Study on Turbulent Bottom Boundary Layer under Non-linear Waves and Its Application to Sediment Transport

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論文内容要旨

Sediment transport induced by wave motion with and without superimposed by currents is one of the most important factors affecting coastal morphology and cross-shore profile evolution. In addition, an accurate prediction of sediment transport rate is of utmost importance in morphological studies of river, coastal and marine environment. Shape of the near-bed wave orbital velocity is a key parameter governing cross-shore sediment transport under breaking and near-breaking waves. Realistic waves in nature often have a shape of saw-tooth or skew waves and asymmetric waves when propagating in the nearshore. Their height increases and length decreases, during this process. Moreover, both wave velocity skewness and asymmetry reach their maximum value at the onset of breaking. The wave asymmetry and skewness play an important role for the occurrence of the net onshore-directed transport rate (accretion) and that of the net offshore-directed transport rate (erosion) of the beaches.

Many studies have been published on wave boundary layer and bottom friction associated with sediment movement induced by sinusoidal wave motion. These studies have shown that the net sediment transport over a complete wave cycle is zero. In reality, however ocean waves often have a strongly non-linear shape with respect to horizontal and vertical symmetry axes. The skew wave represents the asymmetric acceleration along wave cycle related with the skewness parameter, whereas the asymmetric wave depicts the asymmetry of the near-bottom velocity between wave crest and trough and is expressed by the asymmetry parameter. It is envisaged that velocity profile, bottom shear stress and sediment transport behaviors having the effect of acceleration in the asymmetry and the skewness of the wave are different from those in sinusoidal waves. Therefore, the asymmetric and skew waves cause a net cross-shore transport of sediment over a complete wave cycle.

Bottom shear stress estimation is the most important step, which is required as an input to all the practical sediment transport models. Therefore, the estimation of bottom shear stress from a sinusoidal wave is of limited virtue in connection with the sediment transport estimation unless the acceleration effect is incorporated therein. Moreover, for a predictive near-shore morphological model, more efficient approach to calculate the bottom shear stress is required rather than a complex two-phase model. Thus, an understanding of the turbulence structure under asymmetric and skew waves motion, accurate estimation of bottom shear stress are vital factors to accurately predict sediment transport rate and resulting morphological changes in estuarine, coastal and marine environments.

Structure of turbulent wave boundary layers with asymmetry about horizontal and vertical axes under sawtooth and cnoidal wave, respectively were investigated in this study. Therefore, experiments were conducted in an oscillating tunnel over rough bed with air as the working fluid and smoke particles as tracers. The velocity distributions were measured by means of Laser Doppler Velocimeter (LDV). The measured flow velocity record was collected by means of an A/D converter with 1/100s intervals, and the mean velocity profile variation was obtained by averaging over 50 wave cycles. According to Sleath (1987) that for turbulent condition at least 50 wave cycles are needed to successfully compute statistical quantities. The characteristics of the turbulent boundary layer both under sawtooth and asymmetric (cnoidal) waves were investigated according to the wave skewness and the wave non-linearity. It was observed that the mean velocity, turbulent intensity and bottom shear stress under sawtooth and cnoidal waves have different characteristics with that of under sinusoidal waves. Four versions of two-equation model (the original k-ε model, and three versions of the k-ω model, namely Wilcox (1988) k-ω model, and (baseline) BSL and (shear stress transport) SST k-ω model proposed by Menter (1994)) were also employed to study the boundary layer characteristics. Moreover, a quantitative comparison among turbulence models and experimental data was made.

The basic idea of the BSL k-ω model is to retain the robust and accurate formulation of the Wilcox k-ω model in the near wall region, and to take advantage of the free stream independence of the k-ε model in the outer part of boundary layer. It means that this model is designed to give results similar to those of the original k-ω model of Wilcox, but without its strong dependency on arbitrary free stream velocity values. The BSL model gives results similar to the k-ω model of Wilcox in the inner of boundary layer but changes gradually to the Jones-Launder k-ε model towards to the outer boundary layer and the free stream velocity. While, the SST k-ω model is claimed to be more accurate and reliable for wider class of flow than the standard k-ε model as well as the original k-ω model, including the improvement of prediction for adverse pressure gradient flow. In the SST k-ω model the definition of eddy viscosity is modified to account for the transport effects of the principal turbulent shear stress. The governing equations and boundary conditions used for the SST k-ω model are similar to those for BSL k-ω model but the new definition of eddy viscosity was used in this model.

