WAVE SKEWNESS AND ASYMMETRY STUDY USING WAVE PHASE RESOLVING MODEL

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INTRODUCTION

Recent research has revealed the contribution of wave skewness and asymmetry effects to the onshore sediment transport during low to mild wave conditions (Hsu et al, 2006). Efforts were made to include these mechanisms in cross-shore transport models using parameterisation approach (Dubarbier et al, 2015). Due to the simplicity and efficiency reasons, the majority of the existing practical coastal morphology models are based on phase-averaged method, in which the required wave non-linearity effects on near-bed sediment transport are estimated using empirical or semi-empirical formulations as that of Ruessink et al (2012) and Abreu et al (2010). Although it has been used in the literatures with certain good results, Ruessink's formula was developed through parameterisations of many field measurements, and its limitation can be found in some recent studies for the beach with steep slope (Zheng et al, 2023). Rocha et al (2017) also highlighted the necessity to include extra wave parameters to get better near-bed velocity results.

To overcome these difficulties, a new cross-shore morphological model is developed, where a fully nonlinear Boussinesq wave model of Shi et al (2012), FUNWAVE, is utilised to provide wave skewness and asymmetry information to drive a new near-bed sediment transport model. Through the phase-resolving wave model, the wave non-linearity can be obtained directly at every time step. The near-bed transport can therefore be predicted with better confidence.

NUMERICAL MODEL

With the inputs of incident wave characteristics at the boundary and given bed topography, FUNWAVE is able to calculate the instantaneous surface elevation across the beach. The wave non-linearity can be found directly from the model results with good accuracy from shoaling into the surf region. Based on this information, a new model is developed for the prediction of instantaneous near-bed sediment transport rate. The correlation proposed by Henderson (2004) is adopted to convert the FUNWAVE computed free-stream velocity into a near-bed velocity. Following Bernie's (2013) approach, the formula was described as follows:

$$Sk_b^* = K_b^3 x(cos\emptyset_b Sk_\infty^* + sin\emptyset_b As_\infty^*) \qquad (1)$$

Sk_b^* is the skewness at the top of the bottom boundary layer; $Sk_\infty^*$and As_∞^* are the free-stream skewness and asymmetry, respectively. $\emptyset_b$ and K_b^3 are phase lead and attenuation factor, respectively. Using the linear correlation between near-bottom skewness and free-stream asymmetry. The instantaneous near-bed velocity (u_b) is calculated as follows:

$$u_b(y,t) = K_b^3 x(u_\infty(t) + u_\infty(t) x cos\emptyset_b) \qquad (2)$$

where $u_\infty$is the free-stream velocity, y is the vertical coordinate, and t is time. The values of K_b^3 and $\emptyset_b$ are 0.8 and 30º, respectively, as recommended by Bernie (2013).

The bed shear stress (τ_b) can then be calculated using the near-bed velocity by applying quadratic assumption, defined as follow:

$$\tau_b = \frac{1}{2}\rho f_w u_b |u_b| \qquad (3)$$

where ρ is water density; f_w is friction coefficient. The classic Meyer-Peter and Muller (1948) formula is used to calculate the near-bed transport rate. The suspended load transport rate is computed based on the advection-diffusion equations based on the depth-mean velocity and sediment concentration as follows

$$\frac{\partial cH}{\partial t} + \frac{\partial UcH}{\partial x}\frac{\partial VcH}{\partial y} - \frac{\partial}{\partial x}\left[\varepsilon\frac{\partial c}{\partial x}\right] - \frac{\partial}{\partial y}\left[\varepsilon\frac{\partial c}{\partial y}\right] = S \qquad (4)$$

Where cH represents the depth-averaged concentration, U and V are the depth-averaged horizontal velocities, ε and S are turbulent mixing and the source term, respectively. The temporal bed evolution (z_b) is calculated each time step by using the mass conservation principle as follows:

$$\frac{\partial z_b}{\partial t} = \frac{\partial N_b}{\partial x} - \frac{\partial P_s}{\partial x} \qquad (5)$$

where N_b and P_s are the near-bed and suspended load fluxes, respectively.

