NUMERICAL MODELING ON WAVE-CURRENT FLOWS AND BED SHEAR STRESSES OVER AN ALGAL REEF

Yi-Ru Lan, National Central University, fasna0538@gmail.com
Zhi-Cheng Huang, National Central University, zchuang@ncu.edu.tw

INTRODUCTION

Currents in coastal zones under mechanisms in terms of tides, waves, wind, and high roughness are difficult to model; bed shear stresses under wave-current flows are particularly challenging yet not being well studied. In this study, the performance of a numerical modeling on depth-averaged currents and bed shear stresses over an algal reef was examined using a coupled wave-current model (Delft-3D). The detailed methodology is described in Lan and Huang (2023). The aims of this study are (1) to understand the performance of the existing model to predict the bed shear stress, and (2) to explore how the wave-current interaction affects the bed shear stress on the reef.

FIELD MEASUREMENTS

The study site is located in the Taoyuan coastal area on the northwestern part of Taiwan main island (Figure 1). Approximately 27 kilometers of reefs are found on the Taoyuan coastline. Instruments were deployed to measure various hydrodynamic parameters, including tides, waves, currents, and turbulence. An acoustic Doppler current profiler (ADCP, Nortek signature 1000) was deployed at a low-low-water position, located 4 meters below sea level and 350 meters seaward from the coastline. The ADCP continuously measured the waves and currents with hourly bursts of 4096 samples at 4Hz since April 2021. Bed shear velocity was measured using an array of four 6M-Hz acoustic Doppler velocimetries (ADV, Nortek Vector) near the ADCP from 2022/04/25 to 2022/05/25.

MODEL CONFIGURATION

We used a coupled flow-wave model developed by Deltares (Delft 3D) to reproduce the currents and wave fields in the study area. The hydrodynamic motion was simulated using D-Flow FM (Flexible Mesh) module on an unstructured grid in the horizontal plane. Tidal variation was set at the open boundaries with wind stress input and bottom roughness. Depth-averaged currents are obtained by solving the conservation equations of mass and momentum using the unsteady shallow-water approximation in two dimensions. The simulation of wind-generated, random, and short-crest waves was conducted by using the D-Waves module based on the third-generation SWAN (Simulating Waves Nearshore). Bed shear stresses are subject to both current and wave motions, and the nonlinear wave-current interactions contribute to the enhancement of the bed shear stresses. An algebraic approximation using parametric fitting coefficients to the different nonlinear methods was derived by Soulsby (1995), and implemented in the D-Waves module. The time-mean bed shear stress (τ_m) in the parameterization of Soulsby are of the form:

$$|\tau_m| = Y(|\tau_c| + |\tau_w|), \quad (1)$$

with $Y = X\{1 + bX^p(1 - X)^q\}$, and $X = |\tau_c|/(|\tau_c| + |\tau_w|)$. τ_c is bed shear stress due to current along, and τ_w is bed shear stress due to waves along. Parameters b, p, and q vary with different methods. Each wave-current interaction method has its own fitting parameters.

MODEL VALIDATION

The model was performed from 25th April to 25th May, which corresponds to the measurement period of the instruments. To quantify the comparison between model predictions (X_{simu}) and observations (X_{obs}), a measure of model skill (Willmott, 1981) was defined as:

$$skill = 1 - \frac{\sum|X_{simu} - X_{obs}|^2}{\sum\left(|X_{simu} - \overline{X_{obs}}| + |X_{obs} - \overline{X_{obs}}|\right)^2}, \quad (2)$$

where the overbar indicates time averaging over the period of modeling. The parameter ranges from 0 to 1, and a value of 1 and 0 stands for perfect agreement and complete disagreement between model predictions and field observations. The current velocities in the eastern and northern directions, significant wave heights, and wave directions greatly agreed with filed observations, with high skill levels of 0.84 to 0.91, 0.86 and 0.99.

BED SHEAR STRESS

Two wave-current interaction methods were chosen to study the variation of bed shear stress and the nonlinear contribution of bed shear stress from waves. The model proposed by Grant and Madsen (1979) (hereafter, GM79), which gave a good all-around performance (Soulsby, 1997), is implemented in the combined wave-current models in Delft3D. In addition, we used another model proposed by Bijker (1967) (hereafter BK67) to increase the nonlinear contribution of bed shear stress from waves. The model results are shown in Figure 2, and the skill values are summarized in Table 1. Here, the modeled bed shear velocities were derived from shear stresses using the equation, $\tau_0 = \rho u_*^2$, where ρ is water density. The model predicts general well on both the magnitude, trends, and variability of the bed shear velocities. As, Figure 2 shows, the observed shear velocity mainly varies in phase with tide, and modulated by wave. This variability in time can be well captured by both the two models. However, there are discrepancies in magnitude between the observation and model result from GM79, leading to a low skill value of 0.36. On the other hand, bed shear velocities modelled by BK67 are partially enhanced, making noticeable differences between the model results of GM79 and BK67. The normalized root-mean-square error (NRMSE) between the modeled and observed results were computed as:

