Modelling the transport of fine suspended sediments

Nguyen, Hoang Ha

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**MODELLING THE TRANSPORT OF
FINE SUSPENDED SEDIMENTS**

NGUYEN HOANG HA

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

2012

MODELLING THE TRANSPORT OF FINE SUSPENDED SEDIMENTS

NGUYEN HOANG HA

School of Civil and Environmental Engineering

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School of Civil and Environmental Engineering, NTU, Singapore

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Summary

The study of fine sediment transport is complicated because it consists of many separate processes such as flocculation if the sediment is cohesive, settling and mixing, deposition, re-suspension and consolidation, etc. In order to model the transport process accurately, all the above-mentioned individual processes and the hydrodynamic characteristics of the flow field need to be correctly modeled, simultaneously. Many studies on the sediment transport process have been conducted in the past; however, gaps exist in our knowledge on this topic and much scope for improvements exists. The present study focuses on some of the fundamental behaviour of sediments in the aquatic environment. These include floc density, dynamic viscosity, and effects of turbulence and sediment concentration on flocculation and settling velocity of (floc) particles. A physically-based parametric approach is developed to improve the existing models; turbulent Reynolds number ($Re_t \equiv k^2 / \epsilon \nu$, where k and ϵ are the turbulent kinetic energy and its dissipation rate, respectively), which reflects the turbulence level, is used to estimate the strength of flocs and effects of turbulence on the flocculation and settling velocity.

An alternative model for estimating the effective density of flocs ($\Delta\rho_f$) was developed by applying dimensional analysis. The model takes into account the effective density of the primary particles, in addition to the sizes of the floc and primary particles, and does not consider the concept of self-similarity. The model contains three dimensionless products and two empirical coefficients, which were calibrated and verified using data available in the literature. Good comparisons were obtained when the estimated floc settling velocity on the basis of the proposed model for $\Delta\rho_f$ was compared with the measured value.

A new model for estimating the relative viscosity of sediment-fluid mixtures (μ_r) was proposed. The model takes into account the maximum volumetric concentration (ϕ_{max}) and two empirical coefficients and is applicable to mixtures of non-cohesive and/or cohesive sediments. The model was calibrated against

experimental data and compared with predictions by existing models. For non-cohesive sediments, the proposed model provided a good fit to experimental data of μ_r obtained from a variety of sources. For cohesive sediments, floc settling velocity calculations were made using viscosity estimated on the basis of the proposed model. Good comparisons were obtained when the estimated settling velocity was compared against the settling velocity obtained from existing models found in the literature.

Based on a modified form of the force balance equation of a particle, a new model for estimating the drag coefficient of a particle settling in turbulence mixture ($C_{D,mt}$) was proposed. The model contains two fitting coefficients and is applicable to both non-cohesive and cohesive sediments. The Re_t , instead of the shear rate (G), was used to quantify the turbulence level. The new model was verified against available experimental data. Good comparisons were obtained when the relative settling velocity estimated based on the proposed model was compared with available experimental data.

A simplified model for flocculation (aggregation and breakup) of cohesive sediments was proposed. The model utilizes physical arguments and data generated from existing Smoluchowski theory-based models. Three main factors affecting floc size (flow turbulence, sediment concentration, and salinity) are included. The Re_t is used to quantify the turbulence instead of G . The new model considers aggregation and breakup separately. Existing experimental data and data generated from two existing flocculation models were utilized for obtaining and verifying the values of the empirical coefficients of the new model. Compared to the existing models, the new model is much simpler and does not require a numerical solver or iterations, but still gives good predictions for floc size evolution. This makes the new model suitable to implement and amenable to numerical modelling applications for the study of cohesive sediment transport.

The proposed models were incorporated into the MIKE 3 Flow Model FM modelling system by utilizing the ECO Lab module. A new ECO Lab template, which considers sedimentation, deposition, erosion and resuspension, flocculation, advection and dispersion processes, was developed for fine suspended sediment transport in 3D.

The template includes the proposed models. It was tested against the existing Mud Transport module of the MIKE system and applied to the Ems estuary. However, at the moment, due to limitation of the ECO Lab module, it is impossible to implement evolution of floc size, update of bed level, and feedback of density and viscosity to hydrodynamic module. In addition, the new template has yet to consider multi-fractions sediments.

For better understanding of the topic, the present study recommends that the model coefficients need further investigation. Also, an improvement for the ECO Lab template is required. Finally, a review on deposition and erosion processes is necessary to verify if the existing models for these processes are suitable for the numerical application.

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List of Symbols

Symbol	Definition	Unit
α, β, ζ	Empirical coefficients	[-]
α_v, A_v	Empirical coefficients	[-]
α_0	Initial collision-agglomeration factor	[-]
$\Delta\rho_f$	Effective density of flocs	kg/m ³
λ_0	Kolmogorov length scale	m
μ	Dynamic viscosity	Ns/m ²
μ_r	Relative dynamic viscosity	[-]
ν	Kinetic viscosity	m ² /s
π_1, π_2, π_3	Dimensionless groups	[-]
ρ	Density	kg/m ³
τ_c	Current-induced bed shear stresses	N/m ²
τ_{ce}, τ_{cd}	Critical bed shear stress for erosion and deposition	N/m ²
c, ϕ	Mass and volumetric concentration	kg/m ³ , [-]
c_{gel}, ϕ_{gel}	Mass and volumetric concentration at gelling point	kg/m ³ , [-]
C_D	Drag coefficient	[-]
D_f, D_p	Sizes of the flocs and primary particles	m
D_{f0}, D_{fE}	Initial and equilibrium steady state floc sizes	m
D_{p50}	Median size of primary particles	m
$\tilde{D}^*, D^*$	Dimensionless particle parameters	[-]
E, n	Erodibility of bed and power of erosion	kg/m ² /s, [-]
F, n_f	Fractal dimensions	[-]
F_c, D_{fc}	Characteristic values of F and D_f	[-], m
f_c	Current friction coefficient	[-]
g	Gravitational acceleration	m/s
G	Shear rate	1/s
k_1, k_2, k_3	Coefficients in the force balance equations	[-]

k, ε	Turbulent kinetic energy and its dissipation rate	$m^2/s^2, m^2/s^3$
k_s	Bed roughness	m
N	Number of primary particles in a floc	[-]
M, N, n	coefficients in Cheng's approach	[-]
Re_t	Turbulent Reynolds number determined by k- ε model	[-]
Re_p	Particle Reynolds number	[-]
$Re_{p,t}$	Particle Reynolds number under turbulent condition	[-]
R_{50}, N_0	Numbers of primary particles in a floc	[-]
S	Salinity or Sink/Source term	[-]
SF	Corey shape factor	[-]
S_s, S_D, S_E	Sedimentation, deposition, and erosion rate	$kg/m^2/s$
S_m	Normalized maximum floc volume	[-]
SSC	Suspended sediment concentration	kg/m^3
T_0, T^*	Reference time and equilibrium flocculation time	s
V_T	Apparent settling velocity	m/s
w_s	Relative settling velocity of (floc) particle in fluid	m/s
$W_{s,mt}$	Hindered settling velocity under turbulent condition	m/s
z	Distance from grid location to measured point	m

<i>Subscript</i>	<i>refers to</i>
·A	aggregation
·B	breakup
·E	equilibrium
·f	floc
·gel	gelling point
·H	hinder
·m	mixture
·p	primary particle or particle
·s	solid or settling or salinity
·t	turbulence
·w	water

Chapter 1 INTRODUCTION

1.1 Overview

1.1.1 General

Sediments are usually referred to as gravel, sand, silt or clay. According to the American Geophysical Union Sediment Classification System (van Rijn, 1993), gravel refers to the sediments within the size range of 2 to 64 mm, sand from 62 to 2000 μm , silt from 4 to 62 μm and clay from 0.25 to 4 μm . Colloids have sizes smaller than 0.24 μm . Generally, in the natural aquatic environment, the size of sediments in suspension covers a wide range of particle sizes. A simple mathematical form (log-normal or power law) can be applied to describe the distribution of particle size, mass or volume (Gregory, 2006). In addition, natural particles have various shapes described as rods, plates and spheres (Chien and Wan, 1999; Van Rijn, 1993; Gregory, 2006). In sediment transport study, sediments are classified as non-cohesive or cohesive sediments. In general, gravel, sand and silt are non-cohesive whereas clay particles are cohesive. Due to the combination of London-van der Waals and electrical-double layer interactions (DLVO) and non-DLVO forces (hydration effects, hydrophobic, steric interaction of adsorbed layers and polymer bridging) the cohesive particles (primary particles) can stick together to form aggregate (floc) or repel each other (Gregory, 2006). Generally, the shape of the floc is not spherical. In many cases, the (floc) particles are assumed to be spherical and the hydrodynamic properties of a particle with a characteristic size are considered. A common concept of the “equivalent sphere” based on a chosen property of the particle, for e.g. area, volume, weight or settling velocity, etc., is applied to non-spherical particles. The density of quartz and clay mineral is approximately equal to 2,650 kg/m^3 whereas the density of flocs is much smaller and dependent on the size of flocs (Gregory, 2006). The porosity of sediment material is related to the deposition history of the sediment bed. Loose packing occurs when sediments settle from suspension in still water. The maximum porosity of 48% is possible for cubic

arrangement with spherical particles; whereas mud deposits consisting of clay, silt, sand and organic matter, etc. can have larger porosities, up to as high as 80% (van Rijn, 1993). Finally, according to Uittenbogaard (1994), sand particles with a diameter up to 200 μm can properly follow the turbulent movements, occurring in typical tidal flows. Mud is referred to a mixture of water and some combination of clay, silt, sand, organic matter and sometimes gas (Winterwerp, 1999) and the existence of more than 10% of clay particles in the mixture often results in an adhesive behaviour (Soltanpour and Jazayeri, 2009). In the present study, fine sediments are therefore referred to sand with size smaller than 200 μm for non-cohesive sediments, or to clay and mud for cohesive sediments.

Sediment transport has been a widely studied topic due to the preponderance of sediments and its deleterious impacts on water bodies all over the world. Sediments can give rise to the mobilization of contaminants, cause obstruction to shipping vessels from access channels or harbors due to siltation, etc. In the natural environment, there is a continuous transport cycle of material which consists of erosion, flocculation (aggregation and breakup) of cohesive sediments, settling, deposition, consolidation and erosion. These processes are affected by hydrodynamic changes are complicated. Although many studies on cohesive sediment transport have been conducted in the past large gaps however still exist in our knowledge on this topic (Intercoh, 2011; Droppo et al., 2005).

The studies of suspended sediment transport finds solution to the mass balance equation (e.g., Hayter and Mehta, 1986; van Rijn, 1993; Jensen, 2000; Jensen and Fredsoe, 2001), which in 3D is:

$$\frac{\partial c}{\partial t} + \frac{\partial uc}{\partial x} + \frac{\partial vc}{\partial y} + \frac{\partial (w - W_s)c}{\partial z} = \frac{\partial}{\partial x} \left(D_x \frac{\partial c}{\partial x} \right) + \frac{\partial}{\partial y} \left(D_y \frac{\partial c}{\partial y} \right) + \frac{\partial}{\partial z} \left(D_z \frac{\partial c}{\partial z} \right) + SS \quad (1.1)$$

where c is the suspended sediment concentration; t is time; u , v and w are the mean velocity components in x , y and z directions, respectively; W_s is the particle settling velocity; D_x , D_y and D_z are the dispersion coefficients in x , y and z directions, respectively; SS is the sink/source term. The boundary conditions at the bed of the

equation require specifications of the exchange (convection flux, the diffusive flux, and the net flux) of sediments at the bed and depend on deposition and erosion/resuspension processes of sediments. For non-cohesive sediments, the deposition and erosion/resuspension are normally determined on the basis of the difference between c and c_{eq} (equilibrium concentration) at the same small height above the bed; deposition occurs when $c > c_{eq}$ and erosion occurs when $c < c_{eq}$. A survey of the fundamental issues related to the solution to Eq. (1.1) is given below.

1.1.2 Settling and Flocculation

The settling velocity of sediments is one of key parameters in sediment transport analysis since the sedimentation and deposition of sediments are dependent on the settling velocity. A change in factors such as the density of particles, viscosity of the sediment-fluid mixture, and flow conditions will affect the settling velocity (see Chapters 2-5 in this Thesis). This becomes more complicated if the sediments are cohesive. Depending on the fraction and nature of the particles and salinity, these particles can stick together due to physicochemical interaction to form larger flocs, which will settle at higher settling velocities than those of the individual particles. Moreover, the larger flocs can be broken up under flow turbulence into smaller flocs.

Estimating effective floc density is a difficult task as there is no direct method available to measure the density of flocs. Floc density is usually estimated indirectly by using a modified Stokes' law and the measured settling velocity and size of flocs. Using this approach, many empirical or semi-empirical approximations have been proposed to estimate the density of flocs. Recently, the concept of self-similar fractal flocs has been widely used in the estimation of effective floc density. However, the assumption of self-similar fractal flocs is not realistic (Kranenburg, 1994).

For non-cohesive sediments, research on the estimation of relative viscosity of fluid-sediment mixtures includes theoretical, empirical and semi-empirical approximations. For cohesive sediments, Winterwerp (1999) adopted the Einstein formula while Camenen (2008) used a modified form of the Dougherty-Krieger

formula. Generally, there is no general model for the relative viscosity, which can be equally applicable to both non-cohesive and cohesive sediments.

The drag coefficient is another important parameter in the determination of the settling velocity of sediments. For particles settling in a still fluid, there have been many experimental, analytical, and numerical studies on the drag coefficient and many expressions are available for estimating the drag coefficient. Similarly, for particles settling in turbulent flows, there have also been many experimental, analytical, and numerical studies. However, there are conflicting conclusions on whether turbulence increases or decreases the particle settling velocity.

Flocculation of cohesive sediments is a very complicated process consisting of aggregation and breakup processes. Factors such as the sediment concentration, primary particle size and shear rate are important. Most of the existing flocculation models are based on Smoluchowski's theory, which describes aggregation kinetics assuming two-body collisions due to Brownian diffusion, fluid shear, and differential sedimentation. Tambo and Watanabe (1979b) model aggregation and breakup separately; evolution of floc size in the aggregation process is controlled by the breakup process, i.e. the maximum floc size at a given shear rate. In the flocculation model proposed by Gregory (1981), the breakup process is implicitly incorporated into the aggregation process through a collision efficiency factor, which is much less than unity. Winterwerp (1999) modeled the flocculation process by a linear combination of formulations for aggregation and breakup. McAnally and Mehta (2000) considered two- and three-body collisions and showed that the three-body collisions can have a significant effect on the aggregation process. However, there is still a large difference between predicted and measured values of sediment concentration when several existing flocculation models are used in the study of cohesive sediment transport (Spearman and Roberts, 2002).

1.1.3 Deposition

Generally, sediments will deposit onto the bed when the bed shear stress (τ) falls below a critical value for deposition ($\tau_{c,d}$) (Partheniades, 1965). There have been some studies on the deposition of cohesive sediments, among which the results of the studies of Krone (1962) and Mehta and Partheniades (1975) have been mentioned widely (van Rijn, 1993; Winterwerp, 1999; Le Normant, 2000; Hayter et al., 2000; Lesser et al., 2004; DHI, 2009a). Krone (1962) conducted depositional experiments in a straight flume while Mehta and Partheniades (1975) ran experiments in straight and circular flumes, performing their experiments with cohesive sediments under steady flow conditions. Krone (1962) showed that deposition rate depends on concentration. For high concentrations ($c > 10 \text{ kg/m}^3$), the deposition rate is relatively low due to hindered settling effects. The small settling velocity near the bed relative to the large settling velocity at the upper layer results in the formation of a near-bed fluid mud layer. The thickness of this layer will increase when the deposition rate is larger than the consolidation rate. For lower concentrations ($c = 0.3 \text{ to } 10 \text{ kg/m}^3$), the deposition process is rapid due to aggregation effects. For very low concentration ($c < 0.3 \text{ kg/m}^3$), the deposition process is very slow; the deposition rate can be increased by intensifying the turbulence (van Rijn, 1993). Mehta and Partheniades (1975) measured the concentration at equilibrium state with the bed shear stresses both smaller and larger than a critical bed shear stress for full deposition. In their experiments, the initial concentration was 1 to 10 kg/m^3 . Their results show that there are three distinct regions: full deposition ($\tau < \tau_{d,\text{full}}$), hindered or partial deposition ($\tau_{b,\text{full}} < \tau < \tau_{d,\text{part}}$) and no deposition ($\tau > \tau_{d,\text{part}}$). For kaolinite in distilled water, their experiments gives $\tau_{d,\text{full}} \approx 0.15 \text{ N/m}^2$. Following Mehta and Partheniades' (1975) procedure, Winterwerp et al. (1991) carried out experiments with different sediments in The Netherlands and found that $\tau_{d,\text{full}} \approx 0.03 \text{ to } 0.15 \text{ N/m}^2$ for full deposition, and $\tau_{d,\text{part}} \approx 1.4 \text{ N/m}^2$ for hindered deposition (e.g. van Rijn, 1993).

1.1.4 Consolidation

After depositing to the bottom of the fluid column, flocs will develop bonds with the other flocs to form a continuous structure, which can carry a part of its own weight. As a result, the pore water pressure will be lower than the total weight of the structure. The effective stress, $\sigma' = \sigma - u_w = \sigma - (u_o + u)$, where σ is the stress induced by overburden pressure and self-weight; u_w is pressure carried by the fluid; u_o is hydrostatic pressure; and $u = u_w - u_o$ is excess pore-water pressure) causes the soil structure to collapse slowly to form a more condensed structure as pore water is expelled. This phenomenon is known as consolidation (Holtz and Kovacs, 1981). The consolidation process increases the critical bed shear stress for erosion and decreases the bed erodibility. Terzaghi (1925) first developed the theory for 1-D consolidation (Holtz and Kovacs, 1981). By using Darcy's law, relating the hydraulic gradient causing the flow through the pores to the excess pore-water pressure and relating the change in void ratio to the change in the effective stress, Terzaghi (1925) derived the governing equation for 1-D consolidation. Gibson et al. (1967) also used Darcy's law but considered the variation of permeability and compressibility of the clay layer during the consolidation; moreover, they did not make use of the assumption of small strain in the soil. Toorman (1996) compared the consolidation theories used by geotechnical and chemical engineers and showed that there is no difference between the two. Moreover, he described the sedimentation and consolidation processes by a general unifying theory. By using the Darcy-Gersevanov law (Gersevanov, 1934) for the excess pressure gradient and by introducing a diffusive component, he derived a general formula which can be solved with closure equations for permeability and the effective stress. Winterwerp (1999) followed Toorman's (1996) ideas on the processes in still water with the effect of Brownian diffusion to arrive a general equation in the turbulent flow with the effect of turbulent diffusion, which describes settling and consolidation processes.

In addition to theoretical studies, many experiments on consolidation have been carried out by, for e.g., Migniot (1989), Nedeco (1985), van Rijn (1985) and

Winterwerp et al. (1991), etc. (e.g. van Rijn, 1993). Based on experimental data, van Rijn (1993) distinguished three consolidation stages: initial stage (days), secondary stage (weeks) and final stage (years). The consolidation process is strongly affected by the thickness of the mud layer, initial concentration of the mud layer, permeability of the mud layer (sediment composition and size, content of organic material, salinity, etc.) and consolidation time.

1.1.5 Erosion and Resuspension

The deposited flocs develop bonds with the bed flocs. The bed shear stress needed to disrupt these bonds and overcome the submerged floc weight has to be larger than that at which the floc is deposited. This larger value is called the critical bed shear stress for erosion ($\tau_{c,e}$). Generally, the $\tau_{c,e}$ value strongly depends on the deposition process and consolidation history. There are two main types of erosion: surface erosion and mass erosion (van Rijn, 1993). Moreover, under the influence of waves, the effective stress within the structure may become zero resulting in the liquefaction in the soil, which may cause increased erosion (DHI, 2009a). After being eroded, the sediment will be re-suspended due to turbulence in the flow field.

There have been many experimental studies on the critical bed shear stress for erosion, for example, Young and Southard (1978), Migniot (1968), Parchure and Mehta (1985) and Winterwerp et al. (1991). However, according to van Rijn (1993), there are no generally accepted relationships for determining the value of $\tau_{c,e}$ because of the discrepancy between field and laboratory results. The difference may be ascribed to a change in sediment cohesion caused by natural bioturbation (biologically aggregated sediments) yielding lower density in the in-situ observation (van Rijn, 1993).

The critical bed shear stress for erosion of consolidated hard deposits is larger than that of consolidated soft deposits (e.g., van Rijn, 1993). For consolidated hard deposits, the threshold velocity for erosion can be about from 0.3 to 2.0 m/s for loose and compact soil respectively. For consolidated soft deposits, $\tau_{c,e}$ increases with the dry

density (sediment concentration) of the soil, which increases with the depth, and salinity.

1.2 Motivation

As there is no exact closed-form analytical solution to Eq. (1.1), the solution to the equation has to be solved numerically. Conservation equations of mass, momentum and energy, and equations of state are used in the modeling of flow as well as in the modeling of suspended sediments. In mathematical modelling, different turbulence models (Boussinesq eddy viscosity, Prandtl's mixing length model and k- ϵ model, etc.) are used. In practice, widely used modelling systems such as MIKE 3 Flow Model (DHI, 2009a), Delft3D Flow Model (Deltares, 2012), and TELEMAC Model (EDF-LNH and SOGREAH, 1997), etc. apply different treatment for the diffusivity, particle settling velocity, and flocculation of cohesive sediments, etc. Within the frame work of the COSINUS project (Prediction of Cohesive Sediment Transport and Bed Dynamics in Estuaries and Coastal Zones with Integrated Numerical Simulation Models), Violeau et al. (2002) inter-compared five numerical models received from five laboratories or universities (Table 1.1); for the mixing length model, the effects of the suspended sediment to the reduction of the eddy viscosity and the eddy diffusivity were taken into account by applying buoyancy damping functions. The authors compared the results from five models (Fig. 1.1) and showed that the models gave nearly the same velocity profiles; however, the models gave different results for the concentration profile. In addition, none of the models reproduced the measured settling velocity well (Violeau et al., 2002). These lead the authors to remark that the real behaviour of sediment is still subject to a lack of knowledge, even in a simple case and that despite the latest progress in theory, the numerical models are still inconsistent. The results are hardly surprising as suspended sediment transport is very complicated and encompasses many complex processes such as flocculation (for cohesive sediments), settling and mixing, deposition, re-suspension and consolidation, etc. The transport of fine sediments can

only be accurately modeled when all the above processes, together with hydrodynamic characteristics, are correctly modeled, simultaneously.

Figure 1.1 - 1DV case: velocity and concentration profiles for $c_0 = 0.01$ g/l.
(Source: Violeau et al., 2002).

Table 1.1 - Numerical codes used in the inter-comparison (Source: Violeau et al., 2002)

Institute	Model	Numerical method	Turbulence model	Cases
HR Wallingford	SULIS	3D coupled fully implicit finite differences	Mixing length	Test cases
Univ. of Leuven	FENST-2D	2DV fully implicit finite elements	$k-\varepsilon$	Test cases
DHI Water & Env.	MIKE 3	3D semi-implicit finite differences	Mixing length or $k-\varepsilon$	Test cases + Tamar
Univ. of Hannover	TELEMAC-3D	3D semi-implicit finite elements	$k-\omega$	Test cases + Weser
National Hyd. & Env. Laboratory	TELEMAC-3D	3D semi-implicit finite elements	Mixing length	Test cases + Loire

In addition, it is obvious that the settling velocity of sediments is one of key parameters in sediment transport analysis. This is because the sedimentation and deposition of sediments are dependent on the particle settling velocity, which is affected by many factors, mentioned previously in Section 1.1.2, such as density and size of particle, viscosity of mixture, drag coefficient of particle, and flocculation of cohesive sediments. However, most of the models proposed in the literature for the settling velocity are not complete; most of the existing flocculation models are limited in their implementation in a numerical model due to either being too complicated or not present in a form that is amenable to numerical computations. Therefore, improving formulations of pertinent physical processes, in forms that are suitable for implementation in a numerical model, is needed in an effort to better represent the sediment transport.

1.3 Objectives

This study will focus on the properties of cohesive and/or non-cohesive sediment-fluid mixture, flocculation process of cohesive sediment, settling behaviour of particles under the effects of varying concentration and turbulence. The objectives of this research are:

- (i) To propose suitable models via a physically-based approach, which are amenable to application in a numerical model and encompasses flocculation of cohesive sediments, to represent the transport of fine sediments,
- (ii) To incorporate the proposed models into a numerical model, and
- (iii) To apply the numerical model to a real case.

1.4 Research questions

In order to achieve the objectives of this thesis, the following research questions are pertinent:

1. Can the existing equations currently incorporated in numerical models be used to represent the behavior of fine sediments adequately?

A literature review will be carried out on existing equations used to model the physical behavior of sediments and propose improvements to these equations with the ultimate objective of implementing the new equations in a numerical model.

2. If new models are proposed then how can they be calibrated and verified?
Existing data necessary for testing the proposed models will be collected from the literature. The proposed models will be calibrated and verified against these data.

3. How can flocculation be included in the transport of sediments?
A new flocculation model will be proposed to provide estimates of floc size. Based on the estimated floc size, parameters such as floc density, viscosity of mixture, etc. will be calculated. Floc settling velocity can be determined using the calculated values and then adopted in the transport equation.

4. How can the effect of flow turbulence on the settling velocity be modeled?
This effect will be modelled by considering a balance of forces acting on the particle settling in a turbulent fluid.

5. How can the proposed models be implemented into a numerical model?
The proposed models will be incorporated into a hydrodynamic model using the ECO Lab template. The template will then be integrated with a hydrodynamics numerical package in the MIKE (DHI, 2009a) suite of software.

1.5 Scope and Methodology

The scope and methodology of this study include:

i) Review of literature and analysis of existing data

A study of the literature will be conducted to obtain an in-depth analysis on the research that has been carried out on fine sediment transport and to gather existing data in the literature. The study will focus on the behavior of sediment-fluid mixtures in the

aquatic environment including floc density, dynamic viscosity, flocculation, settling velocity, deposition and erosion. Available field and laboratory data needed for calibration and verification of the proposed models will be collected.

ii) Development of new models

After reviewing the literature, the study will identify advantages/disadvantages of the existing models and propose new models by using physically-based arguments. The proposed models will then be calibrated and verified against the field and laboratory data collected previously.

iii) Coupling of the proposed models with a numerical model

This study will use the MIKE suite of modeling software tools by DHI, which is used widely in engineering investigations. The proposed formulations will be directly included in a new ECO Lab template, which will be coupled with the hydrodynamic module of MIKE 3 Flow Model FM modelling system. The template will be tested before applying to field data.

iv) Applying the numerical to field data

MIKE 3 Flow Model FM modelling system in conjunction with the proposed models will be applied to the Ems estuary. Field data such as water level, current speed, salinity, sediment concentration, etc. obtained from DHI-WASY Germany will be used to calibrate the Ems model. The applicability of the proposed models will be verified from this test case.

1.6 Outline of the thesis

This thesis is organized as follows. Chapter 2 presents a simplified physically-based model for estimating effective floc density. Chapter 3 proposes a general formula for estimating the viscosity of cohesive and non-cohesive fluid-sediment mixtures. Chapter

4 covers the effect of turbulence on the drag coefficient and settling velocity of a particle. Chapter 5 deals with flocculation of cohesive sediments. Chapter 6 presents the implementation of the various formulations for the sediment properties and processes into the MIKE 3 Flow Model FM modelling system. Chapter 7 presents the implementation of the proposed models to the Ems estuary. Conclusions and recommendations are given in Chapter 8.

Chapter 2

A Simplified Physically-based Model for Estimating Effective Floc Density

2.1 Introduction

Floc density (ρ_f) is one of key parameters affecting floc settling velocity (w_s) in natural systems. As there is no direct method available to measure ρ_f , ρ_f is usually estimated indirectly by using the measured settling velocity and floc size (D_f), and the modified Stokes' law:

$$w_s = \sqrt{\frac{4\Delta\rho_f g D_f}{3\rho_w C_D}} \quad (2.1)$$

where $\Delta\rho_f = (\rho_f - \rho_w)$ is the floc effective density, g gravitational acceleration, ρ_w density of water, $C_D = f(\text{Re}_p)$ drag coefficient, $\text{Re}_p = w_s D_f / \nu$ (floc) particle Reynolds number, and ν kinematic viscosity of water (Droppo et al., 2005; Khelifa and Hill, 2006). Floc density is also estimated by applying the concept of self-similar fractal flocs. Tambo and Watanabe (1979a) derived the expression for $\Delta\rho_f$ from volume and mass balance:

$$\Delta\rho_f = \alpha(\rho_s - \rho_w) \left(\frac{D_p}{D_f} \right)^{3-n_f} \quad (2.2)$$

where ρ_s and D_p are density and size of primary particles, respectively, $\alpha \approx 1.0$, $n_f \approx 2.1$ and can be considered as the fractal dimension of flocs (Kranenburg, 1994). Khelifa and Hill (2006) proposed an improvement to Eq. (2.2) by using, instead of a constant n_f , a variable 3-D fractal dimension $F = 3(D_f/D_{p50})^\beta$ with $\beta = \log(F_c/3)/\log(D_{fc}/D_{p50})$, D_{p50} median size of primary particles, and F_c and D_{fc} characteristic values of F and D_f , respectively. The effective density of flocs was estimated from:

$$\Delta\rho_f = (\rho_s - \rho_w) \left(\frac{D_{p50}}{D_f} \right)^{3-F} \Psi \quad (2.3)$$

where $\Psi = 1$ for mono-sized primary particles. The authors compiled 26 published datasets covering both field and laboratory measurements of w_s as a function of D_f . Based on this compiled dataset and assuming $\rho_s = 2,300 \text{ kg/m}^3$, the authors used Eq. (2.1) with $C_D = 24(1 + 0.15\text{Re}_p^{0.687})/\text{Re}_p$ to derive $\Delta\rho_f$ as a function of D_f and then calibrated Eq. (2.3). The authors found that for the compiled dataset, D_{p50} varies from $0.05 \text{ }\mu\text{m}$ to $20 \text{ }\mu\text{m}$, with a mean D_{p50} of $1 \text{ }\mu\text{m}$, $D_{fc} = 2,000 \text{ }\mu\text{m}$, $F_c = 2.0$ and $\rho_s = 2,300 \text{ kg/m}^3$. Also, incorporating Eq. (2.3) for $\Delta\rho_f$, Khelifa and Hill (2006) verified the use of Eq. (2.3) by comparing the settling velocity estimated by:

$$w_s = \frac{1}{18} \theta g \frac{\rho_s - \rho_w}{\rho_w \nu} D_{p50}^{3-F} \frac{D_f^{F-1}}{1 + 0.15 \text{Re}_p^{0.687}} \Psi \quad (2.4)$$

with the compiled data. In Eq. (2.4), θ is coefficient depending on the shape of the floc. This model predicts that w_s decreases at large floc sizes ($D_f > \sim 2,000 \text{ }\mu\text{m}$ for mean $D_{p50} = 1 \text{ }\mu\text{m}$). Although fractal analysis has been widely applied, Kranenburg (1994) and Khelifa and Hill (2006) argued that the self-similar fractal flocs may only be an idealization since there is no true fractal entity in the real world; Maggi (2005) argued that real flocs display a complicated network of clusters of primary particles that cannot be simply modeled as fully self-similar structures.

A new model for $\Delta\rho_f$ is proposed in this chapter. The modeling approach is based on dimensional analysis and does not consider the concept of self-similarity of flocs. Non-linear dependence of ρ_f is modeled as a function of not only D_f and D_p but also the effective density of the primary particles. The effects of flow turbulence and sediment concentration, etc. on flocculation and w_s will be considered in Chapter 5 and Chapter 4, respectively.

2.2 Proposed model

Given that $\Delta\rho_f = f(D_f, D_p, \rho_s, \rho_w)$ and applying the Buckingham Pi theorem (Hughes, 1993), the dimensionless groups are $\pi_1 = \Delta\rho_f / (\rho_s - \rho_w)$, $\pi_2 = D_f / D_p$, and $\pi_3 = \rho_s / \rho_w$. Introducing g , v and D_f and combining with π_3 gives:

$$\tilde{D}^* = \left[\left(\frac{\rho_s}{\rho_w} - 1 \right) g / v^2 \right]^{1/3} D_f \quad (2.5)$$

where the inclusion of g and v is to obtain a new dimensionless group. $\tilde{D}^*$ is similar to a floc particle parameter, which is a function of D_f and ρ_f . This parameter accounts for the joint contribution of π_3 and D_f on π_1 . It can be seen that $\tilde{D}^*$ decreases when D_f and/or ρ_s decreases. By trial, it can be shown that a formula for $\Delta\rho_f / (\rho_s - \rho_w) = f(D_f / D_p, \tilde{D}^*)$ can be expressed as:

$$\Delta\rho_f = (\rho_s - \rho_w) \left\{ 1 + \left[\left(\tilde{D}^* \right)^{\alpha_f} \left(\frac{D_f}{D_{p50}} - 1 \right) \right]^{\beta_f} \right\}^{-1.0} \quad (2.6)$$

where α_f and β_f are empirical coefficients, which depend on physical and chemical properties of the primary particles and surrounding liquid. Comparing Eq. (2.6) with Eq. (2.2) shows that the exponent β_f is analogous to $(3 - n_f)$, which reflects the fractal property of the floc, and the component $\left(\tilde{D}^* \right)^{\alpha_f}$ is similar to α . Bache (2004) argued that α in Eq. (2.2) reflects the compaction of the primary particles within the floc. The compaction should be characterized by the mass of the primary particles within a given floc and is a function of ρ_s and D_f . Therefore, in the present study, the component $\left(\tilde{D}^* \right)^{\alpha_f}$, which includes both ρ_s and D_f , is analogous to α and represents the compaction of flocs.

The dependence of $\Delta\rho_f$ on ρ_s is illustrated by a series of curves shown in Fig. 2.1. It is observed from the figure that the curves move upwards when ρ_s decreases. Thus for a given value of D_f , when ρ_s is high, ρ_f is large (point A). When ρ_s decreases, ρ_f becomes smaller (point B), since point B is founded on the curve for smaller ρ_s , located above the curve for larger ρ_s . In the limit, $(\rho_f - \rho_w)/(\rho_s - \rho_w) = 1$ when $\rho_s = \rho_w$ (point C). The effect of $\tilde{D}^*$ on $(\rho_f - \rho_w)/(\rho_s - \rho_w)$ can be seen in Fig. 2.1. In the figure, the shape of the curves depends on $\tilde{D}^*$; $(\rho_f - \rho_w)/(\rho_s - \rho_w)$ increases when ρ_s and/or D_f decreases. Conversely, $(\rho_f - \rho_w)/(\rho_s - \rho_w)$ decreases when ρ_s and/or D_f increases.

Figure 2.1 - Variation of floc density with the floc size.

2.3 Results and Discussion

Following the procedure by Khelifa and Hill (2006), the following values of ρ_s , ρ_w and ν were assigned: $\rho_s = 2,300 \text{ kg/m}^3$, $\rho_w = 1,000 \text{ kg/m}^3$ and $\nu = 1 \times 10^{-6} \text{ m}^2/\text{s}$. Best fit values for α_f , β_f and the estimation of D_{p50} essentially followed a trial-and-error process where $\Delta\rho_f$ was calculated by Eq. (2.6) and compared with the data from Khelifa and Hill (2006). The other parameter to be determined is D_{p50} , which is a physical quantity and is constrained by the size of primary particle in the experiments. This is different

from α_f and β_f which are fitting parameters. Khelifa and Hill (2006) obtained $D_{p50} = 0.05 - 20 \mu\text{m}$ for their model. While the actual values of D_{p50} for the data set computed by Khelifa and Hill (2006) may not be known, the field data of van Rijn (1993) suggests that the maximum value of D_{p50} could be larger, with a maximum value of $100 \mu\text{m}$ (see Table 2.1, reproduced from van Rijn 1993). Thus, setting a range for $D_{p50} = 0.05$ to $100 \mu\text{m}$, the values of α_f and β_f that gave the best fit to the data from Khelifa and Hill (2006) were found to be $\alpha_f = 0.7$ and $\beta_f = 0.8$. The plot of Eq. (2.6) with D_{p50} ranging from 0.05 to $100 \mu\text{m}$ and setting $\alpha_f = 0.7$ and $\beta_f = 0.8$ is shown in Fig. 2.2. A minimum value of $D_{p50} = 0.05 \mu\text{m}$ was chosen, in order to be consistent with the proposal by Khelifa and Hill (2006). Figure 2.2 shows that the mean value of D_{p50} is $2.5 \mu\text{m}$, close to the D_{p50} of kaolinite, which is $3 \mu\text{m}$ according to van Rijn (1993). This is in comparison to the mean value of $D_{p50} = 1 \mu\text{m}$ obtained by Khelifa and Hill (2006). Note that in Fig. 2.2, point A corresponds to $(D_f, \Delta\rho_f) = (100 \mu\text{m}, 1,300 \text{ kg/m}^3)$, and since at this point, $\rho_f = \rho_w + \Delta\rho_f = \rho_s = 2,300 \text{ kg/m}^3$, by definition, $D_p = D_f = 100 \mu\text{m}$. As pointed out by an anonymous reviewer, the scatter in the data in Fig. 2.2 is large and the proposed formula, as well as any other similar formula in the literature, should be used with caution since they represent just an "average order of magnitude" value for $\Delta\rho$.

