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2 Morphological Evolution of the South Passage in the Changjiang (Yangtze River)
3 Estuary, China

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10 **Abstract :**

11 Estuarine morphology of the world's major large rivers have experienced great
12 changes due to intensive anthropogenic activities and natural forcings, especially in
13 the Changjiang Estuary located at the end of the longest river in Asia. This study
14 focuses on morphological changes of the South Passage (SP), which is one of the 4
15 channels in the branching estuary at the mouth of the Changjiang (Yangtze River),
16 China. A multivariate analysis technique of Empirical Orthogonal/Eigen Function
17 (EOF) method was used to examine the major modes of change in the long-term (over
18 26 years) water-depth data. The results show that the morphological changes at the SP
19 could be divided into two stages: between 1987-1997, the SP had a single stable
20 channel with closure of a cross-channel. Between 1997-2012, SP displayed
21 southeastward elongation of a spit into the main channel, and westward shoal incision
22 by a cross-channel. The opening of the SP developed a two-channel morphology,
23 which stabilized and showed infilling during 2003-2012. The average deposition rate
24 was 10 cm/yr. In the past 30 years, the most dominant morphological changes of SP

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included the deposition around the upstream opening of the channel. The second most important pattern of morphological change was related to the downstream elongation, retreat, and lateral migration of the spit of the Jiangyanan Shoal, which resulted in the two-channel configuration of the SP. Additionally, these morphological changes were not triggered by the decline of the distal sediment source from the upstream, but due to the input of proximal sources of the shoal at the upstream opening of the SP and spill-over sediment from the North Passage via a short-cut-channel.

Keywords: Estuarine morphology; Branching estuary; Shoal evolution; River runoff; River sediment load; EOF analysis

1. Introduction

Estuaries are located in the narrow zone of the land-sea boundary, which are valuable areas of both local and global importance. The morphology of estuaries is closely linked to estuarine assets such as natural location to ports (Van der Wegen and Roelvink, 2008). The morphological formation and evolution of estuaries is relatively gradual and has a typical decadal timescale. Small-scale sea-level fluctuations may trigger drastic changes (Dyer, 1997). However, in the last century the gradual development of many estuaries and adjacent area has been interrupted by human activities (Evans, 2012; Gong et al., 2012; Gao and Milliman, 2008; Lane, 2004; Li et al., 2012). Such practices include for example, damming of the river, construction of dikes and groins in the river mouth, and land reclamation (Evans, 2012; Syvitski et al., 2009; Chu et al., 2012; Dai and Lu, 2010).

The reduction of river load due to damming is the cause for risks of erosion and inundation in many estuaries and deltas in the world (Walling and Fang, 2003;

Syvitski et al., 2005). A well-known example is the Nile delta. Because of the Aswan Dam, the erosion rate for the area around Rosetta Promontory was $10 \times 10^6 \text{ m}^3/\text{yr}$ (Inman et al., 1984). Because of the construction of the dam at Adana, the nearby Seyhan delta in Turkey has the erosion rate of $1 \times 10^6 \text{ m}^3/\text{yr}$. Gagliano et al. (1981) estimated the land loss around the mouth of the Mississippi was 102.1 km^2 in 1980, which was higher than those of 1987, 1946, and 1913 at 72.8 , 40.9 , and $17.4 \text{ km}^2/\text{yr}$, respectively. Comparing to the previous century, the Ebro River in Spain lost 99% of its load due to the constructions of dams and reservoirs (Gullén and Palanques, 1997). The Danube lost 35% of its load due to dam construction that lead to the erosion at the river mouth (Milliman and Farnsworth, 2011). Since 1941 the sediment load in the Colorado River has lost almost 100%, which caused irreversible damages to its delta (Pitt, 2001). Because of the sediment load reduction, the Niger delta suffered a recession rate of $10 \text{ m}/\text{yr}$ (Ibe, 1966). All of the examples above point to the link between reduction in the river sediment load and the erosion in the estuary, and shoreline recession of the delta at the river mouth.

