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Effects of suspended sediment concentration and turbulence on settling velocity of cohesive sediment

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ABSTRACT: Using a 5-MHz acoustic Doppler velocimeter (ADV), laboratory experiments were carried out to investigate the effects of suspended sediment concentration (SSC) and turbulence on the settling velocity (w_s) of cohesive sediment. The measurement of w_s with the Clay Bank sediment showed that w_s increased non-linearly with SSC in the range of 300–700 mg L^{-1}, and that turbulence can increase w_s up to one order higher than w_s for non-turbulent conditions. This turbulence effect can explain why w_s derived by ADV is 1 to 3 orders higher than w_s estimated by Owen tube where the ambient turbulence is totally blocked. When the turbulent shear stress was higher than about 0.14 Pa, however, it contributed to tear apart flocs and reduce w_s. This study suggests that ADV is a useful tool to concurrently measure the instantaneous current velocities, SSC and w_s in turbulence-dominant environments without breaking up flocs and disturbing ambient flow.

Key words: settling velocity, suspended sediment concentration, turbulence, cohesive sediment, ADV

1. INTRODUCTION

Settling velocity (w_s) is defined as the terminal velocity of a particle (or floc) settling down when the fluid drag force equals the downward gravity force (Winterwerp and van Kesteren, 2004; Mantovanelli and Ridd, 2006). w_s is a key parameter for predicting the sediment transport and fate in estuarine and coastal environments, because it plays an important role in determining the suspended sediment concentration (SSC) in water column, and the product of w_s and SSC controls the downflux of sediment mass (Manning and Dyer, 2007; Scully and Friedrichs, 2007). For non-cohesive sediment particles which are not subject to aggregation, w_s can be calculated by the well-known Stokes' law based on the size and density of particle as well as the density and viscosity of surrounding fluid, when the grain diameter is less than about 250 μm (Dyer, 1986; van Leussen, 1988; Fletcher and Loh, 1996). Well-accepted formulation for a large range of natural granular particles is also available (e.g., Chang and Liou, 2001). w_s for cohesive sediment, in contrast, is more complicatedly governed by interactions with a number of factors including organic content, degree of flocculation, mineralogy, SSC and properties (e.g., temperature and salinity) of ambient fluid (Manning, 2004). It is generally accepted, therefore, that w_s of cohesive sediment has to be measured at field because flocs cannot survive during sampling and transport to the laboratory (Winterwerp and van Kesteren, 2004).

Although numerous instruments and techniques have been developed to estimate w_s of cohesive sediment (for review, see Mantovanelli and Ridd, 2006), there is still no consensus in both measuring technique and data interpretation due to inherent complexities in settling processes of cohesive sediment. Even at a same field site, the estimated w_s can be quite different depending on the selected instrument or analytical method (Eisma et al., 1997). Among myriad approaches for measuring w_s, most recently, an acoustic Doppler velocimeter (ADV) has emerged as a novel device capable of indirectly estimating w_s in turbulent flows. Although the ADV's successes in in-situ measurements have been claimed in several studies (e.g., Fugate and Friedrichs, 2002, 2003; Voulgaris and Meyers, 2004; Scully, 2005; Maa and Kwon, 2007; Kawanisi and Shiozaki, 2008), the presented data were somehow noisy and the correlation coefficient was sometimes low. This is presumably due to the simplified assumption that w_s can be determined by a balance between the downward settling flux and upward turbulent diffusive flux under a zero mean vertical velocity (for details, see Section 2.2). To verify what causes the ADV's products to be noisy, the laboratory experiment where most conditions are controllable is necessary, because in-situ measurements are involved with more complex environmental parameters.

With the rationale mentioned above, using a 5-MHz ADV, this paper attempted to estimate SSC, turbulence and w_s in a laboratory tank. The objectives are (1) to reveal the dependence of w_s on the SSC and turbulence, (2) to evaluate the confidence of ADV-derived w_s by comparing with other approaches such as Owen tube (OT), and (3) to elucidate the limitation and possible improvement of ADV's analytical approach for estimating w_s.

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2. MATERIALS AND METHODS

2.1. ADV

Since firstly released in 1992, ADV has been widely used to measure 3-D instantaneous flow velocities at a single point with a high temporal (up to 50 Hz) resolution (SonTek, 2001). It is a bi-static current meter which uses the separate transducers to transmit and receive acoustic waves. In the signal processing, ADV utilizes the pulse-to-pulse coherent technology to calculate flow velocities (SonTek, 2001). The transmitter emits two pulses of sound separated by a time lag, and the receiving transducers measure the phase of return signals. Because the change in phase between pulses is proportional to velocities of particles in water, flow velocities are measurable with high resolution by assuming that water might carry suspended particles at the same velocity.

