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How do changes in suspended sediment concentration alone influence the size of mud flocs under steady turbulent shearing?

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ABSTRACT

Modeling the size and settling velocity of sediment under the influence of flocculation is crucial for the accurate prediction of mud movement and deposition in sediment transport modeling of environments such as agricultural streams, large coastal rivers, estuaries, river plumes, and turbidity currents. Yet, collecting accurate and high resolution data on mud flocs is difficult. As a result, models that account for the influence of flocculation on mud settling velocity are based on sparse data that often present non-congruent relationship in floc properties with basic influencers of flocculations such as suspended sediment concentration. This study examines the influence of suspended sediment concentration on floc size populations within a turbulent suspension. Specifically, the work investigates: (1) the relationship between the equilibrium floc size and suspended sediment concentration under conditions of steady concentration and turbulent shearing; and (2) the speed at which mature flocs adapt to an unsteady drop in the concentration when turbulent shear is constant. Two sets of experiments were used to investigate the target processes. All work was conducted in laboratory mixing tanks using a floc camera and a newly developed image acquisition method. The new method allows for direct imaging and sizing of flocs within turbulent suspensions of clay in concentrations ranging from 15 to 400 mg/L, so that no transfer of the sample to another settling column or imaging tank is needed. The primary conclusions from the two sets of experiments are: (1) that the equilibrium floc size in an energetic turbulent suspension is linearly and positively related to concentration over the range of $C = 50$ to 400 mg/L, yet with a smaller-than-expected slope based on previous data and models from low-energy environments; and (2) that floc sizes decrease quickly (with a time lag on the order of 1–15 min) to time-varying decreases in concentration at turbulent shearing of $G = 50\,\text{s}^{-1}$. Overall the data illustrate that equilibrium floc size is a positive function of concentration, but that the rate of increase is weaker than expected. The data also suggest that approximating the size or settling velocity of some muds with a simple equilibrium model might be appropriate if the time steps of interest are on the order of 10 min or larger. The data also shows the importance of calibrating historic mud settling velocity equations for accurate predictions.

1. Introduction

Engineers and scientists rely on physics-based numerical modeling to predict the transport and fate of sediment in river, estuarine, and coastal systems. In terms of predicting the transport and depositional fate of suspended sediment, the accuracy of such models depends heavily on the selection of an appropriate sediment settling velocity, w_s (Dyer, 1989; Winterwerp, 2002; Geyer et al., 2004; Harris et al., 2005; Partheniades, 2009; Chen et al., 2010). For sands, estimating the settling velocity is comparatively straightforward because w_s is a function of the size, density, and shape of the particles found in the deposit (Rubey, 1933; Dietrich, 1982; Ferguson and Church, 2004). The settling velocity of mud is essentially a function of the same properties of size, density, shape, and porosity (Krone, 1963; Dyer, 1989; Winterwerp and van Kesteren, 2004; Partheniades, 2009; Strom and Keyvani, 2011). However, the flocculation process complicates the estimation of these properties at the time of deposition for muds since suspensions of flocs can have sizes, densities, and shapes that are vastly different from the constitutive particles found in the deposit or the water column at a particular moment in time (Krone, 1963; Dyer, 1989; Winterwerp and van Kesteren, 2004; Partheniades, 2009). Therefore, understanding the flocculation process and its impact on settling velocity is crucial for sediment transport modeling of muds in rivers, estuaries, the shelf, and the deep ocean.

Flocculation is a process of simultaneous aggregation and breakup of cohesive particles within the water column (Krone, 1962;

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Winterwerp and van Kesteren, 2004). In general, clay particles in suspension aggregate when they move close enough for their net repulsive forces (generated by a positively charged ion atmosphere) to be overcome by van der Waals attractive forces. From a sediment transport perspective, the result of aggregation is that the mud settling velocity will increase due to the increase in floc size. Flocs can disaggregate due to fluid shear or ballistic impacts from other particles whenever these forces are sufficient to overcome inter-particle bond forces. The breakage of these bonds can occur around the exterior surface of the floc (erosion), or within the interior (fracture); either way, the breakup of flocs leads to a reduction in floc size and settling velocity.

The change in average floc size can be conceptualized as a rate problem (Winterwerp, 1998):

$$\frac{d(d_{f50})}{dt} = A - B \tag{1}$$

where d_{f50} is the diameter of a floc in suspension for which 50% of the flocs are finer by volume, A is the floc aggregation rate [L/t], and B is a floc breakup rate [L/t]. If A and B are unequal, the floc size will change with time and move towards an equilibrium value, d_{f50e}, defined as the floc size when $d(d_{f50})/dt = 0$ or when $A = B$. Many factors, such as: the mineral and organic composition of the mud (Krone, 1963; Partheniades, 2009; Tang and Maggi, 2016), the time history of exposure of the suspension to various levels of turbulent mixing (van Leussen, 1994; Mehta and McAnally, 2008; Keyvani and Strom, 2014), the chemical properties of the water (e.g., ion levels and pH) (Xia et al., 2004; Mietta et al., 2009), and suspended sediment concentration, C (Krone, 1978; Van Der Lee, 1998; Manning and Dyer, 1999; Mikeš and Manning, 2010) all influence the A and B terms for any given suspension. In this paper, we focus on the role that suspended sediment concentration, C, plays in altering the size of suspended mud flocs within a turbulent suspension. To provide context for the work, we briefly discuss, in the next section, the terms and processes related to the growth rate (i.e., Eq. (1)) and equilibrium size, d_{f50e} of mud flocs as it pertains to suspended sediment concentration. Then, an overview of past laboratory and field observations regarding the influence of C on floc size and settling velocity is presented. Following this general discussion, the paper examines how the influence of C can be incorporated into floc settling velocity equations used in sediment transport modeling.

