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Experimental study of turbulent oscillatory boundary layers in an oscillating water tunnel

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ABSTRACT

A high-quality experimental study including a large number of tests which correspond to full-scale coastal boundary layer flows is conducted using an oscillating water tunnel for flow generations and a Particle Image Velocimetry system for velocity measurements. Tests are performed for sinusoidal, Stokes and forward-leaning waves over three fixed bottom roughness configurations, i.e. smooth, “sandpaper” and ceramic-marble bottoms. The experimental results suggest that the logarithmic profile can accurately represent the boundary layer flows in the very near-bottom region, so the log-profile fitting analysis can give highly accurate determinations of the theoretical bottom location and the bottom roughness. The first-harmonic velocities of both sinusoidal and non-linear waves, as well as the second-harmonic velocities of nonlinear waves, exhibit similar patterns of vertical variation. Two dimensionless characteristic boundary layer thicknesses, the elevation of 1% velocity deficit and the elevation of maximum amplitude, are found to have power-law dependencies on the relative roughness for rough bottom tests. A weak boundary layer streaming embedded in nonlinear waves and a small but meaningful third-harmonic velocity embedded in sinusoidal waves are observed. They can be only explained by the effect of a time-varying turbulent eddy viscosity. The measured period-averaged vertical velocities suggest the presence of Prandtl's secondary flows of the second kind in the test channel. Among the three methods to infer bottom shear stress from velocity measurements, the Reynolds stress method underestimates shear stress due to missed turbulent eddies, and the momentum integral method also significantly underestimates bottom shear stress for rough bottom tests due to secondary flows, so only the log-profile fitting method is considered to yield the correct estimate. The obtained bottom shear stresses are analyzed to give the maximum and the first three harmonics, and the results are used to validate some existing theoretical models.

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1. Introduction

In coastal regions, surface waves generate turbulent near-bottom flows which provide the driving forces for sediment transport. Following linear wave theory, wave boundary layers are usually approximated by bottom-parallel oscillations which are uniform in the wave direction, i.e. turbulent oscillatory boundary layers. The early analytical studies assumed a time-invariant turbulent eddy viscosity to solve the boundary layer equation, e.g. Kajiura (1968), Grant (1977) and Brevik (1981) for sinusoidal wave boundary layers, and Grant and Madsen (1979), Fredsøe (1984) and Sleath (1991) for combined wave–current boundary layers. Neglecting the temporal variation of turbulent eddy viscosity is against the unsteady nature of oscillatory flows, so among others, Trowbridge and Madsen (1984a, 1984b), Lavelle and Mofjeld (1983) and Gonzalez-Rodriguez and Madsen (2011) developed more elaborate models based on a time-varying turbulent eddy viscosity. Besides analytical models, numerical models based on various turbulent closure schemes also have been developed (e.g. Davies et al., 1988; Holmedal and Myrhaug, 2006; Scandura, 2007). The development of theoretical models relies heavily on experimental studies. Dimensional analysis (e.g. Sleath, 1987) suggests that turbulent oscillatory boundary layers are controlled by two dimensionless parameters: the amplitude Reynolds number $Re = A_{bm}U_{bm}/\nu$ and the relative roughness A_{bm}/k_b, where U_{bm} is the near-bottom wave orbital velocity amplitude, A_{bm} is the near-bottom excursion amplitude, ν is the molecular kinematic viscosity of the fluid and k_b is the bottom roughness. For a surface wave which can induce noticeable amounts of sediment transport, A_{bm} and U_{bm} can reach the orders of 1 m and 1 m/s, respectively, so the corresponding Re and A_{bm}/k_b can be up to $O(10^6)$ and $O(10^3)$, respectively. Many previous experimental studies are performed in small-scale wave flumes (e.g. Cox et al., 1996; Dixen et al., 2008; Kemp and Simons, 1982, 1983) or shaking platforms (e.g. Hay et al., 2012a, 2012b; Krstic and Fernando, 2001). However, the physical limitations of these facilities make it impossible to achieve the high values of Re and A_{bm}/k_b under prototype flow conditions. Thus, most full-scale experimental studies are conducted in another type of facility: oscillating water tunnels (OWT). These facilities are usually U-shaped tunnels. A piston located at one end of the tunnel produces oscillatory motions in

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the entire tunnel. As pointed out by many researchers (e.g. van der Werf et al., 2009), OWT flows are approximations to those under progressive waves, since they are uniform along the longitudinal direction, i.e. $\partial u/\partial x = 0$. Thus, some boundary layer processes, e.g. the boundary layer streaming suggested by Longuet-Higgins (1953), are not present. Nevertheless, this drawback is offset by the OWT's ability to obtain highly-accurate experimental data at prototype scales. For simplicity, the oscillatory OWT flows will be referred to as waves hereafter. Jonsson (1963) followed by Jonsson and Carlsen (1976) conducted two sinusoidal-wave tests over artificially rippled bottoms in the very first OWT described by Lundgren and Sorensen (1957). After that, Sleath (1987) studied the characteristics of turbulence in oscillatory boundary layers in a relatively smaller OWT. Jensen et al. (1989) performed similar experiments to Sleath (1987) in a higher range of *Re*. These three studies only considered sinusoidal oscillatory flows, however, the non-linearity of coastal waves makes the near-bottom flow skewed (peaked crest and flat trough) and asymmetric (forward-leaning crest). Very few experimental studies have been performed for such flow conditions. Ribberink and Al-Salem (1995) reported limited measurements of skewed oscillatory boundary layer flows as by-products of their experimental study of skewness-induced net sediment transport. Very recently, van der A et al. (2011) systematically studied asymmetric oscillatory boundary layers over rough bottoms.