However, due to the various physiographic characteristics of the river catchment (such as the nature of topography and river bed, spatial scale of the catchment, and degree of human disturbance), the change of suspended sediment load in the upper reaches of a river might not be directly reflected by the load in the lower reaches (Brizga and Finlayson, 1994; Phillips et al., 2004). For example, no dam-related changes in alluvial sedimentation are noticeable in the lower river reaches of southeast Texas, despite large reservoirs control 75–95% of the drainage area, and retention of massive amounts of water behind dams (Phillips, 2003; Phillips et al., 2004). Channel dredging and jetty construction caused the Mersey Estuary lost 0.1% of its volume in the past 150 years (Lane, 2004). Conversely, because of the retaining

walls, a large amount of sediment has accumulated in the middle of the Lune Estuary (Spearman et al., 1998). Furthermore, morphological changes of a river mouth and its adjacent coast could also be caused by land reclamation, dredging of navigational channels, relative sea-level rise, and littoral drift (Phillips et al., 2006; Evans, 2012; Van Landeghem, 2009). Under multiple influences of the changes in the river runoff and sediment load, changes in the local environment, engineering practices, and changes in the estuarine hydrodynamics, the morphological evolution of an estuarine is complex, and needs a comprehensive approach in the analysis.

The estuary of the Changjiang is located at the end of the longest river in China. The width of the river mouth is almost 100 km wide (Fig. 1). At the river mouth, the mean tidal range is 2.67 m, and the mean flow rate is 1 m/s (Dai et al., 2013a). Three islands, Chongming, Hengsha, and Jiuduan Shoal divide the mouth into 4 channels of North Branch, North Channel, North and South Passages (Fig. 1b). In the past century, the river mouth has been prograding seaward (Chen et al., 1985). Because of extensive land reclamation, the North Branch has become a tidally dominated estuary (Yun, 2004). Due to the engineering project to maintain a deep navigational channel, the North Passage has become an artificially controlled estuarine channel (Dai et al., 2013a) (Fig. 1). The engineering project started in January 1998 (Fan and Gao, 2009), which consisted of four parts: the river diversion, construction of north and south jetties along the channel, and dredging of the thalweg. The first stage of the project completed in June 2001, which achieved the diversion of the river flow, partial completion of the jetties, and the navigational channel reached 8.5 m depth. The second stage began in May 2002 and lasted until March 2005, in which the jetties with the attached groins along the length of the N. Passage were completed and the navigational channel reached 10 m depth. The last stage commenced in September

2006 and was completed in March 2010, in which the dredging was the main focus and the navigational channel reached 12.5 m depth. Upon the completion of the channel improvement and maintenance project, the deep-water navigation channel was 92.2 km long, 350-400 m wide, having the thalweg depth of 12.5 m (Fan and Gao, 2009; Fan et al., 2012; Dai et al., 2013a) (Fig. 1).

The world's largest dam, the Three Gorges Dam (TGD), located in the upstream of the Changjiang, became operational in 2003. The measured suspended sediment discharge (SSD) at Datong (the upper limit of the tidal river) dropped sharply to 2.06×10^8 and 1.47×10^8 in 2003 and 2004, respectively, in comparison to over 4.2×10^8 t/yr before the 1970s (BCRS, 2010, 2011). In 2006 and 2011, the sediment delivered to the sea declined further to be 0.84×10^8 , 0.72×10^8 t/yr (BCRS, 2010, 2011). Whether the drastic reduction of sediment load is going to trigger erosion or the progradation of the Changjiang estuary delta will continue has been an international dispute (Liu et al., 2007; Syvitski et al., 2009; Chen et al., 2010; Wang et al., 2009; Dai et al., 2013b; Yang et al., 2007, 2011; Wang et al., 2013; Chu et al., 2013). Based on local cross-sectional changes in the estuary, Yang et al. (2007) found that the reduction of the river sediment load of the Changjiang is the reason for the erosion of estuarine wetlands. However, from the analysis of the morphological changes of the shipping channel along the North Passage, Dai et al. (2013a) found deposition in the peripheral groin fields along the shipping channel and deepening of the shipping channel, which is primarily due to the channel improvement and maintenance engineering. Variability of the river-mouth shoal (seaward migration and size reduction), which is caused by the declining sediment discharge of the Changjiang due to the TGD, and the enhancement of the ebb flow as the result of dredging (Dai et al., 2013a). Furthermore, Jiang et al., (2012) suggest that since 1999 the channel

