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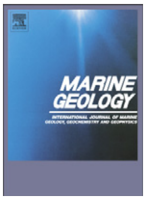

A simple method for calculating in situ floc settling velocities based on effective density functions

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ABSTRACT

We present a simple method to obtain settling velocity estimates of fine-grained suspended sediment using the following: (1) in situ floc volume fraction measurements, (2) calculations of in situ floc mass, (3) measurements of in situ floc size, (4) laboratory measurements of primary particle size and (5) laboratory measurements of % organic matter obtained through loss on ignition. This method is based on the mass distribution over the particle size spectra. Floc properties are incorporated by using information concerning the primary particles and the ratio between the volume concentration and the mass concentration of the in situ measurements. In this manner, the changes in effective densities caused by flocculation and biological mediation are approximated. This method relies solely on measurements conducted with a particle-sizing instrument and on an analysis of water samples. The method is applied to measurements obtained with a LISST, and data from three different estuaries in different climatic zones are used. The settling velocity estimates found using this method are compared to settling tube measurements and to mass settling method estimates, as well as to calculations using fractal dimension methods from the literature. Settling velocities calculated using the method presented in this study lie within the ranges of the three other methods, demonstrating that this simple method produces results within the ranges of settling tube velocities and those predicted by the more comprehensive, multiparameter fractal dimension models. The presented method allows for easy intercomparisons between studies by utilising instruments such as the LISST, and it is believed that this method would also produce reliable settling velocities using other instruments that yield a volume distribution as well as a proxy for total volume and mass concentration, e.g., some camera systems.

1. Introduction

The settling velocity, w_s, has a significant impact on the spatial patterns of sediment deposition because it greatly influences how far a suspended particle may travel before settling. Much effort has been put into developing methods to best measure the settling velocity, which is known to be dependent on the size of the settling particles and the properties of these particles (Fettweis, 2008). The two most commonly used methods for measuring particle sizes are as follows: 1) image systems (Eisma et al., 1990; Dyer and Manning, 1999; Van der Lee, 2000) and 2) laser particle sizers such as the LISST (Laser In Situ Scattering and Transmissometry) (Agrawal and Pottsmith, 2000), as well as combinations of these two methods (Mikkelsen et al., 2005; Winter et al., 2007).

The settling properties of fine-grained particles in the clay and silt size range are influenced by flocculation processes, which result in the aggregation of particles into larger aggregates, called flocs, with lower densities than the constituent primary particles. For clarity, we use the terms flocs and flocculation in reference to particle aggregation processes in suspension and aggregates and aggregation in reference to particle aggregation processes at the bed. Flocculation processes are controlled by the rate and strength of collisions and by the biogeochemical properties of the suspended matter. The main force causing collisions is turbulence, caused by current changes due to tides and waves, which enhances flocculation by increasing collision rates until the turbulent shear exceeds the shear strength of the floc bonds, thus resulting in floc break-up (Pejrup and Mikkelsen, 2010). This threshold largely depends on the properties of the flocs.

Floc properties can vary greatly between different sites, and temporal variation may even be observed at individual sites over the course of a year, e.g. caused by varying biological influence (Andersen and Pejrup, 2011). Floc properties are controlled by the floc composition and the mineral to organic ratio, as well as the aggregation process. In soil–freshwater systems, the colloidal geochemistry is known to strongly influence the particle attractive surface forces (Lead and Wilkinson, 2006). Additionally, it has been shown that the availability and

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concentration of iron alter the flocculation patterns of the freshwater constituent particles (Hassellov and von der Kammer, 2008). However, in most natural freshwater and estuarine waters, biological influences may completely dominate the geochemical differences and are highly influential in flocculation processes (Droppo et al., 1997; Droppo, 2001; Mosley et al., 2003). For instance, organic secretions, such as extracellular polymeric substances (EPS), coat particles and can strongly influence the flocculation efficiency and enhance flocculation in estuarine environments (Decho, 2000; Andersen and Pejrup, 2011). Faecal pellets and pseudo-faeces are other examples of highly biologically influenced flocs that have been shown to have much higher settling velocities than their constituent particles (Andersen and Pejrup, 2002). Such bio-aggregates are eroded or resuspended from the bed, indicating that the origin and formation of flocs vary greatly. Furthermore, aggregates created by biological activity are found in a wide range of sizes and forms and may completely encompass the inorganic components in the form of transparent exopolymer particles (TEP) in freshwater, estuarine and marine systems (Logan et al., 1995; Ayukai and Wolanski, 1997; Passow et al., 2001). The various physical and biogeochemical factors influencing floc composition are very diverse (Droppo, 2001), and the shapes of flocs are highly variable and range from a more or less rounded form to elongated, odd-sized forms (Eisma, 1986; Bainbridge et al., 2012). The result is that the shear strength of floc bonds differs according to composition as well as size, and estuarine flocs have been divided into microflocs, which are relatively small (<100 μm), dense and stable, and more fragile macroflocs (Eisma, 1986). Others have suggested adding the order *flocculi* to distinguish between single particles and very small flocs (10–20 μm) that are never broken by turbulent shear (Francois and Vanhaute, 1985; Lee et al., 2012). However, we use the classic terminology of Eisma, in which primary particles are the primary constituents of microflocs, and both primary particles and microflocs are the building blocks of the macroflocs. Thus, using this terminology, both inorganic mineral particles and organic matter may be considered to be primary particles, and the mean primary particle represents the average primary particle, which is a combination of organic and inorganic matter.

