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Suspended clays and silts: Are they independent or dependent fractions when it comes to settling in a turbulent suspension?

Duc Tran*, Kyle Strom

Civil and Environmental Engineering, Virginia Tech, VA, USA

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ABSTRACT

This research examines whether or not mixes of clay and silt in a turbulent suspension act and settle independent of each other. More specifically, we examine the following three questions: (1) does the presence of silt in suspension alter the size of mud flocs relative to those from a pure clay suspension of equivalent concentration? (2) can silt particles become bound inside clay flocs?; and (3) if silt is bound within flocs, how does this change the settling properties of the clay and silt mixture? These questions are explored through a series of laboratory experiments in which: (a) images of flocs and silt particles within the turbulent suspension are used to measure their size distribution as a function of time; and (b) the settling velocity of the individual aggregates from each of the suspensions are measured in a settling column. The experiments use pure clay, pure silt, and two different mixture ratios of silt and clay. The results show three primary conclusions. First, the presence of silt has no significant impact on floc size. Second, most of the silt in suspension became bound up within the floc aggregates. And third, the bound silt within the flocs increased the floc settling velocity by at least 50%. These results have potential implications for the modeling of suspended mud mixtures in rivers, estuaries, and turbidity currents.

1. Introduction

1.1. Overview

Many riverine, coastal, and marine environments produce conditions where suspended sediment contains a mixture of cohesive clay minerals and non cohesive silt in the size range of $0.1 - 63\ \mu m$. Examples include, low land rivers such as the lower Mississippi (Galler and Allison, 2008), river mouth plume discharges (Walsh and Nittrouer, 2009), turbidity currents (Xu et al., 2014), and deep ocean currents (McCave and Hall, 2006). Understanding and predicting the vertical distribution of such sediment mixtures and the resulting zones and rates of deposition requires one to know the settling velocity of the particles, w_s. Without the presence of clay, the settling velocity of silt, and therefore the settling velocity of the mixture, can be defined using standard terminal settling velocity equations such as Stokes equation or that of Ferguson and Church (2004). However, the settling velocity of a pure clay suspension can be more difficult to define due to the aggregation and breakup process of flocculation. The flocculation process can produce flocs (or clay aggregates) that have sizes, densities, and shapes that are vastly different from the original constitutive, or primary clay particles. Moreover, flocs can grow or shrink in size as the turbulent properties of the flow change (Milligan and Hill, 1998; Manning and Dyer, 1999; Kumar et al., 2010; Wang et al., 2013). This makes the settling velocity of suspended clay potentially dependent on, at least, clay mineral type, flow conditions, water chemistry, and suspended sediment concentration.

A common starting point for modeling mixtures of suspended clay and silt is to assume that the silt fraction is non cohesive, that the clay fraction is cohesive, and that the two fractions mix and settle independent of one another. That is, that the settling velocity of the silt can be defined by the terminal settling velocity of a solid particle, and that the settling velocity of the clay fraction can be defined using empirical floc-modified settling velocity equations (e.g. Hwang, 1989; van Leussen, 1994; Teeter, 2001; Soulsby et al., 2013) or through modeling of the average floc size (e.g. Winterwerp, 1998) or population (e.g. Hill and Nowell, 1995; Verney et al., 2011) coupled with a floc settling velocity equation (e.g. Strom and Keyvani, 2011). This framework allows one to treat the two mud fractions independently using our knowledge of sand transport for the silt and our flocculation models that have been developed for pure clay, and then to calculate the total mixture properties through a simple linear addition. For example, if concentration profiles are linearly additive, then the effective settling velocity of a size distribution is equal to the summation of each size

* Corresponding author.
E-mail addresses: datran6@vt.edu (D. Tran), strom@vt.edu (K. Strom).

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fraction's settling velocity, $w_{s,i}$, multiplied by the fraction of the distribution contained within the size class, p_i; that is, $w_{s,avg} = \sum_{i=1}^{n} p_i w_{s,i}$. With sand or pure silt, this assumption is likely very reasonable because particles in suspension only interact through a slight transfer of momentum during collisions, and these particle collisions do not result in a change in the particle size or density. However, the reasonableness of this assumption for mixes of silt and clay is suspect due to the fragile nature of flocs and the potential for flocs to bind around silt particles. The broad goal of this paper is to explore whether or not clay and silt size fractions can be treated independently when it comes to settling velocity calculations.

1.2. Past work

The general question of whether or not clay and silt or clay, silt, and sand settle independently or together in mass has been a topic of past interest. In some cases, the mixtures have simply been treated as independent fractions. That is, the suspension was considered as having either cohesive-like or non-cohesive-like behavior, and flocculation processes were included through empirical relationships between w_s and the suspended concentration (Van Ledden, 2003; Merckelbach and Kranenburg, 2004; Hir et al., 2011; Carniello et al., 2012). Other laboratory studies have focused on bulk settling of high concentration mixtures of mud in settling columns, with the aim of identifying rates of interface descent and segregation or mixing of the clay and silt fractions in the resulting deposit texture (Amy et al., 2006; Cuthbertson et al., 2016). For instance, Amy et al. (2006) examined five settling regimes that resulted in five distinct sand-mud sedimentation textures in an effort to better understand processes that lead to sandstones with bimodal mud content. The study showed a strong dependence between the bed deposit characteristics and the concentration and ratio of cohesive to non-cohesive sediment in the suspension. Their experiments, however, were conducted in a stagnant column of water void of sustained turbulent shear. In cases where the water is stagnant and concentration of clay is high, flocs can grow to sizes that are much larger than they would be if turbulent shear existed. Hence, in such experiments, the flocculation process will possibly exaggerate its impacts on the suspension and dictate the deposit behavior in comparison to the same type of experiment with dynamic turbulent shear stress environments, e.g., river plumes and turbidity current. Another example is that of Cuthbertson et al. (2016). Employing a non-invasive, electrical resistivity measurement and time-lapsed imaging Cuthbertson et al. (2016) showed that the bulk settling velocity and bed profile varied with the ratio of clay and sand in the mixture. As such, a sharp interface with sand-dominated deposit layer turned to a mixed clay-sand transition layer with the increase of clay fraction in the mixture. Furthermore, it required a longer time to form the transition layer under the clay-dominated condition. Yet, the authors did not address the mechanism of how sand and clay interact in either a field of turbulent shear or at the particle scale.

