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Hindcasting morphodynamic evolution with sand–mud interactions in the Yangtze Estuary

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Abstract Previous work on morphodynamic evolution in the Yangtze Estuary (YE) is based on measured historical bathymetries. To evaluate the sensitivity of sand–mud interaction in the estuarine morphodynamics, a process-based morphodynamic model, Delft3D, is used to examine the morphodynamic behaviour from 1958 to 1997. Different scenarios concerning sand and mud and their combination are designed systematically. The scenarios considering multiple fractions, and especially with four fractions, improve the hindcasting evolution, suggesting the importance of including both sand and mud fractions and a sediment gradient setting of medium grain.

Key words morphodynamic evolution; sand–mud interaction; Delft 3D; Yangtze Estuary.

INTRODUCTON

The bathymetry of the Yangtze Estuary (YE) is continuously changing. The morphological evolution of the estuary has very important impacts for the surrounding environment. Therefore, it is essential to understand the morphodynamic evolution of the YE. Numerous investigations have been conducted to model it. Previous morphodynamic modelling usually used one sand fraction, but some models applied different sediment fractions (Hu, *et al.* 2009). This research focuses on sand–mud interaction effects on the morphodynamic evolution in the YE using the Delft 3D model. It studies morphological change with different sediment fractions and behaviour patterns.

DATA ANALYSIS

2.1 Bathymetry

The Yangtze Estuary is characterized by a three-order bifurcation with its irregular morphology. There is channel branching in series, including straight reaches and curved reaches. And the estuarine morphology changes greatly. Overall, the interactions between the bathymetry, geometry and hydrodynamics determine the morphodynamic evolution.

The estuary splits into North Branch and South Branch. The South Branch separates into the North Channel and South Channel. Moreover, the South Channel divides into the North Passage and South Passage. Therefore, there are four outlets directly into the sea: North Branch, North Channel, South Passage and North Passage (Fig. 1).

The bathymetry applied in the initial situation is based on year 1958. And the resulting hindcasting model makes comparisons to the bathymetry of 1997. This time scale was selected as it is a long period and the processes were dominated by natural evolution

2.2 Hydrodynamics

Datong station is the upstream tidal limit in the dry season in the YE. We apply Datong as the upstream boundary dominated by discharge.

An empirical frequency curve is derived from the annual mean discharge of Datong station (1934−2007), and the corresponding mean discharge, P50% (frequency) is 28 000 m^3/s. From the discharge data, the annual mean discharge of 1953, 1961, 1965, 1967, 1981 and 1984 are around 28 000 m^3/s. The monthly average discharge in long series is compared to the monthly discharge

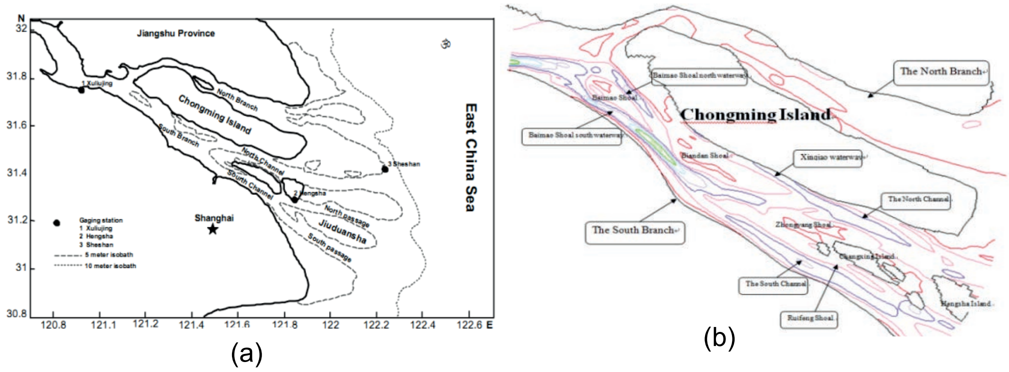

Fig. 1 (a) Sketch map of gauging stations in the Yangtze estuary, China by He *et al*. (2001) and (b) contours of the YE.

