39th IAHR WORLD CONGRESS GRANADA, SPAIN 2022 From Snow to Sea 19-24 June 2022

Proceedings of the 39th IAHR World Congress
19–24 June 2022, Granada, Spain
doi://10.3850/IAHR-39WC2521716X2022514

Solution for a Sluicing Channel with high and coarse Sediment Intake in an alpine River

Jakob Siedersleben[(1)], Marco Schuster[(1)], Markus Aufleger[(1)] and Stefan Achleitner[(1)]
[(1)] Unit of Hydraulic Engineering, Faculty of Engineering Science, University of Innsbruck, Austria
Jakob.siedersleben@uibk.ac.at

Abstract

The presented work is part of the optimization of the sediment management at the hydroelectric power plant in Reutte/Höfen in Tyrol/Austria. The Höfen runoff power plant is situated in an alpine environment and exploits water of the river Lech which transports high rates of coarse material. The lateral water intake is equipped with a sluicing channel located in front of a horizontal bar screen. Thereby, sediments cannot enter the turbine intake and the retained sediments must be sluiced frequently. The objective of the study is the optimization of the sluicing process once the sediments have entered the sluicing channel. Physical model experiments on a scale of 1:15 respecting Froude similarity were conducted using five different particle size classes to replicate the grain size distribution. The experiments of the current state correspond well with the experiences of the powerplant operators, thus validating the experiments considering adaptation measures. To increase sluicing efficiency, a new approach aiming for sediment sluicing while maintaining capacity level was developed: two additional layers with three culverts each were introduced in the original channel, using the natural head between the water surface of the reservoir and the outlet of the culvert. This approach results in pressurized flow through the culverts transporting sediments downstream of the reservoir. Experiments of the culvert design showed that sluicing is most efficient when the capacity level is maintained in combination with energy production. When energy production is stopped, sluicing is less effective. Sluicing with lowered water level is still possible.

Keywords: Sediment management; Sluicing channel; Hydropower; Physical modeling; Morphodynamics

1. INTRODUCTION

Sediment intake in hydroelectric powerplants leads to possible damage and abrasion of turbines and can force the operators to stop energy production (Felix, et al., 2016; Thapa, et al., 2015). For lateral water intakes, sluicing channels constructed in front of the water intakes are supposed to trap incoming sediments. The sediments can be removed by opening a sluice gate, controlling the outflow discharge of the channel. However, this sluicing method is based on normal flow conditions requiring the drawdown of the capacity level resulting usually in a stop of energy production and economic losses for the operator. Additionally, the entire removal of sediments by a sluicing operation is not guaranteed, due to channel design and naturally varying river discharge.

Although there exists a range of publications dealing with the removal of finer sediments, using for example the systems according to Büchi or Dufour (De Cesare, et al., 2014; Ortmanns, 2006). Still, the applicability in combination with coarser sediments, such as gravel, has not been investigated yet. An additional disadvantage is, that these approaches rely on lowering the capacity level and require substantial space. A promising approach was introduced by Jacobson (1997), who executed laboratory and field experiments investigating a "slotted pipe sediment sluicer" which removes sediment by using the natural head between the water surface of the reservoir and the outlet of a pipeline.

In the following, a new design for a sediment sluicing channel is developed using the basic principles introduced by Jacobson. It aims for the possibility of sediment sluicing of larger areas compared to his concept and sediment sluicing while maintaining the capacity level to limit sluicing times and increase efficiency. Additionally, considering the requirements of the operators, movable parts shall be avoided due to concerns, that coarse bed load material will possibly damage and consequently make the system inoperable.

Figure 1 gives an overview of the used case study: the reservoir of the hydroelectric powerplant (HP) Reutte/Höfen at the river Lech, including the installed weirs and intakes. The power plants exploit water of the river Lech, an alpine river transporting high rates of coarse material with an MQ of 44,1 m³/s.

