River Flow 2010 - Dittrich, Koll, Aberle & Geisenhainer (eds) - © 2010 Bundesanstalt für Wasserbau ISBN 978-3-939230-00-7

One- and three-dimensional modeling of surge generated during operation of the hydropower plants Mühlbach and Maiermühle in Landsberg on the Lech River

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ABSTRACT: Part of the Lech River water, upstream of Karolinen weir is deviated on the right side to the Mühlbach channel in Landsberg in the south of Bavaria. From the intake structure to the Mühlbach´s confluence two diversion hydropower plants are situated on the River Lech: HPP Maiermühle on the upper reach und HPP Mühlbach on the lower reach.Flow fluctuations such as surge might originate, among things, from natural processes such as floods and mudflows or as an effect of anthropogenic changes. Surge phenomena due to failure or incorrect operation of one or more components of the two diversion hydropower plants in the Mühlbach channel belong to the latter category and are the present object of this study. In the first part of the study, the surge generated by turbine shutdown (HPP Mühlbach) was calculated by means of one-dimensional and unsteady modeling with HEC-RAS. After considering many scenarios with different discharges, variable turbine shutdown times (HPP Mühlbach) and different flap gate opening times on the surge bypass unit in the event of turbine close, the recommendation was to use a maximum discharge of 11 m^3/s. An hydraulic model and analysis of the surge in the upper part of the channel based on flow interruption or, respectively, closing of both HPP Maiermühle and the intake sluice gate provides a basis for more efficient improvement measures and optimized operation strategies. In the second part of the study, additional approaches are considered, focusing mainly on the interaction and influence of HPP Maiermühle. Because of the strong 3D characteristics of the upper reach, from the intake structure to HPP Maiermühle, this channel section was simulated using the three-dimensional program FLOW-3D. The results presented in this publication are drawn from a project commissioned by the Bayerische Elektrizitätswerke GmbH.

Keywords: Hydroelectric Power plants, Surge, One-dimensional model, Three-dimensional model, Failure analysis, Mühlbach channel

1 INTRODUCTION

Surge phenomena represent a powerful change in normal flow conditions caused by interaction with hydraulic structures in a channel system. Previous investigations in the Mühlbach channel indicated the occurrence of surge phenomena, especially by an abrupt failure or incorrect operation of one or more components of the two diversion hydropower plants.

In order to evaluate the hydraulic security of the existing channel, the surge generated during operation of the hydropower plants Mühlbach and Maiermühle in Landsberg on the Lech River was analyzed by means of computer modeling tools. An additional comparison between the results of one and three-dimensional modeling aims to find an optimum and effective modeling solution considering criteria such as the accuracy of results, and time and effort required for analysis.

2 SITUATION

The Mühlbach channel is a bypass channel, situated in Landsberg on the River Lech in Bavaria. The Mühlbach channel is deviates from the right of the Lech River, just upstream of the Karolinen Weir. The course of the channel is characterized by close interaction with the town within very limited space and it supplies two hydroelectric power plants: Maiermühle hydroelectric power plant (MMHPP) and Mühlbach hydroelectric power plant (MBHPP) as shown in Figure 1.

The HPP Maiermühle, located in the upper reach of the channel, was originally a flour mill operated by a water wheel and in 1996 was converted into a modern hydroelectric power plant with Kaplan bulb turbine. Because of urban planning considerations, the powerhouse was constructed undersurface. An automatic flap gate dams up the water, obtaining a head of 1.70 m for maximum energy production of 155 kW.

Around 400 m downstream and in the vicinity of the river mouth is HPP Mühlbach. The principal elements of the hydroelectric power plant are a Kaplan bulb turbine (net head = 4.8 m, design flow = 11 m³/s and energy output = 472 kW) and a surge bypass unit with an hydraulically operated flap gate (width = 2 m, design flow = 11.5 m³/s at retention water level elevation).