Table 1 Monthly discharges and sediment concentrations for one hydrodynamic year.

Month	1	2	3	4	5	6	7	8	9	10	11	12
Discharge (m^3/s)	9785	9440	9836	26696	30654	45169	49838	45880	39079	36541	18981	14109
Sediment concen tration (kg/m^3)	0.072	0.052	0.047	0.23	0.2	0.58	1.03	1.14	0.63	0.54	0.19	0.14

of these years, in which 1984 shows the least variance. Monthly discharge is amplified in order to give an annual discharge 28 000 m^3/s in 1984.The monthly sediment concentrations in Datong also use data of 1984. The resulting monthly discharges and sediment concentrations for one hydrodynamic year in the hindcasting model are shown in Table 1.

The estuary is set as downstream boundary which is dominated by astronomical tide. The hydrodynamic data is for one year period. To realize the morphodynamic evolution over 40 years, we apply a morphodynamic factor of 40.

2.3Sediment properties

2.3.1 Bed sediment distribution In the vertical scale, based on the sort of sediment in the YE (Liu, 2007), the bed sediment of three fractions is shown in Table 2.There are also large particles of sand which are not cohesive and are not easily transported; this fraction would prevent the channel from getting too deep. Therefore, we added 20% volume sand of 400 μm for bed sediment of four fractions. The fall velocity is assumed to be 0.2 mm/s for D50 = 8 μm and 1 mm/s for D50 = 32 μm. The critical bed shear stress is 0.27 N/m^2 for D50 = 8 μm and 0.13 N/m^2 for D50 = 32 μm (Van Rijn, 2006).

Table 2 Three sediment fraction set for the YE.

Initial condition	Sand/mud	D50 (μm)	Initial percentage (%)	Initial thickness (m)
Bed sediment	sand	170	42	21
	mud	32	42	21
	mud	8	16	8

2.3.2 Suspended sediment In the YE, the suspended sediment in Datong Station range in size from 1 to 100 μm (Wan, 2003). Therefore, in this research, suspended sediment in upstream is defined as sand with D50 = 50 μm.

METHODLOGY

3.1 Applied theory

3.1.1 Sediment behaviour Delft 3D is employed in this research. The reason to choose Delft 3D (WL|Delft Hydraulics) for modelling is that it is a well-established and widely used process-based model. Also, the model is accelerated by a morphological factor to enhance morphodynamic developments. And a multiple layer model is applied in which the sand and mud are both considered as well as a sediment sorting processes. Moreover, the sand–mud interaction effect has already been applied in Delft 3D (Van Kessel *et al*. 2012).

Models in Delft 3D consist of various formula and behaviours. In this research, sand only (with formulae of Engelund-Hansen (1967) and Van Rijn (1993)), mud only (Partheniades-Krone (Partheniades, 1965)), and sand-mud with/without interaction are applied to investigate different morphological change concerning different sediment fraction and behaviour patterns. For sand-mud with/without interaction, the transition between a cohesive and a non-cohesive bed is mainly dominated by clay content (Van Ledden, 2003) and applied in Delft 3D with parameters $p_{m,cr}$ and p_m ($p_{m,cr}$ is critical mud content, p_m is mud content in up layer). For $p_m < p_{m,cr}$ the bed is considered as non-cohesive mixture, and for $p_m > p_{m,cr}$ the bed is regarded as a cohesive mixture (van Kessel *et al*., 2012).

The multiple bed layer model is applied to simulate the sediment sorting processes. The details of the method are referred to in van der Wegen *et al.* (2010).

3.1.2 Bed composition generation This research also applies the bed composition generation (BCG) method (Van der Wegen *et al*., 2010). The BCG method aims to generate an initial distribution of different sediment fractions by running the model without a bed level update. In this way, the bed sediment is more realistic than a uniform initial bed. As horizontal variation of mean grain size is distinct in the YE, it can be assumed that the redistribution of sediment from the initial condition would make a difference in the model.

3.2 Model setting

The grid and resolution of the estuary model is shown in Fig. 2.

