Conference Paper, Published Version

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Verfügbar unter/Available at: https://hdl.handle.net/20.500.11970/99776

Vorgeschlagene Zitierweise/Suggested citation:
Brinkmeier, B.; Aufleger, Markus (2010): Bed load transport processes at river flow power plants - hydraulic model test for the Lower Salzach River. In: Dittrich, Andreas; Koll, Katinka; Aberle, Jochen; Geisenhainer, Peter (Hg.): River Flow 2010. Karlsruhe: Bundesanstalt für Wasserbau. S. 1253-1258.

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

Bed Load Transport Processes at River Flow Power Plants- Hydraulic Model Test for the Lower Salzach River

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ABSTRACT: The design and construction of new hydroelectric power plants has been a much discussed issue with respect to the necessity for increased use of renewable energy on one hand and sensitive ecological requirements on the other. The recently developed concept of a novel river hydro power plant is currently being investigated at the hydraulic laboratory of the University of Innsbruck, Austria. The ongoing feasibility study regarding hydro power use at the lower Salzach River between Austria and Germany should resolve, whether a sustainable use of hydro power is achievable under the given local circumstances. The main challenges are posed by the low water head available (approx. three meters), the ecological requirements mainly relating to fish passability and river ecology, as well as by the complex issue of sediment and bed load transport and its interaction with the structure. Several ideas and concepts regarding effective bed load transport through and around the power plant have been collected and reviewed. This was followed by the optimisation of the arrangement of the structure. The physical model test shall show the feasibility of all proposed measures.

Keywords: Bed load transport, Sediment transport, Model tests, Hydro power

1 INTRODUCTION

The design and construction of new hydroelectric power plants in alpine and pre-alpine regions has been a long discussed issue over the last couple of years. Supporters of hydro electric power have pointed out the possibility of efficient and clean generation of hydroelectricity as the main asset, whereas objectors strongly recommend refraining from construction of any further structures in fragile natural habitats like rivers. Hydroelectric power will continue to be in the area of conflict between the necessity for increased use of renewable energy on one hand and sensitive ecological requirements on the other. In Austria, there is still a potential of about 13 TWh/a, which is not used yet and is rated as technically cost-effective (Pöyry Energy, 2008).

Considering the circumstances, a new hydro power project seems only, if at all, possible, if all ecological requirements are met to a sufficient extent. The following example shows the recently developed concept of a novel river hydro power plant currently being investigated at the Unit of Hydraulic Engineering at the University of Innsbruck. The project is conducted on behalf of Grenzkraftwerke GmbH in cooperation with a number of experts and is supported by the Austrian Climate and Energy Funds.

The main technical challenge of this concept lies in bed load transport processes, as transport through the structure has to be ensured without posing any danger neither to the structure itself nor to the operation of the plant.

2 CONCEPT OF A RIVER FLOW POWER PLANT

The concept of a run-of-river plant as described in this paper was developed for a specific reach of the lower Salzach River on the border between Austria and Germany, but could be applied to many pre-alpine rivers with similar characteristics.

At the Salzach River a strong erosion tendency exists due to river straightening and lining undertaken over the last 150 years. The erosion tendency requires immediate river restoration, which is planned to be achieved by the construction of block ramps to stabilise the river bed locally and decrease the slope of the river in the remaining reaches. The block ramps are intended to cover a height difference of approx. 2.5 to 3.0 meters. The concept of the river flow power plant aims at using the height difference created by the block ramps to generate power.

Figure 1 displays a cross section through the river flow power plant, showing the block ramp on the left side and the power plant on the right.

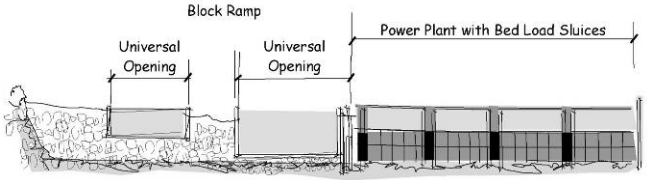

Figure 1. Cross section through a river flow power plant looking downstream (Aufleger, 2009)

