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Settling velocity and mass settling flux of flocculated estuarine sediments

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ABSTRACT

New formulations are presented for the settling velocity and mass settling flux (the product of settling velocity and sediment concentration) of flocculated estuarine mud. Physics-based formulae for these are developed based on assumptions of a two-class floc population (microflocs and Macroflocs) in quasi-equilibrium with the flow. The settling velocities of microflocs and Macroflocs are related to floc size and density via the Kolmogorov microscale as a function of turbulent shear-stress and sediment concentration, including height-dependence and floc-density-dependence. Coefficients in the formulae are calibrated against an existing large data-set of in situ observations of floc size and settling velocity from Northern European estuaries. Various measures of performance show that the resulting formulae achieve an improved level of agreement with data compared with other published prediction methods. The new formulae, with the original calibration coefficients, perform well in tests against independent measurements made in two estuaries.

1. Introduction

1.1. Background

Many estuaries world-wide are dominated by muddy sediments. The presence, suspension and deposition of mud strongly influence the morphology of estuaries, and impact on both their natural characteristics and on man's use of them for transport, industry, commerce, recreation and fishing. Consequently, understanding the mud processes has been a subject of intensive research effort (e.g. Dyer, 1986; Dronkers and Van Leussen, 1988; Healy et al., 2002).

A key aspect of mud dynamics is the settling process resulting in deposition of sediments. Specifying the settling velocity of muddy sediments is much more complex than that of sand, due to its dependence on the state of flocculation, which in turn depends on the concentration of sediment, the turbulence characteristics, properties of the water and sediment, and the time/space-history of all of these. Numerous methods of predicting such settling velocities have been proposed, and some of these will be summarised later.

The aim of the present study is to develop a generic physically-based model for the mass settling flux of natural estuarine cohesive sediments. This is achieved by taking as a starting point the empirical formulae for mud floc settling velocity and mass settling flux presented by Manning and Dyer (2007, hereafter MD07), and referred to as the 'Manning Floc Settling Velocity' (MFSV) model. The MFSV has been applied successfully in various estuarine modelling applications (e.g. Spearman et al., 2011).

Nevertheless the model has some perceived weaknesses: (a) the purely empirical curve-fitting approach used to obtain the MFSV model limits its potential applicability because it is only weakly based on physical principles and could possibly be site-specific; (b) it contains a large number of fitting coefficients, which could lead to unexpected behaviour outside the immediate range of calibration, (c) most of the coefficients are dimensional (i.e. the formulae are not dimensionally homogeneous) which indicates that other dimensional physical variables are missing; (d) outside the range of shear-stresses found in the data, the floc settling velocities are simply held constant at the values occurring at the limits of validity; (e) the settling velocity formulae were fitted piecewise within three bands of shear-stress values, but the three formulae have large concentration-dependent discontinuities at the boundaries between the bands. To overcome the last problem the MFSV algorithm employs interpolation between the curves, but the interpolation method is not well-justified and results are sensitive to the exact method used.

Because of these deficiencies, an improved method was sought, using the same large data-set and employing the same broad interpretation of the dependence of settling velocity on the independent variables of suspended particulate matter (SPM) concentration and turbulence intensity or shear-stress, but with a sounder basis in physics. The resulting physics-based formulae have broader applicability, are

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dimensionally homogeneous, have fewer (mainly nondimensional) coefficients, are continuous with respect to both SPM and turbulence intensity (shear-stress), and are extendible beyond the calibrated range in a more justifiable fashion.

Like the MFSV model, the main goal is to achieve a simple yet accurate mathematical description of the vertical mass settling flux (MSF), which becomes the depositional flux close to slack water. This flux is the product of the SPM concentration and the settling velocity of the suspension. The target is to achieve at least a similar level of agreement with data to that obtained by the MD07 formulae, while reducing the level of empiricism. The new method draws on the interpretations of the data made in the development of the MFSV model by MD07, and also has commonalities with (but also differences from) the method of Winterwerp et al. (2006) in terms of the physics employed.

The MD07 data-set includes 157 field measurements of the settling velocity and size of mud flocs taken in situ between 1996 and 1999 using the INSSEV instrument (Fennessy et al., 1994) in the estuaries of the Tamar (UK), Gironde (France) and Dollard (The Netherlands). We have further tested the new method against independent INSSEV data measured in the Tamar in 2003 and the Scheldt (Belgium) in 2005.

The formulation presented by MD07 made use of the hierarchical division of flocs into microflocs and Macroflocs (e.g. Krone, 1963; Eisma, 1986), elaborated on in Section 3. Note that, because of the similarity in spelling of microflocs and Macroflocs, a capital M will be used for Macroflocs to highlight the distinction. Quantities associated with microflocs and Macroflocs are identified by subscripts μ and M respectively.

