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A TOTAL LOAD FORMULA FOR THE NEARSHORE

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Abstract: A total load sediment transport formula based on recent studies on the bed load and suspended load transport for the nearshore is presented . Phase-lag in the sheet-flow layer or due to ripples, as well as acceleration effects, is included in the formula. A sensitivity analysis is performed to better qualify and quantify the current-related and wave-related sediment transport. It appeared that the prediction of the ripple characteristics is fundamental for a proper estimation of the suspended load in the direction of the waves. For the longshore sediment transport where the current-related total load prevails, the formulas are not as sensitive to ripples.

INTRODUCTION

Accurate prediction of sediment transport rates is an important element in morphological studies for the coastal environment. Most of the existing formulas used in numerical models compute current-related sediment transport only. This component of the sediment transport generally prevails in the longshore direction. However, in the cross-shore direction the waves do not only increase the quantity of sediment available for transport, but they also strongly affect the direction of the sediment transport (Dibajnia and Watanabe, 1992; Ribberink and Al Salem, 1994; Van der Werf and Riberink, 2004). First, asymmetric waves induce onshore wave-related sediment transport. Second, phase-lag in the sediment suspension (which occurs in case of ripples or sheet flow) may reduce the total net sediment transport and even induce a net transport opposite to the wave direction. Ribberink and Al Salem (1994) showed that, assuming the velocity ($u(z)$) and concentration ($c(z)$) equal to a constant part ($\overline{u}(z)$ and $\overline{c}(z)$) and a fluctuating part ($\tilde{u}(z)$ and $\tilde{c}(z)$), the net sediment transport rate ($q_{s,net}$) may be written as the sum of a current-related sediment transport and a wave-related sediment transport according to:

$$q_{s,net} = \int_0^h \overline{u}(z)\overline{c}(z)dz + \int_0^h \tilde{u}(z)\tilde{c}(z)dz \qquad (1)$$

where h is the water depth and z a vertical coordinate. Both components of the sediment transport may be significant in the nearshore zone.

A TOTAL LOAD FORMULA

Camenen and Larson (2005a, b; 2006a, b; 2007) proposed a bed load and suspended load formula for the nearshore calibrated with a large amount of data from both laboratory and field measurements, described in the following.

Bed load sediment transport

The bed load transport (q_{sb}) is expressed as follows (Camenen and Larson, 2005a, 2006a):

$$\begin{cases} \dfrac{q_{sb,w}}{\sqrt{(s-1)gd_{50}^{\;3}}} = a_w \sqrt{\theta_{cw,net}}\,\theta_{cw,m} \exp\left(-b\dfrac{\theta_{cr}}{\theta_{cw}}\right) \\ \dfrac{q_{sb,n}}{\sqrt{(s-1)gd_{50}^{\;3}}} = a_n \sqrt{\theta_{cn}}\,\theta_{cw,m} \exp\left(-b\dfrac{\theta_{cr}}{\theta_{cw}}\right) \end{cases} \qquad (2)$$

where the subscripts w and n correspond, respectively, to the wave direction and the direction normal to the wave direction, s ($= \rho_s/\rho$) is the relative density between sediment (ρ_s) and water (ρ), g the acceleration due to gravity, d_{50} the median grain size, a_w, a_n and b are empirical coefficients, $\theta_{cw,m}$ and θ_{cw} the mean and maximum Shields parameters due to wave-current interaction, θ_{cn} the current-related Shields parameter in the direction normal to the wave direction, and θ_{cr} the critical Shields parameter for the inception of transport. The net Shields parameter $\theta_{cw,net}$ in Eq. 2 is given by:

$$\theta_{cw,net} = (1-\alpha_{pl,b})\theta_{cw,on} + (1+\alpha_{pl,b})\theta_{cw,off} \qquad (3)$$