While the primary function is to measure the velocities, ADV can provide the SSC using a byproduct, backscatter strength, archived in an output file. When the particulate matters (e.g., sediment and small organisms) exist in a remote sampling volume, the acoustic energy is randomly scattered toward all directions and some portion of scattered energy is detected by receivers. Because the strength of backscatter signal is a function of the amount and type of insonified suspended particles, ADV can be used to measure the SSC when the acoustic response to sediment is known (Kawanisi and Yokosi, 1997; SonTek, 1997; Ha et al., 2009). The backscatter strength is maximum when the circumference of particle is close to the acoustic wavelength (i.e., $ka \approx 1$ where k is wave number, and a is particle radius) (SonTek, 1997; Thorne and Hanes, 2002).

In this study, a 5-MHz ADVOcean manufactured by SonTek was employed for simultaneously measuring three variables: (1) flow velocities, (2) SSC and (3) w_s.

2.2. Data Analysis

In the sediment mass conservation equation, by neglecting cross-channel (y) and vertical (z) advection terms, the mass balance can be expressed as

$$\frac{\partial C}{\partial t}+\frac{\partial(uC)}{\partial x}-w_s\frac{\partial C}{\partial z}-\frac{\partial}{\partial z}\left(K\frac{\partial C}{\partial z}\right) = 0 \tag{1}$$

where C is the sediment concentration, t is the time, u is the velocity along channel (x), and K is the eddy diffusivity. As the first order approximation (i.e., steady state and uniform flow), the local concentration change ($\partial C/\partial t$) and the advection term ($\partial(uC)/\partial x$) can be omitted, and thus w_s of aggregated flocs can be obtained analytically (Fugate and Friedrichs, 2002, 2003). That is, the upward turbulent diffusive flux is simply balanced by the downward settling flux.

$$-K\frac{\partial C}{\partial z} = w_s C\,. \tag{2}$$

The turbulent diffusion term is actually a simplified representation of the turbulent mixing by Reynolds flux, so that we can use the original form $-\langle w'C'\rangle$ instead if the data are available.

$$\langle w'C'\rangle = w_s C \tag{3}$$

where w' and C' are the fluctuations of vertical velocity and sediment concentration, and the angular bracket denotes the time average. In the plot of $\langle w'C'\rangle$ vs. C, therefore, the slope of a linear regression equation yields a constant w_s (Fugate and Friedrichs, 2002). An x-axis intercept of the regression equation is interpreted as "background concentration" which represents the non-settling components. Due to the linear relationship between $\langle w'C'\rangle$ and C, this approach only provides a single value of w_s regardless of SSC, and hence it is impossible to address the relationship between w_s and SSC. This is a weakness of original ADV approach proposed by Fugate and Friedrichs (2002), because it is generally known that w_s would exponentially increase with SSC up to a limit, and then start to decrease in high SSC ranges due to the hindered settling (van Leussen, 1988; Eisma et al., 1997; Manning and Dyer, 1999).

In order to overcome this problem, as an extension of the original approach, Maa and Kwon (2007) proposed to use an exponential relationship between these two parameters, instead of the linear regression.

$$\langle w'C'\rangle = mC^n \tag{4}$$

where m and n are empirical constants derived by a non-linear best-fit regression. Consequently, w_s can be expressed as a function of SSC.

$$w_s = mC^{n-1}\,. \tag{5}$$

When the SSC is higher than a certain value (ca. 5–10 g L^{-1}) (Wolanski et al., 1992; Winterwerp, 2002), then the formula in Equation (5) should be modified due to the hindered settling resulting in the decrease in w_s with increasing SSC (van Leussen, 1988). In this study, w_s in the hindered settling regime was not considered since the tested SSC was up to about 700 mg L^{-1}.

For representing the turbulence in the settling water tank, the turbulent kinetic energy (TKE) was calculated by

$$TKE = \frac{1}{2}\rho_w(\overline{u'^2}+\overline{v'^2}+\overline{w'^2}) \tag{6}$$

where ρ_w is the water density, u', v' and w' are three velocity fluctuating components, and the bar denotes the time average. Turbulent shear stress (τ) was calculated from TKE by applying Soulsby's (1983) constant ($c \approx 0.2$) for proportionality (Kim et al., 2000).

