Experiments on water jet induced cyclonic circulation - measurement of flow pattern and sediment concentration at reservoir outlet works

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In the framework of the reservoir sedimentation problematic, a new innovation employing water jets in order to maintain the fine sediments in suspension and to release them through the water intake is studied. Laboratory experiments as well as numerical simulations are performed. The experimental facility consists of a prismatic basin, in which four equal water jets are placed in a circle on a horizontal plane near the bottom where each jet directs in a right angle to the end of the potential core of its neighbouring jet. This jet arrangement creates a cyclonic circulation. Light weight crushed walnut shells with an mean diameter of 60 microns are used as sediments. Turbidity measurements give information about the time evolution of the sediment concentration at strategically interesting locations. Flow velocities and patterns are measured by UVP technique. It could be observed by the laboratory experiments and from the numerical simulations that the flow velocities induced by this jet configuration are strong enough to keep fine sediments in suspension. A sensitivity analysis regarding the momentum flux and the position of the jets has been performed in order to evaluate which configuration gives the optimal combination regarding the suspended sediment release.

Keywords: Reservoir sedimentation, water jet, experiment, flow field, suspended sediment, sediment concentration

1 INTRODUCTION

The process of sedimentation is a severe threat to the man-made lakes serving as reservoirs for hydro power production, drinking water supply or flood protection. It is a long term problem with economical consequences calling therefore for a sustainable solution [1]. The simplest concept is to release continuously the sediments out of the reservoir in order to achieve almost the natural conditions before the dam construction. The method may apply for fine sediments only. This can be done even without loosing precious water volume by releasing them through the turbines.

The present study focuses on the fine sediments right in front of the power intake. Evacuating the sediments in this area avoids clogging of the outlet works and guarantees its functionality. Most of the fine sediments reach this area when they are transported by turbidity currents.

A well arranged set of four water jets creates an artificial turbulence, means a rotational and upward flow, lifting the fine sediments to the height of the water intake from where they are evacuated during operating hours. In alpine reservoirs, these jets are fed by water derived from neighboring water catchments. In this way a minimum of external energy is used when evacuating the fine sediments.

2 MODEL SETUP AND INSTRUMENTATION

2.1 Main parameters

In the physical experiments, a jet layout consisting of four equal water jets placed in a circle on a horizontal plane where each jet points in a right angle to the end of the potential core of its neighbouring jet is tested (Figure 2). Since it is assumed that the influence on the flow of such an arrangement is locally limited, the physical model is reduced to the reservoir section in front of the dam. The experimental model is an elongated basin in a prismatic shape, with a total inner basin length of 4 m and an inner width of 1.97 m. The total basin height is 1.50 m. The front wall of the basin is considered to represent the dam, and the two lateral vertical walls confine the reservoir volume (Figure 1). In case of a locally limited circulation in front of the dam, the elongated basin form guarantees with its water body in the upper part a boundary condition as it exists in nature.

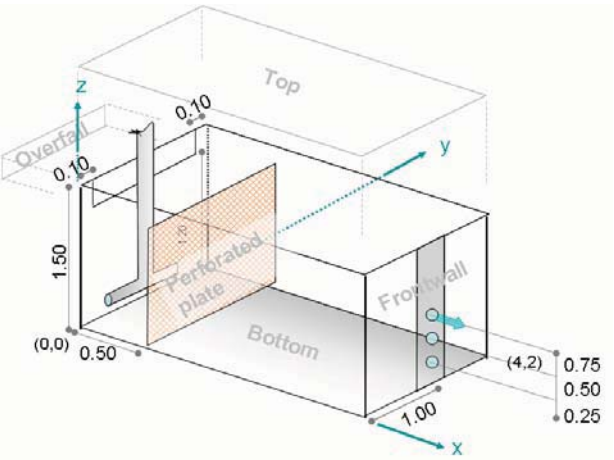

Figure 1: Schematic view of the physical model

The jet nozzle velocities in the experiments are between U_0 = 2.8, 5.6 and 7.5 m/s, while the nozzle diameters d_j are 3, 6 and 8 mm. According to [2], the jet centerline velocity $u_{CL}(s)$ at distance s from nozzle of a turbulent axisymmetric round jet, assuming discharge in s-direction is indirectly proportional to s as follows in Eq. 1:

$$u_{CL}(s) = 6.43 \frac{U_0 d_j}{s} \quad (1)$$

This means that the jet velocity decreases quite rapidly and the range of velocities to be measured in the jet area is rather big.