where $\theta_{cw,on}$ and $\theta_{cw,off}$ are the mean values of the instantaneous Shields parameter over the two half periods T_{wc} and T_{wt} ($T_w = T_{wc} + T_{wt}$, in which T_w is the wave period; *cf.* Fig. 1, where φ is the angle between the wave and the current directions), and $\alpha_{pl,b}$ a coefficient for the phase-lag effects (Camenen and Larson 2006a). The Shields parameter is defined by $\theta_{cw,i} = 1/2 f_{cw} U_{cw,j}^{\;2} / \left((s-1)gd_{50}\right)$ with f_{cw} being the friction coefficient taking into account wave and current interaction. Madsen and Grant (1976) suggested that f_{cw} could be obtained as a linear combination of f_c and f_w ($f_{cw} = X_v f_c + (1-X_v) f_w$ with $X_v = |U_c| / \left(|U_c| + U_w\right)$ and U_c being the steady current velocity and U_w the wave orbital velocity amplitude). A constant value on the friction coefficient over the wave period was also assumed when calculating the Shields parameter. Drake and Calantoni (2001), Nielsen (2002, 2006), Antunes Do Carmo *et al.*

(2003), and Watanabe and Sato (2004) showed that in general the wave friction coefficient depends also on the acceleration of the fluid near the bottom and thus may strongly influence the direction of the sediment transport in the wave direction. This effect will be discussed later.

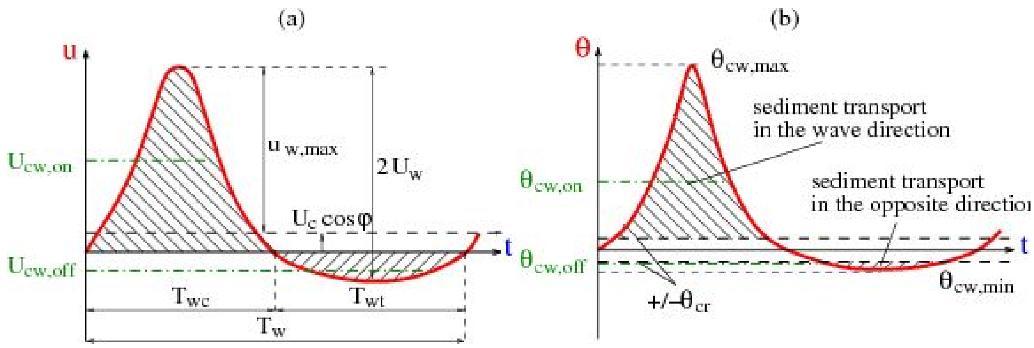

Fig. 1. Schematic view of the instantaneous velocity and shear stress variation over a wave period and in the direction of the waves

Phase-lag effects in the sheet flow layer were included through the coefficient $\alpha_{pl,b} = \alpha_{b,onshore} - \alpha_{b,offshore}$ (Camenen and Larson, 2006a) with:

$$\alpha_{b,i} = \frac{\nu^{0.25} U_{wj}^{\;0.5}}{W_s T_j^{\;0.75}} \exp\left[-\left(\frac{U_{w,crsf}}{U_{wj}} \right)^2 \right] \tag{4}$$

where ν is the kinematic viscosity of water, $U_{w,crsf}$ the critical velocity for the inception of sheet flow, and the subscript j should be replaced either by *onshore* or *offshore*.

Suspended load sediment transport

The suspended sediment load (q_{ss}) may be obtained from (Camenen *et al.*, 2005b; Camenen and Larson 2006b, 2007):

$$\begin{cases} q_{ss,w} = U_{cw,net} \dfrac{c_R \varepsilon}{W_s} \left[1 - \exp\left(-\dfrac{W_s h}{\varepsilon} \right) \right] \\ q_{ss,n} = U_c \sin\varphi \dfrac{c_R \varepsilon}{W_s} \left[1 - \exp\left(-\dfrac{W_s h}{\varepsilon} \right) \right] \end{cases} \tag{5}$$