$$\tau = c\ TKE\,. \tag{7}$$

2.3. Experimental Methods

Prior to each experiment, a sediment-water mixture was placed in a cylindrical water tank (diameter: 0.75 m; height: 1.5 m), and then diluted with tap water until the pre-determined SSC was attained. Submersible bilge pumps were operated to fully mix the sediment slurry and keep the sediment in suspension for 24 h. Once the homogenous mixing is established, the downward-looking ADV was lowered at 0.9 m above tank bottom, and every 5-min time window during the settling was used to determine $\langle w'C' \rangle$ and C. Water samples were withdrawn at ADV's sampling level, and then filtered through pre-weighed and pre-combusted 0.7-μm fiber glass filters (Whatman GF/F; diameter: 47 mm). The residues on filters were oven-dried at 100 ºC for 24 h and reweighed. The SSC was determined by the weight difference divided by the volume of water filtered. Because the instantaneous ADV's backscatter strengths have a lot of noises, the time average of them was used to calibrate against the sample-derived SSC which was treated as the ground truth. An optical backscattering sensor (OBS) was also positioned at 0.9 m above bottom to estimate SSC as another reference. Further details on the ADV signal conversion to SSC were provided by Ha et al. (2009).

During the settling experiment, either no pump or one of two submergible pumps with different pumping rates (1900 or 5700 L h^{-1}) was used to stir up the sediment-water mixture. The pumping vent was connected with one of three types (straight, L- or T-shape) of adaptors to generate artificial conditions with different turbulence intensities (Fig. 1). The pumping level and direction (toward bottom or sidewall) were also adjusted for producing different conditions. It was found that the combination of T-shape adaptor and pumping to sidewall produced a slightly higher τ, compared with that of L-shape adaptor and pumping to bottom. In addition, τ generated at pumping level of 0.3 m above bottom is slightly higher than τ generated at pumping level of 0.05 m above bottom when both pumping direction and adaptor type are same. Detail conditions for each experiment are tabulated in Table 1.

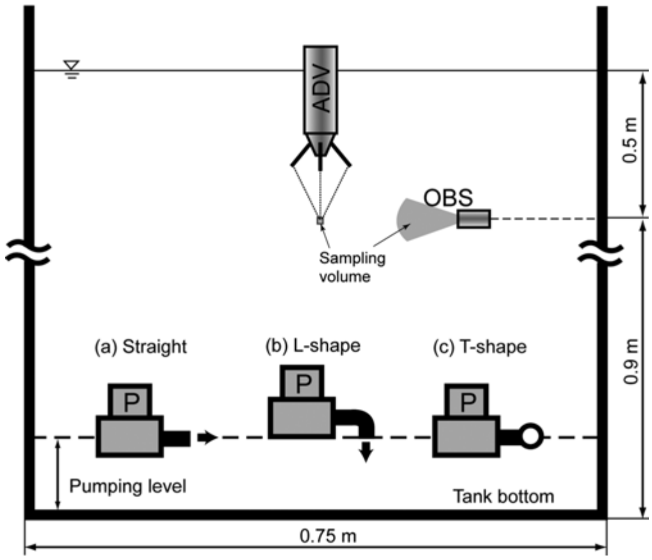

Fig. 1. Schematic experimental setup and artificial turbulent conditions generated by different pumping rates and adaptors. P represents the submersible pump. Thick arrows indicate the pumping direction. T-shape adaptor has the pumping direction perpendicular to this page.

2.4. Sediment

The tested sediment was collected from a Clay Bank site of the York River, Virginia. It shows a bimodal distribution in terms of grain size (Fig. 2). The first (ca. 0.7 μm) and the second mode (ca. 88 μm) are found in the clay and very fine

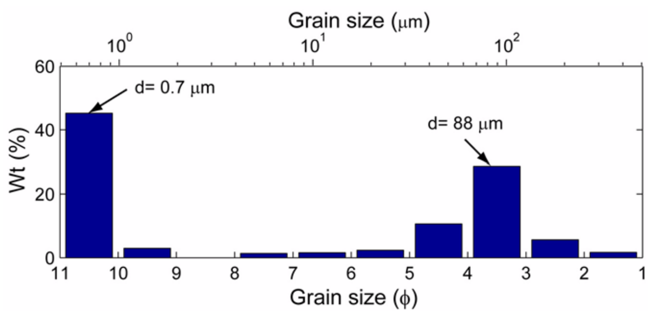

Fig. 2. Grain size distribution of the Clay Bank sediment.

Table 1. Experimental conditions for measuring settling velocity

Experiment ID	Pumping rate (L h^{-1})	Pumping level (m above bottom)	Pumping direction (toward)	Adaptor type	Water temperature (ºC)	Mean turbulent shear stress (Pa)
CB1121	0	n/a	n/a	n/a	21.4	0.0004
CB0727	0	n/a	n/a	n/a	26.7	0.0008
CB1129	1900	0.05	Bottom	L-shape	23.2	0.14
CB1128	1900	0.05	Sidewall	T-shape	23.5	0.15
CB0831	1900	0.3	Bottom	L-shape	24.8	0.20
CB0830	1900	0.3	Sidewall	T-shape	25.1	0.26
CB0809	5700	0	Sidewall	Straight	27.0	0.30

