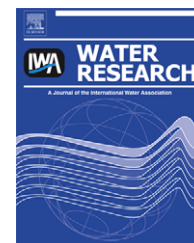


Available at www.sciencedirect.comjournal homepage: www.elsevier.com/locate/watres

The effect of variable yield strength and variable fractal dimension on flocculation of cohesive sediment

M. Son^{a,*}, T.-J. Hsu^b

^aDepartment of Civil and Coastal Engineering, University of Florida, Gainesville, FL 32611, USA

^bCenter for Applied Coastal Research, Civil and Environmental Engineering, University of Delaware, Newark, DE 19716, USA

ARTICLE INFO

Article history:

Received 3 February 2009

Received in revised form

29 April 2009

Accepted 5 May 2009

Published online 20 May 2009

Keywords:

Aggregation

Breakup

Floc

Flocculation

Fractal dimension

Yield strength

ABSTRACT

A new formulation for floc yield strength of cohesive sediment is theoretically derived and incorporated into a flocculation model based on variable fractal dimension. The new flocculation model is validated with existing data on the temporal evolution of floc size measured in the laboratory. Comparing with existing flocculation models using a constant yield strength, it is found that new flocculation model based on variable yield strength and variable fractal dimension is superior in predicting the temporal evolution of floc size. It is also demonstrated that the present model results are very similar to that using an empirical formulation of variable yield strength suggested by Sonntag and Russel (1987. Structure and breakup of flocs subjected to fluid stresses. II. Theory. J. Colloid Interface Sci. 115(2), 378–389) when the empirical coefficient is specified according to our theoretical value. Hence, it is concluded that the new variable yield strength formulation derived in this study and the variable fractal dimension are effective in improving the prediction of flocculation process.

© 2009 Elsevier Ltd. All rights reserved.

1. Introduction

1.1. Purpose of this study

Cohesive sediments, the mixture of fine-grained sediments such as clay, silt, fine sand, organic material and water, have cohesive characteristics due to significant electrochemical or biological–chemical attraction. The physics of cohesive sediment transport is more complicated than non-cohesive

sediment due to flocculation processes (e.g. Dyer, 1989; Winterwerp and van Kesteren, 2004). Cohesive sediments form floc aggregates through binding together of primary particles and smaller flocs (aggregation), and flocs can disaggregate into smaller flocs/particles due to flow shear or collision (breakup or disaggregation) (Dyer, 1989). The properties of floc aggregates constantly change with the fluid condition. The averaged size of cohesive sediment aggregate is determined by flow turbulence, concentration of sediment, biological–chemical

Abbreviations: n , Number of flocs per unit fluid volume; N , Number of primary particles within a floc; N_{rup} , Number of primary particles in the plane of rupture; N_{turb} , Rate of collision of particles due to turbulent flow; D, d , Size of floc and primary particle; D_e , Equilibrium floc size; G , Dissipation parameter (Shear rate); ϵ , Dissipation rate of energy; ν , Kinematic viscosity; t , Time; e_b, e_c, e_d , Efficiency parameter; ϕ , Volumetric concentration; ϕ_s , Solid volume fraction within the floc; c , Mass concentration; ρ_s, ρ_f, ρ_w , Density of primary particle, floc, and water; $\Delta\rho_f, \Delta\rho_s$, Immersed density of floc and primary particle; f_s , Shape factor; F , Three-dimensional fractal dimension of floc; α, β, a, p, q , Coefficient; F_c , Characteristic fractal dimension; D_{fc} , Characteristic size of floc; μ , Dynamic viscosity of the fluid; F_y, τ_y , Yield strength and stress of floc; τ_{y0}, r , Scaling and empirical parameters for τ_y ; $F_{c,p}$, Cohesive force of primary particle; B_1, B_2 , Empirical parameter; λ_0 , Kolmogorov micro scale; K'_A, K'_B , Empirical dimensionless coefficient.

* Corresponding author. Tel.: +1 352 871 6572; fax: +1 302 831 3640.

E-mail address: sonmw@ufl.edu (M. Son).

0043-1354/\$ – see front matter © 2009 Elsevier Ltd. All rights reserved.

doi:10.1016/j.watres.2009.05.016

properties of water, properties of primary particle and so on (Lick et al., 1992). Thus, accurate prediction of cohesive sediment transport may require detailed water column models that resolve time-dependent flow velocity, turbulence and sediment concentration (Winterwerp, 2002; Hsu et al., 2007). In addition to floc size, the density of floc aggregates, which is of great importance to further estimate of settling velocity, has a tendency to decrease or increase as the floc size changes (Dyer, 1989; Mehta, 1987; Kranenburg, 1994). Hence, flocculation process should be appropriately investigated when studying cohesive sediment transport.