While these studies show that there are cases where clays and silts do and do not settle as a mixture, they do not, as a whole, discuss whether or not the presence of silt and clay together in turbulent suspensions can modify the individual floc settling velocity or the settling velocity of the individual silt grains. This is important in more dilute suspensions as might be found in estuaries, plumes, and turbidity currents. The only study we know of that has attempted to look at this was the study of Manning et al. (2013). In their work, Manning et al. (2013) compared the settling velocity of clay flocs with particles and flocs formed in a mixtures of sand, silt, and clay. They concluded that the presence of sand increased the settling speed of microflocs (flocs with diameters <160 μm), but that the presence of the sand decreased the settling velocity of larger, so-called macroflocs. The Manning et al. (2013) study suggests that the presence of sand may alter the settling velocity of flocs. Yet the study does not discuss the fundamental mechanism by which sand modifies the settling speed of flocs of different sizes.

1.3. Important properties that could be impacted by size fraction interaction

The settling velocity of any particle, whether it be a solid or porous aggregate, is largely dictated by the particle or aggregate density and size. Consider the following general relation for the settling velocity of a solid particle or floc aggregate based on a balance between fluid drag and submerged weight (Ferguson and Church, 2004; Strom and Keyvani, 2011):

$$w_s = \frac{gR_f d_f^2}{b_1\nu + b_2\sqrt{gR_f d_f^3}} \tag{1}$$

where g is the acceleration of gravity, $R_f = (\rho_f - \rho)/\rho$ is the submerged specific gravity of the floc or particle, ρ_f is the density of the particle or floc, ρ is the density of the ambient water, d_f is the equivalent diameter of the floc or particle, and b_1 and b_2 are coefficients that are dependent on particle shape and porosity. For a floc aggregate, R_f is a function of floc size, d_f, raised to a negative power (Dyer and Manning, 1999; Markussen and Andersen, 2013). For convenience, one can relate R_f to d_f using a 3D fractal dimension, n_f:

$$R_f = R_s\left(\frac{d_f}{d_p}\right)^{n_f-3} \tag{2}$$

where, R_s is the submerged specific gravity of the sediment itself making up the particle or floc, d_p is the size of the solid particles that any floc may be made of, i.e., the primary particles. Note that $n_f = 3$ yield $R_f = R_s$. Therefore, for a solid particle, $n_f = 3$. For flocs, $n_f < 3$; typically falling between $n_f = 1.8$ and $n_f = 2.5$ (Khelifa and Hill, 2006; Strom and Keyvani, 2011).

Eq. (1) highlights that the floc or particle size, d_f, and density, tied up in R_f, are the two primary parameters that set the value of w_s. For silt, it is unlikely that the presence of clay will impact the settling velocity of an isolated silt grain. However, it is possible that the presence of silt could potentially alter either the size or density of a clay floc relative to that of flocs formed in a suspension of pure clay. Fig. 1 illustrates how increases in floc particle density or size leads to changes in the settling velocity. These increases are expressed in terms of percent change to better highlight the sensitivity of the parameters for flocs of different sizes. For the figure, the changes in floc density are achieved by increasing the floc fractal dimension, n_f (Eq. (3)). Of note in the figure is the sensitivity of w_s to changes in density. For example, for a floc size of 95 μm, a 50% increase in w_s (going from 0.36 mm/s to 0.54 mm/s) can be achieved through an increase in density of 4%. That is, by going from 1108 kg/m^3 to 1, 152 kg/m^3. This is equivalent to an

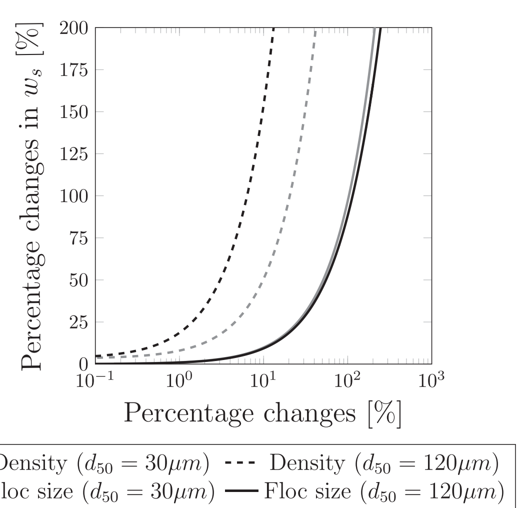

Fig. 1. Settling velocity variation with increase of density and floc size.