Typically, the settling properties of flocs are calculated using floc size and floc effective density, as incorporated in Stokes' Law, and using the relative influences of the forces acting on the settling flocs. Several authors have relied on the theory of fractal dimensions to explain the relationship between floc size and floc effective density (Kranenburg, 1994; Winterwerp, 1998; Ferguson and Church, 2004; Khelifa and Hill, 2006; Maggi et al., 2007; Kumar et al., 2010; Strom and Keyvani, 2011). The resulting methods are quite comprehensive as they aim to take into account all of the physical forces (viscous, drag and gravitational) influencing the settling flocs. However, these methods are based on a simplification of the evolution of floc size by assuming self-similarity of flocs and fixed values for a given dataset. This simplification limits the ability to take into account the potentially large variation in floc properties within a given dataset. Therefore, there seems to be a discrepancy between the comprehensiveness of the methods based on the theory of fractal dimensions and the necessary simplifications in these models. The main motivation for this paper is to present a simple method that seeks to describe the influence of varying floc densities on floc settling velocity and to include a simple proxy for the biological influence on floc settling velocity. The aim of this work is to limit the number of assumptions and necessary equipment so that this method may be used to give reliable, first order estimates of floc settling velocities in situations where more detailed information on floc characteristics (e.g., EPS-coatings or TEPs) is not available. Thus, the method presented in this study is based solely on measurements using an in situ particle sizer and water samples to determine the suspended sediment concentration and primary particle characteristics. The instrument used in this study is a LISST. However, this method is believed to be applicable to other particle sizing instruments, including imaging systems, provided that they give information on the particle size distribution (PSD) as well as proxies for the volume and mass concentration.

A second aim of this method is to use the entire PSD determined by the instrument rather than using only the mean values. In this way, the varying effective density over the size range of the instrument will be incorporated. Such alterations have been carried out by some researchers (Mikkelsen et al., 2005; Curran et al., 2007), but these alterations lack of a thorough description that can be applied by other authors. The goal of this work is that the simple settling velocity method presented in this paper can be used by other authors to allow for easier intercomparisons between studies.

2. Instruments and theory

The LISST (version 100C) is a widely used instrument for in situ measurements of the size distribution of suspended matter in estuarine and marine waters (Mikkelsen and Pejrup, 2001; Voulgaris and Meyers, 2004; Fettweis, 2008; Andrews et al., 2010). This instrument makes measurements by emitting a laser beam through a volume of water over a path length of a maximum of 5 cm. Forward scattering by particles in the water is measured by 32 ring detectors, with a transmissometer measuring the optical transmission in the middle of the ring detectors. Lower transmissions indicate higher concentrations of particles that diffract and/or absorb the beam. The photosensitive ring detectors are logarithmically spaced, which allows for the capture of diffraction angles at distinct ranges. To convert the scattering pattern to a PSD, the signal is inverted using a kernel matrix. This matrix defines how the volume of particles influences the attenuation of light at scattering angles corresponding to the rings. In this work, the updated matrix (“natural particles matrix”), supplied by the manufacturer Sequoia Sci., is used (Agrawal et al., 2008). Every particle scatters at roughly all angles within the range, but the maximum scattering angles change according to the particle size. After the signal is inverted according to the kernel matrix, the result is a volume distribution over the size range of the LISST (roughly 2–400 μm with the applied kernel matrix), and the sum of this distribution is the volume concentration, VC.

It has been shown that the volume concentration obtained using the LISST can be used as a direct measure of the volume concentration of flocs, V_f, (Mikkelsen and Pejrup, 2001; Voulgaris and Meyers, 2004). Therefore, if the floc mass concentration, M_f, can be estimated, the floc density, ρ_f, can be obtained using the equation, $\rho_f = V_f/M_f$. According to this definition, the floc mass concentration is defined as:

$$M_f = M_p + M_w = M_p + \rho_w\left(V_f - V_p\right) = \ M_p + \rho_w\left(V_f - \frac{M_p}{\rho_p}\right) \tag{1}$$

where M is mass per unit volume, V is the volume of flocs or particles per unit volume and suffixes p, w and f denote primary particle, water and floc, respectively (Fettweis, 2008). M_p is the suspended particulate mass concentration (SPMC) and ρ_p is the primary particle density. M_p and ρ_p can be estimated based on the analysis of water samples (see Section 4).

The fractal dimension theory methods also seek to calculate floc density. Fractal dimension theory dictates that primary particles and flocs are statistically self-similar at different scales, meaning that self-similarity exists between a floc of size d_f and the primary particles of size d_p. As d_f increases, the fractal dimension, F, decreases according to the following equation:

$$d_f = d_p \times N^{\frac{1}{F}} \tag{2}$$

provided that the amount of primary particles within the floc, N, is constant (Kranenburg, 1994). F can vary from 1 to 3, with 3 being a sold sphere. According to Winterwerp (1998), very fragile marine