where c_R is the reference concentration at the bottom, W_s the sediment fall speed, ε the sediment diffusivity, and $U_{cw,net}$ the net mean current ($U_{cw,net} = U_c$ for a steady current). The bed reference concentration is written as follows based on the analysis of a large data set on sediment concentration profiles (see Camenen *et al*., 2005; Camenen and Larson, 2007):

$$c_R = 3.510^{-3}\exp(-0.3d_*)\theta_{cw,m}\exp\left(-4.5\frac{\theta_{cr}}{\theta_{cw}}\right) \tag{6}$$

where $d_* = \sqrt[3]{(s-1)g/\nu^2}\,d_{50}$ is the dimensionless grain size. The sediment diffusivity was related to the total energy dissipation, in which the energy dissipation from wave breaking (D_b) and from bottom friction due to current (D_c) and waves (D_w) were added:

$$\varepsilon = \left(\frac{k_c{}^3 D_c + k_w{}^3 D_w + k_b{}^3 D_b}{\rho}\right)^{1/3} h \tag{7}$$

where k_b, k_c and k_w are coefficients with $k_b = 0.01$ corresponding to an efficiency coefficient related to dissipation due to wave breaking, whereas k_c and k_w are associated with the Schmidt number. Assuming the Rouse parabolic profile to be a correct approximation of the vertical sediment diffusivity, its mean value over the depth may be written as follows, for a steady current or non-breaking waves, respectively:

$$\varepsilon_{c/w} = k_{c/w}\left(\frac{D_{c/w}}{\rho}\right)^{1/3} h = \frac{C_w \sigma_{c/w}}{6}\kappa u_{*c/w} h \tag{8}$$

where $\sigma_{c/w}$ is the Schmidt number or the ratio between the vertical eddy diffusivity of the particles ε_v and the vertical eddy viscosity ν_v, $u_{*,c/w}$ is the shear velocity due to current or waves only, respectively, κ von Karman's constant, and $C_w = 1$ in case of current or $C_w = 2/\pi$ in case of waves (this coefficient results from a time-average assuming a sinusoidal wave). Based on the analysis of experimental data, the following expressions were developed for the Schmidt numbers $\sigma_{c/w}$:

$$\sigma_{c/w} = \begin{cases} A_1 + A_2 \sin^2\left(\dfrac{\pi}{2}\dfrac{W_s}{u_{*,cw}}\right) & if \ \dfrac{W_s}{u_{*,cw}} \le 1 \\ 1 + (A_1 + A_2 - 1)\sin^2\left(\dfrac{\pi}{2}\dfrac{u_{*,cw}}{W_s}\right) & if \ \dfrac{W_s}{u_{*,cw}} > 1 \end{cases} \tag{9}$$

where $A_1 = 0.4$ and $A_2 = 3.5$ in case of a steady current only, and $A_1 = 0.15$ and $A_2 = 1.5$ in case of waves only. For wave-current interaction, a weighted value is used for the Schmidt number, $\sigma_{cw} = X_t\sigma_c + (1 - X_t)\sigma_w$ with $X_t = \theta_c/(\theta_c + \theta_w)$ and θ_c being the current Shields parameter and θ_w the wave Shields parameter.

The net current $U_{cw,net}$ is defined in a similar way to the net Shields parameter $\theta_{cw,net}$ in order to take into account a possible sediment transport due to wave asymmetry, as well as phase-lag in the suspended concentration due to ripple effects (Van der Werf and Ribberink, 2004; Camenen and Larson, 2006):

$$U_{cw,net} = (1-\alpha_{pl,s})U_{cw,on} + (1+\alpha_{pl,s})U_{cw,off} \qquad (10)$$

where $\alpha_{pl,s}$ is the coefficient describing phase-lag effects on the suspended load and $U_{cw,j}$ is the root-mean-square value of the velocity (wave plus current) over the half period T_{wj} (*cf.* Fig.1), where the subscript j should be replaced either by on (onshore) or off (offshore). In the same way as for the bed load formula, phase-lag effects in the suspended load due the ripples were included through the coefficient $\alpha_{pl,s} = \alpha_{s,onshore} - \alpha_{s,offshore}$ (Camenen and Larson, 2006b) with:

