Velocity profiles of turbidity currents flowing over a flat bed

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Turbidity currents are the main source of suspended sediment transport in reservoirs and thus one of the main causes of sedimentation. One of the techniques used to avoid reservoir sedimentation is through venting of turbidity currents. In the framework of a research work on venting, velocity measurements of turbidity currents flowing on a flat bed are carried out using Ultrasonic Velocity Profilers (UVP). Five profilers of 4 MHz placed at different positions in an experimental flume provide velocity profiles. Body and head velocities are analyzed and used to calculate the characterizing height and velocity of the currents. The flow regime is described based on Richardson number. Results show decreasing velocity values and thus the deceleration of the currents. Front velocities are also investigated.

Keywords: Ultrasonic Velocity Profilers, turbidity currents, deceleration, body and head velocities, front velocity.

1. Introduction

Turbidity currents are sediment-laden currents driven by density differences due to the presence of suspended sediments in the water. When reaching reservoirs during yearly floods, these currents plunge below the water surface and flow along the bed of the reservoir as a kind of underwater avalanche until reaching the dam. Unless these currents are evacuated, the sediments they transport to the dam will settle leading to reservoir sedimentation. To avoid sedimentation, one of the main means is to vent turbidity currents through bottom outlets or intakes. However, in order to study the operation of venting, a thorough understanding of turbidity currents and their dynamics is essential.

Velocities are an important characteristic of turbidity currents. It provides crucial information on the flow regime, height, and development of turbidity currents. Different techniques exist for the measurement of velocities in flows. Among these techniques, the Ultrasonic Velocity Profiler (UVP), developed by [1], is used to measure instantaneous velocity profiles. Many researchers applied UVP measurements with different types of flows. In experimental investigations of turbidity currents, [2] performed a flow mapping technique with UVP measurements of turbidity currents simulated experimentally. [3] and [4] also applied the UVP technique for the investigation of turbidity currents' velocities. UVP measurements were achieved in other laboratory studies related to suspended sediments and reservoir sedimentation (e.g., [5], [6], [7], [8]).

The present research is conducted at the Laboratory of Hydraulic Constructions (LCH) of the Ecole Polytechnique Fédérale de Lausanne (EPFL). An experimental model is used to investigate the operation of venting of turbidity currents. The efficiency of the evacuation of the turbidity currents is analyzed for currents flowing over a flat bed. Different measurements are carried out, among which velocity profiles using UVP transducers [9]. The present paper firstly describes the experimental set-up, as well as the sediments used for the simulation of the turbidity currents. Then, the results obtained using five UVP probes of 4 MHz each are discussed. The body and head velocity of the turbidity currents are analyzed. The flow regime and characteristics of the simulated turbidity currents are described. Finally, front velocities are presented followed by conclusions.

2. Experimental set-up

2.1 Description

Experimental tests are carried out in an 8.55 m long, 0.27 m wide, and 1 m deep flume. The latter can be tilted with a slope ranging from 0 to 5%. In the case of this paper, the bed is horizontal (0%).

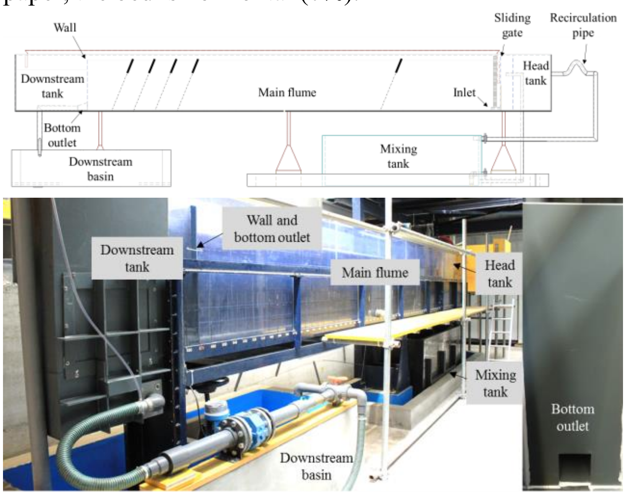

Figure 1: Longitudinal scheme along with a photo showing the different elements of the experimental installation.

