ANALYSES OF THE SUSPENDED-LOAD SEDIMENTATION PROCESS AND ITS DYNAMICS IN RESERVOIRS WITH HIGH DAILY OSCILLATIONS

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abstract

The river water pumped into reservoirs with high daily oscillations, e.g. at pumping hydroelectric power plants, contains different amounts of suspended load depending on the time period and the river's discharge. This paper presents an analysis of the suspended-load sedimentation process that is based on the interaction between the sedimentation, i.e., the settling, velocity and the motion of the water. The settling velocity of spherical particles in the presence of a buoyancy force is a function of the particle size. Laboratory investigations of the suspended material from the river-water samples have determined the ratio between the particle size and the concentration of suspended material with respect to the river discharge, the ratio between the concentration of suspended material in the water and the discharge, and the relationship between the concentration of suspended material and the discharge of water, which is for the first time expressed as an exponential function. The motion of the water in the reservoirs with high daily oscillations is solved by the three-dimensional modeling of the liquid streams. The evaluation of the results is presented for the case of the planned Kozjak pumping hydroelectric power plant on the River Drava.

keywords

suspended load, water motion, sedimentation, sedimentation transport, pumped hydroelectric power plant, reservoir

1 INTRODUCTION

The reservoir system of a pumping power station subjected to high daily oscillations of the pumped water is a place where the sedimentation process of suspended material is a continuous procedure with specific dynamics.

The sedimentation processes in reservoirs and lakes have been reported by many authors, e.g. (Graf, 1984; Fan and Morris, 1992; De Cesare et.al., 2001). In recent years, experimental and numerical model research has been performed by developing a moving boundary model of the deltaic sedimentation in lakes and reservoirs that captures the co-evolution of the river-delta morphology and the associated deposit (Kostic and Parker, 2003). One-dimensional numerical modeling of reservoir sedimentation proposed by Toniolo and Parker (2003) is a simplified model of sand-bed rivers that predominantly transport two grain sizes, sand as a bed material and mud as a wash load, where it is developed and tested as an integral, physically based moving-boundary model that captures the evolution of the river-delta deposit. The three-dimensional reservoir-sedimentation model developed by Campos (2001) is based upon Navier-Stokes equations for incompressible flow to obtain the flow field through the reservoir, and the suspended sediment transport through the reservoir was modeled with the 3D Advection-Diffusion equation.

In this paper the analysis of the suspended-load sedimentation process is performed by a settling velocity and the motion of the water in reservoirs with high daily oscillations. The dynamics of this process depends on the interaction between these two velocities. The settling velocity of spherical particles in the presence of a buoyancy force (Batchelor, 1967; Lamb, 1994) is a function of particle size; therefore, the intention of a laboratory investigation of the suspended material was to investigate different correlations between the particle size, the concentration of suspended material, and the water discharge. The motion of the water in the reservoirs with high daily oscillations is solved by the three-dimensional modeling of liquid streams based on physical models in the scope of numerical algorithms using "Fluent" software (Fluent 6.2, 2005).

Finally, the evaluation of the results is expressed for the case of the planned pumping hydroelectric power plant that is located on the River Drava within the Kozjak region near Maribor. It will be composed of three main parts: an engine house, a water-storage reservoir, and the pipeline that will connect the engine house and the reservoir. The engine house will be located near the River Drava, the reservoir on the 700-m-higher plateau of mountain Kozjak, and the pipeline some ten meters under the eastern slope of Kozjak (Fig.1a). The upper reservoir on the top of the Kolar hill will have a capacity of approximate 3 millions m^3 and lies with the bottom of the embankment, at 975 m, and the top of embankment, at 996 m above sea level, which allows 20 m of water-height oscillation. The entire inner surface will be water-resistant asphalted; at the top of the embankment there will be a maintenance road (Fig.1b).

For this case the laboratory investigations of the suspended material were established in order to achieve an evaluation of the proposed model based on a determination of the quantity of solid materials from the River Drava water and its structural determination. The results were evaluated together and gave an approximate estimation of the sedimented material in the reservoir during the exploitation period per year (Trauner and Vrecl-Kojc, 2007; Trauner et.al. 2008).

2 RESEARCH METHODS AND THE RESULTS

2.1 LABORATORY INVESTIGATIONS OF SUSPENDED MATERIAL

During the period from October 2005 to June 2007, 17 samples of water were collected with the intention of separating the suspended material for further investigations. At the same time the discharge from the River Drava was measured.

