Wastewater Effect on the Deposition of Cohesive Sediment

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Abstract: In this study, the characteristics of sediment deposition with three levels of wastewater, different shear stress, and initial sediment concentration were investigated in an annular flume. Sediment used for experiments was taken from the Pirbalut small dam reservoir, located in southwest Iran. The velocity and the shear stress profiles were measured, using an acoustic Doppler velocimeter (ADV). The results showed that the concentration of cohesive sediment decreased with time, and finally it reached an equilibrium concentration of sediment. The ratio of equilibrium concentration to initial concentration (C_{eq}:C) with a constant shear stress, for different initial sediment concentrations and different levels of wastewater were almost the same. The equilibrium concentration depends on the initial concentration sediment. Adding wastewater to the mixture caused the increasing of threshold and full deposition shear stress. The critical shear stresses for full deposition for three wastewater levels of 0, 30, and 60% are obtained as 0.050, 0.081, and 0.084 $\mathrm{N/m^2}$, respectively. **DOI: 10.1061/(ASCE)EE.1943-7870.0001270.** *© 2017 American Society of Civil Engineers.*

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Introduction

Because of the outlined importance of sedimentation, the hydraulic behavior of cohesive sediments has been a subject of concern and investigation since the inception of the field of hydraulic engineering. Cohesive sediment grains, which range in size from 50 μm to a small fraction of 1 μm, are subjected to a set of attractive and repulsive forces of electrochemical and atomic nature acting on their surfaces and within their mass (Haralampides et al. 2003). These forces are the result of the mineralogical properties of the sediment and of the adsorption of ions on the particle surfaces (Partheniades 2009). When, under certain conditions, the attractive forces exceed the repulsive ones, colliding particles stick together, forming agglomerations known as *flocs*, with size and settling velocities much higher than those of the individual particles. This phenomenon is known as *flocculation*. In a flocculated cohesive sediment suspension, the settling unit is the floc rather than the individual particle (Partheniades 2009). In channel flow condition, according to different values of bed-shear stress, two types of deposition (i.e., full and partial deposition) for cohesive sediments are defined. When the bed-shear stress is smaller than the critical shear stress, full deposition occurs; in this case, all sediment particles and flocs are deposited (Krone 1962). When the bed-shear stress is greater than the critical shear stress, partial deposition takes place.

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A number of investigators used circular flumes for studying the transport of cohesive sediments (e.g., Partheniades and Kennedy 1966; Mehta and Partheniades 1973; Fukuda and Lick 1980; Sheng 1988; Delo 1988; Lau and Krishnappan 1994). These flumes essentially consist of two components: a circular channel and an annular cover plate (ring) that fits inside the channel. In some installations, both components were rotated in opposite directions (Partheniades 2009; Mehta and Partheniades 1973); in others, only the ring was rotated while the flume was held stationary. Experimental observations of Partheniades (2009) and Mehta and Partheniades (1973) suggest that in circular flume assemblies in which only the ring is rotated to generate the flow, the secondary circulations resulting from the centrifugal force could be of substantial strength; hence, using such assemblies for basic studies of cohesive sediment dynamics may be questionable.

Determination and prediction of critical shear stresses for full and partial depositions are not exactly possible. However, it is interesting to note that the accuracy of deposition models primarily depends on their correct values. Many experiments were performed to determine the values of critical shear stress for full deposition of cohesive sediments (Maa et al. 2008).

Krone (1962) performed a series of flume experiments to determine the critical shear stress for full deposition. These experiments were done with San Francisco Bay's sediments, and the critical shear stress obtained for full deposition were 0.06 and 0.078 $\mathrm{N/m^2}$ for sediment concentration of less than 0.3 g/L and greater than 0.3 g/L, respectively.

Mehta and Partheniades (1973) found that critical shear stress for full deposition for kaolinite in distilled water is 0.15 $\mathrm{N/m^2}$. From the flume experiments of Krishnappan and Stephens (1996), the critical shear stress for deposition of Athabasca River sediment was estimated to be 0.10 $\mathrm{N/m^2}$. The critical shear stress for cohesive sediments is relatively small and is usually between 0.06 and 1.1 $\mathrm{N/m^2}$, depending upon the sediment type and its concentration (Huang et al. 2006).

Adding a chemical solution in a mixture of water and sediment changes the physicochemical of the sediments, and the flocculation of the clay particles may increase or decrease. Today, in many countries, the wastewater is used for irrigation sector as an additional water resource (Samadi-Boroujeni 2004). The present study focuses on the effect of urban wastewater on cohesive sediments transport to improve water quality and manage the irrigation systems.

