C1. Wave friction factor

$$f_{wi} = 0.00251 \exp\left[5.21\left(\frac{2T_{iu}}{T_i}\right)^{c_1}\frac{\hat{a}}{k_{sw}}\right]^{-0.19} \quad \text{for } \frac{\hat{a}}{k_{sw}} > 1.587 \quad (21)$$

$$f_{wi} = 0.3 \quad \text{for } \frac{\hat{a}}{k_{sw}} \le 1.587$$

$$f_w = 0.00251 \exp\left[5.21\left(\frac{\hat{a}}{k_{sw}}\right)^{-0.19}\right] \quad \text{for } \frac{\hat{a}}{k_{sw}} > 1.587 \quad (A.4)$$

$$f_w = 0.3 \quad \text{for } \frac{\hat{a}}{k_{sw}} \le 1.587.$$
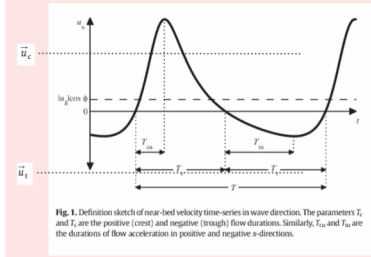
A. Intra-wave velocity time-series

Fig. 1. Definition sketch of near-bed velocity time-series in wave direction. The parameters T_c and T_t are the positive (crest) and negative (trough) flow durations. Similarly, T_{cu} and T_{tu} are the durations of flow acceleration in positive and negative x-directions.

D. Ripple model

$$\mu = \begin{cases} 6 & \text{if } d_{50}\le 0.15\text{mm} \\ 6-\dfrac{5(d_{50}-0.15)}{(0.20-0.15)} & \text{if } 0.15\text{mm}<d_{50}<0.20\text{mm} \\ 1 & \text{if } d_{50}\ge 0.20\text{mm}\end{cases} \quad (A.2)$$

$$\langle|\theta|\rangle = \frac{\frac{1}{2}f_w|u_\delta|^2}{(s-1)gd_{50}} + \frac{\frac{1}{2}f_w\hat{u}^2}{(s-1)gd_{50}} \quad (A.3)$$

$$\eta = \max\{3d_{90}, d_{50}[\mu+6(\langle|\theta|\rangle-1)]\}+0.4\eta^2/\lambda \quad (A.1)$$

$$k_{sw} = \max\{d_{50}, d_{50}[\mu+6(\langle|\theta|\rangle-1)]\}+0.4\eta^2/\lambda. \quad (A.5)$$

C2. Current friction factor

$$f_c = 2\left[\frac{0.4}{\ln(30\delta/k_{sc})}\right]^2 \quad (20)$$

$$(19) \qquad (18)$$

$$\hat{u} = \sqrt{\frac{2}{T}\int_0^T u_w^2(t)\,dt} \quad (8)$$

$$\hat{a} = \frac{\hat{u}T}{2\pi}. \quad (9)$$

$$\tilde{u}_{c,r} = \frac{1}{2}\sqrt{2}\hat{u}_c \quad (10)$$

$$\tilde{u}_{t,r} = \frac{1}{2}\sqrt{2}\hat{u}_t \quad (11)$$

$$u_x(t) = u_w(t) + |u_\delta|\cos\varphi \quad (4)$$

$$u_y = |u_\delta|\sin\varphi \quad (5)$$

$$\vec{u}_{c,r} = \{u_{c,rx}, u_{c,ry}\} = \{\tilde{u}_c + |u_\delta|\cos\varphi, |u_\delta|\sin\varphi\} \quad (12)$$

$$\vec{u}_{t,r} = \{u_{t,rx}, u_{t,ry}\} = \{-\tilde{u}_t + |u_\delta|\cos\varphi, |u_\delta|\sin\varphi\}. \quad (13)$$

$$\theta_i = \frac{\frac{1}{2}f_{wi}|\vec{u}_{i,r}|^2}{(s-1)gd_{50}} \quad (17)$$

calculated by method of eqn 18 but here fw is from eqn. A.4, not eqn. 21

$$(22)$$

wave speed L/T calculated from dispersion relation as approximated by Soulsby (1997)