$$\alpha_{s,i} = 0.7\left(\frac{U_{cw,i}}{W_s}\right)^{0.5}\left(\frac{H_r}{T_{wi}W_s}\right)^{0.25}\exp\left[-0.25\left(\frac{P_{WR,cr}}{P_{WR}}\right)^4\right] \qquad (11)$$

where $P_{WR} = H_r / d_{50}$ (H_r is the ripple height) is the vortex suspension parameter proposed by Van der Werf and Ribberink (2004) to predict the direction of the net sediment transport. The critical value is reached for approximately $P_{WR} = 100$.

APPLICATION OF FORMULA

Transport by steady current and waves

The proposed formula (Eqs. 2 to 11) was compared to a large set of experimental data with prevailing bed load or suspended load for both field and laboratory measurements, with current only or with waves and current combined (Camenen and Larson, 2005a, b, 2006a, b, 2007). It generally yields the best results with respect to other relationships found in the literature when compared to the compiled data set (*cf.* Tab.1 and previous papers for the description of the data sets). As shown in Tab.1 where the prediction (in %) of the sediment transport within a factor two is presented, an improvement of the results was obtained using Eqs. 2 and 5, especially for the bed load cases and when phase-lag effects start to prevail. For the suspended load, a slightly larger dispersion of the results was observed, but the prediction results were still better for most of the cases. The proposed formula should thus improve the prediction of sediment transport rate in both the longshore and cross-shore directions.

Table 1. Prediction (in %) of total load transport rate within a factor of 2 for different regimes (B: bed load; S: suspended load; C: current; CW: wave and current; SF: sheet flow; and PL: phase-lag)

Authors	B-C	B-CW	SF	S-C	S-CW	S-PL
Bailard (1981)	31	48	45	33	19	1
Dibajnia & Watanabe (1992)	30	38	42	42	22	15
Eq. 2 and 5	78	57	53	37	43	46

Longshore sediment transport

The longshore sediment transport is in general current-related, and the waves act primarily as a stirring agent. As observed by Bayram *et al.* (2001), most of the existing formulas yield similar predictive results, *i.e.*, a cross-shore distribution of the longshore sediment transport that is closely related to the cross-shore distribution of the longshore current. The main difference concerns the magnitude of the sediment transport rate, which may be adjusted trough calibration coefficients. A remaining difficulty to describe in the surf zone is that the total sediment transport is often underestimated on the bar, where the waves break, whereas it is often overestimated in the following trough where the breaking waves change to bores. Also, the longshore sediment transport in the swash zone is often neglected although many observations (Wang *et al.*, 2002; *cf.* also Fig.2) have shown that the magnitude of the longshore sediment transport in the swash might be of the same order as magnitude (or even larger than) the longshore sediment transport over the longshore bar. Baba and Camenen (2007) proposed a simple hydrodynamic model for the swash zone to be able to use the formula presented in this paper. Results of comparison between predictions by the present formula (denoted as the Lund-CIRP formula) and measurements from an experimental case presented by Wang *et al*. (2002) are shown in Fig. 2.

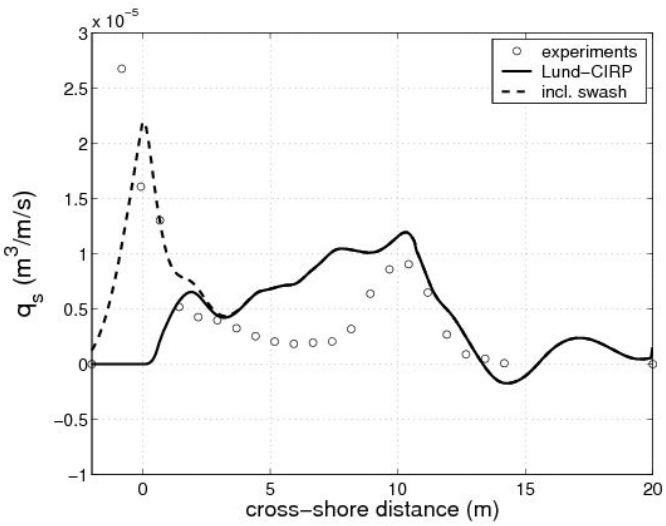

Fig. 2. Cross-shore variation in the longshore sediment transport rate from an experimental case by Wang *et al.* (2002; case 6 with plunging waves)

