Model testing of clogging processes in a free-flowing section

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ABSTRACT: The damming of rivers leads to a reduction of flow velocities and to a slowing down of the flow turbulence. In the impoundment area the effects are settlement of bed load and suspended material. The remobilization of sediment is of advantage for both water resources and environmental reasons. Consequently, the removal of sediment causes an increase of sediment concentration in the downstream sections of a dam during a flushing event. Further, it could be observed that large quanities of sediment are deposited on the river banks downstream of the dam, which are remobilized again by and added to the flow during subsequent minor floods. This transport of sediments results in the clogging of riverbeds and, thus, also in a diminution of the permeability. The clogging of river beds has an impact on the habitat of fauna and flora, as well as on the interaction of surface water and groundwater. In the course of this paper, the results of the model tests on clogging processes in the river Lutz in Vorarlberg, Austria, are presented. Flushings of the reservoir Raggal lead to high sediment concentrations in the downstream section. A 1:1 physical model of a flume was built in the laboratory of the Institute of Hydraulic Engineering and Water Resources Management, at Graz University of Technology. Measurements of percolation, density, or concentration were taken amongst others. Furthermore, the adjustment of an existing clogging formula (Schälchli, 1993) will be introduced.

Keywords: Bed clogging, model test, flushing, percolation, infiltration

1 INTRODUCTION

In the global scheme there are more than 50,000 dams that are higher than 15m and which contain a volume of 3Mio. m^3 or more. Further, more than 100,000 dams with volumes greater than 100,000m^3 and several million smaller dams are scattered all over the world. The volume of all reservoirs is larger than 4,000km^3 and the area covered is 500,000km^2, which is about 1/3 of the ground covered by natural lakes. Over 50% of all rivers feature dams with the annual quantity of trapped sediments of about 15 to 40Gt. In Austria are 35% of the rivers free-flowing, up to 66% show a sediment shortage and roughly the same number of reservoirs show a surplus of sediment (Morris and Fan, 1998; Lempérière and Lafitte, 2006; Habersack et al., 2004; Habersack, 1996).

2 PROBLEM DESCRIPTION AND AIMS

The cause of the deposition of fine and coarse material in reservoirs is the reduction of flow velocities and turbulence due to damming. This is the case due to the fact that dams are interruptions of the natural flow continua. The deposition is mainly bed load at the head of a reservoir which causes the bed to raise with the consequential reduction of the cross-section area for the discharge. This, again, might be dangerous during floods. The fine sediments are transported further towards the dam, so the closer to the dam the finer is the material that will be settled. Downstream of the dam a consistent lack of sediment can be detected. It is necessary, therefore, to flush reservoirs during floods or to dredge them.

Hence, the purpose of reservoir flushings is to remobilize the sediments that were trapped during longer periods of time. This leads to a higher sediment concentration in the downstream section during the flushing events. An increase of both bed load and suspended load transport can be observed. Further, significant quantities of sediment will be deposited at river banks along the stream where the flow is more moderate. These sediments will be remobilized during subsequent flood events and will be added, thus, to the discharge again.A consequence of sediment transport of fine material is the clogging of the river bed. Clogging means a sealing off the bed which results in the reduction of the permeability. This, again, has an impact on the habitat of fauna and flora organisms on the one hand, and on the interaction between surface water and ground water on the other hand.

On the 25th of April, 2005 the reservoir Raggal was emptied and a large amount of sediment (about 100,000m^3) was remobilized and flushed down-stream the dam throughout three days. The reason for the emptying was an official directive for monitoring the usually submerged plant equipment which has to be carried out every decade. For ecological reasons the following package of measures was defined in co-operation with the authorities (Fussenegger and Moser, 2007):

- Emptying during the snow melting period for dilution purposes,
- Duration of the flushing as short as possible,
- Addition of water in the downstream river Ill by adequate operation of other hydro power plants (HPP), and
- Flushing of the river Lutz with clear water after refilling the reservoir.