The focus is put on residual run-off HP at the orog. left Höfen side with a maximum capacity of 15 m³/s. On the orog. right side, the intake structure towards the powerplant Ehenbichl is located, designed for a capacity of 24 m³/s. The reservoir operation is realized by several weirs, a fixed overflow, and two sluice gate systems. In the frame of recent major renovations, the number of weirs on the Höfen side was reduced to three. In that course, a residual run-off HP at the Höfen side was completed in 2018. This residual run-off HP with a design capacity of 15 m³/s utilizes a lateral water intake with a horizontal bar screen having a sluicing channel located in front of it. Due to the high bedload rates, frequent sedimentation of the sluicing channel, while preventing sediments from entering the turbine intake, is the case. Furthermore, efficient sediment sluicing operations require exact regulation of the water level which is operational demanding.

The focus in this work is put on the optimization of the subsequent removal of sediments and conveying them further downstream.

2. LABORATORY EXPERIMENTS

2.1. Overview

In the framework of a project investigating sediment management of the Reutte reservoir, a model respecting Froude similarity was set up. Figure 1 shows the extent of the model covering the left side of the weir system, including the residual run-off powerplant (1), the sediment guiding wall (2), the sluicing channel which is situated immediately in front of the water intake and leads the trapped sediment downstream (3), the powerhouse (4), protected by a horizontal bar screen to prevent coarse material to enter and the three weirs (5,6,7). Section A of the sluicing channel is shown in Figure 2. The Lechweir, a fixed broad crested weir (8), the two bottom outlets (9), and the diversion channel (10) are not part of the model. Sediments of the movable bed are represented by five grain size classes (see Table 1). To prevent cohesive effects when downscaling grain sizes, the minimum particle size diameter is limited to 0.5 mm. This results in a d_m=1.45 mm with cutting off fines compared to a d_m=1.41 mm without cutting off fines. Due to the small change of the d_m (Δdm=0.05 mm), the effects of cutting off fines are expected to be neglectable.

