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A study of in-situ sediment flocculation in the turbidity maxima of the Yangtze Estuary

Chao Guo [a], Qing He [a, *], Leicheng Guo [a], Johan C. Winterwerp [b]

[a] State Key Laboratory of Estuarine and Coastal Research, East China Normal University, Shanghai 200062, People's Republic of China
[b] Section of Environmental Fluid Mechanics, Faculty of Civil Engineering and Geosciences, Delft University of Technology, PO Box 5048, 2600 GA Delft, The Netherlands

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ABSTRACT

In order to improve our understandings of temporal and vertical variations of sediment flocculation dynamics within the turbidity maxima (TM) of the highly turbid Yangtze Estuary (YE), we deployed LISST-100C, a laser instrument for in-situ monitor of the sizes and concentrations of flocculated particles in a wet season. Field data in terms of vertical profiles of flow velocity, suspended sediment concentration (SSC), salinity, flocculated particle size distribution and volume concentration were obtained, based on field works conducted at consecutive spring, moderate, and neap tides.

Data analyses show that the mean floc diameters (D_M) were in the range of 14–95 µm, and flocculation exhibited strong temporal and vertical variations within a tidal cycle and between spring-neap cycles. Larger D_M were observed during high and low slack waters, and the averaged floc size at neap tide was found 57% larger than at spring tide. Effective density of flocs decreased with the increase of floc size, and fractal dimension of flocs in the YE was mainly between 1.5 and 2.1. We also estimated the settling velocity of flocs by 0.04–0.6 mm s^{-1} and the largest settling velocity occurred also at slack waters. Moreover, it is found that turbulence plays a dominant role in the flocculation process. Floc size decreases significantly when the shear rate parameter G is > 2-3 s^{-1}, suggesting the turbulence breaking force. Combined effects of fine sediment flocculation, enhanced settling process, and high sediment concentration resulted in a large settling flux around high water, which can in part explain the severe siltation in the TM of the YE, thus shedding lights on the navigation channel management.

1. Introduction

Flocculation plays an important role in cohesive sediment transport, which has been observed in various natural aquatic environments, including fresh and saline waters (Eisma, 1986; Droppo and Ongley, 1992; Dyer and Manning, 1999). Transportation of fine-grained suspended sediment is heavily dependent on the formation of flocs and their enhanced settling velocities which are orders of magnitude larger than that of the primary particles (Dyer, 1989; Whitehouse et al., 2000; Manning, 2004; Mehta, 2013). Therefore modelling and predicting cohesive sediment behavior demand good understandings of flocculation and floc settling processes (Soulsby et al., 2013). Since flocs are dynamic during transportation and they are highly fragile, traditional water sampling method may disrupt the flocs and unable to get the real properties of flocs in field. Hence in-situ instruments and techniques were needed and well developed, e.g., photography and video system (Eisma et al., 1990; Fennessy et al., 1994a; Manning and Dyer, 1999), and in-situ laser diffraction particle sizers (Agrawal and Pottsmith, 2000; Mikkelsen and Pejrup, 2001). The LISST (Laser In-Situ Scattering and Transmissiometry) is such an in-situ instrument widely used for flocculation studies (Mikkelsen and Pejrup, 2001; Fugate and Friedrichs, 2002; Xia et al., 2004; Curran et al., 2007; Guo and He, 2011; Markussen and Andersen, 2014). It is user-friendly and easy to handle in obtaining floc size distributions and volume concentrations. Moreover, LISST can be used to collect flocs information at different water depths and in a broader space scale, much easier and more quickly and cost efficient than using of cameras.

Brownian motion, differential settling, and fluid shears are three fundamental factors causing collision and aggregation of primary particles (Tsai et al., 1987). Many researches in the early periods had concluded that effects of Brownian motion on flocculation in

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* Corresponding author.
E-mail address: qinghe@sklec.ecnu.edu.cn (Q. He).

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estuarine and coastal environments were negligible (McCave, 1984; Partheniades, 1993; van Leussen, 1994). And the effect of differential settling was found much small through experiments by Stolzenbach and Elimelech (1994). Therefore, a number of researches focused on the effects of turbulent shears, turbidity, salinity, and biochemical processes on the development of flocs (Droppo and Ongley, 1992; Milligan and Hill, 1998; Winterwerp, 1998; Dyer and Manning, 1999; van Leussen, 1999). Fennessy et al. (1994b) reported that high current shears exert controlling influence on flocculation processes based on field data and Mietta et al. (2009) suggested that mean floc size increases with increasing organic matter content based on laboratory examinations and so on. van der Lee (2000) found that an increase in floc size with increasing suspended sediment concentration (SSC) in the Dollard Estuary, which disagrees with the results of Burban et al. (1989). Dyer (1989) provided a classical conceptual diagram on variations of floc size with SSC and turbulent shear, which showed that low shear promotes floc growth due to collision whereas a high shear leads to floc break-up, and the floc size increases with increasing SSC in quiescent water, however, larger flocs formed at higher concentrations are easily disrupted by shears. The conceptual model was confirmed by some works but did not meet all the situations and most of the researches were conducted in the low turbidity environments with SSC smaller than about 0.5 g l^{-1} (Milligan and Hill, 1998; Manning and Dyer, 1999; Xia et al., 2004; Markussen and Andersen, 2014; Sahin, 2014). It thus still needs more work in highly turbid systems to further extend our understandings of flocculation dynamics.