In August, from the 22nd to 23rd, 2005 an extremely high flood occurred in Tyrol and Vorarlberg causing tremendous damages in that area. The enormous discharge in the river Lutz resulted in revolving parts of the bed and destroying levees. Parts of the foreland were flooded and as a consequence and the clogged bed layer was removed. Due to the fact that the groundwater level is several meters beneath the riverbed and the bed itself has a very high permeability, the continuously added compensation water percolates into deeper layers as a consequence. The river Lutz dries up about 1.2km upstream of the estuary. In Spring 2008 a new emptying event is planned. The aim is that the high suspended water will seal the riverbed again, and thus, effecting a decrease of its permeability.

The purpose of this paper is to describe the results that were concluded from hydraulic model tests of clogging processes in the Hermann Grengg Laboratory at Graz University of Technology which were performed in the context of a research project. The understanding of clogging processes, which will occur during and after the flushing, as well as of remobilizing scenes are the subjects of this project. Essential results will be presented in this paper.

3 METHODOLOGY

3.1 Project area

The project area is located in Vorarlberg, the most western province of Austria. Figure 1 shows the location of the project area. The River Lutz lies in the ”Großen Walsertal” and is a small, eastern tributary of the River Ill. Two hydro power plants, which are operated by the ”Vorarlberger Kraftwerke AG”, are located there.

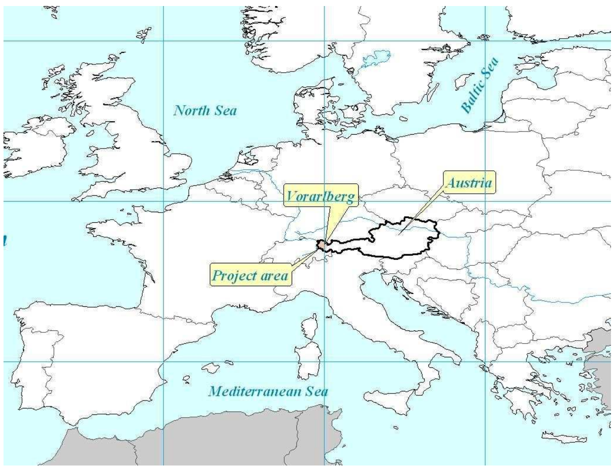

Figure 1: Project area on Vorarlberg/Austria

About 10km upstream of the estuary a reservoir is located, which is called ”Speicher Raggal” .The volume of this reservoir is about 2.4Mio. m^3. The length of the reservoir is 2.3km and the height of the dam is 48m. The residual flow is defined by 500l/s. The diverted water is piped via a 4.5km long pressure tunnel to the surge tank along a vertical shaft to the power station where the tailwater flows into the small reservoir ”Gstins”. Downstream the reservoir ”Gstins” the Lutz flows in a free-flowing section with a length of 5.3km towards the River Ill.

3.2 Clogging

Due to the transport of suspended sediment in open channels clogging is a widespread observed phenomenon. It can be defined as a process where the volume of the pores is reduced and the bed itself, which acts as a filter, is consolidated with the out of this resulting decrease of permeability. At the end a totally impermeable riverbed can be the outcome. Depending on flow velocities different clogging types can be distinguished:

- outer clogging,
- top layer clogging, and
- inner clogging.

Blaschke et al. (2002) describes *outer* clogging as a process occurring at low mean flow velocities up to about 0.3m/s. The sediment settles like in a de-sander and covers the bed on the surface. If velocities are higher than 0.7m/s to 1.0m/s the water tends to infiltrate into the bed and the particles are trapped in the pours of the subsurface. This type is called *inner* clogging. Usually the impermeable bed layer is not visible from the top view.