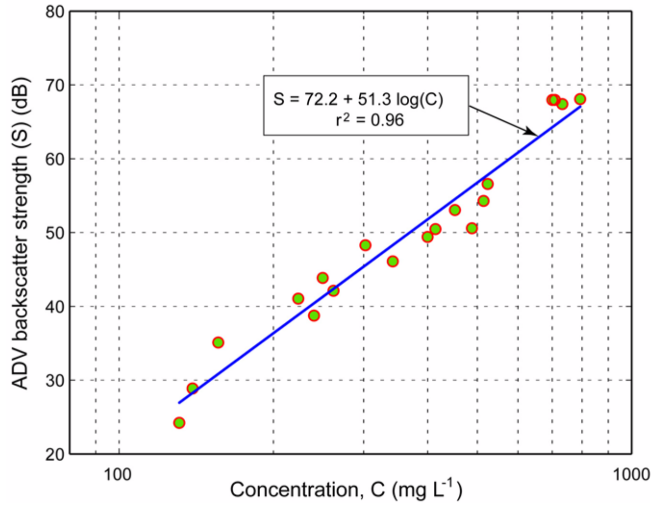

Fig. 3. Averaged backscatter strength vs. sample-derived concentration (after Ha et al., 2009).

sand range, respectively (Ha, 2008).

3. RESULTS

3.1. Signal Conversion to SSC

ADV's backscatter strength was measured in the unit of count, which should be multiplied by 0.43 to be expressed as decibel (SonTek, 1997, 2001). The mean of 2-min averaged backscatter strengths obtained by three receiving transducers was calibrated against the sample-derived SSC. Figure 3 shows a good linear correlation between the backscatter strength in decibel and the logarithm of SSC. The calibration equation was used to determine the SSC and w_s. Ha et al. (2009) demonstrated that the upper limit of linear response was about 1 g L^{-1} for the Clay Bank sediment. Beyond such a linear range, the backscatter strength was saturated due to ADV's internal processing that controls the range of output signal. With further increasing SSC, the strength would even decrease due to the severe sound absorption and associated multiple scattering (Medwin and Clay, 1998; Ha et al., 2009).

3.2. Effect of SSC on w_s

In the fully mixing condition, the initial SSC was about 700 mg L^{-1} for all experiments. The changing rates of w_s against SSC depended on the applied turbulent intensity (see Table 1). Among seven settling experiments, exemplary plots of $\langle w'C' \rangle$ vs. C were given in Figure 4. Although the data were still scattered, it was shown that $\langle w'C' \rangle$ increased with increasing C. Owing to the non-linear regression, w_s was expressed as an exponential function of SSC

