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Seepage effects on bedload sediment transport rate by random waves

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ABSTRACT

The mean net bedload sediment transport rate beneath random waves is predicted taking into account the effect of seepage flow. This is achieved by using wave half-cycle bedload sediment transport formulas valid for regular waves together with a modified Shields parameter including the effect of seepage flow. The Madsen and Grant (1976) bedload sediment transport formula is used to demonstrate the method. An example using data typical to field conditions is included to illustrate the approach. The analytical results can be used to make an assessment of seepage effects on the mean net bedload sediment transport 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 the assessment of the stability of scour protection in the wave environment. A review is e.g. given in Holmedal et al. (2003).

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. This seepage flow has two opposing effects: first, the seepage flow into and out of the bed modifies the wave boundary layer, causing the bed shear stress to increase and decrease, respectively; second, the seepage flow exerts a vertical force on the sediments as the seepage flow into and out of the bed stabilizes and destabilizes the sediment, respectively.

Effects of seepage flow due to waves have been discussed by Sleath (1984), Soulsby (1997) and Nielsen (1992, 2009), for example. Moreover, Conley and Inman (1992) observed a wave crest–wave trough asymmetry in the fluid–sediment boundary layer development due to seepage flow in field measurements. These observations were supported by Conley and Inman (1994) in laboratory experiments. Lohmann et al. (2006) performed Large Eddy Simulation of a fully developed turbulent wave boundary layer subject to seepage flow, and obtained results in accordance with the experimental results of Conley and Inman (1994). Nielsen (1997) was the first to quantify the two opposing effects of seepage flow by defining a modified Shields parameter. He used the shear stress experiments of Conley (1993) and the slope stability experiments of Martin and Aral (1971) to derive the coefficients to use in this modified Shields parameter. Nielsen et al. (2001) used this modified Shields parameter together with their own experiments to investigate the seepage effects on the mobility of sediments on a flat bed under waves. Obhrai et al. (2002) extended this work to investigate the seepage effects on suspended sediments over a flat and a rippled bed.

For the prediction of the inception of motion or transport of seabed material under random waves, a commonly used procedure is to use the root-mean-square (*rms*) 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 net bedload sediment transport rate 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 sediment transport formulas available (see e.g. Soulsby, 1997). However, the purpose here is not to examine the details of them, but to demonstrate how such formulas can be used to find the mean net bedload sediment transport due to seepage flow under random waves. The approach

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is based on assuming the waves to be a stationary Gaussian narrow-band random process, using a wave half-cycle sediment transport rate formula for regular waves including the effect of seepage flow by adopting the Nielsen (1997) modified Shields parameter. The formulation is general, while the Madsen and Grant (1976) wave half-cycle bedload transport formula has been chosen to illustrate the method. An example is also included to demonstrate the applicability of the results for practical purposes using data typical for field conditions.

2. Bedload sediment transport rate by regular waves

The wave half-cycle bedload sediment transport rate for regular waves is given as

$$\Phi = \alpha(\theta_w - \theta_{cr})^{\gamma} \tag{1}$$

where α and γ depend on the formula considered, and

$$\Phi = \frac{q_b}{[g(s-1)d_{50}^3]^{1/2}} \tag{2}$$

$$\theta_w = \frac{u_{*0}^2(1-\kappa(w/u_{*0}))}{g(s-1-\beta(w/K))d_{50}} \tag{3}$$

Here Φ is the dimensionless bedload transport rate, θ_w is the Shields parameter including the effect of seepage, q_b is the volumetric bedload transport rate per unit width [m^2/s], g is the acceleration due to gravity, s is the sediment density to fluid density ratio, and d_{50} is the median grain size diameter. The effect of seepage is taken into account by adopting a modified Shields parameter originally suggested by Nielsen (1997) (and re-presented by Nielsen et al. (2001)) 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, 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. Eq. (3) is based on obtaining $u_*^2/u_{*0}^2 = 1-16w/u_{*0}$ as the best fit to the Conley (1993) 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 (1971). 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. (3) 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. (3) is valid for non-breaking waves over a horizontal bed; see Nielsen et al. (2001) for more details.