Figure 2: Picture from the interior of the physical model showing the jets fed from above in the foreground and the front wall with the water intake in the back.

2.2 Sediments

Walnut shell powder has been chosen for the physical experiments as seeding material. This material has been tested in former studies in the research field of sedimentation in shallow reservoirs [3] and has been proofed to be very well adapted to this kind of tests. It suits well for sediment concentration measures as well as tracer for UVP measurements. It is almost cohesionless, light weight (specific density is $rho_s = 1500\ kg/m^3$) and homogeneous. The particle size distribution is relatively narrow and the settling velocity is small (according to Stokes' theory: $w_s \approx 0.8$ mm/s in water at 15°C). The particles have a median diameter of $d_m = d_{60} = 0.06$ mm. Normal initial concentration was $0.3125\ kg/m^3$.

2.3 Experimental procedure

First, a water-sediment mixture is spread out on the bottom of the basin. Thereafter, the basin is slowly filled (Q_{in} = 1.7 l/s) with water from the back wall, while pressurized air (approx. $6 \cdot 10^5$ Pa) is blown out of the three irrigation pipes lying on the basin bottom thus creating a strong whirling pool. The bubbles have the effect of putting and maintaining the sediments in suspension. Once the basin is filled up to the selected water level (e.g. 1.20 m) the pressurized air is stopped and the experiment starts: The jets get started and the water intake is opened. Turbined water is replaced by clear water entered by the jets, thus maintaining the water depth constant. A normal experiment lasts for four hours, within this period the evacuated sediment amount decreases significantly from a maximum value reached in the first minutes to a small one. After four hours the value remains small and its decrease is insignificant during a long time.

2.4 Measurement technique

The following measurements are taken: suspended sediment concentration (SSC) with SOLITAX sc sensors, and flow velocity measurements by means of ultrasonic velocity profilers (UVP, [4-5]).

The outflowing suspended sediment concentration is measured continuously (one record every 5 seconds), SSC on the horizontal axis of the water intake (at a distance of 0.25, 0.45, 0.65, 0.75, 0.85, 0.95 and 1.00 m from the front wall) and on the rotational (vertical) axis of the jet configuration (on levels 0.10, 0.20, 0.30, 0.40, 0.50, 0.75 and 1.00 m over bottom) are measured sporadically.

Flow velocity measurements are performed in the area of the jet's arrangement and close to the water intake. Therefore, a rack of 5 x 5 2-MHZ-UVP-transducers is fixed at the lower end of a vertical stem (Figure 3). The lateral distance from one sensor to another is 200 mm; the distance between the sensors and the wall is 200 mm. This rack is moved within the front cube from one quadrant to another such that 4 displacements have to be done to get all records on one level, providing a horizontal 2D flow pattern on a plane of 2 x 2 m^2, consisting of a map with totally 100 points each with velocity information in both horizontal directions.

Figure 3: The 5 x 5 UVP-transducers rack fixed on the vertical stem with its remote computer installed on the bridge.

Such horizontal measurements are taken at four different levels: 0.10, 0.30, 0.50 and 0.70 m from the bottom. Vertical measurements are taken on two axes: the longitudinal middle axis corresponding to the water intake axis, and the transversal axis, crossing the rotational axis.

The number of channels was 557, the number of repetitions was 128, the number of cycles was 4 and the number of multiplexer cycles was 8 with 6 profiles per burst.

3 FLOW PATTERN

From the measured flow pattern, it can be observed that water is sucked vertically from the reservoir bottom up and from above down to the level of the jet's plane, from where the water is spread horizontally again. Because of its high 3-dimensionality, the flow pattern is very complex (Figures 4 and 5).

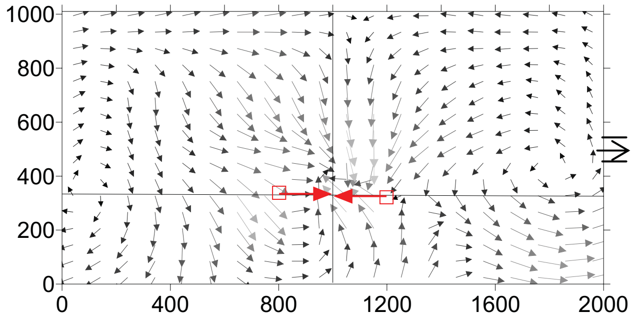

Figure 4: Measured flow pattern in the longitudinal axis, with the water intake at the right edge at the level of h_i = 500 mm. Units in mm. Dark colored arrows: low flow velocities, bright colored arrows: high flow velocities. Total jet discharge equals water intake discharge: 1.125 l/s, constant water depth h = 1.2 m, nozzle diameter d_j = 8 mm, distance between rotational axis and front wall d_{axis} = 1.05 m, jet plane height h_j = 0.35 m, distance between jets l_j = 0.3 m.