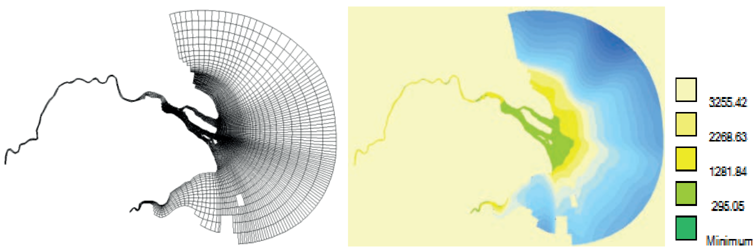

Fig. 2 Grid size of the estuary model.

The resolution inside the estuary is less than 1000 m/grid in the horizontal direction in Fig. 2. The initial bed sediment thickness is 50m. And five layers are set for the models. Based on the hydrodynamic condition and current resolution, the resulting water level and water velocity in stations corresponds to the condition measured in year 1997.

Scenarios 1&2: Single sand model with Van Rijn (1993) and Engelund-Hansen (1967), bed sediment D50 = 200 μm, and no sediment input from upstream.

Scenario 3: Single mud model with Partheniades-Krone formulations, bed sediment D50 = 32 μm and no sediment input from upstream.

Scenario 4: Sand & mud without interaction model with Van Rijn (1993), bed sand D50 = 200 μm, suspended mud D50 = 32 μm from upstream with sediment concentration 0.1 kg/m^3.

Scenario 5: Sand & mud interaction model with Van Rijn (1993), bed sand D50 = 200 μm, suspended mud D50 = 32 μm from upstream with sediment concentration 0.1 kg/m^3.

The process of suspended sediment downstream transport is very complicated. To simplify this process, first ignore sediment from upstream but only calculate equilibrium concentrations in the boundary (Scenario 6). Then apply the concentration of upstream for comparison (Scenario 8).

Scenario 6: Sand & mud interaction model with four sediment fractions, BCG model in advance and no suspended sediment from upstream. Scenario 6 is the standard model.

Scenario 7: Sand mud without interaction compared to Scenario 6.
Scenario 8: Suspended sediment from upstream compared to Scenario 6.
Scenario 9: No BCG model in advance compared to Scenario 6.
Scenario 10: Ignore the North Branch. This is realized by making a thin dam to block flow in the North Branch. Since the North Branch shrinks as a result of natural deposition and human activity (Chen *et al.*, 1988), it is assumed that the model would improve with no flow in North Branch.
Scenario 11: Only considers three (as Table 3) fractions compared to Scenario 6.

Table 3 Summary of scenarios.

Upstream concentration	Sand–mud interaction	Number of sediment fractions	Scenarios	
no	no	1	Scenario 1	vR-S-O
			Scenario 2	EH-S-O
			Scenario 3	M-O
yes	yes		Scenario 4	vR-SM-ni
	no		Scenario 5	vR-SM-i
no	yes	4	Scenario 6	vR-SM-i-nc-BCG-4f
	no		Scenario 7	vR-SM-ni-nc-BCG-4f
yes	yes		Scenario 8	vR-SM-ni-c-BCG-4f
no	yes		Scenario 9	vR-SM-i-nc-nBCG-4f
no	yes		Scenario 10	vR-SM-i-nc-BCG-4f-nN
no	yes	3	Scenario 11	vR-SM-i-nc-BCG-3f

Table 3 summarizes all the scenarios used in the research. Scenarios 1 to 5 focus on comparison of sediment patterns, and Scenarios 6 to 11 are intended to investigate how to improve the model. The resulting analysis for the YE focuses on the South Branch in the YE, as the North Branch would result in less accuracy due to human activity.

3.3 Indicators

3.3.1 BSS number The Brier skill score (BSS) measures the difference between the score for the forecast and the score for the unskilled standard forecast (Van der Wegen, 2010):

$$\mathrm{BSS} = 1 - \frac{\langle(\Delta\mathrm{vol_{mod}} - \Delta\mathrm{vol_{mean}})^2\rangle}{\langle\Delta\mathrm{vol_{mean}}^2\rangle} \tag{1}$$

where Δvol_{mod} is volumetric change compared to the initial bed, mod is modelled quantity,mean is measured quantity, $\langle \quad \rangle$ denotes an arithmetic mean. A BSS of 1.0 indicates a perfect forecast.