As shown in Fig. 1, the flume consists of an upstream head tank ($0.8 \times 0.27 \times 1$ m^3), a main flume ($6.7 \times 0.27 \times 1$ m^3) and a downstream tank ($1.05 \times 0.27 \times 1$ m^3). A sliding gate separates the head tank from the main flume. Downstream of the head tank, an inlet leads to the main flume and has an opening of 4.5 cm. A

tranquilizer is placed at the inlet. It allows the regulation of the scale of turbulence of the released turbidity current and gives an initial uniform distribution for the velocity field of the current.
Below the flume, the water-sediment mixture is prepared in a mixing tank. A fixed amount of sediments is mixed with water and is continuously stirred before and during the tests. The main flume simulates the reservoir where the turbidity current flows before being vented. At the end of the flume (6.7 m from the inlet), a wall simulates the dam with a bottom outlet centered on its width. The wall keeps the water level constant in the main flume during the tests. Finally, a downstream tank receives the residual water.

2.3 Sediments

The material used to simulate the turbidity currents in this study is a Thermoplastic Polyurethane (TPU) with a mass density of 1160 kg/m^3. Its representative diameters are d_{10} = 66.5 µm, d_{50} = 140 µm and d_{90} = 214 µm; d_x being the grain size diameter for which x% of the amount of sediments has smaller diameters. The settling velocity of the particles is 1.5 mm/s, calculated based on Stokes' law using the mean diameter d_{50}.

2.4 Measuring instruments

Throughout the tests, different measurements are carried out. The discharge of the inflowing and outflowing turbidity currents are monitored by electromagnetic flowmeters. The water level upstream and in the main flume are monitored using two ultrasonic level probes. The deposition of the turbidity currents is measured by a depositometer based on electric resistance (ERBD) [10]. Sediment concentration of the inflowing turbidity current as well as the vented flow are monitored using two turbidity probes. Finally, five-4 MHz UVP transducers positioned at 4.1, 5.5, 5.8, 6.0, and 6.2 m from the inlet measure instantaneous velocity profiles with a sampling period of 38 ms and an inclination angle of 25° downstream with respect to the vertical. One transducer measures 27 instantaneous profiles per second before moving to the next one.
Fig. 2a shows the position of the different UVP transducers and Fig. 2b shows the support on which the transducers are mounted. They measure over 70 cm depth (144 channels, 0.74 mm channel width and 4.63 mm spacing).

2.5 Experimental test procedure

At the beginning of each test, the main channel is filled with clear water up to a level of 80 cm. The water-sediment mixture is prepared in the mixing tank with a mean concentration of 27 g/l for all the tests.
The mixture is pumped from the mixing tank to the head tank, and is recirculated between the two elements through a recirculation pipe. This process ensures good mixing and homogeneous concentrations between the two reservoirs.
The water levels in the head tank and the main channel are maintained equal in order to prevent a burst-like initial inflow when opening the sliding gate and releasing the turbidity current. The concentration of the initial mixture is continuously measured using the turbidity probe placed in the head tank.

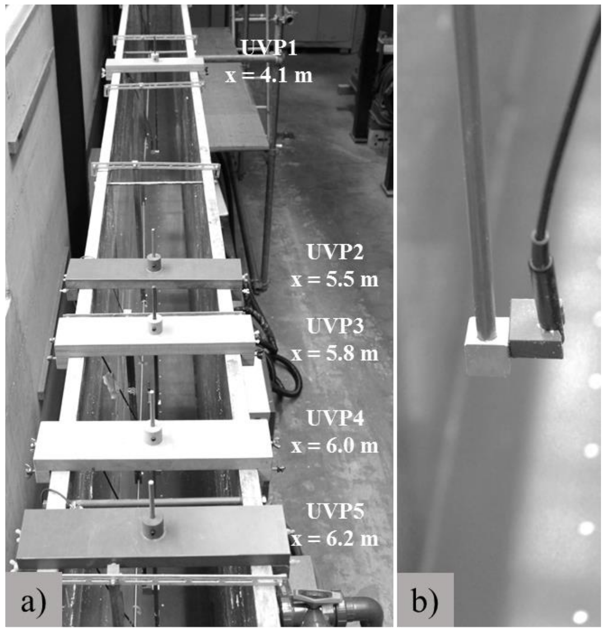

Figure 2: a) position of the 5 different UVP probes from the inlet, b) support on which UVP probes are mounted, the bottom electrodes of the electric resistance-based depositometer are visible.

