Hydraulic analysis of the construction pit of HPP Brežice (Slovenia) and its effect on the runoff regime

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Summary

When planning river infrastructure, hydraulic modelling of runoff regime prior to and after the building is an established tool for the analysis of the potential increase in flood and erosion hazard. Such hydraulic modelling research is less frequently used to analyze the intermediate stages of a project. However, especially with the extensive and complex structures, the construction of which may take several years, it is necessary to analyze the impacts of intermediate phases of construction on the runoff regime, as this could be much more adverse than the planned final state. The paper discusses a hydraulic analysis of the impact of the construction pit of HPP Brežice on flow situation in the impact area. A detailed hydraulic analysis of the construction pit is presented, which was carried out on a scaled physical hydraulic model. The research was focused on optimizing the shape of the diversion channel, optimizing the lining of diversion channel and the riverbank, and optimizing the height of the levee of the construction pit. A model with mobile bed was established in order to study the erosion processes in the diversion channel. The results show that erosion in the diversion channel is present already at relatively low flow rates, while increased flows of the river Sava increase the speed of the erosion.

1. Introduction

For any large structure being built, it is crucial to analyze its environmental impacts, as well as the impact of the environment on the structure. The impact of waters (floods, groundwater etc.) is also taken into account in construction planning. One of the technical bases in environmental impact assessment in and near rivers and in the impact zone is also the analysis of the runoff regime, which indicates the difference between existing and planned states of water flows, depths, shear stresses (erosion) etc. To show that the flood and erosion hazards remain the same or are even mitigated, and to plan and optimize the expected duration of construction, physical and mathematical hydraulic modelling is a common and established practice. However, when planning, the analysis of the impacts of individual construction phases, temporary facilities or measures (e.g. access roads, bridging objects) should also be thorough. Building such elaborate and complex structures can take several years, so the changes in the runoff regime occur gradually, e.g. in the phase of constructing the weir, when a diversion channel is needed, and during the building of levees and accompanying structures, all of which can influence the runoff conditions. It can occur that, compared to the finished structure, an intermediate construction phase can have more negative impacts on the runoff regime and therefore on the flood and erosion hazard of the construction site and other locations. The immediate vicinity of the construction pit and the damn structure need to be researched, and numerical analyses of the wider area need to be made in order to determine the extent of flood, velocity or erosion forces flow distribution and the changes in the entire runoff regime. Together, such analyses and research are used to determine potential hazards and to adjust or optimize the planned construction phases so that hazards are reduced and costs are decreased.

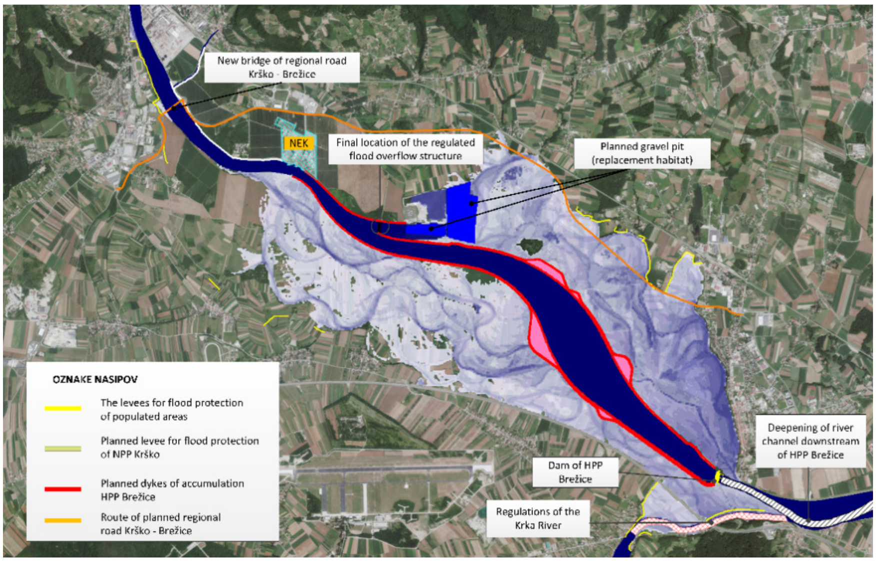

Figure 1. A schematic view of the area of HPP Brežice with all the planned interventions.