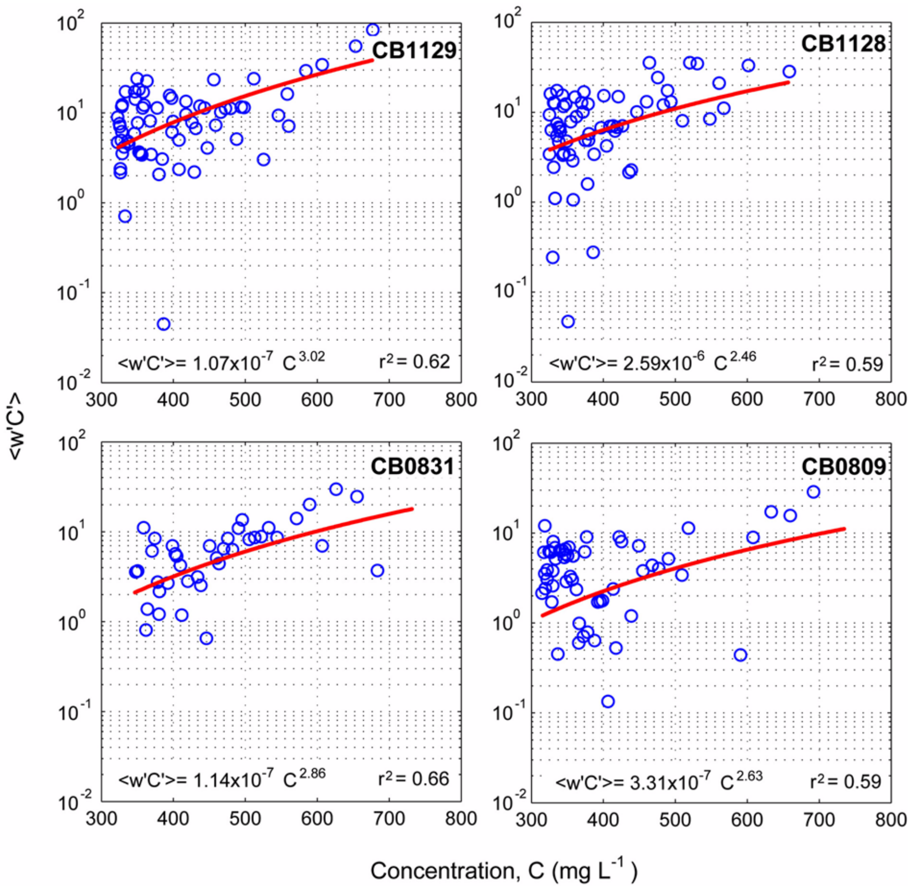

Fig. 4. Representative plots of $\langle w'C' \rangle$ vs. C for estimating settling velocity. Solid lines indicate the best-fit regression equations. Detail experimental conditions were given in Table 1.

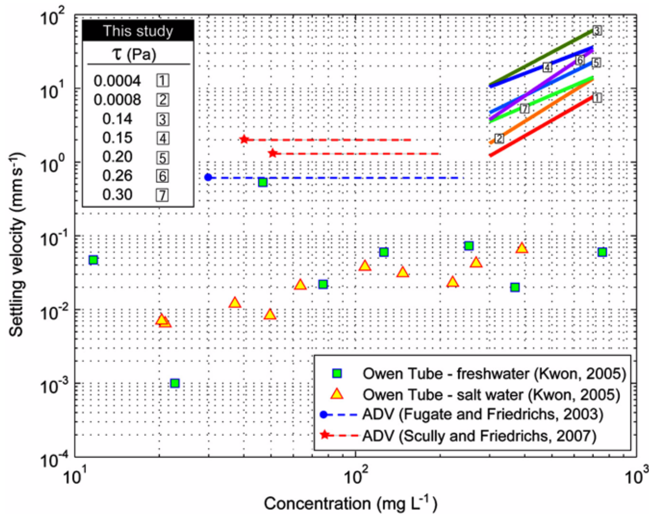

Fig. 5. Effects of concentration and turbulence on settling velocity of the Clay Bank sediment. Solid line 1 and 3 represent minimum and maximum settling velocities, respectively. ● and ★ are the background concentrations.

(see equations in Fig. 4). Because tested SSCs were between 300 and 700 mg L^{-1}, estimated equations for ADV-derived w_s ($w_{s\text{–ADV}}$) were only credible within this range.

For inter-comparison purposes, $w_{s\text{–ADV}}$ outcomes were plotted with the previously published values of w_s (Fig. 5). Within the analysis range, all data from this study showed that w_s increased with SSC. If the equations for $w_{s\text{–ADV}}$ were extrapolated to extend down to about 30 mg L^{-1}, the expected w_s is nearly on the same order of $w_{s\text{–ADV}}$ measured in the Clay Bank area. Fugate and Friedrichs (2003) estimated, for instance, that $w_{s\text{–ADV}}$ was 0.6 mm s^{-1} near bed, and the background concentration was about 29 mg L^{-1}. In addition, Scully and Friedrichs (2007) presented that the values of $w_{s\text{–ADV}}$ were different, 1.3 and 2.0 mm s^{-1} for flood and ebb period, respectively. It is noted that previous values of $w_{s\text{–ADV}}$ were estimated by the linear best-fit regression. For a wide range of SSC, therefore, only a single value of w_s was plotted in Figure 5.

In conditions of high SSC and high τ, the values of w_s that were higher than 10 mm s^{-1} were observed in Figure 5. When SSC was 700 mg L^{-1} and τ was 0.14 Pa, for example, w_s increased up to approximately 55 mm s^{-1}, which is too high to be regarded as w_s of mud flocs on the ground of other previous studies (e.g., Manning and Dyer, 1999; Kwon, 2005; Scully, 2005). According to the Stokes' law, the corresponding particle size would be approximately 245 μm. Thus, this fast w_s must be representative of coarse and dense components (i.e., sand) of the Clay Bank sediment (see Fig. 2). Even though the sandy portion, larger than about 250 μm, is meager (1.7% of total sediment), it might be a contributor producing a fast settling velocity during the initial settling period. Furthermore, the growth of floc by bonding between fast settling sandy particles and ambient cohesive flocs may significantly enhance w_s (Lick et al., 1993; van Leussen, 1997).

As another possible explanation, the fast w_s in high SSC might be attributed to the acoustic sensitivity to particle size, because the 5-MHz acoustic wave is more sensitive to coarse materials ($ka \approx 0.92$ for 88-μm sand) than fine-grained particles ($ka \approx 0.01$ for 0.7-μm clay). Sandy particles have rapidly settled at the beginning of measurement, so that the particle (or floc) size passing through ADV's sampling volume might become smaller and backscatter signal strength might be decreased by combined effects of lower SSC and smaller particle (or floc) size, as the time elapsed. This means that the sediment volume with large particles could produce the stronger backscatter strength, resulting in a pseudo-higher SSC, if sediment volumes insonified are same but particle size distributions change with time. Since w_s has a positive relationship with SSC (see Equation 5), the higher SSC contributes to the increase in w_s. As a result, w_s estimated in suspension encompassing large particles is faster than as expected.