RESULTS

The model is validated against the large-scale wave flume experiment of van Der Zanden et al (2017). Simulations were carried out in a domain of 100 m in length, 3 m in width, and 2.55 m in depth. Regular waves with a period of 4 s and height of 0.85 m were imposed at the offshore boundary. The time step in the simulations was set at 0.05s and the grid size was 0.5 m. The simulation was conducted for one hour and multiplied by a morpho factor of 18 to accelerate the morphological responses.

The wave height (a), skewness (b) and asymmetry (c) produced by the model are compared with the laboratory measurements in the shoaling and breaking zone in Figure 1. The overall agreements are good, especially in the wave height and wave asymmetry. The discrepancies in the wave skewness are largely due to the breaking fluxes that are underestimated by the model. The computed near-bed and suspended load transport are presented in Figure 2(a), together with the total load transport rate measured in the experiment. In the figure, it can be seen that the suspended load transport rate is dominated by the wave-breaking induced offshore undertow currents. The maximum offshore- directed transport is found around the breaking region, where a high amount of sediment materials is being transported away from the shore. The near-bed transport shows a positive value in the shoaling zone due to the wave skewness and asymmetry and then reduces to a small negative value due to the strong offshore directed undertow inside the surf zone. In comparison with the experimental data, the magnitude of near-bed transport produced by the model is underpredicted. Apart from other factors, it is worth to note that the turbulence effect in the near-bed transport was neglected in this simulation.

The morphodynamic evolution produced by the model is presented in Figure 2[B], showing an eroded area around the bar, specifically where the breaking occurs which is similar to that in the laboratory data. However, the deposition area behind the bar is underpredicted by the model, which is largely attributed to the underprediction in the near-bed transport in Figure 2[A]. We address several possible reasons behind this condition, such as the turbulence effect on near-bed transport, vertical variation of the water column, phase-lag effects, and undertow currents.

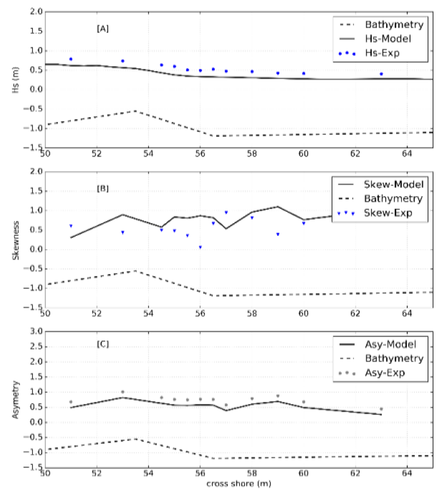

Figure1 - Model and experiment comparison for [A] Significant wave, [B] Wave skewness, and [C] Wave asymmetry.

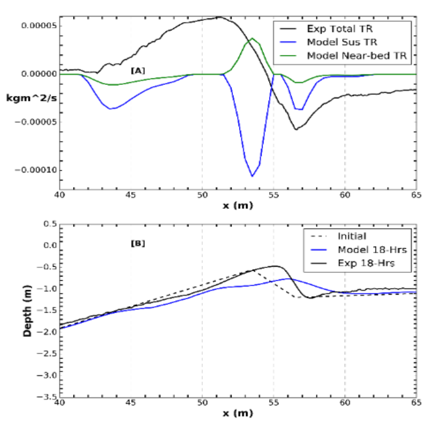

Figure 2A - Total transport rate produced from the experiment (black line), suspended (blue line) and near-bed (green line) load transport rates produced by the model. Figure 2B - Bed profile, at initial condition (dashed black line), after 18 hours produced by the model (blue lined) and the experiment (black lines).

CONCLUSIONS

A new phase-resolving morphological model is developed to simulate cross-shore sediment transport and beach profile changes. The focus is placed on the onshore transport driven by wave skewness and asymmetry process, which is resolved by a Boussinesq wave model, rather than parameterisations based on phase averaged wave characteristics. A new near-bed transport rate prediction method is developed using well-captured wave surface dynamics and free stream wave motion. In comparison with the detailed laboratory data, the model is able to reproduce the onshore transport rate in the shoaling zone as indicated in the experimental data. However, the magnitude of the onshore transport is clearly underpredicted by the skewness and asymmetry-driven near-bed transport process. It is suggested that the effect of turbulence on near-bed sediment transport, phase lag, and vertical variation of the velocities across the water column should be included in the model to improve its performance on the near-bed transport rate.

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