Table 2.1 - Stokes diameter of deflocculated material of natural muds found in The Netherlands and that of kaolinite (van Rijn, 1993).

Mud type	$D_{p50} (\mu\text{m})$	Mud type	$D_{p50} (\mu\text{m})$
Kaolinite	3	Maas (river)	25
Hollands Diep 1 (lake)	5	Brekens Harbour (estuary)	10
Hollands Diep 2 (lake)	10	Delfijn Harbour (estuary)	80
Ketelmeer (lake)	7	Loswal Noord (sea)	100
Biesbosch (lake)	8

Figure 2.2 - Equation (2.6) with $\alpha_f = 0.7$, $\beta_f = 0.8$, $\rho_s = 2,300 \text{ kg/m}^3$, $\rho_w = 1,000 \text{ kg/m}^3$, $\nu = 1 \times 10^{-6} \text{ m}^2/\text{s}$ and (i) $D_p = 0.05 \text{ } \mu\text{m}$ (ii) $D_p = 2.5 \text{ } \mu\text{m}$ (iii) $D_p = 100 \text{ } \mu\text{m}$ [Note: original graph with d being primary particle size is from Khelifa and Hill (2006)].

Independent verification of Eq. (2.6) was carried out by comparing the model predictions with the data found in Camenen (2008). Camenen (2008) used Thorn's (1982) settling velocity data for high concentration mud obtained from the Severn estuary and Dankers et al.'s (2007) settling column data for kaolinite flocs. Note that the data of Thorn (1982) and Dankers et al. (2007) are not included as part of the 26 data sets analyzed by Khelifa and Hill (2006). Camenen (2008) found that $D_f \approx 295 \text{ } \mu\text{m}$, $\rho_f \approx 1,053 \text{ kg/m}^3$ or $\Delta\rho_f = 53 \text{ kg/m}^3$ provided a good fit to Thorn's (1982) data. Similarly, $D_f \approx 97 \text{ } \mu\text{m}$, $\rho_f \approx 1,066 \text{ kg/m}^3$ or $\Delta\rho_f = 66 \text{ kg/m}^3$ was found to fit well the data of Dankers et al. (2007). The proposed model was used to predict the $\Delta\rho_f$ observed in Thorn's (1982) and Danker et al's (2007) experiments. The following values were assigned: $\alpha_f = 0.7$, $\beta_f = 0.8$, $\rho_s = 2,300 \text{ kg/m}^3$, $\rho_w = 1,000 \text{ kg/m}^3$, $\nu = 1 \times 10^{-6} \text{ m}^2/\text{s}$. For the natural mud used in Thorn (1982), $D_{p50} = 20 \text{ } \mu\text{m}$ was assumed. This is within the range of D_{p50} suggested by van Rijn (1993) (see Table 2.1). For the kaolinite used in

Dankers et al. (2007), $D_{p50} = 3 \mu\text{m}$, which is the average value of primary particle size suggested by van Rijn (1993) for kaolinite (see Table 2.1), was assumed. The effective density of flocs was calculated using Eq. (2.6) and compared with the data provided by Camenen (2008). It was found that for mud in the Severn estuary, the predicted value $\Delta\rho_f = 52 \text{ kg/m}^3$ is nearly equal to the value of 53 kg/m^3 suggested by Camenen (2008); for kaolinite, the predicted value $\Delta\rho_f = 50.2 \text{ kg/m}^3$ is close to the value of 66 kg/m^3 suggested by Camenen (2008). Given the discrepancies and scatter associated with data of this nature, the comparison suggests that the model is sufficiently robust.

Figure 2.3 - Settling velocity of flocs with $\alpha_f = 0.7$, $\beta_f = 0.8$ and
(i) $D_p = 0.05 \mu\text{m}$ (ii) $D_p = 2.5 \mu\text{m}$ (iii) $D_p = 100 \mu\text{m}$ [Note: original graph with d being primary particle size is from Khelifa and Hill (2006), and inset is taken from Alldredge and Gotschalk (1988)].

The settling velocity data published in Khelifa and Hill (2006) was used to compare with the calculated w_s using $\Delta\rho_f$ determined by the new model. The modified Stokes law, given in Eq. (2.1) where $C_D = 24(1 + 0.15 \text{Re}_p^{0.687})/\text{Re}_p$, as used by Khelifa and Hill (2006), was adopted in the calculation of w_s . The following values were also assigned: $\alpha_f = 0.7$, $\beta_f = 0.8$, $\rho_s = 2,300 \text{ kg/m}^3$, $\rho_w = 1,000 \text{ kg/m}^3$, and $\nu = 1 \times 10^{-6} \text{ m}^2/\text{s}$.

The calculated w_s are compared with w_s estimated by Khelifa and Hill (2006) in Fig. 2.3. For $D_f < 2,000 \mu\text{m}$, the present model shows that w_s increases with D_f . This is consistent with the model by Khelifa and Hill (2006) and observations by Droppo (2001), who remarked that “... *as floc size increases, settling velocity increases ... as floc size seems to have a much stronger effect over floc settling than density*”. The increase in w_s with D_f for $D_f < 2,000 \mu\text{m}$ is further supported by the data of Curran et al. (2007), Petticrew (2005), and Williams et al. (2008). For $D_f > \sim 2,000 \mu\text{m}$, the present model predicts that w_s increases with D_f while Khelifa and Hill’s (2006) model shows that w_s decreases with D_f . However, it can be argued that the data points in Fig. 2.3 do not show a clear trend of w_s decreasing with an increase in D_f for $D_f > 2,000 \mu\text{m}$. The data points for $D_f > \sim 2,000 \mu\text{m}$ used in Fig. 2.3 were obtained from Diercks and Asper (1997) and Alldredge and Gotschalk (1988). In their paper, Diercks and Asper (1997) stated that their data ($D_f < 5.5 \text{ mm}$) “... *showed a wide variability*” and “*No statistically significant correlation of the aggregate settling speeds with their size, ..., was found*”. On the contrary, Alldredge and Gotschalk’s (1988) data ($D_f < 25.5 \text{ mm}$) showed that w_s increases when D_f increases (see Fig. 3 in Alldredge and Gotschalk, 1988). Hence, it can be remarked here that, for $D_f > \sim 2,000 \mu\text{m}$, the increasing trend in w_s as proposed by the present model is supported by the data of Alldredge and Gotschalk (1988).

2.4 Conclusions

The following can be concluded from this chapter:

- (i) The value of D_{p50} was found to vary from $0.05 \mu\text{m}$ to $100 \mu\text{m}$ with a mean value of $2.5 \mu\text{m}$, which is greater than the value of $1 \mu\text{m}$ suggested by Khelifa and Hill (2006) but is consistent with the D_{p50} of kaolinite.
- (ii) Independent verification of the new model using the data of Thorn (1982) and Dankers et al. (2007) showed that the predicted $\Delta\rho_f$ are close to the values suggested by Camenen (2008).

- (iii) The settling velocity estimated based on the proposed model for $\Delta\rho_f$ is consistent with the calculated w_s based on Khelifa and Hill's (2006) for $D_f < 2,000 \mu\text{m}$ and the measured data by Alldredge and Gotschalk (1988) for $D_f > \sim 2,000 \mu\text{m}$.

Chapter 3

A General Formula for Estimating the Viscosity of Cohesive and Non-Cohesive Fluid-Sediment Mixtures

3.1 Introduction

Research on the estimation of viscosity of fluid-sediment mixtures has been carried out since the early 1900s. These studies include theoretical (Einstein 1906; Vand 1948a), empirical (e.g., Vand 1948b; Camenen 2008) and semi-empirical (e.g., Robinson 1949; Mooney 1951; Dougherty 1959 and Krieger 1972; van Rijn 1993; Cheng and Law 2003) approximations to estimate the viscosity of mixtures. Most of the studies have concentrated on non-cohesive sediments, where the suggested formulae for viscosity depend on volumetric concentration of the sediments only (Einstein 1906; Krieger 1972; Cheng and Law 2003). For a dilute suspension where the volumetric concentration ϕ is less than 0.1, the formula for the relative viscosity of fluid-sediment mixtures, μ_r , proposed by Einstein (1906):

$$\mu_r = 1 + k\phi \quad (3.1)$$

where the intrinsic viscosity, $k \equiv \lim_{\phi \rightarrow 0} [(\mu_r - 1)/\phi] = 2.5$ (Krieger, 1972), is probably the most well-known. At higher concentration ($\phi > 0.1$), μ_r non-linearly increases with ϕ (e.g., Eilers, 1941; Van, 1948a,b; Rueb and Zukoski, 1998; Quemada, 1982; Marshall and Zukoski, 1990; Cheng and Law, 2003). van Rijn (1993) approximated μ_r as a power law, given by:

$$\mu_r = (1.0 + \alpha\phi)^\beta = 1.0 + \dots + (\alpha\phi)^\beta \quad (3.2)$$

where α and β are empirical coefficients. Doolittle (1951) assumed that $\mu_r \rightarrow \infty$ when each particle is in firm contact with neighboring particles, and suggested that:

$$\mu_r = A \exp \left(B \frac{\phi}{\phi_{\max} - \phi} \right) \quad (3.3)$$

where A and B are empirical coefficients, $\phi_{\max}$ maximum value of ϕ . Note that A should be 1.0 since $\mu_r \rightarrow 1.0$ when $\phi \rightarrow 0$ and, as a result, the equation contains only one fitting coefficient (B). Dividing the suspension into two parts, Dougherty (1959) and Krieger (1972) derived μ_r as a product of the relative viscosity of each part in the following form:

$$\mu_r = \left(1 - \frac{\phi}{\phi_{\max}} \right)^{-k\phi_{\max}} \quad (3.4)$$

For cohesive sediments, very limited studies on the modelling of viscosity have been conducted. Winterwerp (1999) and Toorman (2002) adopted Eq. (3.1) and Eq. (3.4), respectively, assuming $k = 2.5$ and ϕ volumetric concentration of flocs. This implies that mixtures having the same volumetric concentration will have the same viscosity regardless of the difference in densities or mass concentration of sediments in each mixture. The use of these models is limited as they are unable to account for the dependence of viscosity on other factors such as density and size of flocs besides volumetric concentration, which would be important in estimating the hindered settling velocity of flocs. Camenen (2008) modified Eq. (3.4) assuming $k = 2.5$ and proposed an empirical formula:

$$\mu_r = \left(1 - \frac{\phi}{\phi_{\max}} \right)^{-\phi_{\max}/2} (1 - \phi_p)^{-2} \quad (3.5)$$

where ϕ and ϕ_p are the volumetric concentrations of flocs and primary particles, which form the flocs, respectively, and $\phi_{\max} \approx 0.8$. For verifying Eq. (3.5), the author utilized measured datasets of Thorn (1982) and Dankers et al. (2007) for floc settling velocity; floc settling velocities with μ_r from Eq. (3.5) were estimated and compared with the measured values (Camenen, 2008). Noted that, for $\phi \rightarrow \phi_p$ or when sediments become non-cohesive, Eq. (3.5) underestimates μ_r (see Section 3.3.1).

There is still the lack of a formula that takes into account other factors, such as density and size of flocs, besides volumetric concentration in the estimation of viscosity in cohesive mixtures. In addition, a model that is general and equally applicable to both non-cohesive and cohesive sediments does not exist. The present study develops a new model for μ_r as a function of ϕ and $\phi_{\max}$. The new model contains two empirical coefficients making the model more flexible than the existing models. The model is further developed to take into account density and size of flocs. Values of the model coefficients were obtained by comparing the calculated viscosity (or settling velocities of particles) with experimental data. The merits and limitations of the model are discussed and conclusions are presented.

3.2 Proposed model

van Rijn's (1993) power law model stated in Eq. (3.2) can be approximated by $\mu_r = 1.0 + (\alpha\phi)^\beta$, which has a form similar to Einstein's (1906) model [see Eq. (3.1)]. Replacing ϕ by $\phi/(\phi_{\max} - \phi)$ [see Eq. (3.3)], the proposed model starts with:

$$\mu_r = 1.0 + \left[\alpha \left(\frac{\phi}{\phi_{\max} - \phi} \right) \right]^\beta \quad (3.6)$$

where α and β are empirical coefficients. Equation (3.6) is schematized in Fig. 3.1. Equation (3.6) is consistent with physical reasoning since it is observed that μ_r becomes: (i) 1.0 when ϕ approaches zero, and (ii) very large when ϕ approaches $\phi_{\max}$ or when each particle is in firm contact with its neighbors. Furthermore, if $\beta = 1$, $k = \alpha/\phi_{\max}$ and Eq. (3.6) approaches Einstein's formula for small values of ϕ if $\alpha/\phi_{\max} = 2.5$.

Figure 3.1 - Schematized variation of μ_r with ϕ (and ρ_f for cohesive sediments).

Bold line indicates $\alpha=f(\rho_f)$ for “softer” flocs and lighter line indicates $\alpha=f(\rho_f)$ for “harder” flocs.

Following Mooney (1951), Dougherty (1959) and Krieger (1972), and Cheng and Law (2003), dividing the suspension into n equal parts, and applying Eq. (3.6) to each part results in:

	Part (1)	Part (2) ... Part (n)
ϕ_i	ϕ / n	ϕ / n
$\phi_{\max, i}$	$\phi_{\max}$	$\phi_{\max} - (\phi / n)$
$\mu_{r, i}$	$1 + \left\{ \alpha \frac{(\phi / n)}{\phi_{\max} - (\phi / n)} \right\}^\beta$	$1 + \left\{ \alpha \frac{(\phi / n)}{\phi_{\max} - 2(\phi / n)} \right\}^\beta$
		$1 + \left\{ \alpha \frac{(\phi / n)}{\phi_{\max} - n(\phi / n)} \right\}^\beta$

The expression for the relative viscosity is then obtained as a product of the relative viscosity for each part. Thus:

$$\mu_r = \prod_{i=1}^n \left[1 + \left(\alpha \frac{\phi / n}{\phi_{\max} - i\phi / n} \right)^\beta \right]_{n \rightarrow \infty} = \prod_{i=1}^n \left[1 + \left(\alpha \frac{[\phi / \phi_{\max}] / n}{1 - i[\phi / \phi_{\max}] / n} \right)^\beta \right]_{n \rightarrow \infty} \quad (3.7)$$

Given that Eq. (3.6) is valid for $\phi_i \leq 0.1$, Eq. (3.7) with $n = 10$ is valid for $\phi \leq \phi_{\max}$. Equation (3.7) is applicable to non-cohesive and cohesive sediments, by appropriating

the values of α and β relevant to the mixture type (cohesive and/or non-cohesive). It is shown latter that β is a constant (the value of β is different for non-cohesive and cohesive sediments) and α depends on the mixture. For non-cohesive sediments, α is a constant, and for cohesive sediments, α depends on the floc properties. For cohesive sediments, it is proposed that the effects of floc density (ρ_f) in addition to ϕ for a given floc size (D_f) should also be included in the estimation of μ_r . The dependence of μ_r on ρ_f can be explained by considering the extreme case when $\phi = \phi_{\max}$; the sample with a lower floc density (“softer sample”) is expected to have a lower viscosity than one with a higher floc density (“harder sample”). On the other hand, since ρ_f depends on D_f , the dependence of μ_r on ρ_f is introduced by making $\alpha = f(\rho_f, D_f)$.

The dependence of μ_r on ρ_f is illustrated schematically by the plot of Eq. (3.7) in Fig. 3.1 for cohesive sediments. The trivial case occurs when $\rho_f \rightarrow \rho_w$, implying $\alpha = 0$, represented by the horizontal line $1/\mu_r = 1$. For $\rho_f \neq \rho_w$, a series of curves is possible, depending on the value of ρ_f , with the curves shifting downwards with increasing values of ρ_f . Thus, for flocs having the same values of ϕ and D_f , μ_r is smaller for smaller values of ρ_f , as represented in Fig. 3.1 by points A and B. These points lie on the curves defined by different values of α . The dependence of α on ρ_f and D_f is schematized in Fig. 3.2 where the joint contribution of ρ_f and D_f on α is characterized by the floc particle parameter D_* :

$$D_* = \left[\frac{(\rho_f / \rho_w - 1)g}{\nu^2} \right]^{1/3} D_f \quad (3.8)$$

As shown in Fig. 3.2, $\alpha = 0$ when $D_* = 0$, or $\rho_f = \rho_w$, and α increases when D_* or ρ_f increases (points A and B in this figure are equivalent to points A and B in Fig. 3.1). The dependence of α on D_* is proposed to be of the form:

$$\alpha = A_v (D_*)^{\alpha_v} \quad (3.9)$$

where A_v is a constant and α_v is a coefficient depending on the properties of the primary particles and surrounding fluid.

Figure 3.2 - Variation of α with ρ_f and D_f . Note: $s = \rho_f/\rho_w$.

3.3 Results and Discussion

In this section, the proposed model, Eq. (3.7), is tested for non-cohesive sediments first by comparing the calculated viscosity with existing models and experimental data. Next, for the viscosity of a mixture of cohesive sediments, the coefficients α , β , α_v , and A_v are calibrated using the experimental data of Winterwerp et al. (1991) for the viscosity of mud and Thorn (1982) and Dankers et al. (2007) data for the hindered settling velocity of flocs. The hindered settling velocities, estimated using the proposed model for viscosity, are also compared to those calculated by Camenen (2008).

3.3.1 Non-cohesive sediments

The experimental data published in Vand (1948b), Robinson (1949), Nir and Acrivos (1974), and Camenen (2008) were used to compare with the calculated results of μ_r using Eq. (3.7), with $\beta = 1.0$ and $n = 10$, shown in Fig. 3.3. The values of $\phi_{\max}$ adopted are $\phi_{\max} = 0.60$ for the data and references used by Camenen (2008) and $\phi_{\max} = 0.55$ for the data and references used by Vand (1948b), Robinson (1949), and Nir and Acrivos (1974). As shown in the figure, Eq. (3.7) with $n = 10$, $\beta = 1.0$, and $\alpha = 1.5$ to 3.5 can reproduce well the wide range of data used by Camenen (2008). In addition, if $\beta = 1.0$,

$\alpha = 1.5$ and $\phi_{\max} = 0.6$, then $\alpha/\phi_{\max}$ is equal to 2.5; and accordingly, Curve (ii) in Fig. 3.3 is close to Eq. (3.4) with $k = 2.5$, and approaches Einstein's curve when ϕ is small. Moreover, with regards to Robinson's (1949) experimental data where non-buoyant rigid particles were used, Curve (i) with a slightly lower value of α ($\alpha = 1.375$), $\beta = 1.0$, and $\phi_{\max} = 0.55$ ($\alpha/\phi_{\max} = 2.5$) gives a good fit to the data. Moreover, the figure shows that almost the data points are above the curves having $k = 2.5$ and therefore, for a wide range of ϕ , the intrinsic viscosity is different from 2.5. In conclusion, the comparison shows that, for non-cohesive sediments, Eq. (3.7) can reproduce the measured experimental data well, with $\beta = 1.0$ and α in the range from 1.375 to 3.5, with $\alpha = 2.0$ providing a good fit to a majority of the data points.

Figure 3.3 - Eq. (3.5) for $\phi \rightarrow \phi_p$ [Curve (A)]; Eq. (3.7) for various combination of α and β , $n = 10$, (i) $\beta = 1.0$, $\alpha = 1.375$, (ii) $\beta = 1.0$, $\alpha = 1.5$, (iii) $\beta = 1.0$, $\alpha = 2.5$, (iv) $\beta = 1.0$, $\alpha = 3.5$, (v) $\beta = 1.0$, $\alpha = 2.0$, and (vi) $\beta = 0.6$, $\alpha = 0.127$. [Figure adapted from Camenen (2008). Note that other data from Vand (1948b) (Δ), Nir and Acrivos (1974) (+), Rutgers (1962) ($\diamond$) and Robinson (1949) ($\bullet$) have been included in the figure].

Note that, Eq. (3.5) by Camenen (2008) with $\phi \rightarrow \phi_p$ or when sediments become non-cohesive becomes $\mu_r = (1 - \phi_p / \phi_{\max})^{-\phi_{\max}/2} (1 - \phi_p)^{-2}$. This formulation, with $\phi_{\max} \approx 0.6$ for non-cohesive sediments (Camenen 2008), is also included in Fig. 3.3 by Curve (A) showing that Eq. (3.5) underestimates the measured data.

Given that there is a large scatter in the data shown in Fig. 3.3 especially when ϕ is high, a sensitivity analysis on the effect of the relative viscosity on the estimation of the hindered settling velocity (W_s) and sedimentation rate (S_s) for fine sands was carried out. Following Cheng (1997b), W_s is estimated by:

$$W_s = (1 - \phi) w_{s,m} \quad (3.10)$$

where ϕ is volumetric concentration of particles; $w_{s,m}$ is the relative velocity between the falling particles and surrounding fluid (subscript $.m$ refers to mixture), given by:

$$w_{s,m} = \sqrt{\frac{4(\rho_s - \rho_m)gD}{3\rho_m C_{D,m}}} \quad (3.11)$$

where ρ_s and ρ_m are density of sand particle and mixture, respectively; g is gravitational acceleration; D is particle size; $C_{D,m}$ is the drag coefficient of sand particle in the mixture, given by Cheng (1997b) as:

$$C_{D,m} = \left[\left(\frac{32}{\text{Re}_{p,m}} \right)^{1/1.5} + 1 \right]^{1.5} \quad (3.12)$$

where $\text{Re}_{p,m}$ is particle Reynolds number of sand particle in the mixture, defined by:

$$\text{Re}_{p,m} = \frac{w_{s,m} D}{\nu_m} \quad (3.13)$$

where $\nu_m = \mu_r \rho_w \nu_w / \rho_m$; ν_w is the kinematic viscosity of water (Cheng, 1997b). The proposed model, Eq. (3.7) with $\beta = 1.0$ was used for estimating μ_r . Given that $D = 200 \mu\text{m}$, $\phi_{\max} = 0.6$ and α varying from 1.5 to 3.5 (see Table 3.1), the estimated W_s , as shown in Fig. 3.4, decreases when α and/or ϕ increase. The difference in W_s as a

function of α for different values of $\phi/\phi_{\max}$ defined as $\text{difference} = \frac{W_s \text{ with } \alpha \neq 2.0}{W_s \text{ with } \alpha = 2.0} - 1$,

is shown in Fig 3.5; note that the difference in the sedimentation rate is the same as the difference in W_s since $S_s = W_s c$ [see Eq. (6.5) in Chapter 6]. As can be seen from the figure:

- (i) for $\alpha = 1.5$, the difference is smaller than 10% for $\phi/\phi_{\max} \leq 0.2$ (or $c \leq 318 \text{ kg/m}^3$) and 22.5% at $\phi/\phi_{\max} = 0.4$ (or $c = 636 \text{ kg/m}^3$);
- (ii) for $\alpha = 2.0 \pm 0.2$ and $\phi/\phi_{\max} \leq 0.4$ (or $c \leq 636 \text{ kg/m}^3$), the difference is smaller than 10%;
- (iii) for $\alpha = 3.5$, the difference is about 45% at $\phi/\phi_{\max} = 0.4$ (or $c = 636 \text{ kg/m}^3$).

In spite of the large deviations especially for large values of $\phi/\phi_{\max}$ and when α deviates from the recommended value of $\alpha = 2.0$, it can be stated that for suspensions not close to the bed and $c \leq 636 \text{ kg/m}^3$ (or $\phi/\phi_{\max} \leq 0.4$), it is reasonable to use Eq. (3.7) with $\alpha = 2.0$ in the estimation of W_s (and also S_s) as the difference is smaller than 10% when there is a small change ($< 10\%$) in α .

Table 3.1 – Values of α used in the estimation of W_s in Fig. 3.4.

α	Remarks
1.5	$\alpha/\phi_{\max} = 2.5$; Curve (ii) and Krieger curve in Fig. 3.3 are very close
1.8	$0.9 \alpha_{\text{mean}}$
2.0	mean value [Curve (v) in Fig. 3.3]
2.2	$1.1 \alpha_{\text{mean}}$
3.5	upper limit [Curve (iv) in Fig. 3.3]

Figure 3.4 - Variation of W_s with $\phi/\phi_{\max}$ and α .
 Note: $D = 200 \mu\text{m}$; Eq. (3.7) with $\beta = 1.0$ is used for estimation of μ_r .

Figure 3.5 – Difference in W_s (also the same for sedimentation rate, S_s)

(Note: $\text{Difference} = \frac{W_s \text{ with } \alpha \neq 2.0}{W_s \text{ with } \alpha = 2.0} - 1$, $\beta = 1.0$ and $D = 200 \mu\text{m}$).

3.3.2 Cohesive sediments

The coefficients, α and β in Eq. (3.7), and α_v and A_v in Eq. (3.9) of the proposed model were obtained using experimental data. Firstly, α and β can be approximated by considering the case when the mixture approaches gelling point. Winterwerp et al. (1991) and Winterwerp (1999) analyzed the data for natural muds in The Netherlands and suggested that at gelling point, $c_{gel} \approx 40$ to 120 kg/m^3 , $\rho_f \approx 1,040 \text{ kg/m}^3$ to $1,130 \text{ kg/m}^3$ and $\mu_r \approx 2$ to 4 . Following Winterwerp's (1999) assumption that the settling velocity of flocs is zero when the mixture becomes a gel ($c = c_{gel}$ or $\phi = \phi_{gel}$), the ratio ϕ/ϕ_{max} in Eq. (3.7) can then be replaced by ϕ/ϕ_{gel} . Thus, the values of α and β in Eq. (3.7) can be obtained directly [i.e. independent of Eq. (3.8) and Eq. (3.9)] by assuming $\mu_{r, max} \approx 4$ when $\phi \approx \phi_{gel}$. With this assumption, α and β were then obtained by trial-and-error. The values of α and β that gave the best fit to the data were found to be $\alpha = 0.127$ and $\beta = 0.6$. Hence,

$$\mu_r = \prod_{i=1}^{10} \left[1 + \left(0.127 \frac{[\phi/\phi_{gel}]/10}{1 - i[\phi/\phi_{gel}]/10} \right)^{0.6} \right] \quad (3.14)$$

Note that $n = 10$ was used in the derivation of α and β and $\mu_r \approx 4.0$ when $\phi/\phi_{gel} = 0.95$, where the use of $\phi/\phi_{gel} = 0.95$ is addressed later in the chapter. Equation (3.14) is shown by Curve (vi) in Fig. 3.3 and approximates Einstein's formula for dilute suspensions. The use of two coefficients makes the model able to meet two boundary conditions (one at high ϕ/ϕ_{max} and one at small ϕ/ϕ_{max}). The horizontal line $\mu_r = 1.0$ defines the clear water condition where $\alpha = 0$, since $D^* = 0$ as $\rho_f \rightarrow \rho_w$. The relative viscosity of suspensions of cohesive sediments is thus bounded within the limits defined by Eq. (3.14) and $\mu_r = 1.0$ (clear water condition). It is assumed that the value of the primary particle size (D_p) varies from about 0 (clear water condition) to a maximum of $100 \text{ }\mu\text{m}$ for Loswal Noord mud (see Table 2.1) as α changes from 0 ($\mu_r = 1.0$) to 0.127 between these two conditions. It is necessary to assume that the value of α

is the same for mixtures having the same primary particle size as this assumption ensures that the value of α will never be larger than the limiting value of $\alpha = 0.127$.

Having established the limiting values of α , α is calibrated next for the general case. For $D_p = 100 \mu\text{m}$, rearranging Eq. (3.9) with $\alpha = 0.127$ results in:

$$\alpha_v = \frac{\log[0.127 / A_v]}{\log[D_*]} \quad (3.15)$$

Note that in Eq. (3.15), A_v is a constant (to be determined) and D_* depends on floc properties. The two unknowns in Eq. (3.15), α_v and A_v , are solved using a trial-and-error procedure.

Determination of α_v and A_v

The steps involved in the determination of A_v and α_v are schematized in Fig. 3.6, using the measured settling velocity data obtained by Thorn (1982) for high concentration mud obtained from the Severn estuary, shown in Fig. 3.7, and Dankers et al. (2007) data for kaolinite flocs obtained from a settling column, shown in Fig. 3.8. Regarding the data, Camenen (2008) found that $D_f \approx 295 \mu\text{m}$, $\rho_f \approx 1,053 \text{ kg/m}^3$ provided a good fit to Thorn's (1982) data; similarly, $D_f \approx 97 \mu\text{m}$, $\rho_f \approx 1,066 \text{ kg/m}^3$ was found to fit the data of Dankers et al. (2007) well.

Figure 3.6 - Flow chart for estimating A_v and α_v .

Figure 3.7 - The hindered settling velocity with Thorn's (1982) data and
 (i) $A_v = 0.001$, $\alpha = 0.0191$, (ii) $A_v = 0.01$, $\alpha = 0.0471$, and (iii) $A_v = 0.1$, $\alpha = 0.1157$
 (Note: original graph is from Camenen 2008; d_s is the floc size).

Figure 3.8 - The hindered settling velocity with Dankers et al. (2007) data and (i) $A_v = 0.001$, $\alpha = 0.0005$, (ii) $A_v = 0.01$, $\alpha = 0.0067$, and (iii) $A_v = 0.1$, $\alpha = 0.0963$ (Note: original graph is from Camenen 2008; d_s is the floc size).

A formula for ρ_f is needed in the determination of D^* [Eq. (3.8)]. The proposed model in previous chapter for the effective density of floc, Eq. (2.6), is used here. The following values were assigned: $\alpha_f = 0.7$, $\beta_f = 0.8$, $\rho_s = 2,300 \text{ kg/m}^3$ and $\rho_w \approx 1,000 \text{ kg/m}^3$.

For each dataset, various values of A_v were first assumed; example calculations for three values of A_v ($A_v = 0.001$, 0.01 and 0.1) used are shown latter in Table 3.3. Next, a separate analysis, detailed in Table 3.2 was adopted to determine α_v . As shown in Table 3.2, for $A_v = 0.01$, ρ_f is calculated from Eq. (2.6), D^* is calculated from Eq. (3.8), and α_v is calculated from Eq. (3.15) for each value of D_f . From this analysis, it was found that α_v can be related to D_f (in μm) by the following relation:

$$\alpha_v = 6.0886 D_f^{-0.2149} \quad (3.16)$$

Thus, the relative viscosity of the mixture when $\phi < \phi_{\text{gel}}$ can be determined by:

$$\mu_r = \prod_{i=1}^{10} \left[1 + \left(\alpha \frac{[\phi / \phi_{gel}]/10}{1 - i[\phi / \phi_{gel}]/10} \right)^{0.6} \right] \quad (3.17)$$

where

$$\alpha = 0.01(D_*)^{\alpha_v} \quad (3.18)$$

and α_v is determined from Eq. (3.16). Note that Eq. (3.16) and Eq. (3.18) were derived for the case of $D_p = 100 \mu\text{m}$ only. Data for $D_p < 100 \mu\text{m}$, however, are not available. Therefore, it is assumed that for a given value of A_v , the value of α_v for $D_p < 100 \mu\text{m}$ is the same as that for $D_p = 100 \mu\text{m}$.

The values of α and α_v were calculated for the floc properties specific to Thorn (1982) and Dankers et al. (2007) data for three values of A_v (Table 3.3). These values of α and α_v were then applied in the determination of the kinematic viscosity of the mixtures (ν_m) after which the settling velocity for the different experiments by Thorn (1982) and Dankers et al. (2007) were estimated.

Table 3.2 - Variation of α_v with D_f for $D_p = 100 \mu\text{m}$, $A_v = 0.01$, $\alpha_f = 0.7$, $\beta_f = 0.8$, $\rho_s = 2,300 \text{ kg/m}^3$, $\rho_w = 1,000 \text{ kg/m}^3$, $\nu = 1 \times 10^{-6} \text{ m}^2/\text{s}$.

$D_f (\mu\text{m})$	$\Delta\rho_f (\text{kg/m}^3)$ [Eq. (2.6)]	D_* [Eq. (3.8)]	α_v [Eq. (3.15)]
100	1300.0	2.30	2.995
200	385.6	3.12	2.236
300	210.3	3.82	1.897
400	138.0	4.43	1.709
500	99.9	4.97	1.586
...	...	...	...
30,000	0.3	45.11	0.667

Table 3.3 - Formulae for α_v and α for various values of A_v and $D_p = 100 \mu\text{m}$, $\alpha_f = 0.7$, $\beta_f = 0.8$, $\rho_s = 2,300 \text{ kg/m}^3$, $\rho_w = 1,000 \text{ kg/m}^3$, $v = 1 \times 10^{-6} \text{ m}^2/\text{s}$.

A_v	Formulae ⁽¹⁾	Thorn (1982) data ⁽²⁾	Dankers et al. (2007) data ⁽³⁾
0.001	$\alpha_v = 11.605 D_f^{-0.2149}$	$\alpha_v = 3.419$	$\alpha_v = 4.342$
	$\alpha = 0.001(D_*)^{\alpha_v}$	$\alpha = 0.0191$	$\alpha = 0.0005$
0.01	$\alpha_v = 6.0886 D_f^{-0.2149}$	$\alpha_v = 1.794$	$\alpha_v = 2.278$
	$\alpha = 0.01(D_*)^{\alpha_v}$	$\alpha = 0.0471$	$\alpha = 0.0067$
0.1	$\alpha_v = 0.5726 D_f^{-0.2149}$	$\alpha_v = 0.169$	$\alpha_v = 0.214$
	$\alpha = 0.1(D_*)^{\alpha_v}$	$\alpha = 0.1157$	$\alpha = 0.0963$

Notes: ⁽¹⁾ D_f in μm

⁽²⁾ $D_f = 295 \mu\text{m}$ and $\rho_f = 1,053 \text{ kg/m}^3$ (Camenen 2008); $D_* = 2.372$

⁽³⁾ $D_f = 97 \mu\text{m}$ and $\rho_f = 1,066 \text{ kg/m}^3$ (Camenen 2008); $D_* = 0.839$

Hindered settling velocity

Following for example Chien and Wan (1999) and Camenen (2008), the hindered settling velocity of flocs, W_s was estimated by:

$$W_s = (1 - \phi)w_{s,m} \quad (3.19)$$

where ϕ is volumetric concentration of flocs; $w_{s,m}$ is the relative velocity between the falling flocs and surrounding fluid (subscript $.m$ refers to mixture), given by:

$$w_{s,m} = \sqrt{\frac{4(\rho_f - \rho_m)gD_f}{3\rho_m C_{D,m}}} \quad (3.20)$$

where ρ_f and ρ_m are density of flocs and mixture, respectively; $C_{D,m}$ is the drag coefficient of flocs in the mixture. Following Cheng (1997b) and Camenen (2008), assuming that $C_{D,m}$ has the same form as the one used by Winterwerp (1999) and Khelifa and Hill (2006) for floc in the clear fluid results in:

$$C_{D,m} = \frac{24}{\text{Re}_{p,m}} \left(1 + 0.15 \text{Re}_{p,m}^{0.687} \right) \quad (3.21)$$

where $\text{Re}_{p,m}$ is particle Reynolds number of flocs in the mixture, defined by:

$$\text{Re}_{p,m} = \frac{w_{s,m} D_f}{v_m} \quad (3.22)$$

In reality, flocs are porous, not solid; pore water inside flocs can move (Droppo, 2001) and flocs are deformable (Tomi and Bagster, 1975). Therefore μ_r does not tend to infinite when $\phi = \phi_{\text{gel}}$. Equation (3.17) will give unrealistic values of μ_r when ϕ/ϕ_{gel} approaches 1.0 ($\mu_r \rightarrow \infty$, $v_m \rightarrow \infty$ and $W_s \rightarrow 0$); therefore, the value of the v_m at $\phi/\phi_{\text{gel}} > 0.95$ is approximated by that at $\phi/\phi_{\text{gel}} = 0.95$. In addition, the calculation was carried out up to a mass concentration $c/c_{\text{gel}} = 0.99$ only because the proposed model does not take into account the consolidation process when $c \geq c_{\text{gel}}$. The values of $c_{\text{gel}} \approx 80 \text{ kg/m}^3$ and $c_{\text{gel}} \approx 100 \text{ kg/m}^3$ were assumed for Thorn's (1982) and Dankers et al.'s (2005) data, respectively.

The original graphs in Fig. 3.7 and Fig. 3.8 are from Camenen (2008). These graphs show the results using Camenen's (2008) models, denoted as 'R & Z modified' and 'mixture theory', together with other models considered by Camenen (2008). In addition, the hindered settling velocity of flocs estimated from the new model has been included in the figures. Note that the same values of D_f and ρ_f as Camenen (2008) applied to existing models for estimating floc settling velocity were used in the new model so that all the estimations are with the same input data. It can be seen from the comparisons in the figures that the use of the proposed model with $A_v = 0.01$ reproduces the measured settling velocity well. Moreover, for Thorn's (2008) data at $c > 40 \text{ kg/m}^3$, the estimated result using the new model for μ_r [Curve (ii) in Fig. 3.7] is close to Camenen's (2008) and better than Winterwerp's (1999); and for Dankers et al.'s (2007) data at $c > 40 \text{ kg/m}^3$, the estimated result [Curve (ii) in Fig. 3.8] is close to Winterwerp's (1999) and better than Camenen's (2008).

