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# Experimental investigation of turbulent wave boundary layers under irregular coastal waves

Jing Yuan*, Sunil Manohar Dash

*Department of Civil and Environmental Engineering, National University of Singapore, 1 Engineering Dr. 2, Block E1A 07-03, Singapore, 117576, Singapore*

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ABSTRACT

In this study full-scale experiments of wave boundary layers under irregular coastal waves are conducted using an oscillatory water tunnel. The flow conditions cover two rough bottoms, three types of wave shapes, i.e. sinusoidal, skewed and asymmetric waves, and two types of irregular-wave sequences. The instantaneous turbulent velocity fields are measured with a 2-dimensional Particle Image Velocimetry system. The measured turbulence statistical values show that the residual turbulence at the end of wave cycle can persist into the next wave cycle, until the next cycle's self-produced turbulence becomes sufficiently strong. Consequently, the Reynolds-averaged flow at the beginning of a wave cycle can behave as if the flow "memorizes" the previous wave cycle. However, this memory effect quickly vanishes, and therefore does not have a significant influence on some key boundary layer characteristics, e.g. bottom shear stress. For irregular wave boundary layers with skewed and asymmetric free-stream velocities, the measured mean current and the associated mean bottom shear stress confirm the existence of a well-known boundary layer streaming due to the imbalance of turbulence between the two halves of a wave cycle, and the measurements of bottom shear stress of individual waves closely resemble those for periodic-wave conditions. These experimental results suggest that modeling irregular wave boundary layers in a wave-by-wave manner is plausible.

## 1. Introduction

In the coastal environment, shoaling waves interact with the underneath seabed through a thin turbulent wave boundary layer (WBL), which plays an important role in determining coastal sediment transport. If the wave length is much longer than the excursion amplitude of the bottom wave orbital motion, local WBLs can be approximated by oscillatory boundary layer flows, which are uniform in the bottom-parallel direction, so prototype flow conditions can be easily achieved in oscillatory water tunnels (OWT). A number of early OWT studies, e.g. Jonsson and Carlsen (1976), Sleath (1987) and Jensen et al. (1989), revealed some key characteristics of WBL and provided valuable measurements for developing or validating predictive models (e.g. Grant, 1977; Justesen, 1988), but they only considered sinusoidal oscillatory flows, which will produce a zero net sediment transport rate over a horizontal seabed.

Coastal waves become increasingly nonlinear as they approach the shore, which leads to two nonlinear features differentiating the two half-periods of the wave bottom orbital velocity, i.e. skewness (the velocity time series has peaked crest and flat trough) and asymmetry (the velocity time series becomes forward-leaning). As a result, the intra-period variation of bottom shear stress exhibits similar features. A number of simple estimators have been proposed to predict the bottom shear stress for skewed and/or asymmetric periodic WBLs, e.g. Gonzalez-Rodriguez and Madsen (2007) and Abreu et al. (2013). Generally speaking, positive skewness and asymmetry lead to larger bottom shear stress under the crest half-cycle, so a net positive (usually onshore) bedload transport rate should be expected, since bedload sand grains can immediately react to the varying bottom shear stress in a quasi-steady manner. This is confirmed by a number of coarse-sand OWT studies in the sheet-flow regime, e.g. Ribberink and Al-Salem (1995) and O'Donoghue and Wright (2004) for flow skewness, van der A et al. (2010) and Ruessink et al. (2011) for flow asymmetry. However, it is also observed that in some fine-sand OWT tests the phase-lag effect, i.e. suspended fine particles cannot immediately settle back to the movable bed at the moment of flow reversal, can reduce the onshore net transport rate or even lead to a net offshore transport rate. Some OWT studies also reveal another important feature of WBLs with skewness and asymmetry, i.e. a boundary layer streaming in the negative (usually offshore) direction (e.g. Ribberink and Al-Salem, 1995; van der A et al., 2011). A number of analytical and numerical models (e.g. Trowbridge and Madsen, 1984;

* Corresponding author.
*E-mail address:* ceeyuan@nus.edu.sg (J. Yuan).

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Holmedal and Myrhaug, 2006; Kranenburg et al., 2012; Yuan and Madsen, 2015) have illustrated that this streaming (hereafter referred to as the TI (turbulence-imbalance) streaming) is due to the imbalance in flow turbulence between the two half-cycles, so it is different from another well-known wave boundary layer streaming (LH-streaming hereafter) first proposed by Longuet-Higgins (1953), which is driven by a net downward transfer of momentum due to the fact that the horizontal and vertical wave orbital velocities in the close vicinity of the bed are not 90° out of phase. Many OWT and large-flume experimental studies have shown that the streaming-related net sediment transport rate can be quite substantial, so a few numerical or analytical models are established to investigate the influence of TI- and LH-streamings on net sediment transport rate (e.g. Ruessink et al., 2009; Holmedal and Myrhaug, 2009; Fuhrman et al., 2013; Kranenburg et al., 2013).