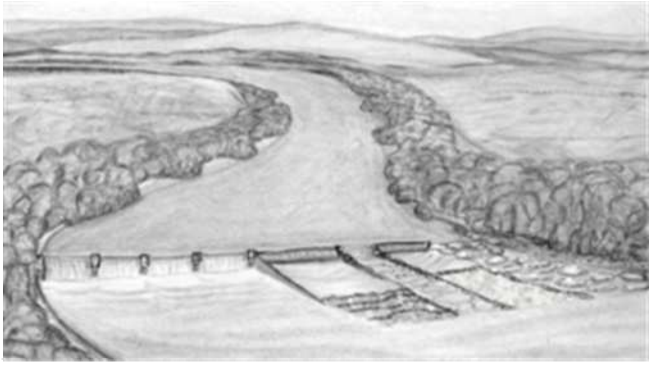

Figure 2. View of river flow power plant with block ramp (right) and overflowed power plant (left) (Pöyry, 2009)

The block ramp has a slope of 1:50 and is interspersed by two universal openings, which are gated by rubber dams. The main purpose of the block ramp besides stabilisation of the bed is to allow for passability of fish as well as bed load. Furthermore, passability for boats heading downstream has to be guaranteed for historical reasons. The openings in the block ramp have various functions. In case of flood flows, they need to provide flow area to keep water levels upstream of the structure low and to ensure sediment transport through the structure. Hydromorphological processes in the upstream river reach could also be regulated by the continuously adjustable rubber dams.

The power plant is intended to be overflowed for reasons of overall appearance. The power plant consists of four blocks containing five matrix turbines each. Additional weirs are located on top of the blocks to allow for overflow and flood water discharge. Sluices for bed load transport are situated in between the turbine blocks. The specific characteristic of this power plant is its low head of approximately 3 meters, which poses high demands on turbine technology and causes high specific construction costs. The main challenge regarding the design of the power plant is to optimise inflow conditions to the plant while minimising the input of bed load into the intake. In addition, fish have to be protected from entering the turbines by means of special screens.

In order to investigate all questions that arise from this concept, a physical model was built at the hydraulic laboratory at the University of Innsbruck. The following chapter describes a series of model tests aiming at optimising the bed-load transport through the structure.

3 MODEL TEST

3.1 *Aims and Objectives*

There are three main objectives which should be met by the model tests carried out at the hydraulic laboratory in Innsbruck. First, the feasibility of the concept regarding effective bed load transport through and around the power plant has to be proved. Second, an optimisation regarding turbine in- and outflow has to be undertaken and third, hydraulics and effectiveness of the block ramp have to be shown. The model tests described below only relate to the optimisation of bed load transport.

3.2 *Model Parameters*

The model test is based on Froude model similarity. A scale of 1:30 was applied to the model, representing an area of 450 meters by 200 meters of the Salzach River. The model features a movable river bed which also requires a device to add bed load material to the river.

The bed load of the Salzach River in the respective reach shows an average particle size of about 20 mm. The particle size distribution is displayed in Figure 3 below. Scaling the particle size with a scale of 1:30 would result in very fine materials to be used for the model test. As model laws are only valid for cohesionless materials and as viscosity effects have to be avoided, materials which are too fine should not be applied for model tests (ATV-DVWK 2003).

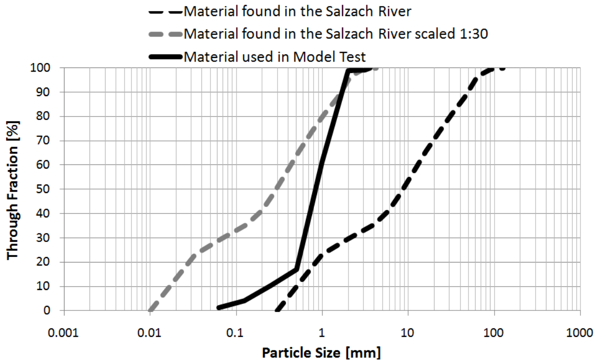

Figure 3. Particle size distribution curves for bed load material in the Salzach River

In the model, a particle size distribution with an average particle size of 0.97mm was used, which represents a coarser material (Figure 3). As a result, Froude numbers of the grain in the natural river and the model test differ. However, this is necessary to impede negative effects such as ripple formation, which would not occur in nature.

Bed load transport rates were determined by the help of Meyer-Peter/Müller's formula and added to the model according to discharge rates.

As changes in the river bed need to be measured and documented, a measuring system containing a 3D terrestrial laser scanner was installed and used.

3.3 *Initial Design*

The initial design implemented in the physical model consists of a straight river reach with the combined block ramp on the left side and the power plant on the right. The arrangement is displayed in Figure 4.