Once the initial concentration and discharge are stable, the recirculation is stopped and the sliding gate is opened releasing the turbidity current the inlet into the main flume. The turbidity current then flows along the channel through a distance of 6.70 m and is monitored for the whole duration of the test. When it reaches the bottom outlet, the latter is opened with a predetermined discharge allowing thus the evacuation of part of the turbidity current. The vented current reaches the downstream basin where a turbidity probe is placed, allowing continuous concentration measurements.
In the following, only data from the UVP will be presented and discussed.

3. Characteristics of the turbidity current

Typically, a turbidity current has a body velocity and a head velocity. The body represents the quasi-steady part of the current and thus velocity profiles from this part are used to characterize the current in terms of velocity and height. The head of the turbidity current is the most turbulent part of the flow. Head velocity is always slightly lower than the body velocity as it entrains clear water from the reservoir and increases in height.

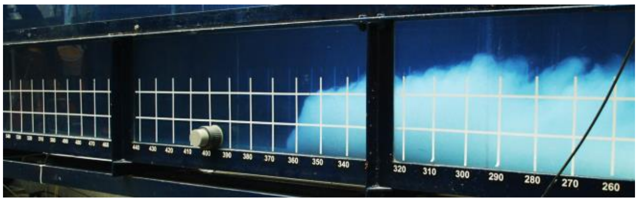

Figure 3: A turbidity current flowing along the main flume (grid of 10 x 10 cm^2)

3.1 Body velocity

Profiles measured by the transducer located at 4.1 m (UVP1) from the inlet are used to determine the body velocity. Profiles from the head of the current are thus not considered in the averaging of the profiles. Only profiles from the body are included in the result shown in Fig. 4 below. The latter is the average of 1161 instantaneous profiles (obtained every 38 ms) belonging to the body of the current.

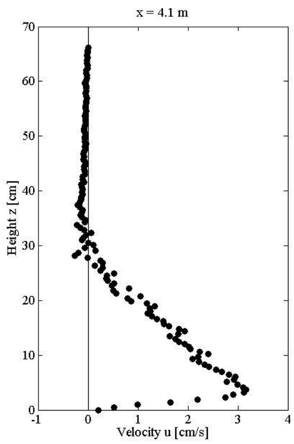

Figure 4: Averaged body velocity profile of the turbidity current at 4.1 m (UVP1) from inlet.

Based on the averaged body velocity profile shown in Fig. 4, and using Turner's equations [11] below, it is possible to determine the characterizing height and mean velocity of the turbidity current:

$$Uh = \int_0^\infty u dz = \int_0^{h_t} u dz \tag{1}$$

$$U^2 h = \int_0^\infty u^2 dz = \int_0^{h_t} u^2\, dz \tag{2}$$

where h_t is the height at which the local velocity u is zero, U is the characterizing velocity of the current, and h the characterizing height of the current. Thus, Richardson number can be calculated:

$$Ri = \frac{1}{Fr_D^2} = \frac{g' h \cos\alpha}{U^2} \tag{3}$$

where Fr_D is the densimetric Froude number, g' the reduced gravity calculated based on the volumetric concentration of the current [12], and α the angle of inclination of the flume which is equal to 0 in the present case.

Using Eqs. (1) and (2), the characteristic height $h = 22.3$ cm and the characteristic velocity $U = 2.05$ cm/s are calculated. This results in $Ri = 11$ and $Fr_D = 0.3$ which means that the turbidity current is subcritical.

3.2 Head velocity

Profiles close to the outlet allow the measurement of velocity profiles mostly in the head of the currents since the latter are reflected as soon as they reach the wall, before the arrival of the body below the UVP transducers.

Fig. 5 shows velocity profiles measured at different positions (UVP2, UVP3, UVP4, UVP5). It can be seen that the current decelerates. On a flat bed, deceleration was also observed by [12] and [13]. This is due to the rapid losses in buoyancy resulting from high deposition. Additionally, the smooth bed used in the case of this study implies that no bed erosion takes place to compensate the high deposition of the sediments. Moreover, as it can be seen in Fig. 5, the ''nose'' of the current rises from the bed. In fact, due to the no-slip condition, the clear water immediately fills up the space below the risen nose [14].

It should be stated that the head of a turbidity current is highly turbulent, and thus velocities in this region can be two or three-dimensional. In the case of this narrow flume, lateral velocities can be neglected but vertical velocities exist, particularly in the head, and can be seen visually. Therefore, these 1D velocity profiles provide part of the information on the behavior of the current in terms of velocities.