125 maintenance engineering practices have on one hand limited the seaward progradation,
126 but on the other hand, induced vertical accretion of the Jiudian Shoal. The combined
127 factors of upstream sediment load reduction and local channel maintenance
128 engineering practices are no doubt making the morphological processes at the mouth
129 of Changjiang more complex.

130 Since both the North Branch and North Passage have been subject to human
131 alteration (such as local reclamation along the North Branch, channel dredging of the
132 North Passage) (Yun 2004), it is difficult to distinguish natural from the
133 anthropogenic causes of morphological development. Although the North Channel has
134 the least human interference, it is not the major conduit for the export of riverine
135 sediment, and it has been the least studied. However, the South Passage (SP) being the
136 major conduit for water and sediment of the Changjiang (Milliman et al., 1985), has
137 also been affected by direct human activities to a limited extent. Since 1987, this
138 channel has been monitored for navigational purposes with uninterrupted yearly
139 nautical topographic records. Thereafter, the objective of this paper is to diagnose the
140 decadal morphological changes of this channel to determine the whether the decline
141 of distal river sediment source or the proximal local influences would affect the
142 development of the SP. The outcome will be valuable to assess the potential response
143 of part or the whole of the Changjiang Estuary to the upstream reduction of sediment
144 supply, and the impact of the natural and man-made factors near and far. It could be
145 well applied to river estuaries with similar distributary mouths worldwide that are also
146 under similar natural and anthropogenic influences.

148 **2. Material and methods**

149 Digitized bathymetry-derived DEM has become a useful tool to study

morphological changes of estuaries (Blott et al., 2006; Jaffe et al., 2007; Lane, 2004; Van der Wal et al., 2002; Thomas et al., 2002). This study collected surveyed bathymetric data of the SP since 1987. The 1987-2000 data came from published nautical charts by the Maritime Survey Bureau of Shanghai, Ministry of Communications of China. The data for 2001-2012 came from the nautical charts published by the Changjiang Estuary Waterway Administration Bureau (CJWAB), Ministry of Transportation of China (Table 1).

All the bathymetric surveys were conducted in August or September each year based on the theoretical low-water datum. Dual-frequency echo sounders and GPS positioning were used. The vertical error was limited to be within 0.1 m. Survey density consisted of 8-20 bathymetric data points per km². Maps of the Changjiang Estuary and SP with the same precision have been applied to studies on estuarine erosion and deposition (Yang et al., 2011), evolution of the river trough (Jiang et al., 2012; Wang et al., 2013; Dai et al., 2013a), and the morphological changes of the estuary and submerged delta (Dai et al., 2014). Besides, the morphological changes in the current study exceed 0.1 m. Accordingly, the surveyed the digital data of the SP is reliable to use for the study of the morphological changes of the SP.

All charts were georeferenced using nine fixed benchmarks, of which the National Grid coordinates were known. The depth values were converted to elevation relative to Beijing-1954 Datum. After obtaining the charts, we digitized them by using ArcGIS 9.3 as the platform for input, output, and comparison. The Kriging scheme was used to interpret the digitized data into grid having resolution of 250 x 250 m.