For Thorn's (1982) and Dankers et al.'s (2007) data, at a given value of ϕ , μ_r inferred from the new model, as shown in Fig. 3.9, is very sensitive to the floc particle parameter (D^*). Meanwhile, μ_r by Eq. (3.5) nearly remains unchanged. This is due to the fact that Eq. (3.5) does not take the effect of D_f on μ_r into account and, for the two data sets, ϕ and ϕ_p do not change significantly because the values of ρ_f are nearly the

same (1,053 g/l and 1,066 g/l). Finally, Curve (i) and Curve (ii) in the figure have the same $\beta = 0.6$ but different values of α and are below Curve (v) even at low value of $\phi/\phi_{\max}$. This implies that, for a wide range of ϕ , k is different from 2.5 and depends on specific cases.

Figure 3.9 - Comparison of μ_r predicted by different models:
(i) and (ii) Eq. (3.17) with $A_v = 0.01$ using Thorn (1982) and Dankers et al. (2007) data,
(iii) and (iv) Eq. (3.5) using Thorn (1982) and Dankers et al. (2007) data,
(v) Eq. (3.1) with $\phi_{\max} = 0.6$, and (vi) Eq. (3.14).

3.4 Conclusions

The following can be concluded from this study:

- (1) A new model containing two empirical coefficients, α and β , for estimating the viscosity of non-cohesive and cohesive sediments was proposed. The new model was calibrated against the available data. For mixtures containing non-cohesive sediments, $\beta = 1.0$ and $\alpha \approx 2.0$ was found to fit the data well. For suspensions not close to the bed and $c \leq 636 \text{ kg/m}^3$, the use of Eq. (3.7) with $\beta = 1.0$ and $\alpha = 2.0$ in the estimation of W_s (and also S_s) can results in the difference in W_s and

hence S_s smaller than 10% when there is a small change ($<10\%$) in α . For cohesive sediments, $\beta = 0.6$ and α varies from 0 to 0.127, depending on the floc properties.

- (2) The settling velocities estimated using the proposed model for viscosity are consistent with the calculated settling velocities using models by Winterwerp (1999) and Camenen (2008), and represent the measured data by Thorn (1982) and Dankers et al. (2007) well.
- (3) The intrinsic viscosity is not always 2.5 (see Fig. 3.3 and Fig. 3.9). The new model suggests that, for cohesive sediments, the viscosity should depend not only on the volumetric concentration of flocs but also on the density and size of flocs.
- (4) Compared to existing models, the new model has some advantages as (i) it includes two calibration coefficients making the new model more flexible than the existing models, (ii) it is applicable to mixtures of both non-cohesive and cohesive sediments, and (iii) the viscosity of the mixture is modeled not only as a function of volumetric concentration but also takes into account the density and size of flocs.

Chapter 4

Modelling the Drag Coefficient of a Particle under Effect of Turbulence

4.1 Introduction

In sediment transport, the settling of sediments is an important process defining changes in morphology. In addition, the drag coefficient is an important parameter in the determination of the settling velocity of sediments. For particles settling in a still fluid, there have been many experimental, analytical, and numerical studies on the drag coefficient and many expressions are available for estimating the drag coefficient (e.g., Chien and Wan, 1999; Cheng, 1997a,b and 2008). Similarly, for particles settling in turbulent flows, there have also been many experimental (e.g., Schwartzberg and Treybal, 1968a,b; Lee 1981; Yang and Shy, 2003; Zhou and Cheng, 2008), analytical (e.g., Hwang, 1985; Mei, 1994), and numerical (e.g., Bosse and Kleiser, 2006; Kawanisi and Shiozaki, 2008) studies. However, there are conflicting conclusions on whether turbulence increases or decreases the particle settling velocity. That isotropic turbulence decreases the relative particle settling velocity has been shown experimentally by Schwartzberg and Treybal (1968a, b), Lee (1981), Zhou and Cheng (2008), analytically by Hwang (1985), Davila and Hunt (2001), and numerically by Lane et al. (2005). Conversely, other experimental (Yang and Shy, 2003; Kawanisi and Shiozaki, 2008), analytical (Maxey and Corrsin, 1986), and numerical (Yang and Lei, 1998; Bosse and Kleiser, 2006) studies have shown that isotropic turbulence increases relative particle settling velocity. For the settling velocity of flocs, Van Leussen (1994) and Winterwerp (1999) showed that turbulence can either increase or decrease the floc settling velocity. These conflicting results show that the determination of the drag coefficient of a particle settling in turbulent flow (and hence the settling velocity of the particle) is a difficult and challenging task.

A new model for the drag coefficient of a particle settling in turbulent flow is developed in this chapter. This model utilizes a modified form of the force balance equation of a particle and the turbulent Reynolds number (Re_t) of the flow, and is applicable to both non-cohesive and cohesive sediments. The proposed model includes two empirical coefficients. A literature review is first presented. A model for estimating the drag coefficient is then proposed. Next, the proposed model is developed and verified by comparing the calculated relative settling velocities of particles with available experimental data. Finally, the merits and limitations of the model are discussed and conclusions are presented.

4.2 Literature review

In 1851, Stokes derived a formula for estimating the settling velocity of a small spherical particle in a still fluid by solving the Navier-Stokes equations with the assumption that the inertia forces in the fluid are negligible (Chien and Wan, 1999). At terminal velocity (settling velocity), frictional force (viscous drag force or Stokes drag force) between the particle and the fluid balances with gravitational force, and this settling velocity of the particle (w_s) is estimated by:

$$w_{s(Stokes)} \equiv \frac{1}{18} \frac{(s-1)gD^2}{\nu} \quad (4.1)$$

where $s = \rho_s/\rho$, ρ_s and ρ are densities of the particle and fluid, respectively, ν is the kinematic viscosity of the fluid, D is the particle size, and g is the gravitational acceleration. Later, Eq. (4.1) was changed into the following form:

$$w_s = \sqrt{\frac{4}{3} \frac{(s-1)gD}{C_D}} \quad (4.2)$$

where $C_D = 24/Re_p$ (Stokes' law) is the drag coefficient, and $Re_p = w_s D/\nu$ is the particle Reynolds number. For a large particle ($Re_p > 0.4$), which is subjected to gravitational, form drag and viscous drag forces (e.g., Chien and Wan, 1999), the

settling velocity of the particle is then determined based on the balance of these three forces, given by:

$$\frac{\pi D^3}{6}(\rho_s - \rho)g = k_1 \frac{\pi D^2}{4} \frac{\rho w_s^2}{2} + k_2 \pi D \mu w_s \quad (4.3)$$

where $\mu = \rho\nu$ is the dynamic viscosity of the fluid, k_1 and k_2 are coefficients (for small spheres, $k_1 \approx 1.0$ and $k_2 \approx 3.0$) (Chien and Wan, 1999). Equation (4.3) can be rearranged into the following form:

$$\frac{\pi D^3}{6}(\rho_s - \rho)g = \left(k_1 + k_2 \frac{8}{\text{Re}_p} \right) \frac{\pi D^2}{4} \frac{\rho w_s^2}{2} = C_D \frac{\pi D^2}{4} \frac{\rho w_s^2}{2} \quad (4.4)$$

where $C_D = (k_1 + k_2 8/\text{Re}_p)$ a modified Stokes' law, is obtained experimentally based on measured settling velocity of the particles (Chien and Wan, 1999). For spherical particles, Cheng (2008) proposed the following formula:

$$C_D = \frac{24}{\text{Re}_p} \left(1 + 0.27 \text{Re}_p \right)^{0.43} + 0.47 \left[1 - \exp \left(-0.04 \text{Re}_p^{0.38} \right) \right] \quad (4.5)$$

which gives a good representation of a complete set of available data reported in the literature for Re_p up to 2×10^5 . For natural sand (non-spherical), Cheng (1997a) proposed that:

$$C_D = \left[\left(\frac{M}{\text{Re}_p} \right)^{1/n} + N^{1/n} \right]^n \quad (4.6)$$

where M , N and n are coefficients. This formula agrees well with widely used diagrams and tables proposed by the US Inter-Agency Committee (1957) with $M = 32$, $N = 1$, and $n = 1.5$. According to Wu and Wang (2006), the coefficients can be approximated by:

$$\begin{aligned} M &\approx 53.5 \exp(-0.65SF) \\ N &\approx 5.65 \exp(-2.5SF) \\ n &\approx 0.7 + 0.9SF \end{aligned} \quad (4.7)$$

where $SF = c/\sqrt{ab}$ is the Corey shape factor of the particle and a, b, and c are lengths of the longest, intermediate, and shortest axes of the particle, respectively; for natural sand, $SF \approx 0.7$. For cohesive sediments, Winterwerp (1999) studied the dynamics of high concentrated mud suspensions; the author suggested using the following formula for C_D :

$$C_D = \frac{24}{Re_p} \left(1 + 0.15 Re_p^{0.687} \right) \quad (4.8)$$

Estimating the settling velocity (or the drag coefficient) of particles settling in turbulent flows is a difficult task due to the complicated interactions between the particles and fluid (Cuthbertson and Irvine, 2007). Although there have been many studies on this topic, there are conflicting results. Some researchers found that turbulence decreases the relative settling velocity and increases the drag coefficient of particles; whereas other researchers showed that turbulence increases the relative settling velocity and decreases the drag coefficient of particles.

In the present study, settling velocity of a particle relative to the surrounding still fluid is denoted by w_s (slip settling velocity or effective settling velocity); settling velocity of the particles relative to the surrounding turbulent fluid is denoted by $w_{s,t} = |V_T - U|$, where V_T is the apparent settling velocity of the particles and U is local vertical velocity of fluid; the drag coefficient of the particles is denoted by $C_{D,t}$ where the subscript $,t$ refers to turbulent conditions.

4.2.1 Studies showing that turbulence reduces the relative settling velocity and increases the drag coefficient

Experimental studies

Schwartzberg and Treybal (1968a, b) studied the motion of fluid and (spherical and non-spherical) particles in an anisotropic turbulence of baffled tanks agitated by six-bladed turbine impellers. The authors used streak photography to measure velocities of fluid and particles. The authors obtained the relative settling velocity by subtracting the fluid velocity from the particle velocity at the same location, and found that the settling

velocity of the particles in turbulent fluid was smaller than that in a still fluid. The authors argued that the reduction in the relative settling velocity is mainly due to enhanced drag rather than upward particle diffusion and the drag coefficient depends on fluctuations of the relative settling velocity.

The experiments by Ho (1964), Murray (1969), and Lee (1981) are summarized in Hwang (1985). These three studies investigated the settling velocity of spherical particles in vertically oscillating flows, which represented fluid variations under wave motion. Ho (1964) conducted experiments on the settling of particles in a vertical cylinder, which was subjected to vertical oscillation; Murray (1969) and Lee (1981) conducted experiments in wave flumes with and without horizontally oscillating grids, respectively. Their experimental results showed that the particles settled with lower velocities than those in a still fluid (see Figures 2, 3, and 4 in Hwang, 1985).

Magelli et al. (1990) investigated distributions of spheres in vessels stirred by multiple impellers, which were evenly distributed along the height of the vessels. A one-dimensional sedimentation-dispersion model was adopted to interpret the solids distribution profiles in the vessels. Based on the measured profiles, the authors concluded that the settling velocities of particles decrease when turbulence is increased and suggested that the reduction in the settling velocity can be related to the interaction between particles and eddies in the stirred suspension by the ratio D/λ , where λ is Kolmogorov length scale.

Brucato et al. (1998) developed a ‘residence time technique’ to measure average settling velocities of spherical and non-spherical particles in a turbulent flow, created in a Couette-type stirred vessel. Measured temporal particle concentrations at two measuring sections were used to determine the mean residence time of particles in the region confined by the two sections. Based on the experimental data, together with a 1-D sedimentation-dispersion model, the authors concluded that turbulence decreases the mean settling velocity and increases the drag coefficient of particles and proposed an empirical formula for the drag coefficient, given by:

$$\frac{C_{D,t}}{C_D} = 1 + 8.76 \times 10^{-4} \exp\left(\frac{D}{\lambda}\right)^3 \quad (4.9)$$

However, Eq. (4.9) does not take changes in particle density into account (Doroodchi et al., 2008). In addition, Zhou and Cheng (2008) argued that Eq. (4.9) could not give a good fit to Zhou and Cheng's (2008) experimental data obtained from experiments with a vertically oscillating grid.

Doroodchi et al. (2008) carried out experiments on the settling of spherical particles in stationary near-isotropic turbulent flow regions, created by two out-of-phase horizontally oscillating grids in a tank, to verify an empirical model for the settling velocity of bubbles in turbulence, proposed by Lane et al. (2005):

$$\frac{V_T}{w_s} = 1 - 1.4St^{0.7} \exp(-0.6St) = f(St) < 1.0 \quad (4.10)$$

where $St = \tau_p/\tau_L$ is the Stokes number, τ_p is a particle relaxation time, and τ_L is an integral time scale. The particle slip velocity was assumed to equal its settling velocity. The authors found that turbulence decreased the particle settling velocity and Eq. (4.10) under-estimated the particle settling velocity. Moreover, based on the experimental data, the authors argued that $\frac{V_T}{w_s} = f\left(St, \frac{D}{L}, \frac{u'}{w_s}\right)$ and suggested

$$\left(\frac{V_T}{w_s}\right)_{\min} = f\left(St, Ri \equiv \frac{g|\rho_s - \rho|}{\rho} \frac{L}{u'^2}\right), \quad \text{where } Ri \text{ is the Richardson number,}$$

$L = \sqrt{8/\pi} u' \tau_E$ is an integral length scale, u' is the r.m.s horizontal velocity of the turbulence, τ_E is Eulerian integral length scale.

Cuthbertson and Ervine (2007) investigated settling rates of fine sand particles in a current flume at relatively high Reynolds number and high relative bed roughness. Fluctuating flow velocities were measured by using an Acoustic Doppler Velocimeter (ADV) and a mini-propeller current meter; a high-speed digital camera and a particle tracking velocimetry technique were employed to record and analyze the motion of the sand particle. A flow visualization technique with a moving frame of reference in the

mean flow direction was used to observe interactions between the particles and the turbulent flow structure, and a quadrant analysis technique was applied to correlate the motions of the sand and the fluid particles. The authors found that as z/H (where H is water depth and z is vertical distance upward from the bottom) decreased, fluid sweeps (a down-rush of high momentum fluid) became dominant over fluid ejections (a lift-up of low-momentum fluid); the settling rate of the particles was retarded in the outer flow region ($z/H > 0.5$) and enhanced in the near-bed ($z/H \leq 0.2$) and intermediate ($0.2 < z/H \leq 0.5$) flow regions. The authors argued that the enhancement in the particle settling velocity resulted from a preferential transportation of the downward fluid motions. This is in agreement with van Rijn (1993), who argued that the presence of fluid bursting processes (sweeps and ejections) results in an asymmetric fluid motion in the vertical direction and a slight increase of the particle settling velocity.

Zhou and Cheng (2008) carried out experiments on the settling velocity of spherical and cylindrical particles in stationary anisotropic turbulent fields, created by one vertically oscillating grid in a tank. The mesh size and stroke of the grid were $M = 5.0$ cm and $S = 5.2$ cm, respectively. The authors could not avoid secondary flows in the tank and claimed that the secondary flows, although weak, can affect the settling velocity to a certain degree (Zhou and Cheng, 2008). The authors measured simultaneous velocities of the settling particle and the ambient fluid; the relative particle settling velocity was obtained by subtracting the vertical fluid velocity from the vertical particle settling velocity. The particle properties and the results from their experiments are indicated in Table 4.1 and Table 4.2, respectively. Based on their experiments, the authors concluded that turbulence decreases the relative particle settling velocity and increase the drag coefficient; they argued that the suggestions by Doroodchi et al. (2008) could not be substantiated and proposed instead:

$$\left| \frac{w_s}{V_T} \right| = 1 + \frac{U}{|w_s|} + \frac{U^2 + U'^2}{|w_s|^2} \quad (4.11)$$

where U and U' are the mean and fluctuating components of the vertical fluid velocity.

Table 4.1 - Test conditions and experimental results for spherical particles (Zhou and Cheng, 2008).

Case	D (mm)	f (Hz)	z (m)	No. of tests	V_T/w_s	$(V_T-U)/w_s$
1	6.35	2	0.034-0.134	14	1.106	0.955
2	6.35	2	0.091-0.191	12	1.046	0.895
3	6.35	2	0.163-0.263	10	1.098	0.974
4	6.35	3	0.034-0.134	10	1.022	0.865
5	6.35	3	0.091-0.191	8	1.032	0.924
6	6.35	3	0.163-0.263	10	0.839	0.913
7	7.94	2	0.034-0.134	8	1.122	0.926
8	7.94	2	0.091-0.191	15	1.057	0.898
9	7.94	2	0.163-0.263	10	1.041	0.935
10	7.94	3	0.034-0.134	10	1.080	0.931
11	7.94	3	0.091-0.191	6	1.115	0.940
12	7.94	3	0.163-0.263	10	1.003	0.981

Note: Particle density $\rho_s \approx 1,050 \text{ kg/m}^3$. For particles with $D = 6.35 \text{ mm}$, $w_s = 8.85 \text{ cm/s}$ and $Re_p = 568$. For particles with $D = 7.94 \text{ mm}$, $w_s = 10.29 \text{ cm/s}$ and $Re_p = 824$. Relative particle settling velocity $w_{s,t} = w_s \times \text{column (7)}$ is shown in second column of Table 4.4.

Table 4.2 - Test conditions and experimental results for cylindrical particles (Zhou and Cheng, 2008).

Case	D (mm)	Re _p	z (m)	V _T /w _s	(V _T -U)/w _s
1	2.779	122	0.116-0.216	1.282	1.005
2	2.945	134	0.073-0.173	1.607	1.022
3	2.846	161	0.073-0.173	0.950	0.974
4	3.037	182	0.073-0.173	1.112	0.945
5	2.763	66	0.073-0.173	1.321	0.962
6	3.037	153	0.073-0.173	1.075	0.972
7	2.903	98	0.073-0.173	1.464	0.909
8	2.998	110	0.073-0.173	1.199	0.907
9	2.882	178	0.073-0.173	1.015	1.006
10	3.031	198	0.073-0.173	1.381	1.172
11	3.112	179	0.073-0.173	0.869	0.643
12	2.817	132	0.073-0.173	0.832	0.875
13	2.978	114	0.073-0.173	1.571	1.131
14	2.985	67	0.073-0.173	0.803	0.818
15	2.985	67	0.073-0.173	1.559	0.852
16	2.952	137	0.073-0.173	1.269	0.927
17	3.050	188	0.073-0.173	0.916	0.809
18	2.972	176	0.073-0.173	1.526	1.039

Note: Particles density $\rho_s \approx 1,077 \text{ kg/m}^3$. D is volume-equivalent nominal diameter. Frequency of the grid $f = 2 \text{ Hz}$. $w_s = v/D \times \text{column (3)}$ and $w_{s,t} = w_s \times \text{column (6)}$.

For cohesive sediments, the number of experiments on the effect of turbulence on settling velocity is limited. Winterwerp (1998 and 1999) conducted experiments with Ems-Dollard mud in a settling column. Vertically oscillating grid(s) created turbulence in the column. The particle properties and the results from the experiments are indicated in Table 4.3. It can be seen from the table that turbulence decreases the (floc) particle settling velocity.

Table 4.3 - Settling column tests with Ems-Dollard mud (Winterwerp, 1999).

Test No.		T71	T137	T69	T139	T73	T141
c_0 (kg/m ³)		0.65	0.98	1.17	1.03	1.21	1.01
f (Hz)		0.10	0.10	0.25	0.25	0.50	0.50
G (s ⁻¹)		7.3	7.3	28.9	28.9	81.7	81.7
D_f (μm)		270	N/A	241	N/A	140	N/A
V_T (mm/s)		0.85	1.20	0.17	0.20	0.09	0.20
ϕ (%)		1.66		2.66		1.60	
Re_t	(i) Lower	0		0		478.2	
	(ii) Eq. (4.31)	1316.5		2723.4		4715.8	
	(iii) Upper	5811.3		7134.8		8954.9	
$w_{s,mt}$ = Eq. (4.25) (mm/s)	(i)	0.84		0.73		0.35	
	(ii)	0.47		0.30		0.14	
	(iii)	0.22		0.17		0.10	
$C_{D,mt}$ = Eq. (4.32)	(i)	115.5		150.9		683.3	
	(ii)	372.2		920.6		4118.3	
	(iii)	1710.3		2837.2		9194.3	
$W_{s,mt}$ = Eq. (4.24) (mm/s)	(i)	0.83		0.71		0.34	
	(ii)	0.46		0.29		0.14	
	(iii)	0.22		0.16		0.09	

Note: The first six rows (Test No., c_0 , f , G , D_f , and V_T) are taken from Winterwerp (1999).

Analytical and Numerical studies

Hwang (1985) applied harmonic analysis for a vertical motion of a spherical particle in a simple harmonic vertically oscillated flow. From the equation of motion of the particle, the author considered fluid pressure gradient, submerged weight of the particle, drag force, and force due to added mass effect. Instantaneous drag coefficient, subjected to change with instantaneous relative settling velocity, was used to determine the drag force. The author neglected higher harmonic terms in the settling velocity of the particle, averaged the equation of motion over an oscillation period, and obtained a balance between submerged weight and averaged drag force. Hwang's (1985) analytical results showed that the drag coefficient of the particle in turbulence is larger

than that in a still fluid and the settling velocity of the particle in turbulence is smaller than that in a still fluid, expressed as:

$$\frac{V_T}{w_s} = f\left(\frac{w_s D}{\nu}, \frac{U_{f,\max}}{w_s}\right) \leq 1.0 \quad (4.12)$$

where $U_{f,\max}$ is the peak velocity of fluid velocity (also see van Rijn, 1993). However, comparing the theoretical results with the experimental data of Ho (1964) shows that Eq. (4.12) is only accurate when $U_{f,\max} < 2 w_s$. In addition, van Rijn (1993) argued that the equation suggests a rather large reduction of the settling velocity, $V_T = 0.5 w_s$, for $U_{f,\max} = 10 w_s$.

Mei (1994) used Monte Carlo simulation to investigate the particle settling velocity in an isotropic turbulent (air) flow. Regarding motions of the (heavy) particles, the author considered inertia force, drag forces, and gravitational force. The equation of motion of the particles is given by:

$$m_p \frac{d\tilde{V}}{dt} = \Phi 3\pi D \mu (\tilde{U} - \tilde{V}) + m_p g \quad (4.13)$$

where m_p is the particle mass, $\tilde{U}$ and $\tilde{V}$ are local velocities of fluid and particles, respectively, $\Phi = 1 + b \text{Re}_{p,t}^n$, $\text{Re}_{p,t} = |\tilde{U} - \tilde{V}| D / \nu$, $b = 0.15$ and $n = 0.687$. By ensemble averaging, after an initial transient period, both sides of Eq. (4.13) and applying a Taylor series expansion to the velocity components, the author obtained the following expression:

$$V_T = \frac{w_{s(\text{Stokes})}}{(1 + b \text{Re}_1^n) + \Delta_1} \quad (4.14)$$

where $\text{Re}_1 = V_T D / \nu$, $\Delta_1 \geq 0$ is a coefficient depending on factors such as fluctuation velocity components of the particle and fluid, V' and U' , respectively [see Eq. (5) and Eq. (6) in Mei (1994)]. Based on simulation results, the author concluded that (i) the non-linearity of the drag associated with the turbulence reduces the particle settling velocity and (ii) trajectory bias, which causes particles to collect in regions of high

strain rate with a higher probability of greater downward fluid velocity, enhances the settling velocity. Note that the first conclusion implies that $C_{D,t}$ is increased due to the turbulence and the second conclusion is in agreement with the arguments by van Rijn (1993) and Cuthbertson and Ervine (2007), mentioned earlier. Moreover, comparing Eq. (4.13) with Eq. (4.3) shows that the author used $C_{D,t} = (24 / \text{Re}_{p,t}) (1 + 0.15 \text{Re}_{p,t}^{0.687})$, which has the same form as Eq. (4.8); and effect of turbulence on $C_{D,t}$ was implicitly taken into account by Eq. (4.14).

Davila and Hunt (2001) applied a similar form for Φ as Mei (1994) and linearized Φ around $(\tilde{U} - \tilde{V})$ to obtain:

$$\Phi \approx \Phi_0 + \Delta_2 \geq \Phi_0 \quad (4.15)$$

where Φ_0 is value of Φ in still fluid and $\Delta_2 \geq 0$ is a coefficient depending on factors such as $\tilde{U}$ and $\tilde{V}$ [see Appendix A of Davila and Hunt (2001)]. Because Φ is a ratio of the actual drag force in turbulence to the Stokes drag, and Φ_0 is a ratio of the actual drag force in still fluid to the Stokes drag, Eq. (4.15) implies that the drag force (or drag coefficient) in the (isotropic) turbulence is larger than that in a still fluid.

4.2.2 Studies showing that turbulence increases the relative settling velocity and reduces the drag coefficient

Experimental studies

Yang and Shy (2003) investigated the settling velocity of tungsten and glass particles in stationary near-isotropic turbulent regions, generated by two out-of-phase vertically oscillating grids in a water tank (Shy et al., 1997). Particle and fluid velocities were obtained by using both particle tracking technique and particle image velocimetry and analyzed by a wavelet transform technique. The authors assumed that the effect of secondary flow on the settling velocity was negligible and did not subtract the local fluid velocity from the particle settling velocity. In general, the experimental results of Yang and Shy (2003) agreed with numerical results by Wang and Maxey (1993) and Yang and Lei (1998); ensemble-average (relative) settling velocity of the particles

under turbulent conditions was found to be higher than that in a still fluid. However, Zhou and Cheng (2008) argued that the unavoidable secondary flow could have affected the experimental result of Yang and Shy (2003).

The effect of turbulence on the settling velocity of suspended sediments was also experimentally and numerically investigated by Kawanisi and Shiozaki (2008). For the experiments, velocities of (spherical and non-spherical) particles and fluid in a current flume were measured by using an ADV. The mean particle settling velocity ($w_{p,mean}$) was obtained by using backscatter signals from the ADV, given by:

$$w_{p,mean} = \frac{1}{I_{mean}} \left(\overline{w_p I} - \overline{w'_p I'} \right) \quad \text{for } I_c < I \quad (4.16)$$

where w_p and w'_p are vertical particle velocity and its fluctuation, respectively, I , I_{mean} and I' are the intensity, mean and fluctuation of the backscatter, respectively, and I_c is a threshold for particle detection. The vertical turbulent flux of particle (second term on the right hand side of Eq. (4.16)) was neglected in the experiments. The mean vertical velocity of fluid was obtained by using tracer particles and then subtracted from the mean particle settling velocity to obtain the mean relative settling velocity of the particle. For the numerical simulation, the authors used the particle settling velocity (instead of the relative particle settling velocity) to calculate Re_p (and $C_{D,t}$) [see Eq. (15) in Kawanisi and Shiozaki (2008)]. From the investigation, they reported that (i) the effect of turbulence on the (relative) settling velocity from the experiments was smaller than that predicted by the numerical simulation, and (ii) the relative particle settling velocity decreases at lower levels of turbulence but increases at higher levels of turbulence. It should be mentioned that, at higher levels of turbulence, their results may be inaccurate since (i) the second term on the right hand side of Eq. (4.16) may not be negligible and (ii) in their numerical simulation, the relative particle settling velocity was not used in the determination of Re_p and $C_{D,t}$.

Recently, Moradian et al. (2009) studied the effects of free stream turbulence on the drag coefficient of a sphere. In their experiments, the drag force on a fixed sphere in a closed circuit wind tunnel was measured. The authors found that the drag force

always decreased with increasing turbulence level. However, in reality, particles rotate when settling; hence, their result may not be applicable, at least, for the study of suspended sediments transport in aquatic environments.

Analytical and Numerical studies

The gravitational settling of aerosol particles in randomly oriented cellular (air) flows was analytically investigated by Maxey and Corrsin (1986). The domain included individual cells, which were randomly rotated over a range from 0 to 2π radians. The particles were assumed to be small and spherical. Regarding the motion of the particles, the authors only considered three forces: inertia force, Stokes drag force induced by the relative velocity between the particle and the ambient fluid, and gravitational force. Mean particle settling velocity was defined as an average of vertical velocities of the particles in the domain. The authors solved Eq. (4.13), with $\Phi = 1.0$ or $C_{D,t} = (24 / \text{Re}_{p,t})$, analytically and concluded that the turbulent (air) flows increased the mean particle settling velocity compared to that in still fluid. However, it should be mentioned that there are several limitations of their analysis since, (i) the cellular flow field is not realistic (Maxey and Corrsin, 1986; Mei, 1994), (ii) considering Stokesian particles rules out a reduction in the settling velocity (Mei, 1994), and (iii) the analytical results were not compared with measured data.

Bosse and Kleiser (2006) also solved the equation of motion of a particle, similar to Eq. (4.13) with $\Phi = 1.0$ or $C_{D,t} = (24 / \text{Re}_{p,t})$, to investigate numerically the motions of small heavy particles in a homogeneous turbulent (air) flow field. The motion was generated by a forcing procedure, which was more realistic than that in Maxey and Corrsin (1986), for one-way coupling (fluid flow is not affected by the presence of the particles) and two-way coupling (particles exert a feedback force on the fluid). Based on the numerical results, the authors also gave a similar conclusion as Maxey and Corrsin (1986), mentioned earlier. Nevertheless, it has to be mentioned that (i) the form drag force was not taken into account in the equation of motion and (ii) the numerical simulations, especially for two-way coupling, over-predicted the

experimental results by Yang and Shy (2005), mentioned previously, (Bosse and Kleiser, 2006).

Yang and Lei (1998) considered the effect of the form drag force by assuming that the drag coefficient of particles in stationary homogeneous isotropic turbulent (air) flows has the same form as that in a still fluid, $C_{D,t} = (24/\text{Re}_{p,t})\Phi$, where $\Phi = 1.0 + f(\text{Re}_{p,t}) \geq 1.0$. The authors solved the governing equations for the flow fields numerically using either Direct Numerical Simulation (DNS) or Large Eddy Simulation (LES) and then used the numerical simulations to solve Eq. (4.13). Based on the numerical results, they also found an increase in the average particle settling velocity compared to that in a still fluid. However, the authors did not verify their results against measured data.

It is noted that there is a common reason that may affect the results of Maxey and Corrsin (1986), Yang and Lei (1998), and Bosse and Kleiser (2006). All of these works assumed that the drag coefficient of the particles in turbulence has the same form as that in a still fluid and only considered the relative velocity between the “average instantaneous” velocities of particle and the fluid; they did not take into account an effect of turbulence on $C_{D,t}$ as was considered by Mei (1994) for the velocity components. In other words, Maxey and Corrsin (1986), Yang and Lei (1998), and Bosse and Kleiser (2006) “smoothed out” turbulence and in doing so, ignored the change of the drag coefficient due to the turbulence. With reference to the Reynolds-Averaged Navier-Stokes (RANS) equations (Versteeg and Malalasekera, 1995), an additional component in the form of the Reynolds stress should be added to the existing formulae for C_D to account for the effect of turbulence. These arguments suggest that the enhancement of the relative particle settling velocity in turbulent flows is still unverified.

4.2.3 Turbulence can either increase or decrease the particle settling velocity

Van Leussen (1994) and Winterwerp (1998 and 1999) proposed models for estimating the settling velocity of flocs. These models include turbulent shear rate G (1/s), which plays an important role in the aggregation and break-up processes of flocs. Under shear, small flocs can stick together to form larger flocs with a faster settling velocity, or the larger flocs can also be broken up due to high shear into smaller flocs with lower settling velocity. However, the authors used the shear rate for modelling flocculation only, not for modelling the effect of turbulence on the drag coefficient (Winterwerp, 1998).

4.3 Proposed model

There is no model available for the settling velocity and drag coefficient of a particle settling in mixture under turbulence. Therefore, there needs a new approach to develop new models of settling velocity and drag coefficient of particle in clear water or mixture under turbulence in forms that are suitable for implementation in a numerical model. Noted that, a particle settling in still clear fluid is subject to gravitational force, form drag and viscous drag, as shown in Eq. (4.3); and the drag coefficient of the particle contains only two well-known components (form drag and viscous drag), as shown in Eq. (4.4). However, turbulence retards the settling velocity and increases the drag coefficient. As such, for a particle settling in turbulent clear fluid, beside the three forces there should be another force; and beside the two drag components there should be another component. That force and that drag component do not exist when the particle falls in still clear fluid; they represent the effect of turbulence on the particle settling velocity. For the present study, the turbulent Reynolds number (Re_t) will be used for quantifying the turbulence in the development of the new model. Using the k - ε model, $Re_t \equiv k^2 / \varepsilon \nu$ (Versteeg and Malalasekera, 1995), where k and ε are the turbulent kinetic energy and its dissipation rate, respectively.

4.3.1 Particle settling in an isotropic turbulent clear fluid

For a particle settling in a turbulent clear fluid, the particle is subjected to gravitational force, form drag and viscous drag forces induced by the relative settling velocity between the particle and the fluid, inertia force, and added mass effect, etc. Except for the first three forces, all the other forces are assumed to be lumped as a “turbulent” force (ΔF_t). The force balance equation for the particle takes the form:

$$\frac{\pi D^3}{6}(\rho_s - \rho)g = k_{1,t} \frac{\pi D^2}{4} \frac{\rho w_{s,t}^2}{2} + k_{2,t} \pi D \mu w_{s,t} + \Delta F_t \quad (4.17)$$

where $k_{1,t}$ and $k_{2,t}$ are coefficients. Referring to Eq. (4.3) and Eq. (4.4), Eq. (4.17) can be in new forms as below:

$$\frac{\pi D^3}{6}(\rho_s - \rho)g = \left(k_{1,t} + k_{2,t} \frac{8}{\text{Re}_{p,t}} + k_3 \right) \frac{\pi D^2}{4} \frac{\rho w_{s,t}^2}{2} \quad (4.18)$$

$$\frac{\pi D^3}{6}(\rho_s - \rho)g = C_{D,t} \frac{\pi D^2}{4} \frac{\rho w_{s,t}^2}{2} \quad (4.19)$$

where

$$C_{D,t} = \left(k_{1,t} + k_{2,t} \frac{8}{\text{Re}_{p,t}} + k_3 \right) \quad (4.20)$$

is the drag coefficient of the particle settling in a turbulent clear fluid and k_3 is a calibration coefficient. The relative particle settling velocity is then estimated by:

$$w_{s,t} = \sqrt{\frac{4(s-1)gD}{3C_{D,t}}} \quad (4.21)$$

The following assumptions are made:

Assumption 1: The coefficients $k_{1,t}$ and $k_{2,t}$ are assumed to have the same form as those in still water and are dependent on $\text{Re}_{p,t}$, which is given by:

$$\text{Re}_{p,t} = \frac{w_{s,t} D}{\nu} \quad (4.22)$$

This assumption implies that $w_{s,t}$, the “average instantaneous” value of the particle settling velocity, is used in the determination of the drag forces and k_3 is a “turbulent” component, which accounts for the effect of turbulence and has the same meaning as the Reynolds stresses in the RANS equations. It also means that $C_{D,t} = C_{D, \text{still form}} + k_3$, where $C_{D, \text{still form}}$ contains the first two components at the RHS of Eq. (4.20) and has the same form as that in Eq. (4.4).

Assumption 2: Turbulence decreases the relative settling velocity and increases the particle drag coefficient $C_{D,t}$. This assumption is based on the conclusions made by Schwartzberg and Treybal (1968a, b) and Zhou and Cheng (2008), and implies that $k_3 \geq 0$. The variation of k_3 in Fig. 4.1 shows that $k_3 \rightarrow 0$ when the effect of turbulence on $w_{s,t}$ is small. This happens when Re_t is small and/or when the particle is large, i.e. $w_{s,t} \rightarrow w_s$ when $Re_{p,t} \gg Re_t$ or $Re_{p,t}/Re_t \rightarrow \infty$. On the other hand, $k_3 \rightarrow \infty$ when the effect of turbulence on $w_{s,t}$ is high. This occurs when Re_t is high and/or when the particle is small, i.e. when $Re_{p,t} \ll Re_t$ or $Re_{p,t}/Re_t \rightarrow 0$. In this case, the particle will hardly settle and will remain in suspension, since $w_{s,t} \rightarrow 0$. As a first approximation, assume that the relationship k_3 versus $Re_{p,t}/Re_t$ can be approximated by a monotonically decreasing function of the form:

$$k_3 = \alpha \left(\frac{Re_t}{Re_{p,t}} \right)^\beta \quad (4.23)$$

where α, β ($\alpha, \beta > 0$) are to be obtained from calibration with experimental data.

Figure 4.1 - Variation of k_3 with $Re_{p,t}$ and Re_t .

