One- and two-dimensional UVP velocity sampling in a cuboidal basin subject to in- and outflow sequences

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In the framework of an experimental study on the influence of in- and outflow sequences on flow patterns and suspended sediment behavior in reservoirs, flow fields and inflowing jet were sampled by Ultrasonic Velocity Profilers (UVP). The laboratory set-up consisted of two interconnected rectangular basins between which water was moved back and forth. A parametric study was performed on the magnitude and the frequency of in- and outflow cycles. Jet centerline velocities during inflow sequences were measured by UVP transducers with sampling frequencies of 0.5 and 1.0 MHz. Results were compared to jet behavior given in literature and used to calibrate a numerical model. Then, the main basin was equipped with seventeen 2 MHz UVP transducers to measure horizontal 2D velocity fields at several levels inside the test volume. Such, flow patterns during in- and outflow sequences were monitored, allowing the detection of three-dimensional flow behavior and the estimation of the mean kinetic energy in the test volume.

Keywords: In- and outflow sequences, reservoir, jet centerline velocity, 2D flow patterns

1 INTRODUCTION

Reservoir sedimentation impacts reliability, efficiency and safety of hydropower schemes. Beside traditional storage plants, also pumped-storage facilities are affected. Such schemes are composed of two reservoirs, between which the water is moved up and down for peak energy generation and grid regulation. The influence of cyclic bidirectional water exchange on flow patterns and suspended sediment behavior in lakes and reservoirs was investigated experimentally at the Laboratory of Hydraulic Constructions (LCH) of the Ecole Polytechnique Fédérale de Lausanne (EPFL).

Understanding of flow behavior in reservoirs submitted to in- and outflow cycles allows specific design of hydraulic structures such as intakes or sluice gates and helps describing entrainment and settling processes of suspended particles. Particle Image Velocimetry (PIV) and Ultrasonic Velocity Profiling (UVP) methods are commonly applied in experimental studies, i.e. to describe flow fields upstream of orifices and sluice gates [1], to study flow patterns in shallow reservoirs [2, 3] as well as to monitor 2D flow fields in front of an intake structure due to jet induced flow [4]. However, most of the studies concern the evolution of flow patterns due to a specific flow direction, while the effect of in- and outflow sequences with different magnitude and frequency has not been analyzed yet.

In preliminary clear water tests, one-dimensional UVP velocity sampling was carried out to calibrate a numerical model and to describe the jet behavior during inflow sequences. During the main testing phase with sediment laden water, two-dimensional UVP flow mapping was performed to evaluate flow patterns due to in- and outflow sequences. This paper briefly describes the test rig and the instrumentation and presents some of the results of one- and two-dimensional velocity sampling by the mean of three different types of UVP transducers.

2 EXPERIMENTAL SET-UP

2.1 Laboratory facility

In- and outflow sequences were effectuated between two interconnected reservoirs, the so-called main basin (subscript *MB*) and the mixing tank (*MT*, Fig. 1). The connecting pipe system was equipped with a pump and a flow diverter allowing rapidly changing two flow directions:

– *IN*: jet entering the main basin (inflow)
– *OUT*: water withdrawn from the basin (outflow)

The intake/outlet is located at the front wall of the main basin and can be positioned at z_i = 0.25, 0.5 and 0.75 m above the reservoir bottom. The intake is followed by a cylindrical throat with an inner diameter of D_i = 4.8 cm, connected to a rigid PVC pipe of a length of L = 1.5 m (~30 D_i).

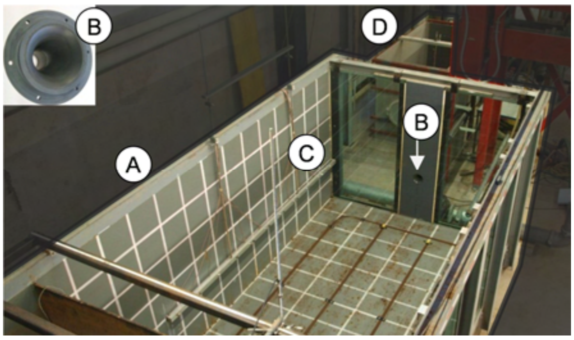
2.2 Instrumentation

To describe jet characteristics for inflow sequences as well as flow fields in front of the intake for outflow sequences, the main basin was equipped with UVP transducers (MetFlow SA, Switzerland). The flow mapping system had been applied in former studies on turbidity currents and 2D flows in shallow reservoirs [3, 5]. Walnut shell powder and hydrogen bubbles were used as flow tracers [6].

For measuring the centerline velocity of the jet, two

MetFlow prototype transducers with sampling frequencies of f = 0.5 and 1.0 MHz were applied. These devices are especially well suited for non-intrusive long distance measurements in the jet axis. The sensors were fixed on a steel bar and placed in the jet axis between s = 0.5 to 1.7 m from the intake/outlet in the main basin.