1.2. Existing models of floc settling

Many theoretical treatments of particle aggregation build on the approach developed in a pioneering paper by Smoluchowski (1917), in which the aggregates are divided into a number of size classes. His general approach is summarised by Elimelich et al. (1995), and is encapsulated in a differential equation in which the growth rate of the number of aggregates in a given class is related to the gain of new members, and loss of existing members, due to collisions between aggregates in different classes. Four mechanisms giving rise to collisions have been identified (e.g. Dyer, 1986; Krishnappan, 1991; Elimelich et al., 1995; Verney et al., 2010), namely Brownian motion, fluid shear, inertial collision, and differential settling. Expressions for the collision rates of all these mechanisms have been deduced in terms of the sizes of the two classes of aggregate involved in the collision. Expressions have also been proposed for the shear-induced break-up of flocs (e.g. Winterwerp, 1999; Verney et al., 2010), although these are less well-established than those for aggregation. Krishnappan (1991) included all four aggregation mechanisms (but no break-up mechanism) in a model of floc formation and settling in rivers, whereas Winterwerp (1999) and Verney et al. (2010) concluded that the most important processes were shear-induced aggregation and shear-induced break-up. Thus low rates of shear increase the size of flocs, high rates of shear reduce the size of flocs, and, for a given shear rate and SPM concentration, an equilibrium distribution of floc sizes will develop after a sufficiently long time. Winterwerp (1999) and Verney et al. (2010) developed fully time-evolving, multi-fraction models of floc formation and break-up, which describe the physico-chemical processes in great detail, but in both approaches a number of site-dependent parameters need to be given values, and the models are relatively heavy on computational time.

In practical applications concerning the erosion, transport and deposition of mud in estuaries, various methods of specifying the settling velocity (w_s) of the mud flocs have been used. These methods involve different combinations of input variables, and different numbers of coefficients (some of which are site-specific) to be specified. They are listed in order of increasing complexity below.

1. Specify a fixed value of w_s, usually in the range 0.5–5 mm.s^{-1}, sometimes used as a tuning parameter to match predicted erosion and deposition patterns to observations for the undisturbed estuary. One coefficient.
2. Relate w_s to the instantaneous SPM concentration through a power law (e.g. Whitehouse et al., 2000). Two coefficients.
3. Relate w_s to the instantaneous SPM concentration through a power law, including hindered settling (e.g. Whitehouse et al., 2000). Three coefficients.
4. Relate w_s to a turbulent shear parameter and a reference settling velocity (Van Leussen, 1994), usually linked to methods 2 or 3. Three to five coefficients.
5. Relate w_s to a turbulent shear parameter and the instantaneous concentration (MD07). 27 empirically fitted coefficients.
6. Relate w_s to a turbulent shear parameter, instantaneous concentration, and water depth (Winterwerp et al., 2006). Seven coefficients.
7. Solve a differential equation to deduce the time-varying representative floc diameter, from which floc density is derived by fractal considerations, and w_s obtained from a Stokes-like formula (Winterwerp, 1999). Six coefficients.
8. Apply a time-evolving two-class population balance equation to determine the spatially and temporally changing distribution of fixed-size microflocs and size-varying Macroflocs for bimodal floc distributions, with a fractal relationship between floc size and mass to derive the distribution of settling velocities (Lee et al., 2011). 17 coefficients.
9. Apply a time-evolving, multi-fraction, model to determine the spatially and temporally changing distribution of the numbers of flocs in each size fraction, with a fractal relationship between floc size and mass to derive the distribution of settling velocities (Verney et al., 2010). At least seven coefficients.

The first six of these methods are relatively quick and easy to apply in practical models of estuarine mud distributions, whereas the last three are much less straightforward, and more computationally demanding. For the present purpose, it was decided that the fifth option, as used by MD07, gives a good compromise between representation of physico-chemical processes and computational simplicity, and a similar level of sophistication was adopted here. This decision was influenced by the good results obtained from modelling studies incorporating the MD07 method (e.g. Baugh and Manning, 2007; Spearman et al., 2011). Approaches such as 4, 6 and 9 above use the shear parameter G [units of s^{-1}], which is the root–mean–square of the gradient in the turbulent velocity fluctuations, and MD07 (approach 5) use the turbulent shear stress τ. These are related (see Section 3.2) through the shear velocity u_* by $G = [u_*^3\xi / \kappa\nu z]^{1/2}$, where κ is von Karman's constant (taken as 0.40), ν is kinematic viscosity of the water, z is height above the bed, h is water depth, and $\xi = 1 - z / h$. Near the bed ($z \ll h$), this reduces to the commonly-used approximation $G = [u_*^3 / \kappa\nu z]^{1/2}$, and $\tau \approx \tau_0 = \rho u_*^2$, where τ is shear-stress at height z, τ_0 is bed shear–stress, and ρ is density of water.

We adopt the two-class approach made up of small, dense microflocs and large, sparse Macroflocs proposed by MD07. The micro/Macrofloc approach was elaborated in the population-balance equations of Lee et al. (2011), who modelled the aggregation and fragmentation processes in detail. However, they felt that further intensive investigation of the aggregation and breakage kinetics would be required before their model was generally applicable. The present study takes a simpler approach to the physics, calibrated against the large MD07 data-set, with the intention that the coefficients obtained will be applicable to a wide range of estuarine situations.