4.3.2 Particle settling in an isotropic turbulent mixture

The procedure for estimating the hindered settling velocity ($W_{s,m}$) of a particle in a still mixture (Chien and Wan, 1999; Cheng, 1997b) was adopted for estimating the hindered settling velocity ($W_{s,mt}$) of a particle in a turbulent mixture:

$$W_{s,mt} \approx (1 - \phi)w_{s,mt} \quad (4.24)$$

where ϕ is the volumetric concentration of particles in the mixture and $w_{s,mt}$ is the relative settling velocity of the particle in the turbulent mixture. $w_{s,mt}$ is approximated by:

$$w_{s,mt} = \sqrt{\frac{4(s_m - 1)gD}{3C_{D,mt}}} \quad (4.25)$$

where $s_m = \rho_s/\rho_m$, ρ_m is density of the mixture and $C_{D,mt}$ is drag coefficient of the particle settling in the turbulent mixture. $C_{D,mt}$ is estimated by:

$$C_{D,mt} = \left(k_{1,mt} + k_{2,mt} \frac{8}{Re_{p,mt}} + k_{3m} \right) \quad (4.26)$$

where $k_{1,mt}$, $k_{2,mt}$ and k_{3m} are coefficients. $k_{1,mt}$, $k_{2,mt}$ are assumed to have the same form as $k_{1,t}$, $k_{2,t}$ in Eq. (4.20). k_{3m} is estimated by:

$$k_{3m} = \alpha \left(\frac{\text{Re}_t}{\text{Re}_{p,mt}} \right)^\beta \quad (4.27)$$

where $\text{Re}_{p,mt}$ is the particle Reynolds number in the turbulent mixture, given by:

$$\text{Re}_{p,mt} = \frac{w_{s,mt} D}{\nu_m} \quad (4.28)$$

$\nu_m = \mu_r \rho \nu / \rho_m$ is the kinematic viscosity of the mixture and μ_r is the relative viscosity of the mixture.

4.4 Results and Discussion

α and β , required for the estimation of $C_{D,t}$ in Eq. (4.20) was estimated using Zhou and Cheng's (2008) data for spheres. Next, the model for estimating $C_{D,t}$ was verified against Zhou and Cheng's (2008) data for spherical and cylindrical particles. Finally, the proposed model for estimating $C_{D,mt}$ [Eq. (4.26)] of a particle settling in an isotropic turbulent mixture will be tested against the experimental data obtained by Winterwerp (1998) for Ems-Dollard mud.

In this Section, the determination of $w_{s,t}$ follows an iteration process: a value of $w_{s,t}$ is assumed, $\text{Re}_{p,t}$ and $C_{D,t}$ are determined, and $w_{s,t}$ is calculated; the process ends when the error between calculated and assumed values of $w_{s,t}$ is very small. The flow chart for estimating $w_{s,t}$ of spheres is shown in Fig. 4.2. The process for determining $w_{s,mt}$ is similar to the one for $w_{s,t}$.

Figure 4.2 - Flow chart for estimating $w_{s,t}$ of sphere.

4.4.1 Particle settling in an isotropic turbulent clear fluid

Applying the first assumption for the proposed model in combination with Eq. (4.5), the drag coefficient of a sphere falling in turbulent flow is given by:

$$C_{D,t} = \left\{ \frac{24}{\text{Re}_{p,t}} \left(1 + 0.27 \text{Re}_{p,t} \right)^{0.43} + 0.47 \left[1 - \exp \left(-0.04 \text{Re}_{p,t}^{0.38} \right) \right] \right\} + \alpha \left(\frac{\text{Re}_t}{\text{Re}_{p,t}} \right)^\beta \quad (4.29)$$

Based on Zhou and Cheng's (2008) data for spheres, as shown in Table 4.1, $C_{D,t}$ and $\text{Re}_{p,t}$ were calculated directly by using Eq. (4.21) and Eq. (4.22), respectively. k_3 , last term in Eq. (4.29) was then obtained, as shown in Table 4.4. Applying a fitting procedure using the least square method, with 90% confidence interval, to $\text{Re}_t/\text{Re}_{p,t}$ and k_3 (Columns 4 and 5 of Table 4.4, respectively), $\alpha \approx 0.0385 \pm 1.8338$ and $\beta \approx 0.6943 \pm 0.8207$. However, α should be larger than zero because $k_3 \geq 0$ (see Assumption 2); therefore α should be in the range from 0 to 1.7823. In addition, $\beta \geq 0$ because k_3 is proportional to $\text{Re}_t/\text{Re}_{p,t}$ (see Assumption 2); therefore, β should be in

the range from 0 to 1.5150. The variation of k_3 estimated by Eq. (4.23), with $\alpha = 0.0385$ and $\beta = 0.6943$, and from the experiment is shown in Fig. 4.3.

Figure 4.3 - Variation of k_3 from experiment (+) [see Table 4.4, column 5] and estimation (line) [Eq. (4.23) with $\alpha = 0.0385$ and $\beta = 0.6943$].

Table 4.4 - Experimental and predicted values of $w_{s,t}$ and $C_{D,t}$ of the spherical particles.

Case No.	Experiment				Prediction					$w_{s,t}$ 90% (cm/s)		$C_{D,t}$ 90%	
	$w_{s,t}$ (cm/s)	$C_{D,t}$	$Re_t/Re_{p,t}$	$\alpha(Re_t/Re_{p,t})^\beta$	$Re_t/Re_{p,t}$	$w_{s,t}$ (cm/s)	Er. $w_{s,t}$	$C_{D,t}$	Er. $C_{D,t}$	Upper	Lower	Upper	Lower
1	8.452	0.581	2.5	0.034	2.6	8.128	-3.8%	0.629	8.1%	8.816	7.439	0.707	0.550
2	7.921	0.662	1.9	0.104	1.8	8.253	4.2%	0.610	-7.9%	8.958	7.548	0.688	0.532
3	8.620	0.559	1.2	0.015	1.3	8.357	-3.0%	0.595	6.4%	9.047	7.667	0.675	0.514
4	7.655	0.709	4.1	0.144	4.0	7.943	3.8%	0.658	-7.1%	8.647	7.239	0.753	0.564
5	8.177	0.621	2.7	0.068	2.8	8.102	-0.9%	0.633	1.9%	8.796	7.407	0.713	0.553
6	8.080	0.636	2.0	0.081	1.9	8.235	1.9%	0.612	-3.7%	8.936	7.535	0.690	0.535
7	9.529	0.572	1.8	0.075	1.7	9.704	1.8%	0.551	-3.6%	10.404	9.003	0.629	0.473
8	9.240	0.608	1.3	0.107	1.2	9.827	6.3%	0.538	-11.6%	10.536	9.118	0.618	0.458
9	9.621	0.561	0.9	0.065	0.9	9.929	3.2%	0.527	-6.1%	10.632	9.226	0.610	0.444
10	9.580	0.566	2.6	0.069	2.6	9.519	-0.6%	0.573	1.3%	10.215	8.824	0.652	0.494
11	9.673	0.555	1.9	0.060	1.9	9.677	0.0%	0.554	-0.1%	10.374	8.981	0.632	0.477
12	10.094	0.510	1.3	0.020	1.3	9.809	-2.8%	0.540	5.9%	10.500	9.119	0.620	0.460

Note: For values of Re_t , see Table A1.2. For columns (8) and (10): Error = (Predicted value – Experimental value) / Experimental value

As a part of the calibration process, the applicability of the values for k_3 , α and β in the determination of $C_{D,t}$ and $w_{s,t}$ for spherical particles were checked. By using Eq. (4.21) for $w_{s,t}$ and using Eq. (4.29), with $\alpha = 0.0385$ and $\beta = 0.6943$, to estimate $C_{D,t}$, $w_{s,t}$ and $C_{D,t}$ as well as the model errors compared with the experimental data were estimated, as shown in Table 4.4 and Fig. 4.4. The 90% prediction intervals for $w_{s,t}$ and $C_{D,t}$ were also made, as shown in Table 4.4 and Fig. 4.5, showing a good agreement between the estimated and measured values.

Figure 4.4 - Experimental (Zhou and Cheng 2008) and predicted values of (a) $C_{D,t}$ and (b) $w_{s,t}$ (cm/s) of spheres.

(a)

(b)

Figure 4.5 - Experimental values (Zhou and Cheng 2008) and 90% prediction intervals of (a) $C_{D,t}$ and (b) $w_{s,t}$ of spheres.

Next, the proposed model was tested for cylindrical particles settling in a turbulent clear water tank (see Table 4.2) using a separate dataset from Zhou and Cheng (2008). The testing procedure was carried out using the mean values of particle size and $w_{s,t}$ from 17 cases (No. 2 to No. 18) reported in Zhou and Cheng (2008). The following were assumed in the testing procedure: the volume-equivalent nominal diameter $D_{\text{mean}} \approx 2.96$ cm, $w_{s,t \text{ mean}} \approx 4.387$ cm/s, $C_{D,t} \approx 1.548$, and $Re_{p,t} \approx 129.8$ (Table 4.2), $Re_t \approx 1,055$ (mentioned later with reference to the Appendix 1) and $Re_t/Re_{p,t} \approx 8.1$. Applying the first assumption for the proposed model in combination with Eq. (4.6), the drag coefficient is given by:

$$C_{D,t} = \left[\left(\frac{M}{Re_{p,t}} \right)^{1/n} + N^{1/n} \right]^n + 0.0385 \left(\frac{Re_t}{Re_{p,t}} \right)^{0.6943} \quad (4.30)$$

Zhou and Cheng (2008) used cylindrical plastic segments with diameter of 2.4 mm, average length of 3.0 mm, density of 1,077 kg/m³, and w_s ranging from 2.05 cm/s to 5.92 cm/s, giving $SF \approx 0.89$, $M \approx 29.9$, $N \approx 0.6$, and $n \approx 1.51$ [see Eq. (4.7)]. Substituting these values in Eq. (4.21) for $w_{s,t}$ and Eq. (4.30) for $C_{D,t}$ results in $w_{s,t} \approx 4.872$ cm/s (+11.0%), $C_{D,t} \approx 1.255$ (-18.9%), $Re_{p,t} \approx 144.13$ (+11.0%), and $Re_t/Re_{p,t} \approx 7.3$ (-9.9%), where the numbers in brackets are the percentage difference compared to the experimental data. The discrepancies between predicted and experimental results are within acceptable limits; hence, the use of Eq. (4.30) for $C_{D,t}$ and Eq. (4.21) for $w_{s,t}$ results in an acceptable value of the relative settling velocity of non-spherical non-cohesive particle under turbulent conditions. The data used for the testing procedure as well as the calculated results are summarized in Table 4.5.

Table 4.5 – Results using Zhou and Cheng's (2008) experiments for cylindrical particles (Note: the numbers in brackets are the percentage difference between calculated value and the measured data).

	ρ_s (kg/m ³)	D (cm)	SF	Re_t	$w_{s,t}$ (cm/s)	$Re_{p,t}$	$C_{D,t}$	$Re_t/Re_{p,t}$
Meas.	1,077	2.96	0.89	1,055	4.387	129.8	1.548	8.1
Calc.					4.872 (+11.0%)	144.13 (+11.0%)	1.255 (-18.9%)	7.3 (-9.9%)

For practical applications, it can be remarked that the Kolmogorov length scale, $\lambda \equiv (\nu^3 / \varepsilon)^{1/4}$, is normally from 100 μm to 1,000 μm in estuaries (Winterwerp 1999). Assuming $\lambda \approx 500 \mu\text{m}$ and $\nu \approx 1 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$ results in $\varepsilon \approx 1.6 \times 10^{-5} \text{ m}^2 \text{ s}^{-3}$, $G \approx 4.0 \text{ s}^{-1}$, and $\text{Re}_t \approx 958.1$. For sand particles with $\rho_s \approx 2,650 \text{ kg m}^{-3}$, $D \approx 200 \mu\text{m}$, $\text{SF} \approx 0.7$. From Eq. (4.6), this gives $C_D \approx 10.8$ and $w_s \approx 20.0 \text{ mm/s}$. Equation (4.30) however gives $C_{D,t} \approx 13.9$ and $w_{s,t} \approx 17.7 \text{ mm/s}$. Therefore, the present model shows that applying w_s for sand in a still fluid leads to an over estimation of the settling velocity by about 11.5%.

4.4.2 Particle settling in an isotropic turbulent mixture

Winterwerp's (1999) settling column data (Table 4.3) was used to test the applicability of Eq. (4.26) and Eq. (4.27) to estimate the settling velocity of flocs in a turbulent mixture. Note that Winterwerp (1999) used the shear rate G (1/s) to evaluate the turbulence level. In order to use Winterwerp's (1999) data, an analysis relating Re_t and G was first carried out (details of the derivation are provided in the Appendix 1). Based on this analysis, the following relationship between Re_t and G (1/s) given as:

$$\text{Re}_t \approx 460.6G^{0.5283} \quad (4.31)$$

was used. The mean, upper and lower bound predictions of Re_t are also shown in Table 4.3 (see also Fig. A1.1). For a given value of G , the predicted value of Re_t can lie between the lower and upper bounds. Applying the first assumption for the proposed model in combination with Eq. (4.8) and using $\alpha = 0.0385$ and $\beta = 0.9026$, which is higher than that used in Eq. (4.30) but still within the range of $\beta = 0$ to 1.5150 obtained earlier, the drag coefficient of the flocs falling in a turbulent mixture [see Eq. (4.26)] can be approximated by:

$$C_{D,mt} = \frac{24}{\text{Re}_{p,mt}} \left(1 + 0.15 \text{Re}_{p,mt}^{0.687} \right) + 0.0385 \left(\frac{\text{Re}_t}{\text{Re}_{p,mt}} \right)^{0.9026} \quad (4.32)$$

The larger value of β required with Winterwerp's (1999) data compared to the data by Zhou and Cheng's (2008) data may be due to the fact that Zhou and Cheng's (2008)

experiments were conducted under low turbulent flow conditions, compared to experiments by Winterwerp (1999). Thus, the difference in the value of β suggests that β may depend on Re_t and $Re_{p,mt}$.

A formula for the density of floc (ρ_f) is needed in the determination of specific density of floc. Following Winterwerp (1999), the formula:

$$\rho_f = \rho + (\rho_s - \rho) \left(\frac{D_p}{D_f} \right)^{3-nf} \quad (4.33)$$

where D_f and D_p are floc and primary particle sizes, respectively, ρ_s is the density of the primary particles, and nf is the fractal dimension of flocs, is used here. The following values were assigned: $D_p = 4 \mu\text{m}$, $nf = 2.0$, $\rho_s = 2,650 \text{ kg/m}^3$ and $\rho = 1,020 \text{ kg/m}^3$ (Winterwerp 1999). In addition, a formula for the relative viscosity (μ_r) is needed in the determination of the kinematic viscosity of the mixture. Following Winterwerp (1999), Einstein's model, given by:

$$\mu_r = 1 + 2.5\phi \quad (4.34)$$

where ϕ is volumetric concentration of flocs, was used. Table 4.3 presents the calculated results. It can be seen from the table that (i) For $G = 7.3 \text{ s}^{-1}$, the prediction gives $W_{s,mt}$ ranging from 0.22 mm/s to 0.83 mm/s; meanwhile experiments T71 and T137 give $V_T = 0.85 \text{ mm/s}$ and $V_T = 1.20 \text{ mm/s}$, respectively, (ii) For $G = 28.9 \text{ s}^{-1}$, the prediction gives $W_{s,mt}$ ranging from 0.16 mm/s to 0.71 mm/s; and experiments T69 and T139 give $V_T = 0.17 \text{ mm/s}$ and $V_T = 0.20 \text{ mm/s}$, respectively, and (iii) For $G = 81.7 \text{ s}^{-1}$, $W_{s,mt}$ is predicted to range from 0.09 mm/s to 0.34 mm/s; for experiments T73 and T141, $V_T = 0.09 \text{ mm/s}$ and $V_T = 0.20 \text{ mm/s}$, respectively. Although the agreement between the model and experimental values is acceptable, no conclusion on the verification can be made because the number of runs for each experiment is limited.

4.5 Conclusions

Based on the modified form of the force balance equation of a particle, a new model for estimating the drag coefficient, and the relative settling velocity, of particles under

turbulent conditions was proposed. The new model containing two fitting coefficients (α and β) was verified against the available experimental data. It was found that α varies from 0 to 1.7823 with a mean value of 0.0385. The value of β ranged from 0 to 1.5150 with a mean value of 0.6943 for particles settling in an isotropic turbulent clear fluid. For particle settling in an isotropic turbulent mixture, $\beta = 0.9026$. The difference in the values of β obtained suggests that β may depend on Re_t and $Re_{p,mt}$.

Chapter 5

A Simplified Model for Flocculation of Cohesive Sediments

5.1 Introduction

In natural environments and engineering systems, cohesive particles can be aggregated to form larger flocs and large flocs can be broken up into smaller flocs. These two processes, known as “flocculation”, can happen simultaneously until an equilibrium steady state condition is reached. Flocculation is controlled by the physicochemical properties of the sediments and surrounding fluid, and plays an important role in the study of cohesive sediment transport. Although many theoretical and experimental studies have been carried out to model the flocculation process (Thomas et al., 1999; Jarvis et al., 2005), however, there is still a large difference between predicted and measured values of sediment concentration when several existing flocculation models are used in the study of sediment transport (Spearman and Roberts, 2002).

The larger flocs can be surface eroded or split into parts while flocs with low strength can be broken up due to the collision of flocs or due to fluid shear, etc. Many studies (Jarvis et al., 2005) have been conducted to quantify the strength of flocs as well as modes of floc rupture. Regarding the effect of the flow on the floc size, the floc strength can be indicated by a steady-state floc size D_f (μm) that can exist at the shear rate G (s^{-1}), given by:

$$D_f \propto G^{-\gamma} \quad (5.1)$$

where γ is an empirical constant depending on the type and historical formation of flocs and ranges from 0.3 to 1.0 (Tambo and Hozumi, 1979; Bache 2004; Jarvis et al., 2005).

Most of the existing flocculation models are based on the Smoluchowski's theory, which describes aggregation kinetics assuming two-body collisions due to Brownian diffusion, fluid shear, and differential sedimentation (Thomas et al., 1999;

Gregory, 2006). Tambo and Watanabe (1979b) model aggregation and breakup processes separately; evolution of floc size in the aggregation process is controlled by the breakup process, i.e. by the maximum floc size at a given shear rate. In the models proposed by Gregory (1981) and Koh et al. (1987), the breakup process is implicitly incorporated in the aggregation process by a collision efficiency factor, which is much less than unity. Winterwerp (1998 and 1999) and Son and Hsu (2008) modeled the flocculation process by a linear combination of simplified formulations for aggregation and breakup; however, their models did not give good predictions for floc size evolution when compared with Biggs and Lant's (2000) experiments (Son and Hsu 2008). McAnally and Mehta (2000) considered two- and three-body collisions and showed that three-body collisions can have a significant effect on the aggregation process. Traditionally, equations to describe the evolution of the number density of flocs incorporate a simple model for floc density. These equations are then solved numerically. Nevertheless, the incorporation of the numerical solver for the equations makes a numerical model for the study of cohesive sediment transport become more complicated and time consuming. Beside the more rigorous flocculation models, there are many heuristic formulae, accounting for aggregation and breakup processes, for estimating the settling velocity of flocs (Spearman and Roberts, 2002).

The present study proposes a simplified model for flocculation of cohesive sediments. The new model is developed by using physical arguments, utilizes the Smoluchowski's theory-based models and contains empirical coefficients which are determined from measured data. The proposed model does not require a numerical solver. Thus, compared to existing models, the new model is simpler to implement and is suitable for incorporation in a numerical model.

5.2 Proposed models

For the present study, instead of the shear rate (G), the turbulent Reynolds number (Re_t) will be used for quantifying the turbulence in the development of the new model. The turbulent Reynolds number is used since this term has a similar meaning as the

traditional Reynolds numbers, frequently used to classify the turbulence in environmental applications. Using the k-ε model, $Re_t \equiv k^2 / \varepsilon \nu$ (Versteeg and Malalasekera, 1995), where k and ε are the turbulent kinetic energy and its dissipation rate, respectively.

5.2.1 Strength of flocs, equilibrium steady state floc size in breakup process

It is generally observed that only small flocs can exist at high turbulent levels and large flocs can exist at low turbulence levels [Eq. (5.1)]. In other words, the floc size approaches primary particle size (D_p) or $(D_f/D_p - 1) \rightarrow 0$ when Re_t is very large, and the floc size can be very large or $(D_f/D_p - 1) \rightarrow \text{large}$ when Re_t approaches zero. This relationship is schematized in Fig. 5.1. In addition, the floc strength can be characterized in terms of Re_t by the following:

$$Re_t = \alpha_B \left(\frac{D_{fB}}{D_p} - 1 \right)^{-\beta_B} \quad \text{or} \quad D_{fB} = D_p \left[1 + \left(\frac{\alpha_B}{Re_t} \right)^{1/\beta_B} \right] \quad (5.2)$$

where flocs of given size (D_{fB}) can exist without breakup, and α_B and β_B ($\alpha_B, \beta_B > 0$) are empirical coefficients depending on properties of the sediments and the surrounding fluid (subscript $_B$ refers to breakup).

Figure 5.1 - Maximum floc size due to the breakup process.

5.2.2 Equilibrium steady state floc size in aggregation process

It is known that the settling velocity of flocs increases with sediment concentration until $c \approx c_H$, where c is mass concentration of sediments and c_H is the hinder concentration. The increase in the floc settling velocity is a result of the increase in floc size due to aggregation process (van Rijn, 1993). At higher sediment concentrations, the floc settling velocity decreases with sediment concentration due to the hindering effect of sediments. According to DHI (2009a) (see Fig. 6.3) and Camenen (2008), it is possible to model the hindered settling velocity of flocs by applying a constant value of floc size. Therefore, it is assumed that: (i) for $c \geq c_H$, the equilibrium steady state floc size in the aggregation process (D_{fA}) is a constant and equal to D_{fH} , the floc size when $c = c_H$, and (ii) for $c \leq c_H$, D_{fA} increases linearly with c in the following form:

$$D_{fA} = D_p + (D_{fH} - D_p) \frac{c}{c_H} \quad (5.3)$$

where subscript $_A$ refers to aggregation. The variation of D_{fA} with c is shown in Fig. 5.2.

Figure 5.2 - Maximum floc size due to the aggregation process.

5.2.3 Equilibrium steady state floc size

The floc size at the equilibrium steady state (D_{fE}) is controlled by a combination of aggregation and breakup processes. D_{fE} cannot be larger than D_{fB} [see Eq. (5.2)] and D_{fA} [see Eq. (5.3)], and is determined by:

$$D_{fE} = \min\{D_{fB}, D_{fA}\} \quad (5.4)$$

5.2.4 Evolution of floc size in the aggregation process

The evolution of floc size in the aggregation process is modeled as shown in Fig. 5.3. If the initial floc size (D_{f0}) is smaller than the equilibrium steady state floc size (D_{fE}), the flocs will be aggregated. Although the breakup of large flocs can occur simultaneously with the aggregation process, the (mean) size of whole flocs will increase with time and be larger than the initial (mean) floc size, as shown in the figure. The aggregation process will last until $D_f = D_{fE}$ at $t = T_*$ with T_* being “equilibrium flocculation time”. Also note that the curves in the figure move to the right when the turbulence level decreases, to account for the observation by Van der Lee (1998) and Winterwerp (1999) that the equilibrium flocculation time at low turbulence will be longer than that at higher turbulence levels. As a first approximation, the transient floc size is assumed to be:

$$D_f = D_{f0} \frac{1 + \frac{D_{fE}}{D_{f0}} \left[(\text{Re}_t)^{\alpha_A} \left(\frac{t}{T_0} \right) \right]^{\beta_A}}{1 + \left[(\text{Re}_t)^{\alpha_A} \left(\frac{t}{T_0} \right) \right]^{\beta_A}} \quad (5.5)$$

where α_A and β_A ($\alpha_A, \beta_A > 0$) are empirical coefficients (subscript $_A$ refers to aggregation), $T_0 = \zeta T_*$ is a reference time of the aggregation process and ζ is an empirical coefficient.

Figure 5.3 - Evolution of floc size during the aggregation process.

5.3 Results and Discussion

5.3.1 Strength of flocs, equilibrium steady state floc size in breakup process

Most of the existing data and models on flocculation are expressed in terms of G . An analysis relating Re_t and G was first carried out (details of the derivation are provided in the Appendix 1) in order to relate Re_t to G . Knowledge of this relationship would then enable us to utilize the existing data. Based on this analysis, the present study used the following relationship between Re_t and G (1/s):

$$Re_t \approx 460.6G^{0.5283} \quad (5.6)$$

to utilize the existing data and models.

Winterwerp (1998 and 1999) proposed a formula for the equilibrium steady state floc size (see Appendix 2), given by:

$$D_{fE} = D_p + \frac{k_A c}{k_B \sqrt{G}} \quad (5.7)$$

where k_A and k_B are empirical coefficients. Winterwerp (1998, 1999) calibrated Eq. (5.7) against their T-series settling column experiments with Ems-Dollard mud and found that $k_A \approx 14.6 \text{ m}^2/\text{kg}$ and $k_B \approx 14.0 \times 10^3 \text{ (s}^{1/2}/\text{m}^2)$. It is noted that for T69 and T73 experiments, the sediment concentrations are nearly the same (1.17 kg/m^3 and 1.21 kg/m^3 , respectively), the shear rate is very high (28.9 s^{-1} and 81.7 s^{-1} , respectively), and the measured floc sizes are $241 \text{ }\mu\text{m}$ and $140 \text{ }\mu\text{m}$, respectively (Winterwerp, 1998 and 1999). In other words, for $c \approx 1.19 \text{ kg/m}^3$ (average value of 1.17 kg/m^3 and 1.21 kg/m^3), floc size decreased from $241 \text{ }\mu\text{m}$ at $G = 28.9 \text{ s}^{-1}$ to $140 \text{ }\mu\text{m}$ at $G = 81.7 \text{ s}^{-1}$, $D_{fA} \geq 241 \text{ }\mu\text{m}$ and floc sizes at G in the range of 28.9 s^{-1} to 81.7 s^{-1} are controlled by breakup process. In addition, for $c \approx 1.19 \text{ kg/m}^3$, Eq. (5.7) gives $D_{fE} = 235 \text{ }\mu\text{m}$ (-2.5%) at $G = 28.9 \text{ s}^{-1}$ and $D_{fE} = 141 \text{ }\mu\text{m}$ (+0.7%) at $G = 81.7 \text{ s}^{-1}$, where the numbers in brackets are the percentage difference compared to the experimental data. Therefore, Eq. (5.7) together with experimental data from T69 and T73 experiments can be used in

estimation of the empirical constants α_B and β_B in Eq. (5.2). Applying Eq. (5.6) and substituting for G in Eq. (5.7) results in:

$$\text{Re}_t = \left\{ 460.6 \left(\frac{1}{D_p} \frac{k_A c}{k_B} \right)^{1.057} \right\} \left(\frac{D_{fE}}{D_p} - 1 \right)^{-1.057} \quad (5.8)$$

Furthermore, it was assumed that for T69 and T73 experiments, $D_{fB} \approx D_{fE}$. This assumption is valid since as mentioned previously, floc sizes are controlled by breakup process in these experiments. Compared with Eq. (5.2), Eq. (5.8) gives $\beta_B \approx 1.06$ and the first term at the RHS of Eq. (5.8) is α_B . Applying data from T69 and T73 experiments ($D_p = 4 \mu\text{m}$, $c \approx 1.19 \text{ kg/m}^3$, $k_A \approx 14.6 \text{ m}^2/\text{kg}$ and $k_B \approx 14.0 \times 10^3 \text{ s}^{1/2}/\text{m}^2$) to the first term at the RHS of Eq. (5.8), it was found that $\alpha_B \approx 1.98 \times 10^5$. Finally, applying Eq. (5.6) for Re_t and substituting for G in Eq. (5.1) results in $D_{fE} \propto \text{Re}_t^{-\gamma/0.5283}$. From Eq. (5.2), $D_{fE} \propto \text{Re}_t^{-1/\beta_B}$. Therefore, $\gamma/0.5283 = 1/\beta_B$; for the range of γ varying from 0.3 to 1.0 (Tambo and Hozumi, 1979; Bache, 2004; Jarvis et al., 2005), $0.53 < \beta_B < 1.76$.

5.3.2 Equilibrium steady state floc size in aggregation process

The relationship between volumetric concentration of flocs (ϕ) and mass concentration of sediment (c) is given by:

$$\phi = \left(\frac{\rho_s - \rho_w}{\rho_f - \rho_w} \right) \frac{c}{\rho_s} \quad (5.9)$$

where ρ_s , ρ_w , and ρ_f are the densities of the primary particle, water, and floc, respectively. Following Tambo and Watanabe (1979a) [also see Eq. (2.2)], the relationship between floc density and floc size (D_f) can be assumed to be:

$$(\rho_f - \rho_w) \approx (\rho_s - \rho_w) \left[\frac{D_p}{D_f} \right]^{3-nf} \quad (5.10)$$

where nf is the fractal dimension of flocs. Combining Eq. (5.9) and Eq. (5.10) and taking $c = c_H$, $\phi = \phi_H$, and $D_f = D_{fH}$ results in:

$$D_{fH} \approx D_p \left[\frac{\phi_H \rho_s}{c_H} \right]^{1/(3-nf)} \quad (5.11)$$

where ϕ_H is the volumetric concentration of flocs when $c = c_H$. Assuming $nf = 2.0$ (Wintwerp, 1998), Eq. (5.11) becomes:

$$D_{fH} \approx \phi_H \frac{\rho_s}{c_H} D_p \quad (5.12)$$

In order to use Eq. (5.12), ϕ_H and c_H must be known. For estimating ϕ_H , data on flocs in saline water in Thorn (1982) and Dankers et al. (2007) were used. Using the data from Thorn (1982), Camenen (2008) suggested that $D_{fH} = 295 \mu\text{m}$ with $\rho_f = 1,053 \text{ kg/m}^3$. Assuming $\rho_s = 2,650 \text{ kg/m}^3$, $nf = 2.0$, and $\rho_w = 1,020 \text{ kg/m}^3$ (Winterwerp, 1999), Eq. (5.10) gives $D_p \approx 6 \mu\text{m}$. Assuming $c_H \approx 3 \text{ kg/m}^3$ [see Fig. 6a in Camenen (2008)], Eq. (5.12) gives $\phi_H \approx 0.056$. For Dankers et al.'s (2007) data with kaolinite, Camenen (2008) suggested that $D_{fH} = 97 \mu\text{m}$. Assuming $D_p \approx 4 \mu\text{m}$, $\rho_s = 2,650 \text{ kg/m}^3$, $nf = 2.0$, and $\rho_w = 1,020 \text{ kg/m}^3$ (Winterwerp 1999), $c_H \approx 3 \text{ kg/m}^3$ (McAnally and Mehta 2000), Eq. (5.12) gives $\phi_H \approx 0.027$. The estimation suggests that in applying Eq. (5.12), ϕ_H cannot take too large a value, within the range $\phi_H < O(0.1)$.

5.3.3 Effect of salinity

Salinity plays an important role in the flocculation process (van Rijn, 1993; Chien and Wan, 1999). Floc size is larger in saline water than fresh water. Hence, the settling velocity of flocs increase with salinity; the settling velocity increases sharply when salinity, S (ppt), increases from 0 to about 2 ppt, is nearly maximum when $S = 10$ ppt, and is approximately constant for $10 < S < 35$ ppt (Chien and Wan, 1999). In addition, c_H varies from 3 kg/m^3 (McAnally and Mehta, 2000) to about 10 kg/m^3 (van Rijn, 1993). Equation (5.12) shows that c_H is inversely proportional to D_{fH} , and as a result, inversely proportional to the floc settling velocity. Therefore, it can be assumed that c_H

decreases from 10 kg/m³ to about 3 kg/m³ when salinity increases from 0 to about 10 ppt, c_H decreases sharply when salinity increases from 0 to about 2 ppt, and the hinder sediment concentration, c_H (kg/m³) according to the following relationships:

$$c_H \approx 10 - \alpha_s S^{\beta_s} \quad \text{for } S < 10 \text{ ppt} \quad (5.13a)$$

$$c_H \approx 10 - \alpha_s 10^{\beta_s} \quad \text{for } S \geq 10 \text{ ppt} \quad (5.13b)$$

where α_s and β_s are empirical coefficients. Equation (5.13), with $\alpha_s \approx 6.15$ and $\beta_s \approx 0.05$ as a first choice, gives $c_H \approx 3.1$ kg/m³ for $S \geq 10$ ppt. Measured datasets of c_H and S should be used in the estimation of α_s and β_s , however, they are limited (see Fig. 11.4.2 in van Rijn, 1993) and not enough for a more rigorous assessment of the model at the moment.

5.3.4 Evolution of floc size in aggregation process

The time evolution of D_f in the aggregation process is modeled using Eq. (5.5) where three empirical coefficients, α_A , β_A and ζ , and T^* must be determined. As shown latter, T^* can be obtained directly from Tambo and Watanabe's (1979b) model. Available experimental data is limited; therefore, Tambo and Watanabe's (1979) model, which is based on Smoluchowski's theory, was used to generate the data. Values of the empirical coefficients were first estimated and tested by using the generated data and then verified using the experimental data.

The flocculation model of Tambo and Watanabe (1979b) was first verified by utilizing Biggs and Lant's (2000) experimental data (details of the verification are provided in Appendix 2). The results obtained in Appendix 2 show that estimated values of $D_f(t)$ using Tambo and Watanabe's (1979b) model are in good agreement with the experimental results. However, as mentioned in Appendix 2, the solution of Tambo and Watanabe's (1979b) model requires a trial-and-error procedure, which is not amenable to numerical applications. Next, Tambo and Watanabe's (1979b) model was used to generate data of D_f as a function of t . This dataset was used in the estimation of α_A , β_A and ζ , which were determined using a trial-and-error procedure.

Essentially values of α_A , β_A and ζ were assumed and the set of values for α_A , β_A and ζ that gave the best fit to Eq. (5.5) was selected. T^* was estimated by [Eq. (A2.14)]:

$$T^* \approx \frac{10.62(S_m)^{-0.2386}}{\alpha_0(1.22GD_{f0}^3N_o)} \quad (5.14)$$

where α_0 is initial collision-agglomeration factor and varies from about 1×10^{-4} (Biggs and Lant, 2002) to $1/3$ (Tambo and Watanabe, 1979b), N_o is the initial number of particles with size D_{f0} , $S_m \equiv (D_{fmax}/D_{f0})^3$ and D_{fmax} is the largest floc size at the equilibrium steady state for a given shear rate G . Details of the derivation of Eq. (5.14) are provided in Appendix 2 and Table 5.1 presents the input data used for the estimation and verification of the empirical coefficients in Eq. (5.5). As shown in Table 5.1, the shear rate within the range of from 1 s^{-1} to 9 s^{-1} was selected since in this range, the shear rate tends to contribute more to aggregation growth (Winterwerp et al., 2002). In addition, since floc size increases with c until $c \approx c_H$, Case 1 and Case 2, where $c \approx 0.5c_H$, were assigned for estimating the coefficients while the last two input data, where $c \approx c_H$, were used for testing the coefficients. The following values of $D_{f0} = D_p \approx 4 \text{ }\mu\text{m}$, $nf \approx 2$, $\rho_s \approx 2,650 \text{ kg/m}^3$, $\rho_w \approx 1,000 \text{ kg/m}^3$, $\phi_H \approx 0.056$, $\alpha_s \approx 6.15$, $\beta_s \approx 0.05$, $\alpha_B \approx 1.98 \times 10^5$, $\beta_B \approx 1.06$ and $\alpha_0 \approx 0.008$ were used. The relationship between Re_t and $G \text{ (s}^{-1}\text{)}$ followed Eq. (5.6), the equilibrium steady state floc size followed Eq. (5.4) and $D_{fE} = \min\{\text{Eq. (5.2), Eq. (5.3)}\}$. The value of S_m used in Tambo and Watanabe's (1979b) model (see Appendix 2) was selected in such a way that Tambo and Watanabe's (1979b) model also resulted in the same value of D_{fE} as that obtained from Eq. (5.4) (see Table 5.1). Thus, the same values of D_{fE} (same boundary conditions) were applied to both Eq. (5.5) and Tambo and Watanabe's (1979b) model for the estimation and verification of α_A , β_A and ζ .

Table 5.1 - Input data for estimation and test of the empirical coefficients in Eq. (5.5).

Case	S (ppt)	c (kg/m ³)	G (s ⁻¹)	S _m	D _{FE} (μm)
1	0	5	1, 4, 9	23,220	32
2	10	1.5	1, 4, 9	1,803,665	95
3	0	10	1, 4, 9	268,328	59
4	10	3	1, 4, 9	25,938,708	185

Note: $D_{f0} = D_p = 4 \mu\text{m}$, $D_{FE} = \min\{\text{Eq. (5.2), Eq. (5.3)}\}$, $\alpha_B = 1.98 \times 10^5$, $\beta_B = 1.06$.

The evolutions of floc size for the first two cases ($c \approx 0.5 c_H$) estimated by Tambo and Watanabe (1979b) model and Eq. (5.5) with $\alpha_A \approx 0.15$, $\beta_A \approx 2.25$, and $\zeta \approx 0.35$ are shown in Fig. 5.4. The figure shows that, with the selected values of the empirical coefficients, both models give similar results for the evolution of floc size. The applicability of the chosen values of the empirical coefficients was carried out by comparing $D_f(t)$ predicted by Eq. (5.5) against the dataset obtained from Tambo and Watanabe's (1997) model in Fig. 5.5, for Case 3 and Case 4 (Table 5.1). The figure shows that there is good agreement between the new model and Tambo and Watanabe's (1979b) model. In addition, it was found that $D_f \approx 0.9D_{FE}$ at $t \approx T_0$ and α_0 is independent on the shear rate. The new model is advantageous over Tambo and Watanabe's (1979b) model since the iteration, as shown in Fig. A2.2, is not necessary.