Horizontal 2D velocity fields were measured at several levels in the main basin. Seventeen 2 MHz UVP transducers were aligned along the side wall of the test volume on an aluminum frame, guaranteeing non-intrusive measurement. Operating azimuth angles of 90° and 45° were applied, allowing flow velocity sampling at 28 grid points in one quadrant of the test volume (Fig. 1b), corresponding to an area of 1.0 x 2.0 m^2. The frame was moved vertically to perform measurements at z = 0.25, 0.50 and 0.75 m from the bottom.

a) 

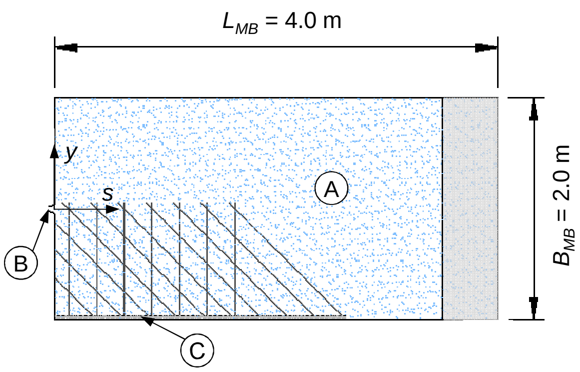
b) 

Figure 1: Picture of test facility (a) and schematic plan view of the main basin (b). A is the main basin; B, the intake/outlet; C, the UVP-frame with indicated 2D velocity sampling grid, and D, the mixing tank.

2.3 Parameter variation and procedure

To investigate the influence of in- and outflow sequences on the flow patterns and fine sediment behavior, parameters were varied as follows: five different cycle magnitudes (discharges) from Q = 0.3 to 1.1 l/s were applied, taking into account the volume of the main basin as well as real case pumped-storage cycles. The basic configuration considered in- and outflow sequences of the duration t_P to achieve steady state conditions in the main basin (Fig. 2b). Then, four cycle frequencies Kt_P were studied, resulting in discharge curves corresponding to a square wave function. As illustrated in Fig. 2, five in- and outflow cycles were fixed for the experiments, resulting in test durations of 1 h 20 min to 13 h 36 min, as t_P depends on discharge. Three more parameters of minor concern for the presented results were the relative duration between in- and outflow sequences $t_{P,IN}/t_{P,OUT}$, the initial sediment concentration C_0 and the intake position z_i.

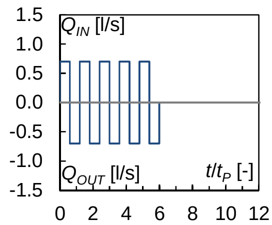
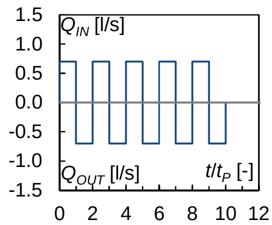
a)  b) 

Figure 2: Configurations of tested in- and outflow cycles, example for Q = 0.7 l/s and Kt_P = 0.6 (a) and 1.0 (b).

The experiments were performed according to Froude similarity, respecting the same ratio between inertia and gravity forces in prototype and model conditions. Reynolds similarity was not an issue due to the turbulent conditions at the intake/outlet for every tested discharge.

After filling the main basin and the mixing tank, the two reservoirs were disconnected from the laboratory circuit. Thus, the total water volume remained constant over the test duration. Consequently, water level in the basins varied according to the operation mode, with maximum level variation in the main basin of ΔH_{MB} = 0.18 m.

UVP measures were carried out once to three times a sequence, depending on the cycle duration t_P.

3 JET CENTERLINE VELOCITY

3.1 Submerged turbulent jet

Water ejected into the basin during inflow sequences forms a so-called submerged axisymmetric turbulent round jet. Such jets consist in an initial core, a transition zone and a fully developed jet region (Fig. 3).

The core flow is nearly free of shear and its velocity is equal to the nozzle exit velocity v_0 under uniform inflow conditions. It is surrounded by a mixing layer, forming a boundary between the core flow and the reservoir fluid. The imprint of the nozzle shape disappears when the turbulent eddies in the shear layer destroy the nozzle core flow and penetrate to the jet axis. The resulting eddy-dominated flow is called fully developed and starts at a distance of s/D_j = 4.3 to 10 from the nozzle.