IMPORTANCE OF WAVE-RELATED TRANSPORT IN CROSS-SHORE DIRECTION

In the cross-shore direction, the current-related sediment transport induces a net transport towards the offshore only (in the direction of the undertow). Including the wave-related sediment transport allows for a possible transport in the onshore direction due to wave asymmetry. However, a complex interaction is obtained that is highly dependent on the bed regime. In case of ripples (offshore zone), the suspended load is prevailing and may be directed offshore due to phase-lag effects, even for strongly asymmetric waves. In a similar manner, in the case of sheet flow (surf zone), the bed load often prevails and it may also be directed offshore due to the phase-lag effects. As a result the total net sediment transport rate along a cross-shore profile may change direction several times and thus induce a multiple bar system. As all these regimes are highly sensitive to ripple predictions and bed shear stress estimates, significant uncertainties in the calculations are expected.

In order to investigate the sensitivity of the formula in the nearshore, a simple model for the hydrodynamics was developed for a cross-shore line based on Larson and Kraus (2002). It includes the wave evolution and asymmetry (Dibajnia *et al.*, 2001), longshore and cross-shore (mean undertow) depth-averaged currents, bed form characteristics (Van Rijn, 1993; or Soulsby and Whitehouse, 2005; assuming wave ripples prevail), induced current and wave-related bed shear stresses, and total sediment load. In Fig.3, results of the hydrodynamic and sediment transport models are presented for a barred beach and estimates of the total load including (d) or not (c) the phase-lag effects, using the Van Rijn formulas (1993) for the ripple characteristics. The roughness height in presence of ripples was calculated with the Kim (2004) formula.