3.3. Effect of Turbulence on w_s

In order to understand the effect of turbulence on w_s, τ was artificially changed in the range of 0.0004–0.3 Pa (Fig. 5). In non-turbulent cases at which a pump did not operate, the weak τ (0.0004–0.0008 Pa) was still observed. This is related to thermal circulation and Brownian motions that may cause suspended particles (or flocs) to move very slowly during the setting. When τ reached about 0.14 Pa, a favorable turbulent condition for floc growth was created, so that w_s of the Clay Bank sediment may become the highest value (Fig. 5).

It is noticeable that w_s measured at non-turbulent conditions (e.g., line 1 in Fig. 5) is one order of magnitude less than the maximal w_s measured at turbulent conditions (e.g., line 3 in Fig. 5), even under the same SSC. This difference is attributed to the fact that turbulence could produce more frequent collisions of suspended particles which result in forming larger flocs (Fennessy et al., 1994). The number of collision is governed mainly by the turbulent shear in water column (Winterwerp, 2002). After 0.14 Pa, however, w_s started to decrease with further increasing τ.

4. DISCUSSION

Since $w_{s\text{–ADV}}$ was higher than w_s measured by OT ($w_{s\text{–OT}}$), it is important to reconfirm the confidence of $w_{s\text{–ADV}}$ and to address possible reasons for explaining the gap between $w_{s\text{–ADV}}$ and $w_{s\text{–OT}}$. Additionally, the role of turbulence is critical for determining the maximal floc size and w_s. These issues are dealt in this section.

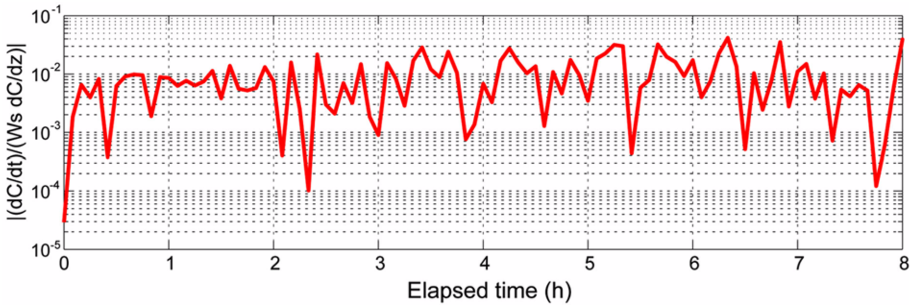

Fig. 6. Comparison between local concentration change term ($\partial C/\partial t$) and downward settling term ($w_s \partial C/\partial z$).

4.1. Validation and Potential Limitation of ADV Approach

One of significant assumptions in estimating w_s from ADV data is neglecting the local concentration change term ($\partial C/\partial t$). In order to evaluate this assumption, the relative importance of settling term ($w_s \partial C/\partial z$) was compared with ($\partial C/\partial t$) which was estimated by the 5-min average of ADV-derived SSC (C_{ADV}) (Fig. 6). Instead of using a single constant value of w_s for all measured times as in Fugate and Friedrichs (2002), we used here w_s defined as a non-linear function of C_{ADV}. This is an improvement to reflect the SSC's role in controlling w_s. The vertical gradient of SSC ($\partial C/\partial z$) was determined with the discrete data of sample-derived SSCs at 0.1 and 1.10 m above tank bottom. Because water samples were not regularly taken at every 5 minutes, the interpolated data of ($\partial C/\partial z$) with 5-min interval were used for comparison. Figure 6 shows that the settling term was 2 to 4 orders of magnitude larger than the local concentration change. This suggests that the assumptions of ADV approach proposed by Fugate and Friedrichs (2002) are still valid for SSC-dependent w_s. The changes of SSC and velocity in the lateral direction are negligibly small due to the limited lateral dimension of tank. Some previous field studies (e.g., Fugate and Friedrichs, 2002; Voulgaris and Meyer, 2004) demonstrated that the advection term is 1 to 2 orders of magnitude less than the settling term for all tidal cycles.

Based on aforementioned results, w_s at a given height above bed, as the first order, can be approximated by a balance between upward turbulent diffusive flux and downward settling flux. However, the ignored terms in simplified assumptions could make data scattered (Maa and Kwon, 2007). Other possible reasons can be taken into account as follows.

