SEDIMENT CONCENTRATIONS AND TRANSPORT DUE TO NEAR-BED JET FLOW: STJET-MODEL

1. Introduction

This note describes the STjet-model, which computes the sediment concentrations and transport generated by a jet-type flow near the bed consisting of mud, silt and sand. A background tide-riven and/or wind-driven flow may be present or not.

2. Hydrodynamics

The vertical distribution of the velocity is represented, as:

$$u_z = u_{max,b}\,(z/\delta)^{1/7} + [u_{mean}/(-1+\ln(h/z_o))]\,\ln(z/z_o) \qquad (2.1)$$

with: $u_{max,b}$= peak velocity of near-bed jet, z= level above bed (m), δ= layer thickness of jet, h= water depth (m), u_{mean}= depth-averaged tide-driven and/or wind-driven velocity, z_o= 0.033$k_{s,c}$ = zero-velocity level, $k_{s,c}$ = current-related bed roughness.

Figure 2.1 shows an example of near-bed jet-type flow near the bed.

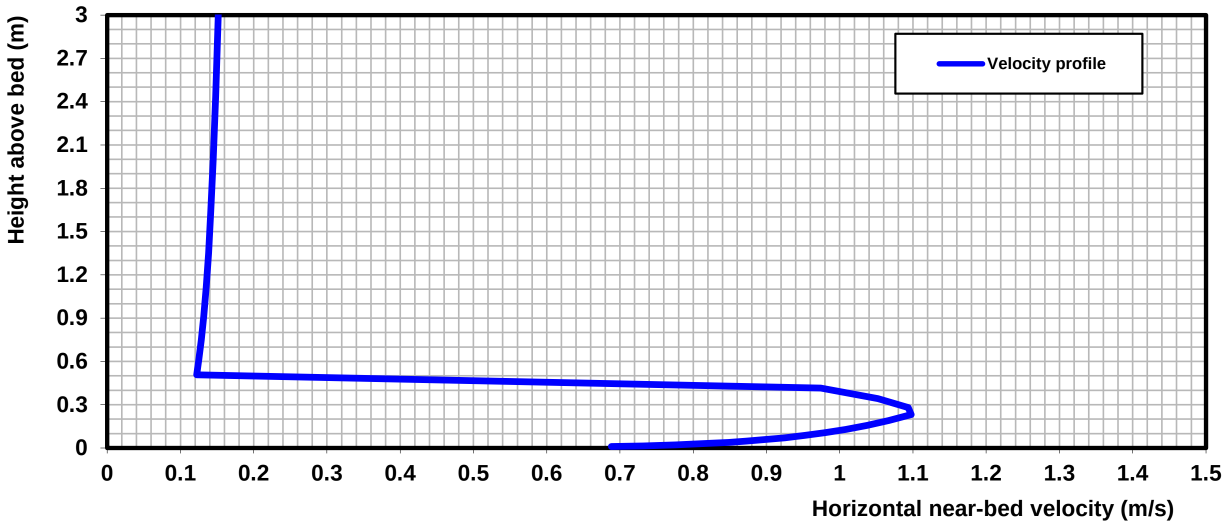

Figure 2.1 *Flow velocity profile (u_{max} = 1 m/s, δ = 0.5 m, u_{mean} = 0.2 m/s, h = 150 m; $k_{s,c}$ = 0.01 m)*

The bed-shear stress is given by:

$$\tau_b = \rho_w\,(u_*)^2 = \rho\,[\kappa\, u_{z=0.5\delta}/\ln(15\delta/k_{s,c})]^2 \qquad (2.2)$$

with: τ_b = bed-shear stress, ρ_w = fluid density, u_*= bed-shear velocity, κ=0.4,

The fluid mixing is given by:

$$\varepsilon_z = [[\varepsilon_{max,b}\,\{1-(1-2z/(2\delta))^2\}]^2 + [\varepsilon_{max,h}\,\{1-(1-2z/(h)\}^2]^2]^{0.5} \qquad \text{for } z < 2\delta \qquad (2.3)$$

$$\varepsilon_z = \varepsilon_{max,h}\,[1-(1-2z/(h))^2] \qquad \text{for } 2\delta < z < 0.5h \qquad (2.4)$$

$$\varepsilon_z = \varepsilon_{max,h} = 0.1\,u_{*m}\,h \qquad \text{for } z > 0.5h \qquad (2.5)$$

with: ε= mixing coefficient, $\varepsilon_{max,b} = 0.05\ u_{max}\ \delta$ = maximum mixing coefficient near the bed due the jet flow, u_{*m}= bed-shear velocity due to the mean current only (= $u_{mean}\ g^{0.5}/C$), C= Chézy-coefficient= $5.75 g^{0.5} \log(12h/k_{s,c})$.

