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Nonuniform sediment transport under non-breaking waves and currents

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ABSTRACT

Empirical formulas have been developed to calculate the fractional bed-load and suspended-load transport rates and near-bed suspended-load concentration under non-breaking waves and currents for coastal applications. The formulas relate the bed-load transport rate to the grain shear stress, the suspended-load transport rate to the energy of the flow system, and the near-bed suspended-load concentration to the bed-load transport rate, velocity and layer thickness. Adequate methods are adopted to determine the bed shear stress due to coexisted waves and currents. The hiding and exposure mechanism in nonuniform bed material is considered through a correction factor that is related to the hiding and exposure probabilities and in turn the size composition of bed material. The developed formulas have been tested using a large database of single-sized sediment transport and several sets of multiple-sized sediment transport data collected from literature, and compared with several existing formulas. The developed formulas can provide reasonably good predictions for the test cases.

1. Introduction

Though nonuniform or graded sediments widely exist in coastal areas, their influence on coastal processes is commonly underestimated due to the difficulty in characterizing and quantifying them (Holland and Elmore, 2008). Nonuniform sediment transport exhibits difference from uniform sediment transport, even when the mean grain size is the same for both cases. The hiding, exposure, and armoring among different size classes in the nonuniform bed material significantly affect sediment transport, morphological change, bed roughness, wave dissipation, etc. For example, bed sediment coarsening can affect the navigation channel near a coastal inlet, and a model prediction based on the assumption of single-sized sediment often overpredicts the channel depth there. It is necessary to develop multiple-sized sediment transport capacity formulas to improve the accuracy and reliability of analysis methods and numerical models for coastal sedimentation.

Many coastal sediment transport formulas, such as Bijker (1968), Bailard (1981), van Rijn (1993), Dibajnia and Watanabe (1992), Ribberink (1998), and Camenen and Larson (2007), had assumed uniform or single-sized sediments. Extensive databases have been established for single-sized sediment transport based on the past laboratory and field measurements (Camenen and Larson, 2007; SEDMOC, 1999). In contrast, only a limited number of studies have concerned nonuniform sediment transport in coastal environments. Among them, Dibajnia and Watanabe (1996) extended their bed-load transport rate formula (Dibajnia and Watanabe, 1992) to mixed sand transport, and verified the extended formula by using mixtures composed of fine sand with a median diameter of 0.2 mm and coarse sand with a median diameter of 0.87 mm. Hassan et al. (2001) applied Ribberink's (1998) bed-load transport formula to calculate the transport rate of nonuniform material under oscillatory sheet flow. Comparing the experimental results with the predicted values, they found that the formula led to better prediction by multiplying the Shields parameter with the hiding/exposure correction factor of Day (1980), which is a function of relative sediment diameter d_k/d_A. Here, d_k is the sediment diameter of size class k and d_A is a representative diameter related to the median diameter and gradation of the bed material. van Rijn (2007a,b,c) extended his bed-load and suspended-load transport formulas in steady river flow to coastal flow under currents and waves and investigated the hiding/exposure correction factors for computing multiple-sized sediment transport. Recently a nonuniform sand transport formula was developed by van der A et al. (2013), considering the hiding and exposure effect through a correction factor, as well as the skewed, asymmetric waves. In recent years, laboratory experiments on mixed sediment transport under coexisted currents and waves have been conducted by several groups (Ahmed, 2002; De Meijer et al., 2002; Dibajnia and Watanabe, 2000; Hassan and Ribberink, 2005; Inui et al., 1995; Jacobs and Dekker, 2000; O'Donoghue and Wright, 2004; Sistermans, 2001) and can be used to validate multiple-sized sediment transport formulas.

Because sediments in rivers often cover a much wider range of sizes from clay to boulders, nonuniform sediment transport by river flow has been investigated relatively more extensively. A dozen of such formulas have been developed in literature, including the Parker (1990) formula, the Ackers and White (1973) formula modified by Day (1980) and

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Proffitt and Sutherland (1983), the SEDTRA module (Garbrecht et al., 1995), the Karim (1998) formula, and the Wu et al. (2000) formula. Ribberink et al. (2002) compared several multi-fraction bed-load transport formulas using the bed-load data of widely graded sediment mixtures in the lower Shields regime and found that the Wu et al. (2000) formula performed better than the other compared formulas, including the Parker (1990) formula, the Ackers and White (1973) formula with the hiding-exposure correction factors of Day (1980) and Proffitt and Sutherland (1983), and the Meyer-Peter and Mueller (1948) formula with the hiding-correction factors of Egiazaroff (1965) and Ashida and Michiue (1971). One of the main advantages of the Wu et al. (2000) formula is that the proposed hiding and exposure correction factor is related to the hiding and exposure probabilities and in turn the size composition of bed material, which is omitted in many other existing formulas.

