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Estuarine, Coastal and Shelf Science 73 (2007) 351−354
ESTUARINE COASTAL AND SHELF SCIENCE
www.elsevier.com/locate/ecss

Short Communication

Using ADV for cohesive sediment settling velocity measurements

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Received 4 October 2006; accepted 15 January 2007
Available online 9 March 2007

Abstract

Using an Acoustic Doppler Velocimeter (ADV) to simultaneously measure the turbulent diffusivities and Suspended Sediment Concentrations (SSC) at one point in the water column provides an *in-situ* approach to measure the settling velocity of cohesive sediments. This approach does not alter the ambient turbulence, SSC, salinity and biological constituents that are the major factors affecting floc density and size, and thus, the settling velocity. The settling velocity measured using this technique is much higher than that obtained from the traditional Owen Tube method, which eliminates the effects of ambient turbulence. Using the settling velocities measured from this new approach and the erosion rates from *in-situ* measurements in a numerical study of the dynamics of turbidity maximum in the York River, the simulated results were quite reasonable. This is encouraging because it was the first time that a modeling study used *in-situ* measured settling velocities and erosion rates together and correctly predicted the formation of turbidity maximum. Although this is a promising approach, there are improvements that should be included to establish the procedures of using an ADV for measuring the settling velocity of cohesive sediments.

Keywords: settling velocity; cohesive sediments; ambient turbulence; measurement technique; suspended sediment

1. Introduction

Among the four main processes (erosion, settling, deposition and consolidation) for cohesive sediments, the settling velocity (w_s) is probably the most important one for understanding and simulating suspended sediment transport in estuaries (Mehta, 1986; Dyer, 1997; Winterwerp and Van Kesteren, 2004). Unfortunately, most modeling efforts on the simulation of suspended sediment transport still treat w_s as a tunable parameter to match with the observed Suspended Sediment Concentration (SSC).

Although w_s of a sediment floc is specified in still water, the nature of turbulent flows to form or to destroy flocs, the existence of salinity and biological constituents to affect the bonding forces and the availability of sediment to form flocs, have effects on w_s. As a result, the change of w_s may span over an order of magnitude at the same site, depend on the ambient conditions. The measurement results may also be different significantly because of the different sampling methods (Eisma et al., 1997). For this reason, it is important to keep the turbulence, SSC, salinity and ambient biological constituents the same while measuring w_s.

Previous approaches either totally block out the ambient turbulence during the measurement periods (*e.g.*, Owen, 1976; Agrawal and Pottsmith, 2000), or making an unrealistic assumption such as the floc density is the same for all size of flocs (Mikkelsen and Pejrup, 2001), or dilute the SSC for taking clear pictures of each individual floc (Fennessy et al., 1994; Manning et al., 2006). Thus, the effect of ambient turbulence and SSC is limited.

With the advance of acoustic techniques for field applications, Fugate and Friedrichs (2002, 2003) used an Acoustic Doppler Velocimeter (ADV) to measure both the current velocity and the SSC (with a careful calibration to convert the

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doi:10.1016/j.ecss.2007.01.008

acoustic backscatter wave strength to SSC) at a point not far from the bed. They further proposed a linear relationship between the measured diffusivity and SSC to estimate w_s. Their effort is the first attempt to provide a new alternative for measuring w_s that does not change the ambient environments at all. Their approach, however, is limited by the assumption they used. Their data were pretty scattered and that implies there are room for improvements. To reveal the limitations and to suggest enhancements of this new approach are the objectives of this communication.

2. Previous findings

Early study results (Burt, 1986; Mehta, 1986) by using the Owen Tube method (Owen, 1976) indicate that w_s may increase with the SSC (Eq. (1)), up to a limit around 5 to 10 g/L.

$$w_s = aC^b \tag{1}$$

where a and b are constant coefficients. When the SSC is higher than the upper limit, Eq. (1) is not valid and w_s actually becomes small, a phenomenon called "hindered settling" which is attributed to the interactions among sediment flocs.