The mean velocity distribution under non-linear waves (i.e sawtooth and cnoidal waves) has shown the different characteristics with that of under sinusoidal waves. Both for experimental and the turbulence model results, the velocity overshoot is much influenced by the effect of acceleration and the velocity magnitude. The velocity overshooting is different appearance on the crest and trough part as shown at the phases B and F for the cases SK1, SK2 and SK3 caused by the difference of acceleration according to the asymmetric acceleration along wave cycle for sawtooth waves. This difference was not visible for Case SK4 with α= 0.500 corresponds to the symmetric wave without skewness. Such characteristics also occurred for the cnoidal waves in which the velocity overshoot at phases of B, C and D are higher than that of at phases of F, G and H. The mean velocity close to the bottom increase as increasing of the wave non-linearity parameter Ni according to the increasing of acceleration effect at the crest part of wave flow. Case CN1 with N_i=0.67 shows the mean velocity close to the bottom is higher than other cases.

A higher level of turbulent intensity in the negative cycle flow for waves which have the higher wave skewness (i.e cases SK 1, SK 2, and SK 3) was attained at the beginning of acceleration phase, while in the positive cycle flow higher u' occurs at the beginning of deceleration phase. However this phenomenon was different from Case SK 4 for α= 0.500, in which a higher level of turbulent intensity in the negative cycle and in the positive cycle flow was attained at phases C and G, respectively due to the higher mean velocity at crest and trough of wave.

Increasing the wave non-linearity parameter N_i causes the lie of the almost uniform turbulent intensity distribution shifts more stay away from the phase where the free-stream velocity is zero, on the contrary for the wave with the wave non-linearity parameter N_i approaches a value of 0.50 (where N_i = 0.5 is for symmetric wave or sinusoidal wave), the lie of the almost uniform turbulent intensity distribution is closer to the phase where the free-stream velocity is zero at phases A and E.

The BSL k-ω model shows comparatively better performance of prediction than others models compared for all experimental data of sawtooth and cnoidal waves in the whole range of phases. The second better one is the k-ε model followed by the k-ω model and the SST k-ω model, respectively. All turbulence models satisfactory predicted the velocity overshooting as one characteristics of typical wave boundary layer.

Although, the SST k-ω model in general showed the most weak performance prediction than others models, however this model has given a more excellent agreement with experimental results for almost all cases of sawtooth and cnoidal waves at phases A and E. It emphasizes that the SST k-ω model lead to major improvements in the prediction of adverse pressure gradient flow in which this pressure dictates the boundary layer flow to reverse.

All turbulence models prediction of turbulent intensity far from the bed is generally good, while near the bed is not so much in good agreement. However, the prediction model qualitatively produces very good indication of the pattern of turbulence generation and it mixing. Moreover, the BSL k-ω model shows as the most superior prediction model followed by the k-ε model, the k-ω model and the SST k-ω model, respectively.

Because the velocity distribution near a rough bed for steady flow is logarithmic. It may be therefore assumed that log-law can be used to estimate the time variation of bottom shear stress $\tau_o(t)$ over rough bed as shown by previous studies (Jonsson and Carlsen (1976) and Hino et al. (1983)). Bottom shear stress under saw-tooth and cnoidal waves produced an asymmetric shape on both crest and trough. The asymmetric of bottom shear stress are caused by wave skewness effect corresponding with acceleration effect but for that of cnoidal waves are caused by wave non-linearity effect corresponding with acceleration effect. Both increasing of wave skewness and wave non-liinearity are followed by increasingly the asymmetric of bottom shear stress, otherwise for the wave without skewness and asymmetric is close to a symmetric shape, as seen in Case SK4 for $\alpha = 0.500$.