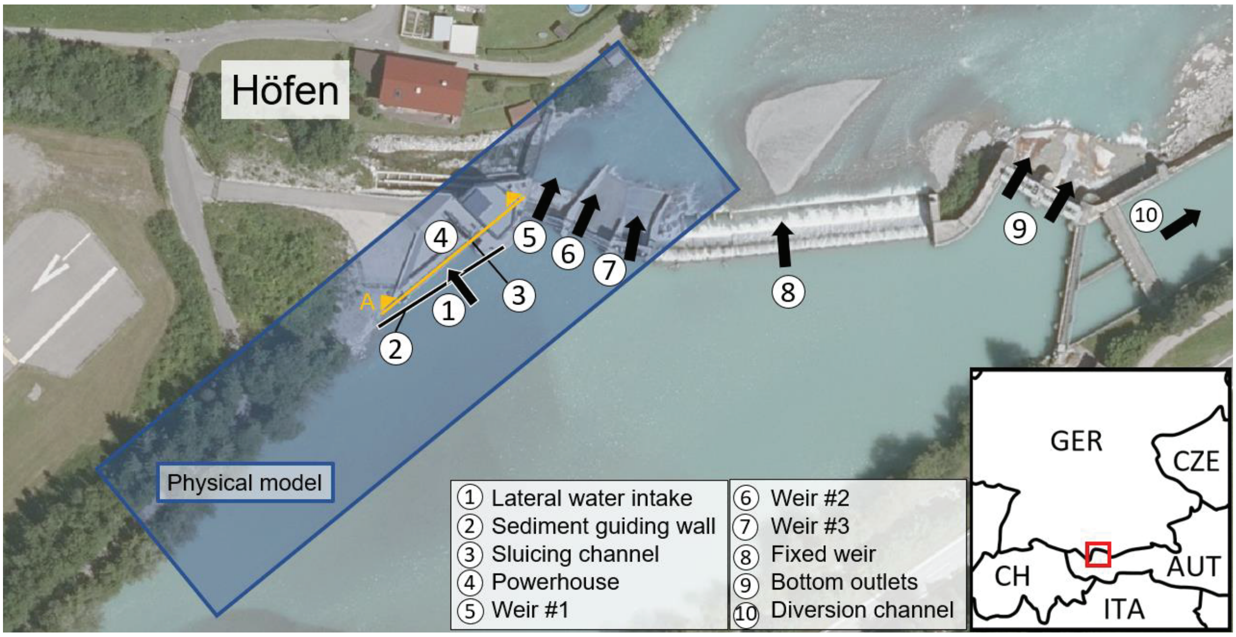

Figure 1: Top view of the study area

Table 1: Sediment classes

	PARTICLE DIAMETRE [MM]	PERCENTAGE [%]
FRACTION 1	0.5 – 1.0	52.5
FRACTION 2	1.0 – 2.2	27.5
FRACTION 3	2.0 – 3.2	12.5
FRACTION 4	3.0 – 5.6	5.0
FRACTION 5	5.0 – 8.0	2.5

2.2. Sluicing channel design

Bottom culverts are introduced in the existing sluicing channel as shown in Figure 2. The current state of the sluicing channel design (Figure 2 (a)) is a rectangular channel, narrowing along its flow path. The additionally introduced culverts are shown in Figure 2(b). The current state design features a 32.9 m long sluicing channel, with an initial width of 3.32 m tapered to 1.5 m being inclined at 2.2 %. The sluicing channel is controlled by a sluice gate. The culvert design features two additional layers: firstly, an intermediate layer with three separate rectangular culverts is installed. Each culvert opening has a size of 1.50 m x 0.5 m. The culvert height is 0.5 m. The widths taper from 0.7 m to 0.45 m. Secondly, on top of the intermediate layer, a top layer with three rectangular culverts is installed with openings facing in the upstream direction. The height is 0.5 m. The width tapers from 0.5 m to 0.45 m. All culvert downstream openings are operated by the existing sluice gate, meaning, that the bottom culverts can be opened separately from the top culverts. The opening of the top-culverts can only be done in combination with the bottom culverts.

When opening the six sluicing culverts, while maintaining the capacity level, a pressure difference results similar to the design developed by Jacobson (1997) (see the difference in water level in Figure 2 upstream and downstream of the sluice gate) moving sediments through the culverts downstream. The difference in the natural head is 2.4 m at maximum. There are two modes of operation: (i) the culverts remain closed during energy production. Only when the channel is filled up with sediments the six culverts are opened by the sluice gate and the sediments are supposed to be transported downstream through the pressurized culverts. Provided that the river discharge is high enough, energy production does not need to be stopped. (ii) The culverts remain constantly open, aiming to avoid the accumulation of incoming sediments in the sluicing channel. Sediments are transported through the sluice channel while maintaining energy production. In the following, the first operational strategy is presented, as the physical process of flushing, a fully sedimented channel is not only demanding but represents a worst-case scenario that may happen during larger flood situations.

