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Flocculation and Settling Velocity Estimates for Reservoir Sedimentation Analysis

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PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) describes fine-grain sediment flocculation and aggregation and provides guidance and recommendations for incorporating physical sediment process descriptions (relevant to reservoir sedimentation and sediment bypassing) into U.S. Army Corps of Engineers (USACE) numerical sediment transport models.

BACKGROUND: Inland waterways provide many benefits to society but serve primarily as conduits of water and sediment. Bank erosion, channel sedimentation, and reservoir infilling remain challenges to the effective management of waterways. Reservoirs have a limited service life, associated in part with the reduced capacity caused by infilling. The USACE manages more than 600 reservoirs, many of which are experiencing reduced flood control or power generation capacity due to sedimentation. Several USACE Districts are seeking solutions to bypass sediment to extend the service life of reservoirs, beneficially use the bypassed sediment, and evaluate the impacts of sediment mobilization during and after dam removal. A key component of successfully evaluating and designing reservoir sediment management plans is numerical modeling of fine-sediment transport processes, particularly those processes related to fine-sediment aggregate settling and transport.

Particle settling is controlled by the balance of gravity, buoyancy, and drag forces, which are determined by particle properties (density, shape, size, porosity) and by fluid properties (density, viscosity). Stokes' law is commonly used to describe settling velocity of a single particle and is applicable when the particle Reynolds number (Re_p) is small ($\ll 1$) and the particle is approximately impermeable and spherical. Re_p is defined as $w_s d_p / \nu$, where

$$w_s = \frac{(\rho_p - \rho_w) g d_p^2}{18\mu} \quad (1)$$

where w_s is settling velocity, ρ_p is particle density, ρ_w is water density, g is gravitational acceleration, d_p is particle diameter, μ is dynamic fluid viscosity, and ν is kinematic viscosity.

Several researchers recognize that large, fast-settling particles disobey the laminar boundary assumption of Stokes' law and have developed corrections for the drag coefficient to extend Stokes' law to higher Re_p (Oseen 1927; Schiller and Naumann 1933). These functions modify the drag approximation for $Re_p > 1$. A common modification to Stokes' law by Schiller and Naumann (1933) is

$$w_s = \frac{gd_p^2 (\rho_p - \rho_w)}{18\mu (1 + 0.15 Re_p^{0.687})} \quad (2)$$

which is applicable for $Re_p < 800$ (Raudkivi 1998). Numerous expressions of floc properties (i.e., density) and settling velocity have been developed based on Stokes-type formulations and Schiller-Naumann drag approximations (e.g., Winterwerp 1998; Khelifa and Hill 2006).

Suspended fine sediments entering reservoirs may exist as soil/sediment aggregates (either dense *bed aggregates* or flocs/aggregates formed in the water column). The larger size of these aggregates results in settling velocities up to several orders of magnitude greater than that of the primary particles of which they are composed. For this reason, numerical models that do not represent fine sediment as aggregates often have to coarsen the sediment size distribution entering a reservoir to match the measured reservoir trapping efficiency. Bed erosion is anticipated for cases of dam removal or reservoir flushing operations; therefore, the processes of aggregate erosion and transport are crucial in predicting the outcome of reservoir management actions. The benefits of this work extend beyond the domain of waterway and reservoir sediment transport to include fine-sediment transport modeling in lacustrine and estuarine settings.

The bulk of fine-sediment flocculation research has been conducted in estuarine and coastal environments. In these environments, the aggregation/disaggregation process strongly controls the vertical flux of fine sediment. Recent observations in rivers and lakes (e.g., Droppo et al. 2005; Williams et al. 2008; Guo and He 2011) suggest that soil, sediment aggregates, and flocs are ubiquitous not only in marine environments but also in freshwater systems. Some of the mechanisms involved in freshwater flocculation are different from that seen in estuarine systems. In freshwater flocculation, bacteria and other microorganisms were found to contribute to floc growth and breakup (Droppo et al. 2005). Bacteria and microorganisms secrete extracellular polymeric substances (EPS), which increase cohesion and promote flocculation (Liao et al. 2001; Black et al. 2002). The current literature lacks an approach to adequately quantify the effects that microbial populations have on the flocculation process in freshwater and marine systems.

