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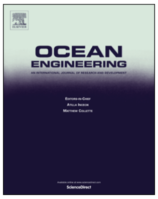

Suspended sediments due to random waves including effects of second order wave asymmetry and boundary layer streaming

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ABSTRACT

The paper provides a practical stochastic method by which the suspended sediment concentration due to long-crested (2D) and short-crested (3D) nonlinear random waves can be calculated. The approach is based on assuming the waves to be a stationary narrow-band random process, and by using the parameterized formulas valid for regular waves presented in Soulsby, R.L., 1997. Dynamics of Marine Sands. Thomas Telford, London. The Forristall, G.Z., 2000. Journal of Physical Oceanography. 30, 1931–1943. wave crest height distribution representing both 2D and 3D nonlinear random waves is also adopted. The model covers sediment suspension over rippled beds and for sheet flow. Comparisons are made with random wave data from Thorne, P.D., Williams, J.J., Davies, A.G., 2002. Journal of Geophysical Research. 107 (C8), 3178 for flow over rippled beds. An example for sheet flow using data typical to field conditions is also included to illustrate the approach.

1. Introduction

Suspended sediment concentrations over sandy seabeds in shallow and intermediate water depths, i.e. in coastal zones and on continental shelves, occur predominantly as a result of the combined action of waves and currents. The waves are the principal cause of the entrainment of the sediment, which are diffused into the flow by turbulent processes, and subsequently transported by the current. Wave–current–sediment interactions are crucial in scour and erosion studies for seabed pipelines and other near seabed structures. This interaction is also important in developing models for the movement of sediment on the seabed in combined action of waves and currents, and the resulting coastal evolution.

In a realistic sea state the surface waves show a complex three-dimensional irregular pattern where the sharpening of the wave crests manifests wave nonlinearity, complicating the problem. The wave-induced bottom shear stress determines the response of sandy seabeds. When the shear stress exceeds the critical value for initiation of sand motion, ripples will be formed as the wave activity increases. Under large waves the seabed ripples are washed out such that a larger layer of high sediment concentration is developed in the vicinity of the bed, i.e. a sheet flow layer with a thickness of the order of mm or cm depending on how it is defined (see e.g. Myrhaug and Holmedal, 2007).

The sheet flow layer is defined as the layer where concentrations are so high that inter-granular forces and sediment flow interaction forces are important. Sheet flow transport is important in the surf zone even under moderate wave conditions, and the associated high concentrations play an important role in erosion, sedimentation and morphology as well as for the design of coastal structures. Under severe wave conditions sheet flow may occur in intermediate water depths, and the intense sediment transport might cause exposure of e.g. buried pipelines and foundations of structures, as well as affect the stability of scour protections of marine structures. Sheet flow conditions might also have ecological implications since the high sand concentrations might directly affect life in the ocean in several ways: for example, highly turbid water might negatively impact fish to feed, as well as reducing their reproduction rate. Thus, knowledge of the response of this thin layer for sheet flow under realistic field conditions is crucial to conserve the diversity of species living in the thin surface bottom sediment layer. The suspended sediments also play an important role in spreading and transport of pollutants, since it affects the upper bottom sediment layer which is brought into suspension. Recent works related to sheet flow are those of e.g. (Myrhaug and Holmedal, 2007; Holmedal et al., 2013; Fuhrman et al., 2013; Chassagneux and Hurther, 2014; and the references therein).

Steady streaming under sinusoidal waves is caused by non-uniformity of the wave boundary layer resulting from spatial

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variation of the orbital velocities. Vertical velocities generated within the bottom boundary layer under progressive waves are not exactly out of phase with the horizontal velocities, leading to a non-zero time-averaged bed shear stress. The steady streaming for a laminar wave boundary layer was determined by Longuet-Higgins (1956). Based on this work, the streaming-related time-averaged bed shear stress can be expressed in terms of the wave friction factor and the wave number (see, e.g. Nielsen, 1992). Nielsen and Callaghan (2003) included the effect of streaming predicting the shear stress and the total sediment transport rate for sheet flow under waves. The effect of streaming was included by adding a constant shear stress corresponding to the streaming-related bed shear stress and by applying a friction factor for rough turbulent flow. This method predicts the real propagating wave observations of Ribberink et al. (2000) quite well. Myrhaug et al. (2004) followed Nielsen and Callaghan (2003) relating the wave-induced current (streaming) for rough turbulent flow and used this to deduce formulas for bottom friction and bedload sediment transport due to boundary layer streaming beneath random waves. The effects of second order wave asymmetry on bottom friction and bedload sediment transport for horizontally uniform oscillatory flow were also part of the study.

