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Fall Velocity of Cohesive Sediments in Dez Dam Reservoir

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Abstract: In order to characterize the settling properties of natural cohesive sediment adjacent to the Dez Dam wall (as a symbol of a large dam reservoir in arid and semi-arid zones), falling velocity of particles have been measured using a 2.50 m height and 0.30 m diameter column. In contrast to the traditional particle size based methods, an approach relying on time and depth variation of sediment concentration was employed to estimate the mean value of fall velocity at any depth and time. Particles in deeper depth, particularly for the samples with higher rate of sediment concentration accelerated faster and stayed at higher velocities for longer duration as a result of higher rate of flocculation. This confirms the greater effect of particle flocculation than their settling competition. The particles in all depths reached their maximum falling velocity same time around 15 min after the beginning of the tests. The low concentration samples reached higher maximum velocity as a result of lower rate of particle compaction but for a much lower duration in comparison to the higher concentrated samples.

Key words: Dez dam, cohesive sediment, fall velocity, flocculation

INTRODUCTION

For large dam reservoir, falling velocity in particular for fine sediment particles is a key parameter for estimation of sediment transport and evaluation of trap efficiency and consolidation. Settling properties of sediments in lakes and reservoirs should be characterized by time and depth variation of the fall velocity of sediment particles. For cohesive sediments, the particle aggregation as a result of flocculation increases falling velocity in contrast to particle competition which tends to reduce it. As the large dam reservoirs are normally long, only fine and cohesive suspended particles are able to reach the dam wall.

Sedimentation and decrease of large dam reservoirs' capacity reduces efficiency and productivity of the dam and power house. In arid and semi-arid zones of the world with finer eroded soils, rivers transport more suspended material into dam reservoirs and sedimentation particularly near dam walls reduce the dam efficacy faster. In some developing countries, where watershed management measures are not carried out effectively, reservoir storage is being lost in much larger rate. This amount in the Asian nations is generally higher than the world average (Liu *et al*., 2002). Based on a report by International Committee of Large Dams (ICOLD), there are more than 40,000 large dam reservoirs worldwide used for water supply, power generation and flood control. An overall estimation by ICOLD reveals that 0.5-0.75% of the total storage volume of these reservoirs is lost each year as result of sedimentation. To maintain current total storage, as many as 300 to 400 new dams need to be constructed each year. However, increasing populations and rate of consumption per capita mean that the demand for storage is rising inexorably despite the increasing use of alternative sources of energy

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and the more efficient use of water (White, 2000). A cost of nine billion dollars is estimated just to replace existing storage capacity without considering the costs to deal with environmental and social issues (Annandale, 2005). Depending on the sedimentation source and condition, many methods are deployed today to control sedimentation and maintain current storage, including watershed management, dredging, density current venting and flushing. Among these, watershed management is an effective approach to control the source of sedimentation and maintaining existing storage capacity, thus minimizing the need to construct as many new dams. It is also advisable to design new dams in a manner that will facilitate sediment management and long-term reservoir conservation. Trapping the density current in the reservoir far enough behind the dam wall is an example of these design techniques.

The problems associated with sedimentation and the reservoir capacity is directly tied with the settling property of the suspended materials flowing through the reservoir. As a turbid river rests in the quiescent water of a reservoir, the process of settling begins and particles concentrate more and more with time at deeper parts of the reservoir. This allows for the settling property of sedimentation to be measured based on time and depth variation of the fall velocity of sediment particles. For modeling of sedimentation in large reservoirs, the increase in rate of concentration can be correlated with the quiescent water depth.

As a major parameter to quantify sediment transport, reservoir trap efficiency and consolidation process, extensive studies have been conducted in the past to determine the settling velocity parameter for cohesive sediments but less is resulted due to its complicated behavior (Fathi Moghadam *et al*., 2007). In nature, due to size difference, particles do not settle at the same pace and thus their fall velocity varies considerably. Larger particles usually have a higher fall velocity than smaller ones. As the settling particles reduce in size, chemical properties of particles and water overcome the physical properties and cause the clumping of fine particles to form larger particles (flocs) which are dropped out more quickly. Fan and Morris (1992) investigated electrochemical properties of fine sediments while interaction of flocs and fluid viscosity on deposition of fine sediments was evaluated by Kranenburg (1999). Morris and Fan (1997) correlated relationships for four distinct stages of consolidation which are beyond the first stage of settling. This study will focus mostly on the first stage.

