Simulation of morphological changes induced by large-scale coastal engineering using a 3D wave–current interaction model

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Present study used a three-dimensional numerical model of multi-fraction sediment transport based on the coupling of a modified code model of environmental fluid dynamics and a model simulating nearshore waves to predict the estuarine morphological changes under the combined action of wind, waves, and current. Wave-current interaction played a remarkable role in increasing the sediment concentration. Distribution of the sediment concentration is better simulated and agreed with the measured data when using the coupled model compared to only considering the currents. Morphological changes predicted by the coupled model are basically coincident with the measured topographic map, and the model’s error is within plus or minus 10 percentage points.

[Keywords: modified environmental fluid dynamics code model; nearshore waves simulation model; wave–current interaction; sediment concentration; morphological changes; the Oujiang River Estuary]

Introduction

Prediction of the morphological behavior of estuaries generally follows two approaches. The first is the use of geological and geomorphological evolution models, which are designed to simulate morphological evolution over very long periods and are sometimes referred to as top-down models1,2,3. Second approach is the use of process models based on two- or three-dimensional (3D) hydrodynamic models combined with sediment transport and morphodynamics modules, known as bottom-up models4,5,6. These models are designed to simulate the physical properties of estuaries in the short term.

However, the numerical prediction of estuary morphological evolution is still in its infancy. Process-based prediction models are valuable tools for assessing local, short-term morphodynamic changes in an estuary, particularly those caused by large-scale man-made coastal engineering works. Due to insufficient knowledge of sediment-transport processes and their link to hydrodynamics, uncertainties in the predictions are amplified by treating sediment with a fixed range of grain sizes and cohesiveness. Furthermore, numerical predictions can exhibit great sensitivity to the initial conditions. In a more basic context, there are limits to the predictability of morphological variables due to the non-linearity of many coastal systems, which may induce chaotic behavior.

Predicting morphological changes effectively depends on the particular mixture of the waves, tides, sediment characteristics, and so on. Interactions between waves and currents are complex in estuarine areas, and sediment transport is predominantly controlled by the currents and wave motion1. In typical estuarine areas, the sediment is mainly suspended by waves and transported by currents. In shallow water, wave breaking also plays an important role in the vertical concentration and distribution of suspended sediment. A better understanding of wave–current interaction-induced sediment transport is crucially important in estuarine areas7,8,9. Intensive studies have been conducted in this field using both experimental and numerical approaches. The assumption of applying a time-invariant eddy viscosity to account for turbulence was adopted in the pioneer wave–current interaction model10. A range of similar models of the wave–current interaction within the seabed boundary layer have been published11. Steady boundary-layer streaming (Eulerian drift) is also caused by turbulence asymmetry in the successive wave half-cycles beneath asymmetric waves. This process was
described in detail by Scandura\textsuperscript{12}. Yu \textit{et al.} \textsuperscript{13} and Hsu \textit{et al.} \textsuperscript{14} investigated the sediment transport beneath asymmetrical wave groups using a two-phase model. Recently, Fuhrman \textit{et al.} \textsuperscript{15} reported that Longuet-Higgins streaming (related to convective effects) is capable of promoting onshore sediment transport, even for highly skewed waves on fine sands. This result is supported by measurements\textsuperscript{16} and is consistent with the findings of Blondeaux \textit{et al.}, who compared the predictions of the sediment-transport rates for oscillating tunnels with those beneath progressive waves\textsuperscript{17}. Other streaming mechanisms still exist, such as the streaming of spatially variable roughness\textsuperscript{18} and the streaming of bed slopes\textsuperscript{19,20,21,22}.

Despite these efforts, predicting the morphological changes induced by large-scale coastal engineering has not been fully described previously, especially using a 3D wave-current interaction model. For the typical silty estuaries of interest here, the sediment is mainly suspended by waves and transported by currents; thus, the combined wave–current action is very important. In shallow water, wave breaking also plays an important role in the vertical distribution of suspended sediment.

Within this context, the present study aimed to develop a numerical model to simulate and predict the morphological changes induced by coastal engineering, namely a large-scale sea embankment in the Oujiang River Estuary of China, under the combined action of wind, waves, and current. A 3D numerical model of multi-fraction sediment transport based on the coupling of a modified environmental fluid dynamics code (EFDC) model and a simulated waves nearshore (SWAN) model was developed and applied in the process.

