Morphodynamics of sandbar in a macro-tidal estuary: a model approach

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Abstract

This paper studied the development and the underlying physical mechanisms of the large sandbar in Qiantang estuary, China, using an idealized morphodynamic model. The model coupled shallow water equations, cohesive sediment transport and bed level update equations. The model was given a fixed geometry and impermeable boundaries, and forced by M\textsubscript{2} tide at mouth and river discharge at the upstream. The sandbar was reproduced on a timescale of 30 years, and the spatial scales of the sandbar were comparable to the real situation. The formation of the sandbar was controlled by the flood dominance due to tide wave deformation and sufficient sediment supply. The morphological development was driven by the nonlinear interaction between hydrodynamics, sediment transport and bed evolution. This morphodynamic model provides a new tool for the analysis of the large-scale morphological behaviour of tidal sandbar.

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1. Introduction

Sandbars occur in many tide-dominated estuaries of the world. They are normally located at the upper reaches of estuaries, connecting the land and the sea. They are often one of the most important morphological features of estuaries and increasingly influenced by human interventions such as maintenance dredging and land reclamation, etc.

The large sandbar in Qiantang estuary (QE), China, is one of the most typical sandbars worldwide. Its length elongates about 100 km and vertical height from the base line at Zapu to the peak crest at Cangqian is about 11 m (Fig. 1). Several researchers have described its historical evolution and the formation

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mechanisms using historical charts and conceptual models [1,2]. Further, several studies have been carried out to analyze its morphological response to human activities such as land reclamation.

In recent years, with the rapid development of numerical models, more and more morphodynamic models have been used to study the morphological evolutions of coastal environments [3,4]. In this contribution, an idealized morphodynamic model has been setup to simulate the formation process of the large sandbar in QE and analyze the underlying physical mechanisms.

2. Study area

QE is located on the west coast of the East China Sea, immediately south of the CE. It is funnel-shaped, covering an area of about 4800 km², with its width being about 100 km at mouth and 2 km at the upstream and its length of around 200 km. The average depth of lower QE is 8-10 m during low tides (Fig. 1). There exists a large sandbar at the upper QE, with average elevation less than 5m and the minimum of -2 m (Fig.1). The semi-diurnal tidal movement is the main driving force for the flow, with the M₂ constituent being the dominant component. The amplitude of the tide is 2-3 m at the mouth and 4-6 m at Ganpu. Tidal currents are strong and the maximal flood velocity can exceed 4.0 m/s. Sediment in the estuary is mainly composed of mud and silt and transported as suspended load. The suspended sediment concentration (SSC) distribution is vertically well-mixed, and varies between 0.5-4.4 kg/m³ [5].

Qiantang River is the most important river in discharging water and sediment directly into QE, with average discharge and sediment discharge are 0.3×10⁹ m³/a and 6.2×10⁴ t/a, respectively. CE is situated immediately north of QE. The average water and sediment discharges from Changjiang River are 925×10⁹ m³/a and 486×10⁶ t/a, respectively. A large part of the discharge and runoff from the CE enters QE and imposes a profound influence on both hydrodynamics and sedimentation of QE.

3. Numerical model description

3.1. Model frame

The morphodynamic model was set up based on the state-of-art Delft3D online morphodynamic modeling system [6]. Delft3D couples descriptions of hydrodynamics and sediment transport processes, and steps forward by updating the bathymetry using sediment mass balance. The principal constituents of the morphodynamic model include the flow, sediment transport and bottom change modules.
Because QE is a shallow and vertically well-mixed estuary, the depth-averaged transport equations can be used for most modeling purposes. Flow was calculated based on the horizontal 2-D shallow water equations. Sediment transport was calculated on the advection-diffusion equation:

$$\frac{\partial c}{\partial t} + \frac{\partial (u c)}{\partial x} + \frac{\partial (v c)}{\partial y} = \frac{1}{h} \frac{\partial}{\partial x}(h e_c \frac{\partial c}{\partial x}) + \frac{1}{h} \frac{\partial}{\partial y}(h e_v \frac{\partial c}{\partial y}) + E - D$$ (1)

where $c$ is SSC ($\text{kg/m}^3$), $h$ is water depth (m), $e_x$, $e_y$ are dispersion coefficient ($\text{m}^2/\text{s}$), $E, D$ are erosion/deposition fluxes ($\text{kg/m}^3/\text{s}$). They were calculated with the Ariathurai-Partheniades equation:

$$E = M \left( \frac{\tau}{\tau_e} - 1 \right), \tau > \tau_e \text{ and } D = w_s \left( 1 - \frac{\tau}{\tau_d} \right), \tau < \tau_d$$ (2)

where $M$ is erosion parameter ($\text{kg/m}^2/\text{s}$), $\tau$ is bed shear stress due to tidal current ($\text{N/m}^2$), $\tau_e$, $\tau_d$ are critical erosion/deposition shear stresses ($\text{N/m}^2$), and $w_s$ is the settling velocity ($\text{m/s}$). The bed elevation was updated at each computational time-step, based on the conservation of sediment mass.