The separation of the suspended material and the water was carried out with the help of the sedimentation of particles by centrifuging and water evaporation (Table 1). The chosen approach required a lot of time, but it enabled us to determine the quantity of suspended material very precisely and to collect enough material for further investigations.

Figure 1a. Draft of the Kozjak hydroelectric power plant.

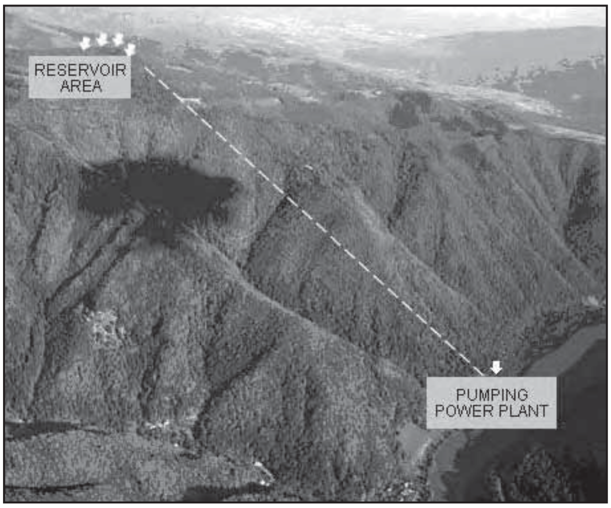

Figure 1b. Visual simulation of the Kozjak reservoir.

Table 1. Time of sampling, temperature of water (T), discharge (Q), concentration of suspended load (c).

Sample	Date	T (°C)	Q (m^3/s)	c (g/m^3)
1	23. 09. 2005	13.3	265	11.4
2	07. 10. 2005	16.6	801	187.4
3	25. 10. 2005	13.0	286	4.9
4	08. 11. 2005	13.0	234	3.4
5	29. 11. 2005	12.0	243	3.1
6	14. 12. 2005	12.5	212	2.6
7	22. 03. 2006	9.5	205	0.3
8	31. 03. 2006	9.5	293	19.1
9	05. 05. 2006	10.0	403	8.6
10	23. 05. 2006	10.0	551	25.2
11	31. 05. 2006	10.0	565	28.6
12	29. 06. 2006	10.0	488	21.1
13	10. 08. 2006	9.5	424	26.0
14	19. 09. 2006	9.5	486	13.7
15	06. 10. 2006	7.0	443	10.3
16	06. 03. 2007	9.0	289	2.6
17	07. 06. 2007	10.0	451	20.2

The results of the investigations showed that the concentration of suspended material in the water strongly depends on the discharge of the River Drava (Fig. 2). In the case when the river discharge does not exceed 750 m^3/s, this relationship can be expressed as an exponential function:

$$c = 0.4019 \cdot e^{0.0079Q} \qquad (1)$$

During a few short periods of time the discharge exceeded 750 m^3/s; in the years 2005-2007 it happened three times for periods of one or two days. In those cases the exponential function does not assume real values for the concentration of the suspended material, instead of this the proposed values approach the asymptote, which is about 240 g/m^3 of suspended material. Fig. 2 shows this case with the dashed curve.

During the project the following extremes of discharge and suspended material were observed: maximum, in October 2005 (Q = 801 m^3/s; c = 187.4 g/m^3), and minimum, in March 2007 (Q = 205 m^3/s, c = 0.3 g/m^3).

The grain size distributions of the tested solids are shown in Fig. 3. It is clear that the suspended material mostly has the size of silt, and only 6 % (weight %) of the grains belong to the clay fraction. Fig. 4 (next page) shows the ratio between the concentration of suspended material and the size of the particles (D) with respect to the discharge.