2. Background

2.1. Overview

For a given mud mixture and fixed water chemistry, the floc growth rate is largely a function of the particle collision rate (McAnally and Mehta, 2000; Winterwerp and van Kesteren, 2004; Partheniades, 2009; Keyvani, 2013). Collisions can be driven by Brownian motion, differential settling, and/or turbulent mixing (Burban et al., 1989; Eisma et al., 1991; Huang, 1994). The mean turbulent shear rate, G, is a quantitative measure of turbulent energy and is defined as $G = \sqrt{\epsilon/\nu} = \nu/\eta^2$, where ϵ is the mean turbulent energy dissipation rate, ν is the kinematic viscosity of the fluid, and η is the Kolmogorov micro length scale (Tambo and Watanabe, 1979). Other factors that impact the collision rate are the particle number concentration, or the mass concentration, C, particle or floc diameter, d_f, and particle shape (Tang et al., 2014). Classic shear-driven collision kinetics show that the rate of collision is $\propto GC^2\rho_s^{-2}d_f^{-3}$, where ρ_s is the sediment density (McAnally and Mehta, 2000). Taking the collision kinetics relationship given above to be true, it is easy to see that increases in C (along with G) will promote collisions, and therefore the potential for an increase in the floc growth rate and floc size. This fact, coupled with empirical observations of suspension settling velocity in stagnant settling columns (e.g., Krone, 1962; Hwang, 1989; Teeter, 2001) have resulted in empirical floc settling velocity equations that take the settling velocity of floc-impacted mud suspensions to be a function of concentration, $w_s = w_s(C)$ (e.g., Wolanski et al., 1989; Hwang, 1989). An example of this style of relation is the three-part settling velocity equation of Hwang and Mehta (1989):

$$w_s = \begin{cases} w_{sf} & C < C_1 \\ a_w \dfrac{C^n}{(C^2 + b_w^2)^m} & C_1 < C < C_2 \\ \sim \text{negligible} & C_2 < C \end{cases} \tag{2}$$

Where w_{sf} is free settling velocity, a_w is velocity scaling coefficient, n is flocculation settling exponent, b_w is hindered settling coefficient, and m is hindered settling exponent. Eq. (2) has a general parabolic form and accounts for the impact of flocculation (due to differential settling) and hindered settling on the net suspension settling velocity. In this formulation, if $C < C_1$, flocculation is thought to have no impact on w_s; the transitional concentration marking the boundary between floc influence and no floc influence is suggested to be around 100–300 mg/L (Mehta and McAnally, 2008). C_2 is the concentration associated with the peak in settling velocity (maximum floc size) and is stated to range from 1 to 15 g/L. For concentrations higher than C_2 floc enhanced settling rates start to decline due to hindered settling affects. While not all floc-settling-velocity equations take the exact form of Eq. (2), many do take $w_s = w_s(C)$ (e.g., Ariathurai and Krone, 1976; Burt, 1986). Furthermore, many larger-scale sediment transport modeling platforms often use some sort of concentration-dependent settling velocity to account for flocculation (such as Eq. (2)) in the transport of mud regardless of whether the equation is being applied to stagnant or turbulent water.

Relations such as Eq. (2) assume that floc size will increase with C without accounting for the level of fluid stress being applied to the flocs. This assumption is an outcome of the fact that all studies which have sought to examine the influence of C on floc size or settling velocity have done so in stagnant settling columns (e.g., Krone, 1962; Huang, 1994; Teeter, 2001; Cuthbertson et al., 2016), or in suspensions for which the shearing or mixing has been turned off for a number of minutes before measurements were made (e.g., Manning and Dyer, 1999). Yet, it has also been shown that the level of turbulent energy, G, plays a key role in limiting the maximum size that a floc can obtain, and that this maximum size is proportional to the Kolmogorov micro length scale, η (van Leussen, 1997; Milligan and Hill, 1998; Manning and Dyer, 1999; Kumar et al., 2010; Braithwaite et al., 2012; Tran and Strom, 2017). Therefore, it is reasonable to expect that both $d(d_{f50})/dt$ and d_{f50e} could be a function of C and G (among other parameters). Or, at least that the function between floc size and C could look different in a turbulent suspension than it would in a stagnant, or near stagnant, settling column or tank.

2.2. Prior results and equations pertaining to the influence of concentration on the equilibrium floc size and a floc-impacted settling velocity

As discussed previously, the influence of C on d_{f50e} and w_s has been examined primarily in stagnant settling columns, in suspensions for which turbulence had been reduced prior to the time of measurement, or in conditions where both C and G covary in the field or lab (Burban et al., 1989; Chen and Eisma, 1995; Milligan and Hill, 1998; Shi, 2010; Sahin et al., 2017). As might be expected, not all of these studies report the same relationship between concentration and d_{f50e} and C (Table 1). For example, most studies have shown that d_{f50e} is positively related to C (Oles, 1992; Eisma and Li, 1993; Berhane et al., 1997; Li et al., 1999; van Leussen, 1999; Gratiot and Manning, 2004; Shi and Zhou, 2004; Law et al., 2013). Yet, a few studies have also concluded that floc size can reduce with increasing concentration (Tsai et al., 1987; Burban et al., 1989; Safak et al., 2013; Sahin et al., 2017; Guo et al., 2018). For example, Burban et al. (1989) concluded that while increasing the concentration enhances the aggregation rate, the effect of disaggregation due to three-body collisions is significant enough to result in