Experiments on turbidity currents influenced by solid and permeable obstacles and water jet screens

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The sustainable use of reservoirs for irrigation, flood protection, water supply, and hydropower may be endangered due to unavoidable reservoir sedimentation. In many reservoirs turbidity currents are the main process for the transport and deposit of sediments. Besides other measures, turbidity currents can be influenced by means of solid obstacles, permeable geotextile screens or the injection of water jets. Physical experiments and numerical simulations of turbidity currents flowing over an obstacle, against a textile screen or through a water jet screen were carried out. In each experiment vertical velocity profiles in the body of the turbidity current were measured with an ultrasonic velocity profiler (UVP). The velocity measurements were made at three locations upstream of the various obstructions and one location downstream. The investigations showed that turbidity currents could be influenced effectively by properly designed constructive measures. Based on the results of the physical experiments and numerical simulations, some design recommendations for solid and permeable obstacles as well as for a jet screen are proposed.

Keywords: Reservoir, sedimentation, turbidity current, water jet, physical modeling, numerical simulations, velocity profiles, sediment deposits

1 INTRODUCTION

The aim behind the efforts to create reservoirs is storing water, however solid material is carried along by the water and is, as a rule deposited there. Long-lasting operation of reservoirs in terms of sustainable use of available water resources involves the need for sedimentation control and release.

Wise development of hydropower resources regarding sedimentation has frequently not been implemented in the past and the sustainable use of reservoirs is not always guaranteed in the long term. In narrow reservoirs with quite steep bottom slopes, turbidity currents are frequently the main process for the transport and deposit of sediments [1] (Fan and Morris 1992). These turbidity currents with high sediment concentrations mainly occur during floods and follow the thalweg to the deepest zones of the reservoir near the dam. Depending on the slope of the thalweg, density currents reach velocities in the range of 0.5–0.8 m/s, and exceptionally up to 2 m/s during floods [2] (Fan 1986). Sediments, which have already settled down, can therefore be eroded again and transported toward the dam. The resulting introduction of additional suspended sediments into a turbidity current increases its density and consequently its velocity [3] (Parker et al. 1986). On the other hand, turbidity currents slow down on low slopes or after a hydraulic jump, which causes the sediments to settle and the current to die out [4] (Altinakar et al. 1990).

If turbidity currents can be entirely stopped in a reservoir, or influenced in such a way that the sediments are not deposited in critical locations like in front of intakes and bottom outlets, the sustainability of the reservoir operation may be increased considerably. Such technical measures to control reservoir sedimentation due to turbidity currents have in principal the purpose to stop, dilute, or divert the flow influencing the location of major sediment deposits. This can be done by a solid or permeable obstacle [5] (Oehy and Schleiss 2007) or a jet screen placed inside the reservoir (Figure 1).

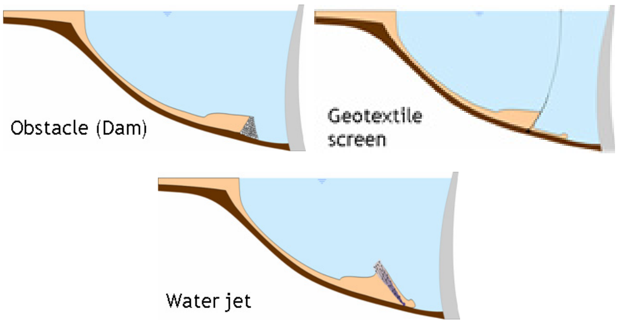

Figure 1: Investigated methods to stop turbidity currents.

2 MODELLING OF TURBIDITY CURRENTS

Turbidity currents have extensively been studied in the laboratory by many investigators [6-9] (Altinakar et al. 1996, De Cesare and Schleiss 1999, Baas et al. 2005, Hosseini et al. 2006). [10] De Cesare et al. (2001) presented three-dimensional numerical simulations of turbidity currents in the Luzzone

Reservoir in Switzerland. The model used in this study is based on the CFX-4 flow solver, where user routines were added to take into account the settling of the suspended sediments and the erosion-deposition at the bottom. The effects of solid obstacles or permeable screens on turbidity currents have been investigated in the case study of Lake Grimsel [11] (Oehy and Schleiss 2001) and Lake Lugano [12] (De Cesare et al. 2006). [13] Bühler et al. (2006) give an excellent overview on the phenomena of flows on inclines passing through water jets directed upstream.

