floating material, as well as the reduction of cases, requiring the simultaneous, complete stoppage of the power plant, should urgently be introduced.

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