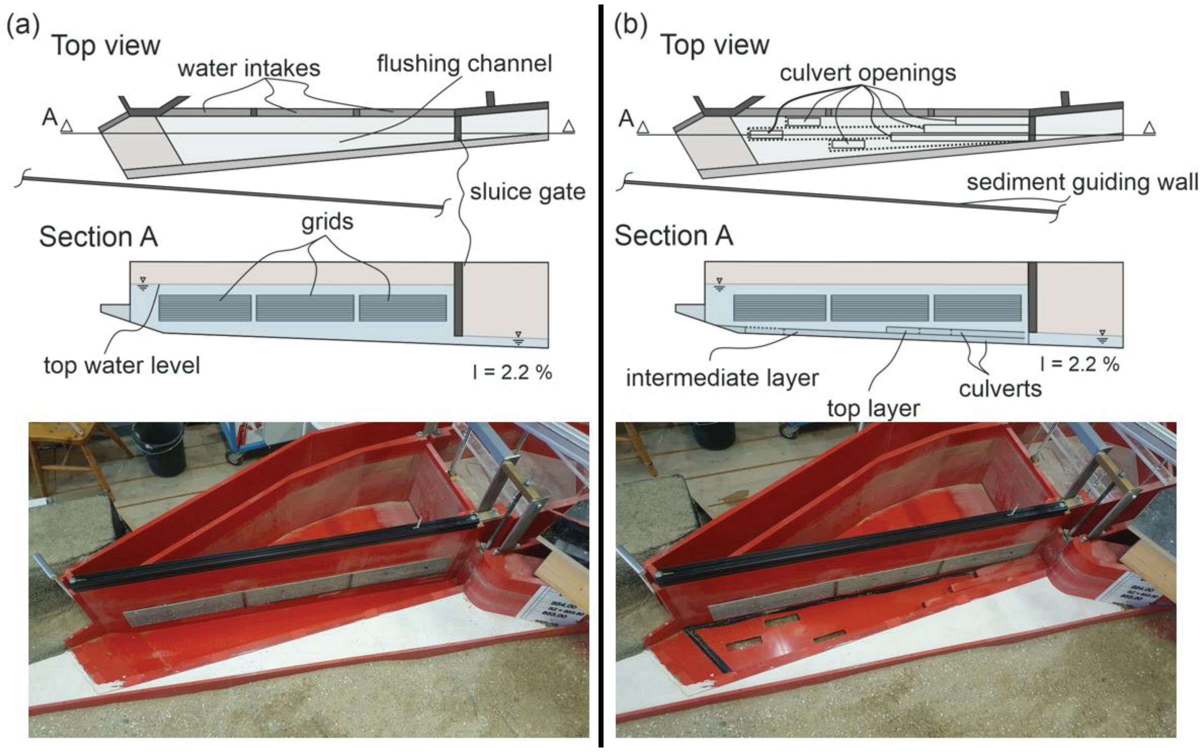

Figure 2: Current state design (a) and pressurized culvert design (b)

2.3. Experiment description

Different situations were tested regarding the capacity level and the maintenance of energy production. The full set of experimental setups can be seen in Table 2, all run with a discharge of 35 m^3/s (natural scale). Experiments A-x and B-x correspond to the current state and the culvert design respectively. Throughout all tests, the stationary discharge is kept the same and the water level is controlled by weirs #1 and #2. Prior to each experiment, the sluicing channel is filled entirely with sediments, assuming preceding sedimentation (see Figure 3 - initial state). For both configurations, the experiment starts with the opening of the sluice gate. For experiments A-x the sluice gate is opened entirely, allowing the development of normal flow without backwater effects from the gate. For experiments B-x the sluice gate is opened stepwise, enabling flow via (1) the bottom culverts, (2) the top culverts, and (3) free surface flow above the culverts by opening the sluice gate entirely. For each of the steps, the success of sediment flushing is documented photographically before and after each experiment.

Table 2: Experiment setups with current state design (A) and pressurized culvert design (B)

	Discharge [m^3/s]	Capacity level	Energy Production
Experiment A-1	35.0	yes	no
Experiment A-2	35.0	yes	yes
Experiment A-3	35.0	no	no
Experiment B-1	35.0	yes	no
Experiment B-2	35.0	yes	yes
Experiment B-3	35.0	no	no

3. EXPERIMENTAL RESULTS

3.1. Overview

In Figure 3, the initial and final sediment distribution after sluicing under the different configurations is shown. The water intake is located on the right side and the sluice gate is located at the lower end of the pictures.

3.2. Experiment A-1

Flushing the channel while keeping the capacity level and no water withdrawal via the turbine has very limited success as can be seen in Figure 3 (A-1). After opening the sluice gate, sediments located in the downstream fifth of the channel are sluiced efficiently, but the remaining sediments rest unmoved. Sluicing time took approximately 4 min (natural time scale). After that, no substantial change of sediment distribution or transport in the channel was observed.