Totally blocking out the ambient turbulence during the period of w_s measurement is the main criticism for using the Owen Tube method. This concern is based on the recognition that turbulence is one of the major factors that affects the flocculation process (*i.e.*, floc size and floc density). Although a new device (*i.e.*, LISST-ST, Agrawal and Pottsmith, 2000) has been developed for *in-situ* measurements of w_s with eight size classes, the basic principal remains the same and turbulence effect is still excluded.

Using the Rouse Equation (Henderson, 1966) to fit measured vertical profiles of SSC is an attempt to resolve the above-mentioned problems for steady, non-stratified flows with a constant w_s for the entire water column. Because of salinity stratification and the variable w_s in the water column for estuary environments, Rouse Equation cannot be used.

3. ADV approach for measuring w_s

For stratified flows with a variable w_s in the water column, the local sediment mass conservation equation still can be used for estimating w_s. To utilize this equation, however, some assumptions are necessary as pointed out next.

Assuming that: (1) steady state; (2) the horizontal gradient of SSC is negligible small; and (3) the knowledge of average vertical velocity, w. Fugate and Friedrichs (2002, 2003) further assumed that $w = 0$ and simplified the three-dimensional sediment mass conservation equation to a vertical one-dimensional equation. Their finding leads to the following algebraic equation that is the first attempt of estimating w_s using ADV.

$$w_s C = \langle w'C' \rangle \tag{2}$$

where w' is the vertical fluid velocity fluctuation, C' is the SSC fluctuation estimated from the ADV backscatter strength, $\langle\ \rangle$ is a symbol to represent time-average and $C = \langle C' \rangle$ is the time-average SSC.

An ADV is designed to measure three instantaneous velocity components (u', v' and w') at one point using the principal of Doppler frequency shift. With careful calibrations, the acoustic scatter signal strength may also be correlated with SSC. Thus, an ADV may be used to collect information of C' as well. By using a linear relationship between C and $\langle w'C' \rangle$, Fugate and Friedrichs (2002) produced a constant w_s and a low limit of SSC which represents the non-settling component of the SSC.

Based on the data given by Fugate and Friedrichs (2002, 2003), however, Kwon (2005) proposed another possible relationship between $\langle w'C' \rangle$ and C:

$$\langle w'C' \rangle = mC^n \tag{3}$$

where m and n are two constants. Using a non-linear least-squares data fitting, the best fitted m and n can be found (Fig. 1). The result (*i.e.*, $w_s = mC^{n-1}$) increases with SSC, also matches with early findings.

In a numerical simulation of the formation of turbidity maximum in the York River, Kwon (2005) used data from *in-situ* measurements on erosion rates and two possible w_s formulations (Fig. 2) to simulate the dynamics of turbidity maximum. The first selected settling velocity formulation was acquired using the traditional Owen Tube method with sediment samples collected in the field. The other selected settling velocity formulation were the average of his ADV approach. It was found that the turbidity maximum simulation results are close to measurements (Fig. 3) if the findings from the second approach were used (Kwon et al., 2006).

At the York River site, the bottom sediments are 90% clay with D_{50} around 20 μm (Maa and Kim, 2002). The clay minerals are mainly Illite (about 75%), and the rest are rather uniformly distributed between Kaolinite, Chlorite and Smectite (around 8% each).

4. Discussion, recommendations and conclusions

Data given by Fugate and Friedrichs (2002, 2003) are quite scattered (Fig. 1). This implies that both the original linear relationship and Kwon's non-linear relationship between diffusivity and SSC may not have a high confidence on the data fitting. The scattering data may caused by two possible reasons: (1) The backscattered signal strength are not well correlated with SSC; and (2) the assumption of $w = 0$. It is widely accepted that the backscattered acoustic wave strength is well correlated with suspended granular sediments. It is not clearly yet what would be the backscatter responses on fluff sediment flocs associated with cohesive sediments. Further laboratory experiments are needed to clarify this issue.