In the paper we describe a hydraulic research of the construction pit of HPP Brežice using both a physical model and numerical modelling. The dam of HPP Brežice consists of an engine room with three Kaplan turbines on the left bank and dam with five spillways of 15 m width along the right bank. The nominal water level is 153.00 m a.s.l. The bottom of the Sava channel is at 140.60 m a.s.l. (upstream – reservoir bottom before the dam). The installed flow rate is 500 m^3/s and the nominal gross gradient is 10.95 m. The maximum power of the HPP is 46 MW. The average annual flow rate is 231.2 m^3/s, which should suffice for an annual production of 148 GWh of electrical energy (http://www.he-ss.si).

2. Hydraulic modelling

The main premise of combining physical and numerical modelling is to join the advantages of both – processes are modelled with a tool that simulates more precisely and reliably, and at the same time, comparisons can be made (Weigerber et al., 2010). Physical models provide the (measured) information about processes that even modern mathematical models are as yet unable to satisfactorily describe (foremost turbulence and related 3D phenomena, erosion processes etc.). Numerical models supplement the physical ones where a large number of variant analyses is required, by verifying large amounts of data in the planning optimization step, and when a comprehensive and efficient rendition of results in the decision-making processes is needed. Numerical models also enable analyses of much larger areas than those that can be represented using physical models, which are limited by the laboratory capacity (e.g. area size, pumping capacity etc.).

2.1 Building and operation of the physical model

In the testing laboratory of the Institute for Hydraulic Research, a physical model was built in the scale 1:45. In its final configuration the model encompasses an engine room and a dam, while in its intermediate phase it includes a construction pit of the HPP with a diversion channel. It also has a suitable upstream pool length and approximately 600 m of the Save downstream from the dam (Figure 2). The choice of the physical model scale was mostly governed by spatial capacities of the laboratory and the pumps capacity. The case under study involves free surface flow, where gravity is the main force, while the contribution of other forces (e.g. viscosity) is negligible. Therefore, the Froude number scaling law of model similarity was employed. The parameters for model scale $\lambda = 45$ are given in Table 1.

Table 1: Parameters for the model scale $\lambda = 45$.

for Froude number	λ^0	1
for length and diameter of model gravel (m)	λ^1	45
for area (m^2)	λ^2	2025
for volume (m^3)	λ^3	91125
for roughness	$\lambda^{1/6}$	1.886
for time (s), for velocity (m/s)	$\lambda^{1/2}$	6.708
for Reynolds number Re	$\lambda^{3/2}$	301.869
for flow rates (m^3/s)	$\lambda^{5/2}$	13584.113

Figure 2. Physical hydraulic model of the HPP Brežice including the construction pit and the diversion channel.

2.2. Development of the mathematical model

To analyze the runoff conditions in the time of HPP Brežice construction, a fully 2D hydraulic modelling tool CCHE2D (developed by the National Center for Computational Hydroscience and Engineering – The University of Mississippi) was used. The main reason for using a fully 2D model is the characteristically two-dimensional nature of flow conditions where the channel of river Sava is re-routed in the area of the construction pit and then returned to its course. Using a 2D model, sufficiently accurate results of the direction and strength of water currents in the channel and its immediate vicinity downstream can be achieved [Weisgerber et al., 2010]. Figure 3 left shows an orthophoto image of the area of the construction pit, and on the right-hand side the numeric mesh of the same area is shown.

