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An experimental study on near-orthogonal wave–current interaction over smooth and uniform fixed roughness beds

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ABSTRACT

An experimental study of periodic waves interacting with near-orthogonal turbulent currents is presented in this paper. Mean velocity profiles for current-alone, wave-alone and combined wave–current flows are measured with Acoustic Doppler Velocimeters to resolve the changes in mean flow kinematics due to wave–current interaction. In this study, the near-bottom wave orbital velocity is approximately 1.5 times greater than the depth-averaged current velocity, and the log-profile method is used to determine the bottom roughness from the measured velocity profiles. The primary focus is on 90° wave–current interaction, while selected findings for 60° and 120° wave–current orientations are also presented. In the smooth bed experiment, the interaction is shown to be linear due to the relatively low Reynolds-number flows generated in the facility — a relatively common scenario in small-scale laboratory setups that has not received much attention in previous studies. The smooth turbulent flow equation, with modification of the input shear velocity, is found to accurately predict the mean flow roughness for linear interaction. The bottom roughness is subsequently increased with the introduction of a layer of uniform 12.5 mm marbles to achieve a more realistic rough turbulent flow regime. The results agree qualitatively with previous experimental findings that showed a reduction in the near-bottom mean velocity due to a wave-enhanced (apparent) roughness. However, the Grant–Madsen (GM) model is found to over-estimate the apparent roughness when the angle of wave–current interaction is large, implying a lack of directional sensitivity of this model under "strong-wave, weak-current" conditions. A tentative explanation of this shortcoming is given in the paper. However, it is not possible to extend the GM model analysis to the present near-orthogonal wave–current flows, as results suggest that both 60° and 120° wave–current cases are sufficiently contaminated by the wave-induced mass transport component in the current direction to invalidate the use of the log-profile method to resolve the bottom roughness. In addition to the modification of current profiles by waves, the present study also shows a drastic transformation of wave-induced mass transport profiles by the external turbulent currents. The veering of mean flow over depth is consistent with the superposition of a wave-induced return flow on the external current, while additional veering in the near-bottom region may be attributed to turbulence asymmetry induced by the current component in the direction of the near-bottom wave orbital velocity which is shown to vary locally by ±10° due to parasitic waves emanating from the current inlet and outlet.

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1. Introduction

It is commonly recognized that coastal circulation and sediment transport are significantly influenced by combined waves and current flows. In coastal waters, the direction of wave propagation is predominantly near-orthogonal to currents, and both flows exhibit considerable differences in time scales. The period, T, of coastal currents is of the order of several hours, and the boundary layer thickness, which is roughly proportional to $\sqrt{T}$, is of the order of meters. Wind-wave periods are usually less than 20 s and suggest that the wave boundary layer thickness is only of the order of centimeters. Hence, wave–current interaction is restricted to a thin layer of water column close to the seabed, further complicated by the presence of bedforms in many cases. Since this interaction is a highly nonlinear process, the combined wave–current flow is considerably different from a direct summation of current-alone and wave-alone kinematics, implying that meaningful studies require both currents and waves to be present simultaneously.

Immense progress has been made in the last few decades on the simulation of wave–current flows, starting from the simple models developed in the 1970s and 1980s [Lundgren (1972), Smith (1977), Grant & Madsen (1979), Fredsøe (1984), Christofferson & Jonsson (1985), Coffey & Nielsen (1986), Myrhaug & Slattelid (1989)], to more recent numerical models that adopt state-of-the-art turbulence closure methods, e.g. Holmedal et al. (2013) for collinear wave–current flows, Davies et al. (1988), Olabarrieta et al. (2010) and Afzal et al. (2015)

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for arbitrary angles of wave–current flows. Detailed review of this subject can be found in Grant & Madsen (1986) and Soulsby et al. (1993). A primary strategy of early-day theoretical studies was to adopt simple turbulence closure models when solving the Navier–Stokes equations for both steady and oscillatory components of the combined flow. The available closure models include the eddy viscosity model, the turbulent kinetic energy closure method and the momentum-deficit integral method (Soulsby et al., 1993). The eddy viscosity model is one of the simplest to use, and wave–current models based on this scheme are generally integrated into large-scale ocean circulation models to enhance computational efficiency of numerical simulation.

Validation of theoretical models has been performed mostly with collinear wave–current experiments (e.g. Kemp & Simons, 1982, 1983; Klopman, 1994; Mathisen & Madsen, 1996a, b; Fredsøe et al., 1999), though a fair amount of experimental work involving near-orthogonal wave–current interaction has also been conducted (e.g. Havinga, 1992; Simons et al., 1992; Arnskov et al., 1993; van Rijn & Havinga, 1995; Musumeci et al., 2006; Madsen et al., 2008; Fernando et al., 2011). The general conclusion is that when waves are present with currents, the near-bottom mean velocity increases (decreases) over smooth (rough) beds. Besides, collinear wave–current studies have also demonstrated that for currents following (opposing) the waves, the near-surface mean velocity decreases (increases) with respect to current-alone conditions (Kemp and Simons, 1982, 1983; Klopman, 1994). When waves interact with currents in orthogonal or near-orthogonal orientations, the mean flows would experience changes not only in terms of magnitude but also in the flow directions due to the superposition of wave-induced return flow on the nominal current, as well as steady streaming induced by momentum transfer (Longuet-Higgins, 1953 — henceforth LH53) and turbulence asymmetry (Trowbridge & Madsen, 1984) within the wave boundary layer. Numerical simulations by Davies et al. (1988 — henceforth DSK88), accounting only for turbulence asymmetry, and Afzal et al. (2015 — hereafter AHM15) who also included mean momentum transfer, have revealed details of this veering of the mean flow for non-collinear wave–current flows. However, to the authors' knowledge, these details have not been supported by experimental evidence.