(a)

(b)

Figure 5.4 - Evolution of flocs using the proposed model (lines) and Tambo and Watanabe's (1997b) model (symbols) for (a) $S = 0$ ppt, $c = 5$ kg/m³, and (b) $S = 10$ ppt, $c = 1.5$ kg/m³.

(a)

(b)

Figure 5.5 - Evolution of flocs using the proposed model (lines) and Tambo and Watanabe's (1997b) model (symbols) for (a) $S = 0$ ppt, $c = 10 \text{ kg/m}^3$, and (b) $S = 10$ ppt, $c = 3 \text{ kg/m}^3$.

The new model was verified against the experimental datasets of McAnally and Mehta (2000) and Spicer et al. (1998). McAnally and Mehta (2000) observed the evolution of floc sizes in a Couette chamber using sediments from the Detroit River. Figure 5.6 presents McAnally and Mehta's (2000) experimental data as well as their

numerical solution for the evolution of flocs with $c = 0.05 \text{ kg/m}^3$, $S = 35 \text{ ppt}$, and $G = 200 \text{ s}^{-1}$. For the new model, the values of $D_{f0} = D_p = 6 \text{ }\mu\text{m}$, $\rho_s \approx 2,650 \text{ kg/m}^3$, $c = 0.05 \text{ kg/m}^3$, $G = 200 \text{ s}^{-1}$, $\alpha_A \approx 0.15$, $\beta_A \approx 2.25$, $\zeta \approx 0.35$, $\alpha_0 \approx 0.0035$, and $D_{fE} \approx 85 \text{ }\mu\text{m}$ giving $S_m \approx 3,901,313$ were used. The floc size evolution, estimated by the new model, is also included in the figure and in good agreement with the experimental data and McAnally and Mehta's (2000) numerical result. The main advantage of the new model over McAnally and Mehta's (2000) model is that the new model does not require the numerical solver, as mentioned in the Introduction Section.

Figure 5.6 - New model (solid line) and McAnally and Mehta's (2000) experimental data and numerical solution (dash line) for evolution of flocs with Detroit River sediment, $S = 35 \text{ ppt}$, $c = 0.05 \text{ kg/m}^3$, $G = 200 \text{ s}^{-1}$.

In Spicer et al.'s (1998) experiment, flocculation of spherical polystyrene particles, with $D_p = 0.87 \text{ }\mu\text{m}$ and $\phi = 1.4 \times 10^{-5}$ for $G_* \approx 50 \text{ s}^{-1}$, was carried out in a baffled stirred tank, similar to the one used by Biggs and Lant (2000). The flocculant was aluminum sulfate hydrate. The experimental data is shown in Fig. 5.7. For the new model, values of $D_{f0} = D_p = 0.87 \text{ }\mu\text{m}$, $\rho_s \approx 950 \text{ kg/m}^3$, $c \approx 0.013 \text{ kg/m}^3$ giving $\phi = 1.4 \times 10^{-5}$, $G \approx 19.4 \text{ s}^{-1}$, $\alpha_A \approx 0.15$, $\beta_A \approx 2.25$, $\zeta \approx 0.35$, $\alpha_0 \approx 0.15$, and $D_{fE} \approx 250 \text{ }\mu\text{m}$ giving $S_m \approx 890,017$ were used. The floc size evolution estimated by the new model, as

shown in Fig. 5.7, is in fair agreement with the experimental data. However, a value of $\beta_A \approx 3.25$ provides a better fit. The discrepancy in β_A with the earlier value of 2.25 suggests that β_A may have a dependence on other physico-chemical properties not considered in this study.

Figure 5.7 - New model (solid line for $\beta_A = 2.25$, dash line for $\beta_A = 3.25$) and Spicer et al.'s (1998) experimental data for evolution of flocs with polystyrene particles.

5.4 Conclusions

A new model for flocculation of cohesive sediments was proposed in this paper. The model takes into account the effects of fluid turbulence, sediment concentration and the hindering concentration. The model was developed by utilizing existing experimental data and models, and compared with Tambo and Watanabe's (1979b) model. Values of the empirical coefficients of the new model were estimated and verified. The comparisons show that the evolutions of floc size in the aggregation process estimated

by the new model are consistent with those by Tambo and Watanabe's (1979b) model, McAnally and Mehta's (2000) model, and experimental data. The new model has an advantage over Tambo and Watanabe's (1979b) model that the iteration, as shown in Fig. A2.2, is not necessary. In addition, the new model does not require a numerical solver necessary for McAnally and Mehta's (2000) model. The new model is therefore simple to implement and amenable to numerical modelling applications for the study of cohesive sediment transport. Finally, it should be noted that the proposed model does not account for the floc structures (size distribution) and historical compaction of flocs, the breakage of large flocs due to fast settling velocity, and irreversible nature of floc breakage.

Chapter 6

Modelling Sediment Transport in ECO Lab

6.1 Introduction

This chapter aims to implement the various formulations, developed earlier for the sediment properties and processes, into the MIKE 3 Flow Model FM modelling system. The system is composed of Hydrodynamic (HD) module as a default and several add-on modules such as ECO Lab module and Mud Transport (MT) module (see Fig. 6.1). The HD module provides the hydraulic basis (for e.g., water level, current speed, eddy viscosity, and salinity, etc.) for the other modules of the system. The ECO Lab module can be used as a numerical ecological lab to simulate transportation and/or transformation of one or more state variables/entities (for e.g., total coliform, heavy metals, and suspended sediments, etc.) in the aquatic environment. User inputs such as equations, constants etc. defining processes to be modeled are entered through an ECO Lab template. The template is loaded into the ECO Lab module which allows user defined processes to be coupled within the MIKE modeling environment. The advection and dispersion transports are included by coupling the ECO Lab module with the Advection-Dispersion (AD) module of the HD module. The transformation of the state variable(s) due to other processes, rather than advection and dispersion, is obtained on the basis of the predefined ECO Lab template, the most important component when using the ECO Lab module. The template is created before being applied to the ECO Lab module and contains mathematical formulations used to describe the transformation of the state variable(s), given by:

$$\frac{d(\text{StateVariable})}{dt} = \sum_{i=1}^n \text{Process}_i \quad (6.1)$$

where the RHS of the equation describes the rate of change of the state variable due to the processes rather than due to advection and dispersion transport (DHI 2009a,b,c).

Figure 6.1 - MIKE 3 Flow Model FM system and the incorporation of the Ecolab_MT, a new predefined ECO Lab template, into the system.

The present study makes use of the ECO Lab module to incorporate the proposed formulations for sediment properties and processes, developed earlier for the sediment properties and processes, into the MIKE 3 Flow Model FM system. The ECO Lab module is integrated with the AD module to compute the advection and dispersion transports of sediments. A new ECO Lab template, called “Ecolab_MT”, was developed using the ECO Lab editor (see Fig. 6.2) to describe the rate of change of sediments due to the other processes, such as deposition and erosion. The template contains descriptions for the following blocks:

- **State variables** - where the suspended sediment concentration and bed layer thickness are the state variables and the RHS of Eq. (6.1) is expressed.
- **Constants** - where the calibration constants/coefficients of the proposed models are described.

- **Forcings** - which contains parameters (for e.g., water level, currents speeds, salinity, k and ϵ , etc.) affecting the auxiliary variables (for e.g., bed shear stress, floc size, and settling velocity, etc.).
- **Auxiliary variables** - where the floc density, viscosity of mixture, hindered settling velocity of particles under turbulence, and floc size due to flocculation, etc. are the auxiliary variables and the proposed formulations for them are described.
- **Processes** - which describes the sedimentation, deposition, and erosion processes.

Figure 6.2 - Development of Ecolab_MT template using ECO Lab editor.

Once the descriptions for the template are saved into a file (“Ecolab_MT.ecolab”), the template (file) can be used in conjunction with MIKE 3 Flow Model FM, as shown in Fig. 6.1, to carry out the sediment transport calculations. Using the ECO Lab module, the user inputs are specific values for the constants and forcings, and initial and boundary conditions, etc. In addition, MIKE 3 Flow Model FM modelling system includes the add-on MT module (also see Fig. 6.1) for mud transport calculations. Results of sediment transport calculations computed using the proposed Ecolab_MT

template will be compared against results from MT module for a few simplified examples in this chapter and applied to a real case in the next chapter. Essential differences between the implementation and results of the proposed template and the existing MT module will be highlighted.

6.2 Formulations for suspended sediment transport

The Ecolab_MT template incorporates the 3D transport model because it has access to water level, current speed, eddy viscosity, k and ϵ , and salinity, etc. from the HD module. Selecting `ADVECTION_DISPERSION` transport option in the Ecolab_MT template, as shown in Fig. 6.2, will integrate the AD module so that the advection and dispersion transports of the state variable are included. As a result, the new template is able to provide the solution to the transport equation:

$$\frac{\partial c}{\partial t} + \frac{\partial uc}{\partial x} + \frac{\partial vc}{\partial y} + \frac{\partial wc}{\partial z} = \frac{\partial}{\partial x} \left(D_x \frac{\partial c}{\partial x} \right) + \frac{\partial}{\partial y} \left(D_y \frac{\partial c}{\partial y} \right) + \frac{\partial}{\partial z} \left(D_z \frac{\partial c}{\partial z} \right) + \frac{\partial S}{\partial z} \quad (6.2)$$

where c is the suspended sediment concentration; t is time; u , v and w are the mean velocity components in x , y and z directions, respectively; D_x , D_y and D_z are the dispersion coefficients in x , y and z directions, respectively; S is the sink/source term including sedimentation rate (S_S), deposition rate (S_D), and erosion/resuspension rate (S_E) of sediments. By default the Ecolab_MT template includes the following treatment for S (DHI, 2009a):

- (i) In the case of current alone, if the current-induced bed shear stress (τ_c) is larger than the critical bed shear stress for deposition (τ_{cd}) then:

$$S_D = 0, \text{ otherwise}$$

$$S_D = c_b W_s \left(1 - \frac{\tau_c}{\tau_{cd}} \right) \quad (6.3)$$

for the near-bed layer, where c_b is near-bed sediment concentration and W_s is settling velocity of sediments. For other layers, $S_D = 0$.

(ii) If τ_c is smaller than the critical bed shear stress for erosion (τ_{ce}) then:

$$S_E = 0, \text{ otherwise}$$

$$S_E = E \left(\frac{\tau_c}{\tau_{ce}} - 1 \right)^n \quad \text{for a bed of constant density } (\tau_{ce} = \text{constant}) \quad (6.4a)$$

$$S_E = E_0 \exp[\alpha(\tau_c - \tau_{ce})^{0.5}] \quad \text{for a bed of increasing density } (\tau_{ce} \neq \text{constant}) \quad (6.4b)$$

for the near-bed layer, where E is erodibility of bed, n power of erosion, E_0 and α coefficients. For other layers, $S_E = 0$.

(iii) $S_S = 0$ for the near-bed layer, and

$$S_S = W_s c \quad (6.5)$$

for other layers.

Note that the current-induced bed shear stress is estimated by:

$$\tau_c = \frac{1}{2} \rho f_c V_b^2 \quad (6.6)$$

where V_b is the average current speed over distance Δz_b above the bed, ρ is the density of fluid, and f_c is the current friction coefficient, estimated by:

$$f_c = 2 \left\{ \frac{1}{\kappa} \left[\frac{z_0}{\Delta z_b} - 1 + \ln \left(\frac{\Delta z_b}{z_0} \right) \right] \right\}^{-2} \quad (6.7)$$

The von Kármán constant, $\kappa = 0.4$, $z_0 \approx k_s/30$, is the bed roughness length scale, and k_s is the bed roughness. For 3D numerical model, c_b and V_b are replaced by SSC and current speed at the near-bed layer, c_1 and V_1 , respectively, Δz_b is replaced by water layer height (thickness) of the near-bed layer (Δh_1). For 2DH numerical model, $c_b \approx c/RC$ assuming Rouse profile with RC being relative height of centroid of the sediment profile, V_b is replaced by depth-averaged current speed, Δz_b is replaced by total water depth (h), S_S is replaced by zero (DHI, 2009a).

As can be seen from Eq. (6.2), estimation of the sink/source term (S) is required in order to predict the suspended sediment concentration. This leads to the requirement of being able to provide good estimates of W_s because S_S and S_D are directly dependent on W_s . As mentioned in previous chapters, for non-cohesive sediments, flow turbulence and sediment concentration, etc. can affect W_s ; for cohesive sediments, factors affecting W_s are flow turbulence, sediment concentration, and flocculation process, etc. At the moment, existing models treat W_s differently. Some models consider W_s as a calibration constant while the others apply heuristic formulations, for e.g. see below for the MT module.

6.2.1 Settling velocity and flocculation in the MT module

In MT module, for cohesive sediments, the hindered settling velocity (W_s) is estimated either by Richardson and Zaki's (1954) formulation, which is:

$$W_s = w_s (1 - \Phi_*)^p \quad (6.8)$$

or by Winterwerp's (1999), given by:

$$W_s = w_s \frac{(1 - \Phi_*)(1 - \phi_p)}{1 + 2.5\phi} \quad (6.9)$$

In the above formulations, w_s is the settling velocity of a single particle in still water, $\Phi_* = \min(1.0, \phi)$, $\phi = c/c_{gel}$, $\phi_p = c/\rho_s$, p is a power constant. w_s is estimated on the basis of the curve in Fig. 6.3, which considers flocculation of cohesive sediments in saline water.

Figure 6.3 - Flocculation model in MT module [The figure is from DHI (2009a)].

In the figure, W_0 is a settling velocity coefficient [m/s], a calibration parameter, c_{Floc} is the concentration at which the flocculation starts, c_H is the concentration at which the hindered settling begins, and γ is a power constant. In fresh/brackish water, w_s is reduced by a factor of $[1 - C_1 \exp(C_2 S)]$, where C_1 and C_2 are calibration parameters, S is salinity [psu] (DHI, 2009a). Default values are: $\rho_s = 2,650 \text{ kg/m}^3$, $c_{\text{Floc}} = 0.01 \text{ kg/m}^3$, $c_H = 10 \text{ kg/m}^3$, $c_{\text{gel}} = 50 \text{ kg/m}^3$, $C_1 = 0.5$ and $C_2 = -0.33$, $\gamma = 1.0$ and $p = 1.0$. Steps for determining the settling velocity in MT module is illustrated in right panel in Fig. 6.4. Note that MT module does not consider the effects of the flow turbulence on the breakup of flocs and on the settling velocity. In addition, as mentioned in Chapter 5, c_H should be a function of the salinity; however, c_H is a calibration constant in MT module.

Figure 6.4 - Determination of the settling velocity in Ecolab_MT template (left panel) and MT module (right panel) [adapted from Cremer (2011)].

6.2.2 Settling velocity and flocculation in Ecolab_MT template

In contrast with MT module, Ecolab_MT template makes use of the modified Stokes law to determine the settling velocity of cohesive sediments (see Chapter 4):

$$W_{s,mt} = (1 - \phi) \sqrt{\frac{4(s_m - 1)gD_f}{3C_{D,mt}}} \quad (4.24)$$

where ϕ is the volumetric concentration of flocs, $s_m = \rho_f/\rho_m$ with ρ_f and ρ_m are the densities of floc and mixture, respectively, D_f is the floc size, $C_{D,mt}$ is the drag coefficient of the floc settling in the mixture under flow turbulence. The floc size is

determined on the basis of the proposed model for flocculation (see Chapter 5), which considers the effect of salinity on the hinder concentration as well as the effect of aggregation and breakup processes, etc. on the floc size. However, at this moment, due to limitation of ECO Lab module, for the Ecolab_MT template, it is impossible to implement the evolution of floc size with time during flocculation process and, similar to MT module, flocs are assumed to be at the equilibrium steady state. The density of flocs is determined by the proposed model for the effective density of floc (see Chapter 2). The proposed model for the drag coefficient of a particle settling in the turbulence mixture (see Chapter 4), together with the proposed model for the viscosity of mixture (see Chapter 3), is used to determine the $C_{D,mt}$. Steps for determining the settling velocity in the template is illustrated in left panel in Fig. 6.4. The template also determines the settling velocity of fine sand (non-cohesive sediment) by the above formulation with density and size of floc replaced with density and size of sand, respectively.

Table 6.1 (also Fig. 6.4) summarizes the main features of Ecolab_MT template and MT module for the estimation of the settling velocity. Compared to MT module, Ecolab_MT template computes the settling velocity in a more detailed way and overall requires fewer assumptions. The settling velocity in the template is determined by the modified Stokes law, which was developed on the basis of the force balance equation for a particle settling in the turbulence mixture. By using the modified Stokes law, effects of salinity, sediment concentration, primary particle size, and flow turbulence, etc. on the settling velocity are included. The proposed models are used to estimate each parameter in Eq. (4.24). In addition, the template includes not only aggregation but also the breakup process, while MT includes only aggregation and does not consider the breakup process. Furthermore, in contrast with MT module, which considers the settling velocity as a calibration parameter by using the settling velocity coefficient W_0 , the template determines the settling velocity on the basis of the primary particle size, a physical quantity. Also, the effect of salinity on the hinder concentration as well as the floc size is accounted for in the template. Finally, the most significant difference between the template and MT module is that the former considers the effect

of turbulence on the settling velocity while the latter does not. The main features/differences between the proposed Ecolab_MT template and existing MT module are summarized in Table 6.1.

Table 6.1 - Main features of Ecolab_MT template and MT module.

Description	Ecolab_MT template	MT module
Aggregation of flocs	Yes (Floc size variation)	Yes (Settling velocity variation)
Breakup of flocs	Yes	No
Evolution of floc size	No	No
Effect of salinity on W_s	Yes (Also on D_f and c_H)	Yes (Only on W_s)
Hinder concentration, c_H	Dependent on salinity	Calibration constant
Effect of flow turbulence on W_s	Yes	No
Formulation for W_s	The modified Stokes law (Force balance equation)	Richardson and Zaki; Winterwerp (Heuristic formulations)
Primary particles	Included	Not included
Properties of floc particles	Considered	Not considered

6.2.3 Formulations used in Ecolab_MT template

The formulae used in the estimation of the sink/source term of Eq. (6.2) are summarized in Table 6.2 and incorporate the newly developed formulations provided in the previous chapters. In addition, the change of bed layer thickness, which depends on deposition and erosion rates, is determined by:

$$\frac{dX}{dt} = \frac{S_D - S_E}{\rho_{bed}} \quad (6.10)$$

where X is bed layer thickness and ρ_{bed} is the dry density of the sediment bed. The erosion rate is limited by the specification of a finite bed layer thickness:

$$S_{E,X} = \frac{\rho_{bed} X}{\Delta t} \quad (6.11)$$

where Δt is simulation time interval. The erosion rate is thus the minimum of the estimates by Eq. (6.4) and Eq. (6.11).

Table 6.2 - Formulations used in the estimation of the Sink/Source term of Eq. (6.2).

No	Description	Formulation	Remarks
1	Hindered settling velocity ^(a)	Eq. (4.24)	Chapter 4
	Relative settling velocity	Eq. (4.25)	
2	Density of floc	Eq. (2.6)	Chapter 2
3	Viscosity of mixture	Eq. (3.7)	Chapter 3
4	Drag coefficient		Chapter 4
	Cohesive sediments	Eq. (4.32)	
	Non-cohesive sediments	Eq. (4.30)	
5	Floc size	Eq. (5.4)	Chapter 5
	D_{fA}	Eq. (5.3)	
	D_{fB}	Eq. (5.2)	
	D_{fH}	Eq. (5.12)	
	Hinder concentration	Eq. (5.13)	
6	Bed shear stress	Eq. (6.6)	Chapter 6
	Friction coefficient	Eq. (6.7)	
7	Sedimentation rate	Eq. (6.5)	Chapter 6
8	Deposition rate	Eq. (6.3)	Chapter 6
9	Erosion rate ^(b)	$\min[\text{Eq. (6.4a), Eq. (6.11)}]$	Chapter 6

Note: (a) For sedimentation, $W_{s,mt}$ is used. For deposition, $W_{s,m}$ is used since effect of turbulence on deposition is already taken into account by $(1 - \tau_c / \tau_{cd})$.

(b) By applying an appropriate value of E and considering n as a calibration constant, Eq. (6.4a) can approximate Eq. (6.4b).

6.3 Development of Ecolab_MT template

Ecolab_MT template, provided in Appendix 3, was developed step-by-step for a diverging open channel flow problem, starting from relatively simple and progressing to more complicated test cases. The final test of the template to a real application is presented in the next chapter. The template was first applied to the simplest situation, a 2D depth averaged velocity (2DH) and constant W_s (without flocculation and hindering

effect). Next, the complexity in the development of the template was increased by moving from 2DH to the 3D case, but still with a constant W_s . Finally, the template is further developed for the more complicated case, 3D with non-constant W_s , where W_s is modeled as a function of floc density (see Chapter 2), hindering effect and viscosity of mixture (see Chapter 3), flow turbulence (see Chapter 4), and flocculation of cohesive sediments (see Chapter 5). In addition, the following definitions are used in the template:

$$\text{sedimentation} = \frac{\partial(\text{sedimentation rate}, S_s)}{\partial z} \quad (6.12)$$

$$\text{deposition} = \frac{\partial(\text{deposition rate}, S_D)}{\partial z} \quad (6.13)$$

$$\text{erosion} = \frac{\partial(\text{erosion rate}, S_E)}{\partial z} \quad (6.14)$$

$$\text{BedChange} = \frac{S_D - S_E}{\rho_{bed}} \quad (6.15)$$

The first three definitions are used for the RHS of Eq. (6.1) and the last one is used for the RHS of Eq. (6.10). Finally, ECO Lab module used in conjunction with the Ecolab_MT template developed in this study is referred to as “ECOLABMT” module.

6.3.1 MIKE 21 – ECOLABMT with constant settling velocity (2DH)

The results, provided by ECOLABMT will be compared with results provided by MIKE 21 MT with constant W_s (without flocculation and hindering effect), for the calculation of τ_c , S_D , S_E , and c . This comparisons aims to check if the template is correctly developed since both modules use the same formulations for τ_c , S_D , and S_E .

Description of the Ecolab_MT template

Suspended sediment concentration, SSC [kg/m^3], is the state variable with scope of “water column” (WC) – a terminology used in ECO Lab editor to signify the environment (in this case, water column) where the state variable is defined. ADVECTION_DISPERSION transport is selected so that advection and dispersion

terms in Eq. (6.2) are included. The processes used to describe the transformation of SSC (see Fig. 6.2) are *deposition* (sink term) and *erosion* (source term), defined in PROCESSES. User specified constants in the template are W_s [m/s] for W_s , Tcd [N/m²] for τ_{cd} , Tce [N/m²] for τ_{ce} , RC [-], ks [m], E [kg/m²/s], n [-]. The forcings in Ecolab_MT are *Depth* and *Current*, which utilize the variables WATER_DEPTH [m] and HORIZONTAL_CURRENT_SPEED [m/s], accessed from the MIKE 21 HD module. The auxiliary variables are $SSCb$ [kg/m³] for c_b , fC [-] for f_c , $Tbed$ [N/m²] for τ_c , SD [kg/m²/s] for S_D , SE [kg/m²/s] for S_E . These parameters have HORIZONTAL spatial variations, which means that they can have different values in each horizontal grid point. Processes include *deposition* [kg/m³/day] [see Eq. (6.13)] and *erosion* [kg/m³/day] [see Eq. (6.14)]. They have water bed (WB) scope (defined at the bed only), HORIZONTAL spatial variation, and TRANSFORMATION type of process.

Verification of ECOLABMT module

A model of an open channel of about 6.0 meters depth was set up using MIKE 21 Flow Model FM modelling system with the activations of HD, ECO Lab, and MT modules. The Ecolab_MT template is inserted in ECO Lab module to form the ECOLABMT module. Model area and boundaries are depicted in Fig. 6.5. The assumed initial and boundary conditions for HD, MT, and ECOLABMT modules are presented in Table 6.3. In addition, the following values were specified: $W_s = 0.005$ m/s, $RC = 0.3$, $k_s = 0.001$ m, $E = 0.0005$ kg/m²/s, $n = 2$, $\tau_{cd} = 1.0$ N/m², $\tau_{ce} = 2.0$ N/m² for ECOLABMT and MT modules.

Fig 6.5 - Model area, boundaries, and “observed” locations; length is in meter.

Table 6.3 - Initial and boundary conditions for HD, MT, and ECOLABMT modules.

Conditions	HD module	MT and ECOLABMT modules
initial	water elevation = 6 .0 m	SSC = 0.05 kg/m ³
upstream	Flux of 9.0 m ³ /s/m, linear variation, soft start with zero flux reference and interval of 20 minutes	SSC = 0.1 kg/m ³
downstream	water elevation = 6 .0 m	SSC with zero gradient

The values of τ_c [N/m²], S_D [kg/m²/s], S_E [kg/m²/s], and SSC [kg/m³] provided by ECOLABMT module at 3 locations, as shown in Fig. 6.5, are compared with the results obtained by MT module in Fig 6.6. Excellent agreement between the two modules was obtained.

Figure 6.6 - MIKE 21 results using ECOLABMT (symbols) and MT (continuous lines) modules, with constant W_s , at three locations for (a) bed shear stress, (b) deposition rate, (c) erosion rate, and (d) SSC. (Note: Horizontal axes are for time).

Conclusion

With constant W_s , ECOLABMT module can reproduce the same results as MT module because both modules use the same formulations for τ_c , S_D , and S_E . The excellent agreement between ECOLABMT and MT modules shows that for this basic case, the Ecolab_MT template was correctly developed and further development could be taken.

6.3.2 MIKE 3 – ECOLABMT with constant settling velocity (3D)

The previous template was further developed for the 3D flow with constant W_s test case. Then, similar to the previous step, the template was verified against the existing MIKE 3 MT with constant W_s to check if the template was correctly developed for the 3D case since both the Ecolab_MT template and MT module use the same formulations for τ_c , S_S , S_D , and S_E .

Description of the Ecolab_MT template

Suspended sediment concentration, SSC [kg/m^3], is the state variable with scope of water column (WC). ADVECTION_DISPERSION transport was selected so that advection and dispersion terms in Eq. (6.2) are included. The processes used to describe the transformation of SSC (see Fig. 6.2) are *sedimentation* and *deposition* (sink terms) and *erosion* (source term), defined in PROCESSES.

User specified constants in the template are Ws [m/s] for W_s , Tcd [N/m^2] for τ_{cd} , Tce [N/m^2] for τ_{ce} , ks [m], E [$\text{kg}/\text{m}^2/\text{s}$], n [-], $sigma1$ [-] for the ratio of the water layer height of the first layer near the bed to the total water depth at the same location.

Forcings are *Depth* (total water depth), *Current* and *dZ*, defined by WATER_DEPTH [m], HORIZONTAL_CURRENT_SPEED [m/s] and WATER_LAYER_HEIGHT [m] in the template, which are assessed from the MIKE 3 HD module.

Auxiliary variables include $dz1$ [m] for water layer height at the near-bed layer, $z0$ [m] for z_0 , fC [-] for f_C . $z0$ has NONE spatial variation (same values in all grid points) while $dz1$ and fC have HORIZONTAL spatial variations.

Processes include *Tbed* for τ_c [N/m²], *sedimentation* [kg/m³/day], *deposition* [kg/m³/day], and *erosion* [kg/m³/day]. The bed shear stress has WB scope so that only current speeds at the near-bed layers can take part in the determination of *Tbed*. The *sedimentation* has HORIZONTAL_AND_VERTICAL spatial variation, SETTLING type of process, WC scope including the near-bed layer. The last two processes are bed-related processes and have WB scope, HORIZONTAL spatial variation, and TRANSFORMATION type of process.

Verification of ECOLABMT module

The open channel model, as shown in Fig. 6.5, was set up using MIKE 3 Flow Model FM modelling system with the activations of HD, ECO Lab, and MT modules. The Ecolab_MT template is inserted in the ECO Lab module to form ECOLABMT module. For the vertical mesh, three layers were applied with $\sigma_1 = 0.2$, $\sigma_2 = 0.3$, and $\sigma_3 = 0.5$, where sigma presents ratio of layer height (thickness) to the total water depth. Initial and boundary conditions for HD, MT, and ECOLABMT modules, as shown in Table 6.3, and the following constant values were used: $W_s = 0.005$ m/s, $k_s = 0.001$ m, $E = 0.0005$ kg/m²/s, $n = 2$, $\tau_{cd} = 1.0$ N/m², $\tau_{ce} = 2.0$ N/m².

The values of τ_c [N/m²], S_D [kg/m²/s], and SSC [kg/m³] at 3 locations (Fig. 6.5) obtained from ECOLABMT module are compared with results obtained for the same three locations from the MT module. The comparison of the results for τ_c and S_D is presented in Fig. 6.7, showing an excellent agreement between two modules. No erosion occurs since $\tau_c < \tau_{ce}$. For SSC comparison, there is a slight difference in SSC between the two modules, as shown in Fig. 6.8. Although the template was carefully checked, the reason for this difference is unclear.

Figure 6.7 - MIKE 3 results using ECOLABMT (symbols) and MT (continuous lines) modules, with constant W_s , at three points for (a) bed shear stress, and (b) deposition rate.

Figure 6.8 - MIKE 3 results for SSC using ECOLABMT (symbols) and MT (continuous lines) modules, with constant W_s , at three points and layers #1, #2.

Conclusion

With constant W_s , the ECOLABMT module can reproduce the same results as MT module for bed shear stress and deposition rate since both modules use the same formulations for τ_c , S_s , S_D , and S_E . Both modules give similar results for SSC. The

good agreement between ECOLABMT and MT modules thus shows that the Ecolab_MT template was correctly developed for the 3D case with constant W_s and the template can be further developed for the non-constant W_s case.

6.3.3 MIKE 3 – ECOLABMT with non-constant settling velocity

The previous simple 3D template was further improved by considering bed layer thickness and non-constant W_s . Formulations for the floc density (see Chapter 2), hindering effect and viscosity of mixture (see Chapter 3), effect of flow turbulence on the drag coefficient (see Chapter 4), and flocculation of cohesive sediments (see Chapter 5) were incorporated in the estimate of W_s . Therefore, compared to MT module, the Ecolab_MT template generally computes the settling velocity in a more detailed way.

Description of the Ecolab_MT template

The template includes two state variables. The first variable is suspended sediment concentration, SSC [kg/m^3]. It has WC scope, ADVECTION_DISPERSION transport. The processes used to describe the transformation of SSC (see Fig. 6.2) are *sedimentation* and *deposition* (sink terms) and *erosion* (source term), defined in PROCESSES. The other state variable is bed layer thickness, *LayerThickness* [m], with scope of WB. The process used to describe the rate of change of the bed layer thickness is *BedChange* defined in PROCESSES. The user specified constants for the template are provided in Table 6.4.

Table 6.4 - User specified constants for the Ecolab_MT template.

No	Name	Unit	Description	Default	Remarks
1	<i>Type</i>		sediment type	3	3 for cohesive, 2 for mixed, 1 for non-cohesive sediments
2	<i>nuy_w</i>	m ² /s	v_{water}	1e-006	
3	<i>ps</i>	kg/m ³	ρ_s	2,650	
4	<i>Dp</i>	m	D_p	1.5e-005	for sand: $D_p = D$
5	<i>DfH</i>	m	D_{fH}	0.0002	size of (sand or floc) particle at high concentration ^(*) ; for sand: $DfH = D$
6	<i>PhiH</i>		ϕ_H	0.05	applicable to cohesive and mixed sediment only
7	<i>SF</i>		SF	0.7	applicable to sand only
8	<i>af</i>		α , floc density	0.7	applicable to cohesive and mixed sediment only
9	<i>bf</i>		β , floc density	0.8	applicable to cohesive and mixed sediment only
10	<i>Av</i>		α , viscosity	0.127	for non-cohesive sediments: $Av = 1.5$ to 3.5 ; for cohesive sediment: $Av = 0$ to 0.127
11	<i>bv</i>		β , viscosity	0.6	for non-cohesive sediments: $bv = 0.6$; for cohesive sediment: $bv = 1.0$
12	<i>AA</i>		A_v , viscosity	0.01	applicable to cohesive sediment only
13	<i>BB</i>		coef., viscosity	6.0886	applicable to cohesive sediment only
13	<i>CC</i>		coef., viscosity	0.2149	applicable to cohesive sediment only
14	<i>at</i>		α , turbulence	0.0385	
15	<i>bt</i>		β , turbulence	0.6943	
16	<i>aB</i>		α , break-up	198,000	applicable to cohesive sediment only
17	<i>bB</i>		β , break-up	1.2	applicable to cohesive sediment only
18	<i>PhiMax</i>		ϕ_{max} or ϕ_{gel}	0.8	for sand: $\phi_{\text{max}} \sim 0.6$; for cohesive: $\phi_{\text{gel}} \sim 0.8$
19	<i>Tero</i>	N/m ²	τ_{ce}	2.0	
20	<i>Tdep</i>	N/m ²	τ_{cd}	0.5	
21	<i>Ee</i>	kg/m ² /s	E	0.0005	
22	<i>n</i>		n	1.0	

23	<i>sigma1</i>		sigma1	0.2	sigma value of the first layer near the bed
24	<i>ks</i>	m	k_s	0.001	
25	<i>Salt_type</i>		Salinity variation	1.0	0 = no, 1 = yes; applicable to cohesive sediment only
26	<i>aS</i>		α , salinity	6.15	applicable to cohesive sediment only
27	<i>bS</i>		β , salinity	0.05	applicable to cohesive sediment only
28	<i>pbed</i>	kg/m ³	ρ_{bed}	150	

(*) For Salt_type = 1, this value has no effect on calculation.

Forcings are *Depth* (total water depth), *current*, *dZ*, *Salt*, *TKE*, and *TKEd*, which take the corresponding values defined as WATER_DEPTH [m], HORIZONTAL_CURRENT_SPEED [m/s], WATER_LAYER_HEIGHT [m], SALINITY [ppt], TKE (turbulent kinetic energy, k) [m²/s²] and TKEd (TKE dissipation rate, ϵ) [m²/s³] from outputs of the HD module.

The auxiliary variables in the template are presented in Table 6.5. *MI*, *NI*, and *nI* are specified with NONE spatial variations, *zo*, *dzI*, and *fC* are specified with HORIZONTAL spatial variations and the other auxiliary variables are specified with HORIZONTAL_ AND_ VERTICAL spatial variations. For mixed sediments, floc density is applied and the viscosity of mixture follows the one for the non-cohesive sediments. For the near-bed layer, *Wsm* is applied because the effect of turbulence on deposition is already taken into account by $(1 - \tau_c / \tau_{cd})$; for the other layers, *Wsm* is applied. The determinations of *Wsm* and *Wsm* require iteration and are looped manually five times as indicated in Rows 22 to 37 and Rows 38 to 51 in Table 6.5, respectively.

Table 6.5 - Auxiliary variables in the Ecolab_MT template.

No	Name	Unit	Description	Remarks/Formulation used
1	<i>pw</i>	m/s	ρ_w	
2	<i>cH</i>	kg/m ³	c_H	Without variation of salinity: Eq. (5.11) (*) With variation of salinity: Eq. (5.12)
3	<i>DfHo</i>	m	D_{fH}	Floc size at $c > c_H$

4	G	1/s	Shear rate, G	
5	Ret		Re_t	Eq. (4.31)
6	DfB	m	D_{fB}	Model for flocculation. Eq. (5.2)
7	DfA	m	D_{fA}	Model for flocculation. Eq. (5.3)
8	Df	m	D_f	Model for flocculation. Eq. (5.4)
9	$D3$		$D\#$	Model for floc density. Eq. (2.5)
10	pf	kg/m ³	ρ_f	Model for floc density. Eq. (2.6)
11	$D8$		D_*	Model for viscosity of mixture. Eq. (3.8)
12	Phi		ϕ	Volumetric concentration of floc/sand
13	pm	kg/m ³	ρ_m	Density of mixture
14	av		α , viscosity	
15	X		$\phi/\phi_{max}/10$	
16	muy_r		μ_r	Model for viscosity of mixture. Eq. (3.7)
17	nuy_m	m ² /s	ν_m	
18	$M1$		M	Eq. (4.7)
19	$N1$		N	
20	$N1$		n	
21	s		s_m	Specific density of floc/sand to density of mixture
22	$W0$	m/s	W_0 , Stokes	First estimation for the relative settling velocity using Stokes law
23	$Rep0$		Re_{p0}	Iteration to determine the relative settling velocity in turbulence mixture using the modified Stokes law.
24	$CD0$		C_{D0}	
25	$W1$	m/s	W_1	
26	$Rep1$		Re_{p1}	
27	$CD1$		C_{D1}	
28	$W2$	m/s	W_2	
29	$Rep2$		Re_{p2}	
30	$CD2$		C_{D2}	
31	$W3$	m/s	W_3	
32	$Rep3$		Re_{p3}	
33	$CD3$		C_{D3}	
34	$W4$	m/s	W_4	
35	$Rep4$		Re_{p4}	
36	$CD4$		C_{D4}	

37	<i>Wsmt</i>	m/s	$W_{s,mt}$	Settling velocity in turbulence mixture. Eq. (4.24)
38	<i>CD5</i>		C_{D5}	Iteration to determine the relative settling velocity in still mixture using the modified Stokes law.
39	<i>W6</i>	m/s	W_6	
40	<i>Rep6</i>		Rep_6	
41	<i>CD6</i>		C_{D6}	
42	<i>W7</i>	m/s	W_7	
43	<i>Rep7</i>		Rep_7	
44	<i>CD7</i>		C_{D7}	
45	<i>W8</i>	m/s	W_8	
46	<i>Rep8</i>		Rep_8	
47	<i>CD8</i>		C_{D8}	
48	<i>W9</i>	m/s	W_9	
49	<i>Rep9</i>		Rep_9	
50	<i>CD9</i>		C_{D9}	
51	<i>Wsm</i>	m/s	$W_{s,m}$	Settling velocity in still mixture. Eq. (3.15)
52	<i>dzl</i>	m	dzl	Water layer height (thickness) of the near-bed layer
53	<i>z0</i>	m	z_0	$k_s/30$
54	<i>fC</i>		f_C	Eq. (6.7)
55	<i>Thickness</i>	m	X	Bed layer thickness

(*) For $Salt_type = 0$, the user specified constant D_{fH} (see Table 6.4) is used in determination of the hinder concentration and $c_H \approx \phi_H \rho_s D_p / D_{fH}$.