Stock's law governs the falling velocity of single particles (non-cohesive) where effects of the competition and flocculation of particles in the process of settling are not considered. Based on Stock's law for considering particle size and fluid viscosity, Krone (1963) and Krishnappan (2000) developed equations for estimation of fall velocity of sediment particles. The mathematical models were also correlated with experimental results in order to estimate settling velocity and sediment transport like in Krishnappan and Marsalek (2002). Toniolo and Parker (2003) and Winterwerp (2002) developed 1-D and 3-D models to estimate fall velocity for long term duration of settling of fine sediments in estuarine mud.

The rate of flocculation and falling competition of particles are main sources of uncertainty in the existing particle size based relationships for estimation of settling velocity of fine sediments (Samadi *et al*., 2005). Even for particular sludge water during the settling process, sizes of flocs vary with depth and time. Despite development of the new models for estimation of settling velocity of cohesive sediments, it is still believed that an analytical approach based on time and depth variation of sediment concentration is more accurate in practice than the methods based on sediment particle size. McLaughlin applied this method graphically using artificial sludge water (uniform particle size of hydrated aluminum silicate in water) in a short column (Simons and Senturk, 1992).

Since, the cohesive sediments receive particular attention near large dam walls, the method is used to estimate depth and time variation of fall velocity for real cohesive sediments any time after a density current event with a particular sediment concentration reaches a dam wall. In nature, real cohesive sediments contain silt and clay with large variety in particle size. This may result in considerable changes in their characteristics compared to ideal cohesive sediment as were studied by McLaughlin. Even geographic location of sediments should be considered in the analysis. The sludge water in this study was obtained from the vicinity of the Dez Dam wall in order to represent characteristics of fine sediments in arid and semi-arid zones.

MATERIALS AND METHODS

Dez Dam Site

The Dez Dam Project in Southwest of Iran, located in a semi-arid zone was completed in 1962 and consists of a 203 m high double curvature arch dam and a 60 km long reservoir. Since completion, the sedimentation in the reservoir has taken up about 20% of the initial reservoir volume of 3,316 million m^3. The sediment drops out along the upper reaches to form a delta, which is slowly progressing to the dam and the bottom set beds of fine sediment are raising adjacent to the dam face. The fine sediment is brought to the dam face by highly concentrated turbidity currents which occur four to six times annually during short-term rainstorms over the watershed (Fathi-Moghadam *et al*., 2008). Recent studies related to extending reservoir life have ranked the option of turbidity current flushing through low-level outlets as a promising option. In order to identify the magnitude and frequency of turbidity currents along the reservoir a measurement program was undertaken during the wet season of January to May, 2003. The largest event of April 23-24 for that year had 1,188,500 m^3 of density current with average sediment concentration of 7 g L^{-1}. The analysis of the results for 26 years before 2003 indicated an annual turbidity current of about 2,243,200 m^3 year^{-1} with sediment concentration up to 30 g L^{-1} for Dez Dam reservoir. They found the extension of reservoir life by flushing of turbidity currents would not be large, but could be economically viable provided that downstream environment guidelines could be adhered to Samadi and Galay (2005). Sediments trapped near Dez dam wall are classified as cohesive with 55% silt and 45% clay. Hamm and Migniot (1994) showed even silt particles with a diameter less than 0.03 mm have reasonable properties of cohesive sediments.