In this study, some experiments were carried out in annular flume using a mixture of cohesive sediment and water with a combination of three levels of wastewater for evaluating their effects on the deposition of cohesive sediments.

Experimental Equipment and Procedure

Rotating Flume

The deposition characteristics of fine sediments were studied in a rotating circular flume located at the Hydraulics Laboratory of Shahrekord University, Iran. The flume is circular and is made of galvanized steel with a Plexiglas window. The flume has a mean diameter of 4.72 m, is 0.30 m wide and 0.47 m deep, and rests on a rotating platform that is 1.9 m in diameter. An annular top cover, called the ring, fits inside the flume, makes contact with the water surface, and can be rotated in both directions. Bed-shear stresses can be controlled by changing the rotational speeds of the flume and its rotating ring. To measure concentration of suspended solids in the water column, 16 sampling valves were installed in four different positions of the flume at heights 5.3, 10.5, 18.3, and 25 cm from the bottom. The flume has two separate electromotors, which are used to rotate the flume and the rotating ring. The flume and its ring can rotate in opposite directions (Fig. 1).

The flow in the flume is caused by rotation around the flume axis, so pumping is not needed. This is the advantage of rotating channels with respect to straight channels, because in these flumes only flow-induced shear stress affects the sediment, and external factors induced by the pump are neglected. In contrast with straight channels, rotating flumes require less space owing to their circular nature. In other words, a rotating flume can be considered as a straight channel with infinite length. To reduce the secondary flow and create uniform distribution of shear stresses across the flume width, the flume and its ring rotate in opposite directions. According to earlier research, for creating a uniform distribution of shear stresses across the width, the ratio of rotational speed of the ring to that of the flume should be greater than one ($N_r/N_f > 1$). Partheniades (2009) stated that if the rotation speed of the flume and its ring are chosen correctly, velocity profiles in rotating flumes will be similar to straight open channels.

To determine the appropriate ratio of rotational speed of the ring to the flume, velocity and shear stress profiles were measured in the rotating flume, using an acoustic Doppler velocimeter (ADV). The velocity was measured at five horizontal and four vertical points, spaced 5 cm from each other, at the flow cross section of the flume (5-cm interval). Experiments were also conducted for different ratios of rotational speed of the ring to the flume. The results showed that secondary rotations are minimized, and shear stress is uniform across the flume width when the ratio of rotational speed of ring to flume is chosen at 1.1 ($N_r/N_f = 1.1$). In this case, based on the obtained results, velocity profiles in the rotating flume were similar to flow pattern in straight channels. Krishnappan and Engel (2004) stated that this ratio is 1.17, for a rotating flume with a 12-cm depth.

Fine Sediments Used in Experiments

In this investigation, fine sediments from the Pribalut dam reservoir were used for experiments. The dam is located in the northern Karun Basin, Iran, with Universal Transverse Mercator coordinate system (UTM) geographic coordinates $X = 4{,}713{,}116$ m and $Y = 3{,}586{,}402$ m. The location of the dam and the field area is shown in Fig. 2(a). These fine sediments contain 63.2% silt and 36.8% clay. The sediment size distribution is shown in Fig. 2(b). The liquid limit (LL), plastic limit (PL), and plasticity index of the sediment was determined based on the ASTM D423 standard (ASTM 1972). The test showed that LL, PL, and plasticity index are 48.0, 37.2, and 10.8%, respectively.

Wastewater Used in Experiments

Wastewater used in the experiments was taken from Shahrekord wastewater treatment plant outlet, which is located south of Shahrekord city, Iran. The concentration of some principal dissolved elements in the treated wastewater, which were measured in the Shahrekord University analysis laboratory, is shown in Table 1.

Experimental Procedure

The tests were carried out for five bed-shear stress conditions, three different initial sediment concentrations, and three levels of wastewater. The shear stresses were chosen in a way that at minimum and maximum shear stresses, 80 and 20% of sediments were deposited, respectively, for different levels of wastewater and sediment concentration. First, ADV was used to measure vertical velocity and shear stress distributions, and based on these measurements, the relationship between hydraulic parameters and the flume rotational speed was obtained. Then, sediment and water mixture with a given initial concentration by weight was prepared and was transferred to the flume. To mix water and sediment completely, the flume and its ring were rotated in opposite directions at their maximum speeds, i.e., 14.8 and 16.2 rpm (shear stress is equal to 11.2 $\mathrm{N/m^2}$), respectively, for 30 min. Then, the speed of the flume and its ring was lowered to reach a rotation speed providing the desired bed-shear stress. All experiments were done for a period of 240 min; meanwhile, the test samples were collected in a sampling interval of 15 min during the first hour and 30 min thereafter. The samples were taken from depths 5.5, 10.3, and 18.3 cm from the bottom; then, sample concentrations were measured by the drying and weighting method (ASTM 1997).