Moreover, due to wave non-linearity, the wave-induced the bottom shear stress distribution is characterized by a large peak over a very short time interval preceding the wave crest. These characteristics are much more obvious for the higher non-linear wave case. As seen that Case CN1 produced a largest peak over shortest time interval preceding the wave crest than others cases. On contrary, CN3 produced smallest peak over longest time interval preceding the wave crest than others cases.

In order to find a more reliable bottom shear stress calculation method under non-linear waves a new calculation method (Method 3) is proposed incorporating both velocity and acceleration terms, that is given through the instantaneous friction velocity, $U^*(t)$ as given in Eq. (1). Both velocity and acceleration terms are adopted from a calculation method proposed by Nielsen (1992, 2002) (Method 2). But that method could not give a good agreement with experimental data as shown by Suntoyo et al. (2004) for sawtooth waves. In the new calculation method is therefore proposed a new acceleration coefficient, a_c expressing both the wave skewness effect on the bottom shear stress under sawtooth waves and the wave non-linearity (asymmetric) effect for cnoidal waves, that are determined empirically from both experimental and BSL k-ω model turbulent model results. The instantaneous bottom shear stress can be calculated proportional to the square of the proposed instantaneous friction velocity, as shown in Eq. (2),

$$U*(t)=\sqrt{f_w/2}\left\{U\left(t+\frac{\varphi}{\sigma}\right)+\frac{a_c}{\sigma}\frac{\partial U(t)}{\partial t}\right\} \tag{1}$$

$$\tau_o(t)=\rho U*(t)\left|U*(t)\right| \tag{2}$$

Here, a_c is the value of acceleration coefficient obtained from the average value of a_c(t) calculated from experimental result as well as the BSL k-ω numerical model results of bottom shear stress expressed in Eq. (3). Hereafter, an equation based on regression line to estimate the acceleration coefficient a_c as function of α (the wave skewness) as well as function of N_i (the wave non-linearity) was proposed. The increase in the wave skewness or decreasing the value of α as well as the increase in the wave non-linearity (increasing the value of N_i brings out the increase of the value of acceleration coefficient, a_c. It was observed that for the symmetric wave without skewness and non-linearity which has $\alpha = 0.500$ and $N_i = 0.50$, the value of a_c is equal to zero.

$$a_c(t)=\frac{U*(t)-\sqrt{f_w/2}\,U\left(t+\frac{\varphi}{\sigma}\right)}{\frac{\sqrt{f_w/2}}{\sigma}\frac{\partial U(t)}{\partial t}} \tag{3}$$

The physical meaning of a_c indicates that the increasing the wave skewness and the wave non-linearity will give the higher value of a_c that will produce the higher value of acceleration term on the bottom shear stress. Otherwise the acceleration term on the bottom shear stress will decrease due to decrease the value of a_c according to decreasing the wave skewness of wave and when the wave is symmetric as sinusoidal wave, so the value of a_c is zero that means that the acceleration term is not significant for calculating the bottom shear stress under sinusoidal wave. Therefore, for sinusoidal wave the acceleration term is not the significant factor on calculation in Method 3, because Method 3 will be equal to Method 1 (usual bottom shear stress calculation method without acceleration term).

Moreover, a relation of phase difference proposed has given very good agreement with phase difference of experimental data for sawtooth waves cases with variation in the value of α. Therefore, it can be concluded that the formula proposed in the present study has been able to express the characteristic of phase difference under sawtooth waves and it further can be used to evaluate the bottom shear stress under sawtooth waves.

Performance of the bottom shear stress calculation methods and the BSL turbulence model has been examined trough the Root-Mean-Square Error (*RMSE*). Method 3 has highest performance than others methods for all cases with *RMSE* = 1.91 for Case SK1, *RMSE* = 1.71 for Case SK2, *RMSE* = 1.78 for Case SK3 and *RMSE* = 1.74 for Case SK4. For cases SK1 and SK2 Method 2 is better than Method 1, while for cases SK3 and SK4 Method 1 is better than Method 2. The performance prediction of the BSL k-ω model is closer to Method 2 and Method 3 than Method 1 for case SK1 and SK2, whereas for cases SK3 and SK4 are closer to Method 1 and Method 3 than Method 2. It can be concluded that the new method (Method 3) can be used to estimate the bottom shear stress under sawtooth waves for higher wave skewness up to the symmetric wave without skewness for $\alpha = 0.500$ with highest performance than others method.