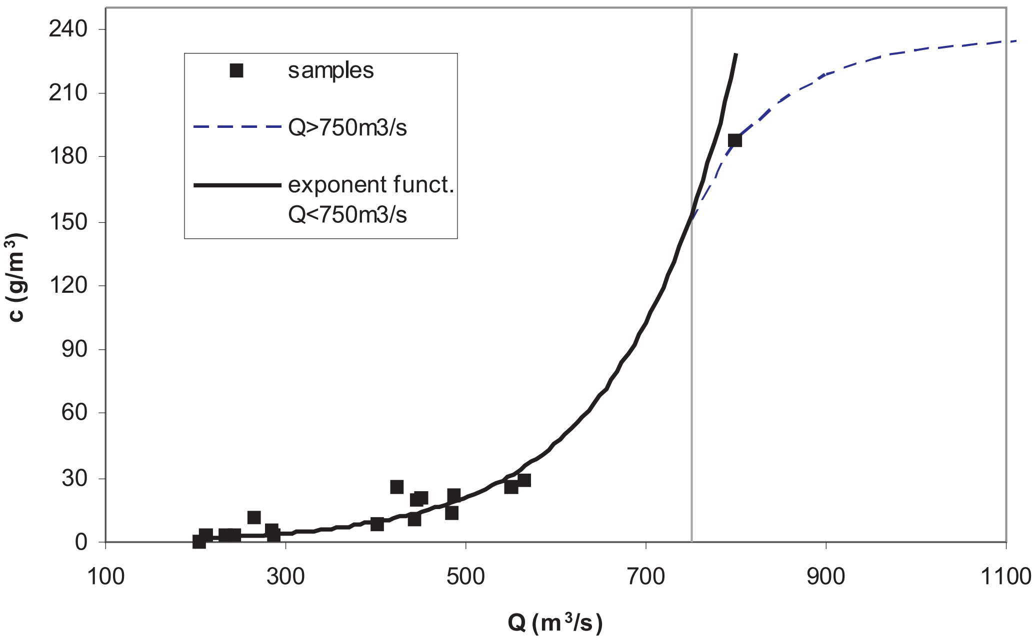

Figure 2. Relationship between the concentration of suspended material and the discharge of the water.

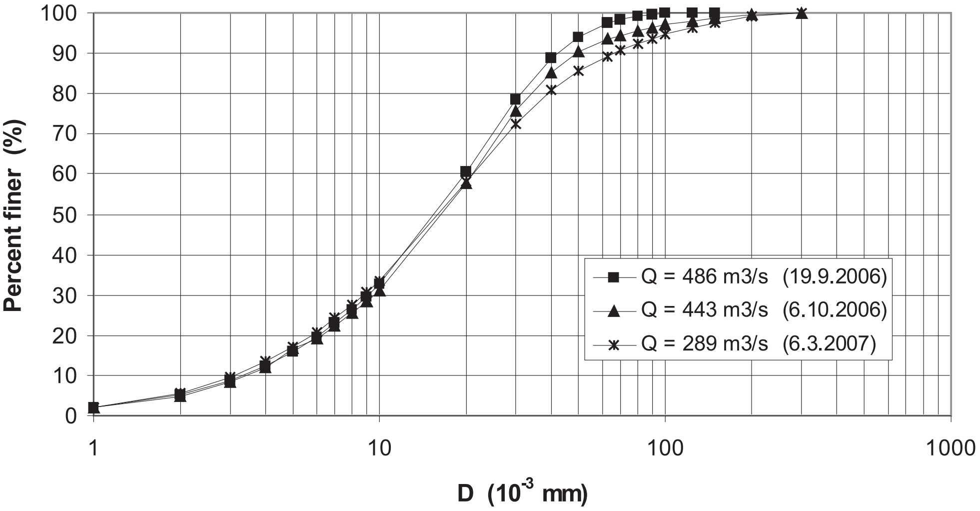

Figure 3. Grain size distribution.

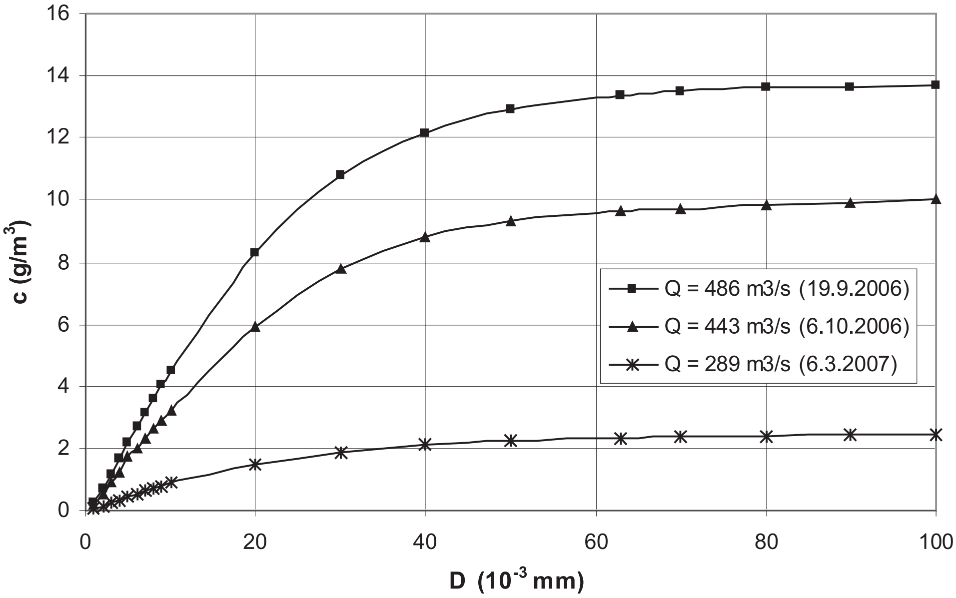

Figure 4. The ratio between the concentration of suspended material and the size of the particles with respect to the discharge.