In the meantime, we collected the river flow data in the study area (source: CJWAB). The tidal flow was measured at S1 and S2 in the SP in the flood season of August in 2002, 2005, 2007, and 2010, respectively (Table 2). The measurements at

the two locations were synchronized and took place during spring tide and lasted over 25 hr.

This study also collected the river runoff and suspended sediment load at the Datong station located at the landward limit of the tidal river (Fig. 1, Hydrological Committee of Changjiang, www.cjw.com.cn) (BCRS, 2010, 2011).

At each hydrographic station, the coefficient of flow dominance (defined as tidal flow rate during the ebb divided by the sum of tidal flow rates of the ebb and flood) was calculated (Simmons, 1955) as follows:

$$A = \frac{Q_e}{Q_e + Q_f} \times 100\% \quad (1)$$

in which A is coefficient of dominance flow, Q_e is cross-sectionally averaged ebb flow rate, Q_f is cross-sectionally averaged flood flow rate. When $A > 50\%$, the flow is ebb-dominant. Conversely, it is flood dominant.

To quantify morphological changes, the -5-m isobath was extracted through the ArcGIS platform. From ArcGIS the max. and mean water depths of each chart were obtained. To quantify erosion/deposition, the volume changes were calculated at 3-4 year increments between 1987 and 2012, which included 26 yearly charts. The spatial and temporal correlations (standardized covariance) of the water depths in the 26-year period were then analyzed by using the multivariate analysis technique EOF (Empirical Orthogonal/Eigen Function) analysis.

EOF is a classical statistical technique, which was used to separate orthogonal modes contained in the data sets (Liu et al., 2000). The advantage of using EOF analysis is that a set of inter-correlated variables can be decomposed into a set of statistically independent modes, which bear physical meanings. Thus, the EOF technique has been widely applied to problems in meteorology, oceanography,

geology, and sedimentology, etc. (Liu et al., 2000; Emery and Thomson, 2001; Liu and Lin, 2004; Lane, 2004; Dai et al., 2013a). Here all the standardized bathymetric variance sets can be deviated to form a single matrix X

$$X = (X_1 \dots X_n)$$

where each X_n represents a single grouped observation of the m variables and X is an $m \times n$ data matrix. m is the number of spatial points, and n is the observed time points.

Mathmatically, the EOFs are the eigenfunctions of the covariance matrix S , which is given by $S = XX'$. Based on singular value decomposition of the matrix S , the eigenvalues $\lambda (\lambda_1, \lambda_2, \dots, \lambda_m)$ of S and spatial patterns (V) can be obtained. Thereafter, the time series describing the loadings (T) can be obtained by $T = V'X$ (Wallace and Dickinson, 1972).

Subsequently, eigenvalues $\lambda (\lambda_1, \lambda_2, \dots, \lambda_m)$ can be ranked according to the amount of data (covariance) they explained, i.e. the variance contribution of each eigenvalue R_k , and the cumulative contribution for the eigenvalues G can be considered as:

$$R_k = \lambda_k / \sum_{i=1}^m \lambda_i \quad [k = 1, 2, \dots, p(p < m)]$$

$$G = \sum_{i=1}^p \lambda_i / \sum_{i=1}^m \lambda_i \quad (p < m)$$

Generally, the better correlated the data are, the more covariance can be accounted for by the first few eigenmodes (Liu et al., 2000; Emery and Thomson, 2001). The remnant eigenfunctions are neglected due to the effect of noise contained in this set (Wallace and Dickinson, 1972).