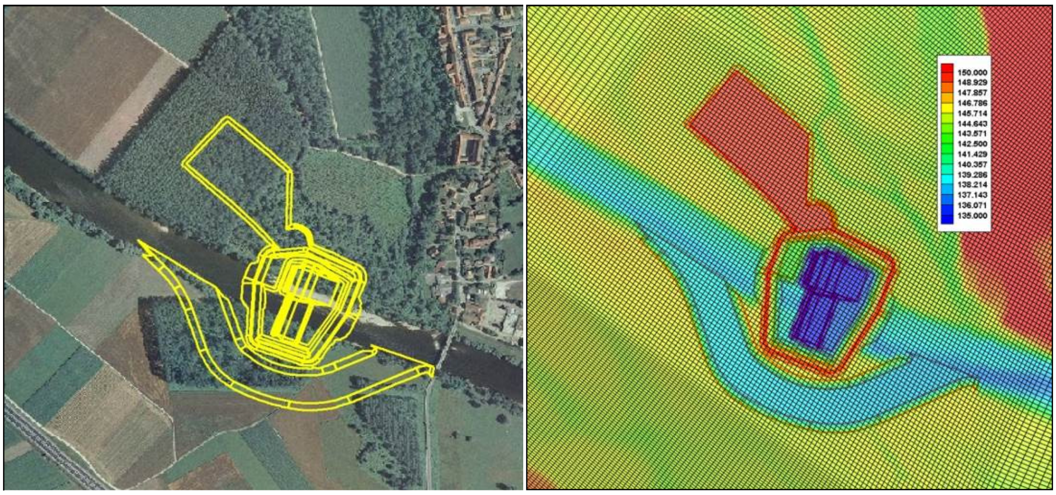

Figure 3. Left – an orthophoto of the construction pit of HPP Brežice; right – a generated mesh of the 2D hydraulic model [Rak et al, 2012a]..

The numerical model CCHE is based on depth-averaged shallow water Navier-Stokes equations. To solve the equations, the implicit finite elements method is used. Shear stresses that occur due to turbulence are modelled with the Boussinesq approximation. For the calculation of turbulent viscosity one of three approaches needs to be chosen.

The area under study is very versatile in its geomorphology and topographic details – from wide plains to topographies that significantly impact the flow regime. To optimize the relation between the accuracy of results and computation time, a numerical mesh of variable density was used. The digital terrain model was thoroughly checked and corrected where needed, in order to achieve good agreement between the topography and its mathematical description, as well as potential obstacles to the flow.

The calibration of the numerical model was performed in 38 points, in the same locations as for the fine calibration of the physical and numerical models of the wider area. To do this, the discharge flows of Sava approximately between 20 and 100 year return periods (Rak et al., 2014) were used. To additionally calibrate the immediate vicinity of the construction pit and the discharge capacities of the diversion channel, and to control the velocity field and runoff conditions, the results of the hydraulic model research were used as comparison.

3. Results

3.1 Detailed research of the construction pit on the physical model

The impact area of the construction pit and the diversion channel was studied on the physical model in scale 1:45 (Bombač and Mlačnik, 2012). In the first phase the shape of the diversion channel of the construction pit was optimized. The channel needs to have a shape and dimensions that ensure the discharge capacity specified in the project. Its shape has to be hydraulically favorable – i.e. the streamlines have to optimally fit the channel form.

Figure 4. Streamlines along the construction pit with an optimized narrower inflow into the diversion channel. A smaller calm zone appears along the construction pit with less prominent vortices at the edge of the pit. The extent of the excavation is also smaller.

The diversion channel will be built on gravel; it is therefore necessary to study the erosion processes. In order to do this, several tests were made on the physical model with mobile bed. The gravel was modelled with round-grained model sand with maximum diameter D_{max} = 1.4 mm, which is in very good accordance with the samples from Sava in this area, especially in its coarser fractions (Figure 5).