Processes include *Tbed* for τ_c [N/m²], *sedimentation* [kg/m³/day], *deposition* [kg/m³/day], *erosion* [kg/m³/day], and *BedChange* [m/day]. The *Tbed* and the last three processes are bed-related processes and have WB scope, HORIZONTAL spatial variation, and TRANSFORMATION type of process. The *sedimentation* has HORIZONTAL_ AND_VERTICAL spatial variation, SETTLING type of process, WC scope including the near-bed layer.

Testing ECOLABMT module

The Ecolab_MT template was tested and the results compared with the MT module for two cases. The first case is for cohesive sediments while the second one is for fine sand. For each case, the test was carried out for the following two situations:

- Effect of turbulence on the settling velocity (and flocculation of cohesive sediments) is neglected in the simulation, and
- Effect of turbulence on the settling velocity (and flocculation of cohesive sediments) is included in the simulation.

Cohesive sediment transport (Case 1)

The open channel model, as shown in Fig. 6.5, was set up using MIKE 3 Flow Model FM modelling system with the activations of HD, ECO Lab, and MT modules. The Ecolab_MT template is inserted in the ECO Lab module to form ECOLABMT module. For vertical mesh, three sigma layers ($\sigma_1 = 0.2$, $\sigma_2 = 0.3$, $\sigma_3 = 0.5$) were applied. The initial and boundary conditions prescribed for HD, MT, and ECOLABMT modules are summarized in Table 6.6. For the constants defined in ECOLABMT module, given in Table 6.7, ECOLABMT module, with $S = 10$ psu, gives $c_H = 3.1 \text{ kg/m}^3$, $D_{fH} = 427 \text{ }\mu\text{m}$, $\rho_f = 1,022 \text{ kg/m}^3$, $w_s = 1.9 \text{ mm/s}$ in still water, and $c_{gel} = 31.0 \text{ kg/m}^3$. For MT module, flocculation calculation is selected using with Winterwerp's formulation for hindered settling calculation, $c_{gel} = 31.0 \text{ kg/m}^3$, $\rho_s = 2,650 \text{ kg/m}^3$, $c_{Floc} = 0.01 \text{ kg/m}^3$, $c_H = 3.1 \text{ kg/m}^3$, $\gamma = 1.0$, $W_0 = 1.63 \text{ m/s}$ for $w_s = 1.9 \text{ mm/s}$ at $c = c_H$, and $C_1 = 0.5$ (for the description of the parameters, see Section 6.2.1).

Table 6.6 - Initial and boundary conditions for salinity [psu] and SSC [kg/m³].

Description	Case 1 (Cohesive)	Case 2 (Non-cohesive)
A. Salinity		
Initial condition	0.2	0.2
Upstream	10	1.0
Downstream	Zero gradient	Zero gradient
B. SSC		
Initial condition	0.2	0.02
Upstream	3.1	0.2
Downstream	Zero gradient	Zero gradient

Table 6.7 - Inputs for ECOLABMT constants ^(a).

No	Name	Unit	Case 1 (Cohesive)	Case 2 (Non-cohesive)
1	Type		3	1
4	Dp	m	1e-005	0.0002
5	DfH	m	0.1 ^(b)	0.0002
10	Av		0.127	2.0
11	Bv		0.6	1.0
14	at		0.0385	0.0385
18	PhiMax		0.8	0.6
25	Salt_type ^(c)		1	0

Note: ^(a) The other constants take their default values (see Table 6.4).

^(b) For Salt_type = 1, this value has no effect on calculation.

^(c) For non-cohesive sediment, Salt_type = 0.

There are several differences between the two modules. ECOLABMT module considers that salinity affects hinder concentration and floc size, which either increases or decreases the settling velocity depending on the sediment concentration, while MT module considers c_H as a calibration parameter and directly applies the heuristic formulation for the settling velocity (see Section 6.2.1). ECOLABMT module includes not only aggregation but also the breakup process, while MT module includes only aggregation and does not consider the breakup process. Furthermore, in contrast with MT module, which considers the settling velocity as a calibration parameter by using

the settling velocity coefficient W_0 , ECOLABMT module uses the modified Stokes law for determining the settling velocity and the primary particle size D_p , a physical quantity, is used as the input parameter instead. Finally, the effect of flow turbulence on the floc settling velocity is included in ECOLABMT module but not in MT module.

The values of τ_c [N/m^2] and SSC [kg/m^3], at three points shown in Fig. 6.5, obtained from the two modules were compared. The result for τ_c is the same as that shown in Fig. 6.7. The result for SSC is presented in Fig. 6.9. In addition, ECOLABMT result for floc size is shown in Fig. 6.10. For the first situation, where the effect of turbulence on the flocculation and settling velocity were neglected in the simulation, although the behavior for SSC is consistent between the two results there is a difference between the two results, as shown in Fig. 6.9(a). This difference is probably due to the difference in the way the two modules estimate the settling velocity, which depends on the salinity and SSC, as shown in Fig. 6.4. ECOLABMT module considers that salinity affects hinder concentration and floc size, which either increases or decreases the settling velocity depending on the sediment concentration, while MT module considers c_H as a calibration parameter and directly applies the heuristic formulation for the settling velocity (see Section 6.2.1). In addition, the ECOLABMT module can give result for floc size, as shown in Fig. 6.10(a), while the MT module does not. Floc size at layer #3 near the water surface is smaller than D_{fH} ($D_f < 427 \mu\text{m}$) since SSC at this layer is lower than c_H ($c < 3.1 \text{ kg/m}^3$); floc size at point 3 is smaller than that at the other points since SSC at this point is smaller. At the other layers, floc size equals D_{fH} ($D_f = 427 \mu\text{m}$) since SSC at these layers is higher than c_H ($c > 3.1 \text{ kg/m}^3$). Note that, for this situation, the effect of turbulence on the breakup process is neglected and floc size is controlled by the aggregation process.

For the second situation, where the effect of turbulence on the flocculation and settling velocity was included in simulation, there is a large difference in the result between the two modules, as shown in Fig. 6.9(b). Compared to the previous situation, MT module gives the same results while ECOLABMT module gives different results for SSC as a result of the inclusion of turbulence effects. In addition, as can be seen from the figure, the results for SSC at the near-bed layers from the two modules are

different. The differences in SSC are due to the fact that ECOLABMT module considers the effect of turbulence on the breakup process and the settling velocity but MT module does not. The difference in SSC in this case implies that the last component in Eq. (6.2) is as important as advection and dispersion transports and the effect of flow turbulence on the W_s as well as on the SSC is clearly recognized. Moreover, for the ECOLABMT results for SSC, comparing Fig. 6.9(b) with Fig. 6.9(a) shows that for this case, SSC at the upper layers is slightly higher since turbulence is able to maintain the sediments in suspension and hence SSC at the near-bed layer is lower. Finally, the ECOLABMT result for floc size is shown in Fig. 6.10(b). Note that, for this situation, the effect of turbulence on the breakup process is included and floc size is controlled by both the aggregation and breakup processes. At layer #3 near the water surface, floc size is smaller than D_{fH} ($D_f < 427 \mu m$) since SSC at this layer is lower than c_H ($c < 3.1 \text{ kg/m}^3$); floc size at point 3 is smaller than that at the other points since SSC at this point is smaller. At the other layers, except location P1-1, floc size equals D_{fH} , ($D_f = 427 \mu m$) since SSC at these layers is higher than c_H ($c > 3.1 \text{ kg/m}^3$) and the turbulence is probably low. At the near -bed layer at point 1 (P1-1), the floc size first increases with SSC but then decreases although $SSC > c_H$. The decrease in floc size at this location is because the turbulence at the later stage is high and the floc size is controlled by the breakup process.

(a)

(b)

Figure 6.9 - Results for SSC [kg/m^3] using ECOLABMT (symbols), (a) without and (b) with effect of turbulence on the flocculation and the settling velocity of cohesive sediments, and MT (continuous lines) modules at three points and layers #1, #2, #3.

(a)

(b)

Figure 6.10 - ECOLABMT results for floc size at three points and layers #1, #2, #3, (a) without and (b) with effect of turbulence on flocculation and settling velocity.

Fine sand transport (Case 2)

The open channel shown in Fig 6.5 with three sigma layers ($\sigma_1 = 0.25$, $\sigma_2 = 0.35$, $\sigma_3 = 0.4$) was used. Initial and boundary conditions for HD, MT, and ECOLABMT modules are shown in Table 6.6. In addition, sand size $D = 200 \mu\text{m}$. The ECOLABMT module constants are summarized in Table 6.7, and $\tau_{ce} = 0.5 \text{ N/m}^2$ and $\tau_{cd} = 0.2 \text{ N/m}^2$. Note that ECOLABMT module considers the Corey shape factor and uses the modified Stokes law for determining the W_s but MT module does not. In addition, ECOLABMT module can include the effect of turbulence on the W_s while MT module cannot.

The values of τ_c [N/m^2] and SSC [kg/m^3], at three points shown in Fig. 6.5, obtained from the two modules were compared. The result for τ_c is the same as that shown in Fig. 6.7. The result for SSC is presented in Fig. 6.11.

While the result for SSC is consistent between the two modules for the first situation, as shown in Fig. 6.11(a), where the effect of turbulence on W_s is neglected in the simulation, there is a large difference in the result between the two modules for the second situation, as shown in Fig. 6.11(b), where the effect of turbulence on W_s is included in the simulation. Comparing Fig. 6.11(b) with Fig. 6.11(a) shows that MT module gives the same results while ECOLABMT module gives different results for SSC as a result of the inclusion of turbulence effects. In addition, as can be seen from Fig. 6.11(b), the results for SSC at the near-bed layers from the two modules are different. The differences in SSC are due to the fact that ECOLABMT module considers the effect of turbulence on the settling velocity, which is not considered in MT. The difference in SSC in this case implies that the last component in Eq. (6.2) is as important as advection and dispersion transports and the effect of flow turbulence on the W_s as well as on the SSC is clearly recognized. Moreover, for the ECOLABMT results for SSC, comparing Fig. 6.11(b) with Fig. 6.11(a) shows that for the second situation, SSC at the upper layers is slightly higher since flow turbulence keeps sediments in suspension and SSC at the near-bed layers is lower.

(a)

(b)

Figure 6.11 - Results for SSC [kg/m³] using ECOLABMT (symbols), (a) without and (b) with effect of turbulence on the settling velocity of fine sand, and MT (continuous lines) modules at three points and layers #1, #2.

Conclusion

Flocculation of cohesive sediments and flow turbulence clearly affect the settling velocity as well as suspended sediment concentration. The difference in result for SSC between ECOLABMT and MT modules is due to the way the two modules estimate W_s . For cohesive sediment transport, ECOLABMT module considers that salinity affects the hinder concentration and floc size, which the module uses for estimating W_s ; meanwhile MT module considers c_H as a calibration parameter and directly applies the heuristic formulation for estimating W_s . ECOLABMT module includes not only aggregation but also the breakup process, while MT module includes only aggregation and does not consider the breakup process. ECOLABMT module can give result for floc size and MT module does not. Furthermore, in contrast with MT module, which considers the settling velocity as a calibration parameter by using the settling velocity coefficient W_0 , ECOLABMT module uses the modified Stokes law for determining the settling velocity and the primary particle size D_p , a physical quantity, is used as the input parameter instead. In addition, the effect of flow turbulence on the floc settling velocity is included in ECOLABMT module but not in MT module. For fine sand transport, ECOLABMT module considers the Corey shape factor and uses the modified Stokes law for determining the W_s while MT module considers W_s as a calibration parameter; ECOLABMT module includes the effect of turbulence on the W_s while this effect is not included in MT module.

6.4 Additional options for Ecolab_MT template

With MT module, it is possible to define maximum sediment concentration due to erosion. Also, MT module can consider the effect of sediment concentration on current speed and bed shear stress, etc. by giving the feedback of density and viscosity of mixture to HD module during simulation. Therefore, two additional options were created for Ecolab_MT template in order to make ECOLABMT module comparable with MT module as much as possible.

Figure 6.12 - Approximation of erosion rate variation (the bold curve).

Firstly, instead of the maximum sediment concentration due to erosion, defined in the MT module, the present study assumes that the erosion rate, S_E proportionally increases with the bed shear stress until τ_c reaches a maximum value of bed shear stress for erosion calculation ($\tau_{\max, \text{ero}}$), beyond which S_E reaches a constant value, as shown by the red curve in Fig. 6.12. By defining the parameter $\tau_{\max, \text{ero}}$, the erosion rate and, therefore, sediment concentration due to erosion are limited. Secondly, concerning the effect of sediment concentration on the bed shear stress, it is assumed that:

$$\tau_{c, \text{sed}} = \frac{c_{\text{reference}} - c}{c_{\text{reference}}} \tau_c \quad (6.16)$$

where $\tau_{c, \text{sed}}$ is the bed shear stress considering the existence of sediments, $c_{\text{reference}}$ a reference value of c , at which bed shear stress equals to zero. This assumption is based on the observation that $\tau_{c, \text{sed}} = \tau_c$ at $c = 0$ and $\tau_{c, \text{sed}} = 0$ at $c = c_{\text{reference}}$. Finally, erosion and deposition rates are estimated using the following modified bed shear stress, which is:

$$\tau_{c, \text{modified}} = \text{MIN}(\tau_{c, \text{sed}}, \tau_{\max, \text{ero}}) \quad (6.17)$$

Note that, due to the limitation of the current ECO Lab module, Ecolab_MT template cannot provide the feedback of density and viscosity of the mixture to HD module during simulation and thus has no effect on HD results (for e.g., water depth, current speed, and eddy viscosity, etc.). On the other hand, MT module can provide the feedback to HD module during the simulation. As a result, advection and dispersion

transports [see Eq. (6.2)] in ECOLABMT module will be different from those in MT module if the option for the feedback in MT module is activated.

6.5 Concluding remarks

A new Ecolab_MT template for fine suspended sediment transport in 3D was developed. The template includes the physically-based models for floc density, viscosity of mixture, effect of turbulence on the hindered settling velocity, and flocculation of cohesive sediments. The verification of the template against the existing MT module of MIKE 3 Flow Model FM modelling system shows that the template was well developed and is able to solve Eq. (6.2) properly. Compared to MT module, the main advantages of the Ecolab_MT template are (i) The settling velocity is not a calibration parameter and is determined based on the specification of the primary particle size, (ii) Both aggregation and breakup processes are included, and (iii) The effect of turbulence on hindered settling velocity is considered. However, it should be mentioned that at the moment, due to limitation of ECO Lab module, it is not possible to implement the evolution of floc size, update of bed level, and feedback of density and viscosity to HD module in the Ecolab_MT template. In addition, the Ecolab_MT template does not consider multi-fractions sediments.

Chapter 7

Implementation of ECOLABMT to Ems Estuary

7.1 Introduction

In previous chapter, the Ecolab_MT template was developed and compared with the Mud Transport (MT) module of MIKE 3 Flow Model FM modelling system for a hypothetical open channel flow case. In this chapter, the template is applied to model sediment transport in the Ems estuary in order to test the applicability of the template to a real case. Relevant field data required for the implementation of the template was obtained from DHI-WASY (Ladage et al., 2011a) as part of an EIA study on fluid mud transport for the Ems estuary; Wasser- und Schifffahrtsamt in Emden (WSA Emden) provided DHI-WASY the data for water level and flow velocity while Niedersächsische Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz in Aurich (NLWKN Aurich) provided DHI-WASY the data for salinity and sediment concentration. The estuary, as shown in Fig. 7.1, is located at the south of German Bight and stretches from Borkum to the tidal weir barrier at Herbrum. At Borkum, the tidal regime is meso-tidal, as depicted in Fig. 7.2. During low tide, a number of intertidal flats at the sea side and at the Dollard basin are exposed. According to Herrling and Niemeyer (2008a), mean maxima, mean and mean minima river discharges at Herbrum are about 375 m³/s, 81 m³/s and 16 m³/s, respectively, with respect to long time series. Over the years, conditions in the estuary have gradually changed due to man-made and natural influences. The man-made activities include land reclamation, construction of groins and storm surge barriers, dredging in harbours and shipping channels, dumping of organic waste, etc. Natural influences include sea level rise arising from climate change impacts. The mentioned influences create tidal pumping resulting in the water become more and more turbid, with consequent effects on water quality and the ecosystem (Talke and Swart, 2006).

Figure 7.1 - Location of Ems estuary [Note: The left figure is from Wang et al. (2009). White dots on the right figure denote locations for the model outputs].

Figure 7.2 - Water level [mNN] at Borkum for year 2008.
[Note: The figure is from Cremer (2011) with the measurement by WSA Emden].

There exist two Estuarine Turbidity Maximas (ETMs). One is near Terborg (Winterwerp, 1999) and the other is between Weener and Papenburg (e.g., see Ladage et al., 2011a). At each ETM, a thick fluid mud layer exists, water is very turbid, and sediment concentration near the bed is very high. Many attempts have been made to understand the dynamics of fluid mud in the estuary by applying 1DV POINT model,

which was developed on the basis of DELFT3D-FLOW but neglects all horizontal gradients except the horizontal pressure gradient (Winterwerp, 1999), 2DH model (Herrling and Niemeyer, 2008a and 2008b), 2DV model (Chernetsky and Schuttelaars, 2009), and 3D model (Weilbeer, 2008). Recently, the World Wide Fund for Nature (WWF) together with regulatory authorities and engineers has been studying solutions to restore the Lower Ems at the upstream part of the estuary (Stoschek and Ladage, 2011). DHI-WASY is involved in the modelling of the hydrodynamics and sediment transport; both MT and ECOLABMT (ECO Lab module in conjunction with the Ecolab_MT template) modules have been used for modelling of sediment transport (Ladage et al., 2011a).

7.2 Model setup

Modelling the sediment transport for Ems estuary using Ecolab_MT template requires a hydrodynamic (HD) model and a setup for ECOLABMT module. During model calibration, different versions of the HD model were set-up by DHI-WASY, covering a wide variation of modeled area, alternate mesh configurations and model parameters, etc. in order to obtain the best fit between the modeled and measured water level, current speed, salinity and sediment concentration data. Once the HD model calibration was completed, the ECOLABMT module was coupled with the HD module and the ECOLABMT module was calibrated using a subset of the available data. For the final version (Ladage et al., 2011a), the modeled area was extended to Bollingerfähr (about 7 km further upstream from Herbrum) and included Leda-Juemme area at the right side of Lerrort; 10 sigma layers were applied for the vertical mesh; the periods used for calibration of the HD model covered low river flow during May to July 2008 and high river flow during February 2008, and spring and neap tides; the ECOLABMT and MT models were calibrated for 20-day period for May 2008.

For the present study, the modeled area does not include Leda-Juemme area and Herbrum is upstream boundary; preliminary results obtained from this version of the HD model are presented as the author was involved in the calibration of the HD model

only up to that stage. Data for the period from 03.05.2008 12:00 to 13.05.2008 12:00 (10 days) was used for calibration. The time interval between the measured data points was 1 minute for the water level at Borkum, 15 minutes for the river flow and 30 minutes for salinity at Herbrum. The same sets of data were used for calibration of the HD and ECOLABMT models. A time step of 30 sec was used in the computation. At the early stage of the calibration of the Ems model, the 10-day simulation period together with five equidistant sigma layers for the vertical mesh were chosen on the basis of several constraints such as CPU speed and available hard disk space; for one run, HD and ECOLABMT modules take about 3 days and ½ day, respectively, and create about 15 Gbytes of data. Finally, at this stage, for modelling the sediment transport in the Ems, the author used ECOLABMT module and DHI-WASY used MT module. For the final version of the Ems model, DHI-WASY (Ladage et al., 2011) used both ECOLABMT and MT modules. The results from the final version, developed by DHI-WASY (Ladage et al., 2011a), are also included at the end of this chapter for further comparison between ECOLABMT and MT modules. Note that the model setup by DHI-WASY (Ladage et al., 2011) for the final version is different from the one in this chapter.

7.2.1 HD setup

The HD model was created using the bathymetry for the main channel surveyed in year 2008 and for the flood plain in year 2005 (Ladage et al., 2011; Cremer, 2011). The model has a mesh of the unstructured type and consists of 176,585 triangular and quadrangular elements and 137,868 nodes. In the vertical, the mesh is divided into five equidistant sigma layers. For horizontal and vertical eddy viscosities, Smagorinsky approach and k-ε model are selected, respectively. Maps of the roughness height and salinity were used for the specification of bed resistance and the initial salinity, respectively. The measured water level (Fig. 7.2) and a constant salinity of 32 psu were applied at Borkum as the downstream boundary condition. Measured discharge and a variable salinity are applied at Herbrum as upstream boundary condition. The model

only considers the case of current and the effects of waves, temperature, wind, precipitation and evaporation were neglected. Finally, the model outputs for current speed and salinity at measuring locations (see Fig. 7.1) were specified at layers which are best accordant with the deployed depth of measuring instruments.

7.2.2 ECOLABMT setup

For ECOLABMT module, simulation period and time step are the same as for HD module. The ECOLABMT constants, forcings, dispersion coefficients, initial and boundary conditions specified are summarized here.

A primary particle size, $D_p = 20 \mu\text{m}$, corresponding to silt, was selected. This was based on the reported data, as described in Ladage et al. (2011a) and Cremer (2011), that bed sediments roughly consist of 20% fine sand, 75% silt and 5% clay. In addition, the following values were specified here: $\tau_{ce} = 0.15 \text{ N/m}^2$, $\tau_{cd} = 0.05 \text{ N/m}^2$, $k_s = 1.5 \text{ mm}$, $\tau_{\text{max, ero}} = 2.0 \text{ N/m}^2$, $c_{\text{reference}} = 10.0 \text{ kg/m}^3$, $\rho_{\text{bed}} = 200 \text{ kg/m}^3$, erodibility over the whole domain varied from 5×10^{-5} to $5 \times 10^{-4} \text{ kg/sm}^2$. Default values, specified in Table 6.4, were adopted for all other constants. For forcings, the values of k and ε obtained from the HD module were used. Dispersion coefficients were scaled with the eddy viscosity by a factor of 1.0. An initial sediment concentration of 20 mg/l was adopted. In addition, a map for initial bed layer thickness was applied. Finally, $\text{SSC} = 150 \text{ mg/l}$ at Herbrum and 20 mg/l at Borkum were adopted as the upstream and downstream boundary conditions, respectively.

The model outputs for SSC at measuring locations (see Fig. 7.1) are specified at layers, shown in Table 7.1, which are best accordant with the deployed depth of measuring instruments.

Table 7.1 - Layer number for ECOLABMT output for SSC.

Location	Layer number	Location	Layer number	Location	Layer number
Knock	2	Leerort	2	Terborg	2
Pogum	2	Weener	2		
Gandersum	5	Papenburg	3		

7.3 Results and Discussion

In the following, the simulated results from HD and ECOLABMT modules are compared with measured data at different locations. In addition, the results by DHI-WASY (Ladage et al., 2011a) for the final version of the model, where 10 vertical sigma layers were used, are also provided.

7.3.1 HD results

The simulation and measured values of water level at Knock, Leerort and Papenburg are presented in Fig. 7.3. For water level, the simulation agrees well with measurement for both magnitude and phase.

Figure 7.3 - Simulated results vs. measured data for water level.
[Note: The measurements were carried out by WSA Emden].

The simulation and measured values of current speed at Knock, Leerort and Papenburg are presented in Fig. 7.4. The simulation underestimates the measured data for the ebb current at Knock (downstream location), agrees well with the measured data at Leerort (midstream location) and provides fair agreement for the ebb current at Papenburg (upstream location).

Figure 7.4 - Simulated results vs. measured data for current speed.
[Note: The measurements were carried out by WSA Emden].

The simulation and measured values of salinity at five measuring locations are presented in Fig. 7.5. Although there is a difference between simulated and measured values at Knock, in general the simulation agrees well with measurement at other locations and shows a decreasing trend towards the upstream direction.

Figure 7.5 - Simulated results vs. measured data for salinity.
 [Note: The measurements were carried out by NLWKN Aurich].

Slightly improved results were obtained by DHI-WASY in the final HD version; however, there are still differences between simulations and measurements for current and salinity (Ladage et al., 2011a), as shown in Fig 7.6 and Fig. 7.7, respectively. The differences between simulations and measurements may be due to many reasons. The measurements may not be accurate. The values of the constants adopted in the sub-modules used for the hydrodynamics calculations (for e.g., Turbulence Module and Temperature/ Salinity Module) may not be appropriate. In addition, the effect of waves was not included (see Section 7.2.1). Lastly, the effect of sediment concentration on density and viscosity of mixture was not included in HD module during the simulation.

Figure 7.6 - Final version: simulated results vs. measured data for current (left y-axis) and simulated water level (right y-axis) at Knock and Leerort.
[Source: Ladage et al. (2011b) with the measurements by WSA Emden].

Figure 7.7 - Final version: simulations vs. measurements for salinity.
[Source: Ladage et al. (2011a) with the measurements by NLWKN Aurich].

7.3.2 ECOLABMT results

The simulated and measured values for SSC are compared in Fig. 7.8 for Knock to Terborg and Fig. 7.9 for Leerort to Papenburg. The comparisons for stations close to the upstream (Papenburg, Weener and Leerort) and downstream (Knock) boundaries are fair, whereas the agreements between the simulated and measured SSC at midstream (Pogum, Gandersum, and Terborg) are good.

Figure 7.8 - Simulations vs. measurements for SSC from Knock to Terborg.
[Note: The measurements were carried out by NLWKN Aurich].

Figure 7.9 - Simulations vs. measurements for SSC from Leerort to Papenburg.
[Note: The measurements were carried out by NLWKN Aurich].

Improvements to the ECOLABMT results were obtained in the final version of the model by DHI-WASY (Ladage et al., 2011a), as shown in Fig. 7.10 and Fig. 7.11. However, there are still differences between simulations and measurements for SSC at Weener and Papenburg at upstream part (Ladage et al., 2011a). The simulations underestimate the measurements during flood tides. In addition, phase differences between the simulations and measurements are recognized.

Figure 7.10 - Final version: SSC by measurement, MT, and ECOLABMT (left y-axis) and computed bed shear stress (right y-axis) for locations from Knock to Terborg [Source: Ladage et al. (2011a) with the measurements by NLWKN Aurich].

Figure 7.11 - Final version: SSC by measurement, MT, and ECOLABMT (left y-axis) and computed bed shear stress (right y-axis) for locations from Leerort to Papenburg. [Source: Ladage et al. (2011a) with the measurements by NLWKN Aurich].

The poorer agreement at locations nearer the upstream and downstream boundaries suggests that the boundary conditions used may have compromised the ECOLABMT results - the poorer agreement between the simulated and measured current speeds, especially at the upstream part could have compromised the ECOLABMT results. Secondly, the bed erodibility was considered to be constant with

bed layer thickness, although in reality, erodibility changes with time. Thirdly, Ecolab_MT considers only one fraction of sediments. Organic material is neglected and not included. Finally, the poorer agreement in SSC between the simulated results and measurements may be due to inaccuracies in measurements. As observed in Fig. 7.11, the measured SSC values exhibit sharp increases during the flood tide and even may go beyond the range of the measuring instrument.

7.3.3 Comparison between ECOLABMT and MT results

For the final version of the Ems model, DHI-WASY applied both ECOLABMT and MT modules for modelling the sediment transport in the Ems (Ladage et al., 2011a). MT results by DHI-WASY are also included in Fig. 7.10 and Fig 7.11. On the whole, ECOLABMT simulations are consistent with MT simulations. Both modules give similar results for SSC, for e.g. at Knock (downstream location), Leerort (midstream location), and Weener (upstream location). Nevertheless, there are still differences between simulations and measurements for SSC at Weener and Papenburg at upstream part. The simulations underestimate the measurements during flood tides. In addition, differences in phase between simulations and measurements are recognized (Ladage et al., 2011a).

Cremer (2011) and Donner (2011), who also applied both ECOLABMT and MT modules to the final version of the Ems model, provide results for SSC at Leerort in detail, as shown in Fig. 7.12, for the reason that among the comparisons for current speed between simulation and measurement, the one at this location was the best (for e.g., see Fig. 7.6). In Fig. 7.12(a), the result from MT module with the option of giving the feedback of bed level change to the HD module during the simulation is also included and shown by the dashed curve. As can be seen from Fig. 7.12(a), comparison between measurement and simulations by ECOLABMT and MT modules for SSC at Leerort is good and ECOLABMT provides slightly better results compared to the MT module. According to Cremer (2011), ECOLABMT is able to reproduce the measured SSC values if the HD model is well calibrated, In addition, Donner et al. (2011) found

that, compared to MT module, ECOLABMT module gives better peaks for longer simulation period, as shown in Fig. 7.12(b) for SSC at Leerort. As can be seen from the figure, ECOLABMT estimates the measured SSC values well, underestimating the peak SSC values only at the latter stage of the simulation. On the other hand, the MT module over-predicts the SSC at the earlier stage of the simulation and underestimates (more than ECOLABMT) the SSC after neap tides from 15 May 2008.

Figure 7.12 - Comparison between measurement and simulations by ECOLABMT and MT modules for SSC at Leerort (a) by Cremer (2011) and (b) by Donner et al. (2011). [Note: The measurements for current speed and SSC were carried out by WSA Emden and NLWKN Aurich, respectively].

7.4 Concluding remarks

The Ecolab_MT template was applied to the Ems estuary. The results for SSC by the new model are encouraging although there are differences between the simulation and measurement. Although differences exist between ECOLABMT and MT modeled results and the measured values, it is noted that the simulation error resulting from ECOLABMT are smaller compared to MT. Nevertheless, the difference between the simulation by ECOLABMT and MT modules and measurement implies that the transport of fine suspended sediment is still a very difficult topic and needs further investigation. It is suggested that providing feedback of density and viscosity of the mixture to the HD module, considering the presence of organic materials and multi-fraction sediments in the system may improve the simulation results.

Chapter 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

In this study, new models for floc density, viscosity of mixture, drag coefficient of particle under effect of turbulence, flocculation of cohesive sediments were developed. In order to incorporate these models into MIKE 3 Flow Model FM modelling system, a new ECO Lab template for fine suspended sediment transport in 3D flow was created. The template was tested for the hypothetical open channel flow case and applied to the Ems estuary. The conclusions are as follows.

Floc density

The assumption that flocs are self-similarity fractal entities is not necessary for modelling floc density but still useful in estimation of the floc size at high sediment concentration, as shown by Eq. (5.12). For the effective floc density, the proposed formula as well as the existing formulae represents just an "average order of magnitude" value (see Fig. 2.2). This may be due to that effects of fluid shear, size distribution of primary particles, and stickiness of the primary particles on the floc density were not included in the proposed model.

Viscosity of mixture

The proposed model for the relative viscosity of mixture, Eq. (3.7), is applicable to mixtures of non-cohesive and/or cohesive sediments. The model coefficients depend on type of mixture. The modified Stokes law with the viscosity estimated by the proposed model can be used for estimating the hindered settling velocity of sediments in a still mixture.

Drag coefficient of a particle under effect of turbulence

The modified Stokes law on the basis of the force balance equation for a particle settling in turbulence mixture is applicable for estimating the hindered settling velocity of sands

or flocs under turbulence condition. By applying the modified Stokes law, effects of sediment concentration, turbulence, and flocculation, etc. on the settling velocity of flocs can be investigated in a detailed way.

Flocculation of cohesive sediments

For modelling the evolution of floc size in the aggregation process, it is acceptable not to consider breakup of flocs although the breakup of large flocs can occur simultaneously with the aggregation process; the (mean) size of whole flocs will increase with time and be larger than the initial (mean) floc size. In addition, although the proposed model does not account for the size distribution of primary particles the model, with the median primary particle size, still gives reasonable results for the evolution of floc size.

Ecolab_MT template

The good comparisons for SSC between the ECOLABMT module and the existing Mud Transport module of MIKE 3 Flow Model FM modelling system and between the ECOLABMT simulations and the measurements for the Ems estuary show that the values in Table 6.4 can be taken as default values for future application.

Suspended sediment transport in the Ems estuary

The difference between the simulation and measurement implies that the transport of fine suspended sediment is still a very difficult topic and needs further investigation. Factors such as hydrodynamic results, erodibility of the bed, initial and boundary conditions affect the fate of sediments in the estuary.

8.2 Recommendations

In order to obtain better results for sediment concentration, the present study gives the following recommendations for future work.

Model coefficients

The proposed models contain several model coefficients. Table 6.4 just gives the order of the coefficients. Depending on specific conditions, the values of the coefficients can

be different from the values in Table 6.4. Therefore, further study is needed to address this issue in detail. In addition, there is only few data available for calibration of k_3 and the data is very scatter (see Fig. 4.3); coefficients in Eq. (4.27) and Eq. (5.13) were not completely verified due to the lack of the experimental data. Therefore, there is a need of the following experiments:

- Experiments on the settling velocity of sediments in clear water and under turbulence,
- Experiments on the settling velocity of sediments in mixture at high concentration and under turbulence,
- Experiments on the effects of salinity on the hindered concentration.

Improvement of the proposed models

The proposed models use the median particle size and does not account for the size distribution of sediments. Considering multi-fraction sediments in floc density, viscosity of mixture, flocculation process, and settling velocity of particles is necessary to obtain more realistic results. In addition, further studies are required to include (i) effects of fluid shear and stickiness of the primary particles on the floc density and (ii) effects of historical compaction of flocs, breakup of large flocs due to fast settling velocity, irreversible nature of floc breakage, and physicochemical properties of primary particles and fluid on flocculation process.

Deposition and Erosion

Beside sedimentation, which was detailed in this study, deposition and erosion processes contribute to the distribution of SSC. The present study used existing models for deposition and erosion. However, the effect of consolidation process on erodibility of bed was not included. For future study, it is necessary to consider the consolidation process and its effect on the erodibility of the bed. Also, further review on deposition, erosion, and consolidation processes is necessary to verify if the existing models for these processes are suitable for model application.

Ecolab_MT template

The advection and dispersion transports of sediments will be obtained more accurately if the template can give the feedback of bed level change, density and viscosity of the mixture to hydrodynamic module. In addition, considering multi-fraction sediments and evolution of floc size and including organic materials will extend the applicability of the template.

Appendix 1 – Empirical relationship between Re_t and G

The influence of a vertically oscillated grid, with size mesh M , frequency f , and stroke S , on turbulence in experimental tanks was investigated by Matsunaga et al. (1999) using the k - ε turbulence closure model. The authors derived analytical solutions for the turbulent kinetic energy (k) and its dissipation rate (ε) at distance z from the grid location.

At the grid location ($z = 0$), for $Re = fS^2 / \nu \leq 5.5 \times 10^3$:

$$\begin{aligned} \frac{k_0}{f^2 S^2} &= 8.1 \times 10^{-3} (S / M)^{1/4} Re^{1/2} \\ \frac{\varepsilon_0}{f^3 S^2} &= 8.2 \times 10^{-5} (S / M) Re \end{aligned} \quad (A1.1)$$

and for $Re = fS^2 / \nu \geq 5.5 \times 10^3$:

$$\begin{aligned} \frac{k_0}{f^2 S^2} &= 6.0 \times 10^{-1} (S / M)^{1/4} \\ \frac{\varepsilon_0}{f^3 S^2} &= 4.5 \times 10^{-1} (S / M) \end{aligned} \quad (A1.2)$$

At a certain level ($z > 0$) away from the grid:

$$\hat{k} = k / k_0 \quad \hat{\varepsilon} = \varepsilon / \varepsilon_0 \quad (A1.3)$$

where

$$\hat{k} = \left(\frac{\hat{z}}{1.82} + 1 \right)^{-5} \quad \hat{\varepsilon} = \left(\frac{\hat{z}}{1.82} + 1 \right)^{-8.5} \quad \hat{z} = z / (k_0^3 \varepsilon_0^{-2})^{1/2} \quad (A1.4)$$

Zhou and Cheng (2008) conducted experiments in a tank with a vertically oscillating grid, similar to the tank used by Matsunaga et al. (1999), and approximated the mean values of k and ε , denoted by k_{mean} and ε_{mean} , in regions between the elevations $\hat{z}_{lower}$ and $\hat{z}_{upper}$ by:

$$k_{mean} = \hat{k}_{mean} k_0 = \frac{\int_{\hat{z}_{lower}}^{\hat{z}_{upper}} \left[\left(\frac{\hat{z}}{1.82} + 1 \right)^{-5} \right] d\hat{z}}{\int_{\hat{z}_{lower}}^{\hat{z}_{upper}} d\hat{z}} k_0 = \frac{\left[-\frac{1.82}{4} \left(\frac{\hat{z}}{1.82} + 1 \right)^{-4} \right]_{\hat{z}_{lower}}^{\hat{z}_{upper}}}{\hat{z}_{upper} - \hat{z}_{lower}} k_0 \quad (A1.5)$$

$$\varepsilon_{mean} = \hat{\varepsilon}_{mean} \varepsilon_0 = \frac{\int_{\hat{z}_{lower}}^{\hat{z}_{upper}} \left[\left(\frac{\hat{z}}{1.82} + 1 \right)^{-8.5} \right] d\hat{z}}{\int_{\hat{z}_{lower}}^{\hat{z}_{upper}} d\hat{z}} \varepsilon_0 = \frac{\left[-\frac{1.82}{7.5} \left(\frac{\hat{z}}{1.82} + 1 \right)^{-7.5} \right]_{\hat{z}_{lower}}^{\hat{z}_{upper}}}{\hat{z}_{upper} - \hat{z}_{lower}} \varepsilon_0 \quad (A1.6)$$

to investigate the effect of turbulence on the settling velocity of a single particle. For $f = 2$ Hz, $M = 5$ cm, and $S = 5.2$ cm, applying Eqs. (A1.1) to (A1.6) results in $k_0 = 6.51 \times 10^{-3} \text{ m}^2/\text{s}^2$, $\varepsilon_0 = 9.98 \times 10^{-3} \text{ m}^2/\text{s}^3$, and for $z = 7.3$ cm to 17.3 cm (see Table A1.2), $k_{mean} = 1.36 \times 10^{-4} \text{ m}^2/\text{s}^2$, $\varepsilon_{mean} = 1.76 \times 10^{-5} \text{ m}^2/\text{s}^3$.