3 EXPERIMENTS

3.1 Experimental set-up

The experiments were carried out in an 8.55 m long, 0.27 m wide and 0.90 m deep multipurpose flume (Figure 2 left). The flume can be tilted in a slope range between 0 and 5%. In the upper part of the flume a stilling box and head tank were installed. A sluice gate allowed the release of the turbidity current in the downstream part simulating a 7.1 m long straight reservoir. An adjacent mixing tank with a capacity of 1.5 m^3 was used to prepare the dense fluid mixture.

Figure 2: Photograph of the experimental flume (left) and the UVP transducer as well as the bottom and reference electrodes (right).

The turbidity current was created by a rapid opening of a sliding gate. Downstream of this gate a tranquilizer composed of small rectangular tubes reduced the scale of the initial turbulence of the released mixture and generated a uniform velocity distribution. A compartment at the downstream end of the flume trapped the turbidity current for withdrawal. For the experiments a cohesionless, fine polymer powder with a density of ρ_s = 1'135 kg/m^3 and a particle diameter of d_{50} = 90 μm was chosen. More details on the experimental set-up can be found in [14] (Oehy 2002).

3.2 Modeling of obstacles (solid and permeable) and of an inclined jet screen

The solid obstacle used in this study was a ridge of 24 cm height, extending across the full width of the flume at a distance of x = 5 m from its inlet. It had a Gaussian shape. This particular form is used because it does not have any edges creating flow singularities, and can simulate an embankment dam. Furthermore, [15] Prinos (1999) investigated two-dimensional density currents over semicircular and triangular obstacles and found that there is no significant effect of the obstacle geometry.

Furthermore, five turbidity current runs through a permeable screen made of two different types of Tricopor® geotextiles of 0.5 m height, also located at x = 5 m from the inlet, were carried out. The respective porosities were 36% and 41%.

In order to investigate the turbidity current flow across an inclined multiport-diffuser, water jets emerged from a rectangular box 60 cm long, 27.2 cm wide and 7 mm thick placed inside the flume on the channel bottom. The jet screen was located x = 5.15 m from the inlet gate.

3.3 Measuring devices

In each experiment four vertical velocity profiles in the quasi-steady body of the turbidity current were measured with an ultrasonic velocity profiler (UVP, Figure 2 right). This method was applied successfully in the earlier cited model tests for the monitoring of laboratory turbidity currents, as well as in a laboratory reservoir sedimentation study by [16] (Kantoush et al. 2008). A device to measure the local evolution of sediment layer thickness during the experiments was developed based on the fact that the electrical resistance of a layer of particles depends on its thickness [17] (De Rooij et al. 1999). The thickness of the sediment deposits can thus be determined by measuring its resistance. The resistance was measured between a 6 mm stainless-steel rod, 6.5 m long, mounted 0.5 m above the flume bottom and 62 electrodes on the bottom (Figure 2 right).

4 RESULTS

4.1 Flow over a solid obstacle

When the turbidity current reached the obstacle, it climbed up, decelerating only slightly as can be seen in the photographic sequence in Figure 3.

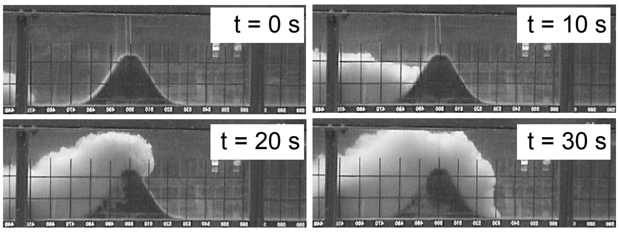

Figure 3: Sequence of a turbidity current flowing over a Gaussian obstacle at time intervals of 10 s. Approach front flow velocity U_f = 0.039 m/s, height of the current h = 0.106 m, grid spacing 0.10 m.