The zero w assumption is another major weakness. Although w is small (for example, w at water surface is about 0.05 mm/s in the York River which has a M_2 tidal range about 1 m), it is still comparable with w_s, especially at low SSC. Thus, the accurate estimation of w becomes important for the correct

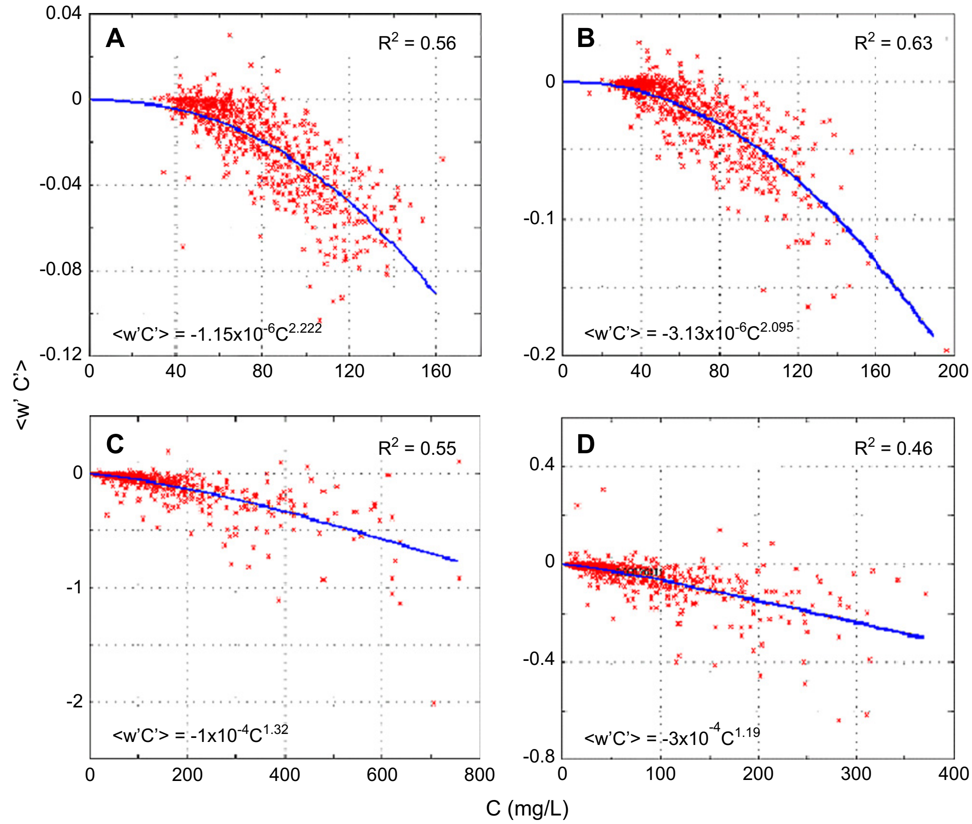

Fig. 1. The suggested non-linear relationship between $\langle w'C' \rangle$ and C for estimating settling velocity using the presented ADV approach. Data were copied from Fugate and Friedrichs (2002).

estimation of w_s. There are two possible sources of producing w: (1) tide; and (2) bathymetry. To minimize the bathymetric induced w, one may select a location that is reasonable flat to carry out the experiments. In general, a location like this should not be difficult to find.

It is difficult to measure the true tidal-induced w directly using an ADV because of the inevitable instrument misalignment during deployments and the presence of a large horizontal velocity, u. Even with an 1° misalignment, the contribution from the large u can be important. For example, an 1° misalignment with $u = 30$ cm/s will produce a false vertical

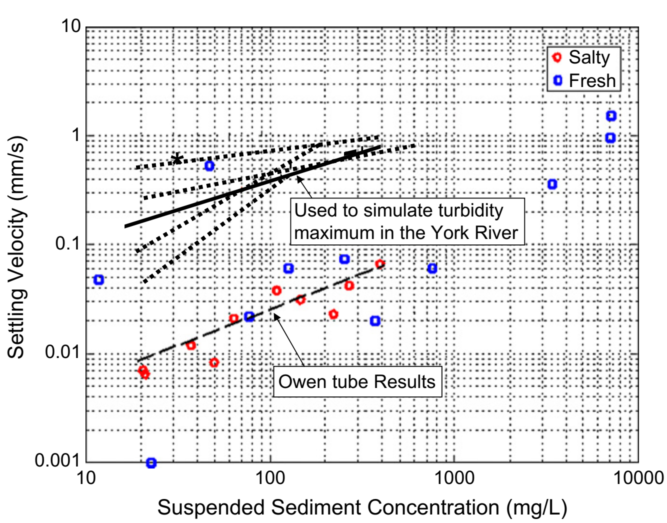

Fig. 2. Results of two possible approaches for measuring w_s in the York River estuary. Using the average of Kwon's approach (solid line) in a numerical simulation of turbidity maximum in the York River Estuary produce a result that is much close to that observed.