Theory

Using a settling column, total derivative of particle concentration (C) as function of time (t) and vertical distance (z) from a datum line is:

$$dC_{(z,t)} = \frac{\partial C}{\partial z}dz + \frac{\partial C}{\partial t}dt \qquad (1)$$

and time and depth variation of concentration for calculation of falling velocity will be (Simons and Senturk, 1992).

$$\frac{dC_{(z,t)}}{dt} = \frac{\partial C}{\partial t} + \frac{\partial C}{\partial z}\cdot\frac{dz}{dt} = 0 \qquad (2)$$

Let, $dz/dt = \overline{w}_{(z,t)}$ = Local mean fall velocity of particles and integrating Eq. 2, the $\overline{w}C$ at any water depth (d) will be:

$$(\overline{w}C)_{z=d} = -\int_0^d \frac{\partial C}{\partial t}dz = -\frac{\partial}{\partial t}\int_0^d C dz \qquad (3)$$

and fall velocity of particles at any time and depth is:

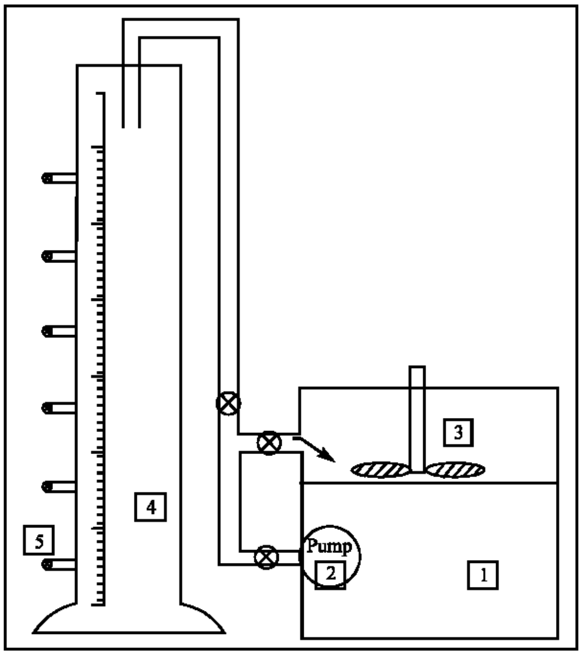

Fig. 1: Experimental setup, (1) storage tank (0.4 m^3) for mixing water and sediment with desirable density, (2) pump to deliver water to settling column, (3) a mixer connected to appropriate electric motor, (4) plexy glass settling cylinder, 3 m height and 0.3 m diameter and (5) sampling outlets, 0.3 m apart

$$(\bar{w})_d = -\frac{\dfrac{\partial \int_0^d C dz}{\partial t}}{C} \tag{4}$$

The integration in Eq. 4 measures Cz in distance 0 to d between two subsequent times.

Experimental Setup

A plexy glass column with 3.0 m height and 0.30 m diameter was used in this study to determine fall velocity of the cohesive sediments of the Dez dam reservoir (Fig. 1). Tests were conducted at the Hydraulics Laboratory of Chamran University of Ahvaz, 200 km south of the dam site. The sludge water for tests was collected from the muddy layer of the reservoir near the dam wall around the low level outlets. The low level outlets are 120 m below the normal water surface and were initially designed to control irrigation water downstream of the dam. They have been blocked by cohesive sediments for about 10 years now. The Master Sizer designated the texture of the sludge water as 55% silt and 45% clay. Using the collected sludge water, concentration rates of 5 and 17 g L^{-1} were prepared in a 0.40 m^3 storage tank and mixed well before being pumped into the testing column (Fig. 1). The concentration rates were selected to represent reasonable ranges of density current events. Water samples were taken at 8 depths along the column through outlets 0.3 m apart, in time intervals of 3, 5, 15, 30, 60, 120, 240 and 480 min starting when water was discharged into the column. To calculate the percentage of sediment concentration, the samples were weighted immediately after being taken from the column and after 24 h of being dried in oven. The measurements for variation of time, depth and sediment concentration were used to construct the curves and calculate the falling velocity as shown in Eq. 4.