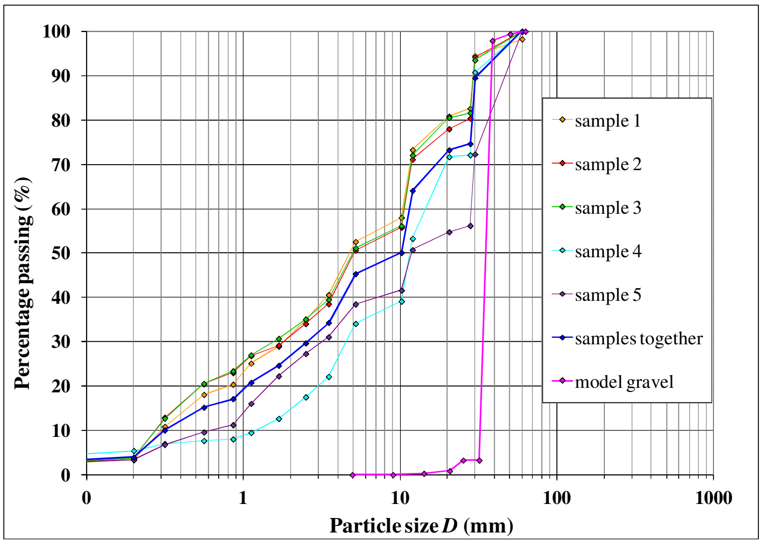

Figure 5. Granulometric composition of the natural gravel and the material used in the model (calculated to natural size).

The first experiment was conducted at the flow rate Q = 500 m^3/s and with gravel on the project channel bottom. The thickness of the gravel layer at the start of the experiment was the same throughout the channel, namely 1 m.

It was found that at this flow rate the bed load discharge is already very prominent, since after 11.7 h (in nature) the water carried away all the material at some places in the channel (Figure 6).

Figure 6. The bottom of the diversion channel on the physical model after 11.7 hours at the flow Q = 500 m^3/s.

Because the first few experiments indicated that erosion in the diversion channel is large, further research on the physical model used a deeper channel, dug to the bedrock level. On this surface new model gravel was applied to the level of the channel bottom before each subsequent experiment. A detailed hydraulic analysis of the area of the planned HPP revealed that the river bed is least stable when the water level in the diversion channel reaches to the upper edge of the embankment and the flow over the floodplains around the construction pit is not yet established. We therefore continued the study of the erosion processes in the diversion channel using the flow Q = 1800 m^3/s, the maximum flow that the diversion channel can still convey. The results after constant flow Q = 1800 m^3/s and duration 27 h are presented in Figure 7. The benchmark water level, that represents the lower boundary condition was H_{SP} = 144.96 m a.s.l. in this case. At the current state of the riverbed, this is equal to water depth of 8 m.

Figure 7. Strong erosion on the concave part of the diversion channel after 27 hours of operation at the flow Q = 1800 m^3/s.

As can be seen in Figure 7, the water eroded all the gravel along the concave part of the channel to the bedrock level. Part of the eroded material accumulated downstream below the diversion channel, and part was deposited by the flow along the convex bank of the channel. It should be emphasized that the gravel transport process is not finished after 27 h. In our estimate, a sufficiently long experiment would result in complete erosion of all the material. According to known hydrographs from high discharge measurements of the river Sava, using a 27 h flood wave is a relatively realistic approximation of a flood wave duration in nature. By prolonging the experiment or repeated high discharge situations in nature, this material is also eroded downstream. Because erosion occurred even at relatively low flow Q = 500 m^3/s, the diversion channel should be excavated to the bedrock, which is on average two meters below the bottom of the channel. In this way the problem of bank fortification is also solved, because banks have to end by the bedrock level.

The water levels and velocities were measured for discharges of different return periods along the construction pit and the diversion channel. Water level measurements showed that the construction pit in the studied range of Sava discharges is safe from overflowing, since the highest observed flow Q_{50} = 3365 m^3/s yields a safety level H_v = 2 m, which is high for a construction pit and enables the design engineers to optimize levee levels. Flow velocity measurements were performed with a 2D ultrasound probe (SonTek) at frequency 25Hz and measurement interval of 15 s, which in nature is 3.7 Hz in an interval of 100 s. Measurements were conducted in points with highest velocities. The values shown in Figure 8 and Figure 9 represent the velocity component parallel to the bank. Each graph has three lines – the average velocity in the observation point and the envelopes of measured velocities representing the standard deviation or 95% of all the measurements dispersed around the mean value.