**Materials and Methods**

The Oujiang River Estuary (ORE), 35 km long and 30 km wide at the mouth, is characterized by its bifurcated shape and its two outlets (through the north and south branches) into the East China Sea. The complex estuarine geometry consists of tens of staggered shoals, deep tidal creeks, and more than 40 large and small islands, which are scattered outside the mouth of the ORE. The tide in the ORE is a semidiurnal tide, with an average tidal range of 4.5 m and a maximum value over 7 m. Wenzhou Shoal, lying between Lingkun Island and Niyu Island, is a well-developed, large-scale mouth bar in the ORE. Wenzhou Shoal is very shallow in the most of the region. Large intertidal zones exist at the mouth of the river, which are submerged at high tides and exposed at low tides.

To meet the increasing land demands of urban expansion and deep-water port construction, the Chinese government has built the Ling-Ni Embankment, which connects Lingkun Island and Niyu Island. The full length of the embankment is 13 km, and it was completed in April 2005 (Fig. 1). The present paper utilized the Ling-Ni Embankment as an example and simulated the morphological changes induced by its construction using a 3D numerical model based on a combination of the modified EFDC model and SWAN model.

### Modified EFDC model

The EFDC model is a public domain surface-water modeling system that fully incorporates integrated hydrodynamics. This model was originally proposed by John Hamrick, \textsuperscript{23} includes a turbulence closure model, and can simulate wave boundary layers, wave-induced currents, and combined wave–current bottom shear stress with cohesive and non-cohesive sediment of multiple size classes. The EFDC model is coupled with a spectral wave model for wave-induced re-suspension, but it does not take the wave-breaking effect into consideration. Considering that wave breaking plays an important role in vertical sediment distribution and sediment transport in nearshore zones, we modified the EFDC model by incorporating the wave-breaking effect using a sediment-mixing coefficient.
A sediment-diffusion coefficient under the combined action of wave-induced currents can be represented by the non-linear superposition of the diffusion coefficients under the currents and waves alone:  

\[ \varepsilon_{cw} = \left[ \varepsilon_c^2 + \varepsilon_w^2 \right]^{0.5} \]  

(1)

where \( \varepsilon_c \) is the current-related mixing coefficient \( (m^2/s) \), and \( \varepsilon_w \) is the wave-related mixing coefficient \( (m^2/s) \). van Rijn further proposed the calculation of a sediment-diffusion coefficient under the action of breaking waves:  

\[ \varepsilon_w = \begin{cases} \varepsilon_{ch} + (\varepsilon_{cm} - \varepsilon_{ch}) \left( \frac{z-\delta}{0.5h-\delta} \right), & 0.0035 \leq z < 0.5h \\ 0.0035 \frac{hH}{T_p}, & z \geq 0.5h \end{cases} \]  

(2)

where \( \varepsilon_{w,bed} = 0.018\gamma_w,\beta_w,\delta_e,\delta_r \) \( \varepsilon_{w,max} = 0.035\gamma_w,\frac{hH_s}{T_p} \) \( \varepsilon_{w,bed} \) is the wave-related sediment-mixing coefficient near the bed, \( \varepsilon_{w,max} \) is the maximum of the wave-related sediment-mixing coefficient near the bed, \( z \) is the height above the bed; \( h \) is the water depth, \( \delta_e \) is the thickness of the effective near-bed sediment-mixing layer, \( \gamma_w \) is the empirical coefficient related to wave breaking, \( H_s \) is the significant wave height, \( T_p \) is the significant wave period, \( \delta_e,\delta_r \) is the representative near-bed peak orbital velocity based on the significant wave height, \( \beta_w = \text{coefficient}= 1 + 2 \left( \omega_s / u_n \right)^2 \) with \( \beta_w \leq 1.5 \), \( w_s \) is the total velocity of suspended sand, and \( u_n \) is the wave-related bed-shear velocity.

Generally, the sediment-diffusion coefficient can be considered equivalent to the turbulent-diffusion coefficient.  