Schulz et al. (2006) investigated experimentally and theoretically near-isotropic turbulence flows in a region between two out-of-phase vertically oscillated grids in a water tank. The z -axis was upward and from $z = 0$, chosen at the midpoint between the two grids. The standard k - ε model was used to obtain theoretical approximations for $\hat{k}$ and $\hat{\varepsilon}$, compared to the measured data [see Fig. 13 in Schulz et al. (2006)]. In addition, the authors argued that $\varepsilon = f(k)$ [see Eq. (10) in Schulz et al. (2006)]. From their experimental results, a correlation between k and ε can be approximated by:

$$\varepsilon = A k^B \quad (A1.7)$$

where A and B are constants. It was found that $B \approx 1.71$ for $S = 5.0$ cm and $f = 2.0$ Hz, and $B \approx 1.77$ for $S = 2.0$ cm and $f = 2.0$ Hz [see Fig. 11 and Fig. 12 in Schulz et al. (2006)].

From Eq. (A1.4), $B = 8.5/5 = 1.70$; it can be seen that results of Schulz et al. (2006) and Matsunaga et al. (1999) are in good agreement. Therefore, Matsunaga et al.'s (1999) results are assumed to be applicable to general turbulent flow fields including turbulence in a vertically oscillating multiple-grids settling column in Maggi (2005).

Using the k - ε model, shear rate and turbulent Reynolds number are defined by $G \equiv \sqrt{\varepsilon/\nu}$ and $Re_t \equiv k^2 / \varepsilon \nu$ (e.g., Versteeg and Malalasekera, 1995). Equation (A1.4) and Eq. (A1.7) suggest that $Re_t = f(G)$. Using Matsunaga et al.'s (1999) measurements for k_0 and ε_0 (see Table A1.1) the relationship between Re_t and G (s^{-1}) can be approximated by:

$$Re_t \approx 460.6 G^{0.5283} \quad (A1.8)$$

Table A1.1 - Experimental parameters, $\nu = 1.15 \times 10^{-6} \text{ m}^2/\text{s}$ (see Table 1 in Matsunaga et al., 1999).

Run No.	$k_o \text{ (cm}^2/\text{s}^2)$	$\varepsilon_o \text{ (cm}^2/\text{s}^3)$	$G \text{ (1/s)}$	Re_t
24	28	20	41.7	3408.7
25	75.2	101	93.7	4868.7
26	153	341	172.2	5969.4
27	250	731	252.1	7434.7
28	357	1470	357.5	7539.1
29	95	132	107.1	5945.3
30	172	315	165.5	8166.7
31	400	1300	336.2	10702.3
32	727	2830	496.1	16239.9

Using t-distribution and values of G_i and $\text{Re}_{t,i}$ in the last two columns of Table A1.1, 90% confidence interval and 90% prediction interval about Eq. (A1.8) at a given value of G are determined by Eq. (A1.9) and Eq. (A1.10), respectively, given by:

$$460.6G^{0.5283} - t_{0.05,n-2} \times \sqrt{\hat{\sigma}^2 \left[\frac{1}{n} + \frac{(G - \bar{G})^2}{S_{gg}} \right]} \leq \text{Re}_t \leq 460.6G^{0.5283} + t_{0.05,n-2} \times \sqrt{\hat{\sigma}^2 \left[\frac{1}{n} + \frac{(G - \bar{G})^2}{S_{gg}} \right]} \quad (\text{A1.9})$$

$$460.6G^{0.5283} - t_{0.05,n-2} \times \sqrt{\hat{\sigma}^2 \left[1 + \frac{1}{n} + \frac{(G - \bar{G})^2}{S_{gg}} \right]} \leq \text{Re}_t \leq 460.6G^{0.5283} + t_{0.05,n-2} \times \sqrt{\hat{\sigma}^2 \left[1 + \frac{1}{n} + \frac{(G - \bar{G})^2}{S_{gg}} \right]} \quad (\text{A1.10})$$

where $n = 9$, $\bar{G} = \frac{1}{n} \sum_{i=1}^n G_i$, $S_{gg} = \sum_{i=1}^n (G_i - \bar{G})^2$, $\hat{\sigma}^2 = \frac{SS_E}{n-2}$, $SS_E = \sum_{i=1}^n (\text{Re}_{t,i} - 460.6G_i^{0.5283})^2$, and $t_{0.05,n-2} = 1.895$. Equation (A1.8) together with its 90% confidence interval as well as 90% prediction interval, and experimental “data” by Zhou and Cheng (2008) (see Table A1.2) are shown in Fig. A1.1. The figure shows that Eq. (A1.8) is also a good approximation for Re_t at low values of G .

Table A1.2 - Turbulent parameters in measured regions in Zhou and Cheng's (2008) experiments for spherical particles, $\nu = 1.0 \times 10^{-6} \text{ m}^2/\text{s}$ (see Table 4.1).

Case	k_0 (cm^2/s^2)	ε_0 (cm^2/s^3)	$\hat{z}_{lower}$	$\hat{z}_{upper}$	k_{mean} (cm^2/s^2)	ε_{mean} (cm^2/s^3)	G_{mean} (1/s)	$Re_t \text{ mean}$
1, 7	65.1	99.8	0.65	2.55	4.15	1.29	11.3	1338.3
2, 8	65.1	99.8	1.73	3.63	0.88	0.08	2.9	955.3
3, 9	65.1	99.8	3.10	5.00	0.21	0.01	0.8	674.4
4, 10	147.5	341.7	0.65	2.56	9.33	4.35	20.9	2000.6
5, 11	147.5	341.7	1.74	3.64	1.98	0.27	5.2	1427.4
6, 12	147.5	341.7	3.11	5.02	0.48	0.02	1.5	1007.3

Figure A1.1 - Experimental “data” by Matsunaga et al. (1999), denoted by (□), and by Zhou and Cheng (2008), denoted by (●), and the empirical approximations (i) Eq. (A1.8), (ii) 90% confidence interval about Eq. (A1.8), and (iii) 90% prediction interval about Eq. (A1.8).

Appendix 2 – Evolution of floc size by Winterwerp's (1999) and Tambo and Watanabe's (1979) models

A2.1 Evolution of floc size by Winterwerp's (1999) model

Winterwerp (1998, 1999) utilized Smoluchowski's theory on flocculation kinetics, modeled the flocculation process by a linear combination of formulations for aggregation and breakup, and proposed a model for evolution of floc size in an implicit form as following:

$$t = T' \left[\ln \left(\frac{D_{fE} - D_{f0}}{D_{fE} - D_f} \frac{D_f}{D_{f0}} \right) + \frac{D_{fE}}{D_{f0}} - \frac{D_{fE}}{D_f} \right] \quad (\text{A2.1})$$

where

$$T' = \frac{1}{k_B G^{3/2} D_{fE}^2} \quad (\text{A2.2})$$

$$D_{fE} = D_p + \frac{k_A c}{k_B \sqrt{G}} \quad (\text{A2.3})$$

where k_A and k_B are empirical coefficients, which were calibrated against T-series settling column experiments with Ems-Dollard mud to be $k_A \approx 14.6 \text{ m}^2/\text{kg}$ and $k_B \approx 14.0 \times 10^3 \text{ s}^{1/2}/\text{m}^2$. For given values of c and G , the evolution of floc size is determined by obtaining D_{fE} from Eq. (A2.3) and T' from Eq. (A2.2), assuming values of D_f to calculate values of t from Eq. (A2.1), and then obtaining pairs of data (t, D_f) (Winterwerp, 1998).

In term of the evolution of floc size, among the T-series experiments, T69-experiment is the best one that clearly shows the evolution of floc size when flocs reach the equilibrium steady state (see Fig. 4 in Winterwerp, 1998). For this experiment, measured values are $G = 28.9 \text{ s}^{-1}$, $c = 1.17 \text{ kg}/\text{m}^3$, and $D_{fE} \approx 241 \text{ }\mu\text{m}$. Following Winterwerp (1998), assume that $D_{f0} = D_p = 4.0 \text{ }\mu\text{m}$, $k_A \approx 14.6 \text{ m}^2/\text{kg}$, $k_B \approx 14.0 \times 10^3 \text{ s}^{1/2}/\text{m}^2$, Eq. (A2.1) gives $D_f \approx 241 \text{ }\mu\text{m}$ at $T^* \approx 580$ seconds.

A2.2 Evolution of floc size by Tambo and Watanabe's (1979) model

Tambo and Watanabe (1979) model aggregation and breakup separately. The evolution of floc size in the aggregation process is limited by the breakup process, i.e. median floc size increases until it reaches a maximum median floc size at a given shear rate. The authors utilized Smoluchowski's theory on flocculation kinetics to develop an equation of floc growth in turbulent flow condition. Their numerical solution to the equation (see Fig. 11 in their paper) is shown in Fig. A2.1 with:

$$\alpha_0 m \equiv \alpha_0 (1.22 G D_{f0}^3 N_o t) \quad (\text{A2.4})$$

$$S_m \equiv \left(\frac{D_{f \max}}{D_{f0}} \right)^3 \quad (\text{A2.5})$$

$$R_{50}^* \equiv \frac{R_{50}}{R_{50,ultimate}} \quad (\text{A2.6})$$

where α_0 is initial collision-agglomeration factor, N_o number of initial particles of size D_{f0} , $D_{f \max}$ the largest floc size at the equilibrium steady state under the given shear rate G , R_{50} number of the initial particles corresponding to 50% cumulative floc volume of floc size distribution at time t , $R_{50,ultimate}$ number of the initial particles corresponding to 50% cumulative floc volume of ultimate equilibrium floc size distribution, given by:

$$R_{50,ultimate} \approx 0.42S \quad (\text{A2.7})$$

where S is number of the initial particles in the largest floc of size $D_{f \max}$ (Tambo and Watanabe, 1979).

Figure A2.1 - Tambo and Watanabe's (1979) numerical solution for evolution of floc size.

The relationship between $\alpha_0 m$ and S_m in Fig. A2.1 can be approximated by:

$$\alpha_0 m \approx 10.62(S_m)^{-0.2386} \quad \text{for } R_{50}^* = 1.0 \text{ (equilibrium state)} \quad (\text{A2.8a})$$

$$\alpha_0 m \approx A(S_m)^{-B} \quad \text{for } R_{50}^* = 0.4 \text{ to } 1.0 \text{ (transient state)} \quad (\text{A2.8b})$$

where

$$A \approx 0.1284 \exp(4.3935 R_{50}^*) \quad (\text{A2.9a})$$

$$B \approx -0.5964(R_{50}^*)^2 + 1.0199 R_{50}^* - 0.1817 \quad (\text{A2.9b})$$

Following Winterwerp (1999), assume that the flocs are self-similar fractal objects and nf is the fractal dimension of flocs, the following expressions:

$$R_{50} = \left(\frac{D_f}{D_{f0}} \right)^{nf} \quad (\text{A2.10a})$$

$$R_{50,ultimate} = \left(\frac{D_{fE}}{D_{f0}} \right)^{nf} \quad (\text{A2.10b})$$

$$\rho_{f0} = \rho_w + (\rho_s - \rho_w) \left(\frac{D_p}{D_{f0}} \right)^{3-nf} \quad (\text{A2.11})$$

$$N_0 = \left(\frac{\rho_s - \rho_w}{\rho_{f0} - \rho_w} \right) \frac{c}{\rho_s} \frac{6}{\pi} \frac{1}{D_{f0}^3} \quad (\text{A2.12})$$

$$S = (S_m)^{1/nf} \quad (\text{A2.13})$$

where D_{fE} is the median floc size at equilibrium state, c mass concentration of sediments, and ρ_{f0} density of the initial floc particles, are adopted in the estimation of the floc size evolution. Procedure for estimating floc size at time t is shown in Fig. A2.2. In addition, combining Eq. (A2.4) with Eq. (A2.8a) the “equilibrium flocculation time” T_* can be estimated by:

$$T_* = \frac{10.62(S_m)^{-0.2386}}{\alpha_0 (1.22GD_{f0}^3 N_o)} \quad (\text{A2.14})$$

Figure A2.2 - Flow chart for estimating ($D_f \sim t$) using Tambo and Watanabe (1979) model.

In order to use Tambo and Watanabe model, the initial collision-agglomeration factor (α_0) must be known. In the present study, this factor was estimated by using Winterwerp's (1999) T69-experiment data with $G = 28.9 \text{ s}^{-1}$, $c = 1.17 \text{ kg/m}^3$, $D_{f0} = D_p = 4.0 \text{ }\mu\text{m}$, $D_{fE} = 241 \text{ }\mu\text{m}$ at $T^* \approx 580$ seconds (see Section A2.1), and $nf = 2.0$. Applying Eq. (A2.10b) for $R_{50,ultimate}$, Eq. (A2.7) for S , Eq. (A2.13) for S_m , Eq. (A2.12) for N_0 , and Eq. (A2.14) for α_0 , results in $\alpha_0 \approx 0.008$, which is consistent with the value of $O(0.01)$ used by Winterwerp (1999).

Next, the experimental data in Biggs and Lant (2000) shown in Fig. A2.3 was used for testing the results based on Tambo and Watanabe (1979) model for evolution of floc sizes. Biggs and Lant (2000) stirred activated sludge in a batch mixing vessel and obtained ($D_f \sim t$) by using a Malvern Mastersizer. For estimation of the shear rate G , the authors used the overall energy dissipation rate of the impeller (ε_*) [see Eq. (2) in their paper]. However, Tambo and Watanabe (1979) argued that the dissipation rate of fluid turbulent kinetic energy (ε) is much less than ε_* [see Eq. (21) in Tambo and Watanabe (1979)] and that $\varepsilon = (0.1 \text{ to } 0.2)\varepsilon_*$. Therefore, in the present study, it is assumed that $\varepsilon \approx 0.15 \varepsilon_*$ or $G \approx 0.3873 G_*$ (see Table A2.1) where G_* is the share rate estimated by Biggs and Lant (2000). In addition, the following values were assumed: $D_p = 4.0 \mu\text{m}$, $c = 1.19 \text{ kg/m}^3$, $\rho_s = 2,650 \text{ kg/m}^3$, $n_f = 2.0$, $\alpha_0 \approx 0.008$, and values of D_{f0} and S_m at different values of the shear rates are assumed given in Table A2.1. For different values of the shear rate, following the procedure in Fig. A2.2, $D_{f\text{max}}$ and D_{fE} are calculated and shown in Table A2.1, the evolutions of floc size estimated by using Tambo and Watanabe (1979) model is shown in Fig. A2.3. As can be seen from the figure, the estimated results are in good agreement with the experimental results.

Table A2.1 - Equilibrium flocs estimated by using Tambo and Watanabe's (1979) model with Biggs and Lant's (2000) data.

No	G_* (1/s)	G (1/s)	D_{f0} (μm)	S_m	$D_{f\text{max}}$ (μm)	D_{fE} (μm)
1	19.4	7.5	13	39,803	443.9	119
2	37	14.3	15	9,711	320.0	96.5
3	113	43.8	15	988	149.4	54.5
4	346	134	15	34	48.7	23.5

Note: Biggs and Lant (2000) used overall energy dissipation rate of impeller to estimate G_* .

The present study applied $G = 0.3873 G_*$ in the estimation of evolution of floc size.

Figure A2.3 - Evolution of flocs using Tambo and Watanabe's (1979) model (four sets of points with "o, $\square$, Δ , $\diamond$ " symbols) compared with Biggs and Lant's (2000) experimental data [Note: the original graph is from Biggs and Lant (2000), who used the overall energy dissipation rate of impeller to estimate G].

Appendix 3 – Ecolab_MT template

```
// Created : 2011-04-4 13:17:13
// DLL id : C:\Program Files
(x86)\DHI\2009\bin\pfs2004.dll
// PFS version : Mar 15 2009 20:08:49

[ECO_LAB_SETUP]
  DESCRIPTION = 'No description'
  ONLINE_HELP = ""
  DOCUMENTATION = ""
[STATE_VARIABLES]
  DESCRIPTION = 'No description'
  ONLINE_HELP = ""
  DOCUMENTATION = ""
[STATE_VARIABLE_1]
  SYMBOL = 'SSC'
  ID = 1
  DESCRIPTION = 'Suspended Sediment
Concentration'
  ONLINE_HELP = 'For sand: Max = 1500 kg/m3;
For mud: MaxGEL = 150 kg/m3'
  DOCUMENTATION = ""
  SCOPE = 'WC'
  TRANSPORT = 'ADVECTION_DISPERSION'
  EUM_TYPE = 999
  UNIT = 'kg/m^3'
  DEFAULT_VALUE = 0.02
  MIN_VALUE = 0.02
  MAX_VALUE = 1500
EndSect // STATE_VARIABLE_1

[STATE_VARIABLE_2]
  SYMBOL = 'LayerThickness'
  ID = 2
  DESCRIPTION = 'Layer thickness'
  ONLINE_HELP = ""
  DOCUMENTATION = ""
  SCOPE = 'WB'
  TRANSPORT = 'FIXED'
  EUM_TYPE = 999
  UNIT = 'm'
  DEFAULT_VALUE = 0.5
  MIN_VALUE = 0
  MAX_VALUE = 100
EndSect // STATE_VARIABLE_2

EndSect // STATE_VARIABLES

[CONSTANTS]
  DESCRIPTION = 'No description'
  ONLINE_HELP = ""
  DOCUMENTATION = ""
[CONSTANT_1]
  SYMBOL = 'Type'
  ID = 3
  DESCRIPTION = 'Type of sediment (cohesive = 3;
mixed = 2, non-cohesive = 1)'
  ONLINE_HELP = ""
  DOCUMENTATION = ""
  IS_USER_SPECIFIED = 'YES'
  BUILT_IN_ID = -1
  SCOPE = 'NOT_SPECIFIED'
  SPATIAL_VARIATION = 'NONE'
  EUM_TYPE = 999
  UNIT = 'm'
  DEFAULT_VALUE = 1.5e-005
  MIN_VALUE = 0
  MAX_VALUE = 0.01
EndSect // CONSTANT_1

SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION = 'NONE'
EUM_TYPE = 999
UNIT = ""
DEFAULT_VALUE = 3
MIN_VALUE = 1
MAX_VALUE = 3
EndSect // CONSTANT_1

[CONSTANT_2]
  SYMBOL = 'nuv_w'
  ID = 4
  DESCRIPTION = 'Kinematic viscosity of pure
water'
  ONLINE_HELP = ""
  DOCUMENTATION = ""
  IS_USER_SPECIFIED = 'YES'
  BUILT_IN_ID = -1
  SCOPE = 'NOT_SPECIFIED'
  SPATIAL_VARIATION = 'NONE'
  EUM_TYPE = 999
  UNIT = 'm^2/s'
  DEFAULT_VALUE = 1e-006
  MIN_VALUE = 5e-007
  MAX_VALUE = 1.5e-006
EndSect // CONSTANT_2

[CONSTANT_3]
  SYMBOL = 'ps'
  ID = 5
  DESCRIPTION = 'Density of primary particle'
  ONLINE_HELP = ""
  DOCUMENTATION = ""
  IS_USER_SPECIFIED = 'YES'
  BUILT_IN_ID = -1
  SCOPE = 'NOT_SPECIFIED'
  SPATIAL_VARIATION = 'NONE'
  EUM_TYPE = 999
  UNIT = 'kg/m^3'
  DEFAULT_VALUE = 2650
  MIN_VALUE = 1500
  MAX_VALUE = 3000
EndSect // CONSTANT_3

[CONSTANT_4]
  SYMBOL = 'Dp'
  ID = 6
  DESCRIPTION = 'Primary particle size (Dp50)'
  ONLINE_HELP = 'For sand: D = Dp'
  DOCUMENTATION = ""
  IS_USER_SPECIFIED = 'YES'
  BUILT_IN_ID = -1
  SCOPE = 'NOT_SPECIFIED'
  SPATIAL_VARIATION = 'NONE'
  EUM_TYPE = 999
  UNIT = 'm'
  DEFAULT_VALUE = 1.5e-005
  MIN_VALUE = 0
  MAX_VALUE = 0.01
EndSect // CONSTANT_4
```

```

[CONSTANT_5]
  SYMBOL = 'DfH'
  ID = 7
  DESCRIPTION = 'Particle size at equilibrium
aggregation process (DfH)'
  ONLINE_HELP = 'Size of (sand or floc) particle at
high concentration'
  DOCUMENTATION = "
  IS_USER_SPECIFIED = 'YES'
  BUILT_IN_ID = -1
  SCOPE = 'NOT_SPECIFIED'
  SPATIAL_VARIATION = 'NONE'
  EUM_TYPE = 999
  UNIT = 'm'
  DEFAULT_VALUE = 0.0002
  MIN_VALUE = 0
  MAX_VALUE = 0.01
EndSect // CONSTANT_5

```

```

[CONSTANT_6]
  SYMBOL = 'PhiH'
  ID = 8
  DESCRIPTION = 'Vol concentration at equilibrium
aggregation process (PhiH)'
  ONLINE_HELP = 'Applicable to cohesive and
mixed sediment only'
  DOCUMENTATION = "
  IS_USER_SPECIFIED = 'YES'
  BUILT_IN_ID = -1
  SCOPE = 'NOT_SPECIFIED'
  SPATIAL_VARIATION = 'NONE'
  EUM_TYPE = 999
  UNIT = "
  DEFAULT_VALUE = 0.05
  MIN_VALUE = 0
  MAX_VALUE = 0.1
EndSect // CONSTANT_6

```

```

[CONSTANT_7]
  SYMBOL = 'SF'
  ID = 9
  DESCRIPTION = 'Shape Factor'
  ONLINE_HELP = 'Applicable to sand and mixed
sediments only'
  DOCUMENTATION = "
  IS_USER_SPECIFIED = 'YES'
  BUILT_IN_ID = -1
  SCOPE = 'NOT_SPECIFIED'
  SPATIAL_VARIATION = 'NONE'
  EUM_TYPE = 999
  UNIT = "
  DEFAULT_VALUE = 0.7
  MIN_VALUE = 0
  MAX_VALUE = 1
EndSect // CONSTANT_7

```

```

[CONSTANT_8]
  SYMBOL = 'af'
  ID = 10
  DESCRIPTION = 'af'
  ONLINE_HELP = 'Applicable to cohesive and
mxied sediment only'
  DOCUMENTATION = "
  IS_USER_SPECIFIED = 'YES'

```

```

  BUILT_IN_ID = -1
  SCOPE = 'NOT_SPECIFIED'
  SPATIAL_VARIATION = 'NONE'
  EUM_TYPE = 999
  UNIT = "
  DEFAULT_VALUE = 0.7
  MIN_VALUE = 0.5
  MAX_VALUE = 1
EndSect // CONSTANT_8

```

```

[CONSTANT_9]
  SYMBOL = 'bf'
  ID = 11
  DESCRIPTION = 'bf'
  ONLINE_HELP = 'Applicable to cohesive and
mixed sediment only'
  DOCUMENTATION = "
  IS_USER_SPECIFIED = 'YES'
  BUILT_IN_ID = -1
  SCOPE = 'NOT_SPECIFIED'
  SPATIAL_VARIATION = 'NONE'
  EUM_TYPE = 999
  UNIT = "
  DEFAULT_VALUE = 0.8
  MIN_VALUE = 0
  MAX_VALUE = 2
EndSect // CONSTANT_9

```

```

[CONSTANT_10]
  SYMBOL = 'Av'
  ID = 12
  DESCRIPTION = 'av'
  ONLINE_HELP = 'For sand: av = 1.5 to 3.5; For
cohesive sediment: av = 0 to 0.127'
  DOCUMENTATION = "
  IS_USER_SPECIFIED = 'YES'
  BUILT_IN_ID = -1
  SCOPE = 'NOT_SPECIFIED'
  SPATIAL_VARIATION = 'NONE'
  EUM_TYPE = 999
  UNIT = "
  DEFAULT_VALUE = 0.127
  MIN_VALUE = 0
  MAX_VALUE = 3.5
EndSect // CONSTANT_10

```

```

[CONSTANT_11]
  SYMBOL = 'bv'
  ID = 13
  DESCRIPTION = 'bv'
  ONLINE_HELP = 'For sand: bv ~ 1.0; For
cohesive sediment: bv ~ 0.6'
  DOCUMENTATION = "
  IS_USER_SPECIFIED = 'YES'
  BUILT_IN_ID = -1
  SCOPE = 'NOT_SPECIFIED'
  SPATIAL_VARIATION = 'NONE'
  EUM_TYPE = 999
  UNIT = "
  DEFAULT_VALUE = 0.6
  MIN_VALUE = 0
  MAX_VALUE = 1.5
EndSect // CONSTANT_11

```

```

[CONSTANT_12]

```

```

SYMBOL = 'AA'
ID = 14
DESCRIPTION = 'AA'
ONLINE_HELP = 'Applicable to cohesive sediment
only'
DOCUMENTATION = "
IS_USER_SPECIFIED = 'YES'
BUILT_IN_ID = -1
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION = 'NONE'
EUM_TYPE = 999
UNIT = "
DEFAULT_VALUE = 0.01
MIN_VALUE = 0.0001
MAX_VALUE = 0.1
EndSect // CONSTANT_12

[CONSTANT_13]
SYMBOL = 'BB'
ID = 15
DESCRIPTION = 'BB'
ONLINE_HELP = 'Applicable to cohesive sediment
only'
DOCUMENTATION = "
IS_USER_SPECIFIED = 'YES'
BUILT_IN_ID = -1
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION = 'NONE'
EUM_TYPE = 999
UNIT = "
DEFAULT_VALUE = 6.0886
MIN_VALUE = 0
MAX_VALUE = 10
EndSect // CONSTANT_13

[CONSTANT_14]
SYMBOL = 'CC'
ID = 16
DESCRIPTION = 'CC'
ONLINE_HELP = 'Applicable to cohesive sediment
only'
DOCUMENTATION = "
IS_USER_SPECIFIED = 'YES'
BUILT_IN_ID = -1
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION = 'NONE'
EUM_TYPE = 999
UNIT = "
DEFAULT_VALUE = 0.2149
MIN_VALUE = 0.15
MAX_VALUE = 0.25
EndSect // CONSTANT_14

[CONSTANT_15]
SYMBOL = 'at'
ID = 17
DESCRIPTION = 'at'
ONLINE_HELP = 'Turbulence'
DOCUMENTATION = "
IS_USER_SPECIFIED = 'YES'
BUILT_IN_ID = -1
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION = 'NONE'
EUM_TYPE = 999
UNIT = "

DEFAULT_VALUE = 0.0385
MIN_VALUE = 0
MAX_VALUE = 0.1
EndSect // CONSTANT_15

[CONSTANT_16]
SYMBOL = 'bt'
ID = 18
DESCRIPTION = 'bt'
ONLINE_HELP = 'Turbulence'
DOCUMENTATION = "
IS_USER_SPECIFIED = 'YES'
BUILT_IN_ID = -1
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION = 'NONE'
EUM_TYPE = 999
UNIT = "
DEFAULT_VALUE = 0.6943
MIN_VALUE = 0
MAX_VALUE = 1
EndSect // CONSTANT_16

[CONSTANT_17]
SYMBOL = 'aB'
ID = 19
DESCRIPTION = 'aB'
ONLINE_HELP = 'Break-up'
DOCUMENTATION = "
IS_USER_SPECIFIED = 'YES'
BUILT_IN_ID = -1
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION = 'NONE'
EUM_TYPE = 999
UNIT = "
DEFAULT_VALUE = 198000
MIN_VALUE = 180000
MAX_VALUE = 210000
EndSect // CONSTANT_17

[CONSTANT_18]
SYMBOL = 'bB'
ID = 20
DESCRIPTION = 'bB'
ONLINE_HELP = 'Break-up'
DOCUMENTATION = "
IS_USER_SPECIFIED = 'YES'
BUILT_IN_ID = -1
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION = 'NONE'
EUM_TYPE = 999
UNIT = "
DEFAULT_VALUE = 1.2
MIN_VALUE = 0.5
MAX_VALUE = 2
EndSect // CONSTANT_18

[CONSTANT_19]
SYMBOL = 'PhiMax'
ID = 21
DESCRIPTION = 'Maximum value of Phi'
ONLINE_HELP = 'For sand: PhiMax ~ 0.6; For
cohesive: PhiGel ~ 0.8'
DOCUMENTATION = "
IS_USER_SPECIFIED = 'YES'
BUILT_IN_ID = -1

```

```

SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION = 'NONE'
EUM_TYPE = 999
UNIT = "
DEFAULT_VALUE = 0.8
MIN_VALUE = 0
MAX_VALUE = 1
EndSect // CONSTANT_19

[CONSTANT_20]
SYMBOL = 'p'
ID = 22
DESCRIPTION = 'Exponent of hinderring effect'
ONLINE_HELP = 'Similar to Richardson and
Zaki"s model'
DOCUMENTATION = "
IS_USER_SPECIFIED = 'YES'
BUILT_IN_ID = -1
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION = 'NONE'
EUM_TYPE = 999
UNIT = "
DEFAULT_VALUE = 1
MIN_VALUE = 0
MAX_VALUE = 8
EndSect // CONSTANT_20

[CONSTANT_21]
SYMBOL = 'Tero'
ID = 23
DESCRIPTION = 'Critical bed shear stress for
erosion'
ONLINE_HELP = "
DOCUMENTATION = "
IS_USER_SPECIFIED = 'YES'
BUILT_IN_ID = -1
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION = 'NONE'
EUM_TYPE = 999
UNIT = 'N/m^2'
DEFAULT_VALUE = 0.2
MIN_VALUE = 0
MAX_VALUE = 10
EndSect // CONSTANT_21

[CONSTANT_22]
SYMBOL = 'Tdep'
ID = 24
DESCRIPTION = 'Critical bed shear stress for
deposition'
ONLINE_HELP = "
DOCUMENTATION = "
IS_USER_SPECIFIED = 'YES'
BUILT_IN_ID = -1
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION = 'NONE'
EUM_TYPE = 999
UNIT = 'N/m^2'
DEFAULT_VALUE = 0.5
MIN_VALUE = 0
MAX_VALUE = 1
EndSect // CONSTANT_22

[CONSTANT_23]
SYMBOL = 'Ee'
ID = 25
DESCRIPTION = 'Erodibility of bed'
ONLINE_HELP = "
DOCUMENTATION = "
IS_USER_SPECIFIED = 'YES'
BUILT_IN_ID = -1
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION = 'HORIZONTAL'
EUM_TYPE = 999
UNIT = 'kg/m^2/s'
DEFAULT_VALUE = 0.0005
MIN_VALUE = 0
MAX_VALUE = 0.001
EndSect // CONSTANT_23

[CONSTANT_24]
SYMBOL = 'n'
ID = 26
DESCRIPTION = 'Power of erosion'
ONLINE_HELP = "
DOCUMENTATION = "
IS_USER_SPECIFIED = 'YES'
BUILT_IN_ID = -1
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION = 'NONE'
EUM_TYPE = 999
UNIT = "
DEFAULT_VALUE = 1
MIN_VALUE = 0
MAX_VALUE = 10
EndSect // CONSTANT_24

[CONSTANT_25]
SYMBOL = 'C1'
ID = 27
DESCRIPTION = 'Scale for bed shear stress'
ONLINE_HELP = "
DOCUMENTATION = "
IS_USER_SPECIFIED = 'YES'
BUILT_IN_ID = -1
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION = 'NONE'
EUM_TYPE = 999
UNIT = "
DEFAULT_VALUE = 1
MIN_VALUE = 0
MAX_VALUE = 5
EndSect // CONSTANT_25

[CONSTANT_26]
SYMBOL = 'C2'
ID = 28
DESCRIPTION = 'Scale for sedimentation'
ONLINE_HELP = "
DOCUMENTATION = "
IS_USER_SPECIFIED = 'YES'
BUILT_IN_ID = -1
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION = 'NONE'
EUM_TYPE = 999
UNIT = "
DEFAULT_VALUE = 1
MIN_VALUE = 0
MAX_VALUE = 1.5
EndSect // CONSTANT_26

```



```

[CONSTANT_27]
  SYMBOL = 'C3'
  ID = 29
  DESCRIPTION = 'Scale for deposition'
  ONLINE_HELP = ""
  DOCUMENTATION = ""
  IS_USER_SPECIFIED = 'YES'
  BUILT_IN_ID = -1
  SCOPE = 'NOT_SPECIFIED'
  SPATIAL_VARIATION = 'NONE'
  EUM_TYPE = 999
  UNIT = ""
  DEFAULT_VALUE = 1
  MIN_VALUE = 0
  MAX_VALUE = 100
EndSect // CONSTANT_27

[CONSTANT_28]
  SYMBOL = 'C4'
  ID = 30
  DESCRIPTION = 'Scale for erosion'
  ONLINE_HELP = ""
  DOCUMENTATION = ""
  IS_USER_SPECIFIED = 'YES'
  BUILT_IN_ID = -1
  SCOPE = 'NOT_SPECIFIED'
  SPATIAL_VARIATION = 'NONE'
  EUM_TYPE = 999
  UNIT = ""
  DEFAULT_VALUE = 1
  MIN_VALUE = 0
  MAX_VALUE = 200
EndSect // CONSTANT_28

[CONSTANT_29]
  SYMBOL = 'sigma1'
  ID = 31
  DESCRIPTION = 'sigma value of near bed layer'
  ONLINE_HELP = ""
  DOCUMENTATION = ""
  IS_USER_SPECIFIED = 'YES'
  BUILT_IN_ID = -1
  SCOPE = 'NOT_SPECIFIED'
  SPATIAL_VARIATION = 'NONE'
  EUM_TYPE = 999
  UNIT = ""
  DEFAULT_VALUE = 0.2
  MIN_VALUE = 0
  MAX_VALUE = 1
EndSect // CONSTANT_29

[CONSTANT_30]
  SYMBOL = 'ks'
  ID = 32
  DESCRIPTION = 'bed roughness'
  ONLINE_HELP = ""
  DOCUMENTATION = ""
  IS_USER_SPECIFIED = 'YES'
  BUILT_IN_ID = -1
  SCOPE = 'NOT_SPECIFIED'
  SPATIAL_VARIATION = 'HORIZONTAL'
  EUM_TYPE = 999
  UNIT = 'm'
  DEFAULT_VALUE = 0.001

```

```

  MIN_VALUE = 0
  MAX_VALUE = 1
EndSect // CONSTANT_30

```

```

[CONSTANT_31]
  SYMBOL = 'z0coef'
  ID = 33
  DESCRIPTION = 'z0 coefficient'
  ONLINE_HELP = ""
  DOCUMENTATION = ""
  IS_USER_SPECIFIED = 'YES'
  BUILT_IN_ID = -1
  SCOPE = 'NOT_SPECIFIED'
  SPATIAL_VARIATION = 'NONE'
  EUM_TYPE = 999
  UNIT = ""
  DEFAULT_VALUE = 30
  MIN_VALUE = 0
  MAX_VALUE = 100
EndSect // CONSTANT_31

```

```

[CONSTANT_32]
  SYMBOL = 'Salt_type'
  ID = 34
  DESCRIPTION = 'Salinity variation (no = 0; yes =
1)
  ONLINE_HELP = ""
  DOCUMENTATION = ""
  IS_USER_SPECIFIED = 'YES'
  BUILT_IN_ID = -1
  SCOPE = 'NOT_SPECIFIED'
  SPATIAL_VARIATION = 'NONE'
  EUM_TYPE = 999
  UNIT = ""
  DEFAULT_VALUE = 0
  MIN_VALUE = 0
  MAX_VALUE = 1
EndSect // CONSTANT_32

```

```

[CONSTANT_33]
  SYMBOL = 'aS'
  ID = 35
  DESCRIPTION = 'aS'
  ONLINE_HELP = 'applicable to salinity changes'
  DOCUMENTATION = ""
  IS_USER_SPECIFIED = 'YES'
  BUILT_IN_ID = -1
  SCOPE = 'NOT_SPECIFIED'
  SPATIAL_VARIATION = 'NONE'
  EUM_TYPE = 999
  UNIT = ""
  DEFAULT_VALUE = 6.15
  MIN_VALUE = 0
  MAX_VALUE = 100
EndSect // CONSTANT_33