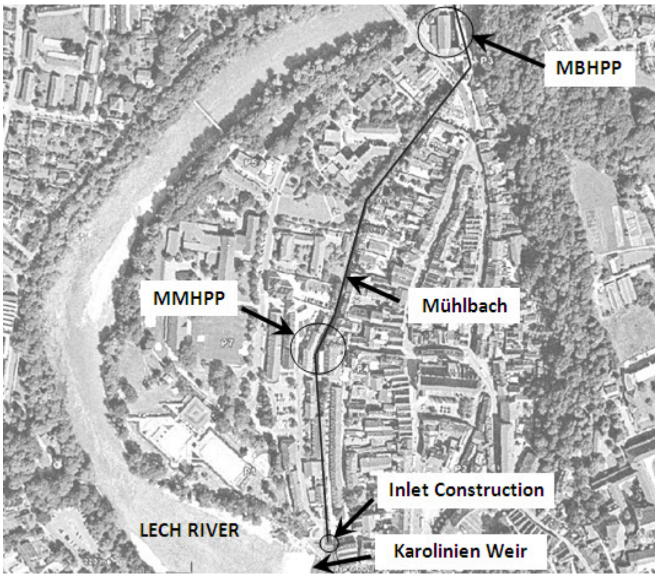

Figure 1: Mühlbach Channel aerial view.

3 OPERATION SYSTEM

The inflow into the channel is controlled by the intake sluice gate at the right of the Karolinen Weir. This intake sluice gate is operated by remote control from HPP Mühlbach. The outflow from the Lech River into the channel can be automatically regulated by means of a control unit according to the water level in the gauge situated directly after the intake structure.

The Mühlbach water flow passes through the HPP Maiermühle situated downstream of the deviation in the upper reach of the channel. HPP Maiermühle has no interaction with the intake structure control system.

The amount of water fed into the HPP Mühlbach´s turbine is automatically controlled by means of three gauges located upstream of the turbine inlet. Gauge signals are sent to the control unit in the powerhouse and processed in order to maintain an optimum and constant flow rate.

In case of rapid turbine shutdown (closing time 28 s) two components of the system are activated automatically: opening of the surge bypass unit flap gate (opening time 12 s) and 20 cm closure of the intake sluice gate (closing time 55 s). These operation times were determined in situ.

Both operational effects also are triggered automatically in the event of increase of the upper water level above 581.54 m.s.l., caused by abnormal operating conditions.

Once a failure of the system has been rectified, the intake sluice gate operates again in the initial position.

In normal operating conditions HPP Mühlbach processes an average discharge of 10 m³/s when the upper water level is 581.30 m.s.l. Maximum discharge is approximately 14 m³/s for the same upper water level.

Surge phenomena due to failure or incorrect operation of one or more components of the two diversion hydropower plants in the Mühlbach channel are described in the following sections. In the first part of the study, the surge generated by turbine closure (HPP Mühlbach) was calculated by means of one-dimensional and unsteady modeling with HEC-RAS.

4 MODELING AND SIMULATION BASIS

The channel is characterized by a concreted surface with a rectangular section. The modeling section extends from shortly after HPP Maiermühle to HPP Mühlbach. The Mühlbach channel covers a distance of about 350 m between the two hydroelectric power plants. Based on the channel geometry, namely 18 profile sections (Figure 2), including critical bank levels (lower edge of windows, balconies, etc.) provided by the Bayerische Elekrizitätswerke GmbH (BEW), a one dimensional model was created using the program HEC-RAS (River Analyses System) Version 4.0 Beta, of the US Army Corps of Engineers.

This model aims to calculate the surge generated by different scenarios, i.e. different discharges, variable times of turbine shutdown and opening (both in the surge bypass unit and in the intake structure).

Use was made of hydrograph curves to simplify the upstream flow both from HPP Maiermühle and from the intake structure, as well as the downstream flow at HPP Mühlbach including surge bypass unit.

The model was adjusted based on the retention water level of 581.30 m.s.l. for 8.5m³/s channel discharge, obtaining a plausible Strickler coefficient (50m1/3/s) for the concreted bed and wall channel.