2.2 SETTLING VELOCITY UNDER DIFFERENT CONDITIONS USING STOKES' LAW

The aim of the analysis was to determine the influence of different prepositions on the quantity and space distribution of the sediments on the bottom of the reservoir and consider the following: the grain size analyses, the relationship between the concentration of the suspended load and the discharge of the water, the settling velocity of the spherical parts in a still stream and in turbulent water with regard to the vectors of water motion expressed as position function and temperature rates (Morris and Fan, 1998). The water motion depends on the position point that is expressed as a vector function of time. The limitations and suppositions are as follows: the short time period of the investigation; the analysis was solved by a simplified hydro-dynamic method; the forms and sizes of the sediments should conform to the spherical form of the particles; and the diameter should be equivalent to the real shape of the sediment (Mott, 2000).

The settling velocity of fine particles is assumed to be as follows. In the case when a viscous fluid with spherical particles flow with a velocity that gives a Reynolds number Re < 1 (Rott, 1990), or when the particle moves through the still stream viscous fluid, the resistance force is acting on a spherical particle. Stokes' law with Eq. 2 is valid for a range of diameters, 0.2 μm to 100 μm.

The settling velocity (v_s) of the fine spherical particles in a laminar flow is given by (Lamb, 1994):

$$v_S = \frac{(\rho_S - \rho_T)}{18 \cdot \mu_T} \cdot g \cdot D^2 \qquad (2)$$

where ρ_S is the density of the spherical particles, ρ_T is the density of the water at temperature T, g is the acceleration of gravity and μ_T dynamical viscosity of the water at temperature T (see Table 2).

Table 2. Approximate values of the water's physical properties at different temperatures.

T (°C)	ρ_T (kg/m^3)	μ_T (Ns/m^2)
0	1000	1.790×10^{-3}
5	1000	1.510×10^{-3}
10	1000	1.310×10^{-3}
15	999	1.140×10^{-3}
20	998	1.000×10^{-3}
25	997	0.891×10^{-3}

The ratios between the grain size for fine spherical particles and the settling velocity of the suspended material in the water with regard to the temperature used in Eq. (2) are shown in Fig. 5.

The settling velocity of rough spherical particles, larger than 200 μm in the presence of a buoyancy force is given by (Lamb, 1994):

$$v_S = \sqrt{\frac{4 \cdot D \cdot g}{3 \cdot C_D} \cdot \left(\frac{\rho_S - \rho_T}{\rho_T} \right)} \qquad (3)$$

For laminar flow the drag coefficient of spherical particles (C_D) needs to be considered with:

$$C_D = \frac{24}{\text{Re}} \qquad (4)$$

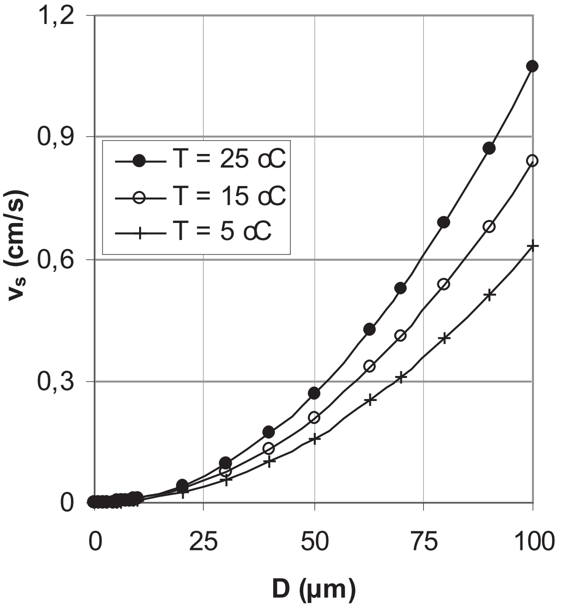

Figure 5. Relationship between the grain size of the fine suspended material and the settling velocity.

For turbulent flow the drag coefficient for the natural shape of particles cannot be expressed in an analytical form. The settling velocity needs to be determined experimentally. In the case of simplifying the real shape into the equivalent diameter of a spherical part and with the Reynolds number Re > 1000, the drag coefficient of spherical particles can be taken as the constant $C_D = 0.4$ (Lamb, 1994).

