Characteristics of Sediment Concentration and Suspended Sediment Transport Due to Horizontal and Vertical Asymmetric Waves

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Abstract

Wave phenomenon in ocean often has the shape in the horizontal and vertical asymmetric waves when propagating in the near-zone with high non-linearity. The orbital velocity due to the wave asymmetries and nonlinearities could generate the flow patterns that drives cross-shore sediment transport in the near-shore zone. A new calculation method for bottom shear stresses and bed-load sediment transport rate for the horizontal and vertical asymmetries waves proposed by¹² was implemented to model the concentration sediment and suspended sediment transport. The characteristics of the concentration sediment and suspended load induced by the horizontal and vertical asymmetrical waves have been examined. The modeling results showed that the smaller α and the higher Ni indicate more wave skew-ness and more non-linearity of waves causing a higher the bottom shear stress and the net bed load transport while the net suspended load transport decrease with the decreasing of the wave skew-ness. The higher skewed waves indicated the higher acceleration causing increase the value of the net onshore transport rate for bed load sediment transport and decrease the value of the net offshore transport rate for suspended sediment transport.

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1. Introduction

Bottom shear stress estimation is the most important step required as an input to all the practical sediment transport models. An accurate prediction of sediment transport rate is of utmost importance in morphological studies of river, coastal and marine environment. Realistic waves in nature often have a shape of horizontal and vertical axes asymmetry when propagating in the near-shore. Ocean wave propagate into near-shore, several effect of non-linear, asymmetric, velocity and acceleration skewness occur and play a fundamental role in the particle motion and sediment transport. Ocean waves with a strongly non-linear shape with respect to horizontal and vertical axis caused the net sediment transport over a complete wave cycle is non-zero, while for symetris wave gave the net sediment transport is zero, e.g.1,2,3,4,5. Thus, waveform in the ocean has a significant influence in coastal morphological change6. A new method for calculating the bottom shear stress under skew waves has been proposed and applied to sheet flow sediment transport modelling validated by sediment transport experimental data from7 with zero velocity skewness. In the present study, the new calculation method of bottom shear stress proposed by1,2 were used to evaluate the near-shore waves with velocity and acceleration skewness and it is applied to calculate the sediment concentration and suspended load sediment transport induced by horizontal and vertical asymmetric waves. Recently, the characteristics of the bottom shear stress and sediment transport for acceleration-skewed waves has been examined in variation of the sediment median diameter i.e. 0.001mm, 0.05 mm, 0.10 mm and 0.20 mm by8. However, the characteristics of the concentration sediment and suspended load induced by the horizontal and vertical asymmetries waves have been not examined, the latter of which will be achieved in the present study.

2. The Definition of Horizontal and Vertical Asymmetric Waves

![Fig. 1. Definition sketch for (a) horizontal and (b) vertical asymmetric waves](image)

The definition sketch for horizontal and vertical asymmetric waves are shown in Fig. 1(a) and 1(b) as shown in1,2,9. Here, $U_c$ is the velocity at wave crest, $T$ is wave period, $t_p$ is time interval measured from the zero-up cross point to wave crest in the time variation of free stream velocity. $N_i =\frac{U_c}{\bar{u}}$ is the non-linearity index, $\bar{u}$: the total velocity amplitude, $\alpha$ is the wave skewness parameter. The smaller $\alpha$ and the higher $N_i$ indicate more remarkable wave skewness and non-linearity, respectively, while the symmetric wave without skewness and non-linearity have $N_i=0.50$ and $\alpha=0.50$.

3. Model Description

1.1. Bottom shear stress calculation method

The new calculation method of bottom shear stress under skew waves is based on incorporating velocity and acceleration terms provided through the instantaneous wave friction velocity, $U^*(t)$ as given in Eq. (1). Both velocity and acceleration terms are adopted from the calculation method proposed by10. The phase difference was determined from an empirical formula for practical purposes1. In the new calculation method a new acceleration coefficient, $a_i$ is
used expressing the wave skew-ness effect on the bottom shear stress under saw-tooth waves, that is determined empirically from experimental and BSL $k$-$\omega$ model results. The instantaneous friction velocity, can be expressed as:

$$\tau_w(t) = \rho U^* U'(t)$$

Here $\tau_w(t)$ is the instantaneous bottom shear stress, $t$ is time, $\sigma$ is the angular frequency, $U(t)$ is the time history of free stream velocity, $U^*$ is the time average of free stream velocity, $f_w$ is the wave friction factor. The value of acceleration coefficient $a_c$ is obtained from the average value of $a_c(t)$ calculated from experimental result as well as the BSL $k$-$\omega$ model results of bottom shear stress. The results of averaged value of acceleration coefficient $a_c$ from both experimental and numerical model results as function of the wave skew-ness parameter, $D$ and as function of the non-linearity index, $N_i$ are then plotted. Hereafter, an equation based on regression line to estimate the acceleration coefficient $a_c$ as a function of $D$ and $N_i$ is proposed as:

$$a_c = -0.36 \ln(\alpha) - 0.249 \quad \text{for horizontal axes asymmetry waves}$$

$$a_c = 0.592 \ln(N_i) + 0.411 \quad \text{for vertical axes asymmetry waves}$$

The increase in the wave skew-ness (or decreasing the value of $\alpha$) and in the wave non-linearity, $N_i$ brings about an increase in the value of acceleration coefficient, $a_c$. For the symmetric wave where $\alpha = 0.500$ and $N_i = 0.500$, the value of $a_c$ is equal to zero.