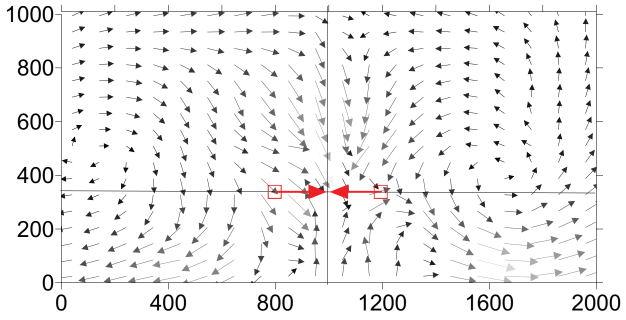

Figure 5: Measured flow pattern in the transversal axis, right through the rotational axis. Units in mm. Dark colored arrows: low flow velocities, bright colored arrows: high flow velocities. The same parameters as in Figure 4 have been adopted.

Numerical steady state simulations performed with the Navier-Stokes-equation based solver ANSYS-CFX confirm these observations (Figures 6 and 7).

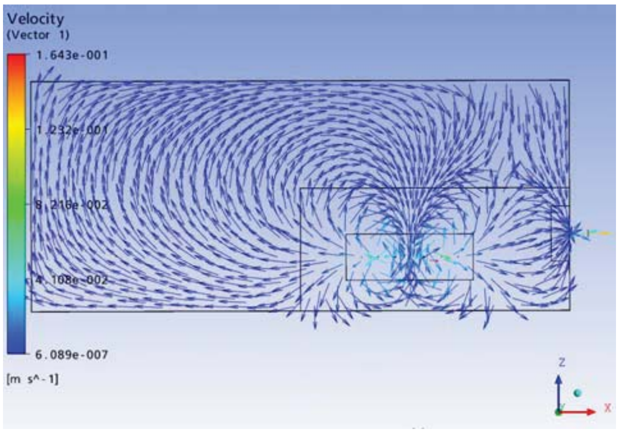

Figure 6: Calculated flow pattern in the longitudinal axis, with the water intake at the right edge (see arrows). Red: high velocities, blue: low velocities.

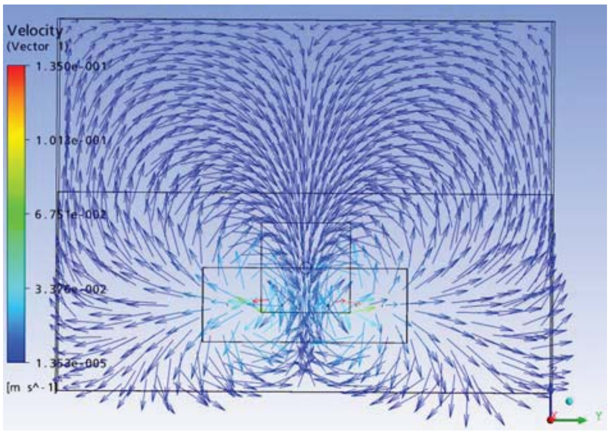

Figure 7: Calculated flow pattern in the transversal axis, right through the rotational axis. Red: high velocities, blue: low velocities.

4 EVACUATED SEDIMENTS

Raw SSC data of six geometrically identical experiments recorded outside of the power intake are displayed in Figure 8. Each experiment was performed with a different jet discharge. They are compared with the SSC measured during the first 4 hours of the experiment where no inflow and no outflow of the basin took place. The latter measurements were recorded on the level z = 0.5 m over the basin bottom.