For determining clogging processes the equation 1 was introduced in Schälchli (1993).

$$V_A = A_F \frac{-\beta + \sqrt{\beta^2 + 2rC\Delta p_G \frac{1}{\eta} t}}{rC} \quad (1)$$

where:

- A_F. . . area of filter [m^2]
- C . . . sediment concentration [g/l]
- Δp_G. . . pressure difference water level surface and ground water [N/m^2]
- η . . . dynamic viscosity [kg/ms]
- t . . . time [s]
- θ . . . non-dimensional shear stress [−]
- r . . . specific resistance of filter [m/kg]

$$r = \frac{5.0 * 10^{12} \theta^{0.5}}{(d_{10}/d_m)^3 Re^{1.5} i} \quad (2)$$

- β . . . resistance of unclogged filter medium [m^{-1}]

$$\beta = \frac{Lg}{k_0 \nu} \quad (3)$$

- g . . . acceleration of gravity [9.81m/s^2]
- k_0. . . initial permeability of soil material [m/s]
- ν . . . kinematic viscosity, ν = η/ρ [m^2/s]
- d_{10}, d_m. . . characteristic diameters
- L . . . depth of filter medium [m]
- Re . . . Reynolds number
- i . . . hydraulic gradient after Darcy

The limits of validity for equation 1 are defined as:

- $0.0115 \leq d_{10}/d_m \leq 0.178$
- $0.008 \leq C \leq 1.2$g/l
- $2400 \leq Re \leq 24800$
- $0 \leq i \leq 0.93$

For the estimation of the occurring clogging processes as well as for the determination of the input data for equation 1 several physical model tests were performed at the Hermann Grengg Laboratory at Graz University of Technology.

3.3 Physical models

As an input and as an initial estimate for the 1 : 1 physical model, which will be described in this paper, two small pre-models were installed in the lab. A description and the results of these models are given in Schneider et al. (2007) and Brunner (2007).

The 1 : 1 model itself is depicted in figure 2. The water flows in a circular flow where a pump with a maximum discharge of about 200l/s pumps the water from a hexagonal tank into a longish feed tank. From there the water flows into a 6.22m long and 37.3cm wide perspex chute and overflows two sediment boxes, which were filled with sediments from the river Lutz. The sediment was tipped into the boxes and compressed after each layer. The slope of the chute has 1% and natural sediment is glued at the invert of the chute in order to get a rougher surface and therewith also more natural flow conditions.

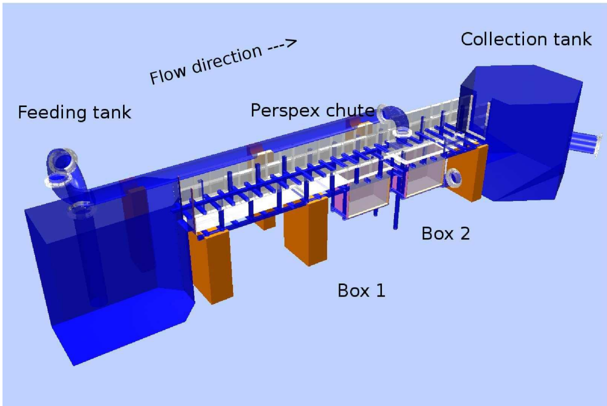

Figure 2: Test facility, 3D view

The sediment laden water infiltrates vertically into the sediment boxes and the suspended particles settle at the most upper layer due to the clogging process. The water, which percolates through the sediment into the box, is measured by means of gauging weirs (higher discharges) and tipping-bucket rain gauges (low discharges) and is collected in a box where the water is pumped back into the water circulation.

Figure 3 shows the grain size distribution of the bed material and the suspended sediment respectively. Some characteristic grain size diameters of the bed load are d_{max}= 63mm and d_{90}= 40mm. Tests were performed with natural and artificial suspended sediments. The natural suspended sediments were extracted from the reservoir Raggal. For reasons of comparison and mainly for an optical estimations calcium carbonate, since it is a bright sediment, was used in some tests. The grain size distribution of this fine material is similar to the natural one as it can be seen in figure 3.

For determining positive and negative stresses in the sediment boxes eight 30cm long tensiometers (diameter 5mm) were installed as can be seen in figure 4.