The comparison between theoretical models and experimental results require a precise knowledge of the bed resistance over which the flows interact, and this is commonly expressed as the equivalent Nikuradse sand grain roughness (henceforth bottom roughness, k_n). For the case of steady rough turbulent flows over a uniform flat sand bed, k_n is characterized by the diameter of the sand grains, with numerous studies suggesting that k_n is of the order 1 to 10 d_{50} (Nielsen, 1992). Several notable studies on oscillatory flows over movable beds (Carstens et al., 1969; Lofquist, 1986) conclude that k_n is approximately four times the ripple height, η, when bedforms are present. However, for oblique wave–current flows in a basin, the movable bedforms tend to exhibit greater spatial variability (Madsen, et al., 2008), which results in ambiguity of the value of k_n. This problem can be partly overcome by using fixed 2D bedforms, but strong directional-dependency of k_n is usually observed for this type of bed configuration due to drastic changes in bed resistance when the angle between mean flow and bedform axis varies (Barrantes & Madsen, 2000). The above shortcomings may be resolved by generating wave–current flows over a uniform, fixed 3D bottom configuration, where k_n is spatially homogenous as well as directional-independent. Unfortunately, experimental measurements involving near-orthogonal waves and currents over this type of bed configuration are relatively scarce.

The aforementioned gap motivates the present study, which is aimed at obtaining high-quality experimental data for near-orthogonal wave–current flows over smooth and uniform fixed roughness beds. The focus is on waves interacting with currents at 90°, and a large number of near-bed measurement data were collected to facilitate the determination of bottom roughness with the log-profile analysis. Selected findings on 60° and 120° wave–current flows are also discussed. In addition to the modification of current flows by waves, the present study is also aimed at understanding the changes in wave-induced mass transport flows due to wave–current interaction, a phenomenon that has not received much attention in past studies but could have significant implications for cross-shore sediment transport since there is a strong dependency of bedload transport on near-bed mean currents.

The organization of this paper is as follows: Section 2 discusses the experimental setup and preliminary tests used to establish the measurement regions and uncertainties. The smooth bed experiments for 90° wave–current interaction are detailed in Section 3. Section 4 presents the 90° flow experiments conducted over a uniform fixed roughness bed and compares them with predictions afforded by the GM model. Potential mechanisms influencing the veering of near-bottom mean flow are also discussed. Selected results on 60° and 120° wave–current interaction are presented in Section 5, with discussions of the contamination of log-profile analysis by near-orthogonal waves. The final section presents conclusions of the study and recommendations for future work.

2. Experiments and methodology

2.1. Experimental setup

Experiments were performed in the Hydraulic Engineering Laboratory of the Department of Civil & Environmental Engineering, National University of Singapore (NUS). Current-alone, wave-alone and combined wave–current flows were generated in a 33 m (L) × 10 m (W) × 0.9 m (D) wave–current basin. A photo of the facility is shown in Fig. 1 while the overall layout is presented in Fig. 2. Water depth, h was maintained at 0.4 m for all experiments. A section of the basin (19 m × 1.5 m) parallel to the direction of the wave propagation was converted into a reservoir to generate steady current flows in the test area. The flows exited the basin over an adjustable weir at the outlet and were re-circulated to the reservoir by two 75HP centrifugal pumps. Current inlets of width 2.5 m were constructed along the wall of the reservoir and aligned such that currents would intersect with waves at 60°, 90° and 120° when both flows were present. For notation purpose, the current channel that connects Inlet 2 with the outlet is known as the 90° current channel, while those that connect Inlets 1 and 3 with the outlet are denoted as the 60° and 120° current channel, respectively (refer to Fig. 2). Honeycomb filters consisting of 50 cm-long, 5 cm-diameter PVC pipes were installed at the inlets to ensure

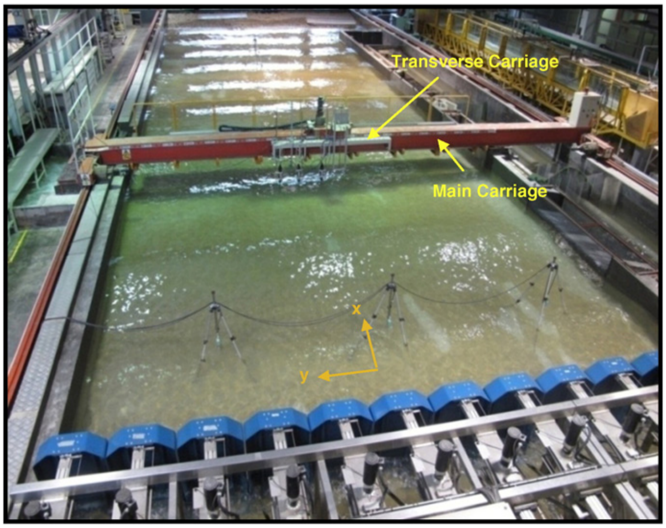

Fig. 1. Bird's eye view of the wave–current basin in the Hydraulic Engineering Laboratory, NUS.

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