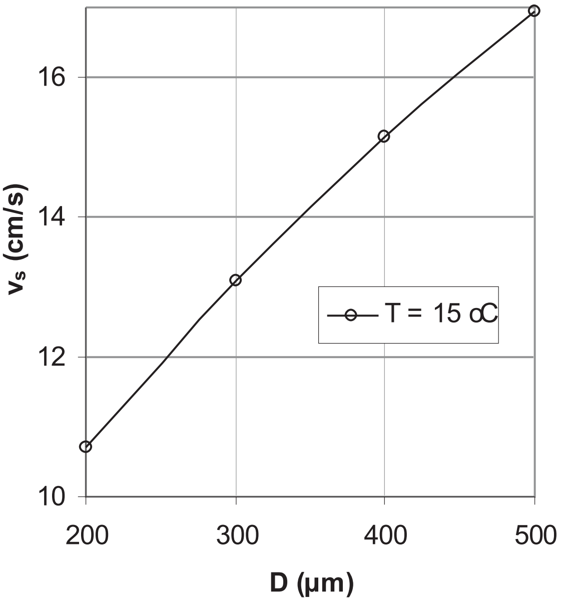

Figure 6. Relationship between the grain size of the rough suspended material and the settling velocity.

It is assumed that the particles bigger than 200 µm will sediment in the reservoir near the inflow-outflow chamber, so there is a probability of washing out these particles through the pipeline. The grain size distributions of the tested solids (Fig. 3) show that the quantity of particles of this size is less than 1%.

2.3 STUDY OF THE WATER MOTION IN THE RESERVOIR

An analysis of the water-flow velocity was performed with computer software for a fluid analysis named "Fluent" in a three-dimensional state (Fluent, 2005). The input parameter of this study was time, i.e., 24 hours (one day) of water motion in the reservoir: 4-hour inflow (pumping the water), 4-hour outflow (producing the electricity). The intention and scope of this research were to discuss two conditions that will occur during the exploitation phase in the reservoir: turbulence state, and the laminar state. The aim of the analysis was to determine the influences of each state on the velocities of the sediments.

The results present an estimation that forms a basis for evaluating the quantities of sediments according to the time period. Fig. 7 shows the results from a hydrodynamic numerical analysis of water behavior during the exploitation conditions in the reservoir (water inflow).

In addition, a quasi-stable CFD Simulation at Three Different Water Depths was also performed. In these analyses the emptying of the reservoir at three different depths was quasi-stationary observed. The simulations were achieved using the "Fluent" program. In particular, the currents in the reservoir were determined. Both, the scalar and vector velocities, were calculated with the help of numerical models. A complete 3-dimensional analysis was accomplished at a depth of 3 m (Fig. 8 and Fig. 9).

The simplified simulations cover in detail the following: the networking of the storage reservoir for three different depressions (3, 12 and 19 m), the definition of the simplified physical boundary conditions (volumetric flow rate at the emptying channel: 48 m^3/s, ambient pressure at the flat water surface), the single-phase simulation of the quasi-stable flow state, and the results in the form of the velocity vectors, the shear stress distribution as well as the streamlines.

