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Influence of cycles of high and low turbulent shear on the growth rate and equilibrium size of mud flocs

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ABSTRACT

Effects of repeated exposure to multiple cycles of high and low turbulent shear on mud floc growth pattern and equilibrium size were investigated through a laboratory study. The specific research questions examined were: (1) do repeated cycles of floc growth and breakup change the equilibrium floc size from one cycle to the next?; and (2) do these repeated cycles impact the floc growth rate and path to equilibrium? For the experiments, a 50 mg/l mixture of kaolinite and montmorillonite clay was sonicated and introduced to a mixing chamber to allow for flocculation under a mean turbulent shear rate of $G = 35\ s^{-1}$. Floc size time series, floc circularity index, and time series of the number of flocs were measured using a camera system and image processing routines. After the flocs reached an equilibrium size, the floc suspension was broken down with vigorous turbulent mixing ($G = 400\ s^{-1}$) for 15 h. Flocs were then allowed to regrow at a shear rate of $G = 35\ s^{-1}$. This procedure was repeated seven consecutive times. The data show that the different initial particle size distributions after sonication and after intense shearing had almost no effect on the equilibrium floc size, but that difference in initial size did significantly impact the floc growth pattern before the equilibrium was reached. With each repeated floc breakup and growth cycle, the rate of floc growth decreased. Each of the seven regrowth cycles was modeled with the Winterwerp (1998) equation for the mean floc size by calibrating the collision and breakup efficiency coefficients for each cycle. To obtain a good fit to the data, both the collision and breakup efficiency coefficients had to be reduced with each successive cycle. The observations and modeling results suggest that flocs become slightly stronger and less reactive with each repeated cycle of growth and breakup. The consistency of the equilibrium floc size in the experiment suggest that given enough time, floc settling velocity maybe reasonably modeled as a function of local conditions. However, if the time it takes to reach equilibrium is larger than the time scale of the flow of interest, then the floc settling velocity may be difficult to define without knowledge of the turbulent shear conditions encountered prior to the point of analysis; even when using a size evolving floc modeling approach.

1. Introduction

The evolution of estuarine and deltaic environments, along with the eventual lithified sedimentary texture, is significantly affected by the depositional patterns of mud. In addition to current and wave conditions, the primary factor controlling the depositional behavior of mud and sand delivered to estuaries and coastal regions is the settling velocity of the material in suspension (Geyer et al., 2004; Harris et al., 2005). Settling velocity is a function of particle size, shape, and density (Ferguson and Church, 2004; Strom and Keyvani, 2011). For sands and gravels, reasonable estimates of settling velocities at the time of deposition can be made from particles in the deposit. However, this is not the case for muds since the size, shape, and density of mud aggregates at the time of deposition can vary dynamically as a result of the flocculation process. The flocculation process, therefore, adds a layer of complication in settling velocity estimates of mud (Einstein and Krone, 1962; Dyer and Manning, 1999; Fox et al., 2004), and it makes understanding and predicting flocculation one of the key components in predicting the transport of mud in estuaries, deltas, and along the shelf (Dyer, 1989; Fox et al., 2004; Geyer et al., 2004; Dalrymple and Choi, 2007; Walsh and Nittrouer, 2009; Manning et al., 2010; Schieber, 2011).

Flocculation is a process of simultaneous aggregation and breakup of cohesive particles within the water column (Krone, 1962; Winterwerp and van Kesteren, 2004) that is important in a variety of fields including, chemical and environmental engineering, oceanography, and river and estuarine mechanics (Argamam and Kaufman, 1970; Kranck, 1973; Gibbs, 1985; McAnally and Mehta, 2000; Biggs et al., 2003; Manning et al., 2010). In general, clay particles in suspension aggregate when they are brought close enough to each other for their overall net repulsive force (generated by a positively charged ion atmosphere) to be overcome by van der Waals attractive forces. Whether or not this can happen is largely a function of the type of clay present and the thickness of the diffuse ion atmosphere surrounding the particles. Much more on

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double and Stern layer theory within the context of clay particles can be found in van Olphen (1977) and Partheniades (2009).

In the absence of biological polymers and alterations in the thickness of the ion atmosphere surrounding through changes in ion concentration, the rate of floc growth becomes largely a function of particle collision rate. These collisions are driven by Brownian motion, differential settling, and turbulent mixing (Burban et al., 1989; Eisma et al., 1991; Huang, 1994). In natural systems, turbulent mixing dominates over Brownian motion and differential settling in driving particle collisions (McAnally and Mehta, 2000). The mean turbulent shear rate, G, is a quantitative measure of turbulent mixing and is defined as $G = \sqrt{\varepsilon/\nu} = \nu/\eta^2$, where ε is the mean turbulent energy dissipation rate, ν is the kinematic viscosity of the fluid, and η is the Kolmogorov microscale (Tambo and Watanabe, 1979). Other factors that strongly impact the collision rate are the mass concentration, C, and particle size, D. Classic shear driven collision kinetics show that the rate of collision is $\propto GC^2\rho_s^{-2}D^{-3}$, where ρ_s is the sediment density (McAnally and Mehta, 2000). While turbulent mixing drives collisions, and therefore growth, the level of turbulent shear also influences maximum floc size. The more energetic the mixing, the smaller the smallest eddies in a flow get. This results in turbulent stress being transmitted to smaller and smaller scales, and ultimate floc size being roughly proportional to η (Tambo and Hozumi, 1979; Akers et al., 1987; van Leussen, 1988).

