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A behavior-oriented formula to predict coastal bathymetry evolution caused by coastal engineering

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ABSTRACT

The two common expressions of near-bed sediment flux (also called erosion and deposition flux) in terms of sediment carrying capacity and bed shear stress are unified in this study. A behavior-oriented formula to calculate coastal bathymetry evolution caused by coastal engineering on a muddy coast is also developed based on the unified expression. Compared with the other common behavior-oriented formulas on a muddy coast, the vertical suspended sediment distribution and near-bed sediment exchange mechanism are considered, and the formula has the advantage of calculating both bed siltation and erosion distribution. The formula is applied to simulate the local morphology change resulting from the siltation-promoting works at the mouth of the Yangtze River estuary of China. A comparison between the measurement and the calculated results of other common formulas shows that the morphology change caused by the project is well reproduced, and the behavior-oriented formula can be used to predict the coastal bathymetry evolution caused by coastal engineering on muddy coast.

1. Introduction

As the most closely connected area between human beings and oceans, the coastal zone has become the gold zone of the world's economic development. In recent decades, a significant amount of coastal engineering has been built, including harbors, waterways, and reclamation works. Coastal engineering breaks the natural hydrodynamic and sediment transport processes, resulting in local bathymetry evolution and re-adaptation to the new morphodynamics within time scales varying from months to years. This bathymetry evolution is of great concern in coastal research because it affects many aspects including structure safety, harbor siltation and beach protection.

Over the past decades, various methods have been developed to predict the bathymetry evolution caused by natural events and human activities. Generally, these methods can be classified into two groups, referred to as the process-based models (Dubarbier et al., 2015; Lesser et al., 2000; Ribberink et al., 2005; Van Rijn, 1986, 1993; Zhang et al., 2013) and the behavior-oriented models (Eysink and Vermaas, 1983; Gole et al., 1971; Jiang et al., 2007; Liu and Zhang, 1992a, 1992b; Mayor-Mora et al., 1976; Wang et al., 2001). The process-based models simulate detailed hydrodynamic and sediment transport processes to describe the behavior of natural systems based on underlying physical mechanisms. They have achieved great success in short-term processes (hours to days) but suffer from numerical instability and long computation time when working with medium-term (seasons to decades) and long-term (decades to centuries) bathymetry evolution owing to complex numerical methods and the processing capacity of computers. The behavior-oriented models understand the main mechanism of the evolution and neglect the specific underlying physical process. They use simple conceptual and empirical formulas to calculate medium- and long-term bathymetry evolution. They tend to be simple, less computationally complex yet still popularly used in engineering practice because they provide reasonable results. The present study will focus on the behavior-oriented models.

The behavior-oriented models have been widely used in the study of beach profile response, shoreline change, and sandbar migration. Among them, the most well-known model is that of the equilibrium beach profile formulas, also called the Bruun rule. Its basic concepts are that the shoreface tends to maintain the same slope for a given water depth and wave exposure and that there is a tendency for natural processes to establish an equilibrium beach and nearshore profile that provides a balance between the tendency of wave action to move sediment on shore and the tendency of gravity and currents to move sediment offshore (Bruun, 1954). This concept was further developed to predict the response of an erodible soft sediment shore to a rise in sea level (Bruun, 1962; Dean, 1991; Dean and Maurmeyer, 1983).

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Nomenclature

D	the water depth
d_{50}	the mean diameter of deposits (in mm)
h_0	the water depth at the beginning of the tide level rising during a tidal cycle
F_s	the deposition and erosion term, also called the near-bed sediment flux or erosion and deposition flux
g	the acceleration of gravity
HA	the area of harbor basin inside the harbor
h	the tide-averaged water depth
h_s, h_h	water depths of shoals and basins, respectively
h_*	the height of centroid of vertical sediment distribution from bed surface
K, k_0	coefficients
M	the erosion coefficient
n	the number of tidal cycles in time t
p_f	the trapping efficiency
Q	the water volume of exchange during a tide
S, S_*	the depth-averaged sediment concentration and sediment carrying capacity, respectively
S_{out}	suspended sediment concentration outside of harbor basin
s_{*b}, s_b	sediment carrying capacity near bed and sediment concentration near bed, respectively
T	the tidal cycle
TA	the area of harbor basin
T_r	the retention time
U	the tide-averaged current velocity
U_{in}	flow velocity inside the harbor basin
$U_{in,c}$	the critical flow velocity for deposition
U_x, U_y	the depth-average flow velocities in the x and y directions, respectively
u_*	the shear velocity
z_{Rouse}	the Rouse parameter, $z_{Rouse} = \frac{\omega_s}{\kappa u_*}$
α, α_e', α_e	coefficients
β	the ratio of the near-bed sediment concentration to the depth-averaged sediment concentration
β_*	the ratio of the near-bed sediment carrying capacity to the depth-averaged sediment carrying capacity
ψ, ξ	coefficients
η_d, η_e	coefficients
γ_0	dry density of deposits
τ_b	the bed shear stress
τ_{ce}, τ_{cd}	the critical shear stress for erosion and deposition, respectively
ω_s	the settling velocity of suspended sediment
Δh	the tidal range
$\Delta z_{bed}(t)$	the siltation thickness (m) in time t
Δz_c, Δz_m	the calculated and measured siltation thickness, respectively