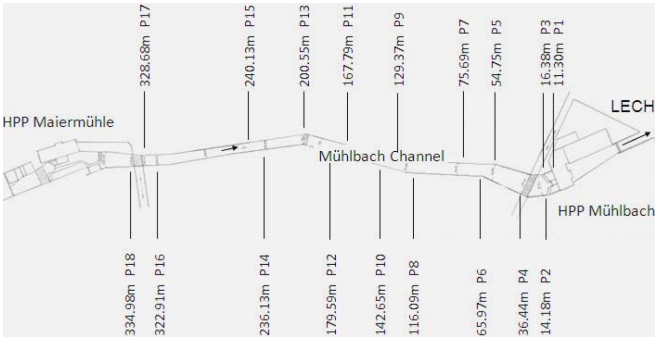

Figure 2: Profiles location in the modeling section.

5 SURGE MODELING AND SIMULATION

Specifically two variants were analyzed according to the operating conditions: on the one hand the real shutdown time of the turbine and opening time of the surge bypass unit flap gate, and in the other hand a very unfavorable and fictitious worst case scenario. In each case the average and maximum discharge were considered respectively. In this way four scenarios were defined (Table 1).

Table 1. Surge simulation scenarios.

Operating condition	Time	Z_s*	Q	t_c turbine	t_o flap gate	Item
		m.s.l.	m^3/s	s	s	
Average discharge	real	581.30	10	28	12	5.1
	worst case	581.30	10	4	30	5.2
Maximum discharge	real	581.30	14	28	12	5.3
	worst case	581.30	14	4	30	5.4

* Zs: retention water elevation.

5.1 *Scenario 1: average discharge – real times*

In this case the simulation does not show evidence of a surge as a result of the faster opening time of the surge bypass unit flap gate (12 s) as compared to the rapid turbine shutdown time (28 s).

The surge bypass unit is characterized by a higher design flow (11.5 m^3/s) in relation to the channel average discharge (10 m^3/s). Therefore the water level is gradually reduced until a stationary water level is reached, as a result of 20 cm closure of the intake sluice gate, implying a flow reduction into the channel from 10 m^3/s to 8.5 m^3/s.

5.2 *Scenario 2: average discharge – "worst case" times*

Since the worst case involves a faster turbine shutdown time (4 s) and a slower flap gate opening (30 s), results a surge with a maximum height of 20 cm immediately before HPP Mühlbach.

The surge running time between the two hydroelectric power plants is approximately 2 minutes. The surge is reduced by around 50 % at the level of HPP Maiermühle.

Despite the surge, the simulation shows no overbank flooding along the channel with the exception of around 10 cm in 142.65 m profile section. According to observations made during an in situ inspection, there is a local opening in the wall, in which water through-flow is obstructed by a panel. For this reason no overflow of the bank line is to be expected.

5.3 *Scenario 3: maximum discharge – real times*

Similarly to the first case this scenario involves the real times for turbine shutdown (28 s) and surge bypass unit flap gate opening (12 s).

Since the capacity of the surge bypass unit (11.5 m^3/s) is inferior to the incoming flow into the channel (14 m^3/s), the water level initially rises, beginning at the Mühlbach hydroelectric power plant. After about 2 minutes of water level increment, there is a tendency towards compensation, as a result of a gradual flow reduction at the intake structure, from 14 m^3/s to 11.7 m^3/s as shown in Figure 3.

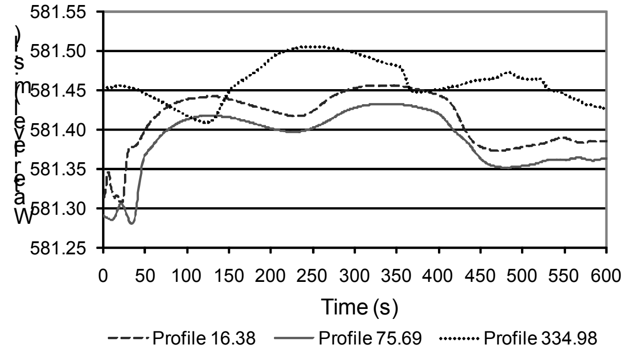

Figure 3: Water level for scenario 3: maximum discharge - real times.

The simulation results indicate an isolated case of local overbank flooding at profile section 142.65 m similar to situation 5.2, but only by 5 cm. This suggests no significant overflow of the bank line.