3.3.2 Erosion/sedimentation patterns The erosion/sedimentation pattern is the bed level difference from the initial bathymetry to the ultimate bathymetry. The difference of measured bathymetry of 1958 and 1997 is used as a criterion, and compared with the erosion/sedimentation pattern of different scenarios.

RESULT AND DISCUSSION

4.1 Erosion/deposition pattern

In Fig. 3 (a) and (b) it appears that the Baimao Shoal accretes and the Baimao Shoal north and south waterway erodes. The waterway downstream of Biandan Shoal accretes as well as the South Channel. The area of Zhongyang Shoal accretes severely.

Scenarios 1 to 5 represent differences of sand mud behaviours. Due to a smaller proportion of bed-load transport in Van Rijn (1993), the channel gets deeper without enough sand compensation from upper levels, so Scenario 1 results in a sharper slope of the bank and deeper channel compared to Scenario 2. Scenario 3 results in very severe conditions for either accretion or erosion (no bed slope effect considered since mud calculates as suspended load only). Scenarios 4 and 5 result in moderate erosion/sedimentation pattern. For Scenarios 6 to 11, Scenario 7 results in less severe conditions and is the only one with accretion in the South Channel. Scenario 11 with three sediment fractions shows more severe erosion/sedimentation patterns than those with four sediment fractions.

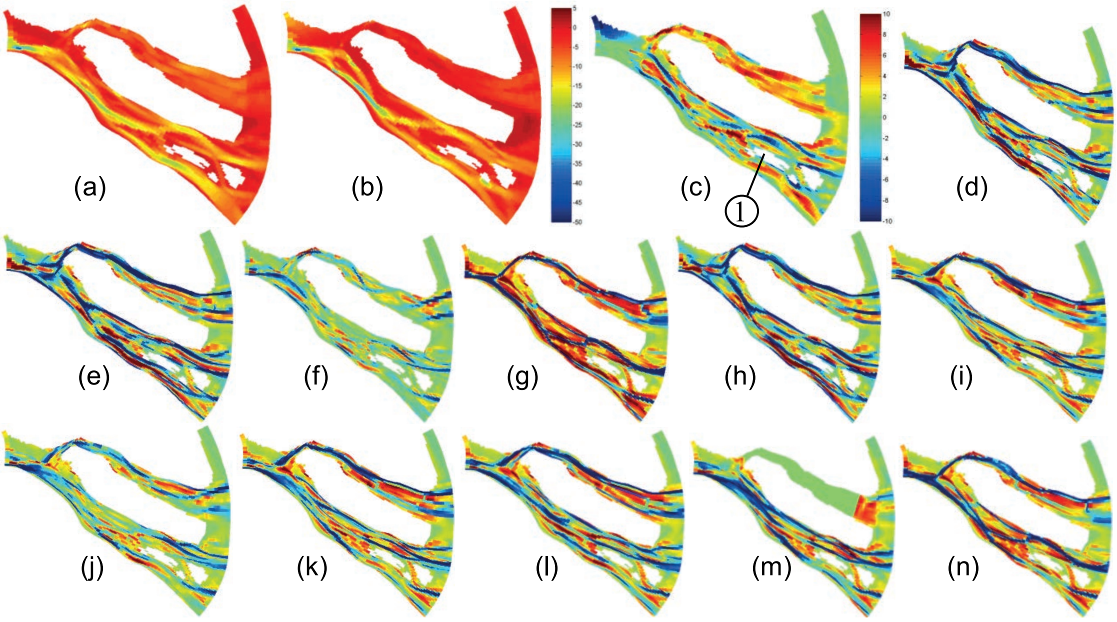

Fig. 3 Bathymetry: (a) Measured 1958, (b) Measured 1997; Erosion/sedimentation patterns: (c) Measured, (d) Scenario 1, (e) Scenario 2, (f) Scenario 3, (g) Scenario 4, (h) Scenario 5, (i) Scenario 6, (j) Scenario 7, (k) Scenario 8, (l) Scenario 9, (m) Scenario 10, (n) Scenario 11.