Table 1: Depth variation of concentration at t = 15 min (C = 5 and 17 g L^{-1})

Initial concentration C (g L^{-1})	Depth (cm)	Sediment weight (g)	Sludge volume (cm^3)	Particle concentration (g L^{-1})
5	30	0.121	62.272	1.943
	60	0.233	54.828	4.250
	90	0.319	72.667	4.390
	120	0.343	77.884	4.404
	150	0.273	61.828	4.422
	180	0.325	73.298	4.434
	210	0.335	73.771	4.541
	240	0.350	75.646	4.627
	Reference sample	1.072	219.391	4.886
17	30	0.786	67.513	11.642
	60	1.175	71.672	16.394
	90	1.638	99.774	16.417
	120	1.404	84.171	16.680
	150	2.187	130.955	16.700
	180	1.714	102.585	16.708
	210	1.651	98.779	16.714
	240	1.480	88.499	16.723
	Reference sample	3.539	209.543	16.889

Results of particle concentration after 15 min of sampling from depths of 0.30, 0.60, 0.90, 1.20, 1.50, 1.80, 2.10 and 2.40 m for the sludge water with initial concentrations 5 and 17 g L^{-1} are shown in Table 1. Similar tables were constructed for the elapsed times of 3, 5, 15, 30, 60, 120, 240 and 480 min.

RESULTS AND DISCUSSION

Fine sediments delivered by rivers normally travel more distance along the reservoir and settle near the dam wall. This is undesired in large and multipurpose dams as the intakes to the powerhouse and other water demand control outlets in or adjacent to the dam wall are under blockage threat. As a major parameter for reservoir sediment management (sediment transport, trap efficiency, sedimentation and consolidation), the fall velocity of cohesive sediments near the Dez dam wall was estimated using a settling column. Due to the fact that field samples contain particles with considerable size variation, time and depth variation of sediment concentration were used to estimate mean settling velocity.

Using Table 1, time variation of concentration for various depths has been compared in Fig. 2 for initial particle concentrations of 5 and 17 g L^{-1}. The curves merge together in a much longer time for the denser sludge waters as a result of a balance between process of fluctuation and particle competition.

Using Table 1 and the rest of the time difference tables for the initial concentration of 5 g L^{-1}, the percentage of particle concentration (relative to the initial concentration) for all sampling depths were calculated and sketched in Fig. 3a for every sampling time step. Similar is done for 17 g L^{-1} in Fig. 3b and the rest of the sludge waters with different initial concentrations. The curves can be used to identify texture and other physical and chemical properties of the deposited sediments in a particular time and place. The correlation of the data can result determination of the sediment ability to flocculate and even the floc size. For example, the larger percentage of the sediment examined in this study were silt and flocculated particles which traveled more than 2 m in the first hour for the initial concentration of 5 g L^{-1}. For 17 g L^{-1}, almost twice the time was required due to elongation of the process of flocculation and particle fall competition. For the considerably low part of the sediments which are very fine, more time is required for evaluation of fall velocity.

The integration of Cdz in Eq. 4 can be obtained from the area under the curves from 0 to any distance z for a particular time. Time variation of this integral is the difference in the measured areas