Based on linear wave theory, the near-bed velocity due to oscillatory flow (waves) is given by:

$$u_w = \pi\ H_s/(T_p \sinh(kh) \qquad (2.6)$$

with: H_s= significnt wave height, T_p= peak wave period, h= water depth, $k=2\pi/L$, L= wave length.

The bed-shear stress due to oscillatory flow is given by:

$$\tau_{b,w} = \rho_w\ (u_{*,w})^2 = 0.25\ \rho\ f_w\ (u_w)^2 \qquad (2.7)$$
$$f_w\ = \exp(-6+5.2(A_w/k_{s,w})) \qquad (2.8)$$

with: u_w= =peak orbital velocity (linear wave theory), A_w= $T_p/(2\pi)u_w$ =peak orbital excursion, T_p= peak wave period, f_w= wave-related friction coefficient, $k_{s,w}$= wave-related roughness.

The effective bed-shear stresses for sediment transport are represented as:

$$\tau_{b,c}^{/} = \mu_c\ \tau_{b,c} \qquad (2.9)$$
$$\tau_{b,w}^{/} = \mu_w\ \tau_{b,w} \qquad (2.10)$$

μ_c= $f_c^{/}/f_c$= current-related efficiency factor, f_c= $0.24/(\log(12h/k_{s,c}))^2$= current-related friction coefficient, $f_c^{/}$= $0.24/(\log(12h/d_{90}))^2$=grain-related friction coefficient, d_{90}= grain size of sediment mixture.
μ_w= $0.7/D_*$= wave-related efficiency factor ($\mu_{w,min}$=0.14, $\mu_{w,max}$=0.35).

3. Sediment concentrations and transport

3.1 Definitions

In most tidal basins the sediment bed consists of a mixture of sand, silt and mud. The sand-silt-mud mixture generally behaves as a mixture with cohesive properties when the mud fraction is dominant (p_{mud}>0.3) and as a non-cohesive mixture when the sand fraction is dominant (p_{sand}>0.7). The distinction between non-cohesive mixtures and cohesive mixtures can be related to a critical mud content ($p_{mud,cr}$). Most important is the value of the clay/lutum-fraction (sediments<16 μm) in the mixture. Cohesive properties become dominant when the clay-fraction is larger than about 0.05 to 0.1.

Three sediment fractions are distinguished, as follows:
- mud; particles smaller than 16 μm with cohesive properties;
- silt; particles between 16 and 63 μm with non-cohesive properties;
- sand; particles larger than 63 μm with non-cohesive properties.

The velocities and sand concentrations are computed as a function of height (z) above bed.
The grid points over the depth (50 points) are distributed according to an exponential function, as follows:

$$z=a[h/a]^{(k-1)/(N-1)} \qquad (3.1)$$

with: a= reference height above bed (input value), h= water depth between bed and water surface, k= index number of point k, N= total number of grid points (=50).

Near the bed the sediment concentrations are strongly decreasing in vertical direction resulting in stratification effects as the fluid density will decrease in vertical direction. Stratification effects will result in the damping of turbulence because turbulence energy is consumed in the mixing of heavier fluid from a lower level to a higher level against the action of gravity.
The usual method to account for the stratification effect on the velocity and concentration profiles is the reduction of the fluid mixing coefficient by introducing a damping factor related to the Richardson-number (Ri), as follows: $\varepsilon = \phi\, \varepsilon_o$ with ε_o=fluid mixing coefficient in water without sediment, ϕ= F(Ri) = damping factor (< 1), Ri = local Richardson number.

3.2 Sediment concentration equations

The vertical distribution of the sediment concentrations in uniform flow can be described by:

$$c\, w_s + \varepsilon\, dc/dz = 0 \qquad (3.2)$$

$$dc/dz = -(w_s/\varepsilon_s)\, c \qquad (3.3)$$

$$c_z = c_{z-\Delta z} + \Delta c = c_{z-\Delta z} - (w_s/\varepsilon_s)\, c\, \Delta z = c_{z-\Delta z}\, [1 - (w_s/\varepsilon_s)\, \Delta z] \qquad (3.4)$$

with: w_s= settling velocity of sediment, $\varepsilon_s = \phi\, \varepsilon$= sediment mixing coeficient, ϕ= turbulence damping coefficient.