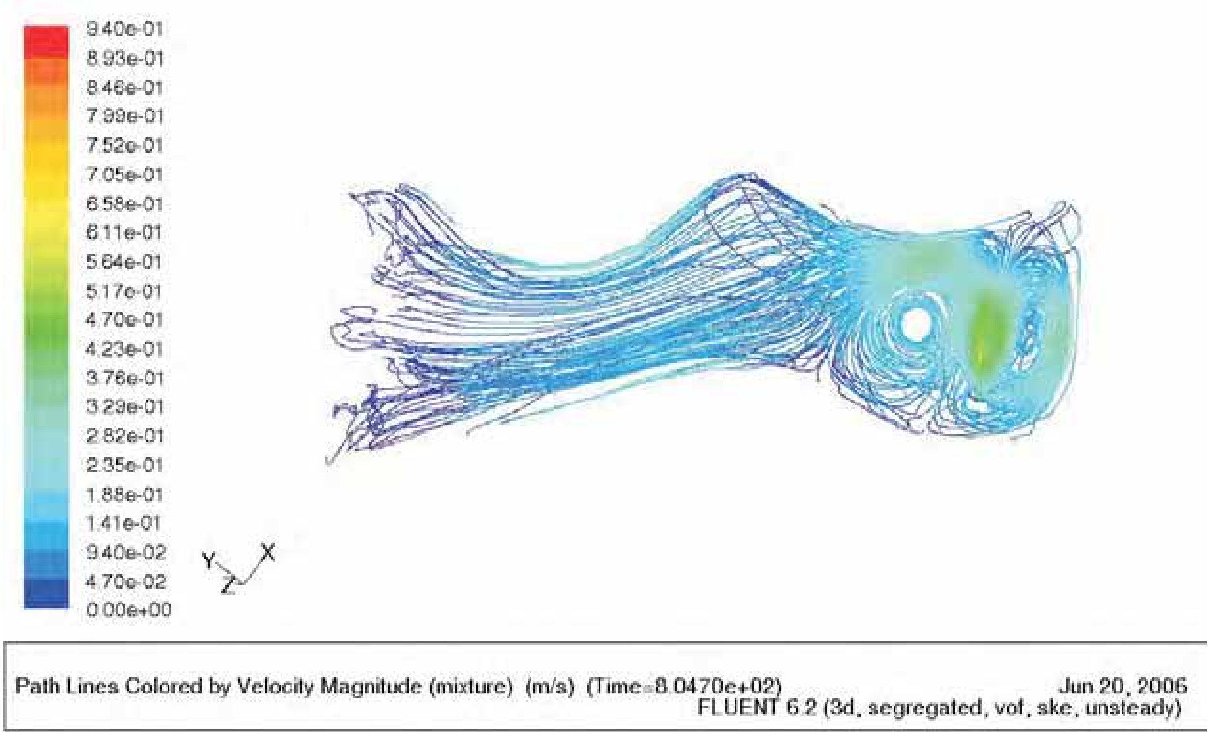

Figure 7. Results of the hydrodynamic numerical analysis of water inflow in the reservoir.

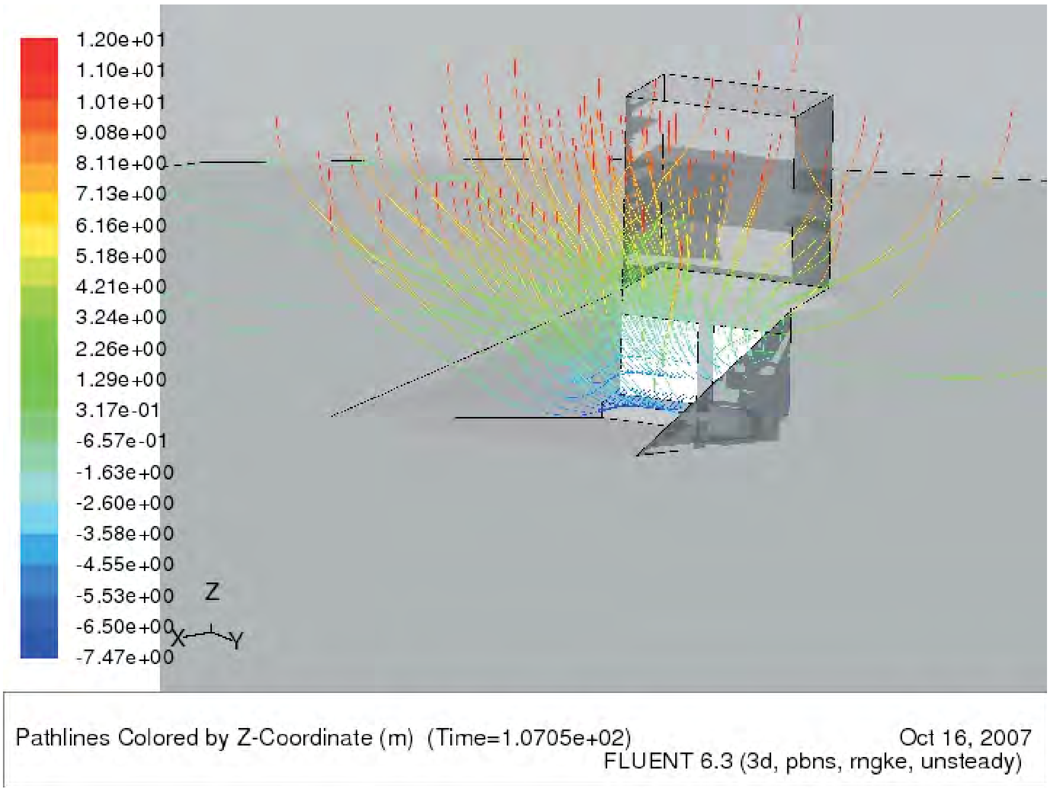

Figure 8. The distribution of velocity at the inflow-outflow chamber: water inflow in the reservoir.