In case the jets were used, it could be observed that the evacuated sediment ratio ESR, defined in Eq. 2 as the evacuated sediment volume V_{out} compared to the sediment volume initially added to the basin V_{in}, is almost proportional to the sum of the jet nozzle discharges Q times the square root of the current time t in seconds (Eq. 3):

$$ESR = V_{out} / V_{in} \qquad (2)$$

$$ESR = 1.0465 \cdot \left(\frac{Q}{h} \cdot \sqrt{\frac{t}{\Pi \cdot V_{\tan k} \cdot v_{ss}}} \right)^{1.04} \qquad (3)$$

where h is the water depth, V_{tank} is the basin volume, v_{ss} is the estimated settling velocity of an average walnut shell powder grain (see paragraph 2.2). This equation is valid for h/d_j higher than 400, for t less than four hours and for test conditions. Its validity hasn't been tested yet for prototype scale.

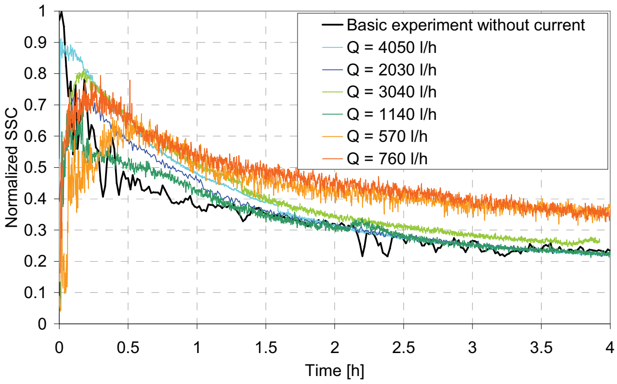

Figure 8. Raw data of outflowing suspended sediment concentration (SSC) measurements and of SSC measured in the basic experiment. Each experiment is done with 4 equivalent jets. Two of the experiments were performed with a jet diameter d_j = 8 mm, two with d_j = 6 mm, and another two with d_j = 3 mm. The jet diameters were combined with three different jet velocities, v_j, leading to 6 different total jet nozzle discharges Q.

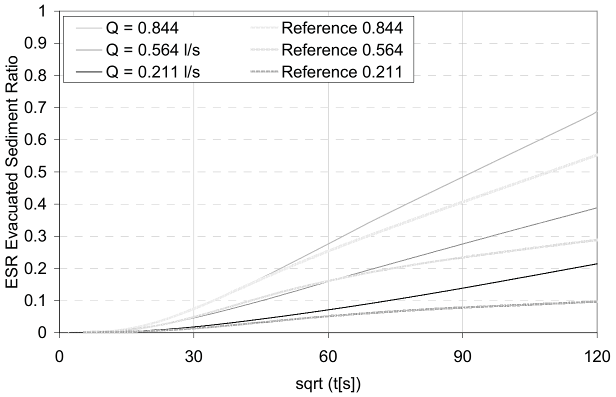

Figure 9: After around 15 minutes (sqrt (t [s]) = 30) the evacuated sediment ratio is proportional to the square root of time in seconds. Higher jet discharges are more effective, the evacuated sediment ratio is higher. The evacuated sediment ratio achieved using jets is after 2 hours approximately as high as after 4 hours without jets.

The experiments varying other parameters like the jet position relative to each other, relative to the basin bottom and relative to the front wall let arise, that the influence of these geometrical parameters is in the range of the error, thus negligible.

In Figure 9 it can be observed that in case no jet is used ESR is smaller than in case jets are employed.

SUMMARY AND CONCLUSION

With an experimental set-up systematic experiments have been performed concerning the continuous evacuation of suspended sediment in reservoirs. In an elongated cuboidal basin, four equivalent jets are arranged in a circular configuration. The described installation is used to investigate the most efficient jet configuration regarding the evacuated sediments quantity. The sediments are simulated with ground walnut shells.

Several combinations of jet diameters and jet velocities are tested, as well as their position relative to each other, relative to the basin bottom and water intake elevation as well as relative to the front wall.

In case jets are used, the experiments show that after two hours the evacuated sediment ratio is approximately as high as after four hours in case no jets are used when releasing the same water discharge through the water intake. In other words, after four hours without jets approximately 80 % of the sediment quantity released with jets is achieved. Thus it seems that this method could be very promising bearing in mind that no extra energy consumption is needed apart from the head and discharge provided by water tunnels. Moreover, the analysis of the experiments conducted with water jets and sediments put in evidence that the evacuated sediment ratio is proportional to the sum of the jet discharges and to the square root of time.

Further studies will compare the results of numerical simulations performed with ANSYS-CFX. The measures obtained with the experiments will be analyzed in detail.

ACKNOWLEDGMENTS

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