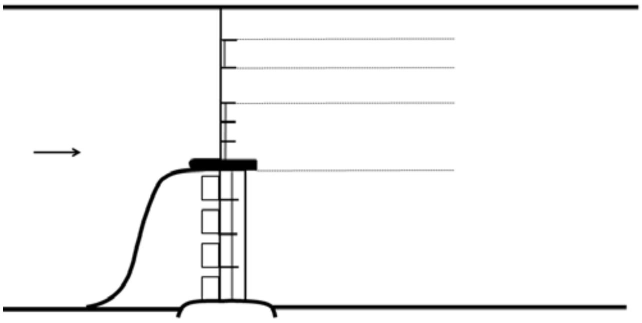

Figure 4. Initial arrangement of the river flow power plant (upper half: block ramp with openings, lower half: power house with bed load barrier)

To avoid bed load input into the immediate power plant area, a bed load barrier is situated across the intake area leading towards the universal opening as shown in Figures 4 and 5.

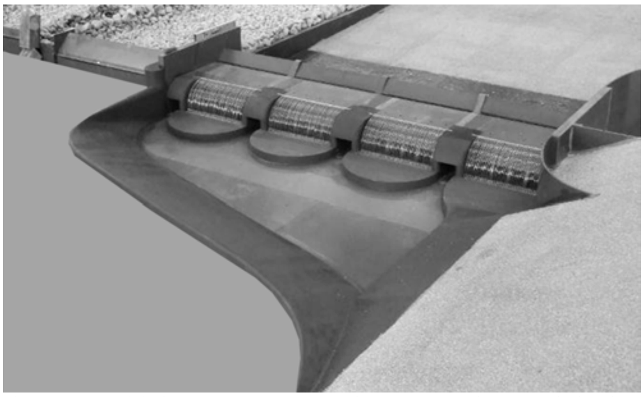

Figure 5. Initial arrangement of the power plant and the bed load barrier

The crest of the barrier is 0.5 meters above the planned river bed upstream of it, and well above the turbine inflow. In front of the turbine blocks semicircular sills should help to keep turbines free of bed load and support bed load transport through the sluices.

The initial design was tested with a 1 in 2 year flood event with a discharge of 1240 m³/s (251 l/s in model). The discharge was kept constant over a period of 16 hours (equiv. of 88 hours in nature) with a calculated bed load transport of 20 g/s added to the model (equiv. of 88 kg/s in nature). For this event all turbines were shut and all sluices open and the water level was kept to a given threshold.

The results of the first test showed major bed load accumulations in front of the power plant within the barrier. However, the screens were not blocked at all and no deposition occurred on the semicircular sills (see Figure 6). The area just upstream of each sluice was kept free of depositions as well. Downstream of the power plant only very minor depositions built up.

Figure 6. Results of first model test

The laser scan results in Figure 7 illustrate the dimensions of the depositions, which reach a maximum of 5 meters depth equivalent in the intake area.

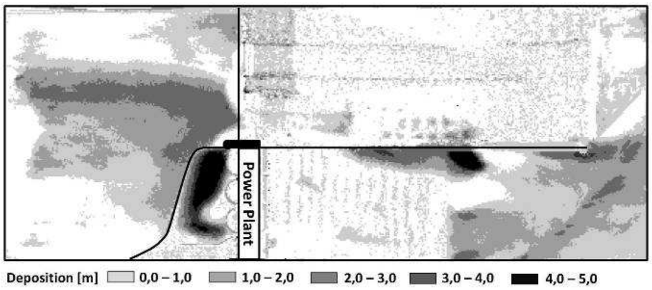

Figure 7. Laser scan results of first model test

3.4 *Optimised Design*

As the results of the first test were not satisfying, several amendments to the layout of the structure were developed.

First of all, the width of the block ramp was increased allowing more water to pass over the ramp and the openings in case of bed load transporting discharges, resulting in a decrease of bed load input into the intake. This amendment showed some improvement, but asked for further changes.

In a next step, the arrangement of the bed load barrier was entirely modified. By shifting the upstream right bank towards the middle of the river (Figure 8) secondary flows are induced in order to enforce bed load transport towards the universal opening. By situating the intake of a power plant in the outer bend of a river the input of bed load into the intake can be reduced significantly (Scheuerlein, 1984). In the Salzach river itself the intake of the power plant will be located at an outer bend. However, the outer bend could not be modelled in the model test due to lack of space in the laboratory. Instead, a straight river reach was reproduced, which in terms of bed load input is supposed to give conservative results. The bed load barrier was placed further upstream and now shows a steeper angle towards the opening in the ramp. The 's'-shape of the barrier in plan view prevents bed load transport over the barrier at the upstream end of the barrier due to secondary flows, but facilitates bed load transport over the barrier close to the pier separating the power plant from the ramp.