The Richardson number (Ri), which expresses the near-bed stratification effects close to the sediment bed, is defined as follows:

$$Ri = [-(g/\rho)][d\rho/dz]/[(du/dz)^2] = [-(\rho_s-\rho_w)g/((\rho_w+(\rho_s-\rho_w)c)][dc/dz]/[(du/dz)^2] \qquad (3.5)$$

with: ρ= fluid-sediment mixture density=$\rho_s c+(1-c)\rho_w$, c= volume sediment concentration, ρ_w= fluid density, ρ_s= sediment density.

The concentration and velocity gradients are determined by using the values at heights z_{k-1} and z_{k-2}.

The damping function is expressed as:

$$\phi = (1+\alpha_d\, Ri^{0.5})^{-1} \qquad (3.6)$$

with: α_d= input value (in range of 5 to 20), Ri=Richardson number.

The reference concentration c_a of the sediment fractions is described by:

$$c_a = 0.015\, \alpha_{ca}\, (p_i)\, f_{silt,i}\, (d_{m,i}/a)\, (T_i)^{1.5}\, (D_{*,i})^{-0.3} \qquad (3.7)$$

with: α_{ca}= scaling coefficient (default=1), p_i= sediment fraction ($\sum p_i=1$; three fractions), $d_{m,i}$= mean particle size of sediment fraction i, $D_{*,i}= d_{m,i}[(s-1)g/\nu^2]^{0.333}$= dimensionless particle parameter of sediment fraction i, $f_{silt,i}=d_{sand}/d_{m,i}$ (with f_{silt}=1 for $d_{sand}/d_{m,i}<1$), d_{sand}= 0.00063 m (smallest sand size), $T_i=(\tau'_{b,cw}-\chi\tau_{b,cr,i})/\chi\tau_{b,cr,i}$= dimensionless bed-shear stress parameter, $\tau_{b,cr,i}$= critical bed-shear stress of sediment fraction i, $\tau'_{b,cw}= \mu_c\tau_{b,c}+\mu_w\tau_{b,w}$= effective bed-shear stress due to current and waves, $s=\rho_s/\rho$= relative density, χ= factor representing the effects of mud on the critical shear stress of silt and sand fraction i, ν= kinematic viscosity coefficient, ρ_s= sediment density, ρ= fluid density.

3.3 Settling velocity

Mud

The concentration-dependent settling velocity of the mud fraction is represented as:

$w_{mud} = \exp[\alpha_1 \ln(c) + \alpha_2 - \alpha_3]$; for flocculation range $c \le 0.0025$ (3.8)

$\alpha_1 = 0.182 \ln(w_{mud,max}/w_{mud,min})$

$\alpha_2 = 2.09 \ln(w_{mud,max})$

$\alpha_3 = 1.09 \ln(w_{mud,min})$

$w_{mud} = w_{mud,max}(1-c)^4$ for hindered settling range $c > 0.0025$ (3.9)

with:
$w_{mud,max}$= maximum settling velocity at c=0.0025 ($w_{mud,max}$=0.0005 to 0.003 m/s or 0.5 to 3 mm/s; input value),
$w_{mud,min}$= minimum settling velocity at c=0.00001 ($w_{mud,min}$=0.00005 to 0.0001 m/s or 0.05 to 0.1 mm/s; input value).

The settling velocity at height z_k is determined by using the concentration values at height z_{k-1}.