First reason is associated with the dependence of backscattered signal on the particle size. Acoustic backscatter strength is proportional to SSC multiplied by a form factor describing the backscattering characteristics of the n-th class particle in suspension and divided by the particle diameter (Vincent and Downing, 1994; Thorne and Meral, 2008). The form factor is proportional to the fourth power of ka in the Rayleigh scattering regime (ka < 1) (Urick, 1983; SonTek, 1997). Provided that the suspended sediments are composed of multi-class particles and their size distribution significantly changes with time, ADV would selectively detect the coarser and denser component among insonified materials due to a much higher acoustic sensitivity (Ha, 2008). Even though the backscattered signals were also produced by the fine-grained component in suspension, its contribution is relatively small in the total scattered amount (Thorne and Hanes, 2002). This different response can influence the accuracy of C and C'. The time averaging can alleviate the level of noises but not perfectly remove them. Ha et al. (2009) argued that ADV's sensitivity is mainly governed by the ratio of transmitted acoustic wavelength to suspended particle size, and that the floc size somewhat contributes to the enhancement of backscatter strength if the bonding structure of floc is strong enough for acoustic wave to detect as a single particle. It is feasible, therefore, that ADV approach may yield more noises in the condition that the particle size and the degree of flocculation are highly changing with time.

Secondly, the negative turbulent diffusion may contaminate the data quality for w_s. Figure 7 shows an example of C_{ADV} and $\langle w'C' \rangle$ measurements under a moderate ($\tau = 0.14$ Pa) turbulent condition. Both variables decreased with a settling

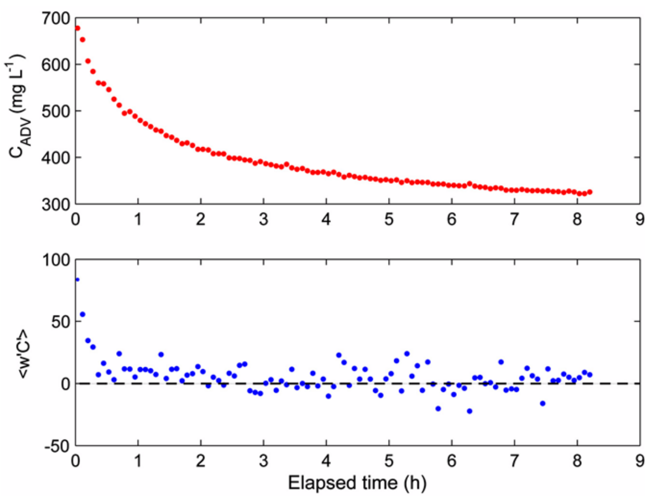

Fig. 7. Variations in ADV-derived concentration (C_{ADV}) and the turbulent diffusive flux ($\langle w'C' \rangle$) at the moderate turbulent condition (CB1129).

time. It is noticed that most of $\langle w'C' \rangle$ were positive, but some were occasionally negative. Due to a random chance, the instantaneous product of w' and C' before time averaging can be positive or negative. The time average of $\langle w'C' \rangle$, however, should have a consistent sign indicating the direction of flux. During the settling experiment, $\langle w'C' \rangle$ should not only approach $w_s C$ but also be positive to represent the upward flux direction. Depending on the applied turbulent conditions, however, about 10–30% of total flux data were negative. By increasing the time span for averaging, the number of negative signs can be reduced to a certain degree, but not totally eliminated. The negative values of Reynolds concentration flux indicate that there are factors which might be excluded in the calculation of turbulent diffusion.

In order to enhance the correlation coefficient, as a remedy, Scully (2005) only selected the positive $\langle w'C' \rangle$ for analysis, and further grouped noisy ADV data into several bins with an equal increment of C. The median of each bin was used to determine w_s. It was revealed that w_s estimated from binned data is close to w_s derived from non-binned data, but the correlation was highly improved. Such an analysis, therefore, might be an alternative to partially solve the scatterance of ADV data.

4.2. ADV Approach vs. Owen Tube

It was shown that $w_{s\text{–ADV}}$ is much greater than $w_{s\text{–OT}}$ (see Fig. 5). The higher $w_{s\text{–ADV}}$ is most likely due to the effect of ambient turbulence which was totally blocked in OT (Maa and Kwon, 2007). Not only the turbulence effect, but OT itself also breaks up flocs while trapping samples into the tube. In particular, high porous macroflocs (>160 μm; Manning and Dyer, 2007) can be more easily broken than low porous microflocs (<160 μm), so that $w_{s\text{–OT}}$ might be underestimated. Besides, the collected sediment particles (or flocs) may stick to the inner wall of tube during the settling, which leads to retard w_s. The viscosity change and convection in settling column during the experiment (>1 h) might be another contributor to a bias. It is plausible, therefore, that $w_{s\text{–OT}}$ could be underestimated compared to the true w_s. Several studies (e.g., Dearnaley, 1996; Eisma et al., 1997; Maa and Kwon, 2007) reported that $w_{s\text{–OT}}$ is 1 to 3 orders of magnitude less than w_s derived by in-situ video image analysis as well as indirect ADV approach. Nonetheless, the methodology of OT is still being widely used as a good reference in sediment communities, because $w_{s\text{–OT}}$ would be still comparable to w_s measured by other approaches under careful handling conditions.

