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Experimental study on fall velocity of fine sediment in the Yangtze Estuary, China

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ABSTRACT

Fall velocity (FV) is such a fundamental parameter for sediment researchers that its accurate determination has been regarded as a top priority in improving numerical modelling and conceptual understanding of fine sediment dynamics. With their cohesive nature, fine sediments are prone to aggregation and form flocculation network structures (flocs). The rheological behaviour of fluid may complicate this problem. By means of a new apparatus, FV of fine Yangtze Estuary sediment can be studied in the laboratory. The experimental data show that (1) suspended sediment concentration (SSC), salinity and temperature all affect FV, but to different extents; (2) the relationships between the FV of estuarine fine sediments and its determinants are highly dependent upon specific environmental conditions; (3) the dependencies of various determinants (SSC, salinity and temperature) on FV in different flocculation stages are varied; and (4) for Yangtze estuarine mud, the FV peaks when the SSC is in the range 3–8 g/l, and the salinities for maximum flocculation settling are approximately 7 and 10 PSU in dry and wet seasons, respectively.

1. Introduction

In coastal sedimentology and morphodynamics, especially for those fine sediment estuaries with median grain size (D_{50}) finer than 62 μm (Mehta and McAnally, 2008), fall velocity (FV), also known as settling velocity, is a critical parameter in the understanding of sediment behaviour and dynamics. FV directly determines the vertical distribution of suspended sediment concentration (SSC) and near-bed deposition flux, and its accurate determination has been regarded as a priority in characterizing fine sediment transport. In the past, extensive efforts, e.g., (Fennessy et al., 1994; Gratiot et al., 2005; Krishnappan et al., 2004; Markussen and Andersen, 2013; McLaughlin, 1961; Mehta, 1989; Owen, 1971; Rouse, 1938; van Leussen, 2011), have been made to enhance our understanding of the physical process of fine sediment settling and a number of empirical and semi-empirical formulas for FV have been proposed in various forms.

Generally, it is difficult to record or track the fall trajectory of a single fine-sediment particle or an individual floc visually or using instrumentation. Three types of indirect methods have commonly been used to determine FV including (1) The theoretical method (e.g., the Stokes formula) (Chien and Wan, 1999; Shao et al., 2011) used to calculate FV based on fluid properties (density and temperature) and the grain size of an individual particle or floc. Moreover, other theoretical models (Winterwerp, 1998; Zhang and Zhang, 2011) taking into account the behaviours of collision, coagulation and flocs growth and break-up have been setup to determine FV. (2) The FV of fine sediment has been investigated using in situ methods (Agrawal and Pottsmith, 2000; Fennessy et al., 1994; Owen, 1971; Owen and Zozulya, 2000; van Leussen, 1994) via an in situ settling tube or chamber. It was reported that the advantage of in situ method is that those facilities were operated under "natural conditions" (Berlamont et al., 1993; Dyer et al., 1996). One of the disadvantages of the in situ method is the disturbance of the natural flocs during sampling and measurement (Manning et al., 2010). Moreover, gravity-induced settling is confounded by other physical processes, such as diffusion and advection, which maybe simultaneously occurr. These processes cannot be removed or controlled during field surveys, and so in situ methods cannot separate the settling process from vertical transport processes. Another insurmountable problem preventing in situ FV measurement is that this method cannot distinguish individual flocs under high SSC condition. Even slight increases in SSC can cause single flocs to become entirely indistinguishable, meaning that the method is only valid for relatively low SSC

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(Markussen and Andersen, 2013). (3) The use of laboratory experiment (by settling column) for measuring the FV has a long history (Camp, 1936; Fathi-Moghadam et al., 2011; McLaughlin, 1961; van Leussen, 1988). The main advantages of this method lie in the ability to measure FV under controllable conditions. Many factors, such as SSC, salinity and temperature, have been regarded as the independent variables of FV.

Based on previous studies on this issue, an improved approach using a new apparatus is presented for measuring the FV of suspended fine sediment in the laboratory. Subsequently, based on the experimental results, the dependencies of FV on SSC, salinity and temperature are investigated, and an empirical formula for determining FV is presented.

2. Methods

Following the classic approach (Camp, 1936; Fathi-Moghadam et al., 2011; McLaughlin, 1961; van Leussen, 1988) for measuring FV, this study improves the formulation and the facility: (1) in comparison with the McLaughlin (1961) formula, the median FV is introduced as a representative value for a set of natural sediment in a specified condition; (2) OBS method for SSC measurement is proposed instead of the drying weighting method.

2.1. Formula

The vertical mass balance equation has the following form if the diffusion term is assumed to be negligible:

$$\frac{\partial C}{\partial t}+\frac{\partial(\omega C)}{\partial z}=0 \tag{1}$$

in which, C is the instant SSC at the time t and at the depth h, t is the time, z is the height above the bed and ω is the instantaneous depth-dependent FV at the depth h.

Integrating Eq. (1) over depth yields

$$(\omega C)_{z=h}=-\frac{\partial}{\partial t}\int_0^h C dz \tag{2}$$

By multi-depth SSC sampling of a settling column at several time steps, the time- and depth-varied FV could be obtained using a finite-difference method (FDM). However, the problem is that FV is a parameter that is dependent upon other two independent variables (time and water depth), and is not practical for application. Therefore, a depth-dependent median FV is presented in Eq. (2), which refers to the concept of D_{50}. D_{50} is defined as the value of the particle diameter at 50% of the normal cumulative distribution (Mehta, 2014), which is an easy and meaningful statistical way of quantifying the particle size of natural non-uniform sediment.

$$(\omega_{50})_{z=h}=\frac{1}{t_{0.5}}\int_0^{t_{0.5}} \omega_{i,h} dt \tag{3}$$

in which, ω_{50} is the median FV, $t_{0.5}$ is the elapsed time after the SSC decreased to 50% of its initial value at a given depth, and $\omega_{i,h}$ is the instantaneous depth-dependent FV.

The median FV means that when the SSC decreases by 50% over a certain depth, FV could be measured through the integration of the instantaneous FV over the elapsed time. Compared to other formulas, the McLaughlin formula has a strong physical meaning that is consistent with its original definition. It is widely employed for calculation of fine sediment FV (e.g., McLaughlin, 1961; Tambo, 1964; You, 2004).

2.2. Experiment setup

The deployment and distinctive characteristics of the experimental equipment of FV are addressed, and a detailed operational procedure of the FV experiment is presented.

2.2.1. Apparatus

From a series of experiments (Wan, 2013) performed in a traditional settling column (Gibbs, 1972; Dearnaley, 1996) with a diameter of 40 cm, a height of 2.5 m, and with eight multi-depth outlets (intervals are 20 cm) for SSC sampling (Fig. 1), the following drawbacks of traditional experimental procedures could be identified: (1) Intakes are mounted at the fixed depths; therefore, the vertical SSC profile is not continuous to obtain a FV value of high resolution, the SSC gradient between each 2 outlets is ignored. (2) Owing to unfavourable wall effects during sampling, the sampled SSC would be smaller than the actual value, especially when the SSC value is higher than about 2–3 g/l. (3) When the SSC is lower than approximately 1 g/l, it is more prone to error induced by the drying weighting or pycnometric density methods. (4) Because sampling occurs at multiple depths and times, resulting in water volume loss, the originally unrestricted settling

Fig. 1. Photo of a traditional settling column, the outlets are connected together to a shaft to insure simultaneous sampling (Photo courtesy: HUANG Wei).