RESERVOIR PROCESSES: The presence of dams and reservoirs in a fluvial system can have considerable impacts on the flow of water and sediment, often resulting in long-term morphological changes. Reservoir sedimentation can decrease a reservoir's active flood control and water supply capacity. Sediment buildup near dams can decrease dam stability, leading to reduced operational capacity of the outlet system and increased maintenance operations. Erosion and degradation downstream of a dam can undermine the foundation, reducing dam stability and safety. Reservoir sedimentation can adversely affect a reservoir's water quality, water volume, hydropower operation, and recreational benefits. Excessive sediment buildup in reservoirs can also have negative impacts in downstream fluvial reaches due to flow alteration and reduction in bed material sediment, which tends to increase downstream erosion—leading to system-wide channel degradation. Reservoir sediments often contain a high percentage of fine sediment, and their mechanical behavior is largely controlled by the interparticle attraction caused by electrostatic and physiochemical forces. These properties give clays their *stickiness* and control essential phenomena such as flocculation, sedimentation rate, sediment gelling and compaction, the angle of repose, and resistance to erosion. Therefore, it is essential to consider fine-sediment transport processes in the planning, design, operation, and maintenance of a reservoir.

FLOCCULATION PROCESSES: The mechanisms of erosion, deposition, transport, and consolidation of fine sediment are governed by a complex assortment of physical, chemical, and biological factors. A key component of fine-sediment dynamics is the settling process resulting in deposition of sediment. Due to flocculation, the settling velocity of fine sediments is significantly more complex and dynamic than that of noncohesive sediments. *Flocculation* is a reversible process through which suspended fine-sediment particles are aggregated in the water column to produce flocs. Flocculation is the product of concurrently occurring aggregation and breakup processes. *Flocs* are complex composite structures composed of organic (e.g., bacteria and detritus) and inorganic (e.g., clay particles) materials that are formed through attractive electrochemical forces, biochemical bonding/binding, and interparticle collisions (Mehta 2014).

Flocs are commonly formed in suspension and/or derived from the surface of the bed via complex physical, chemical, and biological processes and are associated with apparent densities between 1,010 and 1,200 kilograms per cubic meter (kg/m^3) (van Leussen 1994; Leppard and Droppo 2005; Smith and Friedrichs 2011). *Bed aggregates* are similar in composition to flocs but are generally smaller and have higher apparent densities between 1,200 and 1,800 kg/m^3 (Winterwerp and van Kesteren 2004; Smith and Friedrichs 2011). The origin of bed aggregates are attributed to resuspension of moderately consolidated sediment from the bed (van Leussen 1994; Smith and Friedrichs 2011). The settling velocity of flocs is dependent on floc properties (i.e., size, density, shape, strength, and porosity), which in turn are controlled by turbulence, fluid properties (i.e., viscosity and density), biologic activity, and suspended sediment concentration.

The aggregation process is controlled by three collision mechanisms: (1) Brownian motion, (2) differential settling, and (3) turbulence-induced shear. In estuaries and coastal settings, with energetic hydrodynamic conditions, the relative effects of Brownian motion and differential settling on flocculation are commonly considered to be small (van Leussen 1994; Winterwerp and van Kesteren 2004). In most natural systems, turbulent shear is generally considered the dominant collision mechanism. Particle size and concentration also factor into the rate of particle collisions. Collision rate increases with increasing particle size and concentration. Ultimately, not all collisions result in larger aggregates; cohesion strength and interparticle arrangement influence the fraction of particle collisions that result in aggregation (aggregation efficiency). Factors such as the presence and abundance of biological coatings, polymer chains, organic filaments, and the varying cohesive strength of clay minerals influence aggregation efficiency (van Leussen 1994; Droppo 2001). The disaggregation (breakup) process occurs when external forcing, either from turbulence-induced stresses in the surrounding flow or collisions with other aggregates, exceeds the strength of the floc. *Floc strength* is the resistance to disaggregation and is a function of cohesion, size, primary particle orientation within the floc, and organic content (Mehta and McAnally 2008). In the near-bed zone, where the steepest velocity gradients and turbulent bursting occur and where slight contact with the bed can curtail free rotation and dramatically increase stresses in the aggregate, turbulent shear is usually the dominant breakup mechanism (Mehta and Partheniades 1975).