Without considering breaking waves can be represented as follows:  

\[ A_0\varepsilon_{cw},\kappa z, z_0 \leq z < \delta_c \]  

\[ K_c = \begin{cases} A_0\varepsilon_{cw},\kappa \delta_c, \delta_c \leq z < \frac{q_{cw}}{q_c} \delta_c \\ A_0\kappa z, z \geq \frac{q_{cw}}{q_c} \delta_c \end{cases} \]  

(5)

where \( A_0 \) is a constant, usually 0.4; \( q_{cw} \) is the wave-current-related turbulence intensity; \( q_c \) is the current-related turbulence intensity; and \( \kappa \) is the von Kármán coefficient, usually 0.4. Based on these theories, we introduced Eq. (5) and (2) into Eq. (1), and we obtained the following equation to calculate the sediment-diffusion coefficient:

\[ \varepsilon_{cw} = \begin{cases} A_0\varepsilon_{cw},\kappa z, z_0 \leq z < \delta_c \\ A_0\varepsilon_{cw},\kappa \delta_c, \delta_c \leq z < \frac{q_{cw}}{q_c} \delta_c \\ A_0\kappa z, z \geq \frac{q_{cw}}{q_c} \delta_c \end{cases} \]  

(6)

Without breaking waves, currents primarily play a suspending role for the sediments far away from the bed; when wave breaking occurs, the waves control the distribution of the suspended sediments in the upper water body. Because Eq. (6) can reflect the phenomenon of sediment diffusion well, it makes up for the deficiencies of source programs that do not consider wave breaking.

In addition, other factors such as wind shear stress on the surface, drying and wetting in shallow water, bed sediment transport, bed scour and deposition, settling velocity, and reference concentrations were also incorporated into this model.

**SWAN model**  
SWAN is a third-generation wave model based on the wave-action balance equation formulated for coastal applications. The effects of wind wave generation, refraction, shoaling, bottom friction dissipation, white capping, nonlinear wave–wave interactions, and
ambient currents on the wave properties are
considered in SWAN\textsuperscript{29}. In this study, 2D and
time-dependent waves were calculated to simulate
wave-induced sediment resuspension. The
following transport equation was used to calculate
the wave-action density $N$ (the energy density
divided by the relative frequency):

$$\frac{\partial N}{\partial t} + \frac{\partial c_x N}{\partial x} + \frac{\partial c_y N}{\partial y} + \frac{\partial c_{\sigma} N}{\partial \sigma} + \frac{\partial c_{\theta} N}{\partial \theta} = \frac{S_w}{\sigma}$$

(7)

where $c_x$ and $c_y$ are the propagation velocities in
the $x$ and $y$ directions, respectively. SWAN
accounts for shoaling and refraction through the
dependent variations in $c_x$ and $c_y$. The term $S_w$ on
the right-hand side is a source/sink term
representing the effects of wind-wave generation,
wave breaking, bottom dissipation, and nonlinear
wave–wave interactions. SWAN also accounts for
the effects of diffraction, partial transmission, and
reflection. Specific formulae for wind input,
bottom stress, white capping, wave–wave
interactions, etc. were previously described in
detail\textsuperscript{30}.

**Coupling between the EFDC and SWAN models**

The SWAN and EFDC models were coupled
through data exchange in the regional and coastal
domains, respectively: EFDC provided SWAN
with time series of water elevation and current
velocity, and SWAN supplied EFDC with arrays
of radiation stress (see Fig. 2).

**Verification**

In the modified EFDC model, the effect of
wave breaking on the sediment-diffusion
coefficient was considered. The calculation
accuracy of this model was tested. The simulated
sediment concentration profiles with and without
the breaking effect were compared with the
measured sediment concentration from Han et al.\textsuperscript{31} (Fig. 3). As shown in the figure, the modified
EFDC model incorporating the wave-breaking
effect was more likely to predict the actual
situation, and the modified EFDC model reliably
simulated sediment transport.
To calibrate the high concentration layer near the seabed, the sediment-concentration profiles due to combined waves and currents for multi-sized sediment simulated by the modified model are compared with the experimental values reported by van Rijn et al.32, and the results are shown in Fig. 4. The simulated sediment concentrations match very well with the experimental values from van Rijn et al.32, which demonstrates that the modified EFDC model is able to accurately predict the high concentration layer near the seabed, to a certain extent.