Previous OWT studies provide valuable experimental results for understanding turbulent oscillatory boundary layers, but the work is still not finished. A significant problem is the experimental determination of bottom shear stress. As will be introduced in Section 5, bottom shear stress is generally inferred from velocity measurements via three methods: the log-profile fitting method, the momentum integral method and the Reynolds stress method. Ideally, they should give identical estimates. However, Sleath (1987) showed that the observed Reynolds stress was significantly smaller than the shear stress given by the momentum integral method. A less significant but still noticeable discrepancy was observed by van der A et al. (2011). They also showed that the momentum integral method gave bottom shear stresses which are 30%–50% smaller than those from the log-profile fitting method. Similar discrepancies are observed in experimental studies using other types of facilities, such as the shaking platform experiments by Hay et al. (2012b). Thus, the three methods generally give bottom shear stress in the sequence: Reynolds stress < momentum integral < log-profile fitting. It is unknown which method yields the correct estimate, so researchers face the problem of having to choose the "right" measurements for model validations, e.g. Abreu et al. (2013) chose the results from the momentum integral method which is argued invalid by van der A et al. (2011). Another unsettled issue is the quantification of bottom roughness which is an important input parameter for most theoretical models. The seminal work by Nikuradse (1932, 1933) provides a quantitative understanding of bottom roughness for steady turbulent boundary layers, but whether his findings are applicable for unsteady flows must be confirmed through a systematic experimental study which is comparable to Nikuradse's work. Previous OWT studies did not pay much attention to bottom roughness, so a detailed experimental effort devoted to the clarification of this issue is desirable.

In this study, we conduct full-scale experiments using a newly-built OWT (see Yuan et al. (2012) for a detailed description) for flow generation and a state-of-the-art Particle Image Velocimetry (PIV) system for velocity measurements. Tests are performed for three types of periodic oscillatory flows over three different fixed bottom roughness configurations. Several flow conditions are covered for each combination of flow type and bottom roughness configuration, so the number of tests is sufficiently large to ensure the reliability of the obtained conclusions. The experimental setup is introduced in Section 2. The experimental determination of bottom roughness will be discussed in Section 3. Some characteristics of turbulent oscillatory boundary layers will be presented in Section 4. The experimental determination of bottom shear stress will be addressed in Section 5.

2. Experimental setup

2.1. Experimental facility

The experimental facility is a newly-built OWT, named the Wave–Current–Sediment facility (WCS), in the Hydraulic Engineering Laboratory of the Department of Civil and Environmental Engineering at the National University of Singapore, as shown in Fig. 1. The main part is a 10 m-long, 50 cm-deep and 40 cm-wide horizontal test channel with glass sidewalls and acrylic lids along its entire length. Below the 50 cm working depth, a 20 cm-deep trough for holding sediments is currently fitted with wooden false bottom blocks which can serve as the foundation to mount bottom roughness plates. The transparency of sidewalls and lids makes it very convenient to set up any experimental apparatus which requires introducing light or laser beams into the channel. Two stainless steel vertical cylindrical risers of 1 m-diameter are connected to the test channel through honeycomb filters to make in- and outflows uniform. One riser is open to the atmosphere and the other contains a programmable, hydraulically actuated piston which can generate a variety of periodic or irregular oscillations. The maximum excursion amplitude of the piston is 500 mm which corresponds to roughly 2 m maximum excursion amplitude of flows in the 40 cm-by-50 cm test section. Limited by the 40 kN maximum driving force of the piston, the maximum amplitudes of piston velocity and acceleration are 500 mm/s and 500 mm/s^2 for periods $2\text{ s} < T < 12\text{ s}$, so the corresponding maximum amplitudes of flow velocity and acceleration in the test section are about 2 m/s and 2 m/s^2. The entire structure is supported by a pivot and a hydraulic jack, so it can be tilted (up to 1/20) to include the bottom slope effect into our physical modeling. A current generation system has been built to superimpose a current on oscillatory flows. The core part is a Börger EL1550 Rotary Lobe pump placed in the basement underneath the WCS. It can produce a current of up to 60 cm/s average velocity in the test section. One significant feature of this pump is that it can maintain a steady discharge even when the pressure difference across the pump changes in time, e.g. due to wave generation. Moreover, the direction of the current can be easily reversed by reversing the pump's rotation. A sediment trap tank is inserted in the pipe system to capture suspended sediments when performing experiments with significant suspended sediment transport. The current enters or leaves the main test section through flexible telescoping pipe connections, allowing tilting the entire facility with the current generation system operating. With all these features, the facility is able to model most important physical processes of oscillatory boundary layers in coastal regions.

2.2. PIV measurements

Velocity measurements are obtained using a 2-dimensional PIV system supplied by the TSI Corporation. The flow is seeded with nearly neutrally-buoyant silver-coated seeding particles with diameter of 10 μm. To illuminate the near-bottom flow field, a double-pulsed YAG 135-15 Litron Nano L laser produces a thin laser sheet which is introduced into the test channel vertically downward through the transparent lid. Since the primary flow is in the longitudinal direction, the laser sheet is carefully aligned with the lateral center line of the test channel to remove sidewall effects. It is also located close to the longitudinal center of the test channel, so the end effect is reduced to a minimum. For each sampling, two images of the illuminated area are captured using a high-speed Powerview 4M Plus 2000-by-2000 pixel camera with a very short time interval Δt. The firing of laser and the image capture by the camera is controlled and synchronized by a 610035 LaserPulse Synchronizer. For most tests in this study, the camera is about 70 cm from the target flow field and uses a lens with fixed 105 mm focal length, which gives a resolution parameter $\lambda =$ 50 μm/pixel. This corresponds to a roughly 10 cm-by-10 cm captured area. For some tests with over 10 cm thick boundary layers, another

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