Results and Discussion

Hydraulic Parameters

Fig. 3 shows vertical velocity distribution for five linear velocities of the flume (with depth average velocities of $V_1 = 13.9$, $V_2 = 18.8$, $V_3 = 23.7$, $V_4 = 26.8$, and $V_5 = 33.8$ cm/s), and $\alpha = 1.1$. Relative flow velocity is defined as flow velocity at any point to depth average velocity. As Fig. 3 shows, the velocity profile has an S shape for all flume velocities, i.e., it increases, then decreases, and finally increases and agrees with Partheniades (2009). Fig. 3 also shows that velocity fluctuates highly near the walls, and the fluctuations decrease in the central part of the flume. The velocity gradient is almost negligible far away from the bed and the ring.

A relationship between the average flow velocity and the rotational speed of the flume and the ring was obtained using regression

$$V = 19.024 \ln(\omega) - 5.3 \quad R^2 = 0.98 \tag{1}$$

where V = average velocity (m/s); and ω = total rotational speed of the flume and the ring (rpm). Experimental and theoretical studies of

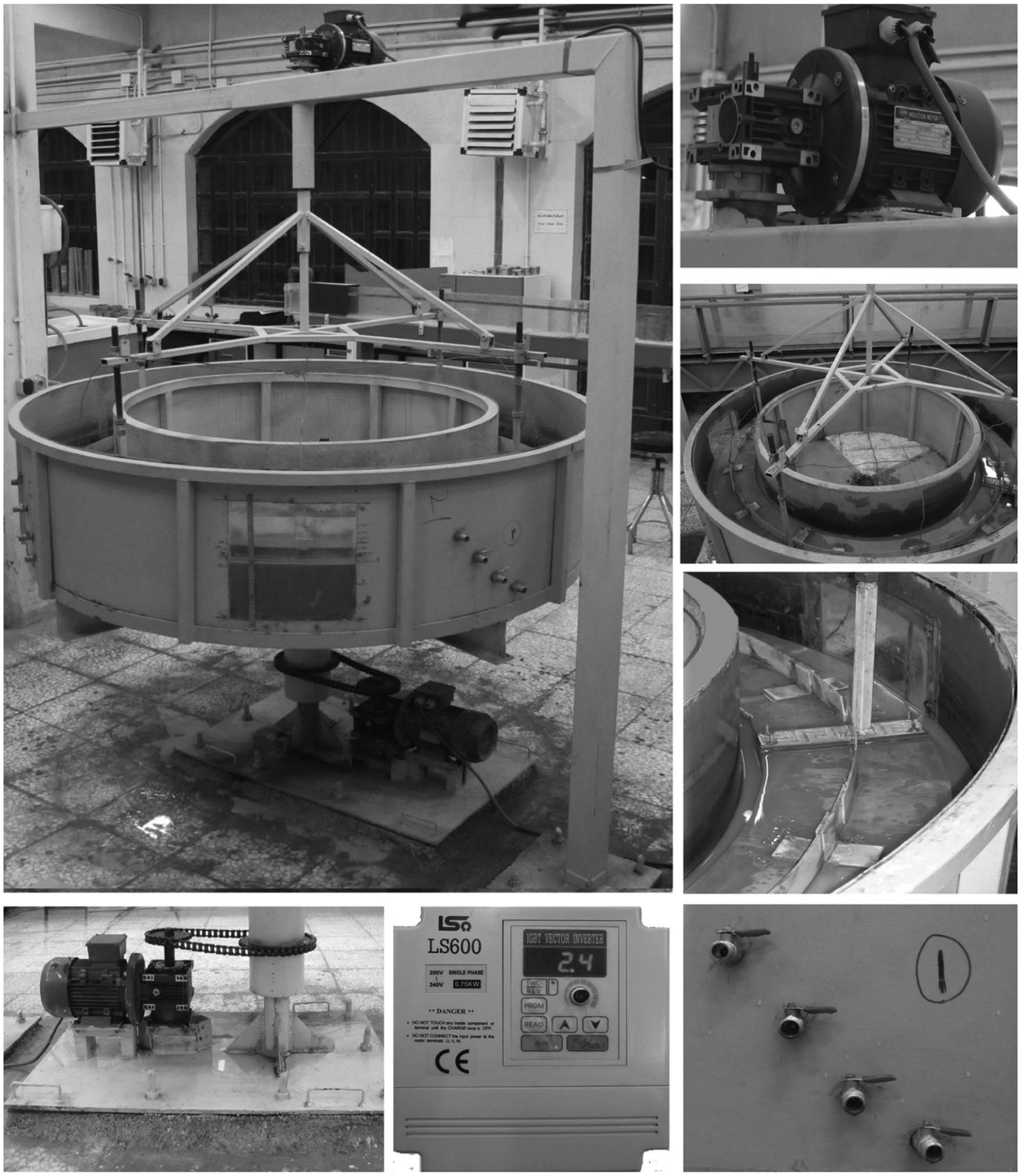

Fig. 1. Rotating flume assembly

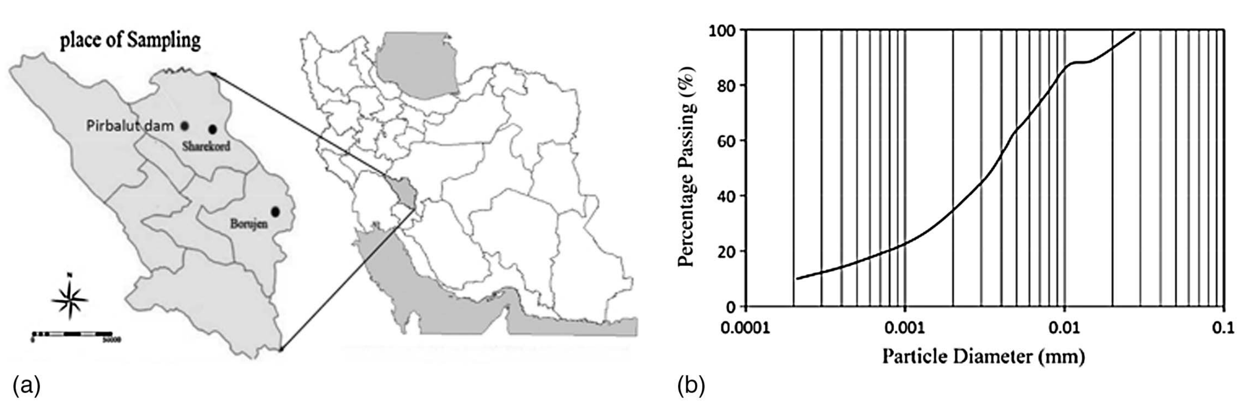

Fig. 2. (a) Location of Pirbalut dam; (b) sediment gradation curve

Table 1. Concentration of Some Principal Dissolved Elements in the Wastewater Used in Experiments

Parameter	Unit	Value	
		Wastewater	Water
pH	—	7.89	7.6
BOD	mg/L	18.45	1.26
COD	mg/L	30	7.1
Total dissolved solids (TDS)	mg/L	442	285
Electrical conductivity (EC)	ds/m	0.775	0.343
Sodium adsorption ratio (SAR)	$(\mathrm{mmol/L})^{1/2}$	1.66	0.338
Calcium (Ca)	mg/L	65.44	2.3
Magnesium (Mg)	mg/L	16.66	0.5
Sodium (Na)	mg/L	2.52	0.4
Potassium (K)	mg/L	2.64	0.1
Chloride (Cl)	mg/L	85	0.5
Nitrates (NO_3)	mg/L	15.48	5.3

Note: BOD = biochemical oxygen demand; COD = chemical oxygen demand.

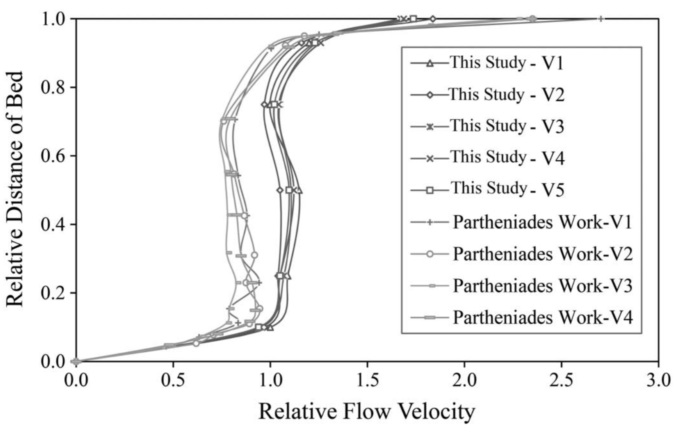

Fig. 3. Vertical velocity profiles in rotating flume ($\alpha = 1.1$), compared with the results of Partheniades (2009)