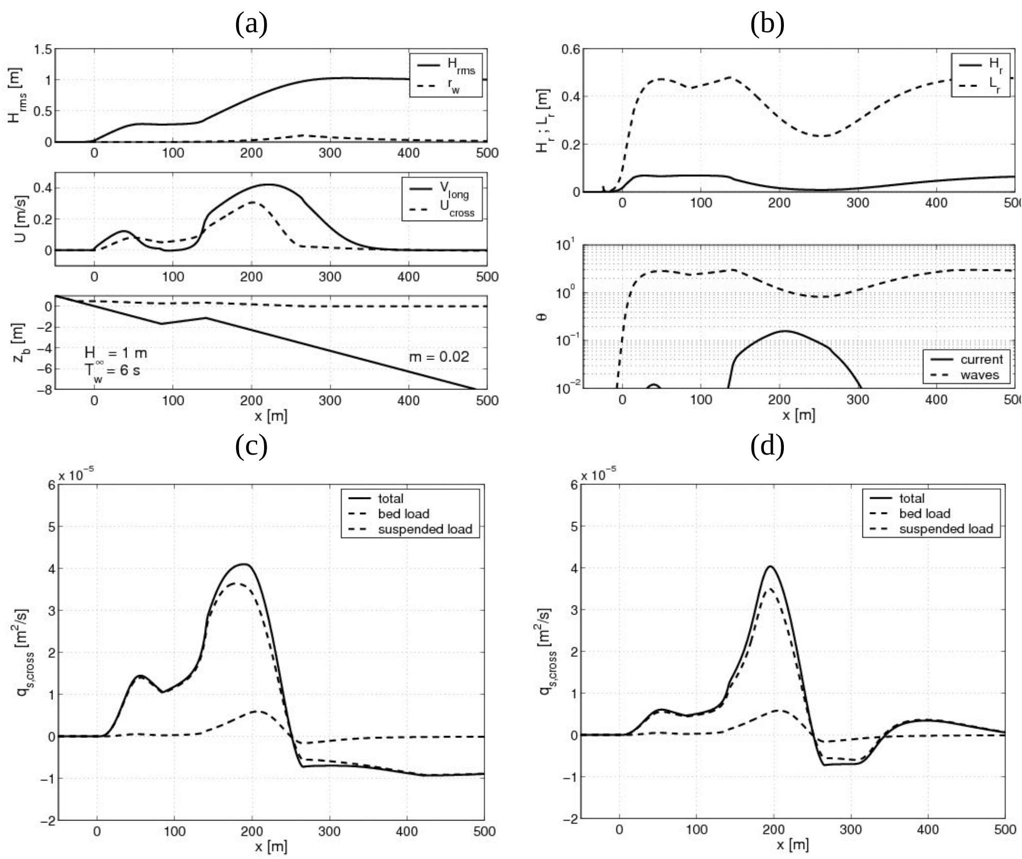

Fig. 3. Test on the sensitivity of ripple predictions using the Van Rijn formula (b) and the induced total load formula with (d) and without (c) the phase-lag effects for typical beach and hydrodynamic conditions (a)

When no phase-lag effects are included, the sediment transport is controlled by the balance between the undertow (which leads to offshore sediment transport) and the wave asymmetry (which leads to onshore sediment transport). If the undertow effects prevail in the surf zone, the wave asymmetry prevails in the offshore zone (cf. Fig.3(c)). A second observation is that the suspended load dominates over the bed load everywhere on a cross-shore line, even in the zone where the ripples are washed out. Fig.3(c) and (d) show how significant the influence of the phase-lag is on the suspended load. Two phenomena occur: First, a reduction of the total sediment flux is observed in the surf zone. Some phase-lag effects are observed since the offshore velocity is larger than the onshore velocity (because of the undertow). This phenomenon may, however, be unrealistic and only an artifact of Eq.11 which allows negative values on $\alpha_{pl,s}$. Second, strong phase-lag occurs in the offshore zone due to the ripples which leads to an opposite direction for the net sediment transport compared to the case when no phase-lag effects are included.

(a) (b)

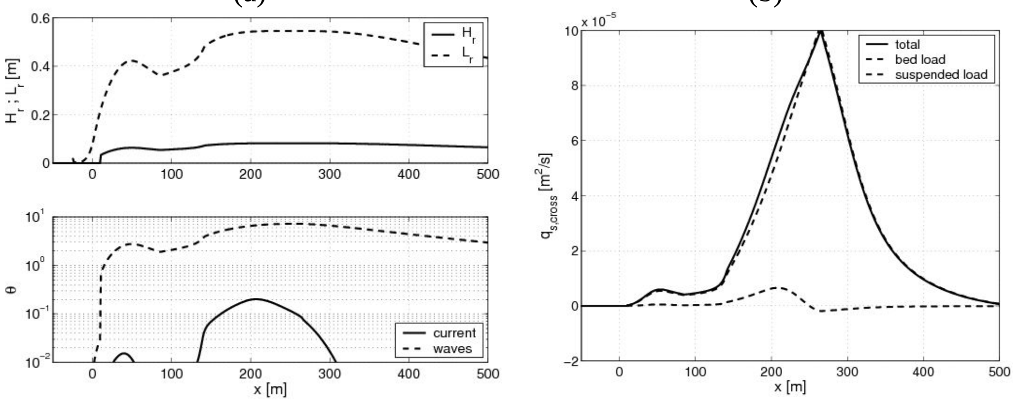

Fig. 4. Test on the sensitivity of the ripple predictions using the Soulsby and Whitehouse formula (a) and the induced total load formula with the phase-lag effects (b) for the same conditions as in Fig.3.