Davidson et al. (2013) developed a behavior-orientated model for predicting shoreline displacement forced by wave-driven cross-shore sediment transport. Hysteresis effects are shown to be important and are included in the model, whereby present shoreline change is influenced by past morphodynamic conditions. Plant et al. (1999, 2006) and Pape et al. (2010) developed behavior-orientated models to simulate cross-shore sandbar behavior on the timescales from days to years, based on the break point paradigm that computes sandbar migration towards a breaking-point-dependent equilibrium location. It is noted that the above models are used on sandy coasts, whose evolution is wave-dominated, and the effects of human activities are not included in the models. Therefore, they may not be suitable for tide-dominated muddy coastal evolution affected by engineering projects, which is common on China's coast and is the main concern of this paper.

Xu (1991) developed a behavior-oriented formula to calculate the sediment siltation quantity for a semi-closed harbor basin on muddy coasts. Liu and Zhang (1992a) (1992b) developed behavior-oriented formulas to calculate the sediment siltation rate in navigation channels and harbor basins due to dredging works on muddy coasts. The Delft Hydraulics Laboratory derived a behavior-oriented formula for sediment siltation in dredged channels based on disturbance of the natural conditions and relative changes in the vertical diffusive sediment transport, and the formula was further improved by Eysink and Vermaas (1983). Eysink (1989); Eysink and Vermaas (1983) and Ariathurai and Mehta (1983) proposed a behavior-oriented formula to evaluate the quantity of siltation caused by suspended sediment in a semi-closed harbor basin. Wang et al. (2001) developed a simple behavior-oriented formula to calculate the sediment siltation distribution around the reclamation area on muddy coasts. The aforementioned approaches are based on a similar hypothesis that coastal engineering, such as dredging and reclamation works, changes the hydrodynamic and morphodynamic conditions and that the change in the local sediment carrying capacity of tidal current changes leads to suspended sediment settling and bed siltation. These formulas are suitable for local bed siltation near the engineering projects in tide-dominated muddy coasts, where most sediments are transported as suspended loads. However, these formulas are based on a two-dimensional depth-averaged sediment transport process, and the vertical sediment distribution and near-bed sediment exchange mechanism are not considered. In fact, the high concentration layer near-bed is the major factor causing local scour or siltation. Suspended sediments in middle and upper water layers make small contributions to local erosion and deposition. Moreover, most of these formulas focus on predicting sediment siltation, whereas less attention has been paid to bed erosion.

In this paper, we develop a behavior-oriented formula for bathymetry evolution caused by coastal engineering on a muddy coast. The formula can calculate both bed siltation and erosion. The formula will be tested against the measured bathymetry change around a siltation-promoting project and compared with other common formulas. However, before the derivation and testing of the behavior-oriented formula, two common near-bed sediment flux equations of suspended sediment transport are introduced, and then a unification expression of near-bed sediment flux is given, which is the basis of the behavior-oriented formula.

2. Unification of the near-bed sediment flux

On a muddy coast, sediments are fine-grained and cohesive, and most are transported as suspended load. The 2-dimensional uniform suspended sediment transport equation under the non-equilibrium condition is written as:

$$\frac{\partial DS}{\partial t} + \frac{\partial DU_xS}{\partial x} + \frac{\partial DU_yS}{\partial y} = \frac{\partial}{\partial x}\left(\varepsilon_x D\frac{\partial S}{\partial x}\right) + \frac{\partial}{\partial y}\left(\varepsilon_y D\frac{\partial S}{\partial y}\right) + F_s \tag{1}$$

where x and y are space coordinates; t is time; D is the water depth; S is the depth-averaged sediment concentration; U_x and U_y are the depth-average flow velocities in the x and y directions, respectively; ε_x and ε_y are the depth-averaged diffusion coefficients in the x and y directions, respectively; and F_s is the deposition and erosion term, also called the near-bed sediment flux or erosion and deposition flux.

There are various interpretations in terms of theories and methods of near-bed sediment flux owing to complicated sediment movement