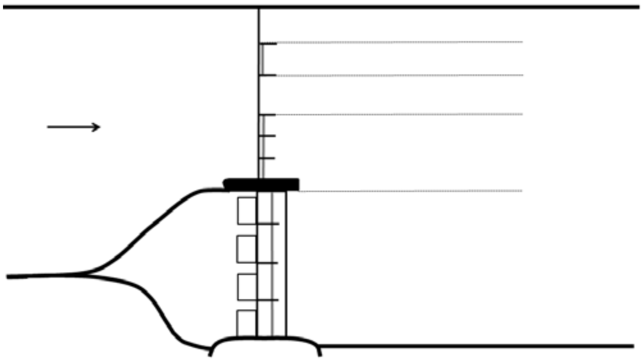

Figure 8. Arrangement of optimised design

To mitigate this negative effect, the crest of the barrier was raised at the end towards the pier. The crest of the barrier was also designed cantilevering as shown in Figure 9 (left) to enhance the secondary flow along the barrier towards the opening (Queißer et al, 2006).

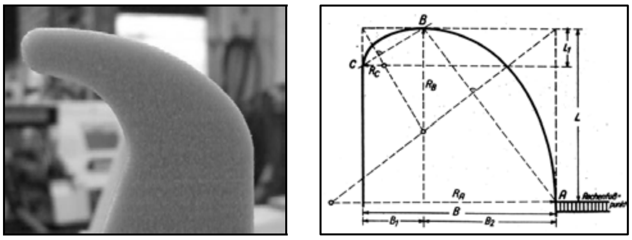

Figure 9. Left: crest of bed load barrier revised according to Queißer (2006); Right: optimised design of pier.

Furthermore, to improve flow separation at the pier the shape of the pier was optimised by use of ellipse segments (Figure 9, right) according to Rouvé (1958).

Moreover, the semicircular sills in front of the turbine blocks were removed, as there was no evidence of their function. The initial screens were replaced by inclined screens due to ecological considerations regarding fish protection.

To analyse the function of the optimised version the same model test parameters as before were used. Results show a major improvement to the situation at the intake of the plant. Only a relatively small amount of bed load was deposited within the barrier. No bed load passed through the screens or remained in the sluices. The depositions within the intake show a maximum depth of 3.60 meters in front of the left half of the power plant.

As it was not expected that the area within the barrier could be kept completely free of depositions, this was a rather satisfying result.

Based on the fact that in case of a flood event the area within the barrier cannot completely be kept free of depositions, the important point is to show that depositions can be removed from that area during normal operation. For this purpose a flushing test was undertaken. For a duration of 16 hours (equiv. of 88 hours in nature) a relatively small discharge was run through the model with only the bed load sluices open intending to clear the deposited bed load from the area.

The results show that a good portion of the deposition could be removed by flushing through the sluices. Unfortunately, during this flushing event a certain amount of bed load was moved through the screen towards the turbines of the innermost block.

To enhance the flushing effect and avoid input of bed load to the turbines, an additional sluice was installed replacing the middle turbine of the innermost block (Figure 10). The flushing test was repeated and results were very positive. Only a very small amount of bed load remained upstream of the power plant (see Figure 11).

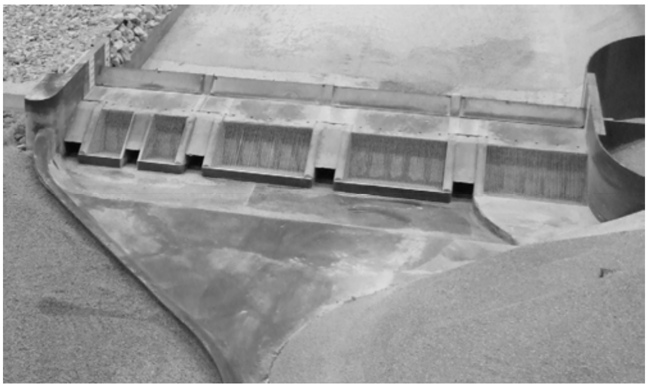

Figure 10. Arrangement of optimised design

Arrangements of the model test including a variety of groynes were checked but did not show any major improvements to the situation.