Many studies have made measurements of flocs in situ (Fennessy et al., 1994; Shumin Chen and Kalf, 1994; Dyer et al., 1996; Milligan et al., 2001; Lefebvre et al., 2012), but much of our understanding about floc dynamics has also come from laboratory experiments (e.g., Manning and Dyer, 1999; Gratiot and Manning, 2004; Manning et al., 2007; Cuthbertson et al., 2010). Most laboratory experiments that have been performed to investigate flocculation with implications for natural systems, tend to examine floc growth under a variety of steady turbulent shear and salinity conditions (Li and Logan, 1997; Marchisio et al., 2006; Mietta et al., 2009a; Kumar et al., 2010). Under steady turbulent mixing, floc sizes grow from an unaggregated state to some ultimate, equilibrium floc size where aggregation and breakup rates are balanced (Spicer et al., 1998; Biggs and Lant, 2000; Jarvis et al., 2005). Examining floc growth under constant turbulent shear rate is a natural place to start in studying flocculation. However, changes in shearing conditions due to variation in fluvial outflow and tidal cycles may lead to multiple cycles of floc growth, breakup, and regrowth that produce conditions different than the steady-state conditions often examined in the lab (Li et al., 1999; Guo and He, 2011). In situ measurements of floc size distributions in deltas and estuaries indicate that floc size and shape can be quite sensitive to changes in shear rate. For example, significant differences in floc size distributions have been observed during the slack, ebb, and flood portions of a tidal cycle in a single estuary (Eisma and Li, 1993; Braithwaite et al., 2012). Moreover, field measurements at various river mouths show that the river input during high and low flow seasons substantially affects the floc size distribution and settling properties of the mud (Chang et al., 2006; Uncles et al., 2010; Lefebvre et al., 2012). These field observations raise the question of how floc growth and structure are impacted by cycles of growth and breakup under variable turbulent shearing. Is growth independent of the levels of turbulence experienced by a suspension up to that point and only dependent on the initial clay type, particles size distribution, and turbulence level at the time of formation? Or, does the repeated high and low turbulent shear experienced by the floc suspension also factor into the growth and structure of the flocs with time?

Several studies within the waste water treatment field have examined the question of how floc sizes and growth patterns change under multiple cycles of high and low shear rates (e.g., Chaignon et al., 2002; Biggs et al., 2003; Bouyer et al., 2004; McMinn et al., 2004; Xiao et al., 2011; Slavik et al., 2012). However, such studies tend to examine the role of various flocculants and polymers on flocculation and reflocculation with the end goal being the development of better clarifier processes in waste water treatment (Gregory, 2004; Yukselen et al., 2006; Wu and van de Ven, 2009). In these types of studies, flocculation is largely governed by the additive, and the experiments are typically run for amounts of time that are less than the time scale of natural mud flocculation. These studies characterize sediment and additive mixtures as being either irreversible or reversible depending on whether or not the re-flocculation behavior is different or similar before and after grown flocs have been broken with high turbulent mixing (Leu and Ghosh, 1988; Clark and Flora, 1991; Spicer et al., 1998). Based on such studies, Spicer et al. (1998) suggests that in the presence of ionic salts such as NaCl, the behavior of flocs is reversible. Whereas, flocs formed with precipitates and polymers tend to result in irreversible flocculation. The irreversible behavior of floc suspensions has been related to breakage of sediment and flocculant or polymer bonds that result in reduced collision sticking efficiencies under re-flocculation (Leu and Ghosh, 1988).

1.1. Research questions

The question of how multiple cycles of floc growth and breakup under variable turbulent shear rates impact the growth patterns of estuarine and deltaic muds has not been examined in detail. In this study, we investigate how changes in the shear rate that create multiple floc growth and breakup cycles influence floc growth patterns in time using a mixture of kaolinite and montmorillonite without any flocculant additive. The specific research questions examined are: (1) does repeated cycles of growth and breakup change the equilibrium floc size from one cycle to another?; and (2) do these repeated cycles impact the floc growth rate and path to equilibrium? Another way of phrasing this question is as follows: do the flocs have memory of previous shear conditions, or are they simply a product of the conditions at the time of formation? The answers to these questions have implications for how flocs are treated in numerical sediment transport models of coastal zones. To examine these questions, floc growth and breakup cycles are created in a laboratory mixing chamber where turbulence and suspended sediment concentration conditions can be precisely controlled and the particle size distribution evolution can be measured at a high temporal resolution.

2. Methods

2.1. Experimental setup

The experimental setup in this study uses a 13 liter mixing chamber (27.5 × 27.5 × 25 cm) with a rotating paddle, a high-resolution camera, and an LED strobe (Fig. 1). The camera is a 1392 × 1040 pixel AVT Firewire progressive scan, monochrome 8 mm CCD camera fitted with a 2× primary magnification objective lens (Kumar et al., 2010). The optics and camera allow for measurement of individual particles ranging from 10 μm to 2.2 mm (Kumar, 2009). To eliminate the need to extract flocs from the chamber for sizing, a waterproofed LED strobe is placed inside the chamber to provide illumination and to freeze the motion of the flocs in the turbulent suspension. The camera and LED are synchronized through a data acquisition device and controlled through LabVIEW (1998).

For our system, mean turbulent energy dissipation rate was estimated as a function of the ratio of the required power for rotation of the paddle in the fluid to the water mass in the chamber (Logan, 1999). The formula proposed by Logan (1999) uses paddle area, paddle rotation velocity, and total water volume to convert the mean energy dissipation rate to the mean shear rate:

$$G = \left(\frac{52.3 b_{d,p} A_p s^3 {R_p}^3}{\nu_w V_T}\right)^{1/2} \tag{1}$$

where $b_{d,p}$ is a drag coefficient for the paddle, A_p the cross-sectional area of the paddle normal to the fluid, s is the paddle speed in revolutions per