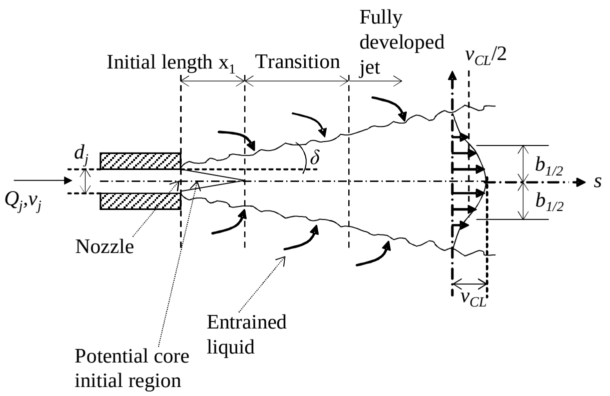


Figure 3: Jet flow behavior according to [7].

In the fully developed jet region, the centerline velocity v_{CL} continuously decreases with the distance s in jet direction. Centerline velocity can be defined as

$$v_{CL}(s) = C_1 \frac{v_0 \cdot D_j}{s} \tag{1}$$

where C_1: a constant [-],
v_0: the jet velocity at the nozzle [m/s],
D_j: the jet diameter at the nozzle [m], and
s: the distance from the nozzle [m].

According to literature, values of the constant vary between C_1 = 5.75 and 7.32 [7-10].

3.2 Experimental results

Two low frequency UVP prototype transducers were tested to describe the jet behavior in the main basin during inflow sequences. Sampled centerline velocities were compared to values given in literature and should provide a calibration possibility to define the adequate turbulence model for numerical simulations. Velocities are commonly normalized by the approach flow velocity in the pipe $v_0 = Q_{IN}/A$, lengths are normalized by the jet diameter D_j.

With increasing sampling distance, the recordable velocity magnitude of the UVP decreases. When the ultrasonic beam emitted by the transducer exceeds the jet dimensions, ambient stagnant water will be taken into account for velocity averaging. Such, a transducer located far away from the jet nozzle will record reliable data until the point when the emitted ultrasonic beam exceeds the jet dimensions. From there, the probe starts underestimating the jet velocity. Therefore, the centerline velocity v_{CL} over a distance up to s/D_j = 30 was established by several measures, as illustrated in Fig. 4. Based on the different UVP measurements, an envelope curve could be established, as indicated in Fig. 4a.

The particular bell mouth shaped intake/outlet geometry leads to slightly different jet characteristics than investigated by other authors. The jet core is short and the centerline velocity is higher than the estimated inflow velocity v_0, indicating a non-uniform velocity distribution at the nozzle. The distance up to s/D_j = 5 is marked by a drop to approximately v_{CL}/v_0 = 0.8. Then, the decrease of centerline velocity follows the values given in literature with C_1 = 6 approximately, independent on discharge. The short and fast decrease of v_{CL} over a length of approximately s/D_j = 5 to 6 is common for all tested discharges.

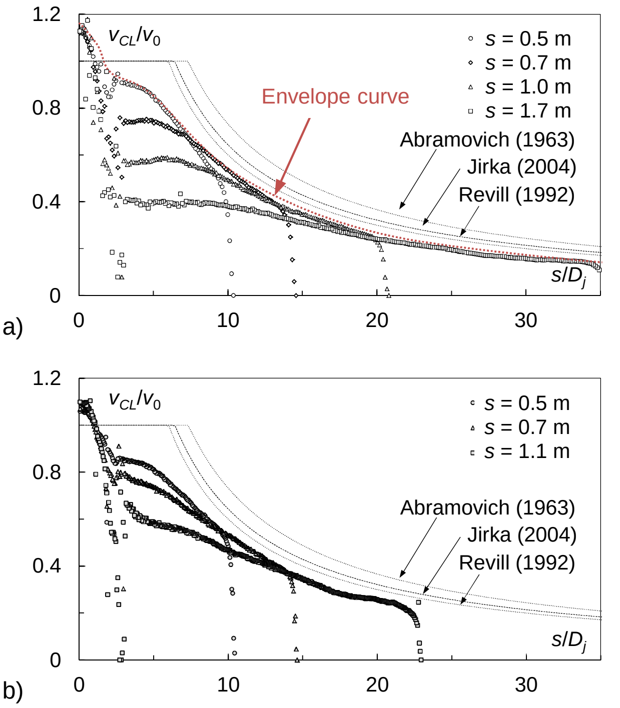


Figure 4: Dimensionless jet centerline velocity v_{CL}/v_0 as a function of dimensionless distance s/D_j from the nozzle. Comparison between experiments and values from literature. 0.5 MHz UVP sampling for Q_{IN} = 0.7 l/s (a) and 1.0 MHz UVP sampling for Q_{IN} = 0.5 l/s (b).

4 TWO DIMENSIONAL FLOW PATTERNS

Results from 2D flow mapping are represented for one quadrant of the main basin (Fig. 1b) and the case z_i/B_{MB} = 0.25. Based on the 28 UVP measuring points, linear interpolation allowed a finer grid to illustrate the flow patterns. Distances s and y are normalized by the main basin width B_{MB}, while velocities are normalized by the approach flow velocity in the pipe v_0.