```

```

[CONSTANT_34]
  SYMBOL = 'bS'
  ID = 36
  DESCRIPTION = 'bS'
  ONLINE_HELP = 'applicable to salinity changes'
  DOCUMENTATION = ""
  IS_USER_SPECIFIED = 'YES'
  BUILT_IN_ID = -1
  SCOPE = 'NOT_SPECIFIED'

```

```

    SPATIAL_VARIATION = 'NONE'
    EUM_TYPE = 999
    UNIT = "
    DEFAULT_VALUE = 0.05
    MIN_VALUE = 0
    MAX_VALUE = 1
EndSect // CONSTANT_34

[CONSTANT_35]
    SYMBOL = 'Tcmax'
    ID = 37
    DESCRIPTION = 'Limitation for BedShearStress
(Erosion)'
    ONLINE_HELP = "
    DOCUMENTATION = "
    IS_USER_SPECIFIED = 'YES'
    BUILT_IN_ID = -1
    SCOPE = 'NOT_SPECIFIED'
    SPATIAL_VARIATION = 'NONE'
    EUM_TYPE = 999
    UNIT = 'N/m^2'
    DEFAULT_VALUE = 2.5
    MIN_VALUE = 0
    MAX_VALUE = 1000
EndSect // CONSTANT_35

[CONSTANT_36]
    SYMBOL = 'pbed'
    ID = 38
    DESCRIPTION = 'Density of bed layer'
    ONLINE_HELP = "
    DOCUMENTATION = "
    IS_USER_SPECIFIED = 'YES'
    BUILT_IN_ID = -1
    SCOPE = 'NOT_SPECIFIED'
    SPATIAL_VARIATION = 'NONE'
    EUM_TYPE = 999
    UNIT = 'kg/m^3'
    DEFAULT_VALUE = 180
    MIN_VALUE = 50
    MAX_VALUE = 1800000000
EndSect // CONSTANT_36

[CONSTANT_37]
    SYMBOL = 'Time_Step'
    ID = 39
    DESCRIPTION = 'Time Step'
    ONLINE_HELP = "
    DOCUMENTATION = "
    IS_USER_SPECIFIED = 'NO'
    BUILT_IN_ID = 19
    SCOPE = 'NOT_SPECIFIED'
    SPATIAL_VARIATION = 'NONE'
    EUM_TYPE = 999
    UNIT = 'Seconds'
    DEFAULT_VALUE = 30
    MIN_VALUE = 1
    MAX_VALUE = 86400
EndSect // CONSTANT_37

EndSect // CONSTANTS

[FORCINGS]
    DESCRIPTION = 'No description'
    ONLINE_HELP = "

DOCUMENTATION = "
[FORCING_1]
    SYMBOL = 'Depth'
    ID = 40
    DESCRIPTION = 'Water depth'
    ONLINE_HELP = "
    DOCUMENTATION = "
    IS_USER_SPECIFIED = 'NO'
    BUILT_IN_ID = 10
    SCOPE = 'WC'
    SPATIAL_VARIATION = 'HORIZONTAL'
    EUM_TYPE = 999
    UNIT = 'm'
    DEFAULT_VALUE = 8
    MIN_VALUE = 0
    MAX_VALUE = 12000
EndSect // FORCING_1

[FORCING_2]
    SYMBOL = 'dZ'
    ID = 41
    DESCRIPTION = 'Water layer height'
    ONLINE_HELP = "
    DOCUMENTATION = "
    IS_USER_SPECIFIED = 'NO'
    BUILT_IN_ID = 4
    SCOPE = 'WC'
    SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
    EUM_TYPE = 999
    UNIT = 'm'
    DEFAULT_VALUE = 2
    MIN_VALUE = 0.0001
    MAX_VALUE = 8000
EndSect // FORCING_2

[FORCING_3]
    SYMBOL = 'TKE'
    ID = 42
    DESCRIPTION = 'Turbulent kinetic energy'
    ONLINE_HELP = "
    DOCUMENTATION = "
    IS_USER_SPECIFIED = 'YES'
    BUILT_IN_ID = -1
    SCOPE = 'NOT_SPECIFIED'
    SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
    EUM_TYPE = 999
    UNIT = 'm^2/s^2'
    DEFAULT_VALUE = 1e-007
    MIN_VALUE = 1e-007
    MAX_VALUE = 1000
EndSect // FORCING_3

[FORCING_4]
    SYMBOL = 'TKEd'
    ID = 43
    DESCRIPTION = 'TKE dissipation rate'
    ONLINE_HELP = "
    DOCUMENTATION = "
    IS_USER_SPECIFIED = 'YES'
    BUILT_IN_ID = -1
    SCOPE = 'NOT_SPECIFIED'
    SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'

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```

EUM_TYPE = 999
UNIT = 'm^2/s^3'
DEFAULT_VALUE = 1e-010
MIN_VALUE = 1e-010
MAX_VALUE = 1000
EndSect // FORCING_4

[FORCING_5]
SYMBOL = 'Current'
ID = 44
DESCRIPTION = 'Horizontal current speed'
ONLINE_HELP = ""
DOCUMENTATION = ""
IS_USER_SPECIFIED = 'NO'
BUILT_IN_ID = 11
SCOPE = 'WC'
SPATIAL_VARIATION =
'HORISONTAL_AND_VERTICAL'
EUM_TYPE = 999
UNIT = 'm/s'
DEFAULT_VALUE = 0.2
MIN_VALUE = 0
MAX_VALUE = 10
EndSect // FORCING_5

[FORCING_6]
SYMBOL = 'Salt'
ID = 45
DESCRIPTION = 'Salinity'
ONLINE_HELP = ""
DOCUMENTATION = ""
IS_USER_SPECIFIED = 'NO'
BUILT_IN_ID = 5
SCOPE = 'WC'
SPATIAL_VARIATION =
'HORISONTAL_AND_VERTICAL'
EUM_TYPE = 999
UNIT = 'psu'
DEFAULT_VALUE = 0
MIN_VALUE = 0
MAX_VALUE = 350
EndSect // FORCING_6

EndSect // FORCINGS

[AUXILIARY_VARIABLES]
DESCRIPTION = 'No description'
ONLINE_HELP = ""
DOCUMENTATION = ""
[AUXILIARY_VARIABLE_1]
SYMBOL = 'pw'
ID = 46
DESCRIPTION = 'Density of water'
ONLINE_HELP = ""
DOCUMENTATION = ""
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION =
'HORISONTAL_AND_VERTICAL'
UNIT = 'kg/m^3'
EXPRESSION = ""1000""
EndSect // AUXILIARY_VARIABLE_1

[AUXILIARY_VARIABLE_2]
SYMBOL = 'cH'
ID = 47
DESCRIPTION = 'Hindered concentration cH'
ONLINE_HELP = ""
DOCUMENTATION = ""
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION =
'HORISONTAL_AND_VERTICAL'
UNIT = 'kg/m^3'
EXPRESSION = ""IF Salt_type <1 THEN
PhiH*ps*Dp/DfH ELSE 10-aS*POW(MIN(10,Salt),bS)""
EndSect // AUXILIARY_VARIABLE_2

[AUXILIARY_VARIABLE_3]
SYMBOL = 'DfHo'
ID = 48
DESCRIPTION = 'DfH'
ONLINE_HELP = ""
DOCUMENTATION = ""
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION =
'HORISONTAL_AND_VERTICAL'
UNIT = 'm'
EXPRESSION = ""IF Salt_type <1 THEN DfH
ELSE PhiH*ps*Dp/cH""
EndSect // AUXILIARY_VARIABLE_3

[AUXILIARY_VARIABLE_4]
SYMBOL = 'G'
ID = 49
DESCRIPTION = 'Shear rate'
ONLINE_HELP = ""
DOCUMENTATION = ""
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION =
'HORISONTAL_AND_VERTICAL'
UNIT = '1/s'
EXPRESSION = ""SQRT(TKEd/nuy_w)""
EndSect // AUXILIARY_VARIABLE_4

[AUXILIARY_VARIABLE_5]
SYMBOL = 'Ret'
ID = 50
DESCRIPTION = 'Turbulent Reynolds number'
ONLINE_HELP = ""
DOCUMENTATION = ""
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION =
'HORISONTAL_AND_VERTICAL'
UNIT = ""
EXPRESSION = ""460.6*POW(G,0.5283)""
EndSect // AUXILIARY_VARIABLE_5

[AUXILIARY_VARIABLE_6]
SYMBOL = 'DfB'
ID = 51
DESCRIPTION = 'DfB'
ONLINE_HELP = 'Floc size due to break-up
process'
DOCUMENTATION = ""
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'

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        SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
        UNIT = 'm'
        EXPRESSION = "IF Ret > 0 THEN
Dp*(1+POW(aB/Ret,1/bB)) ELSE 1"
        EndSect // AUXILIARY_VARIABLE_6

[AUXILIARY_VARIABLE_7]
        SYMBOL = 'DfA'
        ID = 52
        DESCRIPTION = 'DfA'
        ONLINE_HELP = 'Equilibrium floc size due to
aggregation process'
        DOCUMENTATION = "
        OUTPUT = 'NO'
        SCOPE = 'NOT_SPECIFIED'
        SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
        UNIT = 'm'
        EXPRESSION = "IF SSC<cH THEN Dp+(DfHo-
Dp)*SSC/cH ELSE DfHo"
        EndSect // AUXILIARY_VARIABLE_7

[AUXILIARY_VARIABLE_8]
        SYMBOL = 'Df'
        ID = 53
        DESCRIPTION = 'Size of (floc or sand) particle'
        ONLINE_HELP = 'Equilibrium floc size due to
aggregation and break-up processes'
        DOCUMENTATION = "
        OUTPUT = 'NO'
        SCOPE = 'NOT_SPECIFIED'
        SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
        UNIT = 'm'
        EXPRESSION = "MIN(DfA,DfB)"
        EndSect // AUXILIARY_VARIABLE_8

[AUXILIARY_VARIABLE_9]
        SYMBOL = 'D3'
        ID = 54
        DESCRIPTION = 'D#'
        ONLINE_HELP = 'See floc density model for D#'
        DOCUMENTATION = "
        OUTPUT = 'NO'
        SCOPE = 'NOT_SPECIFIED'
        SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
        UNIT = "
        EXPRESSION = "Df*POW((ps/1000-
1)*9.81/nuy_w/nuy_w,1/3)"
        EndSect // AUXILIARY_VARIABLE_9

[AUXILIARY_VARIABLE_10]
        SYMBOL = 'pf'
        ID = 55
        DESCRIPTION = 'Density of (floc or sand) particle'
        ONLINE_HELP = "
        DOCUMENTATION = "
        OUTPUT = 'NO'
        SCOPE = 'NOT_SPECIFIED'
        SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
        UNIT = 'kg/m^3'

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        EXPRESSION = "pw+(ps-pw)/(1+POW((Df/Dp-
1)*POW(D3,af),bf))"
        EndSect // AUXILIARY_VARIABLE_10

[AUXILIARY_VARIABLE_11]
        SYMBOL = 'D8'
        ID = 56
        DESCRIPTION = 'D*'
        ONLINE_HELP = 'Particle parameter'
        DOCUMENTATION = "
        OUTPUT = 'NO'
        SCOPE = 'NOT_SPECIFIED'
        SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
        UNIT = "
        EXPRESSION = "Df*POW((pf/1000-
1)*9.81/nuy_w/nuy_w,1/3)"
        EndSect // AUXILIARY_VARIABLE_11

[AUXILIARY_VARIABLE_12]
        SYMBOL = 'Phi'
        ID = 57
        DESCRIPTION = 'Vol concentration of (floc or
sand) particles'
        ONLINE_HELP = "
        DOCUMENTATION = "
        OUTPUT = 'NO'
        SCOPE = 'NOT_SPECIFIED'
        SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
        UNIT = "
        EXPRESSION = "(ps-pw)/(pf-
pw)*MAX(SSC,0)/ps"
        EndSect // AUXILIARY_VARIABLE_12

[AUXILIARY_VARIABLE_13]
        SYMBOL = 'pm'
        ID = 58
        DESCRIPTION = 'Density of mixture'
        ONLINE_HELP = "
        DOCUMENTATION = "
        OUTPUT = 'NO'
        SCOPE = 'NOT_SPECIFIED'
        SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
        UNIT = 'kg/m^3'
        EXPRESSION = "(1-Phi)*pw+Phi*pf"
        EndSect // AUXILIARY_VARIABLE_13

[AUXILIARY_VARIABLE_14]
        SYMBOL = 'av'
        ID = 59
        DESCRIPTION = 'av'
        ONLINE_HELP = "
        DOCUMENTATION = "
        OUTPUT = 'NO'
        SCOPE = 'NOT_SPECIFIED'
        SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
        UNIT = "
        EXPRESSION = "IF Type <3 THEN Av ELSE
AA*POW(D8,BB*POW(Df*1000000,-CC))"
        EndSect // AUXILIARY_VARIABLE_14

[AUXILIARY_VARIABLE_15]

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SYMBOL = 'X'
ID = 60
DESCRIPTION = 'Phi/PhiMax/10'
ONLINE_HELP = "
DOCUMENTATION = "
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
UNIT = "
EXPRESSION = "IF Phi/PhiMax < 0.95 THEN
Phi/PhiMax/10 ELSE 0.95/10"
EndSect // AUXILIARY_VARIABLE_15

[AUXILIARY_VARIABLE_16]
SYMBOL = 'muy_r'
ID = 61
DESCRIPTION = 'Relative viscosity'
ONLINE_HELP = "
DOCUMENTATION = "
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
UNIT = "
EXPRESSION = "(POW(av*X/(1-
X),bv)+1)*(POW(av*X/(1-2*X),bv)+1)*(POW(av*X/(1-
3*X),bv)+1)*(POW(av*X/(1-4*X),bv)+1)*(POW(av*X/(1-
5*X),bv)+1)*(POW(av*X/(1-6*X),bv)+1)*(POW(av*X/(1-
7*X),bv)+1)*(POW(av*X/(1-8*X),bv)+1)*(POW(av*X/(1-
9*X),bv)+1)*(POW(av*X/(1-10*X),bv)+1)"
EndSect // AUXILIARY_VARIABLE_16

[AUXILIARY_VARIABLE_17]
SYMBOL = 'nuy_m'
ID = 62
DESCRIPTION = 'Kinematic viscosity of mixture'
ONLINE_HELP = "
DOCUMENTATION = "
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
UNIT = 'm^2/s'
EXPRESSION = "muy_r*1000*nuy_w/pm"
EndSect // AUXILIARY_VARIABLE_17

[AUXILIARY_VARIABLE_18]
SYMBOL = 'M1'
ID = 63
DESCRIPTION = 'M (N.S. Cheng)'
ONLINE_HELP = "
DOCUMENTATION = "
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION = 'NONE'
UNIT = "
EXPRESSION = "53.5*EXP(-0.65*SF)"
EndSect // AUXILIARY_VARIABLE_18

[AUXILIARY_VARIABLE_19]
SYMBOL = 'N1'
ID = 64
DESCRIPTION = 'N (N.S. Cheng)'
ONLINE_HELP = "

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DOCUMENTATION = "
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION = 'NONE'
UNIT = "
EXPRESSION = "5.65*EXP(-2.5*SF)"
EndSect // AUXILIARY_VARIABLE_19

[AUXILIARY_VARIABLE_20]
SYMBOL = 'n1'
ID = 65
DESCRIPTION = 'n (N.S. Cheng)'
ONLINE_HELP = "
DOCUMENTATION = "
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION = 'NONE'
UNIT = "
EXPRESSION = "0.7+0.9*SF"
EndSect // AUXILIARY_VARIABLE_20

[AUXILIARY_VARIABLE_21]
SYMBOL = 's'
ID = 66
DESCRIPTION = 'Specific density of (floc or sand)
particles'
ONLINE_HELP = "
DOCUMENTATION = "
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
UNIT = "
EXPRESSION = "pf/pm"
EndSect // AUXILIARY_VARIABLE_21

[AUXILIARY_VARIABLE_22]
SYMBOL = 'W0'
ID = 67
DESCRIPTION = 'W0'
ONLINE_HELP = "
DOCUMENTATION = "
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
UNIT = 'm/s'
EXPRESSION = "(s-1)*9.81*SQR(Df)/18/nuy_m"
EndSect // AUXILIARY_VARIABLE_22

[AUXILIARY_VARIABLE_23]
SYMBOL = 'Rep0'
ID = 68
DESCRIPTION = 'Rep0'
ONLINE_HELP = "
DOCUMENTATION = "
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
UNIT = "
EXPRESSION = "W0*Df/nuy_m"
EndSect // AUXILIARY_VARIABLE_23

[AUXILIARY_VARIABLE_24]

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SYMBOL = 'CD0'
ID = 69
DESCRIPTION = 'CD0'
ONLINE_HELP = "
DOCUMENTATION = "
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
UNIT = "
EXPRESSION = "IF Type<3 THEN
POW(POW(M1/Rep0,1/n1)+POW(N1,1/n1),n1)+at*PO
W(Ret/Rep0,bt) ELSE
24/Rep0*(1+0.15*POW(Rep0,0.687))+at*POW(Ret/Rep
0,bt)""
EndSect // AUXILIARY_VARIABLE_24

[AUXILIARY_VARIABLE_25]
SYMBOL = 'W1'
ID = 70
DESCRIPTION = 'W1'
ONLINE_HELP = "
DOCUMENTATION = "
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
UNIT = 'm/s'
EXPRESSION = "SQRT(4/3*9.81*Df*(s-1)/CD0)""
EndSect // AUXILIARY_VARIABLE_25

[AUXILIARY_VARIABLE_26]
SYMBOL = 'Rep1'
ID = 71
DESCRIPTION = 'Rep1'
ONLINE_HELP = "
DOCUMENTATION = "
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
UNIT = "
EXPRESSION = "W1*Df/nuy_m""
EndSect // AUXILIARY_VARIABLE_26

[AUXILIARY_VARIABLE_27]
SYMBOL = 'CD1'
ID = 72
DESCRIPTION = 'CD1'
ONLINE_HELP = "
DOCUMENTATION = "
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
UNIT = "
EXPRESSION = "IF Type<3 THEN
POW(POW(M1/Rep1,1/n1)+POW(N1,1/n1),n1)+at*PO
W(Ret/Rep1,bt) ELSE
24/Rep1*(1+0.15*POW(Rep1,0.687))+at*POW(Ret/Rep
1,bt)""
EndSect // AUXILIARY_VARIABLE_27

[AUXILIARY_VARIABLE_28]
SYMBOL = 'W2'

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ID = 73
DESCRIPTION = 'W2'
ONLINE_HELP = "
DOCUMENTATION = "
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
UNIT = 'm/s'
EXPRESSION = "SQRT(4/3*9.81*Df*(s-1)/CD1)""
EndSect // AUXILIARY_VARIABLE_28

[AUXILIARY_VARIABLE_29]
SYMBOL = 'Rep2'
ID = 74
DESCRIPTION = 'Rep2'
ONLINE_HELP = "
DOCUMENTATION = "
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
UNIT = "
EXPRESSION = "W2*Df/nuy_m""
EndSect // AUXILIARY_VARIABLE_29

[AUXILIARY_VARIABLE_30]
SYMBOL = 'CD2'
ID = 75
DESCRIPTION = 'CD2'
ONLINE_HELP = "
DOCUMENTATION = "
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
UNIT = "
EXPRESSION = "IF Type<3 THEN
POW(POW(M1/Rep2,1/n1)+POW(N1,1/n1),n1)+at*PO
W(Ret/Rep2,bt) ELSE
24/Rep2*(1+0.15*POW(Rep2,0.687))+at*POW(Ret/Rep
2,bt)""
EndSect // AUXILIARY_VARIABLE_30

[AUXILIARY_VARIABLE_31]
SYMBOL = 'W3'
ID = 76
DESCRIPTION = 'W3'
ONLINE_HELP = "
DOCUMENTATION = "
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
UNIT = 'm/s'
EXPRESSION = "SQRT(4/3*9.81*Df*(s-1)/CD2)""
EndSect // AUXILIARY_VARIABLE_31

[AUXILIARY_VARIABLE_32]
SYMBOL = 'Rep3'
ID = 77
DESCRIPTION = 'Rep3'
ONLINE_HELP = "
DOCUMENTATION = "
OUTPUT = 'NO'

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SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
UNIT = "
EXPRESSION = ""W3*Df/nuy_m""
EndSect // AUXILIARY_VARIABLE_32

[AUXILIARY_VARIABLE_33]
SYMBOL = 'CD3'
ID = 78
DESCRIPTION = 'CD3'
ONLINE_HELP = "
DOCUMENTATION = "
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
UNIT = "
EXPRESSION = ""IF Type<3 THEN
POW(POW(M1/Rep3,1/n1)+POW(N1,1/n1),n1)+at*PO
W(Ret/Rep3,bt) ELSE
24/Rep3*(1+0.15*POW(Rep3,0.687))+at*POW(Ret/Rep
3,bt)""
EndSect // AUXILIARY_VARIABLE_33

[AUXILIARY_VARIABLE_34]
SYMBOL = 'W4'
ID = 79
DESCRIPTION = 'W4'
ONLINE_HELP = "
DOCUMENTATION = "
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
UNIT = 'm/s'
EXPRESSION = ""SQRT(4/3*9.81*Df*(s-1)/CD3)""
EndSect // AUXILIARY_VARIABLE_34

[AUXILIARY_VARIABLE_35]
SYMBOL = 'Rep4'
ID = 80
DESCRIPTION = 'Rep4'
ONLINE_HELP = "
DOCUMENTATION = "
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
UNIT = "
EXPRESSION = ""W4*Df/nuy_m""
EndSect // AUXILIARY_VARIABLE_35

[AUXILIARY_VARIABLE_36]
SYMBOL = 'CD4'
ID = 81
DESCRIPTION = 'CD4'
ONLINE_HELP = "
DOCUMENTATION = "
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
UNIT = "

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EXPRESSION = ""IF Type<3 THEN
POW(POW(M1/Rep4,1/n1)+POW(N1,1/n1),n1)+at*PO
W(Ret/Rep4,bt) ELSE
24/Rep4*(1+0.15*POW(Rep4,0.687))+at*POW(Ret/Rep
4,bt)""
EndSect // AUXILIARY_VARIABLE_36

[AUXILIARY_VARIABLE_37]
SYMBOL = 'Wsmt'
ID = 82
DESCRIPTION = 'Ws,mt'
ONLINE_HELP = "
DOCUMENTATION = 'used to determine
sedimentation of layer 2 and above'
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
UNIT = 'm/s'
EXPRESSION = ""IF SSC>0 THEN POW(1-
Phi,p)*SQRT(4/3*9.81*Df*(s-1)/CD4) ELSE 0.000001""
EndSect // AUXILIARY_VARIABLE_37

[AUXILIARY_VARIABLE_38]
SYMBOL = 'CD5'
ID = 83
DESCRIPTION = 'CD5'
ONLINE_HELP = "
DOCUMENTATION = "
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
UNIT = "
EXPRESSION = ""IF Type<3 THEN
POW(POW(M1/Rep0,1/n1)+POW(N1,1/n1),n1) ELSE
24/Rep0*(1+0.15*POW(Rep0,0.687))""
EndSect // AUXILIARY_VARIABLE_38

[AUXILIARY_VARIABLE_39]
SYMBOL = 'W6'
ID = 84
DESCRIPTION = 'W6'
ONLINE_HELP = '1'
DOCUMENTATION = "
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
UNIT = "
EXPRESSION = ""SQRT(4/3*9.81*Df*(s-1)/CD5)""
EndSect // AUXILIARY_VARIABLE_39

[AUXILIARY_VARIABLE_40]
SYMBOL = 'Rep6'
ID = 85
DESCRIPTION = 'Rep6'
ONLINE_HELP = "
DOCUMENTATION = "
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
UNIT = "
EXPRESSION = ""W6*Df/nuy_m""

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EndSect // AUXILIARY_VARIABLE_40

[AUXILIARY_VARIABLE_41]
  SYMBOL = 'CD6'
  ID = 86
  DESCRIPTION = 'CD6'
  ONLINE_HELP = ""
  DOCUMENTATION = ""
  OUTPUT = 'NO'
  SCOPE = 'NOT_SPECIFIED'
  SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
  UNIT = ""
  EXPRESSION = "IF Type<3 THEN
POW(POW(M1/Rep6,1/n1)+POW(N1,1/n1),n1) ELSE
24/Rep6*(1+0.15*POW(Rep6,0.687))"
EndSect // AUXILIARY_VARIABLE_41

[AUXILIARY_VARIABLE_42]
  SYMBOL = 'W7'
  ID = 87
  DESCRIPTION = 'W7'
  ONLINE_HELP = '2'
  DOCUMENTATION = ""
  OUTPUT = 'NO'
  SCOPE = 'NOT_SPECIFIED'
  SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
  UNIT = ""
  EXPRESSION = "SQRT(4/3*9.81*Df*(s-1)/CD6)"
EndSect // AUXILIARY_VARIABLE_42

[AUXILIARY_VARIABLE_43]
  SYMBOL = 'Rep7'
  ID = 88
  DESCRIPTION = 'Rep7'
  ONLINE_HELP = ""
  DOCUMENTATION = ""
  OUTPUT = 'NO'
  SCOPE = 'NOT_SPECIFIED'
  SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
  UNIT = ""
  EXPRESSION = "W7*Df/nuy_m"
EndSect // AUXILIARY_VARIABLE_43

[AUXILIARY_VARIABLE_44]
  SYMBOL = 'CD7'
  ID = 89
  DESCRIPTION = 'CD7'
  ONLINE_HELP = ""
  DOCUMENTATION = ""
  OUTPUT = 'NO'
  SCOPE = 'NOT_SPECIFIED'
  SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
  UNIT = ""
  EXPRESSION = "IF Type<3 THEN
POW(POW(M1/Rep7,1/n1)+POW(N1,1/n1),n1) ELSE
24/Rep7*(1+0.15*POW(Rep7,0.687))"
EndSect // AUXILIARY_VARIABLE_44

[AUXILIARY_VARIABLE_45]
  SYMBOL = 'W8'
  ID = 90
  DESCRIPTION = 'W8'
  ONLINE_HELP = '3'
  DOCUMENTATION = ""
  OUTPUT = 'NO'
  SCOPE = 'NOT_SPECIFIED'
  SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
  UNIT = ""
  EXPRESSION = "SQRT(4/3*9.81*Df*(s-1)/CD7)"
EndSect // AUXILIARY_VARIABLE_45

[AUXILIARY_VARIABLE_46]
  SYMBOL = 'Rep8'
  ID = 91
  DESCRIPTION = 'Rep8'
  ONLINE_HELP = ""
  DOCUMENTATION = ""
  OUTPUT = 'NO'
  SCOPE = 'NOT_SPECIFIED'
  SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
  UNIT = ""
  EXPRESSION = "W8*Df/nuy_m"
EndSect // AUXILIARY_VARIABLE_46

[AUXILIARY_VARIABLE_47]
  SYMBOL = 'CD8'
  ID = 92
  DESCRIPTION = 'CD8'
  ONLINE_HELP = ""
  DOCUMENTATION = ""
  OUTPUT = 'NO'
  SCOPE = 'NOT_SPECIFIED'
  SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
  UNIT = ""
  EXPRESSION = "IF Type<3 THEN
POW(POW(M1/Rep8,1/n1)+POW(N1,1/n1),n1) ELSE
24/Rep8*(1+0.15*POW(Rep8,0.687))"
EndSect // AUXILIARY_VARIABLE_47

[AUXILIARY_VARIABLE_48]
  SYMBOL = 'W9'
  ID = 93
  DESCRIPTION = 'W9'
  ONLINE_HELP = '4'
  DOCUMENTATION = ""
  OUTPUT = 'NO'
  SCOPE = 'NOT_SPECIFIED'
  SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
  UNIT = ""
  EXPRESSION = "SQRT(4/3*9.81*Df*(s-1)/CD8)"
EndSect // AUXILIARY_VARIABLE_48

[AUXILIARY_VARIABLE_49]
  SYMBOL = 'Rep9'
  ID = 94
  DESCRIPTION = 'Rep9'
  ONLINE_HELP = ""
  DOCUMENTATION = ""
  OUTPUT = 'NO'
  SCOPE = 'NOT_SPECIFIED'
  SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'

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UNIT = "
EXPRESSION = ""W9*Df/nuy_m""
EndSect // AUXILIARY_VARIABLE_49

[AUXILIARY_VARIABLE_50]
SYMBOL = 'CD9'
ID = 95
DESCRIPTION = 'CD9'
ONLINE_HELP = "
DOCUMENTATION = "
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION =
'HORISONTAL_AND_VERTICAL'
UNIT = "
EXPRESSION = ""IF Type<3 THEN
POW(POW(M1/Rep9,1/n1)+POW(N1,1/n1),n1) ELSE
24/Rep9*(1+0.15*POW(Rep9,0.687))""
EndSect // AUXILIARY_VARIABLE_50

[AUXILIARY_VARIABLE_51]
SYMBOL = 'Wsm'
ID = 96
DESCRIPTION = 'Ws,m'
ONLINE_HELP = "
DOCUMENTATION = 'used to determine
deposition of layer 1 within WB'
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION =
'HORISONTAL_AND_VERTICAL'
UNIT = 'm/s'
EXPRESSION = ""IF SSC>0 THEN POW(1-
Phi,p)*SQRT(4/3*9.81*Df*(s-1)/CD9) ELSE 0.000001""
EndSect // AUXILIARY_VARIABLE_51

[AUXILIARY_VARIABLE_52]
SYMBOL = 'dz1'
ID = 97
DESCRIPTION = 'near bed water layer height'
ONLINE_HELP = "
DOCUMENTATION = "
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION = 'HORISONTAL'
UNIT = 'm'
EXPRESSION = ""sigma1*Depth""
EndSect // AUXILIARY_VARIABLE_52

[AUXILIARY_VARIABLE_53]
SYMBOL = 'z0'
ID = 98
DESCRIPTION = 'zero-velocity level'
ONLINE_HELP = "
DOCUMENTATION = "
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION = 'HORISONTAL'
UNIT = 'm'
EXPRESSION = ""ks/z0coef""
EndSect // AUXILIARY_VARIABLE_53

[AUXILIARY_VARIABLE_54]
SYMBOL = 'fX'
ID = 99
DESCRIPTION = 'auxiliary variable for fC'
ONLINE_HELP = "
DOCUMENTATION = "
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION = 'HORISONTAL'
UNIT = "
EXPRESSION = ""2.5*(z0/dz1-1+LN(dz1/z0))""
EndSect // AUXILIARY_VARIABLE_54

[AUXILIARY_VARIABLE_55]
SYMBOL = 'fC'
ID = 100
DESCRIPTION = 'Friction coefficient'
ONLINE_HELP = "
DOCUMENTATION = "
OUTPUT = 'NO'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION = 'HORISONTAL'
UNIT = "
EXPRESSION = ""2*fX/fX""
EndSect // AUXILIARY_VARIABLE_55

[AUXILIARY_VARIABLE_56]
SYMBOL = 'Thickness'
ID = 101
DESCRIPTION = 'Layer thickness for erosion
calculation'
ONLINE_HELP = "
DOCUMENTATION = "
OUTPUT = 'YES'
SCOPE = 'NOT_SPECIFIED'
SPATIAL_VARIATION = 'HORISONTAL'
UNIT = 'm'
EXPRESSION = ""MAX(LayerThickness,0)""
EndSect // AUXILIARY_VARIABLE_56

EndSect // AUXILIARY_VARIABLES

[PROCESSES]
DESCRIPTION = 'No description'
ONLINE_HELP = "
DOCUMENTATION = "
[PROCESS_1]
SYMBOL = 'Tbed'
ID = 102
DESCRIPTION = 'BedShearStress for erosion
calculation'
ONLINE_HELP = "
DOCUMENTATION = "
OUTPUT = 'YES'
PROCESS_TYPE = 'TRANSFORMATION'
SCOPE = 'WB'
SPATIAL_VARIATION = 'HORISONTAL'
UNIT = 'N/m^2'
EXPRESSION =
""MIN(1/2*1000*fC*Current*Current*C1,Tcmax)""
EndSect // PROCESS_1

[PROCESS_2]
SYMBOL = 'sedimentation'
ID = 103
DESCRIPTION = 'sedimentation'
ONLINE_HELP = "
DOCUMENTATION = "

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OUTPUT = 'NO'
PROCESS_TYPE = 'SETTLING'
SCOPE = 'WC'
SPATIAL_VARIATION =
'HORIZONTAL_AND_VERTICAL'
UNIT = 'kg/m^3/day'
EXPRESSION =
""MAX(Wsmt,0)*MAX(SSC,0)/dZ*86400*C2""
EndSect // PROCESS_2

[PROCESS_3]
SYMBOL = 'deposition'
ID = 104
DESCRIPTION = 'deposition'
ONLINE_HELP = ""
DOCUMENTATION = ""
OUTPUT = 'NO'
PROCESS_TYPE = 'TRANSFORMATION'
SCOPE = 'WB'
SPATIAL_VARIATION = 'HORIZONTAL'
UNIT = 'kg/m^3/day'
EXPRESSION = ""IF Tbed >Tdep THEN -
sedimentation ELSE MAX(Wsm,0)*(1-
MAX(Tbed,0)/Tdep)*MAX(SSC,0)/dZ*86400*C3-
sedimentation""
EndSect // PROCESS_3

[PROCESS_4]
SYMBOL = 'erosion'
ID = 105
DESCRIPTION = 'erosion'
ONLINE_HELP = ""
DOCUMENTATION = ""
OUTPUT = 'NO'
PROCESS_TYPE = 'TRANSFORMATION'
SCOPE = 'WB'
SPATIAL_VARIATION = 'HORIZONTAL'
UNIT = 'kg/m^3/day'
EXPRESSION = ""IF Tbed < Tero THEN 0 ELSE
IF Thickness>0 THEN MIN(Ee*POW((Tbed/Tero-
1),n)/dZ*86400*C4,Thickness/Time_Step*pbed/dZ*8640
0) ELSE 0""
EndSect // PROCESS_4

[PROCESS_5]
SYMBOL = 'Dep2'
ID = 106
DESCRIPTION = 'deposition rate'
ONLINE_HELP = ""
DOCUMENTATION = ""
OUTPUT = 'YES'
PROCESS_TYPE = 'TRANSFORMATION'
SCOPE = 'WB'
SPATIAL_VARIATION = 'HORIZONTAL'
UNIT = 'kg/m^2/s'
EXPRESSION = ""IF Tbed >Tdep THEN 0 ELSE
MAX(Wsm,0)*(1-MAX(Tbed,0)/Tdep)*MAX(SSC,0)*C3""
EndSect // PROCESS_5

[PROCESS_6]
SYMBOL = 'Ero2'
ID = 107
DESCRIPTION = 'erosion rate'
ONLINE_HELP = ""
DOCUMENTATION = ""

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OUTPUT = 'YES'
PROCESS_TYPE = 'TRANSFORMATION'
SCOPE = 'WB'
SPATIAL_VARIATION = 'HORIZONTAL'
UNIT = 'kg/m^2/s'
EXPRESSION = ""IF Tbed < Tero THEN 0 ELSE
IF Thickness>0 THEN MIN(Ee*POW((Tbed/Tero-
1),n)*C4,Thickness/Time_Step*pbed) ELSE 0""
EndSect // PROCESS_6

[PROCESS_7]
SYMBOL = 'BedShearStress'
ID = 108
DESCRIPTION = 'BedShearStress'
ONLINE_HELP = ""
DOCUMENTATION =
'1/2*1000*fC*Current*Current*(50-SSC)/50*C1'
OUTPUT = 'YES'
PROCESS_TYPE = 'TRANSFORMATION'
SCOPE = 'WB'
SPATIAL_VARIATION = 'HORIZONTAL'
UNIT = 'N/m2'
EXPRESSION =
""1/2*1000*fC*Current*Current*C1""
EndSect // PROCESS_7

[PROCESS_8]
SYMBOL = 'BedChange'
ID = 109
DESCRIPTION = 'Rate of bed thickness changed'
ONLINE_HELP = ""
DOCUMENTATION = ""
OUTPUT = 'NO'
PROCESS_TYPE = 'TRANSFORMATION'
SCOPE = 'WB'
SPATIAL_VARIATION = 'HORIZONTAL'
UNIT = 'm/day'
EXPRESSION = ""(MAX(Dep2,0)/pbed-
MAX(Ero2,0)/pbed)*86400""
EndSect // PROCESS_8

EndSect // PROCESSES

[DERIVED_OUTPUTS]
DESCRIPTION = 'No description'
ONLINE_HELP = ""
DOCUMENTATION = ""
EndSect // DERIVED_OUTPUTS

[STATE_VARIABLE_EQUATIONS]
[STATE_VARIABLE_EQUATION_1]
SSC = ""-deposition-sedimentation+erosion""
EndSect // STATE_VARIABLE_EQUATION_1

[STATE_VARIABLE_EQUATION_2]
LayerThickness = ""BedChange""
EndSect // STATE_VARIABLE_EQUATION_2

EndSect // STATE_VARIABLE_EQUATIONS

EndSect // ECO_LAB_SETUP

```

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