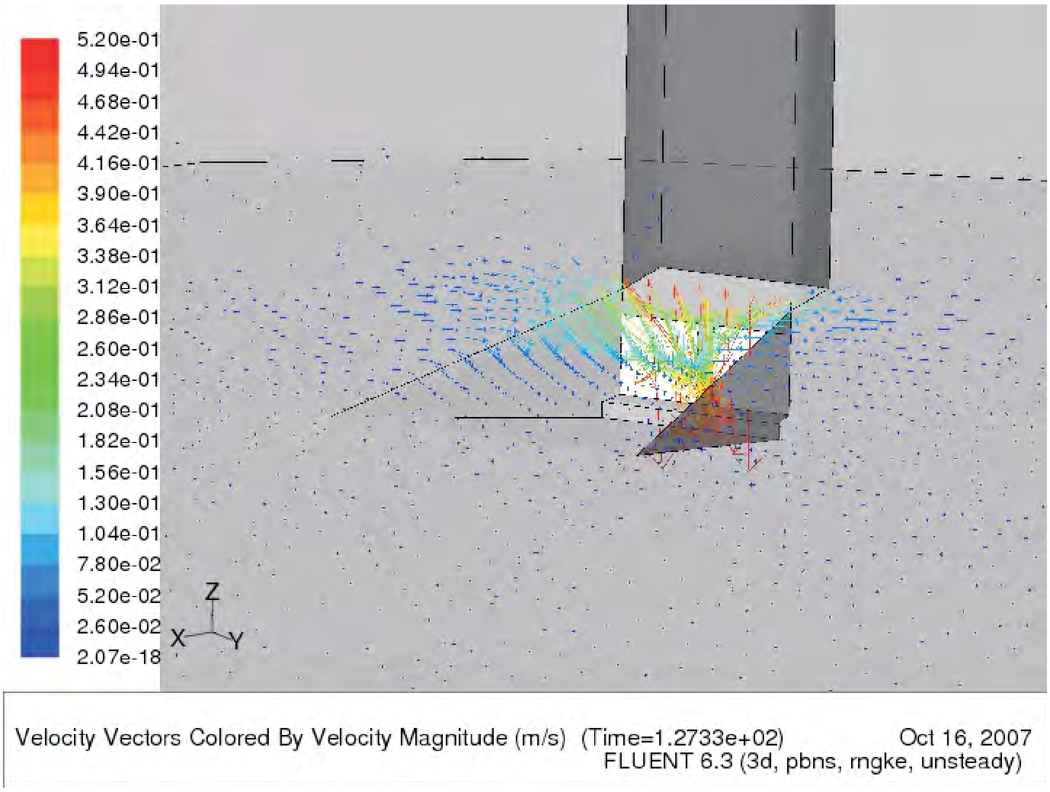

Figure 9. The distribution of velocity at the inflow-outflow chamber: water outflow from the reservoir.

3 EVALUATION OF THE RESULTS

The quantity of sedimented material in the reservoir is evaluated on the basis of the data on water flow rates for HPP Fala on the River Drava for a period of one year (September 2005 - August 2006). The size of the surface integral under the curve Q represents the water flow rate for this period, which amounts to $Q_{year} = 8.75e^9$ m^3/year (Fig. 10).

The concentration of suspended material in relation to the actual daily flow rates in the selected time can be calculated with Eq. (1). The size of the surface integral under the curve c shows the total concentration of suspended material in the River Drava, which is $c_{year} = 2962.06$ g/m^3/year (Fig. 10).

The discharge of the water at the reservoir inflow-outflow chamber takes 47 m^3/s and the daily time of pumping the water into the reservoir lasts 14 hours. Considering these two suppositions, and the daily concentration of suspended material of water at HPP Fala on the River Drava, the estimation of the daily quantity of sedimented material in the reservoir is achieved. Finally, the yearly quantity of sedimented material in the reservoir is estimated to be 7017 tons/year. The evaluated density of the suspended particles is 1750 kg/m^3; therefore, the total quantity of sedimented material on the reservoir bottom takes approximately 4010 m^3 per year, which with regard to the water-storage volume represents 0.13 % or a 5.6 cm thick layer per year, if it is assumed that all the material will be sedimented on 2/3 of the area of the lake bottom, which is a total of 107,511 m^2.

This calculated quantity of sedimented material has to be reduced by the quantity of material that will be washed out through the pipeline during the water outflow into the River Drava.