5.4 *Scenario 4: maximum discharge – "worst case" times*

A surge of about 30 cm is the result of a faster turbine shutdown than the flap gate opening time.

On reaching HPP Maiermühle after approx. 2 minutes, the surge is attenuated by about 30 %.

The inflow into the channel is reduced from 14 m³/s to 11.7 m³/s as an effect of 20 cm closure of the intake structure sluice gate, as to be expected. Two reflections of the surge peak are observed in Figure 4.

In this case there is an additional overflow of the water level beyond the left-hand bank between profiles 179.55 m and 200.55 m. In this section the bank wall is directly connected to an earth embankment of more than 50 cm as observed at on-site inspection. Therefore this scenario is also considered not to be hazardous in the event of a surge.

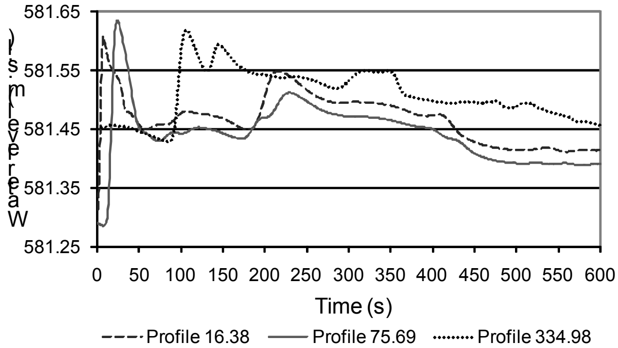

Figure 4: Water level for scenario 4: maximum discharge – “worst case” times.

6 FAILURE ANALYSIS

In accordance with the results of the one-dimensional simulations shown in this study, no significant overflow of the channel banks is expected when the system is operating properly, even in case of surge, maximum flow and worst case conditions.

Operation failure of the following system components have been analyzed, namely: surge bypass unit flap gate, intake sluice gate, HPP Maiermühle. Two variants were considered in each case: average discharge (Q = 10 m³/s) and maximum discharge (Q = 14 m³/s). Table 2 provides an overview of the scenarios considered.

The simulation section was extended for this purpose, from HPP Mühlbach to the intake structure, i.e. the complete Mühlbach channel. The turbine of HPP Maiermühle was simulated assuming a flap opening which ensures a retention water elevation of 583 m.s.l. corresponding to Q = 10 m³/s. If the water level is higher than 583 m.s.l. flows occur from the upper to the lower reach due to the overflow flap.

Table 2. Consider failure scenarios. Retention water elevation Zs = 581.30 m.s.l. in each case.

Failure scenario	Discharge	Q	t_c turbine	t_o flap gate	Item
		m³/s	s	s	
“Flap gate”	average	10	28	-	6.1
	maximum	14	28	-	6.1
“Intake gate”	average	10	28	12	6.2
	maximum	14	28	12	6.2
“HPP Maiermühle”	average	10	28	12	6.3
	maximum	14	28	12	6.3

6.1 *Failure of the surge bypass unit flap gate*

In case of failure, i.e. no opening of the surge bypass unit flap gate, overbank flooding occurred in the lower reach of the channel, even after a few minutes, for both 10 m³/s and 14 m³/s, despite possible water overflow ahead of the flap upper edge.

Potential improvements were suggested in the first part of this project in order to reduce the probability of occurrence of this scenario, e.g.:

- Technical measures applied to the surge bypass unit flap gate: improvement of the operation system of the flap gate e.g. by means of additional control valves, snow and ice elimination, for example by means of an air bubbling system, heating system, etc.
- Turbine operation in the event of a surge: even in the event of a surge it may be feasible to direct part of the discharge out through the turbine.

The following possible solutions to mitigate this failure case were simulated:

- Closure of intake sluice gate:

The situation of a complete flow suspension by closing the intake sluice gate was analyzed, both at normal and rapid closure velocity. Despite complete flow suspension by closing the intake sluice gate, overbank flooding occurred in the lower reach even after a few minutes due to emptying in the upper reach.