3.3. Experiment A-2

Comparing the two images of Figure 3 (A-1) and (A-2) suggests, that flushing the channel while keeping the capacity level and maintaining energy production has little to no advantages compared to experiment A-1. Additionally, due to forcing implied by the water intake, a fraction of the sediment load is transported into the powerhouse. Sluicing was efficient for approximately 5 min (natural time scale). After that, no substantial change of sediment distribution or transport in the channel was observed.

3.4. Experiment A-3

As clearly visible in Figure 3 (A-3) sluicing the channel while lowering the capacity level leads to successful sluicing of the entire channel. No substantial sediment load remains in the channel. However, the water level must be kept at a certain level such that the flow entering the sluice channel approaches mainly from upstream and not from the side. Thus, maintaining the water level at the most efficient level demands precise control of the weirs over a relatively long period of 77 min (natural time scale) to remove all sediments.

3.5. Experiment B-1

After opening the bottom culverts, while maintaining the capacity level, sediments in direct proximity to the openings are transported efficiently. However, sediments remain in between the openings. The same situation is observed at the top culverts. After opening the sluice gate entirely, sediments in the lower part of the channel are removed, similar to the situation in A1. The full flushing operation took 8 min (natural time scale).

3.6. Experiment B-2

Maintaining capacity level and energy production during the sluicing operation improved the sluicing success considerably compared to experiment B-1. Due to the lateral forcing applied by the water intake, turbulence occurs and moves the sediment in proximity to the culverts' openings. Almost no sediment remains in the channel as displayed in Figure 3 (B-2). However, a fraction of the sediment load is transported in the powerhouse, comparable to experiment A-2. The entire operation took 39 min (natural time scale).

3.7. Experiment B-3

Sluicing sediments while lowering the capacity level was successful. However, to remove all sediments, it is necessary to artificially create a fluctuating water level by periodically alternating the sluice gate opening. This is difficult in execution and demands extended sluicing time. But if executed correctly, no substantial sediment load remains in the channel as suggested in Figure 3 (B-3). The entire operation took 58 min (natural time scale).

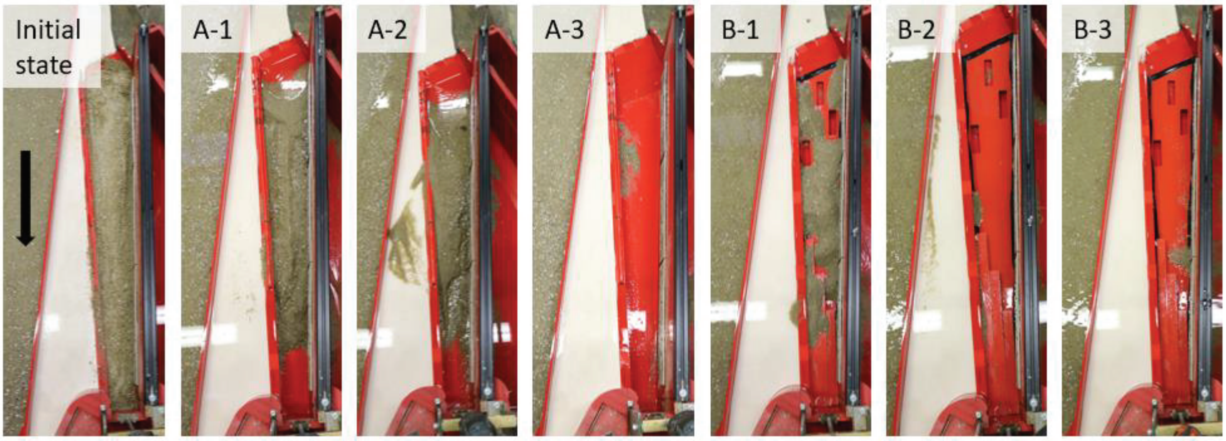

Figure 3: Top view of the initial state of each experiment and the sluicing channel for current state design (A) and culvert design (B) at the end of each experiment. The flow direction is from top to bottom (see black arrow)