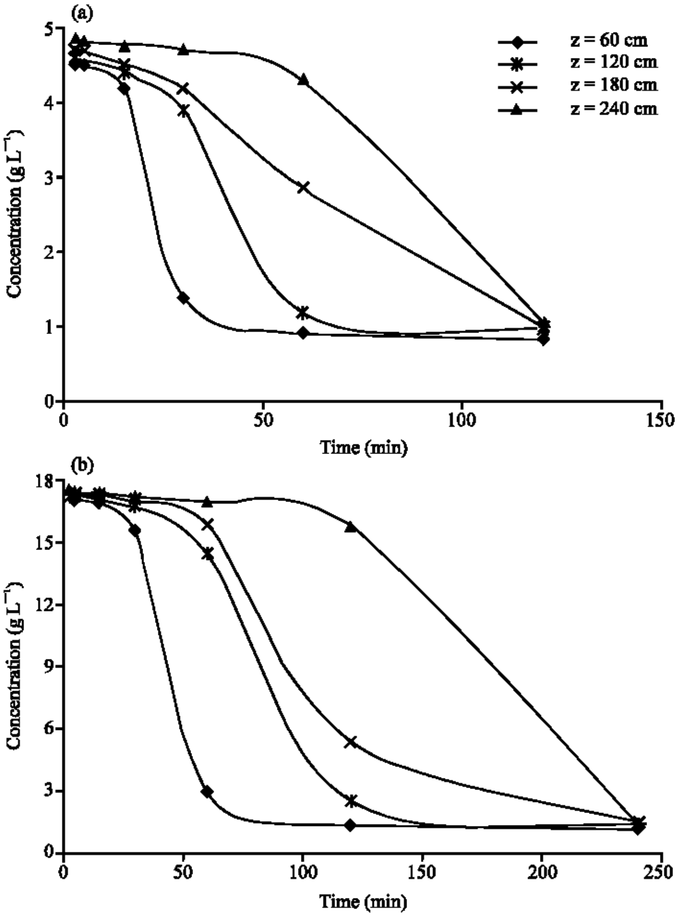

Fig. 2: Time and depth variation of particle concentration (a) 5 g L^{-1} and (b) 17 g L^{-1}

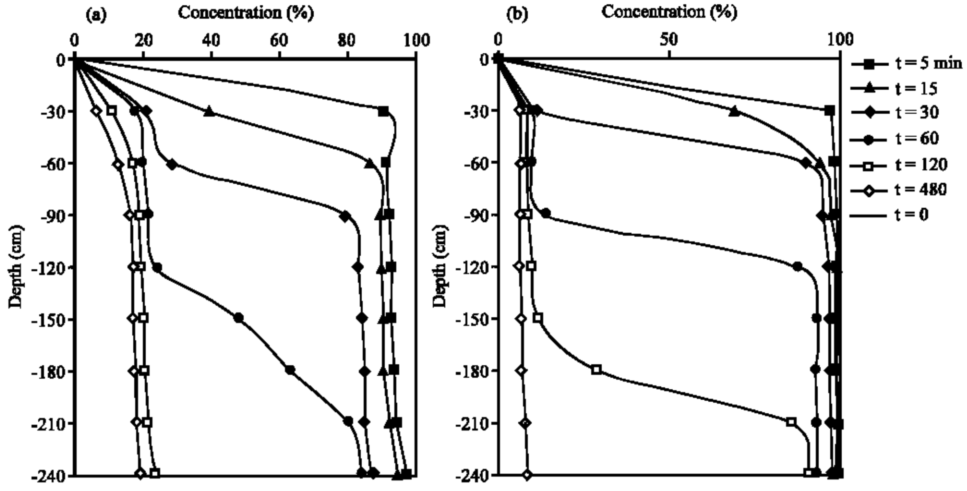

Fig. 3: Depth variation of particle concentration with time, (a) 5 g L^{-1} and (b) 17 g L^{-1}

Table 2: Area under curves $\left(\partial\int_0^d Cdz/\partial t\right)$ for initial concentrations 5 and 17 g L^{-1}

C (g L^{-1})	Depth (cm)	Time (min)						
		3	5	15	30	60	120	240
5	30	-9.09	-84.13	-77.17	-6.35	-2.00	-0.08	-0.27
	60	-19.77	-95.61	-145.70	-40.94	-2.56	-1.58	-0.41
	90	-28.86	-179.70	-222.90	-47.29	-4.56	-2.38	-0.68
	120	-48.63	-275.30	-368.50	-88.23	-7.12	-3.96	-1.09
	150	-77.49	-455.10	-591.40	-135.50	-11.68	-6.34	-1.76
	180	-126.10	-730.40	-960.00	-223.70	-18.79	-10.31	-2.85
17	30	-8.49	-44.95	-66.08	-40.39	-0.64	-0.29	-0.04
	60	-15.69	-48.97	-78.63	-121.20	-1.34	-0.59	-0.07
	90	-24.19	-93.91	-144.70	-161.60	-1.98	-0.88	-0.12
	120	-39.88	-142.90	-223.30	-282.90	-3.32	-1.47	-0.19
	150	-64.06	-236.80	-368.10	-444.50	-5.31	-2.34	-0.30
	180	-103.90	-379.70	-591.40	-727.40	-8.63	-3.81	-0.49

