河川・海岸系での物質輸送モデル（3） Cohesive Sediment Transport

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1. Introduction

The prediction of concentrations of suspended cohesive sediments and their transport is vital importance to their management with respect to the maintenance of environments. It is well known that the transport and fate of fine-grained sediment in dynamic environment such as estuaries and coastal waters is a function of the effective settling velocity of the sediment, which in turn is affected by flocculation. This paper focuses on the research to introduce flocculation process on the cohesive sediment transport.

From the description of mud flocs, which is treated as self-similar fractal entities, a new formulation for the settling velocity as a function of floc size is derived. The evolution of floc size in turbulent environment is described through flocculation model (Winterwerp, 1999) in a Eulerean framework that includes the effects of turbulence induced aggregation and floc breakup.

The flocculation model is implemented in a three-dimensional hydrodynamic and sediment transport model, ECOMSED, an applied to simulate the evolution of settling velocity of cohesive sediments.

2. Model outline

A three-dimensional finite difference model system for hydrodynamics and cohesive sediment transport, ECOMSED solves the Navier-Stokes equations with a free surface boundary condition and the advection-diffusion equations of the temperature, the salinity and any other variable. Density effects, wind stress on the free surface, heat exchange with the atmosphere and the Coriolis force are included in the model. Variations of the density are taken into account in the momentum equation via the Boussinesq approximation. The physical problems considered allow assuming that the pressure is hydrostatic.To model sediment transport, two specific modules were developed:

2.1 *The suspended sediment module*

The transport of suspended sediment is described by the following advection-diffusion equation:

$$\frac{\partial c}{\partial t}+\frac{\partial uc}{\partial x}+\frac{\partial vc}{\partial y}+\frac{\partial (w-w_s)c}{\partial z} = \frac{\partial}{\partial x}\left(A_H\frac{\partial c}{\partial x}\right)+\frac{\partial}{\partial y}\left(A_H\frac{\partial c}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_H\frac{\partial c}{\partial z}\right)$$

in which c: concentration of the suspended sediment, and u, v, w: velocity component. A_H is horizontal diffusivity and K_H is vertical eddy diffusivity.

2.2 *A model for flocculation and settling velocity*

<u>Relation between settling velocity and floc size</u>

Winterwerp (1998) developed three-dimensional Eulerian model of the evolution of the settling velocity of fine-grained cohesive sediment in turbulent open channel flow:

$$w_{sr}=\frac{\alpha}{18\beta}\frac{(\rho_s-\rho_w)}{\mu}D_p^{3-n_f}\frac{D^{n_f-1}}{1+0.15\,Re^{0.687}}$$

which D is the actual floc size, D_p is the diameter of the primary particle and n_f is fractal dimension for sediment particles. α and β are coefficients depending on the spherity of the particles, and Re is the particle Reynolds.

Mud flocs seldom settle as individual particles. When their concentration becomes high enough, the settling flocs start to hinder each other in their movement, generally known as hindered settling. The effective settling velocity w_s in suspension of cohesive sediment affected by the process of hindered settling defined as:

$$w_s=w_{sr}\frac{(1-\phi_*)(1-\phi_p)}{1+2.5\phi}$$

In which the factor $(1-\phi_*)$ accounts for the return-flow effect. The volumetric concentration $\phi_* = \min(1,\phi)$ to account for the fact that c/c_{gel} can exceed unity in a consolidating fluid mud layer.

<u>A model for turbulence-induced flocculation</u>

The differential equation for the flocculation of cohesive sediment under the influence of turbulent shear, then becomes:

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial x_i}\left(\left(u_i-\delta_{i,3}\frac{(1-\phi_*)(1-\phi_p)}{(1+2.5\phi)}w_{sr}\right)N\right) - \frac{\partial}{\partial x_i}\left((D_s+\Gamma_T)\frac{\partial N}{\partial x_i}\right) = -k'_A(1-\phi_*)GD^3N^2 + k_BG^{q+1}(D-D_p)^pD^{2q}N+E_{b,N}$$

in which the parameter k'_A and k_B are defined as follows (e.g. Winterwerp, 1998):

$$k'_A=\tfrac{3}{2}e_c\pi e_d \quad \text{and} \quad k_B=ae_bD_p^{-p}\left(\frac{\mu}{F_y}\right)^q \qquad (1)$$

Those set of equation, forming the flocculation model are implemented in ECOMSED and solved simultaneously. The turbulent shear flow and sediment concentration govern the flocculation process, hence the settling velocity. The settling velocity affects the vertical concentration profile, hence the eddy viscosity and thus the velocity profile.