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Contributions to the wave-mean momentum balance in the surf zone

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A B S T R A C T

Mean (wave-averaged) cross-shore flow in the surfzone has a strong vertical variation. Good understanding and prediction of this mean velocity profile is of crucial importance, as it determines the advective transport of constituents, such as sediment, and consequently the coastal morphological evolution. Most modeling systems for coastal hydrodynamics and morphodynamics do no resolve the wave motion, and wave-current coupling is a challenging topic. This paper investigates stresses and forces that control mean surfzone hydrodynamics based on detailed wave flume velocity measurements above a fixed sloping bed including two breaker bars. The data show that the vertical distribution of normal stress below the wave trough level is fairly uniform. At the same time, the data suggest that a significant part is concentrated between the wave trough and crest level. Furthermore, it is concluded that the horizontal radiation stress gradients and the vertical shear stress gradients can be of the same order of magnitude in the vicinity of the breaker bar. Although usually ignored in 3D mean flow modeling systems, the wave Reynolds stress makes an important contribution to the mean shear stress. The normal stress below the wave trough level could be reasonably well predicted using the classical [16] expression, accounting for the contribution between wave crest and trough. The model of [39] reproduces the main trends in the wave Reynolds stresses above the bottom boundary layer.

1. Introduction

Mean (wave-averaged) surfzone hydrodynamics are strongly affected by the presence of waves. Waves generate currents through mean transport of mass and momentum.

The mean and depth-integrated horizontal momentum transport caused by the waves only is known as radiation stress (see e.g. [16,28]). For a uniform coast the cross-shore variation in the cross-shore component of the radiation stress tensor is responsible for the setdown and setup of the mean water level. The cross-shore gradient of the longshore radiation stress component is the driving force for longshore currents.

The cross-shore radiation stress gradient is not uniformly distributed over the water depth under breaking waves; it is higher near the surface. The opposing pressure due to the water level gradient has a (nearly) uniform vertical distribution. This results in a seaward wave-averaged current near the seabed (undertow) and onshore flow higher in the water column in the inner surfzone (see e.g. [19]).

The mean vertical fluxes of horizontal momentum have a turbulence contribution, the turbulent Reynolds stress, and a direct contribution due to the wave orbital motion, also known as wave Reynolds stress.

The wave Reynolds stress can yield a non-zero mean value when the horizontal and vertical orbital motions are not exactly 90° out of phase due to bed friction, bed slope or wave breaking effects (see e.g. [6,39,12]). This wave-averaged shear stress leads to a small near-bed mean current (wave boundary streaming) that is generally onshore-directed [15].

This process acts opposite to the net current generated in a turbulent bottom boundary layer by a velocity-skewed or acceleration-skewed oscillation (wave shape streaming). This near-bed current is generated by a non-zero wave-averaged turbulent stress, due to the different characteristics of the time-dependent turbulence during the on- and offshore phase of the wave [35,21].

Due to the above-described effects, the mean horizontal current within the surfzone has a strong variation in the vertical direction. Better understanding of this mean current profile is of crucial importance for a better understanding and prediction of the advective transport of constituents, such as suspended sediment, and consequently the coastal morphological evolution.

Most modeling systems for ocean and coastal hydrodynamics and morphodynamics (e.g. Delft3D and ROMS) do no resolve the wave

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motion, and wave-current coupling is a challenging topic. Many theoretical approaches and implementations have been proposed for this (see for a review [2]).

In this paper we will investigate the stresses and forces that control mean surfzone hydrodynamics based on detailed wave flume velocity measurements above a fixed sloping bed including two breaker bars [3]. This paper distinguishes itself from other experimental studies (e.g [24,33,34,30,31,7,8,38]) by the focus on the controlling forces, the level of detail of the measurements and the inclusion of breaker bars in the bed profile. An important aim of this paper is to provide insight in the contributions to the momentum balance that should be accounted for in 3D coastal modeling systems.

The paper is organized as follows. Section 2 presents the mean momentum balance. The experimental set-up, measurements and data-processing are described in Section 3. Section 4 discusses the experimental results. The discussion and conclusions are presented in Section 5.

2. Mean momentum balance

2.1. Depth-dependent

We can decompose the velocities and pressure in a turbulent, orbital and wave-mean part, for example

$$u = \overline{u} + u' = \langle u\rangle + \tilde{u} + u' \tag{1}$$

for the horizontal velocity where $\overline{\cdots}$ means averaging over the turbulent timescale and $\langle\ldots\rangle$ over the wave timescale. We can then derive the wave-averaged 2DV momentum equation in the horizontal x-direction (see e.g. [19]):

$$\frac{\partial}{\partial x}[\rho\langle u\rangle^2] + \frac{\partial}{\partial z}[\rho\langle u\rangle\langle w\rangle] = -\frac{\partial\langle p\rangle}{\partial x} - \rho\frac{\partial}{\partial x}[\langle\overline{u'^2}\rangle + \langle\tilde{u}^2\rangle] - \rho\frac{\partial}{\partial z}[\langle\overline{u'w'}\rangle + \langle\tilde{u}\tilde{w}\rangle] \tag{2}$$

in which ρ is the water density, u the velocity in x-direction, w the velocity in z-direction, p is pressure and g the acceleration due to gravity. This equation ignores temporal variation, viscous stresses and other body forces than gravity.