Note that the profiles shown in Fig. 5 below are the average of respectively 85, 36, 25, and 10 instantaneous profiles (obtained every 38 ms) belonging to the head of the current.

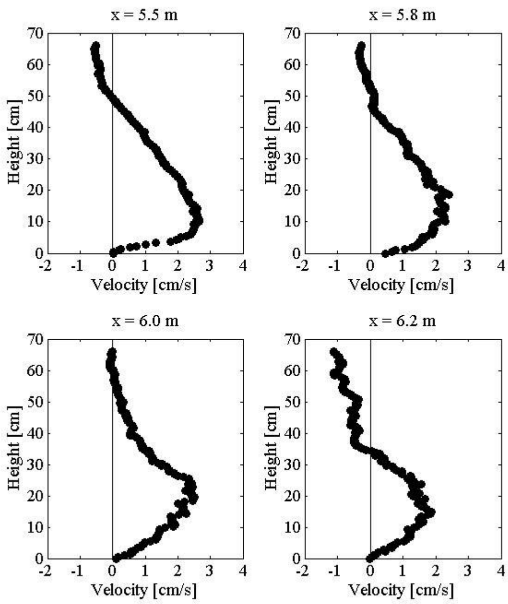

Figure 5: Averaged head velocity profiles of the turbidity current at 5.5, 5.8, 6.0, and 6.2 m (UVP2, UVP3, UVP4, UVP5) from inlet.

3.3 Front velocity

Front velocities U_f were also calculated through video recordings of the turbidity currents. Fig. 6 shows the variation of front velocities relatively to the current's position x/L where x is the position from the inlet and L = 6.7 m the length of the flume. Data is used from different tests where the parameter of outlet discharge (Q_{vent}) normalized by the inflow discharge of the turbidity current (Q_{turb}) was varied. However, since initial conditions (i.e., inflow discharge and concentration) of the turbidity currents remained more or less constant for the different tests, these observations are used to have more velocity data.

Front velocity values are obtained by progressively considering two different positions of the turbidity current in the flume and marking the duration spent to pass from one position to the other. Then, the resulting velocity is calculated and plotted relatively to the position half-way between the two positions considered.

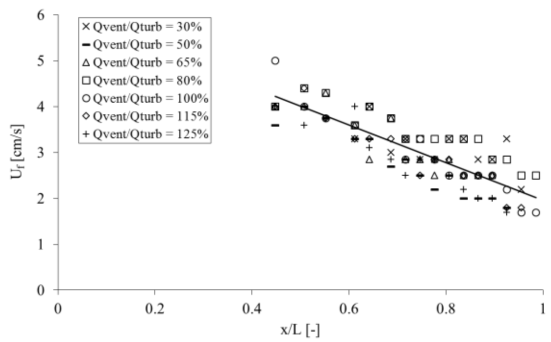

Figure 6: Front velocities relatively to the position of the turbidity current in the flume. The trend line shown corresponds to the average front velocity at each point.

Front velocities also reveal a deceleration of the turbidity currents. They decelerate from an average velocity of 4.1 cm/s to an average of 2.1 cm/s. There are no velocities shown in the first part of the channel (upstream of x/L = 0.4 due to the presence of a metallic wall in the flume's structure.

4. Conclusions

Turbidity currents are the main transport mechanism for suspended sediments inside reservoirs. Such events occur in different reservoirs during yearly flood events. Unless they are evacuated, the sediments transported by turbidity currents settle and fill up the reservoir with sediments on the long-term. In the framework of an experimental study on venting operations, different measurements on turbidity currents were carried out, among which UVP velocity measurements.

The suspended sediments in turbidity currents provide good tracers for UVP measurements. One of the main advantages of this measuring instrument is its non-intrusiveness.

Results from the present study point out that turbidity currents flowing over flat beds tend to decelerate due to high depositional rates and therefore loss of buoyancy. Body velocities lead to the conclusion that the simulated turbidity currents are subcritical. Head velocities show that the nose of the current rises while it decelerates. Finally, front velocities confirm the deceleration of the currents.

The rate of deceleration of the turbidity currents can be used to explain the rate of deposition measured on the bed or vice-versa. Additionally, velocity profiles measured by the UVP can serve to compare experimental with eventual numerical simulations. Finally, understanding the flow regime of turbidity currents offers a better understanding in the process of optimization of turbidity currents venting.

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