A summary of results from models and experiments on wave-induced streaming near the seabed is given by Davies and Villaret (1997, 1998, 1999). Above a smooth bed, the measured streaming at the edge of the wave boundary layer is in reasonable agreement with the Eulerian drift predicted by Longuet-Higgins (1956). Over a flat rough bed, however, the Eulerian drift is reduced in magnitude. The reason is that the phase difference between the outer velocity and the near-bed velocity is smaller for rough turbulent flow than for laminar flow. This feature is described by Trowbridge and Madsen (1984) for flows in which momentum transfer is dominated by turbulent processes, i.e. for $A/z_0 \geq 900$, where A is the near-bed orbital displacement amplitude and z_0 is the bed roughness. Trowbridge and Madsen (1984) also included the effect of second order wave asymmetry by including second order terms in a specified time-varying eddy viscosity for flow over flat rough beds. They found that this reduced the Eulerian drift at the edge of the boundary layer with a mean flow reversal (negative drift) occurring for very long waves, i.e. for small kh, where k is the wave number and h is the water depth.

Holmedal and Myrhaug (2009) investigated in detail the Longuet-Higgins streaming, the streaming due to wave asymmetry and the interaction between these two mechanisms. For realistic physical situations the seabed boundary layer beneath both propagating linear waves and Stokes second order waves, as well as horizontally uniform oscillatory bottom boundary layer flow with second order asymmetric forcing were investigated. They found that the Longuet-Higgins streaming velocities beneath propagating linear waves are always in the wave propagation direction, while the streaming velocities in horizontally uniform boundary layers with asymmetric forcing are opposite the wave propagation direction. This work was extended by Holmedal et al. (2013) investigating the effect of streaming on the seabed boundary layer flow beneath combined waves and current for waves following and opposing a current. They found that for wave-dominated conditions the mean (i.e. averaged over one wave period) velocity profile beneath following waves and current is significantly different from the mean velocity profile beneath opposing waves and current. Both linear and second order Stokes waves were taken into account (a review and more details are given in Holmedal et al. (2013) and in the references therein). Recently Afzal et al. (2015) extended this to waves at an angle with the current.

The reader should note the difference between the two effects considered in this work; the second order wave asymmetry and streaming. Due to the second order wave asymmetry effect, the magnitude of the wave crest velocity is larger than that of the wave trough velocity at the edge of the boundary layer. On the other hand, streaming is caused by the presence of a vertical velocity component in the boundary layer under progressive waves giving a weak current at the edge of the boundary layer. For the parameter regime considered here, this current is in the wave propagation direction.

For the prediction of suspended sediment concentration due to random waves, a commonly used procedure is to substitute the wave-related quantities with their characteristic statistical values, for example the *rms* (root-mean-square) values in an otherwise deterministic approach (see e.g. Soulsby, 1997). Comparison of results from field measurements and empirical models of suspended sediments under waves and currents have been made by representing the random waves by their characteristic statistical values (see e.g. Cacchione et al., 2008; Dolphin and Vincent, 2009; Bolanos et al., 2012). However, this procedure does not account for the stochastic feature of the processes included. Moreover, sharpening of the wave crests manifests wave-nonlinearity. To the present authors knowledge no stochastic method for prediction of suspended sediment concentration beneath random waves is available in the open literature.

The purpose of this study is to provide a practical stochastic method for calculating the suspended sediment concentration over rippled seabeds and for sheet flow due to random waves including effects of second-order wave asymmetry. For sheet flow the effect of wave boundary layer streaming is also provided. The approach is based on assuming the waves to be a stationary narrow-band random process, adopting the Forristall (2000) wave crest height distribution representing both long-crested (2D) and short-crested (3D) random waves, and using parameterized formulas valid for regular waves presented in Soulsby (1997). The model covers sediment suspension over rippled beds for linear and 2D nonlinear random waves, and comparisons are made with data obtained from measurements of suspended sediment concentrations over rippled bedforms beneath 2D random waves in a large-scale flume reported by Thorne et al. (2002). An example for sheet flow is also included to demonstrate the applicability of the results for practical purposes using data typical for field conditions.

2. Suspended sediments due to regular waves

Many parameterizations to calculate the suspended sediment concentration in the water column close to the seabed under regular waves have been proposed in the literature; these parameterizations were reviewed and presented in Soulsby (1997). In the following the formulas for regular waves, which are used as the basis for suspended sediments due to random waves given in Section 3, will be summarized.

2.1. Rippled beds

For rippled beds the concentration profile is given by

$$C(z) = C_0 \exp\left(-\frac{z}{\ell}\right) \tag{1}$$

where $C(z)$ is the sediment concentration at the height z above the bed, C_0 is the reference concentration at the seabed, and ℓ is the decay length scale. Here the Nielsen (1992) expressions for ℓ and C_0 are adopted

$$\ell = 0.075\frac{U}{w_s}\eta \quad \text{for} \quad \frac{U}{w_s} < 18 \tag{2}$$