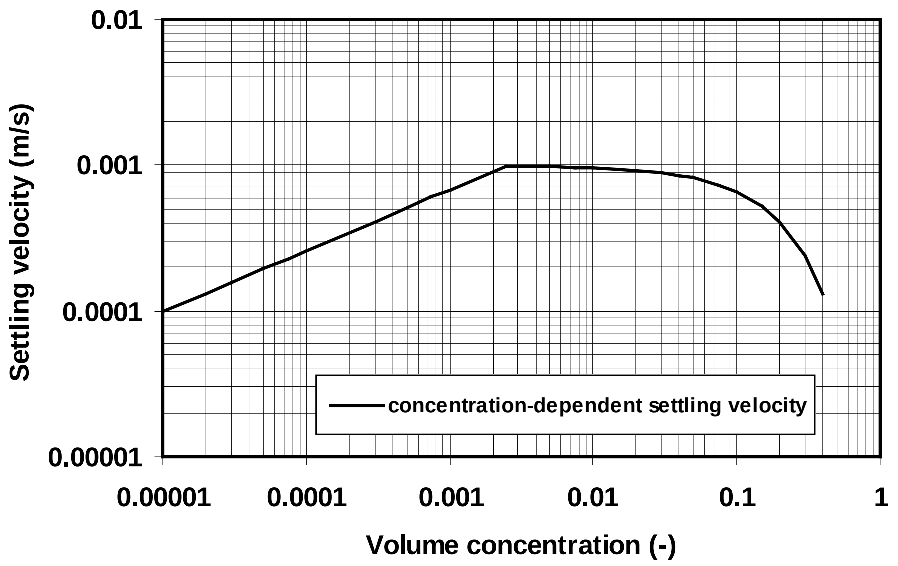

Figure 3.1 *Settling velocity as function of volume concentration; flocculation range for c<0.0025 and hindered settling range for c>0.0025; $w_{mud,max}$=0.001 m/s, $w_{mud,min}$=0.0001 m/s*

Some characteristic values of the settling velocity w_{mud} are:

c=0.0025 (=6.6 kg/m^3)	w_{mud}=0.001 m/s	= 1 mm/s
c=0.00025 (=0.66 kg/m^3)	w_{mud}=0.00038 m/s	= 0.38 mm/s
c=0.000025 (=0.066 kg/m^3)	w_{mud}=0.000145 m/s	= 0.145 mm/s
c=0.025 (=66 kg/m^3)	w_{mud}=0.0009 m/s	= 0.9 mm/s
c=0.1(=265 kg/m^3)	w_{mud}=0.00066 m/s	= 0.66 mm/s

Equation (3.8) using $w_{mud,max}$=0.001 m/s and $w_{mud,min}$=0.0001 m/s, is shown in **Figure 3.1**.

Silt and sand

The settling velocity of the silt and sand fractions are assumed to be constant (not dependent on concentration).

3.4 Suspended load and bed load transport

The suspended sand transport q_s can be computed by integration of the product of velocity and concentration over the water depth:

$$q_s = \int_a^h (u\ c)\ dz \qquad (3.10)$$

The bed load transport (in kg/m/s) can be computed as:

$$q_b = c_a\ u_a\ a \qquad (3.11)$$

with: c_a= near-bed concentration (see Equation 3.7), u_a= flow velocity a level z=a.

The total load transport is computed as:

$$q_{tot} = q_s + q_b \qquad (3.12)$$

4 Example computation

Table 4.1 shows an example of the model input parameters.

INPUT VALUES			
Water depth	h	150	(m)
Depth-averaged velocity	Umean	0.2	(m/s)
Peak water velocity near-bed jet flow	Umax,near bed	1	(m/s)
Layer thickness of near bed jet flow	Delta	0.5	(m)
Wave height	Hs	0	(m)
Wave period	Tp	15	(s)
Salinity-induced density gradient (max. value 0.001)	dρ/dx	0	(kg/m3/m)
Coeff. salinity-induced flow (0.5 to 2; larger yields smaller effect)	Gamma	1	(-)
Percentage of MUD<16 um	pmud	0.2	(-)
Percentage of SILT (16 to 63 um)	psilt	0.3	
Percentage of SAND >63 um	psand	0.5	(-)
Mean size of MUD fraction <16 um	dm,mud	0.00001	(m)
Mean size of SILT fraction 16 to 63 um	dm,silt	0.00003	(m)
Mean size of SAND fraction >63 um	dm,sand	0.0001	(m)
Selection of MUD settling velocity; 1=constant=ws,max, 2=non-constant		2	
Maximum MUD settling velocity at conc=0.0025	ws,max,mud	0.002	(m/s)
Minimum MUD settling velocity at c=0.00001	ws,min,mud	0.0002	(m/s)
Settling velocity of SILT fraction	ws,silt	0.006	(m/s)
Settling velocity of SAND fraction	ws,sand	0.015	(m/s)
Critical bed-shear stress of MUD fraction	tb,cr,mud	0.5	(N/m2)
Critical bed-shear stress of SILT fraction	tb,cr,silt	0.3	(N/m2)
Critical bed-shear stress of SAND fraction	tb,cr,sand	0.3	(N/m2)
Sediment density	rhos	2650	(kg/m3)
Fluid density seawater	rhow	1025	(kg/m3)
Fluid viscosity	nu	0.000001	(m2/s)
Bed roughness for shear stress/mixing-currents	ks,c, bed surface	0.01	(m)
Bed roughness for shear stress/mixing-waves	ks,w,bed surface	0.01	(m)
Effective roughness for velocity profile	ks.c, velocity profile	0.01	(m)
Reference level	a	0.01	(m)
Scaling Coefficient reference concentration MUD		1	(-)
Scaling Coefficient reference concentration SILT		1	(-)
Scaling Coefficient reference concentration SAND		1	(-)
Coefficient turbulence damping		5	(-)