The real coastal waves are always irregular, so a big question is how to extend the existing periodic-wave-based knowledge and predictive models to irregular-wave scenarios. In the literature two main approaches are commonly adopted to realize the extension, i.e. the probabilistic and the representative-wave approaches. The latter simply conceptualizes the irregular waves as a representative periodic wave. Madsen (1994) analytically showed that a periodic wave with its amplitude and period being the root-mean-square (RMS) velocity and average period of the irregular wave bottom orbital motion, respectively, can be used for modeling irregular wave-current boundary layers. This model is recently validated by the OWT experiment of Yuan (2016). The representative wave for modeling sediment transport is rather arbitrarily defined. For example, van der A et al. (2013) proposed to use the significant amplitude and the peak spectral period of wave bottom orbital velocity in their formula for net sediment transport rate under non-breaking waves and currents, which is calibrated mostly based on periodic-wave experiments. It can be hypothesized that different representative waves should be adopted for different boundary layer or sediment transport processes, so more research effort is required to further improve the representative-wave approach. The probabilistic (or wave-by-wave) approach treats irregular waves as a set of independent periodic waves following a certain probability distribution, so existing periodic-wave-based models can be directly applied to yield the probability distributions for some physical quantities of interest, e.g. net sediment transport rate. Myrhaug (1995) followed by Myrhaug et al. (2001) adopted this method to obtain the probability distribution of the maximum wave bottom shear stress under waves or wave-current flows with the assumption that the wave motion is a stationary Gaussian narrow-band random process. The same principle has been adopted for modeling bedload transport under wave-current flows (Holmedal and Myrhaug, 2004) and sediment suspension under the influence of skewed and asymmetric bottom shear stress and LH-streaming (Myrhaug et al., 2015). The advantage of the probabilistic approach is that it can rigorously account for the difference among individual waves, e.g. each wave can have its own skewness and asymmetry. However, this approach assumes that a wave can be modeled as being in a periodic wave train, which may not be suitable for some boundary layer processes that cannot react immediately to the change of wave condition. It can be argued that WBLs may have some "memory", i.e. some residual influence of a wave cycle will persist into the next wave cycle. This memory effect makes waves within an irregular wave train not truly independent, and therefore undermines the probabilistic approach. Should these concerns be cleared with full-scale experimental evidences, the probabilistic approach will be a powerful tool, which can be used in developing or verifying the representative-wave approach (e.g. Yuan and Madsen, 2010).

Very few experimental studies of turbulent boundary layers under irregular waves are available in the literature. Simons et al. (1994) directly measured bottom shear stress under irregular waves plus currents using shear plates in their wave-basin experiments. Chassagneux and Hurther (2014) conducted a flume experiment of wave boundary layer under irregular breaking waves over a movable bed. These small scale experiments provide some insights to the bottom shear stress and the flow structure of irregular wave boundary layers. Bhawanin et al. (2014) reported a full-scale OWT study of irregular wave boundary layers over fixed rough beds. Their irregular waves were generated by amplitude-modulating a train of periodic waves, so the memory effect can be studied by comparing tests with different modulations. Their experimental results suggest that the memory effect is probably negligible in the near-bottom region, but are not totally absent at higher levels from the bed. They suggested that more experimental work with detailed measurements of boundary layer flows and bottom shear stress is still required to further elucidate the memory effect. It is also unclear whether and how wave irregularity affects the bottom shear stress and the TI-streaming of irregular WBLs with skewed and asymmetric free-stream velocities.

In this study full-scale experiments of irregular turbulent wave boundary layers are conducted over fixed rough bottoms in an OWT. The main objectives are (1) to study the memory effect on key wave boundary layer physics and (2) to investigate how wave irregularity influences the bottom shear stress and the TI-streaming of skewed and asymmetric irregular WBLs. The outline of this paper is as follows. The experimental conditions and some data analysis methodology are introduced in Section 2. Section 3 discusses the memory effect on boundary layer turbulence, Reynolds-averaged flow and bottom shear stress. The influences of wave irregularity on skewed and asymmetric irregular WBLs are presented in Section 4. Conclusions are provided in Section 5.

## 2. Experimental conditions and data analysis methodology

### 2.1. Experimental facility

Our experiments are conducted using the Wave-Current-Sediment (WCS) facility at the hydraulic lab of National University of Singapore. The WCS is essentially a U-shape OWT with a 10 m-long, 40 cm-wide and 50 cm-deep horizontal test section. A uniform oscillatory flow in the test section is generated by a hydraulic-driven piston located in a vertical cylindrical riser attached to one end of the test section. Thus, oscillatory flows equivalent to full-scale near-bed flows under coastal waves can be produced, except that the vertical wave orbital velocity is absent in the WCS. For simplicity we hereafter refer to these oscillatory flows as waves. Some previous studies, e.g. Yuan and Madsen (2014) and Yuan (2016), have demonstrated that the WCS can precisely generate the intended periodic or irregular waves, so the readers are referred to these publications for details on the WCS. Our experiments are conducted over two fixed rough bottoms, i.e. a sandpaper bottom and a marble bottom. They are created by gluing roughness elements onto flat aluminum plates, i.e. slip-resistant sandpaper tapes (physical roughness height of about 1 mm) and a mono-layer of 12.5 mm-diameter ceramic marbles, respectively. Through a rigorous log-profile fitting analysis Yuan and Madsen (2014) obtained the theoretical bottom location $z = 0$ and equivalent Nikuradse sand grain roughness $k_N$ for these two bottoms. For the sandpaper bottom, $z = 0$ is found to be 0.6 ± 0.1 mm below the mean crest level of bottom roughness elements and $k_N$ is 3.7 ± 0.1 mm. For the ceramic-marble bottom, $z = 0$ is 4.0 ± 0.4 mm below the top of the marbles and $k_N$ is 20 ± 3 mm. These results are directly adopted in this study.

### 2.2. Flow conditions

The free-stream velocity of irregular wave boundary layers are obtained by modifying a train of periodic waves as follows. Three periodic wave shapes are considered in this study, i.e. sinusoidal, skewed and asymmetric waves. The free-stream velocity for the latter two are given by the superposition of two harmonics

$$u_{p,\infty}(t) = U_{\infty 1}[\cos(\omega t) + \alpha\cos(2\omega t + \varphi_{\infty 2})] \tag{1}$$

where $\omega = 2\pi/T$ is the wave angular frequency with $T$ being the wave