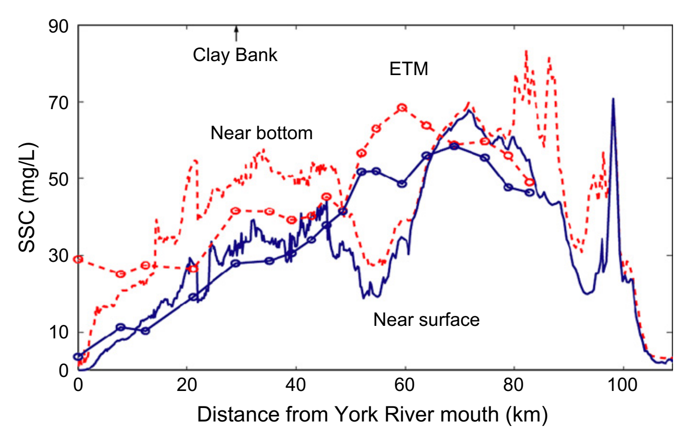

Fig. 3. Example of simulated (lines without circles) and observed (lines with circles) SSC at two depths along the York River using the average w_s information obtained from Kwon's ADV approach. Solid and dashed lines represent average of 1 m from surface and 1 m from bottom SSC, respectively. Data are from a slack water survey carried out in April 11, 2002. The Estuarial Turbidity Maximum was located at 60 km from the York River mouth.

velocity component of 0.52 cm/s. One will notice immediately that the contribution of instrument alignment could have a profound influence on the measured w, and therefore, on the estimation of w_s. Since the best tilt angle measurement device has an accuracy of about 1°, it is practically impossible to have a perfect instrument alignment in the field.

It is not difficult, however, to calculate w by using tidal information, as the change of tidal elevation is caused by w. For example, the integration of w at water surface from the time of low slack to the high slack gives the tidal range. Since the tidal range information for calculating w (Eq. (4)) can be obtained from tide tables, it would be easy to find $w(z, t)$ at any specified elevation using the shallow water wave equation

$$w(z, t) = C\left(1+\frac{z}{h}\right)\sum_{i=1}^{N} A_i k_i \sin(\sigma_i t - \phi_i) \tag{4}$$

where A_i, k_i, σ_i and ϕ_i are the amplitude, wave number, frequency and phase for the ith tidal wave component, respectively, $C = (gh)^{1/2}$ is the shallow water wave velocity, g is the gravitational acceleration, h is the mean water depth, z is the vertical coordinate with $z = -h$ at the bottom and N is the total number of tidal components used for the estimation of w (Dean and Dalrymple, 1992). Eq. (4) can also be written as $w(z, t) = (1 + z/h)$ $w(0, t)$, where $w(0, t)$ is the time average vertical velocity at the water surface. In general, at least the seven major tidal components are required to calculate w. If available, the more complete set of 36 tidal components should be used. From the field measurements, a pressure gauge to record the time series of water surface elevation, $\eta(t)$, is all that is required. The temporal gradient of η, *i.e.*, $d\eta/dt$, is the vertical velocity at the water surface, $w(0, t)$. With the given information of ADV location in the water column, $w(z, t)$ can be calculated accurately.

Even without this improvement, the results are already quite encouraging when used in a numerical simulation. This may be attributed to the fact that there are positive and negative w's in the estimation of w_s, and thus, the use of average data still give reasonable results. Nevertheless, with the suggested approach to estimate w and experiments to find a clear relationship between the backscattered acoustic wave strength and SSC, it is expected that the data would be much less scattered. Laboratory and field experiments based on the above understanding are under consideration for establishing a better procedure to measure w_s. In conclusion, the ADV method appears to be an effective and suitable way to estimate the settling velocity in turbulence dominant environments.

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