4.1 Flow patterns for variable cycle discharge

UVP flow maps show that during inflow sequences, the jet starts developing immediately after the start of the sequence and oscillates slightly along its axis. Small circulation cells are formed at the boundary between the jet and the surrounding water. This initial behavior is similar for all discharges. By the end of a sequence, a big recirculation cell is established which occupies the entire sampling section for high discharges. For lower discharges, the boundary of the recirculation cell establishes at approximately s/B_{MB} = 0.4 (Fig. 5a).

Flow patterns at $z/B_{MB} = 0.125$ and 0.375 during inflow sequences show the expansion of the jet as well as some unsteady behavior with an oscillating and sometimes deflected jet due to secondary flow phenomena. These sections also include the recirculation cells around the jet. For discharges $Q = 0.9$ and 1.1 l/s, backflow zones toward the intake/outlet are systematically observed at $z/B_{MB} = 0.125$ (Fig. 5c). This movement on the bottom layer of the basin might be interesting regarding suspended sediment behavior. For lower discharge, such conditions do not establish in the bottom layer (Fig. 5b).

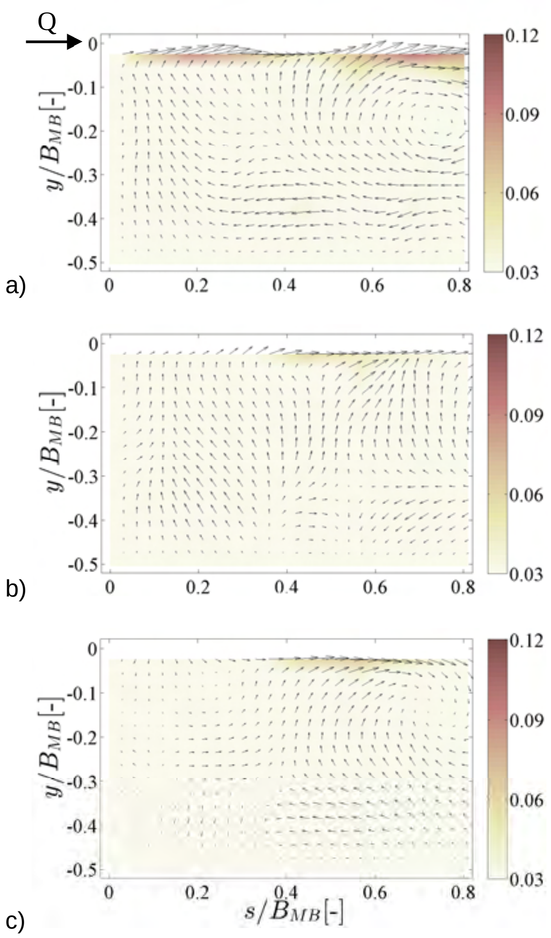


Figure 5: Sampled flow patterns for a jet entering at $s/B_{MB} = y/B_{MB} = 0$ and $z_i/B_{MB} = 0.25$, for $Kt_P = 0.8$ and $Q = 0.7$ (a & b) and 1.1 l/s (c). Dimensionless velocity v/v_0 at $z/B_{MB} = 0.25$ (a, at jet axis) and 0.125 (b & c, below jet axis).

The flow patterns at $z/B_{MB} = 0.25$ recorded shortly after the change in operation mode, i.e. at the beginning of an outflow sequence, show that the big recirculation cell persists in time before dissipating its energy. Independent on discharge, the velocities near the intake/outlet are mainly orientated toward the latter by the end of an outflow sequence, while the rear of the sampled section is quasi stagnant.

The 2D flow pattern at $z/B_{MB} = 0.125$ and 0.375 are very similar with fluctuating flow orientation, influenced by the precedent inflow sequence.

4.2 Flow patterns for variable cycle frequency

Cycle frequency influences the time available for flow patterns development. Thus, for $Kt_P = 0.6$ and 0.8 flow direction is reversed before flow patterns in the main basin reach steady state conditions. For $Kt_P = 1.2$, the flow patterns are supposed to be steady as observed for $Kt_P = 1.0$. Higher frequency of in- and outflow cycles leads to an amplification of movement in the main basin. The shorter outflow sequences do not allow entire dissipation of the recirculation cells. This leads to a slightly faster jet formation during the following inflow sequence.

5 CONCLUSIONS

One-dimensional velocity sampling with 0.5 and 1.0 MHz UVP transducers allowed adequate description of centerline velocity of the inflowing jet. Results were used later on to calibrate a numerical model of the experimental test rig.

The 2D UVP flow mapping allowed the analysis of horizontal flow fields at three levels in the main basin. Flow patterns at intake axis revealed the recirculation cells establishing for inflow sequences, while sampling in horizontal sections above and below the intake/outlet axis allowed the observation of some 3D behavior in the test volume.

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