The wave field was computed using the SWAN model, and the input wind data were observations from the Dongtou Island weather station. Depth-induced wave breaking was enabled with the default options and parameters. The bottom friction was computed by the Madsen scheme with the default equivalent bottom roughness length scale. The model had 18 grid consists of 12161 grid cells in the horizontal direction with a grid size from 10 m to 1000 m. Six layers were divided in the vertical direction according to the relative water depth, i.e., the surface, 0.2, 0.4, 0.6, 0.8, and the bottom. The water elevation at the offshore open boundary was forced by eight tidal constituents, namely Q1, O1, P1, K1, N2, M2, S2, and K2. These constituents account for most of the tidal energy in the East China Sea. The time step for the circulation module was 5 min, with 1 min as a sub time step for the transport module. The Coriolis force was included, and Manning’s coefficients were 0.01–0.025 according to the distribution of the medium diameters of bed materials measured in recent years33. The Smagorinsky constant for the horizontal eddy viscosity coefficient takes a typical value of 0.12. The sediment was divided into five fractions with the particle sizes of 0.005, 0.01, 0.03, 0.06, and 0.08 mm and settling velocities k of 0.0004, 0.0006, 0.0011, 0.0064, and 0.0075 m/s, respectively34. The bed sediment porosity was 0.5, and the bed sediment-specific weight was 2.535.

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The ORE is bounded by a complex shoreline and contains many islands and a complex terrain. A curvilinear orthogonal discrete grid and the depth of domain are shown in Fig. 5. The model
uniformly distributed directions, and the frequency resolution was determined by $f_{i+1} = 1.9f_i$ with $f_{\text{max}} = 1.0 \text{Hz}$ and $f_{\text{min}} = 0.04 \text{Hz}$.

The calculation flow of the seabed evolution is summarized in Fig. 2. First, the tidal levels, current velocities, and current directions in the construction area at different times were calculated with the hydrodynamic force module of EFCD. The results were then input into the SWAN wave model, which allowed the effect of the dynamic force of tidal currents on the wave field to be considered during the calculations. Finally, the wave height, directions, and periods obtained based on the SWAN model were input into the sediment module of the EFDC. The coupling of two-way waves and currents was realized.

To understand the changes in the topography of the sea bottom near the Ling-Ni Embankment after construction was completed, the East China Sea Investigation and Design Institution of the State Bureau of Oceanic Administration and the Zhejiang Institute of Hydraulics & Estuary mapped 1:10000-1:25000 bathygrams of this area in October 1999 (before the construction) and May 2007 (after the construction), as directed by the Chinese government. This study took the Ling-Ni Embankment construction as an example and predicted the changes to the topography of this area after construction, with the simulation spanning from October 1999 to May 2007. The results based on the simulation and the field measurement data were compared to test the precision of the calculation from the coupling model established in this study.

**Results and Discussion**

**Hydrodynamic simulation**

We used the EFDC hydrodynamic module to compute the current fields (Fig. 6). As shown in Fig. 6, the calculated tidal level and phase were consistent with those measured (Fig. 1), which were sampled from October 10 to 12, 1999. The absolute error of the tidal level is generally less than 0.1 m.

**Wave simulation**

We used the SWAN model to compute the wave fields (Fig. 7). As shown in Fig. 7, the simulated wave processes are consistent with the measured wave height (Fig. 1) from October 10th to 12th, 1999.

**Sediment simulation**

We used the EFDC sediment module for the computation of sediment transport. Fig. 8 shows the comparison of the suspended-sediment distribution with and without a wave effect at the surface layer and the bottom layer. The impact of waves on suspended sediment distribution is remarkable and can greatly increase sediment concentration (Fig. 8). The vertical distribution of sediment concentrations of the proposed coupled model and the current model at the time of high and low tidal levels were compared (Fig. 9). The simulated sediment concentrations of the proposed coupled model show a better match with the measured values than those from the current model.
Fig. 9--Verification of vertical sediment concentration. (a), at the time of a high tidal level. (b), at the time of a low tidal level.