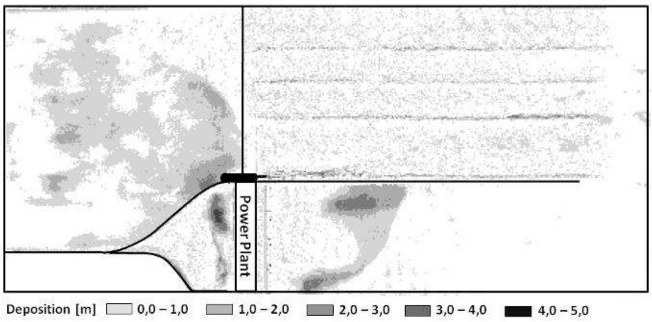

Figure 11. Laser scan results of optimised design after flushing with additional sluice

The first sets of model tests to analyse the initial and optimised design were performed using a discharge of 1240 m³/s. In order to demonstrate that the optimised arrangement works properly for higher discharges, a 1 in 20 year event as well as a 1 in 100 year event were investigated.

For the 1 in 20 year event, a constant peak discharge of 1725 m³/s was simulated over a period of 8 hours (equiv. of 44 hours in nature) with a calculated bed load transport of 32 g/s added to the model (equiv. of 141 kg/s in nature). For the 1 in 100 year event, a typical hydrograph with a peak discharge of 2050 m³/s was run for a duration of 55 hours in nature with corresponding rates of bed load transport.

Both events showed a very similar picture to prior events. The 1 in 20 year event resulted in moderate bed load depositions upstream of the power plant. Prior flushing tests had shown that depositions of this magnitude can be nearly completely removed from this area.

For the 1 in 100 year event depositions in the upstream area were surprisingly low, whereas depositions downstream of the plant were rather substantial (Figure 12). Nevertheless, prior tests had shown that downstream depositions can easily be removed during regular operation of the plant and are hence of no further concern.

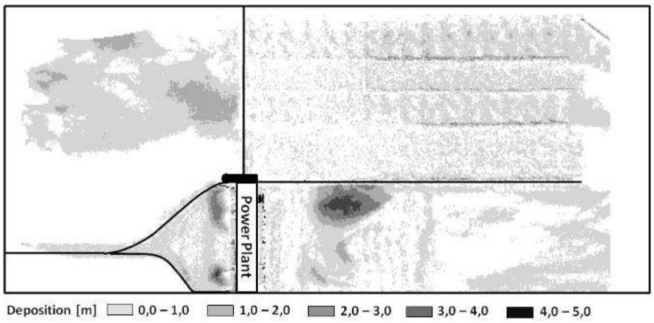

Figure 12. Laser scan results of the 1 in 100 year event

In summary, the functionality of the proposed concept regarding bed load transport through the structure could be proved for a wide range of discharges.

4 PERSPECTIVES

Up to this point the main focus of research was put on optimisation of the structure regarding sediment transport with use of physical model tests.

The physical model will be used for a variety of further tests, including the optimisation of turbine inflow, hydraulic investigation and optimisation of the combined block ramp and stability tests of the block ramp, as well as investigation of passability of the ramp for fauna and boats.

Furthermore, 2D - numerical simulations looking into hydraulics and sediment transport of the whole river reach will be undertaken.

In addition, there will be 3D modelling of different aspects of the power plant using FLOW 3D. Special interest will be laid on the inflow to the power plant in general as well as inflow to turbines.

As the concept of the run-of-river plant is complex, a variety of further research areas arise from it. These include

- the elaboration of a comprehensive sediment management tool supported by physical and numerical modelling,
- the examination of turbine technology looking particularly at fish friendliness, sediment transport. screens and costs,
- the assessment of fish protection measures and fish passability options,
- the assessment of river characteristics
- and possibly life cycle assessment of the plant

5 CONCLUSIONS

The presented example shows a recently developed concept of a novel river hydro power plant currently being investigated. The main technical challenge of the concept lies in bed load transport processes, as transport through the structure has to be ensured without posing any danger neither to the structure itself nor to the operation of the plant. The concept was optimised by use of a physical model test in such a way that bed load transport was directed through the openings in the block ramp and transport through the power plant itself was kept to a minimum. After successful demonstration of the functionality of the structure regarding bed load transport, the existing physical model will be used for hydraulic optimisation.

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This research project is supported by the Austrian Climate and Energy Funds within the 'New Energies 2020' framework.