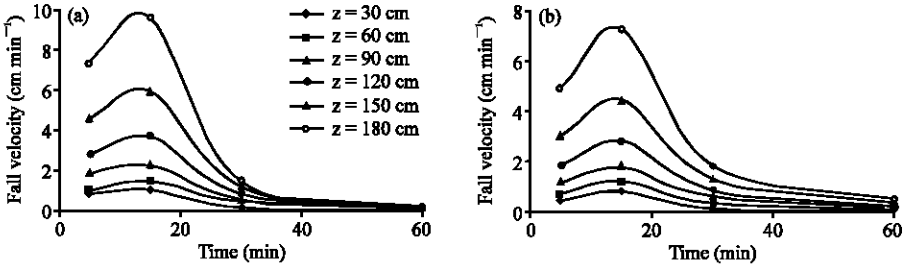

Fig. 4: Fall velocity of the sludge water collected near the Dez dam wall, (a) 5 and (b) 17 g L^{-1}

from time to time for the same distance (Fig. 3). Table 2 shows time variation of this integration for the initial sludge water with 5 and 17 g L^{-1}. Using Table 2 and initial concentration (C), the representative fall velocity for any distance z and time interval t is calculated from Eq. 4. The calculated fall velocities are shown in Fig. 4a, b for sludge waters with initial particle concentrations of 5 and 17 g L^{-1}. These concentrations were selected to show considerable effect of density on fall velocity while being more convenient to work with in practice. To assume column is endless, fall velocities below the 180 are not considered in the analysis.

For the lower concentration (5 g L^{-1}), the maximum fall velocity in all depths accrued in the same time around 15 min after beginning of the experiments. This may explain the low effect of flocculation and particle competition. For higher dense water (17 g L^{-1}), the recession side of the curves has shifted to the right as a result of higher rate of flocculation. Also, all the curves showed that particles in deeper parts of the column have higher falling velocities. This is due to higher rate of flocculation as a result of having higher concentration than in shallow parts. This result along with the range of calculated fall velocities in Fig. 4 are in accordance with McLaughlin's results (Simons and Senturk, 1992). The difference in curves and considerable increase in fall velocity to those reported by McLaughlin is due to particle size variation and large quantity of silt particles in the test samples which are particular properties of cohesive sediments near the wall of large dam reservoirs. Mehta *et al*. (1982) showed that when particle and floc concentrations exceed 5-10 g L^{-1}, the fall velocity will be reduced. This is correct for maximum fall velocity as observed in Fig. 4b when, it is being compared with the lower concentration of 5 g L^{-1} curves in Fig. 4a. But it should be noted that curves in Fig. 4b will remain in higher fall velocities for a much longer duration as result of flocculation.

CONCLUSIONS

Time and depth variation of particle concentrations in a column were used to estimate the fall velocity of fine sediment deposited in the Dez dam reservoir near the dam wall. The tested samples can be considered as representative of the natural cohesive sediment in large dam reservoir in arid and semi-arid environments. The column was long enough to allow the falling velocity to reach a steady state. The constructed curves for time and depth variation of concentration are capable of estimating the texture and settling properties of the fine sediments. Using the results of this study for a density current when reaches a large dam wall with a particular concentration, the time and depth variation of fall velocity can be estimated. This receives particular interest for evaluation of the reservoir capacity and sediment trap efficiency. The estimated fall velocities lay well among the estimated fall velocities by McLaughlin while the maximum fall velocities were in accordance with Mehta *et al*. (1982) and Mehta (1993). The lower concentration samples showed to have higher maximum fall velocities than higher concentration samples but for a much shorter duration. This is due to lower falling competition of particles. For lower particle concentration, the maximum fall velocity for all depths occurred after 15 min while it seems to have delayed as initial concentration increases. However, it is believed that more data is required for the development of a relationship for estimation of fall velocity of cohesive sediments for the dam reservoirs in arid and semi-arid environments.

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