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A rational approach to seepage flow effects on bottom friction beneath random waves

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ABSTRACT

The bottom friction beneath random waves is predicted taking into account the effect of seepage flow. This is achieved by using wave friction factors for rough turbulent, smooth turbulent and laminar flow valid for regular waves together with a modified Shields parameter which includes the effect of seepage flow. Examples using data typical to field conditions are included to illustrate the approach. The analytical results can be used to make assessment of seepage effects on the bottom friction based on available wave statistics. Generally, it is recommended that a stochastic approach should be used rather than using the *rms* values in an otherwise deterministic approach.

1. Introduction

At intermediate and shallow water depths the bottom wave boundary layer is a thin flow region dominated by friction arising from the combined action of the wave-induced near-bottom flow and the bottom roughness. The wave boundary layer flow determines the bottom shear stress, which affects many phenomena in coastal engineering, e.g. sediment transport and assessment of the stability of scour protection in the wave environment. A review is, e.g. given in Holmedal et al. [1].

In coastal areas the seabed is often sandy and permeable, and seepage flow in the seabed may occur naturally due to the horizontal pressure gradient caused by the difference between the pressure at the seabed under the wave crest and the wave trough, respectively. This will vary in time and space following the wave motion inducing flow into the seabed as the wave crest passes and out of the seabed as the wave trough passes (see, e.g. Lohmann et al. (2006, Fig. 12)). This seepage flow has two opposing effects. First, the seepage flow into and out of the bed modifies the wave boundary layer by increasing and decreasing the velocity gradient at the bed, respectively, leading to that the bed shear stress increases and decreases, respectively (see, e.g. Lohmann et al. (2006, Figs. 12, 18)). Second, the seepage flow exerts a vertical force on the sediments within the bed; the seepage flow into and out of the bed stabilizes and destabilizes the sediment, respectively.

Effects of seepage flow due to regular waves have, e.g. been discussed by Sleath [2], Soulsby [3], Nielsen [4,5]. Moreover, Conley and Inman [6] observed a wave crest – wave trough asymmetry in the fluid – sediment boundary layer development due to seepage flow beneath near-breaking waves in field measurements. These observations were supported by Conley and Inman [7] in laboratory experiments for regular waves. Lohmann et al. [8] performed Large Eddy simulation of a fully developed turbulent wave boundary layer subject to seepage flow for regular waves, and obtained results in accordance with the experimental results of Conley and Inman [7]. Nielsen [9] was the first to quantify the two opposing effects of seepage flow by defining a modified Shields parameter for regular waves. He used the shear stress experiments of Conley [10] for regular waves and the slope stability experiments of Martin and Aral [11] for steady flow to derive the coefficients to use in this modified Shields parameter. Nielsen et al. [12] used this modified Shields parameter together with their own experiments for regular waves to investigate the seepage effects on the mobility of sediments on a flat bed under waves. Obhrai et al. [13] extended this work to investigate the seepage effects on suspended sediments over a flat and a rippled bed for regular waves. Myrhaug et al. [14] provided a practical approach by which the stochastic properties of the net bedload sediment transport rate due to the seepage flow can be derived from the irregular wave motion outside the seabed wave boundary layer.

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For the prediction of the bottom friction under random waves, a commonly used procedure is to use the *rms* (root-mean-square) value of the wave height (H_{rms}) or the near-bed orbital velocity amplitude (U_{rms}) in an otherwise deterministic approach. However, this approach does not account for the stochastic feature of the processes included.

The purpose of the present paper is to provide a practical approach by which the stochastic properties of the bottom friction due to seepage flow can be derived from the irregular wave motion outside the seabed wave boundary layer. For regular waves there is a variety of bottom friction coefficient formulas available (see, e.g. Soulsby [3]). However, the purpose here is not to examine the details of them, but to demonstrate how such formulas can be used to find the bottom friction due to seepage flow under linear random waves over a flat seabed. The approach is based on assuming the waves to be a stationary Gaussian narrow-band random process, using wave friction factors for regular waves including the effect of seepage flow by adopting the Nielsen [9] modified Shields parameter. Thus the only wave asymmetry effect considered in this study is that contained in the modified Shields parameter. Examples are also included to demonstrate the applicability of the results for practical purposes using data typical for field conditions.

2. Bottom friction by regular waves

The effect of seepage flow is taken into account by adopting a modified Shields parameter originally suggested by Nielsen [9] (and re-presented by Nielsen et al. [12]):

$$\theta_w = \frac{u_{*0}^2(1-\kappa(w/u_{*0}))}{g(\gamma-1-\beta(w/K))d_{50}} \tag{1}$$