Using the Soulsby and Whitehouse (2005) formulas for the prediction of the ripple characteristics, the results are similar as for the Van Rijn (1993) formula, if the phase-lag effects are not included. However, the presence of ripples on the bar as predicted by the Soulsby and Whitehouse (2005) formula seems unrealistic and induces larger values for the Shields parameter and the suspended load over the bar (cf. Fig. 4(a)). When the phase-lag effects are included, since the Soulsby and Whitehouse formula predicts larger ripple heights on the seaward side of the bar, the phase-lag effects on the suspended load is also stronger. The direction of the net sediment transport is now offshore everywhere on the cross-shore profile. Thus, it seems that the estimate of the ripple characteristics strongly affects the prediction of the net suspended load (and then total load), especially when phase-lag effects are included. The predictors for the ripples characteristics over the domain have to be carefully chosen. Estimation of ripple washout appears to be one of the key issues to improve the prediction of sediment transport in the cross-shore direction.

IMPROVEMENT AND APPLICATION OF FORMULA IN INNER SURF ZONE AND SWASH ZONE

Because of the wave transformation in the surf zone, the wave change to a bore which induces a different velocity profile in the inner surf zone and swash zone (saw-tooth shaped). The asymmetry in the amplitude of the onshore and offshore parts of the velocity may be negligible ($r_w = 0$), but an asymmetry appears in the acceleration profile due the saw-tooth shaped velocity profile (cf. Fig. 5). This asymmetry may be defined with the coefficient $R_{ac} = T_{cu} / T_{cd}$ (for relatively simple wave velocity profile where $r_w = 0$, $R_{at} = T_{tu} / T_{td} = R_{ac}$). On the contrary to T_{wc} and T_{wt}, T_{cu}, T_{cd} T_{tu}, and T_{td} are not function of the steady current U_c and $T_{cu} + T_{cd} + T_{tu} + T_{td} = T_w$. In that sense, the proposed definition slightly differs from the definition proposed by Watanabe and Sato (2004). Watanabe and Sato (2004) observed that an increase in the acceleration asymmetry yields an increase in the suspension at the maximum velocity. They attributed this effect to an increase in the effective near-bed velocity. To treat this problem, Nielsen (2002, 2006) introduced a phase shift between the free stream velocity and the bed shear stress at the peak frequency. This so called "time domain filter method" yields an increase in the instantaneous bottom shear stress for the accelerated part of the flow.

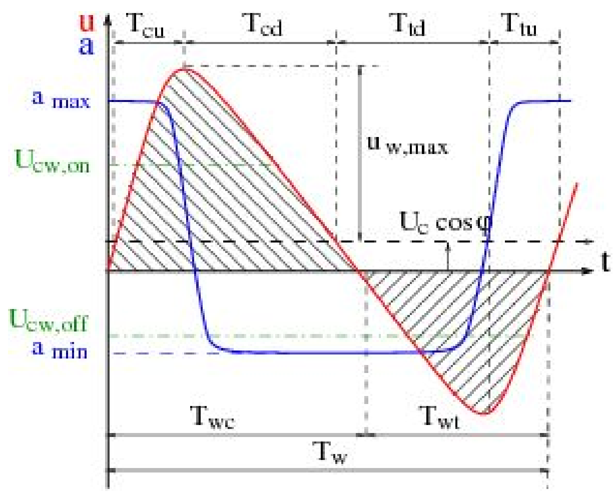

Fig. 5. Schematic view of the instantaneous velocity and acceleration variation for a bore over a wave period and in the direction of the waves

