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Review

Advances in sediment transport under combined action of waves and currents

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ABSTRACT

The coastal zone continuously changes due to natural processes and human activities. In order to understand and predict these morphological changes, an accurate description of sediment transport, caused by waves and currents (tidal or wave-induced), is important. This paper presents a review of the state-of-the-art knowledge in this field, including sediment incipient motion, bed forms, bed roughness, bed-load transport, suspended-load transport, equilibrium sediment concentration, and sheet flow. Some possible research fields and topics for future study also are proposed.
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1. Introduction

Estuarine and coastal regions of the world are the centers of socio-economic activity. Protection and utilization of coastal areas have been studied extensively, for example, storm surge defenses, development of harbors and navigation channels, coastal area reclamation, etc. The evolution and utilization of estuarine and coastal regions are mainly controlled by sediment problems.

In estuarine and coastal regions, both wave and current movements are important to sediment transport (Wang, 1989). The hydrodynamic condition under wave–current interaction controls and affects sediment resuspension, mixing, and transport processes. Furthermore, pollutants are mainly transported with sediment particles. Thus, sediment and pollutant transport under complex hydrodynamic conditions could be considered as unsteady transport of materials under the combined action of waves and currents. Understanding these processes is fundamental for reasonable utilization and protection of estuarine and coastal areas (Lu et al., 2009). For example, during a storm surge, a large amount of sediment on the sea bed will be suspended by strong waves and then be rapidly transported by strong currents. Significant deposition may occur in the nearby channels (especially newly excavated channels in shallow water) due to the weakening of flow dynamics close to the bed. In China, such rapid siltation is a common phenomenon during storm surges (Lu et al., 2005). Therefore, a comprehensive understanding of these processes is highly significant in both academic research and engineering practice.

This paper presents a review of the state-of-the-art knowledge of sediment transport under waves and currents, including sediment incipient motion, bed forms, bed roughness, bed-load transport, suspended-load transport, equilibrium sediment concentration, and sheet flow. Some further possible research fields and topics also are proposed.

2. Sediment incipient motion

For understanding and predicting coastal morphological changes, the first step is to predict the threshold of sediment incipient motion. Critical bed shear stress is generally used to express critical conditions for sediment incipient motion under combined action of waves and currents.

Compared with a steady flow condition, a sediment particle experiences an extra body force under the waves or combined action of waves and currents. However, the body force is far less than drag force and lift force, so that it is possible to extend Shields' curve which includes the fundamental factor that determines the bed shear stress for sediment incipient motion under steady flow conditions (Shields, 1936) to the situation under wave or wave–current conditions. Following this approach, some useful explorations have been done on two aspects (Willis, 1978; van Rijn, 1993; Cao et al., 2003; Zhao, 2003; Zhou, 2008). Firstly, the particle

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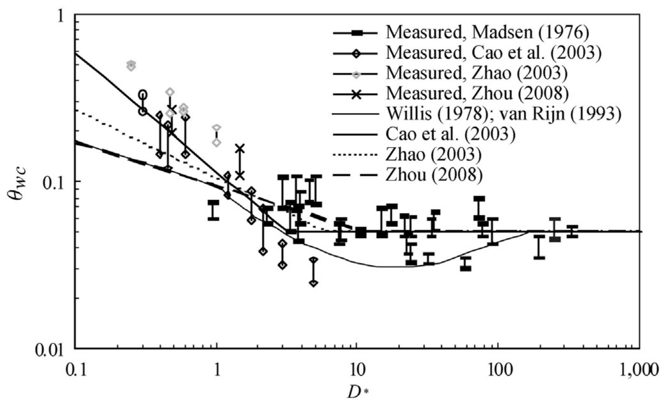

Fig. 1. Criterion curve for sediment incipient motion under combined action of waves and currents.

Reynolds number $R_e^*=u^*d/\nu$ was replaced by a nondimensional sediment diameter $D^*=[(\rho_s/\rho-1)gd]^{0.5}d/4\nu$, where ρ_s=sediment density, ρ=water density, d=grain diameter, u^*=bed shear velocity, g=gravitational acceleration, and ν=kinematic viscosity. Then the bed shear stress was replaced by that for wave or wave–current conditions. With the foregoing modifications, Willis (1978) and van Rijn (1993) concluded that the criterion curve coincided with the original Shields' curve. Cao et al. (2003), Zhao (2003), and Zhou (2008) proposed the modified criterion curve, as $\theta_{wc}=a_0D^{*b_0}$ in the laminar flow regime and θ_{wc}=0.05 in the turbulent flow regime, but with different points of intersection (Fig. 1), where θ_{wc} = wave–current Shields parameter = $\tau_{wc}/[(\rho_s-\rho)gd]$, τ_{wc}=wave–current bed shear stress, a_0 and b_0 are both constants. Through Fig. 1, it can be found that Willis (1978) and van Rijn (1993)'s curves seem lower than dotted measured point for $D^*>3$ which may be induced by the unknown mic-mechanism for sediment exchange near bed while Willis (1978), van Rijn (1993) and Zhou (2008)'s curves seem lower than dotted measured point for $D^*<1$ which may be induced by the ignoring of cohesive force between sediment particles. It is worthwhile to note that Zhou (2008) pointed out that when Shields' curve was applied to wave or wave–current conditions, the boundary layer should be adjusted correspondingly. He was the first to theoretically explain the shape of criterion curve under waves or combined wave-currents. More recently, Li et al. (2013) and Li et al. (2014) discussed the criterion curve under combined wave–current action in consideration of boundary layer characteristics, and argued that the criterion curve under combined wave–current action shifts between that of waves-only and currents-only, depending on the ratio of intensities of waves and currents.