- Closure of intake sluice gate and additional HPP Maiermühle shutdown:

Additional shutdown of HPP Maiermühle was considered, parallel to complete intake sluice gate closure.

Directly after a rapid shutdown of HPP Mühlbach a quick closure time of 3 min was assumed, both at HPP Maiermühle and at the intake sluice gate, whereby the sluice gate propulsion system should be redesigned.

This approach was effective in case of average discharge (10 m³/s), since simulation results show no overflow of the bank line in the lower reach.

In case of maximum discharge (Q = 14 m³/s) the additional shutdown of HPP Maiermühle leads to no acceptable solution because bank line overflow both at the left and right of the channel are imminent, especially in the low section.

Since the Mühlbach duration curve specifies 14 m³/s or more only a few days in the year (Figure 5), a reduced maximum discharge of 11 m³/s was considered for additional simulations. Running the model with different closing times (2 min, 1 min and 30 seconds) both at Maiermühle and the intake sluice gate showed that only in the case of a 30-second closing time was the overflow of the bank line insignificant. The surge at rapid HPP Maiermühle shutdown generated on the upper reach should be analyzed separately.

Surge generated in the upper reach with the scenario “closure of intake sluice gate and additional HPP Maiermühle shutdown” requires a special study considering the trigger effect in HPP Maiermühle caused by closing the intake sluice gate. More detailed analysis of this approach is the main topic of section 7 “Upper reach considerations”. A model optimization in reference to the closing time of the HPP Maiermühle is a recommendation of this study.

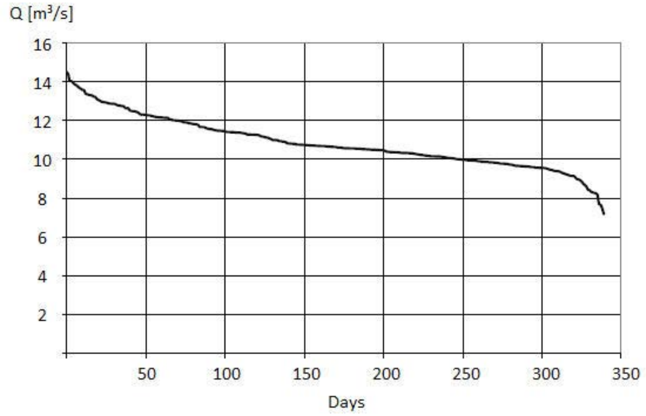

Figure 5: Mühlbach duration curve.

6.2 *Failure of the intake sluice gate*

When the turbine shutdown (28 s) and the surge bypass unit flap gate opening (12s) are regular, however, non-closure of the intake sluice gate by 20 cm occurs as planned, the channel inflow from the River Lech remains unchanged.

At average discharge (10 m³/s) into the channel, the water level is reduced by 25 cm at the level of HPP Mühlbach as a consequence of the higher capacity of the surge bypass unit (11.5 m³/s). This situation is not characterized by overbank flooding. In contrast, a water level increase at HPP Mühlbach is observed when flow through the channel is 14 m³/s, with corresponding minor overflow of the bank line only at 142.6 m and between 179.55 m und 200.55 m. Long-term simulation shows a virtually stationary condition after 60 minutes, probably because of possible water overflow above the flap upper edge.

6.3 *Unplanned horizontal placement of HPP Maiermühle flap gate*

There is not major bank overflowing risk by unplanned horizontal placement of the flap gate in HPP Maiermühle (120 s), neither by 10 m³/s nor 14 m³/s. In both cases an irrelevant overflow of the bank line by 142.6 m is registered.

Additionally by average discharge, upper water level of 581.54 m.s.l is reached, triggering on turbine shutdown, surge bypass unit flap gate opening and intake sluice gate closure by 20 cm.

7 UPPER REACH CONSIDERATIONS

In a second stage of the project the influence of the Maiermühle HPP and the consequences of its operation for the upper reach were investigated in detail for failure case 6.1 “Failure of the surge bypass unit flat gate”. For this purpose the actual geometry and operating control of the Maiermühle HPP and the geometry of the upper reach between Maiermühle HPP and Mühlbach intake sluice gate were taken into account.