The turbidity current head passed over the obstacle, whereas a gap developed behind the head. A less important current followed the head region and kept flowing over the top of the obstacle down the flume. The normal shape of the frontal region was reestablished at some distance downstream of the obstacle. Due to the presence of the obstacle, the flow rate changed and an internal bore traveled upstream. Bores are moving hydraulic jumps and also occur in open-channel flows.

4.2 Flow through a permeable screen

When the turbidity current reached the vertical screen, it was nearly blocked due to the increased flow resistance (Figure 4). The turbidity current then climbed up the screen to a height of 2 - 3 times the height of the oncoming turbidity current, and decelerated as it rose. The turbidity current then started to seep through at the bottom of the screen driven by the pressure gradient. As the interface upstream rises, more fluid passes through the screen, forming a small and slow outgoing turbidity current. Due to the flow resistance of the screen, part of the flow is reflected and moves upstream as an internal bore similar to the experiments with a solid obstacle.

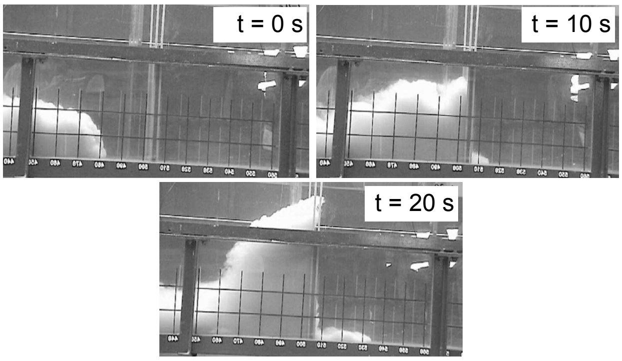

Figure 4: Sequence of a turbidity current flowing through a permeable screen (41% porosity) at time intervals of 10 s. Approach front flow velocity U_f = 0.051 m/s, height of the current h = 0.112 m.

4.3 Flow through a water jet screen

Figure 5 shows a photographic progression of the turbidity current flowing through the jet screen.

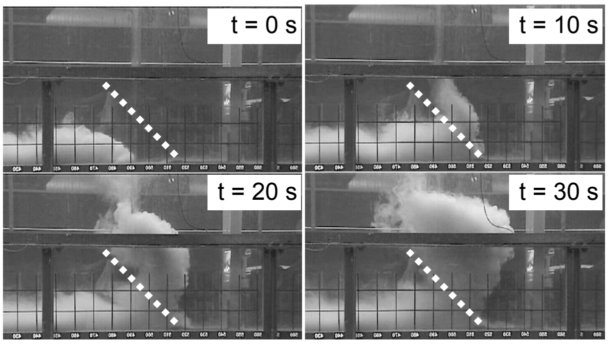

Figure 5: Turbidity current flowing through the 45° inclined jet screen at time intervals of 10 s. Approach flow velocity U_f = 0.042 m/s, height of the current h = 0.106 m.

The sequence starts just before the turbidity current reaches the inclined jet screen. A small amount of the turbidity current passes through while the major part of it remains upstream and is pushed upwards.

4.4 Velocity profiles of the turbidity currents

Computed profiles of streamwise velocity were compared with the values determined from measurements by UVP using time-averaged profiles in the quasi-steady part of the turbidity current body.

The computed velocity profiles are compared with the experimental results as shown in Figure 6 for the passage over a solid obstacle and through a permeable screen.