This study is devoted to examining flocculation in the estuarine turbidity maxima (TM) of the Yangtze Estuary (YE), a river- and tide-controlled muddy system with high SSC. Based on the laboratory and field researches, it was found that floc size increased with increase of SSC below 10 g l^{-1}, and the optimum salinity range for flocculation was 4–15‰ and the critical current velocity for flocculation was about 40–50 cm s^{-1} in the YE (Zhang et al., 1995; Guan et al., 1996; Jiang et al., 2002; Tang, 2007; Wan et al., 2015). But most of the existed researches in the YE were from lab experiments, and less research had been focused on the variation of flocculation through water column in spring-neap tidal cycles.

Training works in the North Passage (NP) of the YE in the aim to achieve a 12.5 m deep-water navigation channel lead to a huge amount of dredging requirement (60–100 million m^3 every year) (Xie et al., 2010; Song and Wang, 2013). It is thus eagerly to know where the sediments come from and how the sediments deposit in the NP. Since the NP locates in the estuarine TM zone of the YE which is characterized by high SSC of fine sediment, understandings of flocculation processes and their impacts on sediment transport will benefit searching for answers of why siltation is such high in the NP. We aim to get a better understanding of flocculation dynamics in the estuary, and the purposes of this study are to reveal floc properties at different tidal phases in the TM of the YE, and identify its implications on the channel siltation from the point view of flocculation.

2. Field work and methodology

2.1. Introduction to the Yangtze Estuary

The YE is a meso-tidal estuary with a mean tidal range of 2.66 m and spring tidal range up to 5 m. The annual river flow is approximately 9000 km^3 (1950–2010) at Datong, a station about 640 km landward the estuary mouth, and the water discharge at Datong is usually used to represent discharge to the YE. The mean and maximal water discharges in 2014 are about 28,000 $m^3\ s^{-1}$ and 56,300 $m^3\ s^{-1}$, respectively. And the decadal maximal discharge at Datong is 65,100 $m^3\ s^{-1}$ (2005–2014). The morphology of the YE is featured by three bifurcations and four outlets (see Fig. 1a). The NP is now a man-made 12.5 m (below reference level) deep-water navigational channel. The NP is 92.2 km long and the observation site located in the middle part of this channel, where most back-silting occurred in recent years (Fig. 1b).

The tide is irregularly semi-diurnal and the mean ebb tide duration is approximately 7.5 h. Water depth is about 13 m (below mean water level) at the observation site and peak ebb and flood current velocities are 2.8 m s^{-1} and 1.8 m s^{-1} at spring tide, and peak ebb and flood velocities are 1.6 m s^{-1} and 1.2 m s^{-1}, respectively, at neap tide. The median diameters of suspended primary particles are mainly about 6–9 μm, and constitutes of particles include about 40% clay, 54% silt, and 6% sand in this area.

2.2. In-situ measurements

Field works were conducted between July 13 and July 23 (wet season) in 2014, including spring, moderate, and neap tidal conditions. River discharges are about 46,000 $m^3\ s^{-1}$ at Datong during the field survey. A shipboard downward-looking ADCP (Acoustic Doppler Current Profilers) was used to measure current velocity. The sampling interval was 10 s and the bin size was 0.5 m. In-situ flocculated particle size distributions were measured with the LISST-100 (type C), and the range of particle size that the LISST-100C can differentiate is 2.5–500 μm with an accuracy of 1 phi. The LISST is based on light transmittance through a sample volume of water, it emits and records the laser in 32 scattering angle ranges, and then the signal is inverted to a volume distribution over 32 rings (Agrawal and Pottsmith, 2000). The LISST was lowered through the water column at a steady speed from 0.5 m below surface to 1 m above the bottom at a depth interval of about one-fifth of water depth every hour. LISST was set to sample every 5 s, and it measured at each layer (totally 6 layers) for at least 1 min. A volume 1.2 L of water sample was also collected every hour at 7 different water depths (0, 0.2, 0.4, 0.6, 0.8, 0.9 and 1.0 water depth) with an alpha water sampler, which was used for analyzing salinity, SSC, and primary particle size distribution.

Primary particle sizes were analyzed by a Coulter Counter after removing organic material and destroying flocs with sonification. By removing organic materials with hydrogen peroxide in lab, information of primary particles of both the macroflocs and microflocs could be obtained (van Leussen, 1999). SSC were determined by filtration through pre-weighed filters, then the filters were dried at 60 °C for eight hours. The organic matter contents of the sediment collected in spring and neap tide were determined through ignition at 450 °C for 6 h, results showed that organic matter in the mud of YE was about 3% (±1%).

2.3. Data processing

2.3.1. Floc properties

The LISST-100C recorded in-situ particle size distributions every 5 s, and then the raw data were analyzed by the LISST-SOP (version 5.00). The processed data were averaged over 1 min in each layer in order to eliminate short-term variations (Mikkelsen and Pejrup, 2001). The mean floc diameter D_M was calculated from the volume concentration distribution, and mean effective density of floc $\Delta\rho$ was calculated as below (Fettweis, 2008):