flow in rotating circular flumes showed that the flow field was two-dimensional with almost constant bed-shear stress across the flume width (Milburn and Krishnappan 2003). Therefore, the covariance of temporal velocity in the xz-plane was used in determining the shear stress, and a relationship was obtained between the bed-shear stress and the rotational speed of the flume and the ring as

$$\tau = 0.0228\omega^{1.8554} \quad R^2 = 0.99 \tag{2}$$

where τ = bed-shear stress ($\mathrm{N/m^2}$); and ω = total rotational speed of the flume and the ring (rpm). Ha and Maa (2009) also found an exponential relationship between the shear stress and the rotational speed of the flume.

Variations of Suspended Sediment Concentration with Respect to Time

The results showed that partial deposition occurs in this study. In all cases, during the first 15 min, the sediment concentration drops suddenly and then decreases gradually to reach its equilibrium concentration. This equilibrium concentration is a function of the initial sediments concentration and the bed-shear stress. For example, Fig. 4 demonstrates the sediment concentration for a case in which the initial sediments concentration is 10 g/L and wastewater levels are 60%, 30%, and 0.

Equlibrium Sediment Concentration

Results showed that in a constant shear stress, the ratio of equilibrium sediment concentration to initial sediment concentration is almost constant. In addition, the equilibrium concentration is totally dependent on the initial concentration. Fig. 5 shows variations of the sediment concentration versus time with different wastewater levels. Because only a fraction of sediments form strong flocs, the remaining part is a function of the initial concentration. The flocs are loose at samples with high sediment concentration. Therefore, equilibrium concentration would be large at these samples.

The ratio of equivalent concentration to initial concentration is shown in Table 2 for three wastewater levels and different initial concentrations. Fig. 6 shows the deposition fraction with respect to time for three wastewater levels. Table 2 and Fig. 6 both show the ratio of the equilibrium concentration to the initial concentration, C_{eq}:C_0, is almost constant in many conducted experiments with different wastewater levels and with a specific shear stress. This means the deposition fraction is constant for different wastewater levels and with a specific shear stress.

Fig. 7 shows variations of the average ratio of the equilibrium sediment concentration to the initial sediment concentration versus the bed-shear stress for three wastewater levels. The equilibrium sediment concentration decreases as the wastewater level increases; however, the curves at wastewater levels of 30 and 60% are closed together. Similar results are obtained for other values of shear stress.

The following relationships were obtained between C_{eq}:C_0 and the shear stress using regression for each wastewater level

$$\text{For } W_0\text{: } \frac{C_{eq}}{C_0} = 0.2978\ln(\tau) + 0.9974 \quad R^2 = 0.99 \tag{3}$$

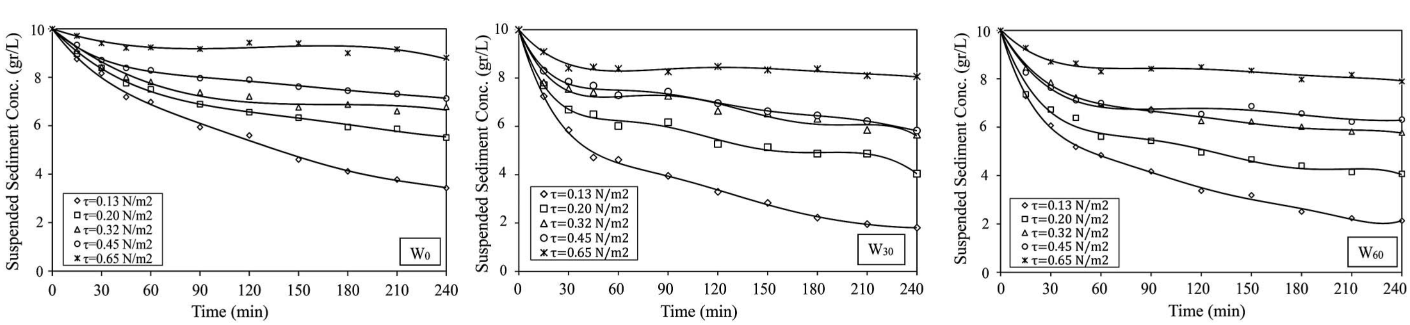

Fig. 4. Variations of suspended sediment concentration versus time for three wastewater levels and initial concentration 10 g/L