In this study, the formulas of Wu et al. (2000) are enhanced to compute bed-load and suspended-load transport rates and near-bed suspended-load concentration under non-breaking waves and currents for coastal applications. Methods are adopted to determine the bed shear stress due to combined currents and waves. This paper describes the bed shear stress calculation, the hiding and exposure correction factor, the enhanced formulas and their testing against available measurement data.

2. Bed shear stress under currents and waves

The bed shear stress is an important parameter of the flow carrying sediment transport. The methods used in this study to determine the bed shear stress due to only currents, only waves and combined currents and waves are described below.

2.1. Bed shear stress due to currents

For a sediment bed with sand grains and bed forms (such as sand ripples and dunes), the bed shear stress is composed of two contributions: the grain shear stress due to the drag on individual sand grains, and the form shear stress due to the pressure field acting on the bed forms. The grain shear stress due to currents, $\tau_{b,c}'$, is determined by (Meyer-Peter and Mueller, 1948; Wu et al., 2000)

$$\tau_{b,c}' = \left(\frac{n'}{n}\right)^{3/2} \tau_{b,c} \tag{1}$$

where n' is the Manning coefficient of grain roughness determined by $n' = d_{50}^{1/6}/20$ with d_{50} as the median diameter of bed material (Wu et al., 2000), n is the Manning coefficient of bed roughness (including grain and form roughness), and $\tau_{b,c}$ is the total bed shear stress due to currents. $\tau_{b,c}$ is related to the depth-averaged current velocity through the Manning equation as

$$\tau_{b,c} = \frac{\rho g n^2}{h^{1/3}} U_c^2 \tag{2}$$

where U_c is the depth-averaged current velocity, h is the water depth, ρ is the water density, and g is the gravitational acceleration. The Manning's n is related to the flow and bed conditions. In the original formula of Wu et al. (2000), it can be calibrated using measurement data if available. In this study, it is determined using the following logarithmic formula:

$$n = \frac{h^{1/6}}{18 \log(12h/k_s)} \tag{3}$$

where k_s is the equivalent roughness height, which consists of grain roughness, k_s', and form roughness, k_s'':

$$k_s = k_s' + k_s''. \tag{4}$$

Note that some scientists (e.g., Camenen and Larson, 2007; van der A et al., 2013) include the roughness due to sediment transport when calculating the total equivalent bed roughness in Eq. (4), whereas others (e.g., Einstein, 1950; van Rijn, 1984a,b) do not. The present study chooses not to include the roughness due to sediment transport since it is usually much smaller than the form (ripple) roughness.

The grain roughness height k_s' has been given different values in literature, such as $2d_{50}$ (Camenen and Larson, 2007) and $3d_{90}$ (van Rijn, 1984a,b). In this study, k_s' is set as 1.5–3.0 times d_{90}, which will be discussed in the section of formula testing. Here, d_{90} is the particle size at which 90% by weight of the bed material are finer.

The bed forms considered in the coastal context usually are sand ripples. The ripple roughness height, k_s'', is estimated using the method of Soulsby (1997):

$$k_s'' = A_r \frac{\Delta_r^2}{\lambda_r} \tag{5}$$

where Δ_r and λ_r are the ripple height and length, respectively, and A_r is a coefficient which varies from 5.0 to 40.0. Nielsen (1992) suggested $A_r = 8.0$, and van Rijn (1993) proposed $A_r = 20.0$. In this study A_r is set as a constant of 12.0. The height and length of ripples in case of only currents are determined using the method of Raudkivi (1998):

$$\Delta_r = 0.074 \lambda_r d_{mm}^{-0.253} \tag{6}$$

$$\lambda_r = 245 d_{mm}^{0.35} \tag{7}$$

where d_{mm} is the sediment median diameter in mm. The units of Δ_r and λ_r in Eqs. (6) and (7) are mm.

For convenience, Eq. (1) is rewritten as

$$\tau_{b,c}' = \frac{1}{2} \rho f_c' U_c^2 \tag{8}$$

where f_c' is the grain friction coefficient due to currents, which is given as follows by using Eq. (2):

$$f_c' = 2\left(\frac{n'}{n}\right)^{3/2} \frac{g n^2}{h^{1/3}}. \tag{9}$$

2.2. Bed shear stress due to waves

The bed shear stress due to non-breaking waves is determined using the formula of Jonsson (1966):

$$\tau_{b,wm} = \frac{1}{4} \rho f_w U_w^2 \tag{10}$$

where $\tau_{b,wm}$ is the mean bottom wave stress averaged over a wave cycle, U_w is the amplitude of wave orbital velocity near the bed at the edge of wave boundary layer, and f_w is the bed friction coefficient of waves determined using the Soulsby (1997) formula:

$$f_w = 0.237 (A_w/k_s)^{-0.52} \tag{11}$$

where A_w is the wave excursion $A_w = U_w T_w / 2\pi$, with T_w being the wave period.

The mean grain shear stress due to waves, $\tau_{b,wm}'$, is calculated as

$$\tau_{b,wm}' = \frac{1}{4} \rho f_w' U_w^2 \tag{12}$$