For cnoidal waves, Method 3 has also shown the highest performance than others methods for all cases with *RMSE* = 1.84 for Case CN1, *RMSE* = 2.13 for Case CN2 and *RMSE* = 2.14 for Case CN3. Method 1 gives the better performance than Method 2 for cases CN1 and CN2 otherwise for Case CN1 Method 2 is better than Method 1. The performance prediction of the BSL k-ω model is closer to Method 3 than Method 1 as well as Method 2 for all cases. Moreover, it can be observed that the performance of Method 2 decreases as decreasing the wave non-linearity index. It can be concluded that the new method (Method 3) can be used to estimate the bottom shear stress under cnoidal waves (asymmetric waves) for higher wave non-linearity up to the symmetric wave for $N_i = 0.50$ with highest performance than others method. Although the acceleration term has been included in Method 2, however Method 2 gave over estimate value especially at positive wave cycle for all cases. It indicated that Method 2 was not a reliable method for calculating the bottom shear stress under cnoidal waves.

Furthermore, both the phase difference and the acceleration coefficient defined in the new method were sufficient for these calculations. It can be concluded that the new method for calculating the instantaneous bottom shear stress both under sawtooth waves and cnoidal waves proposed in this present study has a sufficient accuracy. Therefore, this method can be used to an input sediment transport model under rapid acceleration in a practical application.

The new calculation method of bottom shear stress based on incorporating both the acceleration and velocity terms proposed in the present study is further applied to formulate the sheet-flow sediment transport rate under skew wave by using the experimental data from Watanabe and Sato (2004). The number of the net sediment transport data induced by skew waves alone is 33 data. At first, the instantaneous sheet flow sediment transport rate $q(t)$ is expressed as function of the Shields number $\tau^*(t)$ as given in the following expression,

$$\Phi(t) = \frac{q(t)}{\sqrt{(\rho_s/\rho - 1) g d_{50}^{\,3}}} = A\ sign\{\tau^*(t)\}|\tau^*(t)|^{0.5}\{|\tau^*(t)| - \tau^*_{cr}\} \qquad (5)$$

Here, $\Phi(t)$ is the instantaneous the dimensionless sediment transport rate, ρ_s is bottom material density, g is gravitational acceleration, d_{50} is median diameter of sand particle, A is coefficient, *sign* is the sign of the function in the parenthesis, $\tau^*(t)$ is the Shields parameter defined by $(\tau(t)/(((\rho_s/\rho)-1)gd_{50}))$ in which $\tau(t)$ is the instantaneous bottom shear stress calculated from both Method 1 and Method 3. While τ^*_{cr} is the critical Shields number calculated using the next expression as proposed by Tanaka and To (1995).

The net sediment transport rate, which is averaged over one-period is expressed in the following expression according to Eq. (5).

$$\Phi = A\,F = \frac{q_{net}}{\sqrt{(\rho_s / \rho - 1) g {d_{50}}^3}} \tag{6}$$

$$F = \frac{1}{T} \int_0^T sign\{\tau^*(t)\} |\tau^*(t)|^{0.5} \{ |\tau^*(t)| - \tau^*_{cr} \} \; dt \tag{7}$$

Here, ν is kinematics viscosity, Φ is the dimensionless net sediment transport rate, F is the function of Shields parameter and q_{net} is the net sediment transport rate in volume per unit time and width. Moreover, the integration of Eq. (7) is 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.