To introduce the effects of the acceleration asymmetry in the bed load formula (Eq. 2), the friction coefficient for wave-current interaction f_{cw} (used for the calculation of the mean shear stress $\theta_{cw,on}$ and $\theta_{cw,off}$) may be modified, assuming that f_{cw} is time-dependent. This modification relies on the assumption that an accelerated flow combined with an increasing velocity yields an increase in the instantaneous friction coefficient (compared to its time-averaged value); an accelerated flow combined with a decreasing velocity yields a decrease in the instantaneous friction coefficient. Eq.3 is thus rewritten:

$$\theta_{cw,net} = (1-\alpha_{pl,b})(1+\alpha_a)\theta_{cw,on} + (1+\alpha_{pl,b})(1-\alpha_a)\theta_{cw,off} \quad (12)$$

where α_a is a coefficient that is a function of R_{ac}. Using the data provided by Watanabe and Sato (2004), the following relationship is proposed:

$$\alpha_a = \frac{1-R_{ac}}{1+R_{ac}} \quad (13)$$

In Fig. 6 is a comparison between the predicted and measured values presented using Eqs.12 and 13 and the experimental data by Watanabe and Sato (2004). About 65% of the data are correctly predicted within a factor two allowed. Even if α_a may also be a function of the medium grain size and the wave period, Eq.13 already yields improved results.

As observed by Nielsen (2006), such an approach requires wave-by-wave analysis for irregular waves which is not very convenient for a simple nearshore model. As a first approximation, a constant value for R_{ac} may be employed also for the case of irregular waves.

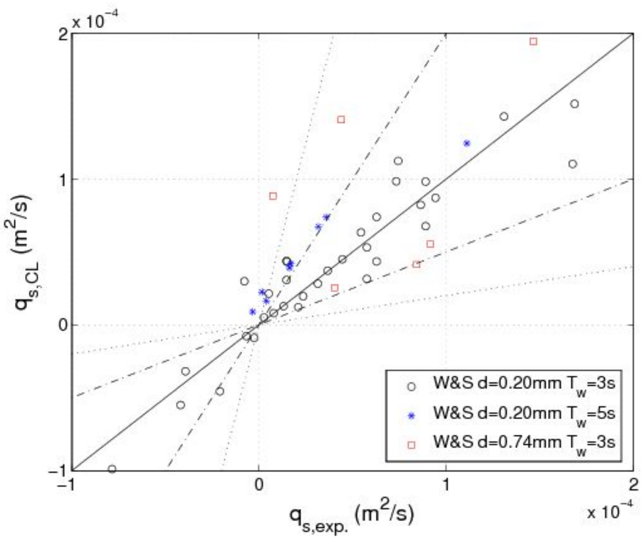

Fig. 6. Comparison between predicted and measured sediment transport rate using Eqs. 2, 12 and 13, and the experimental data from Watanabe and Sato (2004), which illustrates the influence of the acceleration asymmetry

In the same manner as Dibania *et al.* (2001) proposed an empirical relationship for the wave asymmetry across the surf zone (based on a large experimental data set), there is a need of a relationship to estimate the acceleration asymmetry across the surf zone and the swash zone. This latter quantity may be estimated using experimental data and numerical Boussinesq-type wave models.

CONCLUSIONS

A total load sediment transport formula is presented based on recent studies on the bed load and suspended load transports for the nearshore. Phase-lag in the sheet-flow layer or due to ripples, as well as acceleration effects, is included in the formula. This total load formula yields the best results among the studied formulas using a large data set of laboratory and field measurements for various regimes where bed load or suspended load prevails and with possible phase-lag effects in the sheet-flow layer or over the ripples. The formula also appeared to be applicable in the swash zone thanks to a simple hydrodynamic model.

A sensitivity analysis was performed to better qualify and quantify the current-related and wave-related sediment transport. It appeared that the prediction of the ripple characteristics (and the phase-lag effects over the ripples) is fundamental for a proper estimation of the suspended load in the direction of the waves. The ripple washout criterion may be one of the key issues. For the longshore sediment transport where the current-related total load prevails, the formulas are not as sensitive. Some improvement may be made for the effects of the breaking waves and rollers on the suspension.

Finally, the formula was improved to include the effects of a possible acceleration asymmetry in the wave velocity profile. The formula yields correct results compared to the experimental data by Watanabe and Sato (2004). There is however a need of a simple model to estimate the acceleration asymmetry across the surf zone and the swash zone.

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