$$NRMSE = \sqrt{\frac{\sum(X_{simu} - X_{obs})^2}{\sum(X_{obs})^2}}, \quad (3)$$

As shown in Figure 3, the NRMSEs between the observed and modeled shear velocities are plotted as a function of current magnitude (U) and as a function of $U_{orb}/(U_{orb}+U)$, where U_{orb} is wave orbital velocity. During high wave orbital motions, the higher emphasis on nonlinear contribution from waves greatly enhances the magnitude of bed shear velocity as the modelled results of BK67, and therefore significantly lowers the model error. The result indicates that nonlinear interaction in wave-current flows plays a critical role in the bed shear stress variation on the reef system.

Table 1 - Model settings and results for different methods of wave-current interaction methods

		Model Skill		
Case	Wave-current Interaction Models	Bed shear velocity	Current velocity E-W component	Current velocity N-S component
GM79	Grant and Madsen (1979)	0.37	0.84	0.91
BK67	Bijker (1967)	0.51	0.72	0.76

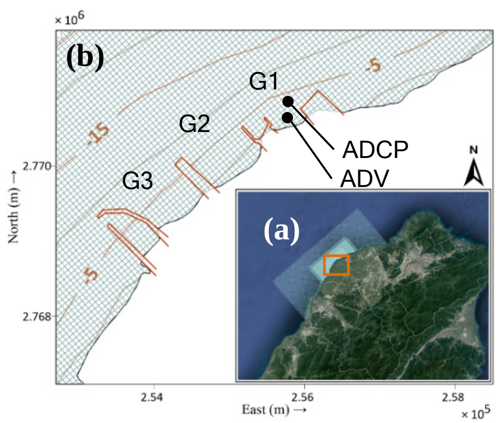

Figure 1 - Study area and computational grids. (a) Satellite image of Taoyuan coast from Google Earth, with the whole computational grids. (b) detailed view of model grids with bathymetry contours of the domain specified by the orange rectangle in (a), where black dots: instrument sites of ADCP and ADV.

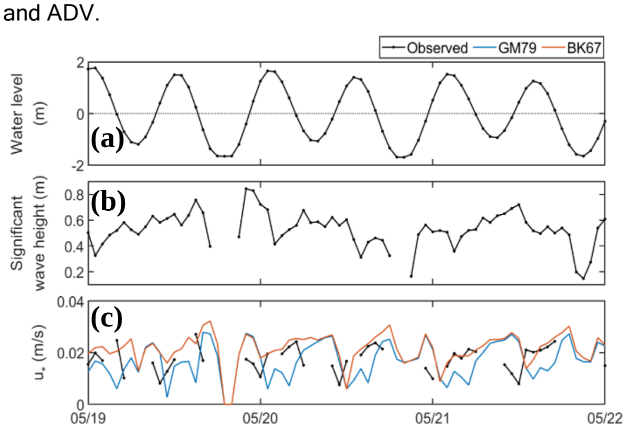

Figure 2 - Comparison between observed and modelled results, where u* indicates the shear velocity. (a) time series of water level, (b) significant wave height and (c) u*. Notes that only period from 2022/05/19 to 2022/05/22 are shown for easily seen.

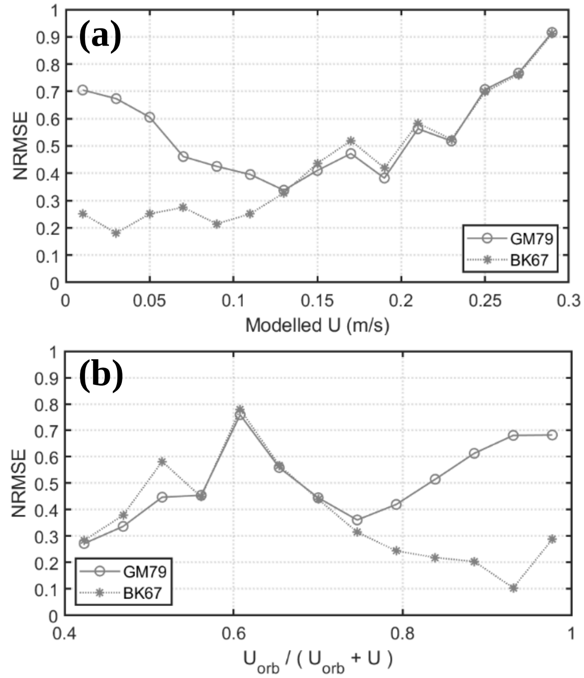

Figure 3 - Normalized-root-mean-squared-error (NRMSE) between observed and modelled bed shear velocity(u*) as a function of (a) flow velocity (U), and (b) the ratio of modelled wave orbital velocity (U_{orb}) to the sum of wave orbital velocity and flow velocity (U).

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