[28] derived the following expression for the wave-averaged pressure:

$$\langle p\rangle = \rho g(\langle\zeta\rangle - z) - \rho\langle\tilde{w}^2\rangle - \rho\langle\overline{w'^2}\rangle \tag{3}$$

by vertical integration of the 2DV momentum equation in z-direction. $\langle\zeta\rangle$ is the wave-averaged water surface elevation. This expression ignores the contribution due to $-\rho\langle w\rangle^2$ and the wave-mean of the horizontal derivative of the vertical integral of shear stresses, as these are generally small. If we combine Eqs. (2) and (3) we get:

$$\frac{\partial}{\partial x}(\rho\langle u\rangle^2) + \frac{\partial}{\partial z}(\rho\langle u\rangle\langle w\rangle) = -\rho g\frac{\partial\langle\zeta\rangle}{\partial x} + \frac{\partial\sigma_{xx}}{\partial x} + \frac{\partial\tau_{xz}}{\partial z} \tag{4}$$

with

$$\sigma_{xx} = -\rho(\langle\tilde{u}^2\rangle + \langle\overline{u'^2}\rangle - \langle\tilde{w}^2\rangle - \langle\overline{w'^2}\rangle) \tag{5}$$

the mean normal stress and

$$\tau_{xz} = -\rho(\langle\tilde{u}\tilde{w}\rangle + \langle\overline{u'w'}\rangle) \tag{6}$$

the mean shear stress.

2.2. Depth-integrated

In case of mild surface and bedslope, the time-averaged, depth-integrated momentum equation reads (see e.g. [28]):

$$\rho\frac{\partial}{\partial x}\left\langle\int_{-d}^{\zeta}u^2dz\right\rangle = -\rho gh\frac{\partial\langle\zeta\rangle}{\partial x} - \frac{\partial S_{xx}}{\partial x} + \langle R_x^s\rangle - \langle\tau_{bx}\rangle \tag{7}$$

in which $z = -d$ is the bed level, $h = (\langle\zeta\rangle + d)$ the mean water depth, $\langle R_x^s\rangle$ the mean stress at the surface in x-direction and $\langle\tau_{bx}\rangle$ the mean bed shear stress in x-direction. S_{xx} is the radiation stress, i.e. the excess flux of momentum due to the presence of waves (including turbulent contributions):

$$\begin{aligned} S_{xx} &= \left\langle\int_{-d}^{\zeta}(\rho\tilde{u}^2 + \rho\overline{u'^2} + p)dz\right\rangle - \frac{1}{2}\rho gh^2 \\ &= \left\langle\int_{-d}^{\zeta}(\rho\tilde{u}^2 + \rho\overline{u'^2} - \rho\tilde{w}^2 - \rho\overline{w'^2})dz\right\rangle + \frac{1}{2}\rho g\langle\eta^2\rangle \end{aligned} \tag{8}$$

using the time-dependent variant of Eq. (3) and with $\eta = (\zeta - \langle\zeta\rangle)$ the water level variation due to wave motion.

[16] derived the following expression for the radiation stress (without turbulence) using linear wave theory for $\tilde{u}$, $\tilde{w}$ and η, and ignoring higher order terms ($O(kh)^3$, with k the wave number):

$$S_{xx,\mathrm{LHS}} = \left(2n - \frac{1}{2}\right)E \tag{9}$$

in which $n = c_g/c$ with c_g the wave group celerity and c the wave celerity, and with $E = 1/8\rho gH^2$ the wave energy with H the wave height.

We can see the similarity between Eqs. (8) and (5). The difference appears in the second term on the RHS of Eq. (8) which is the hydrostatic pressure contribution due to the presence of waves:

$$\begin{aligned} \left\langle\int_{\langle\zeta\rangle}^{\zeta}\rho g(\zeta - z)dz\right\rangle &= \left\langle -\frac{1}{2}\rho g(\zeta - z)^2\Big|_{\langle\zeta\rangle}^{\zeta}\right\rangle = \left\langle\frac{1}{2}\rho g(\zeta - \langle\zeta\rangle)^2\right\rangle \\ &= \frac{1}{2}\rho g\langle\eta^2\rangle = \frac{1}{2}E \end{aligned} \tag{10}$$

using linear wave theory. There is thus a substantional pressure contribution to the radiation stress which takes place above the wave trough level (see also [11,17,13]). This contribution is not present in Eq. (5) as the expression for the wave-average pressure, Eq. (3), does not include it.

Energy dissipated during the breaking process is generally assumed to be first converted into organised vortices (the surface roller) before being dissipated into small-scale, disorganised turbulent motions [5]. The roller transports mass and momentum, and exerts a shear stress to the water below, affecting wave setup and undertow [26,27,11]. The expression of [16] does not account for the roller contribution.

3. Wave flume experiments

3.1. Experimental set-up

The experiments were carried out in the 40 m long, 0.8 m wide and 1.05 m deep wave flume of Delft University of Technology [3]. The fixed bed profile was based on a natural beach and included two breaker bars with a trough in between (see Fig. 1). The bed was built up with a fill of sand and a mortar toplayer, which was smoothened to reduce bed roughness. The Nikuradse bed roughness was estimated to have a value of about 0.5 mm. The still water level was at 0.75 m above the flume bottom.

In this paper we study data from two irregular wave (JONSWAP spectrum) conditions: 1B and 1C. Table 1 shows the experimental conditions, including the surf similarity parameter (also known as the Iribarren number) ξ defined as:

$$\xi = \frac{\tan\beta}{\sqrt{\frac{H}{L}}} \tag{11}$$

where $\tan\beta$ is the beach slope and L the wave length. We have calculated ξ using the offshore slope of the first breaker bar (0.054), the offshore (spectral) significant wave height ($H_{\mathrm{m0,off}}$) and the wave length following linear wave theory using the offshore spectral peak