7.1 *One-dimensional Model*

The HPP Maiermühle, the upper reach (~200 m length) and the intake sluice gate were integrated in the existing HEC-RAS model. The change from the upper to the lower reach at the HPP Maiermühle is observed in figure 6. Figure 7 shows a longitudinal section of the extended HEC-RAS model.

Large parts of the upper reach are overbuilt by houses and bridges. Furthermore the extended model considers also a lateral weir in the headwater of the HPP Maiermühle connected via a bypass with the tail water. It has a capacity of up to 4 m³/s.

Figure 6: The Mühlbach channel at HPP Maiermühle. Change from upper (foreground) to lower reach (background).

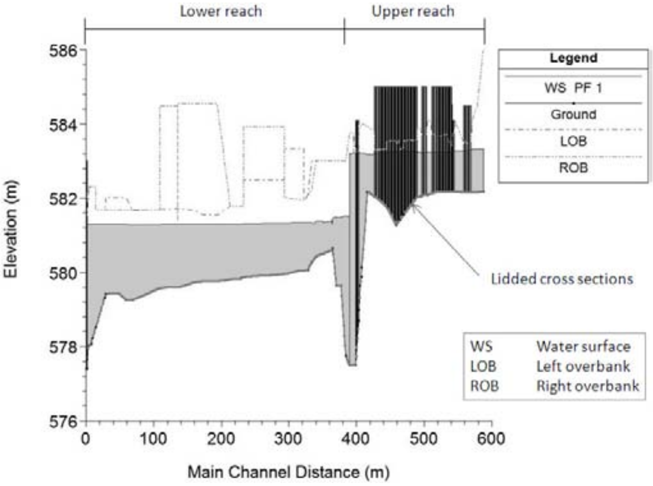

Figure 7: Extended HEC-RAS model schema; black bars indicate lidded cross sections; flow from right to the left.

The cross section geometry for the extended model section (upper reach) is based on 10 profiles from the HPP Maiermühle headwater, 9 from its tail water and 45 profiles which were derived from plans relating to the HPP intake, the bottom edges of buildings and bridges and the intake sluice gate.

The extended model was adjusted as described in the first part of this work, with an additional consideration of pressurized flow in the lidded cross sections by using the Priessmann slot theory and the corresponding details concerning the HPP Maiermühle such as the lateral weir in the headwater connected via a bypass with the tail water.

A number of unstable scenarios were simulated, considering different operational conditions of the HPP Maiermühle and also of the HPP Mühlbach and the intake sluice gate. In order to achieve a quasi steady condition, a total time of 30 minutes was simulated for each scenario. The first three minutes after the operation disturbance were thoroughly analyzed on a second resolution, because in this time the major surge dynamic processes occur. Following scenarios were analyzed:

- Turbine shutdown (10.2 s) with flap gate opening (2 s) at the HPP Maiermühle for both, average (10 m^3/s) and maximum (14 m^3/s) channel discharge - No critical water surface elevations occurred.
- Turbine shutdown (10.2 s) without flap gate opening at the HPP Maiermühle for both average (10 m^3/s) and maximum (14 m^3/s) channel discharge - The simulations show rather insignificant surge phenomena ending with a constant water surface elevation increase, which results in overbank flooding for the maximum discharge.
- Turbine shutdown (10.2 s) without flap gate opening at the HPP Maiermühle and simultaneous turbine shutdown (28 s) with flap gate opening (12 s) at the HPP Mühlbach, including a resulting reduction of the intake sluice gate (20 cm in 55 s) for the scenarios with average (10 m^3/s) and for the maximum discharge (14 m^3/s) – In terms of the surge generation the results for this case do not vary much from those of the previous simulation, so interaction is negligible. However the final water surface elevations are lower and no overbank flooding occurs.
- Turbine shutdown (10.2 s) without flap gate opening at the HPP Maiermühle, turbine shutdown (28 s) without flap gate opening at the HPP Mühlbach and closure of the intake sluice gate in a time x for different discharges – No matter how small x is, surge and overbank flooding will result in the lower reach for discharges greater than 11 m^3/s.