At the beginning of each test an armored layer was initiated by a higher discharge with clear water. After the armored layer was developed the discharge and the sediment concentration were adjusted. To set a constant concentration level within a range, a turbidity probe was calibrated. When the sediment concentration fell under a certain level a sediment feeder was activated. Additionally, a density probe was installed for reasons of comparison. The

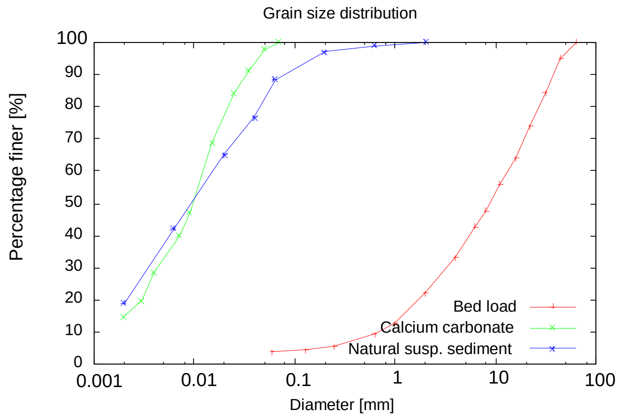

Figure 3: Grain size distributions

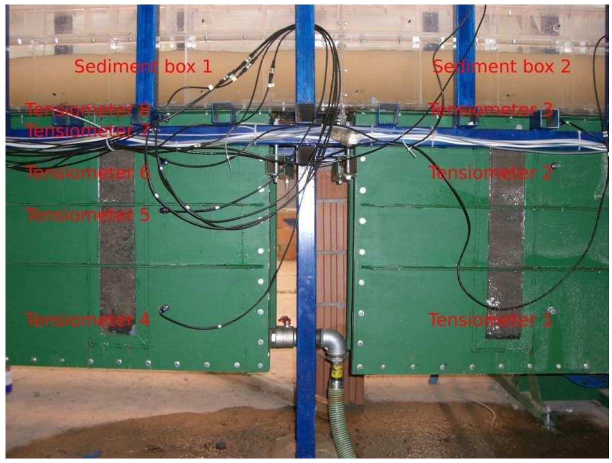

Figure 4: Arrangement of the tensiometers within the sediment boxes

turbidity probe was calibrated before the tests and validated by taking samples during the tests.

All in all 26 tests were performed up until now whereas tests were carried out with and without aerated sediment boxes in order to counteract underpressures which might have occurred. The suspended sediment for three tests was calcium carbonate and for the other tests natural sediment.

4 RESULTS

In Schälchli (1993) clogging has to be expected up to a depth of h_k= 3d_m+ 0.01 [m], which is about 0.05m (dm = 14.75mm). The visual observations in our model show lower values concerning clogging depths. The depths never exceeded values higher than 20mm. The measured mean velocities in the chute lie between 0.77m/s and 1.16m/s depending on the different discharges. One would have to expect, therefore, the *inner* clogging type in our model (as described in Blaschke et al. (2002)). However, we could observe typical *top layer clogging* results. This occurred apparently because the velocities near the bottom were in the range between 0.43m/s and

0.53m/s (see figure 5). These specific velocities are definitely more relevant for clogging processes than mean velocities.