The purpose of this study is to improve the existing flocculation models to better predict temporal evolution of floc size by incorporating more realistic parameterization on floc yield strength. A brief literature review is given in Section 1.2. Based on the assumption of fractal structure (Section 2.1), the number of primary particles in ruptured plane of a floc is calculated (Section 2.2). The heuristic equation determining the yield strength is theoretically derived based on the fractal theory (Section 2.3). This new formulation of floc strength, along with that proposed empirically by Sonntag and Russel (1987), are incorporated into the flocculation model developed by Son and Hsu (2008) (Section 3). The new flocculation model is validated with experimental data and compared with the previous flocculation models of Winterwerp (1998) and Son and Hsu (2008) based on constant yield strength (Section 4). It is concluded that utilizing variable yield strength and variable fractal dimension is critical to the prediction of the temporal evolution of floc size.

1.2. Previous studies

It is well known that the flocculation of cohesive sediment depends on collisions resulted from Brownian motion, differential settling, and turbulent shear (Dyer, 1989; Dyer and Manning, 1999; Lick et al., 1993). Hunt (1982) has investigated the effects of Brownian motion, differential settling, and turbulent shear on flocculation and concludes that turbulent shear is dominant unless for weak turbulence condition (see also Stolzenbach and Elimelech (1994), O'Melia (1980), McCave (1984), and van Leussen (1994)).

To better control the intensity of turbulent shear, many laboratory experiments have been conducted. Mixing tank experiments are carried out to obtain the temporal evolution of floc size using activated sludge (Biggs and Lant, 2000), a synthetic mineral (Bouyer et al., 2004), and synthetic resin (Spicer and Pratsinis, 1996; Spicer et al., 1998). To investigate the effect of turbulent shear and critical mechanisms causing collision for various particle sizes, Tsai et al. (1987) and Tsai and Hwang (1995) use Couette viscometers composed of two concentric cylinders to generate a velocity gradient. From these experiments, temporal variations of median floc sizes and steady-state floc size distributions are obtained.

To quantitatively predict changes of floc properties, such as density and size, many types of flocculation models (FM) have been developed. McAnally and Mehta (2000) developed a dynamic model for aggregation rate of cohesive sediment. This model considers both binary and multi-body collisions. Parker et al. (1972) consider the change of number concentration as a function of turbulent shear quantified by the dissipation

parameter (or shear rate), $G = \sqrt{\epsilon/\nu}$. Herein, ϵ is the turbulent dissipation rate and ν is the kinematic viscosity of the fluid.

Winterwerp (1998) developed a semi-empirical flocculation model which describes the rate of change of averaged floc size in turbulent flow. This model is based on: the collision frequency derived by Levich (1962); dimensional analysis; and assuming that flocs are of a fractal structure with a constant fractal dimension (van Leussen, 1994). Aggregates of cohesive sediments (flocs) have been considered as fractal entities (Tambo and Watanabe, 1979; Huang, 1994; Logan and Kilps, 1995). However, the assumption of constant fractal dimension for floc aggregate may be too restricted for modeling general cohesive sediment transport that has a wide range of flow condition and sediment concentration. Khelifa and Hill (2006) suggest a model for floc composed of mono-sized primary particles based on variable fractal dimension using a power law (see Eq. (2)). Maggi et al. (2007) also adopt a variable fractal dimension to develop a size-classes flocculation model and conclude that the use of a variable fractal dimension results in better predictions of flocculation process. More recently, Son and Hsu (2008) further extend the floc dynamic equations of Winterwerp (1998) for variable fractal dimension suggested by Khelifa and Hill (2006). Son and Hsu (2008) show that none of the two flocculation models of Winterwerp (1998) and Son and Hsu (2008) is in satisfactory agreement with experimental results for the temporal evolution of floc size in mixing tanks (see Son and Hsu (2008) or Fig. 1 (c) for more details). They conjecture that the constant yield strength adapted by these flocculation models may be the main reason causing such deficiency.

The yield strength of a floc is a very important parameter in flocculation process because it has a direct relationship with breakup process of flocculation. Many types of cohesive sediments and techniques have been employed to determine the yield strength of flocs (e.g. Leentvaar and Rebhun, 1983; Francois, 1987; Bache and Rasool, 2001; Wu et al., 2003; Gregory and Dupont, 2001; Wen and Lee, 1998; Yeung and Pelton, 1996; Zhang et al., 1999). For example, Wen and Lee (1998) apply a controllable ultrasonic field to a floc suspension and observe floc erosion. Zhang et al. (1999) squeeze a single floc in suspension between a glass slide and fiber optic using a force transducer. The values of the floc yield strength estimated in these studies are in very wide range between the orders of -2 and 3 (N/m²) (see Jarvis et al. (2005) for more details). McAnally (1999) proposes an equation for the yield stress of floc. His derivation starts with the assumption that the floc yield strength is constant as Kranenburg (1994) suggests. Whereas, Tambo and Hozumi (1979) postulate that the yield strength is related to the net solids area at the plane of rupture.

From previous studies, it is known that the fractal dimension and yield strength play an important role in modeling physics of cohesive sediment, flocculation.

2. Study on floc structure and yield strength

2.1. Fractal dimension

Under the assumption that the structure of flocs follows the self-similarity, flocs can be considered as fractal entities (e.g.

Download English Version:

<https://daneshyari.com/en/article/4484137>

Download Persian Version:

<https://daneshyari.com/article/4484137>

[Daneshyari.com](https://daneshyari.com)