### 3.2. Model setup

In this paper, we tried to simulate the formation of the sandbar in QE with an idealized morphodynamic model. The QE was schematized as a trapezoid based on the dimensions of QE (Fig.2). The model was given a fixed geometry and impermeable boundaries. The width at the mouth of the estuary was about 100 km, and narrowed linearly landward to be 2 km at the upstream in a length of 200 km. The initial water depth was 7 m at the mouth and decreased linearly to be 5 m at the upstream. The model was forced by M2 tide of 2 m amplitude at mouth and river discharge of 300 $\text{m}^3/\text{s}$ at the upstream. A constant SSC of 0.5 $\text{kg/m}^3$ was given for the mouth boundary to represent the sediment input from the sea and no sediment discharge was set for the upstream because sediment from Qiantang River is negative. Sediment on the bed was assumed to be cohesive sediments, with the sediment parameters were defined empirically. The sediment transport calculation and bed level change update were started when the flow field became steady, until the sandbar was reproduced. Five observation sites, P1-P5 along the middle longitudinal section were set for the model result analysis.

![Fig.2 Configuration of the idealized model and the initial depth.](image)

### 4 Model results

Understanding the hydrodynamic processes is an essential precondition for an evaluation of the sediment transport and morphological evolution problems. To analyze the main contribution of these processes, the hydrodynamics results at initial stage was analyzed at first. Fig. 3 shows tidal level variations with time at the five stations for computational observation shown in Fig.2. The differences between tidal ranges of P1, P2, P3, P4 were not apparent, all around 4 m. Tidal range increased gradually from P4 upwards and reached 5 m at P3. Landward, the flood durations became shorter and the ebb durations became longer gradually. At P1, the flood and ebb durations were 5h20m and 7h10m, respectively, while at P5 they are 2h50m and 9h30m. This indicates that flood dominance increased landward due to tidal wave deformation. Hence over one tidal cycle, the residual sediment transport was landward. As shown in Fig. 4 sediment deposits around the upstream of the estuary while at other area the
bed was mainly eroded. Fig. 4 also shows the current fields at flood and ebb maxima and the spatial distribution of SSC during maximal flood. Tidal currents were almost parallel to the banks and the tidal propagated like a line because the seabed was flat relatively at the initial state. The maximum turbidity zone was around 5 km from the upstream and the maximal SSC was under 0.5 kg/m³.

A long-term simulation was carried out for 30 years until the sandbar was reproduced. Fig. 5 illustrates the morphological processes for the development of the sandbar and Fig. 6 shows the bed evolution along the middle longitudinal section. At the early stage, sediment from the out sea was transported upwards. Most deposited in the upper reach of the estuary and little deposited in the lower reach. The bed elevation in the upper reach increased from about 4m to around 1m in 18 years. After 24 years the bed elevation increased to be -1m. Then the bed elevation became stable relatively and increased only by 0.2 m in the last 6 years. The formed sandbar is comparable with the real situation, i.e. the length and the height of the sandbar are about 100 km and 6 m, respectively. The morphological evolution of the sandbar was relatively rapidly at the early stage and then slowed down gradually with time. This is consistent with precious studies, such as that of tidal channels, embayment and tidal inlets, etc [3,4].

![Fig. 3 Time series of tidal levels at stations for computational observation at initial state](image)

![Fig. 4 Flood and ebb maxima, SSC distribution at flood maxima and erosion/deposition patterns at initial state](image)

![Fig. 6 Bed elevation changes along the middle longitudinal section.](image)
4. Conclusions

In this paper, an idealized morphodynamic model was set up to simulate the formation of the large sandbar in Qiantang estuary, China. The sandbar was reproduced on a timescale of 30 years. The modeled sandbar was comparable with the real situation. Two principal factors controlled the development of the sandbar: sufficient sediment supply from the adjacent Changjiang estuary, and the landward sediment transport induced by flood dominance. The development of the sandbar is controlled by the nonlinear interaction between hydrodynamics, sediment transport and the bed evolution.

Appreciating the need for further validation and analysis, it can be concluded that this model provides a tool, complementary to fieldwork, theoretical behavior analyses and laboratory experiments, for the analysis of the large-scale morphological behavior of the sandbar. In the next, this model would be extended to contain more complex physical descriptions to analyze the morphological response of the large sandbar in Qiantang estuary to human activities such as land reclamations and water diversions, etc.

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