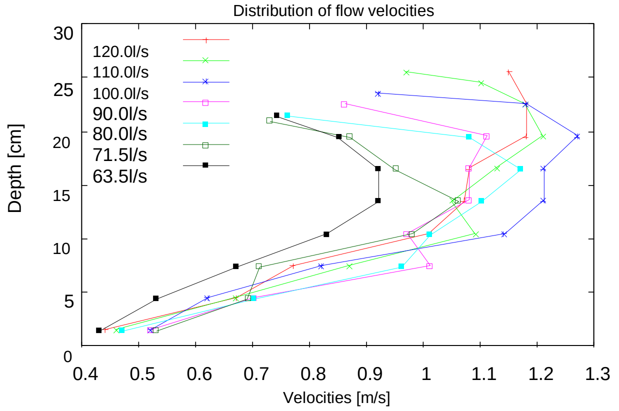

Figure 5: Velocity profiles in the chute at different discharges

The run of the curves in figure 6 exemplify the typical progress of the clogging process. In test No. 3 the discharge in the flume was adjusted to 100l/s. About one hour later the FNU-value is 840, which corresponds to 3.3g/l. At the same time the discharge in box 1 decreases from 0.26l/s to $3 * 10^{-3}$l/s 12 hours later. The readings of the tensiometer 8, which is the most on top located probe, decrease, starting from hydrostatic pressure, and show negative readings about 2 hours after the initiation. This applies to the other probes, temporally delayed, as well. The pressures of tensiometers 5 to 8 resume to fall, oscillate a little bit, rise again, and level off in the range of −200mm. The readings of tensiometer 4, which is located lowest, decrease continuously until it reaches the same value. Negative pressures are expected due to the suction power in unsaturated zones. However in test 3 the air supply was interrupted and therefore the pressures were lower.

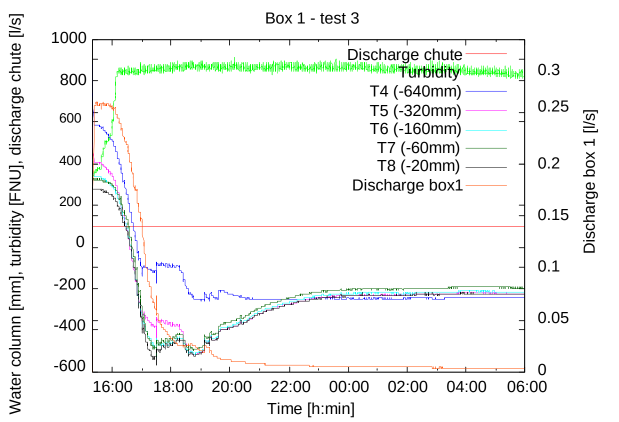

Figure 6: Turbidity, percolation water and pressures at box 1 for test 3

Figure 7 demonstrates the pore water pressure in different depths during test 3. One can see again the hydrostatic pressure at the beginning of the test, the decrease, and the maximum negative pressures after three hours, and the leveling off of the pressures twelve hours later.

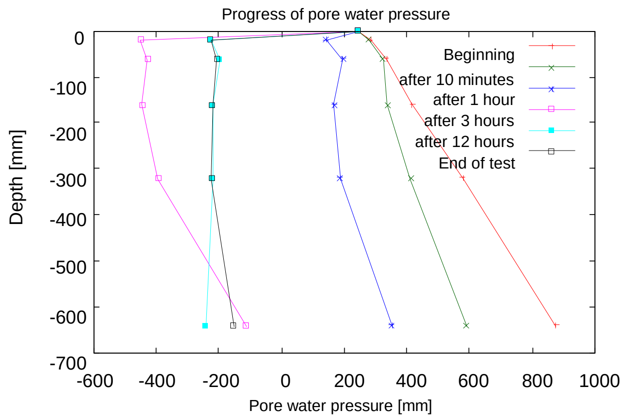

Figure 7: Gradient of pore water pressures at box 1 for test 3

It can be gathered from figure 8, that high sediment concentrations lead to an earlier sealing off the river bed, but the difference is minor. E.g. tests 5, 6 or 7 were performed with high sediment concentrations in the suspension. It can be seen that after a few hours the percolation is low and the increase of the cumulative curve is marginal. The curves of tests 8, 9 or 13 which depict tests with low turbidity show higher cumulated amounts of water than the other curves. This results only from the high infiltration at the beginning of the tests. Twelve to twenty-four hours later these curves are almost horizontal too. Only test 11 presents an exception where the horizontal course of the graph has appeared later. The reason for that was the extremely high permeability of the sediment in that case. These tests showed that clogging appears more or less independent from sediment concentration.