The evaluation of the water motion in the reservoir leads ot the following remarks. The analyses have shown that the water inflow in the reservoir presents an unstable hydrodynamic process, which means that the water velocity in this stage is not constant with regard to appointed areas of the lake. It traverses from the initial turbulent state into the later laminar state. The active flow motion will be limited to the first part of the reservoir near the inflow-outflow chamber where the velocities will reach from 0.65 m/s to 0.25 m/s in two major whirls. The highest velocities of flow appear next to the inflow-outflow chamber, in the area of both embankments approach to a new, slightly increase of velocity. In the second third of the reservoir, a large number of local whirls will be present; the velocities of which will be negligibly small (0.1 m/s). In the last third of the reservoir the velocities are close to 0 m/s, the water is in general standing still with possible vertical whirls that can occur within a radius width of around 10 m. They could raise the sediments in this area; however, this would not have an influence on increasing or decreasing the material quantities in the reservoir.

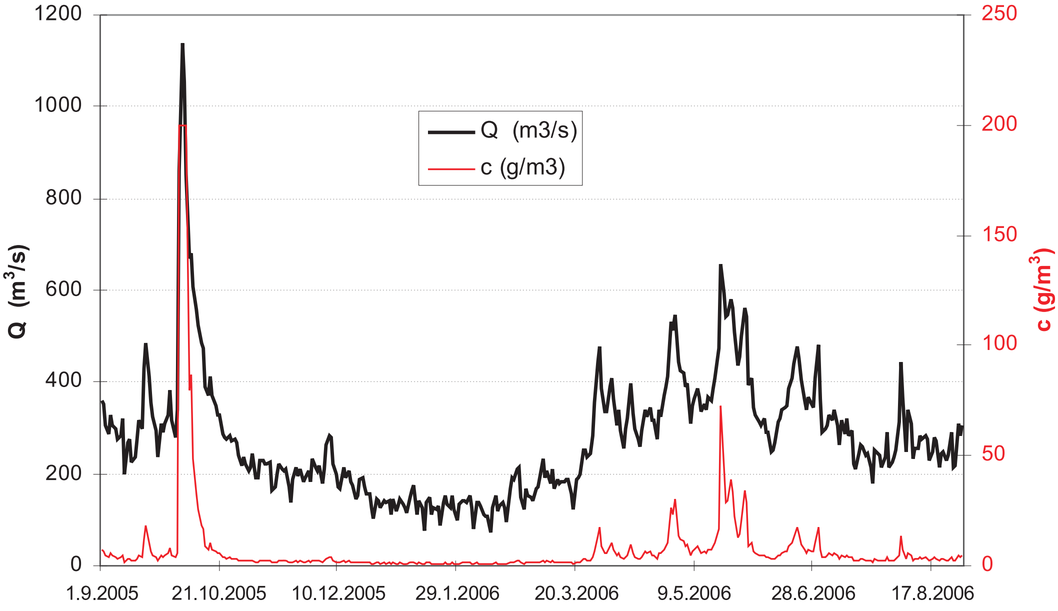

Figure 10. Water flow rate Q for the HPP Fala for the period between 1 September 2005 and 30 August 2006.

4 CONCLUSIONS

Analyses of the suspended-load sedimentation process performed by the interaction of the settling velocity and the motion of the water in reservoirs with high daily oscillations expressed the dynamics of this process. The laboratory investigation results of the suspended load of water samples taken from the river is given as the ratio between the concentration of suspended material and the size of the particles with respect to the discharge, which is an important correlation for the settling velocity of the spherical particles in the presence of a buoyancy force, because it is a function of the particle size. The investigations also gave the relationship between the concentration of suspended material and the discharge of water, which is for the first time expressed as an exponential function. The motion of the water in the reservoirs with high daily oscillations solved by three-dimensional modeling using “Fluent” software has shown that the water inflow in the reservoir represents an unstable hydrodynamic process, which means that the water velocity in this stage is not constant with respect to appointed areas of the lake. It traverses from the initial turbulent state into the later laminar state.

It is foreseen that during the exploitation conditions in the reservoir the active flow motion will be limited to the first part of the reservoir, near the inflow-outflow chamber. The highest velocities of flow appear next to the inflow-outflow chamber, in the area of both embankments there is an approach to a new, slightly increased velocity. In the second third of the reservoir, a large number of local whirls will be present; the velocities of which will be negligibly small. Therefore, the analyses of the water’s motion and sedimentation have given estimation that the main part of the sedimeted material with a presumed weight of 7017 tons/year will be sedimented on 2/3 of the area of the lake.

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