In natural systems, flocs can be extremely irregular, with complex geometric structures and high porosity. Krone (1962) was one of the first to suggest that these irregular particles were progressively constructed of self-similar units. In other words, larger flocs are composed of smaller, similar flocs, and these flocs are composed of even smaller, similar flocs and so forth. This

self-similarity of fine-sediment aggregates led subsequent researchers such as Kranenburg (1994) and Winterwerp (1998) to describe floc properties based on the principles of fractal geometry.

MODELS OF FLOC SETTLING: In practical applications involving erosion, transport, and deposition of fine sediments in natural waters, various methods of identifying the settling velocity of flocs have been used. Numerous empirical and numerical models have been developed from laboratory and field data predicting the settling velocity of flocculated material. These models are grouped into six classes based on methods of formulation and level of complexity. The six classes are listed in order of increasing complexity: (1) constant settling velocity, (2) simple empirical (Owen 1971; Gibbs 1985; Kranck and Milligan 1992), (3) process-based empirical (van Leussen 1994; Teisson 1997; Teeter 2001; Soulsby et al. 2013), (4) complex empirical (Soulsby 2000; Teeter 2001; Manning and Dyer 2007; Pejrup and Mikkelsen 2010), (5) fractal-based (Winterwerp 1998; Khelifa and Hill 2006; Strom and Keyvani 2011), and (6) Population Balance Equations (Verney et al. 2011; Lee et al. 2011). These classes are discussed below.

Constant Settling Velocity. A first approximation of fine-sediment settling velocities is to apply values that remain constant in both time and space. The constant settling velocities usually range from ~0.1 – 1.5 millimeters per second (mm/s). Different aggregate classes may be used, and the constant settling velocities can be determined from field or laboratory measurements (i.e., Particle Imaging Camera System, IN-Situ SETTLING Velocity-instrument, Owens Settling Column), or appropriately selected ranges of values from the literature. A caution of this approach is that in many systems, settling velocities vary over time scales of hours to seasons and spatial scales of meters to tens or hundreds of kilometers. Constant settling velocities are commonly applied as calibration parameters when observations are not available. In these cases, the variation of the settling velocity should be constrained within a plausible and defensible range.

Simple Empirical. Data collected from laboratory and in situ gravimetric settling columns have been used to relate settling velocity to a single variable (concentration or floc size) through a power law relationship. These relationships commonly require site-specific sediment coefficients to be derived empirically. Several authors (e.g., Owen 1971; Kranck and Milligan 1992) have reported an exponential relationship between median settling velocity and suspended sediment concentration (SSC) in the general form

$$w_s = aC_M^n \quad (3)$$

where w_s is settling velocity, a is an empirical coefficient, C_M is mass sediment concentration, and n is an empirical coefficient which requires a site-specific determination of w_s and C_M . Suggested values of the coefficients a and n range between 0.0002 to 0.002 and 0.6 to 1.4, respectively, based on the best fit of Equation 3 to settling velocity (m/s) and suspended mass sediment concentration (kg/m^3) data reported in Whitehouse et al. (2000).

Process-Based Empirical. Several authors have proposed simple descriptions relating settling velocity to flocculation processes. These models are empirical but provide identifiable terms associated with physical processes. One example of this class of model is that given by van Leussen (1994) and Teisson (1997) in the form of Equation 4, for which the concentration-

dependent settling velocity is expressed in the leading term and the aggregation and disaggregation processes are expressed in the numerator and denominator, respectively, of the fractional term:

$$w_s = aC_M^n \frac{(1 + \lambda_1 G)}{(1 + \lambda_2 G^2)} \quad (4)$$

where w_s is settling velocity, λ_1 is an empirically determined coefficient, λ_2 is an empirically determined breakup coefficient, and G is shear rate