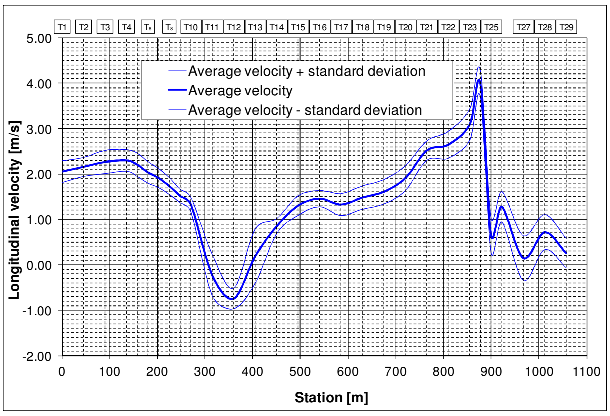

Figure 8. Longitudinal velocity profile along the right bank of the diversion channel of the construction pit at Q_{50} = 3365 m^3/s.

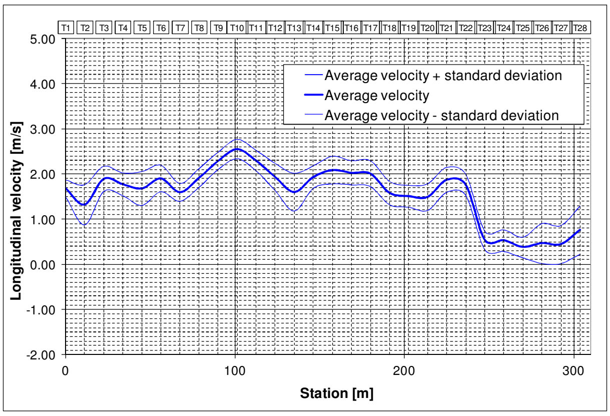

Figure 9. Longitudinal velocity profile along the levee of the construction pit at Q_{50} = 3365 m^3/s.

It can be seen from Figure 8 and Figure 9 that the highest velocities along the right bank of the diversion channel occur by its downstream connection with Sava and reach approximately 4 m/s. Along the levee of the construction pit the highest velocities were measured at the upstream edge of the pit and were about 3 m/s.

3.2 Impact of the construction pit and diversion channel of HPP Brežice on the runoff regime

The impact of the intermediate phase of HPP Brežice construction, namely the construction pit and diversion channel, on the flood hazard of the impact area was determined using the mathematical model. According to the original plan, the excavated material from the construction pit would be deposited on the right bank of Sava and the material from the diversion channel on the left bank (Figure 10). To minimize the excavation expenses of the diversion channel, the best location for the disposal site would be as close as possible to the cannel. Taking into account the velocity field in the existing state, the planned temporary disposal sites were designed to closely follow the water flow (Figure 10). With the existing state, the occurrence of a 100 year return period event (Q_{100} = 3750 m^3/s) would result in a quarter of the entire discharge (approx. 900 m^3/s) flowing along the right floodplain between Sava and the highway. With the positioning of the construction pit and diversion channel, the velocity field changes substantially, because the area of the pit is excluded from the flow and the remaining cross-section has a decreased throughput. Currents (and consequently depths, velocities, erosion etc.) are thus redistributed. Material disposal in the suggested area would additionally narrow the cross-section on the right bank, which would cause a barrage and an increase of water levels upstream, thereby increasing the flood hazard. At the same time, velocities and shear stresses between water and ground would also rise, increasing the erosion hazard of the agricultural areas and highway infrastructure.