$$(15)$$

F. Sheet flow thickness

$$\theta_i = \frac{f_w\hat{u}_i^2}{(s-1)gd_{50}} \quad (C.2)$$

$$\frac{\delta_{sl}}{d_{50}} = \begin{cases} 25\theta_i & \text{if } d_{50}\le 0.15\text{ mm} \\ 25-\dfrac{12(d_{50}-0.15)}{(0.20-0.15)} & \text{if } 0.15\text{ mm}<d_{50}<0.20\text{ mm} \\ 13\theta_i & \text{if } d_{50}\ge 0.20\text{ mm}\end{cases} \quad (C.1)$$

B. Entrained sand load

$$\Omega_i = \begin{cases} 0 & \text{if } |\theta_i| \le \theta_{cr} \\ m(|\theta_i|-\theta_{cr})^n & \text{if } |\theta_i| > \theta_{cr}\end{cases} \quad (2)$$

E. Phase lag

$$w_{sc} = w_s - w_{\min}(r_c) \quad (29)$$

$$w_{st} = \max(w_s - w_{\max}(r_t), 0) \quad (30)$$

$$\Omega_{cc} = \begin{cases} \Omega_c & \text{if } P_c \le 1 \\ \dfrac{1}{P_c}\Omega_c & \text{if } P_c > 1\end{cases} \quad (23)$$

$$\Omega_{ct} = \begin{cases} 0 & \text{if } P_c \le 1 \\ \left(1-\dfrac{1}{P_c}\right)\Omega_c & \text{if } P_c > 1\end{cases} \quad (24)$$

$$\Omega_{tt} = \begin{cases} \Omega_t & \text{if } P_t \le 1 \\ \dfrac{1}{P_t}\Omega_t & \text{if } P_t > 1\end{cases} \quad (25)$$

$$\Omega_{tc} = \begin{cases} 0 & \text{if } P_t \le 1 \\ \left(1-\dfrac{1}{P_t}\right)\Omega_t & \text{if } P_t > 1\end{cases} \quad (26)$$

$$P_c = \begin{cases} \alpha\left(\dfrac{1-\xi\hat{u}_c}{c_w}\right)\dfrac{\eta}{2(T_c-T_{cu})w_{sc}} & \text{if } \eta > 0 \text{ (ripple regime)} \\ \alpha\left(\dfrac{1-\xi\hat{u}_c}{c_w}\right)\dfrac{\delta_{sc}}{2(T_c-T_{cu})w_{sc}} & \text{if } \eta = 0 \text{ (sheet flow regime)}\end{cases} \quad (27)$$

$$P_t = \begin{cases} \alpha\left(\dfrac{1+\xi\hat{u}_t}{c_w}\right)\dfrac{\eta}{2(T_t-T_{tu})w_{st}} & \text{if } \eta > 0 \text{ (ripple regime)} \\ \alpha\left(\dfrac{1+\xi\hat{u}_t}{c_w}\right)\dfrac{\delta_{st}}{2(T_t-T_{tu})w_{st}} & \text{if } \eta = 0 \text{ (sheet flow regime)}\end{cases} \quad (28)$$

G. Main function

$$\vec{\Phi} = \frac{\vec{q}_s}{\sqrt{(s-1)gd_{50}^3}} = \frac{\sqrt{\theta_c}\,T_c\left(\Omega_{cc}+\frac{T_c}{2T_{cu}}\Omega_{tc}\right)\frac{\vec{\theta}_c}{\theta_c} + \sqrt{\theta_t}\,T_t\left(\Omega_{tt}+\frac{T_t}{2T_{tu}}\Omega_{ct}\right)\frac{\vec{\theta}_t}{\theta_t}}{T} \quad (1)$$

The colored circles and lines show variables that come from formulas. Each color is specific to a variable. The quantities identified by black rectangles are the following physical constants or tuning parameters:

s=(rho_s-rho)/rho according to section 2 of VDA13

g is the constant of gravity

d50 is the median sand grain size

delta=0.2 m is the wave boundary layer thickness assumed in the VDA13 model

alpha_w = 0.424 is a scale factor for the wave Reynolds stress