$$G = \sqrt{\frac{\varepsilon}{\nu}} \quad (5)$$

where ε is the turbulent energy dissipation rate and ν is the kinematic viscosity of water. Approximations of the turbulent energy dissipation rate, ε , can be found in Tennekes and Lumley (1994). This model requires site-specific measurement of settling velocity, C_M , and water properties (i.e., density, viscosity). The site-specific data are used to determine the empirical coefficients a , n , λ_1 , and λ_2 . Model inputs include C_M , G , a , n , λ_1 , and λ_2 . Suggested values, to include units, of λ_1 and λ_2 are 266 s and 9 s², respectively (Teeter 2001).

Complex Empirical. This group represents empirical models that relate settling velocity to a set of influencing variables (e.g., concentration, floc size, shear stress, and temperature). Soulsby (2000) presents an empirically derived, explicit settling velocity expression that is a function of concentration, floc size, and density given by

$$w_s = \frac{\nu}{d_e} \left[\left(X_1^2 + X_2 (1 - C_f)^m D_*^3 \right)^{1/2} - X_1 \right] \quad (6)$$

$$d_e = IC^{n/2}$$

$$I = \left[\frac{19.8 \rho_w \nu \rho_p^n a}{g(\rho_e - \rho_w)} \right]^{1/2}$$

$$\rho_e = \rho_w + C_{in}(\rho_p - \rho_w)$$

$$C_f = \frac{(\rho_p - \rho_w)C}{\rho_e - \rho_w}$$

$$D_* = d_e \left[\frac{g(\rho_s - \rho_w)}{\rho_w \nu^2} \right]$$

where d_e is the effective floc diameter, l is a length scale, ρ_e is the effective floc density, C_{in} is the internal volume concentration inside a floc, C is the volumetric concentration of sediment in suspension, X_1 and X_2 are nondimensional empirical constants, C_f is the volumetric concentration of flocs in water, m is the hindered settling exponent, and D^* is the nondimensional flow diameter. This model was expanded from Soulsby's (1997) formulation, which was developed for estimating settling velocities of sand. The empirical relationship for sand was expanded to describe the settling of flocs with the following assumptions: (1) flocs can be treated as low-density, impermeable particles, (2) floc increase in size with increasing concentration, and (3) floc density is constant. Soulsby's model requires site-specific measurement of settling velocity, floc density, particle size, volume concentration of grains in suspension, and water properties. The following empirical coefficients a , n , and m are determined from field data. Model input parameters include, C , C_{in} , X_1 , X_2 , ρ_p , a , n , m , and water properties (for estimating v and ρ_w). The empirically derived constants X_1 and X_2 have values of 10.36 and 1.049, respectively (Soulsby 2000), and suggested values of m range from 2.5 to 5 (Richardson and Zaki 1954).

Fractal-Based. Settling velocity models based on fractal theory have recently gained wider application by mathematicians and numerical modelers. Winterwerp (1998) presented the following fractal-based implicit model, expanded from Equation 2.

$$w_s = \frac{\beta g}{18\varphi\mu} (\rho_p - \rho_w) d_p^{3-n_f} \frac{D_f^{n_f-1}}{1 + 0.15 Re_f^{0.687}} \quad (7)$$

where β and φ are particle shape factors, n_f is the fractal dimension, D_f is the floc size, and Re_f is the floc Reynolds numbers defined as

$$Re_f = \frac{w_{s,r} D_f}{\nu} \quad (8)$$

where $w_{s,r}$ is the settling velocity of a single floc in still water. Winterwerp and van Kesteren (2004) present both Lagrangian and Eulerian forms of a process- and fractal-based flocculation model. For simplicity, only the Lagrangian form is presented here:

$$\frac{dD_f}{dt} = k_a C_M G D_f^{4-n_f} - k_b G^{q+1} (D_f - d_p)^p D_f^{2q+1} \quad (9)$$

where the dimensional aggregation parameter k_a and floc breakup parameter k_b are defined as

$$k_a = k'_a \frac{(d_p^{n_f-3})}{n_f f_s \rho_p} \quad (10)$$

$$k_b = k'_b \frac{(d_p^{-p})}{n_f} \left(\frac{\mu}{F_y} \right)^q \quad (11)$$

where q and p are nondimensional, empirical exponents, k'_a and k'_b are nondimensional, empirical coefficients, f_s is a shape factor for flocs ($\pi/6$ for spherical flocs), and F_y is the yield strength of the flocs (empirically calibrated).