Table 4.1 *Input data STjet-model*

Figure 4.1 shows the results of an example computation based on the data of **Table 4.1**.
The bed consists of sand (50%), silt (30% and mud (20%).
A jet-type flow near the bed is present with maximum velocity u_{max}= 1m/s over a tickness of δ= 0.5 m.
The background flow in water depth of h= 150 m has a mean velocity of u_{mean}=0.2 m/s.
The near-bed sediment concentrations are in the range of 1 to 10 kg/m^3.
The sand fraction is suspended up to a level of 0.25 m above the bed; so mainly bed laod transport.
The silt fraction is suspended up to a level of 1 m above the bed.
The mud fraction with concentrations larger than 10 mg/l (0.01 kg/m^3) is suspended up to a level of 20 m above the bed.
The mixing effect of the weak background flow is too small to generate significant mud concentrations above 20 m.

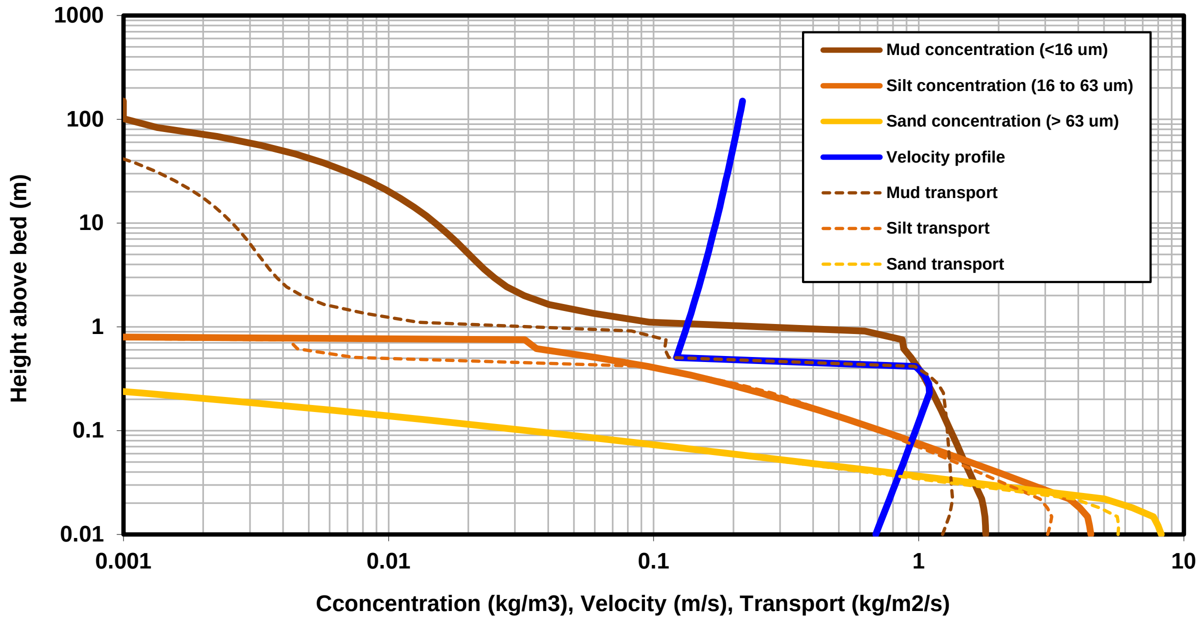

Figure 4.1 *Sediment concentrations and transport of example computation*