In general, the studies of sediment incipient motion under waves or combined wave–current action still follow the approach used under current-only conditions, with modifications of some of the main dynamic parameters. Some microscopic mechanisms for the sediment exchange in the boundary layer typically are ignored. Li et al. (2013, 2014) tried to study the criterion curve from the viewpoint of the boundary layer, but how to quantify the characteristics of wave–current boundary layer still needs to be further studied.

3. Bed forms and bed roughness

After sediment starts its initial motion, bed forms develop gradually. Different bed sand and combinations of waves and currents would result in different bed forms, and, hence, bed roughness, which directly controls the bed shear stress, flow structure, and sediment concentration near the bed. Thus, an accurate simulation of the sediment alluvial process in the boundary layer requires a delicate understanding of bed forms and related bed roughness.

3.1. *Bed forms*

Although bed forms under waves-only or currents-only have been studied extensively, very few studies have been done on changes of bed forms subjected to the combined action of waves and currents.

Li and Amos (1999) reported the detailed bed form evolution process on the Nova Scotia coast during three storm surges. It was found that during the dynamic-increasing period, first ripples occurred with height, η, in the range of several centimeters and length, λ, in the range of tens of centimeters; when the flow dynamics became stronger, sand dunes appeared with height in the range of tens of centimeters and length in the range of hundreds of centimeters; with further strengthened flow dynamics, the bed could become smooth, exhibiting sheet flow. During the dynamics-damping period, the bed would experience a reverse process from sheet flow to sand dunes to sand ripples. Obviously, different bed forms developed under different combinations of waves and currents. Different from the steady current condition, sand ripples play an important role in determining bed shear stress and sediment suspension for waves or combined wave–current conditions, because the ripple scale is equivalent to the scale of the orbital excursion close to the bed, resulting from vortex separation around ripples. The ripples reach a maximum height and length, which are dependent on the grain diameter (d), wave period (T), and peak nearbed orbital velocity of combined waves and currents (u_{wc}). Based on the analysis of many data sets, ripples are found to be dominant for ψ_{wc}=wave–current mobility number=$u_{wc}^2/(\rho_s/\rho-1)gd$ in the range of 50–150 and disappear for $\psi_{wc}>150$ (van Rijn, 2007). The study of ripples includes three topics: the prediction of the bed form types under different hydrodynamic conditions, the prediction of the ripple characteristics in equilibrium, and the prediction of ripples response to flow dynamic variations (Soulsby & Whitehouse, 2005).

The criterion of different types of bed forms obviously is correlated to the ratio of intensities of waves and currents, as well as the angle of wave and current directions. For example, for the wave-dominated condition, the bed form exhibits the characteristics of a symmetrical shape with a steep crest and gentle trough; for the current-dominated condition, the bed form exhibits the characteristics of an asymmetric shape with a gentle forward slope and a steep lee slope; for the condition of wave–current dynamic equivalence, the bed form exhibits combined characteristics. For different angles of wave and current directions, the bed form displays significant three-dimensional (3D) characteristics, as shown in Fig. 2. Li and Amos (1998) used a factor u_w^*/u_c^* to distinguish current-dominated ripples ($u_{*w}/u_{*c}<0.75$), wave–current ripples ($0.75<u_w^*/u_c^*<1.25$), wave-dominated ripples ($1.25<u_w^*/u_c^*<2$), and pure wave ripples ($2<u_w^*/u_c^*$), where u_w^*, u_c^* represent bed shear velocity for waves-only and current-only conditions, respectively. Kleinhans (2005) summarized previous results and defined bed form categories as immobility, sheet flow, current ripple, vortex ripple, and mixed ripple. The criterion defining these conditions was expressed through a diagram with parameters of current Shields' parameter, θ_c, wave Shields' parameter, θ_w, and dimensionless grain diameter D^{*} ', where $\theta_c=\tau_c/[(\rho_s-\rho)gd]$, τ_c=current bed shear stress, $\theta_w=\tau_w/[(\rho_s-\rho)gd]$, τ_w=wave bed shear stress, $D^{*}{}'=d_{50}[(\rho_s-\rho)g/\rho\nu^2]^{1/3}$, and d_{50}=median sediment diameter.

Many formulas are available for predicting ripples under waves, such as the Nielsen (1981) formula, Vongvisessomjai (1984) formula, Wiberg and Harris (1994) formula, Mogridge et al. (1994) formula, and so on. Although based on different assumptions, these formulas exhibit similar structures: the dimensionless ripple length (λ/A, λ/d, λ/λ_0) and ripple height (η/λ, η/d, η/η_0) usually correlate to

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