First of all, the wave velocity profile, $U_w(t)$ which was obtained from the time variation of acceleration of cnoidal wave theory first order by its integrating at the time as provided in the experimental of Watanabe and Sato (2004) are applied to calculate the bottom shear stress by using Method 1 and Method 3. The relation between the dimensionless net sediment transport rate (Φ) of experimental results and the function of bottom shear stress F, which has been averaged by one wave cycle is further examined by Method 1. Method 1 could not explain the net sediment transport rate over a complete crest and trough cycle, because the integral value of F for a complete one cycle is zero. In other word, it can be concluded that the bottom shear stress calculation method, which only consider the velocity term (Method 1) may not be applied for calculating the net sediment transport rate under skew waves. Because of the acceleration effect has been included in Method 3, it then causes the bottom shear stress at crest and trough part became the asymmetric one for example calculation, and therefore the integration value F defined by Eq. (7) was not zero. Moreover, the obtained relation has given a good linear relation between F and the dimensionless net sediment transport rate Φ was seen. Thus, a constant A shown in Eq. (6) was obtained as the result of 11.

The new calculation method of bottom shear stress (Method 3) has been applied to the net sediment transport experimental data intended for sheet flow by Watanabe and Sato (2004) and empirical formula was obtained. Moreover, the characteristic of the net sediment transport was also examined and good agreement between calculation and experimental results have been obtained. In addition, incorporating the acceleration effect in calculation of bottom shear stress also has given a significant effect on the net sediment transport calculation under cnoidal waves. Therefore, the new calculation method of bottom shear stress and bed load sediment transport rate proposed in the present study may improve the accuracy of sediment transport model for non-linear waves according to the beach morphological change model.

論文審査結果の要旨

波動下における漂砂量は底面摩擦力と密接な関係を有している．このため，波動下における底面摩擦に関する多くの研究がなされてきた．しかし，これまでその多くは正弦波を対象として行われてきた．しかし，現実の波浪は浅海域に伝搬するにつれ非線形性が強まり，正弦波からのずれが顕著になる．これに伴い加速度の効果が顕在化し，従来の正弦波とは異なるせん断力特性・漂砂特性を示すものと予想される．しかし，このような底面摩擦・漂砂特性を扱った研究例はきわめて少ない．このような背景を考慮し，本研究においては，非線形波動下における乱流境界層特性について検討を行い，底面せん断力の算定手法に関する研究を行った．

第１章では本研究の背景，目的およびその意義について述べている．

第２章においては，波動境界層に関する研究のレビューを行い，特に非線形波動のもとでの底面せん断力に関する知見が不足していることを明らかにした．

第３章においては，実験手法について述べている．作業流体には，水に比べて扱いが容易である空気を用い，流速鉛直分布から，対数分布則を用いて底面せん断力を求めている．これまで多用されている正弦波の実験手法とは全く異なり，任意の波形を入力する手法について述べており，重要な成果である．

第４章では，数値計算に使用するモデルについて述べている．これまで，k-εモデルをはじめとする乱流モデルは定常流れに適用されることが多く，非定常運動への応用例は少ない．本章では，非定常運動での乱流モデルの計算手法について詳述しており，貴重な成果である．

第５章では，代表的な非線形波動として，砕波帯内の波浪を模擬する前傾化した波動を取り上げ，底面摩擦に関する実験を行った．実用に供することが容易な簡便な底面せん断力算定式として，主流速の二乗に比例すると仮定する算定法，Nielsen (2002) による手法のいずれの方法においても，波形が前傾化するにつれて峰位相における算定精度が低下することを示した．そこで，加速度効果を加味した新たな係数を提案し，これを室内実験により定めた．また，実験値との比較により，その精度が十分であることを示した．これは，海岸工学上重要な成果である．

第６章では，二つめの非線形波動としてクノイド波を取り上げ，先の前傾化した波動と同様に，加速度効果を加味した新たな係数を提案し，これを室内実験により定めた．また，実験値によりその検証を行った．これは，海岸工学上重要な成果である．

第７章では，第５，６章の成果を漂砂現象に応用し，その定式化の過程において加速度効果を加味することの重要性を示した．この結果は，今後の海浜変形シミュレーションにおいて勘案すべき重要な成果である．

第８章は結論と今後の課題を示したものである．

以上要するに，非線形波動下に底面境界層特性を明らかにし，また，漂砂現象への応用手法を示しており，海岸工学分野の発展に寄与するところが少なくない．

よって，本論文は博士(工学)の学位論文として合格と認める．