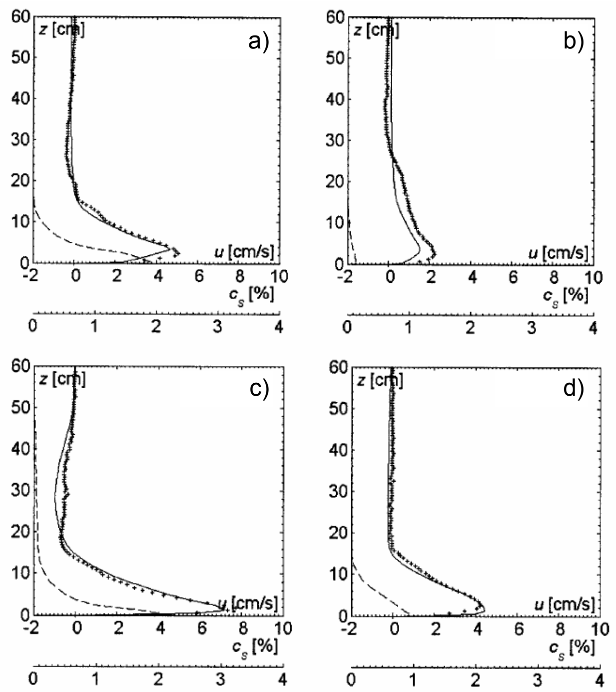

Figure 6: Vertical velocity profiles upstream and downstream of the obstacle a) and b) and of the permeable screen c) and d). Computed velocity, u (thin solid line); measured velocity (plus signs); and computed concentration, c_s (dashed line).

In addition, the computed concentration distribution using CFX-4 is shown on the same graphs. It can be seen that the numerical results agree fairly well with the measured distribution of the streamwise velocity. The height at which the concentration vanishes coincides approximately with the height of zero velocity. Due to the effect of the obstacle and screen, the downstream velocity as well as the concentration is strongly reduced, whereas the height is increased.

4.5 Influence on sediment deposition

The measured evolution of the sediment deposits along the flume is shown in Figure 7 and has been compared to the results from the numerical model. Both approaches showed that sedimentation downstream of the diffuser is significantly reduced while the upstream deposition is increased due to the flow and sediment retention.

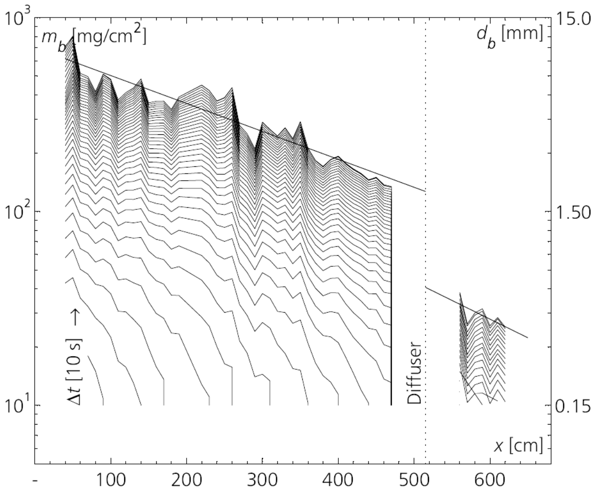

Figure 7: Measured evolution of sediment deposit of the turbidity current partially blocked by the 45° upward inclined water jet screen at time intervals of 10 s.

5 CONCLUSIONS

The long term use of reservoirs for irrigation, flood protection, water supply and hydropower may be endangered due to unavoidable reservoir sedimentation. The challenge for designers and dam operators is to achieve sustainable storage volumes by means of wise reservoir sedimentation management. Very often turbidity currents are the governing process for the transport and deposition of suspended sediments in reservoirs. Physical experiments and numerical simulations of turbidity currents flowing over a solid obstacle and through a geotextile screen as well as through an inclined water jet screen were carried out.

Based on the tests and simulations it can be concluded that solid obstacles with reasonable heights (at least twice the high of the approaching turbidity current) allow for efficient blocking of turbidity currents. The laboratory tests as well as numerical case studies revealed this significant effect of obstacles. The investigations showed also that, in certain configurations, turbidity currents can be considerably slowed down by a geotextile or an inclined water jet screen and therefore most of the sediments can be retained upstream.

The technical measures presented may also be of interest in combination with other traditional methods, such as flushing or turbidity current venting, but also with new concepts of sediment management in reservoirs.

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