The design of the HPP Maiermühle, with its large open air overflow gate and the additional lateral weir, proved to be relatively safe concerning turbine closure with or without flap gate opening. Almost no surge can be observed and the water level elevation rise due to flap gate failure is only critical for high channel discharge larger than 11 m^3/s. Furthermore the optimization of the approach to solve the flap gate failure case at the Mühlbach station showed that surge and bank flooding is inevitable in the lower reach for discharges above 11 m^3/s. So finally the feasibility of the approach from the first investigation was proved and the maximum possible discharge was clarified with the extended HEC-RAS model.

7.2 *Three-dimensional model*

To account for the three-dimensional flow situation at the intake of the Maiermühle power station, especially in connection with the lateral weir, a detailed analysis of this area and the surge formation there was found to be necessary. Therefore a

FLOW3D model of the power station and its intake was set up to verify the correctness of the 1D model results with a 3D reference calculation. The 3D model is illustrated in Figure 8.

Use was made of an RNG-based turbulence model for the simulation. It had a position-related spatial grid solution up to 0.2 m which resulted in half a million cells. A calculation with cell size 0.1 m resulting in four million cells was run to ensure grid independence of the numerical solution. The HEC-RAS reference calculation was carried out for the HPP Maiermühle turbine design discharge of 12.6 m³/s. During several restart simulations the cylindrical hole which was representing the turbine was calibrated at first to meet this discharge water surface elevation relation. Furthermore quasi static initial conditions were established. Then, in a subsequent simulation a moving object was used to close the turbine opening within the corresponding time (10.2 s), simulating turbine closure without flap gate opening scenario. This resulted in an almost invisible surge and above all in a water surface level rise, up to a point where steady conditions were achieved. The two steady situations are illustrated in Figures 9 and 10.

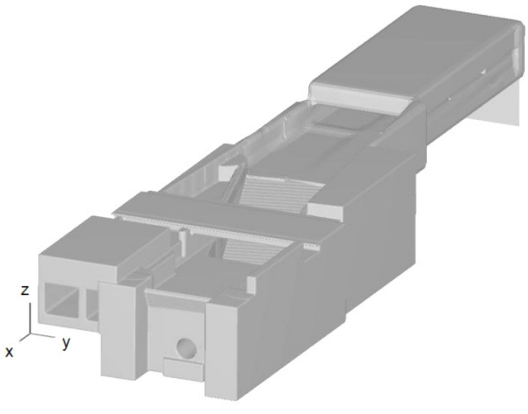

Figure 8: Flow-3D model geometry; flow from top right to bottom left.

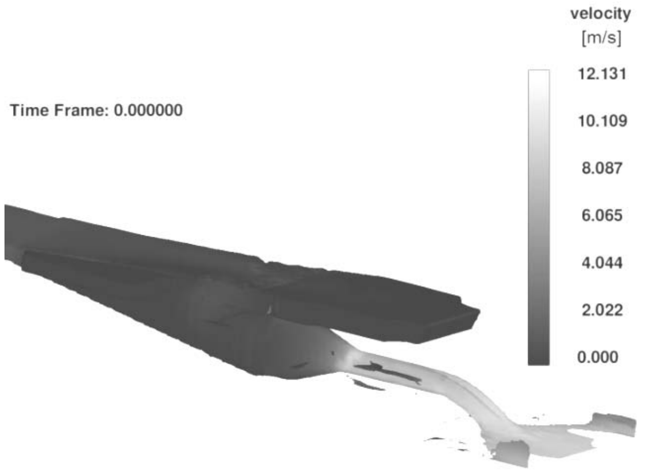

Figure 9: Initial conditions for 3D simulation (only the water body); flow from top left to bottom right.