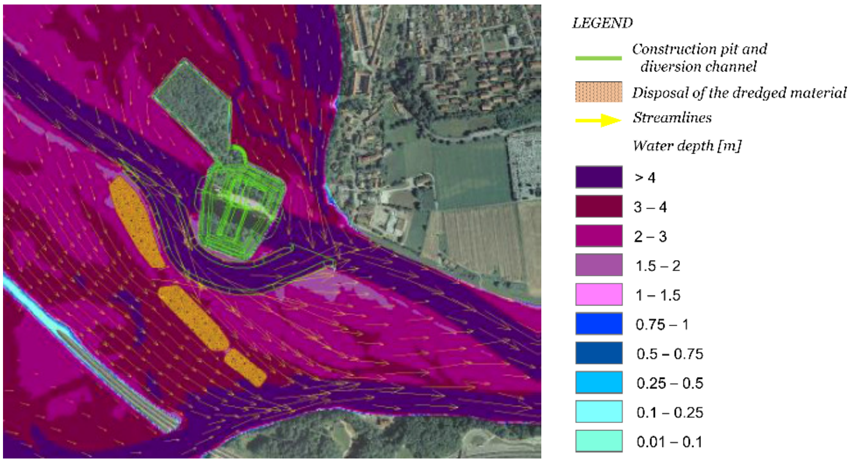

Figure 10. Proposed disposal sites for excavated material, showing also the velocity field.

The construction pit alone would cause a rise in water levels on the left and right floodplain of up to 0.45 m at the studied flows, the effects of which would diminish approximately 2 km upstream. Due to altered runoff conditions the dykes near some settlements would need to be built in the starting phases of construction of HPP Brežice. The calculated combined impact of the construction pit and disposal sites would be sufficient to cause flooding of the highway in case of a 100 year return period event, and the disposal sites would partially obstruct the return of water from the right floodplain toward the confluence of Sava and Krka Rivers, or would direct the flow more downstream toward the Krka section below the highway bridge. This would cause higher water levels in the channel of river Krka and worsen the flooding conditions in the upstream settlements.

The initially planned placement of the disposal sites of excavated material had to be changed due to decreased cross-section and consequently worsened runoff conditions. In terms of costs and flood safety, a more suitable placement would be upstream of the construction pit, where the cross-section of the right floodplain is sufficiently large and the impact of disposal sites would be smaller. However, this is not feasible due to an archeological site where research will continue also during the construction phase of the HPP. For other locations along the right bank of Sava the calculations show that the critical point in the building of the dam and embankments is on the narrowed part between the construction pit and the highway. The only other option was therefore to place the disposal site as far away from Sava River as possible, on the left bank of the Krka River (Figure 11). In this way the disposal site in the corner between the left bank of Krka River and the highway embankment would temporarily function also as a levee to avert the intrusion of water from Sava from the right floodplain into the channel of the Krka River. This will achieve better flood safety of surrounding settlements already in the construction phase. Possitive effects of building a dyke on the left bank of Krka River were previously determined in a study by Rak et al. (2012b). Temporary material disposal in this area would decrease the levels of Krka in the profile of the highway bridge (compared to the current state) by up to 0.50 m, which would also decrease the flood hazard for upstream settlements. The disposal site redirects the flow toward Sava, so the water levels next to the construction pit are consequently somewhat higher.

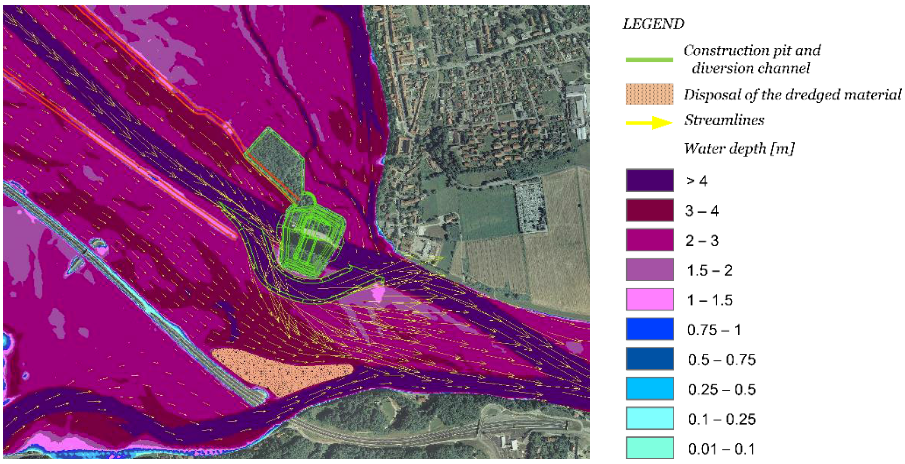

Figure 11. Final location and shape of the disposal site for excavated material from the construction pit and diversion channel, showing the velocity field at 100 year return period event.