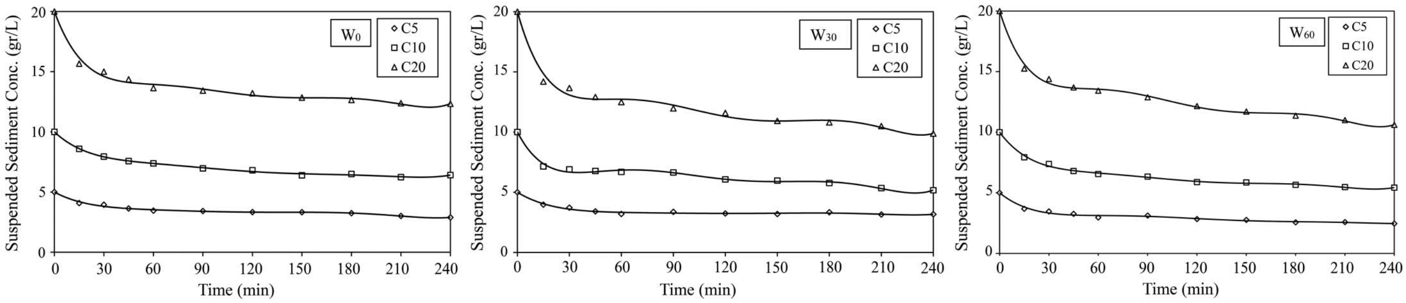

Fig. 5. Variations of sediment concentration versus time with different wastewater level

$$\text{For } W_{30\%}\colon \frac{C_{eq}}{C_0} = 0.3403\ln(\tau) + 0.9575 \quad R^2 = 0.96 \tag{4}$$

$$\text{For } W_{60\%}\colon \frac{C_{eq}}{C_0} = 0.3353\ln(\tau) + 0.9307 \quad R^2 = 0.97 \tag{5}$$

In some of the experiments, the suspended sediment concentrations had not reached an equilibrium value at the end of the test (240 min). Thus, the data obtained from these tests were not used in the regression analysis. Also, Fig. 8(a) compares observed and predicted values of C_{eq}:C_0 and illustrates that the model has a good performance in predicting the equilibrium sediment concentration. The variations of C_{eq}:C_0 versus the shear stress are shown in Fig. 8(b) for both observed and predicted data, demonstrating that the model has a low error in predicting the equilibrium sediment concentration.

Table 2. Ratio of the Equilibrium Concentration to the Initial Concentration for Different Wastewater Levels and Shear Stresses

Descriptions	Concentration (g/L)	Shear stress (N/m^2) 0.13	0.20	0.32	0.45	0.65
Water containing 0% wastewater	5	0.381	0.501	0.613	0.760	0.836
	10	0.360	0.569	0.669	0.722	0.898
	20	0.329	0.558	0.681	0.750	0.868
Water containing 30% wastewater	5	0.253	0.477	0.615	0.690	0.822
	10	0.188	0.445	0.575	0.602	0.808
	20	0.183	0.453	0.582	0.685	0.802
Water containing 60% wastewater	5	0.219	0.469	0.527	0.607	0.854
	10	0.218	0.411	0.580	0.627	0.803
	20	0.231	0.435	0.567	0.634	0.753

Critical Shear Stress for Deposition

As stated in the introduction, two types of critical shear stress (i.e., shear stress for full and partial deposition) are considered for the deposition of cohesive sediments. At critical shear stress for partial deposition, the ratio of the equilibrium concentration to the initial concentration is one ($C_{eq}/C_0 = 1$). At the critical shear stress for full deposition, all sediment particles will be deposited. In this case, C_{eq}:C_0 approaches zero. According to the value of critical shear stresses, full and partial deposition may occur. The value of full and partial deposition can be obtained using Eqs. (3)–(5), and the results are shown in Table 3. The results showed that the wastewater increases critical shear stresses for both full and partial deposition. In other words, the sediments in wastewater partially deposit in larger shear stress than in clean water, and

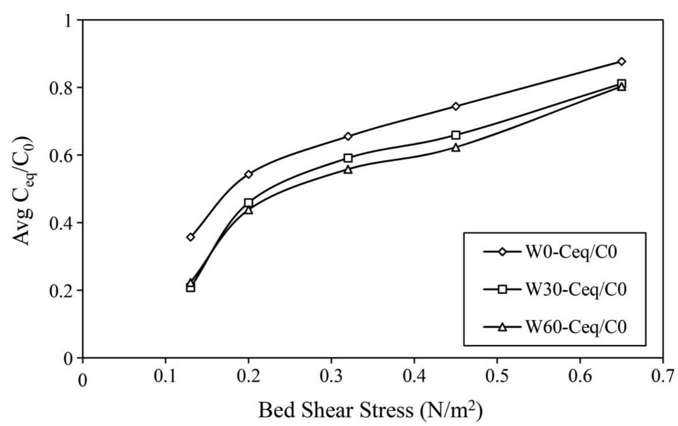

Fig. 7. Variations of the average ratio of the equilibrium concentration to the initial concentration versus the bed-shear stress for three wastewater levels