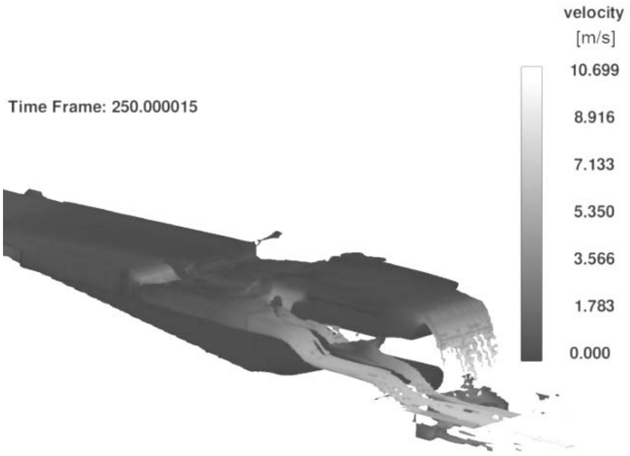

Figure 10: Final state of 3D- simulation (only the water body); flow from top left to bottom right.

In the second project stage additional approaches in failure case 6.1 "Failure of the surge bypass unit flap gate" were analyzed including the application of one and three-dimensional models, which were evaluated comparing the water surface elevation at three points.

In terms of results evaluation the water surface levels at three reference points for results in case 6.1 "Failure of the surge bypass unit flap gate" of both one- and three-dimensional models were compared. The point positions and the water surface levels are shown in Figure 11.

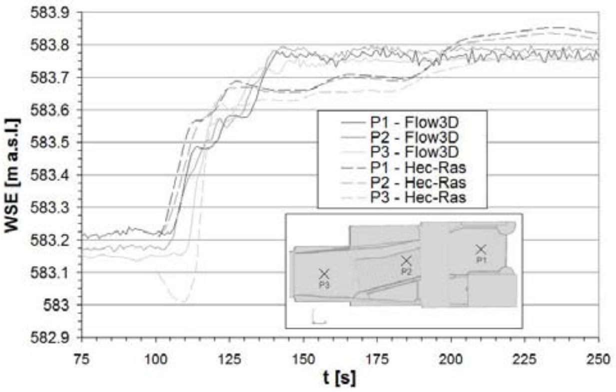

Figure 11: Comparison of water surface elevation (WSE) time development in 3D (line) and 1D (dashed) simulation and the positions of used reference points (small graphic); turbine shutdown at t = 100 s.

Both methods (1D & 3D) show a rapid increase in the water surface elevation of about 0.6 m after the turbine closure. The surge generated by the abrupt flow change is rather insignificant and just visible as small local maxima or an increase like a step function. Finally both calculation procedures lead to similarly constant water surface levels. The three-dimensional approach shows a quasi constant water surface elevation of averaged 583.76 m.s.l. about 40 s after the closure event began. The one-dimensional method yields a constant water surface level of averaged 583.79 m.s.l. about 200 s after the turbine shutdown. However, the one-dimensional method shows results which vary about 0.1 m from the three-dimensional results for the first two minutes after the incidence.

8 CONCLUSION

The first project stage indicated that no critical water levels are to be expected, both by average and by maximum discharge, as long as normal operation of the system components and the real times for turbine shutdown and surge bypass unit flap gate opening are maintained. Under these conditions operational safety can be assumed with respect to surge phenomena.

Based on the failure analysis it can be concluded that in the case 6.2 “Failure of the intake sluice gate” under average discharge conditions or in the case 6.3 “Unplanned horizontal placement of HPP Maiermühle flap gate” are considered to be nonhazardous, thus confirming the operational safety of the system. To avoid critical water levels in failure case 6.1 “Failure of the surge bypass unit flap gate”, technical modifications of the surge bypass unit might reduce the probability this failure occurring.

In the second project stage additional approaches in failure case 6.1 “Failure of the surge bypass unit flap gate” were analyzed including the application of one and three-dimensional models, which were evaluated comparing the water surface elevation at three reference points. On the whole, the two calculations showed acceptable agreement regarding to general accuracy.

So with regard to the project, the correctness of the results of the simplified one-dimensional HEC-RAS model is affirmed and no further modifications of the HPP Maiermühle or the lateral weir is required. Concerning general consideration of the quality of one dimensional methods compared to three-dimensional approaches such as FLOW 3D, this study indicates that also very simplified energy considerations can be a time and cost-effective alternative instead of elaborate three-dimensional calculations. However, the limits of correctness remain unclear and call for individual investigations as presented in this study.

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