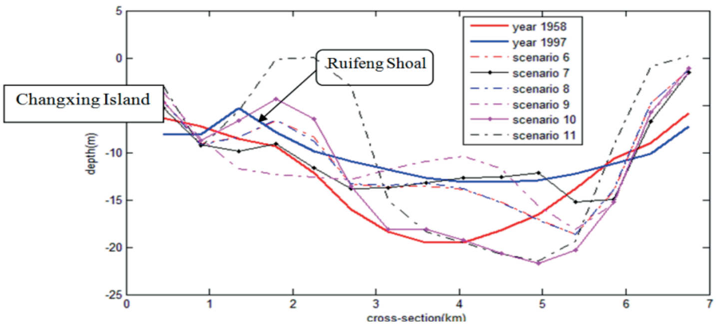

Fig.4 Cross-section of the South Channel for scenarios 6–11.

To study the change in a more visual way, the cross-section in Fig. 3(c) is scattered (Fig. 4). It is obvious that in 1958 there was only a channel near Changxing Island, but in 1997, the South Channel gets accretion and forms the Ruifeng Shoal near Changxing Island. The Ruifeng Shoal was modelled in all scenarios except Scenario 9. Scenarios 10 and 11 show erosion in the channel part.

To conclude, the sand only model with Engelund-Hansen (1967) and models with four fractions produce the most moderate erosion/sedimentation pattern and most resemble the measured data.

4.2 BSS number

Scenario 7 results in a better BSS number than Scenario 6 (Table 4). This means that sand mud without interaction performs better than sand mud interaction model in BSS number. Scenarios 6, 8 and 9 have similar BSS numbers, indicating almost no change for including upstream concentration or BCG process. Scenario 10 shows less accuracy than Scenario 6. Therefore, the human activity should be included in the model in a more realistic way.

Table 4 BSS numbers for south branch according to scenarios 1 to 11.

		BSS number			BSS number
Scenario 1	vR-S-O	–1.82	Scenario 6	vR-SM-i-nc-BCG-4f	–1.27
Scenario 2	EH-S-O	–0.24	Scenario 7	vR-SM-ni-nc-BCG-4f	–0.44
Scenario 3	M-O	–4.24	Scenario 8	vR-SM-ni-c-BCG-4f	–1.29
Scenario 4	vR-SM-ni	–1.59	Scenario 9	vR-SM-i-nc-nBCG-4f	–1.26
Scenario 5	vR-SM-i	–1.77	Scenario 10	vR-SM-i-nc-BCG-4f-nN	–1.91
			Scenario 11	vR-SM-i-nc-BCG-3f	–2.76

CONCLUSIONS

- The single sand model with the Van Rijn (1993) formula results in a steeper and deeper channel than the formula of Engelund-Hansen (1967), as a result of distinguishing the bed-load and suspended transport with Van Rijn's formula which leads to more influence of the bed slope effect.
- The single mud scenario leads to the most severe erosion/sedimentation pattern as well as worst BSS number.
- The models with multiple sediment fractions have the best performance (expect for sand only model with Engelund-Hansen (1967)), especially the models of four fractions. These models compromise the extreme mud transport condition, and perform well qualitatively and quantitatively. Therefore, it is crucial to make the sediment gradient in the model. Also, the models of four fractions are more theoretical as the complex sediment content is included, compared to the sand only condition, and are expected to get better results by resetting the parameters for mud transport in a systematic way.
- The better performance of sand mud without interaction than sand–mud interaction shows more research is required in the sand mud interaction investigation.
- The BCG does not contribute much in this model. The sediment redistribution is a natural process, and it can be assumed that the simulation time of 40 years is long enough for the natural process of sediment redistribution. This model may lead to better results in short-term simulation.

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