Eq. (1) was originally given with Eq. (3) for $w=0$, and is applicable to bedload transport and applies if θ_w is larger than the threshold value $\theta_{cr} \approx 0.05$. A review of wave half-cycle bedload sediment transport rate formulas is given in e.g. Soulsby (1997); Soulsby proposed $\alpha=5.1$ and $\gamma=3/2$; Madsen and Grant (1976) proposed $\alpha = 12.5 w_s d_{50}/[g(s-1)d_{50}^3]^{1/2}$, $\gamma=3$ and $\theta_{cr}=0$, where w_s is the grain settling velocity. More discussion will be given in Section 3.2.

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

$$\frac{\tau_{w0}}{\rho} = \frac{1}{2} f_w U^2 \tag{4}$$

where U is the orbital velocity amplitude at the seabed, and f_w is the wave friction coefficient taken as (Myrhaug et al., 2001)

$$f_w = c\left(\frac{A}{z_0}\right)^{-d} \tag{5}$$

$$(c,d) = (18,1) \text{ for } 20 \lesssim A/z_0 \lesssim 200 \tag{6}$$

$$(c,d) = (1.39,0.52) \text{ for } 200 < A/z_0 \lesssim 11{,}000 \tag{7}$$

$$(c,d) = (0.112,0.25) \text{ for } 11{,}000 < A/z_0 \tag{8}$$

where $A=U/\omega$ is the orbital displacement amplitude at the seabed, and $z_0=2.5d_{50}/30$ is the bed roughness based on the median grain size diameter d_{50}. Note that Eq. (7) corresponds to the coefficients given by Soulsby (1997) obtained as best fit to data for $10 \lesssim A/z_0 \lesssim 10^5$. The advantage of using this friction factor for rough turbulent flow is that it is possible to derive the stochastic approach analytically. One should note that all the wave-related quantities in Eqs. (1)–(5), 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. Bedload sediment transport rate by random waves

3.1. Outline of stochastic method

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 formulas for bedload sediment transport rate for regular waves given in the previous section, are valid for irregular waves as well.

Based on the present assumptions, the (instantaneous) time-dependent bed orbital displacement and velocity, $a(t)$ and $u(t)$, respectively, associated with the harmonic motion, are both stationary Gaussian narrow-band processes with zero expectations and with single-sided spectral densities

$$S_{aa}(\omega) = \frac{S_{\zeta\zeta}(\omega)}{\sinh^2 kh} \tag{9}$$

$$S_{uu}(\omega) = \omega^2 S_{aa}(\omega) = \frac{\omega^2 S_{\zeta\zeta}(\omega)}{\sinh^2 kh} \tag{10}$$

Now the orbital displacement amplitude at the seabed, A, the orbital velocity amplitude at the seabed, U, and the wave height, H, are Rayleigh-distributed with the cumulative distribution function (*cdf*) given by

$$P(\hat{x}) = 1-\exp(-\hat{x}^2), \quad \hat{x} = x/x_{rms} \geq 0 \tag{11}$$

where x represents, A, U or H, and x_{rms} is the *rms* value of x representing A_{rms}, U_{rms} or H_{rms}. Now A_{rms}, U_{rms} and H_{rms} are related to the zeroth moments m_{0aa}, m_{0uu} and $m_{0\zeta\zeta}$ of the amplitude, velocity and free surface elevation spectral densities, respectively (corresponding to the variances of the amplitudes (σ_{aa}^2), the velocity (σ_{uu}^2) and the free surface elevation ($\sigma_{\zeta\zeta}^2$)), given by

$$A_{rms}^2 = 2m_{0aa} = 2\sigma_{aa}^2 = 2\int_0^{\infty} S_{aa}(\omega)d\omega \tag{12}$$