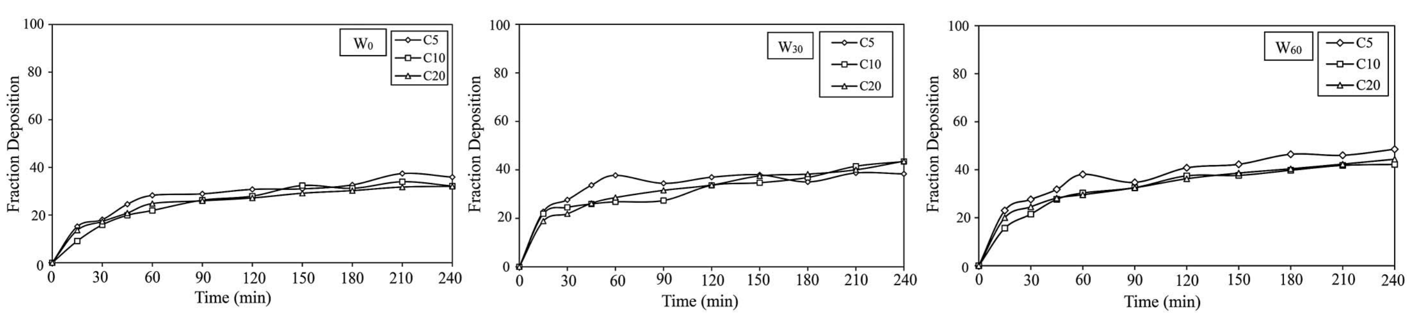

Fig. 6. Variations of the deposition fraction versus time for different wastewater levels and with $\tau = 0.32\ N/m^2$

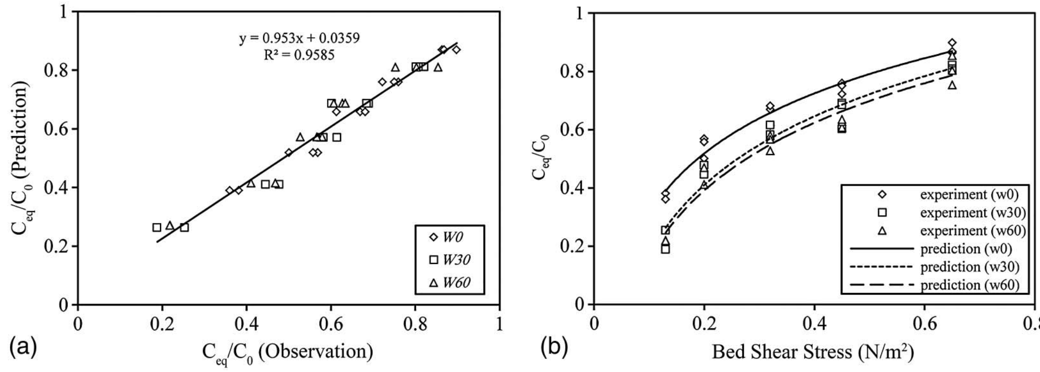

Fig. 8. (a) Observed C_{eq}/C_0 versus predicted C_{eq}/C_0; (b) predicted and observed C_{eq}/C_0 versus bed-shear stress

Table 3. Critical Shear Stresses for Partial and Full Deposition for Different Levels of Wastewater

Description	No wastewater (W_0)	30% wastewater (W_{30})	60% wastewater (W_{60})
Critical shear stresses for partial deposition (N/m^2)	1.01	1.19	1.23
Critical shear stresses for full deposition (N/m^2)	0.050	0.081	0.084

the sediments in wastewater fully deposit in larger shear stress than in clean water. It is the reason why the sediment diameter increases, or flocs become strong against the shear stress in wastewater. Therefore, it is necessary to consider critical shear stress for wastewater in designing open channels. In each of the wastewater levels, the differences between full and partial deposition critical shear stresses are significant.