### 1.2. Bed-load sediment transport model

The instantaneous bed-load sediment transport rate, $q(t)$ is expressed as function of the Shields number $\tau^*(t)$ as given in the following expression,

$$q(t) = A w^*(t) \left\{ \left[ w^*(t) \right]^{0.5} \left[ w^*(t) - w^*_{cr} \right] \right\}$$

Here, $w(t)$ is the instantaneous the dimensionless sediment transport rate, $\rho_s$ is bottom material density, $g$ is gravitational acceleration, $d_{50}$ is median diameter of sand particle, $A$ is coefficient, $\text{sign}$ is the sign of the function in the parenthesis, $w^*(t)$ is the Shields parameter defined by $((w(t)/(\rho_s/\rho - 1)gd_{50}))$ in which $w(t)$ is the instantaneous bottom shear stress. In the new bed-load transport rate formula the bottom shear stress was calculated from Eq. (2).

The net sediment transport rate, which is averaged over one-period is expressed as follows

$$\Phi = AF = \frac{1}{T} \int_0^T w^*(t) \left\{ \left[ w^*(t) \right]^{0.5} \left[ w^*(t) - w^*_{cr} \right] \right\} dt$$

Here, $\Phi$ is the dimensionless net sediment transport rate, $F$ is the function of Shields parameter and $q_{sw}$ is the net sediment transport rate in volume per unit time and width. In this study, the roughness high ($k_s$) was defined $k_s = 2.5 \ d_{50}$. Thus, a constant $A$ used is 11. Moreover, the integration of Eq. (4) was assumed to be done only in the phase $|\tau^*(t)| > \tau^*_{cr}$ and during the phase $|\tau^*(t)| < \tau^*_{cr}$ the function of integration is assumed to be 0.

### 1.3. Suspended sediment transport model

The total suspended rate ($qs$) may be found by integration from:
In which \(c(z)\) is the actual concentration value, \(c_a\) is a reference concentration at height \(z_a\) as a reference level and \(w_s\) is a settling velocity given in Eq. (7), Eq (8) and Eq (9), respectively.

\[
\frac{c(z)}{c_a} = \left[\frac{z_a(h-z)}{z(h-z_a)}\right]^{\frac{w_s}{ku}} (7)
\]

\[
C_a = \frac{0.331 (z^2 - 0.045)^{-1.75}}{1+0.72 (z^2 - 0.045)^{-1.75}} (8)
\]

\[
z_a = 2.5D_{50} (9)
\]

\[
w_s = \frac{1}{D} \left[\left(10.36^2 + 1.049D_{50}^2\right)^{\frac{1}{2}} - 10.36\right] \text{ for all } D. (10)
\]

2. Results and Discussion

Fig 2. Presented the net bed load, suspended load and total load sediment transport in variation with the value of \(N_i\), it can be seen that the value of bed load and suspended load sediment transport increased in line with the increase in the value of \(N_i\). However, the increase in value of suspended load is not as high as with the bed load sediment transport, for the low values of \(N_i\), the suspended sediment transport is more dominant than the bed load sediment transport, while the sediment is the sum total bed load and suspended load sediment transport. This is because the value of sediment transport is expressed in the function parameter shield and shield critical parameter, which automatically has a close relationship with the value of shear stress. Therefore, if the value the greater the shear stress will also be an increase in the value of sediment transport.
the smaller the value of $z$, the acceleration is increasing. While sediment concentrations were also having the same tendency that when the wave experience greater acceleration, then the sediment concentration before the peak ($t = 0.4$ s) also becomes larger.

Fig. 3. Orbital velocity in variation with the value of Ni for $t = 0.45$ s

Fig. 4. Sediment concentration in variation with the value of Ni for $t = 0.45$ s
Fig. 5. Orbital velocity in variation with the value of $D$ for $t = 0.40$ s

Fig. 6. Sediment concentration in variation with the value of $D$ for $t = 0.40$ s
3. Conclusions

The characteristics of the bottom shear stress, bed-load and suspended sediment transport rate including the sediment concentration due to the horizontal and vertical asymmetric waves motion in variation of the wave skewness ($\alpha$), the wave nonlinear ($N_i$) and the median sediment diameter ($d_{50}$) were investigated. The new calculation method of bottom shear stress for skew and asymmetric waves given a good agreement with the experimental data. The inclusion of the acceleration effect in the calculation bottom shear stress has significantly improved the net sediment transport rate. The modeling results showed that the smaller $\alpha$ indicate more wave skew-ness and the higher $N_i$ causing a higher the bottom shear stress and the net bed load transport while the net suspended load transport decrease with the decreasing of the wave skew-ness and the wave asymmetric, respectively. The higher skewed waves and the higher wave asymmetric indicated the higher acceleration causing increase the value of the net onshore transport rate for bed load sediment transport and decrease the value of the net offshore transport rate for suspended sediment transport. Thus the proposed method can be used to modelling sediment transport and morphological change in practical applications.

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