4.3. Floc Size and Turbulence

The energy in turbulent flow is dissipated by transferring from large eddies to small eddies (Kolmogorov, 1941). The size of suspended sediment particle (or floc) changes in the range of a few μm (primary particles) to a few mm (macrofloc). In the interactions between turbulence and flocs, the dimension of turbulent eddies plays an important role in determining the attainable floc size (van Leussen, 1997). It is known that the smallest turbulent eddy scale, often referred to as the Kolmogorove microscale (η), is comparable to the dimension of floc (Berhane et al., 1997), and it depends on the kinematic viscosity (ν) of fluid and the turbulent dissipation rate (ε).

$$\eta = \left(\frac{\nu^3}{\varepsilon}\right)^{1/4} \tag{8a}$$

$$\varepsilon = \frac{u_*^3}{\kappa z} \tag{8b}$$

where u_* is the turbulent shear velocity, κ is von Karman's constant (0.41), and z is the height above bed.

To calculate the floc size comparable to η, either w_s or density of floc should be known. Although these two variables were not measured in present study during the settling, we can infer the size of flocs using empirical relationships that other authors suggested. In the Chesapeake Bay, for example, Sanford et al. (2005) presented an empirical relationship between floc diameter (d_f in m) and w_s (in mm s^{-1}) through a floc camera system as follows:

$$w_s = 1.4715 * 10^5 d_f^{1.3923}. \tag{9}$$

On the basis of this relationship, the floc size was inferred from $w_{s\text{–ADV}}$ when SSC was 300 mg L^{-1}. Figure 8 shows the variations in η and floc size under different turbulent shear stresses. At the calm condition, η was much larger than the inferred floc size. This is because large flocs have already fallen and only small flocs remained in suspension when τ approached zero. In other words, turbulence plays little role in determining the floc size when the SSC is low. When τ was around 0.14 Pa, the floc size calculated by Equation (9) increased up to about 1 mm. After that, the floc size gradually decreased because η limited the floc size and its corresponding w_s. These two opposite behaviors suggest that turbulence plays dual roles in promoting the growth of flocs and limiting the maximal attainable size (van Leussen, 1988;

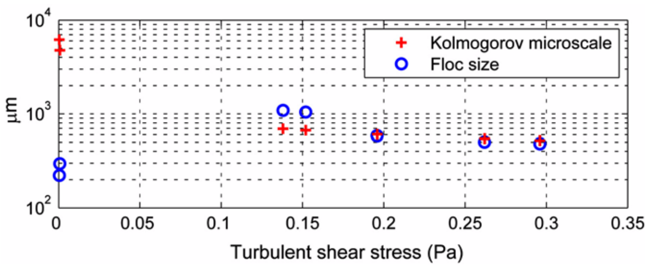

Fig. 8. Variations in Kolmogorov microscale and floc size over experimental turbulent shear stresses.

Wolanski et al., 1992; Whitehouse et al., 2000). At the low turbulence intensity, the floc size may be in a growth phase. In contrast, the severe turbulence may tear apart large and heavy flocs, and thus w_s decreases accordingly. After $\tau = 0.2$ Pa, the floc size was close to Kolmogorov's. This observation enforces the fact that flocs start to be broken when η is roughly on the same order of floc size (van Leussen, 1988, 1997; Berhane et al., 1997; Manning, 2004; Scully and Friedrichs, 2007).

5. CONCLUSIONS

The conclusions withdrawn from this study are as follows:

(1) The laboratory measurement of w_s with the Clay Bank sediment showed that w_s increased non-linearly with SSCs between 300 and 700 mg L^{-1}.

(2) Turbulence can increase w_s, up to one order higher than w_s for non-turbulent conditions. This effect can explain why $w_{s\text{–ADV}}$ was 1 to 3 orders of magnitude higher than $w_{s\text{–OT}}$ where the ambient turbulence was totally blocked. When τ was higher than about 0.14 Pa, however, it contributed to the decrease in the floc size and w_s.

(3) While its primary function is to measure instantaneous 3-D flow velocities, ADV is a useful tool to concurrently measure the SSC and w_s in turbulence-dominant environments without breaking up flocs and seriously disturbing ambient flow.

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