Winterwerp's model includes fractal-based dependencies between floc size and floc density. Unavoidably, the model requires site-specific determination of six parameters p , q , k'_a , k'_b , n_f , and F_y , reflecting the site/system sensitivity to complex factors such as biological activity, sediment mineralogy, and numerous other factors. Winterwerp (1998) calibrated the model to flocculation data obtained in the laboratory by van Leussen (1994). An equivalent field dataset would need to cover an extended period of time to obtain sufficient variation in input parameters for the calibration. Model inputs include d_p , G , C_M , ρ_p , f_s , ϕ , β , and water temperature and salinity (for estimating μ and ρ_w). Additionally, an initial condition for D_f is required. Suggested values of n_f range from 1.7 to 2.4, depending on floc density (Winterwerp 1998; Smith and Friedrichs 2011) with a typical mean value of $n_f \approx 2$ (Winterwerp 1998).

Population Balance Equations. The most complex class of settling velocity models involve the population balance equations (PBEs), which are nonlinear systems describing the dynamic processes of aggregation, disaggregation, and transport processes. PBEs are integrated by numerical methods and coupled to sediment mass conservation equations. Models of PBEs describe population changes and exchanges for a finite set of floc size classes. By including multiple size classes, this method allows a wider range of settling velocities, which is more consistent with field observations. The downside of additional size classes is the added computational burden and increased complexity of the model calibration. Model input requirements for models of PBEs are comparable to the most complex of the previously described models. Specific input requirements vary by model but generally include G , C_M , and empirical parameters related to aggregation, breakup, floc density, and floc strength. The relationships between floc size, density, strength, and settling velocity must be prescribed through fractal geometry and/or empirical power-law relationships. A full description of models of PBEs is beyond the scope of this technical note but can be found in Lick and Lick (1988), Chisholm (1999), Winterwerp (2002), and Verney (2011).

RECOMMENDATIONS: Flocculation of fine sediment involves the complex interactions of particles, fluid, biology, and chemistry through the processes of aggregation, breakup, settling, and transport. As this CHETN describes, there are varying degrees of complexity in the models used to describe the influence of flocculation on particle settling velocities. In general, increased model complexity demands increased code development and testing effort, higher computational expense, more input parameters, and increased data collection for empirical relationships and model evaluation. In choosing an appropriate flocculation model for their application, developers and users of numerical sediment transport models should carefully consider the data requirements (field-, laboratory-, and model-derived), complexity of the physical processes in the natural or engineered system, the level of complexity required for the application and results, and the present limits of understanding for flocculation and settling of fine sediments. Flocculation model complexity should be compatible and consistent with the time- and space-resolution of the process descriptions in the numerical hydrodynamic model. For instance, a model with low resolution or highly simplified hydrodynamic processes should not be coupled with a flocculation model that requires inputs (such as G) that are unavailable or grossly simplified in the hydrodynamic model.

A general recommendation is to use the simplest model possible to adequately describe the system for the intended application. For screening-level studies or systems with limited spatial or temporal variability in settling velocities, the constant settling velocity approach may be sufficient to meet the study objectives. The constant settling velocities may be derived from field or laboratory experiments, published values, or model calibration coefficients (constrained to plausible and defensible values). Systems characterized by concentration (C_M) or shear (G) influences on flocculation may require one of the simple or process-based empirical approaches. The simple and process-based empirical approaches require experimental data to populate their empirical parameters. Often these methods require a substantial quantity of field data for successful parameterization. The more complex empirical methods and PBEs are best reserved for applications requiring a high degree of settling process description. These approaches usually require a substantial quantity of experimental data, additional effort in defining the empirical coefficients, and higher computational effort during simulation.

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