As mentioned in chapter 3.2 the limit of validity for equation 1 concerning the hydraulic gradient lies between 0 and 0.93. The abstracted literature review in Gutknecht et al. (1998) show differences in the potential lower than 1 in most cases too. In Alpine regions the hydraulic gradient is often higher in many cases due to significantly lower groundwater levels than surface water levels. Basically it is not possible to use equation in our case study because of this boundary condition. E.g. for test 3, which is described above, the observed hydraulic gradient at the most upper layer (depth of filter

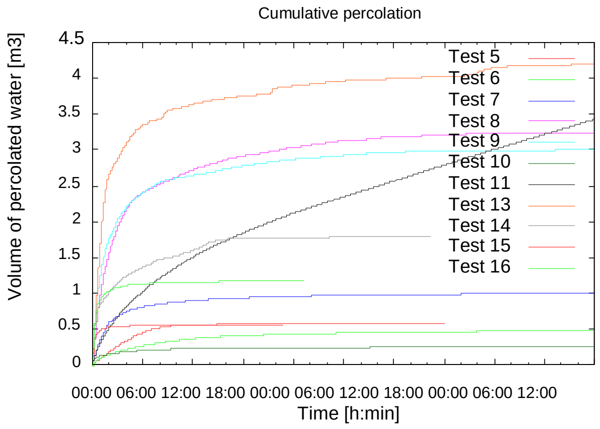

Figure 8: Cumulative curve of percolation in box 1

medium 16.3cm) was 3. However, although the limit of validity for equation 1 is not valid in our case, it was nevertheless used in our research project to find out if it is applicable for higher hydraulic gradients too.

Figure 9 depicts the results of the calculated volume of percolated water in comparison with the measured volume. It is evident, that equation 1 underestimates the amount of water at the beginning and intersects the graph of measured values after some time. The higher pressure gradients in comparison to Schälchli seems to fit quite well although a reconsideration has to be taken into account because these are the first preliminary findings concerning the clogging equation.

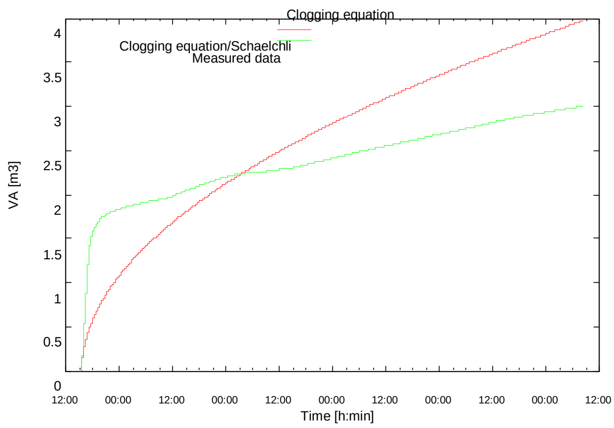

Figure 9: Volume of percolated water measured (test 3) and calculated

5 CONCLUSION

This paper describes some important results of hydraulic model tests in the Hermann Grengg Laboratory of Graz University of Technology which were performed to investigate clogging processes. The emptying of the reservoir Raggal in Vorarlberg leads to high concentrations of suspended sediment downstream of the dam with its subsequent clogging processes. For a better understanding of these processes 26 flume model tests were performed in which the reduction of percolation was observed. It could be shown that the sediment concentration plays only a small role in the sealing off the river bed. Schälchli (1993) introduced an equation for determining clogging processes which was compared with our results. Although, a different hydraulic gradient in our model was present the equation seems to work quite well. Further research has to be undertaken concerning the clogging equation which will be done within the next weeks.

ACKNOWLEDGEMENTS

This project was co-funded by the Federal Ministry of Economics and Labour of the Republic of Austria, as well as by the provincial governments of Styria, Carinthia, and Tyrol in the scope of the competence network Water Pool (www.waterpool.org). The Vorarlberger Illwerke AG is the economic partner, who contracted this Project and co-funded it as well.

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