Figure 11 shows the final shape of the disposal site. It would contain all the material excavated from the diversion channel. The disposal site is shorter in the direction along Krka than the planned levee and its shape is adjusted according to the streamlines in the right inundation at the construction pit.

4. Conclusions

For suitable placement of infrastructure and spatial planning that can have significant impacts on the runoff regime and could potentially increase flood and erosion hazard, it is necessary to take into account both the impact on the water environment and the impact of the water on the planned infrastructure and measures. When assessing the impacts of such structures, the emphasis is usually on determining the differences between the existing state and the final one after the construction is finished. However, with projects that take long to build, the water regime can change significantly and high discharges can occur also during construction. Because of temporary structures, disposal sites etc. and some construction phases (e.g. building levees on river segments) the planned infrastructure does not yet function as a whole. It is therefore necessary to analyze also the potential negative impacts of the altered (runoff) conditions on the annual flood and erosion hazard to the users of waterside and downstream locations. An important impact of the temporary state can occur also at shorter return periods.

The paper demonstrates that the use of hydraulic analysis during the construction process is equally important as in planning and optimization of the final infrastructure. By comparing the intermediate phases and results of the present and end state, it was possible to determine and evaluate the potential deterioration in each phase of construction. This assists the design engineer to better plan the phases and to include measures to mitigate hazards during construction.

The physical model of the area around the construction pit was used to determine the optimal shape of the diversion channel that conducts sufficient amounts of water at smaller excavations. The analysis of erosion processes in the diversion channel has shown that the channel has to be excavated to the bedrock; in all other cases, erosion is too strong. By measuring water depths in the diversion channel it was found that it is possible to lower the levee of the construction pit. A detailed hydraulic analysis of the construction pit made on a physical model with mobile bed provided us with answers to numerous questions and enabled the design engineer to optimize the construction of HPP Brežice.

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Martin Bombač was born in Ljubljana, Slovenia, in 1980. He graduated in 2005 at the Hydraulics Division of the Faculty of Civil and Geodetic Engineering of the University of Ljubljana (UL FGG) with the thesis “Hydraulic Optimization of the Intake Part of the Runoff-river Power Plants”. He started working as a researcher in the hydraulic laboratory of the Institute for Hydraulic Research in 2005, where his main task is combining mathematical and physical hydraulic modelling. His work focuses primarily on the research in the field of hydropower dams and flood protection systems. In the most recent publication he also deals with fishways hydrodynamics. During his postgraduate studies, he examined different kinds of turbulence models built into the 2D mathematical model PCFLOW2D developed by the researchers of the Chair of Fluid Mechanics with Laboratory, UL FGG. He obtained his PhD with the dissertation "Mathematical and physical modeling of flow in rivers with floodplains" in June 2014. Memberships: SDHR.

Gašper Rak graduated in 2006 with thesis ˝Using spatial data in open channel hydraulic˝ at the Faculty of Civil and Geodetic Engineering of the University of Ljubljana, where he was subsequently employed as assistant. Main focus of his work is numerical modeling of river hydraulics, flood hazard assessment, flood risk management, spatial information systems etc. In recent years he has also been involved in numerous studies for two large hydro projects dealing with the designing process. During his postgraduate studies, he analyzed a floodplain land use impact on the runoff regime in a retention area and consequently on flood wave propagation. In 2013 he obtained his MSc title with the thesis "Hydraulic Analysis of Floodplain Land Use Effects on Flood Wave Propagation". Memberships: SDHR.