where $u_{*0} = (\tau_{w0}/\rho)^{1/2}$ is the friction velocity with no seepage, τ_{w0} is the maximum bottom shear stress with no seepage, ρ is the density of the fluid, g is the acceleration due to gravity, γ is the sediment density to fluid density ratio, d_{50} is the median grain size diameter, w is the vertical seepage velocity taken as positive upwards, κ and β are dimensionless coefficients recommended as $(\kappa, \beta) = (16, 0.4)$, and K is the hydraulic conductivity of the sand (to be specified later). Eq. (1) is based on obtaining $u_*^2/u_{*0}^2 = 1 - 16w/u_{*0}$ as the best fit to the Conley [10] data for $-0.05 < w/u_{*0} < 0.025$, where $u_* = (\tau_w/\rho)^{1/2}$ is the friction velocity with seepage, and τ_w is the maximum bottom shear stress with seepage. Moreover, $\beta = 0.4$ was determined using the slope stability experiments of Martin and Aral [11]. This modified Shields parameter includes two opposing effects. First, the flow into and out of the bed will make the boundary layer thinner and thicker and thereby the bed shear stress increases and decreases, respectively. Second, the flow into and out of the bed stabilizes and destabilizes the sediments, respectively. The numerator in Eq. (1) includes the change in the bed shear stress, i.e. to increase the shear stress for downward seepage ($w < 0$) and to reduce it for upward seepage ($w > 0$). The denominator includes the change in the effective weight due to the seepage, i.e. to stabilize the particles for downward seepage and to destabilize the particles for upward seepage. It should also be noticed that Eq. (1) is valid for non-breaking waves over a horizontal bed; see Nielsen et al. [12] for more details.

The maximum bottom shear stress within a wave-cycle without seepage is taken as

$$\frac{\tau_{w0}}{\rho} = \frac{1}{2} f_w U^2 \tag{2}$$

where U is the orbital velocity amplitude at the seabed, and f_w is the wave friction factor given for laminar (Eq. (3)), smooth turbulent (Eq. (5)) and rough turbulent flow (Eqs. (7)–(10)).

For laminar flow, the wave friction factor is given as that for Stokes' second problem [15]

$$f_w = 2Re^{-0.5} \quad \text{for} \quad Re \leq 3\times10^5 \tag{3}$$

where

$$Re = \frac{UA}{\nu} \tag{4}$$

is the Reynolds number associated with the wave motion, $A = U/\omega$ is the maximum near-bed orbital displacement, ω is the wave frequency, and ν is the kinematic viscosity of the fluid.

For smooth turbulent flow, the Myrhaug [16] smooth bed wave friction factor is adopted

$$f_w = rRe^{-s} \quad \text{for} \quad Re > 3\times10^5 \tag{5}$$

with the coefficients

$$(r, s) = (0.0450, 0.175) \tag{6}$$

Alternative coefficients (r, s) for smooth turbulent flow are given in Soulsby [3].

For rough turbulent flow, the friction factor proposed by Myrhaug et al. [17] is used

$$f_w = c\left(\frac{A}{z_0}\right)^{-d} \tag{7}$$

$$(c, d) = (18, 1) \quad \text{for} \quad 20 \lesssim A/z_0 \lesssim 200 \tag{8}$$

$$(c, d) = (1.39, 0.52) \quad \text{for} \quad 200 \lesssim A/z_0 \lesssim 11,000 \tag{9}$$

$$(c, d) = (0.112, 0.25) \quad \text{for} \quad 11,000 \lesssim A/z_0 \tag{10}$$

where $z_0 = 2.5d_{50}/30$ is the bed roughness based on the median grain size diameter d_{50}. Note that for rough turbulent flow Eq. (8) is obtained as best fit to irregular wave data, and that Eqs. (9) and (10) are obtained as best fit to regular wave data (see Myrhaug et al. [17] for more details). Also note that Eq. (9) corresponds to the coefficients given by Soulsby [3] obtained as best fit to regular wave data for $10 \lesssim A/z_0 \lesssim 10^5$. The advantage of using these friction factors is that it is possible to derive the stochastic approach analytically. One should note that all the wave-related quantities in Eqs. (1)–(7), i.e. τ_{w0}, U and A are the quantities associated with the harmonic motion. Thus a stochastic approach based on the harmonic wave motion is feasible, as will be outlined in the forthcoming.

3. Bottom friction by random waves

The present approach is based on the following assumptions: (1) the free surface elevation $\zeta(t)$ associated with the harmonic motion is a stationary Gaussian narrow-band random process with zero expectation described by the single-sided spectral density $S_{\zeta\zeta}(\omega)$, and (2) the bottom friction for regular waves given in the previous section, are valid for irregular waves as well.

The second assumption implies that each wave is treated individually, and consequently that the bottom friction is taken to be constant for a given wave situation and that memory effects are neglected. The accuracy of this assumption has been justified by Samad [18] for laminar and smooth turbulent flow, for which the bottom friction is given by Eq. (2); f_w is given in Eq. (3) for laminar flow, and by Eq. (5) using $(r,s) = (0.041, 0.16)$ for smooth turbulent flow. Samad [18] found good agreement between his measured bed shear stresses (laminar and smooth turbulent) under irregular waves and simulations and bed shear stresses based on individual wave formulas. For rough turbulent flow the validity of the second assumption was confirmed for seabed shear stresses by Holmedal et al. [1] for high values of A/z_0 (at about 30,000). Characteristic statistical values of the resulting seabed shear stress amplitude deviated less than 20% from those obtained by the Monte Carlo