Sediments Deposition Fraction

Fig. 9 shows the sediment deposition fraction versus the ratio of bed-shear stress to critical shear stress for different wastewater levels. When the bed-shear stress is smaller than the critical shear stress, sediments can deposit; on the other hand, deposition fraction will decrease as the bed-shear stress increases. For the wastewater levels (0, 30, and 60%) when shear stress is equal to 21, 15, and 15 times the critical shear stress, respectively, deposition fraction is zero, and all sediments remain suspended.

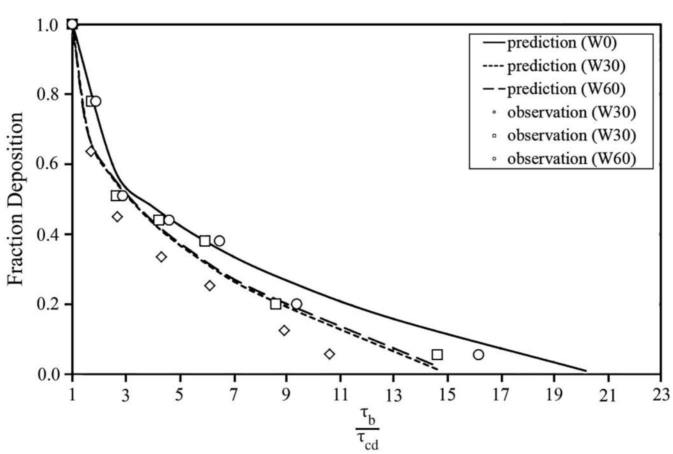

Fig. 9. Sediment deposition fraction versus the ratio of bed-shear stress to critical shear stress for different wastewater levels

Because the critical shear stress for full deposition is determined, an equation is obtained to describe deposition fraction as a function of the ratio of the bed-shear stress to the critical shear stress for different wastewater levels as follows:

$$\text{For } W_{0\%}: f_d = 1 - 0.36\left(\frac{\tau_b}{\tau_{cd}} - 1\right)^{0.34} \quad 1 < \frac{\tau_b}{\tau_{cd}} < 21 \tag{6}$$

$$\text{For } W_{30\%}: f_d = 1 - 0.39\left(\frac{\tau_b}{\tau_{cd}} - 1\right)^{0.35} \quad 1 < \frac{\tau_b}{\tau_{cd}} < 15 \tag{7}$$

$$\text{For } W_{60\%}: f_d = 1 - 0.38\left(\frac{\tau_b}{\tau_{cd}} - 1\right)^{0.36} \quad 1 < \frac{\tau_b}{\tau_{cd}} < 15 \tag{8}$$

where f_d = deposition fraction; τ_b = shear bed stress; and τ_{cd} = critical shear stress for full deposition. For the case in which $\tau_b/\tau_{cd} \leq 1$, values of $f_d = 1$. The predicted values are shown in Fig. 9 with solid lines. Eqs. (6)–(8) show that τ_b/τ_{cd} reduce as the wastewater level increases. Therefore, the deposition fraction of suspended sediments in wastewater occurs in a smaller ratio of the bed-shear stress to the critical shear stress than in clean water. Milburn and Krishnappan (2003) obtained that the critical shear stress for full deposition is 0.8 N/m^2 for Hay River's sediment and obtained the following relationship for fraction deposition:

$$f_d = 1 - 0.455\left(\frac{\tau_b}{\tau_{cd}} - 1\right)^{0.57}, \quad 1 < \frac{\tau_b}{\tau_{cd}} < 5 \tag{9}$$

Conclusions

The results show that in a constant shear stress, the equilibrium suspended sediments concentration is large when the initial concentration is large, and wastewater decreases the equilibrium concentration. This may be due to the affecting wastewater chemical characteristic on sediment flocs stability. Moreover, the ratio of equilibrium concentration to the initial concentration is constant for a constant shear stress. Furthermore, wastewater increases the critical shear stresses for both full and partial deposition. The critical shear stresses for full deposition for three wastewater levels of 0, 30, and 60% are obtained as 0.050, 0.081, and 0.084 Pa, respectively. The obtained results also show that for each of the wastewater levels, the differences between full and partial deposition critical shear stresses are significant, but for wastewater levels of 30 and 60%, the differences between full and partial deposition, critical shear stresses are not significant. Finally, relationships between the ratio of bed-shear stress to critical shear stress and deposition fraction were obtained. When τ_b/τ_{cd} is 21, 15, and 15 for the first, second, and third wastewater levels, respectively, all sediment particles remain suspended. The findings from this work are considerable for the case study and the reservoirs that have similar condition. Results may not necessarily be generalized to all of the sites owing to the wide variability in sediment properties across sites.

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