4. DISCUSSION

Experiments A-x suggest, that effective sediment sluicing using the current state design is only possible when lowering the capacity level maintaining free-flow conditions. Still, the water level must be set in a small bandwidth and must introduce water mainly from the upstream end of the channel. Lowering the water level locally is hardly realizable. Current operational practice is that a drawdown is made during flushing in the entire reservoir, which is a time-consuming procedure. Consequently, energy production must be stopped, resulting in economic losses for the operators. Sluicing the channel while keeping the capacity level is not feasible as experiments A-1 and A-2 show very limited flushing success. These findings correspond to the operational experience of the operator and thus validate the model setup used.

Experiments B-x suggest, that sluicing while maintaining the capacity level is only successful when energy production is maintained. Flushing operations while keeping the capacity level, but without energy production are locally successful, but a substantial part of the initial sediment load rests unmoved (see Figure **3** (B1)). This is due to the limited area affected by each of the culvert openings. However, for sluicing channels covering lower areas, this mode of operation could be nevertheless successful.

The successful sluicing while maintaining the capacity level and energy production is caused by the water flow entering the intake. This applies additional lateral forcing on the sediment load in the channel, consequently, turbulences arise and move sediments through the channel towards the culvert openings. Additionally, the sediment guiding wall fortifies the effect of turbulence due to its position close to the sluicing channel. The main adverse issue of this mode of operation is, that a fraction of the sediment load enters the powerhouse. However, the entirely filled sluicing channel, which was investigated in the experiments represents a worst-case scenario, meaning that under most conditions, the sediment intake in the powerhouse should be significantly smaller. Additionally, provided that the river discharge is high enough, a continuous culvert opening during energy production is an option for continuous diversion of sediments. Using this option could prevent the channel from the entire sedimentation similar to the initial setting used during the experiments made here. Thus, refinement of the scenario consideration concerning initial sediment loading and intermediate and continuous sluicing is subject to further investigations.

Furthermore, with the culvert design, successful sediment removal is still possible when temporarily lowering the water level. This can be done by periodically varying the flow conditions (normal flow to backwater conditions) through sluice gate operations. Still, this method is demanding and leads to extended time to fully eliminate sediments.

5. CONCLUSIONS

The work presented focuses on the flushing operation of a sediment channel located in front of a water intake. The physical model used was realized as part of a larger project investigating the sediment management of the reservoir Reutte/Höfen, which is used to withdraw water from the river Lech for energy production. The study aims for a more efficient sediment removal of the sluicing channel protecting the residual hydro powerplant. Besides testing the existing design, a new approach was developed to improve the efficiency of the sluicing operations. The proposed design uses culverts with top openings to withdraw sediments. They are realized in two layers with three culverts each and the existing sluice gate is used to control the pressurized discharge through the culverts. The pressure difference arises due to the different water levels at the opening and outlets of the culverts. Several experiments were conducted to compare the current state and the culvert design and were executed with a filled sluicing channel, corresponding to a worst-case scenario. Experiments showed, that sediment sluicing while maintaining the capacity level and energy production works efficiently, although a fraction of the initial sediment load is transported in the powerhouse, which may pose problems concerning turbine abrasion. An advantage is that the culvert design works best while maintaining the capacity level, meaning that reduced flushing times apply and the energy production needs no or only short interruptions. Still, from an operational point of view, driftwood, bushes, and similar must be considered. Such aspects, bearing the potential to block the culvert openings or enter the culverts were not investigated so far. Of further interest are long-time experiments, which start with an empty sluicing channel (contrary to the executed experiments) but continuous sediment load is applied, while maintaining the capacity level and energy production.

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