For the current model, the predicted sediment concentration is very low, and its vertical distribution is far below the measured value. The interaction of waves and currents increases sediment resuspension and transport in nearshore waters. The sediment concentration is sensitive to wave propagation, and the wave effect on the sediment distribution should not be neglected. The suspended sediment observation station is located near Wenzhou Shoal with a water depth of -6 m relative to the mean sea level (Fig. 1), which is in the surf zone. The effects of breaking waves on the sediment distribution are expected to be large because the water column will be mixed by the strong wave-current shear resulting from the waves breaking in shallow water. Therefore, the 3D EFDC model was modified by incorporating the wave-breaking effects in nearshore zones, and the modified version is able to more reasonably predict sediment transport.

Numerous shallow areas often exist in the alongshore regions of an estuary, which are located within the wave-breaking zone. Wave breaking is accompanied by large wave-energy dissipation, which causes strong turbulence of the water body and consequently a great increase in the concentration of suspended sediments. Meanwhile, the vertical distribution of sediments at different depth levels also greatly differs. This point has been proven in numerous studies. Therefore, reasonable inversion of the complex alongshore sediment movement under the combined action of waves and currents during suspended-sediment simulation cannot be achieved without considering the effect of wave breaking on the sediment-diffusion coefficient.

Simulation of morphological changes

We used the EFDC sediment module to compute the morphological changes induced by the Ling-Ni Embankment. Fig. 10 shows the comparison of the measured topographic map and the simulated topographic map. The simulated topographic maps predicted by the coupled model agree well with the measured topographic map. The relative error between the simulated values and the measured values is within plus or minus 10 percentage points (Table 1).

<table>
<thead>
<tr>
<th>Position</th>
<th>Measured data</th>
<th>Simulated data</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wenzhou Shoal</td>
<td>2276.3</td>
<td>2467.1</td>
<td>8.4%</td>
</tr>
<tr>
<td>Qidutu–Lingkun up</td>
<td>-232.6</td>
<td>-216.9</td>
<td>-6.7%</td>
</tr>
<tr>
<td>Lingkun up–Niyu</td>
<td>-420.1</td>
<td>-385.5</td>
<td>-8.2%</td>
</tr>
<tr>
<td>Oufei Shoal</td>
<td>695.7</td>
<td>761.5</td>
<td>9.5%</td>
</tr>
</tbody>
</table>

"-" is the amount of erosion sediment; "+" is the amount of deposition sediment.

Fig. 10--Comparison of the simulated and measured morphology. (a), measured morphology. (b), simulated morphology.

Lu et al. developed a 2D mathematical model for sediment transport influenced by waves and tidal currents. This model was used to study the effects of the reclamation scheme for Caofeidian Harbor on the hydrodynamic environment, sediment transport, and morphological changes. The relative error between the calculated data and the observations on the patterns and magnitude of sedimentation and erosion in the related area was between minus 7 percentage points and 58 percentage points. However, their model has two major deficiencies, which cause low simulation precision: 1) The 2D model fails to reflect the vertical distribution of the sediments; therefore, it cannot simulate the high sediment content of the water near the sea bottom; and 2) although their model considers the effect of wave–current coupling, it does not consider the effect of wave breaking on suspended sediment movement near the shore.

Conclusions

In this study, a 3D numerical model for multi-fraction sediment transport based on the coupling of a modified EFDC model and a SWAN model was developed and applied to predict the
morphological changes caused by a large-scale sea embankment in the ORE of China under the combined action of wind, waves, and current. The results showed that our model was effective and reliable for the current task. Based on these results, we drew the following conclusions:

1. The 3D EFDC model was modified by incorporating the wave-breaking effects in nearshore zones, and the modified model is able to predict the nearshore sediment transport more accurately.

2. The model takes advantage of the two-way coupling between the EFDC and SWAN models, that is, it considers both the time-to-time effect of the tidal levels, current velocities, and current directions on the wave field output by EFDC and the effect of the wave height, directions, and periods on the current field output by SWAN, thereby establishing a sediment-movement model influenced by the combination of two-way waves and currents.

3. Impact of waves can greatly increase sediment concentrations near shore, and the simulated vertical distribution of sediment concentration using the proposed coupled model agrees with the measured values to a greater extent.

4. Because the simulated water level, wave height and sediment concentration essentially agreed with the measured data, the coupled model was used to predict the morphological changes induced by the Ling-Ni Embankment in the ORE. The simulated topographic maps predicted by the coupled model agreed well with the measured topographic map, and the relative error between the simulated values and the measured values was within plus or minus 10 percentage points.

Acknowledgments
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