3. Results

3.1 Bathymetric changes along the SP

Jiangyanan Shoal is located at the upstream opening of the SP. Prior to 1997, Jiangyanan Shoal and Jiudian Shoal were disconnected, as the downstream part of the South Channel (Fig. 2a). Currently, Jiudian Shoal is located on the north side of the SP, and Nanhui Shoal is on the south side of the SP (Fig. 1c, 2b). Based on the changes of the location of the -5-m isobath (Fig. 1c, Fig. 3), the morphological changes at the SP can be characterized by 2 stages. In the first stage of 1987-1997 there was a single channel at the SP, which is clearly shown in the nautical chart of 1990 (Fig. 2a). In the early period of this stage the -5-m isobaths of Jiangyanan Shoal and Jiudian Shoal were not connected. There was a short-cut-channel about 1 km wide separating the two sand bodies (Fig. 3a), allowing exchange between the North and South Passages. Along the south side of the SP there was a 'spur' on the -5 m isobath pointing to the spit of the Jiangyanan Shoal (Fig. 3a). In the following years of 1990-1994, the -5-m isobaths of Jiangyanan and Jiudian Shoals connected. The north side of the short-cut-channel was filled in. In the meantime, the spit at the southern end of the Jiangyana Shoal migrated northward by 1260 m (Fig. 3b) but the thalweg of the SP was located toward the north side of the channel along Jiudian Shoal. In 1994-1997, the short-cut-channel was completed closed as shown by the -5-m isobath. The spit of Jiangyanan Shoal was eroded by 1060 m (Figs. 3c). The Jiangyanan Shoal and Jiudian Shoal were merged so that the bank of SP extended to include the Jiangyanan Shoal. Thereafter, between 1987-1997, with closure of the short-cut-channel the SP had a single stable channel. As a result, the SP had a relatively straight thalweg. The short-cut-channel became a wide flood cove.

In the second stage of morphological changes in 1997-2012, the spit of the Jiangyanan Shoal elongated downstream, making the opening of the SP into a dual

channel system (Figs. 3d, 3e). In the period of 1997-2000, the erosional pattern of the spit turned to accretionary and the spit extended downstream by 6430 m. In the same time, the -5-m isobath of the southern bank of the SP extended northward, to form a narrow gap of 800 m between the spit of the Jiangyanan Shoal and the southern bank of the SP (Fig. 3d). The flood cove between the two shoals narrowed and its northern end moved downstream by 1670 m in response to the elongation of the spit (Fig. 3d). In 2000-2003, the spit of Jiangyanan Shoal continued to accrete into the relative stable channel of SP by 2380 m. However, the entire spit shifted northward by 1300 m together with the flood cove on its north side (Fig. 3e).

As the spit of the Jiangyanan Shoal grew in the southwestern direction, the SP became a shoal-trough complex, which is clearly reflected in the 2006 nautical chart (Fig. 2b). The spit increments in the periods of 2003-06, 06-09, and 09-12 were 1200, 4100, and 3500 m, respectively. The flood tidal cove on the north side of the spit became narrower (near 800 m in 2006 and less than 500 m in 2012). Comparing to 2009, the position of the flood tidal cove moved NW by 6800 m (Figs. 3f-3h). Cross-sectional wide, due to the downstream accretion of the spit in the upper part of SP, the lower part of the SP deepened and the thalweg remained closer to the Jiudian Shoal. Thus, the present-day SP formed a complex morphology.

3.2 The bathymetry and associated volume change at the SP

The yearly average water depth of the study area in the 30-year period between 1987 and 2012 fluctuated between 5.1~6.7 m, by over 1 m, but also showed a decreasing trend (Fig. 4a). A sudden drop over 1 m occurred in 1999. During the same period, the max. water depths also showed decreasing trend (Fig. 4b), which had a sudden decrease from 9 m in 1998 to 7 m in 2000, that is also reflected in the drop of the yearly mean depth (Fig. 4a).

The volume capacity of SP has been gradually decreasing from $0.69 \times 10^9 \text{ m}^3$ at 1987 to $0.59 \times 10^9 \text{ m}^3$ at 1994, a reduction by 14% (Fig. 5), implying infilling of the SP. In 1994-1996, the capacity increased by $0.04 \times 10^9 \text{ m}^3$. After 1998, the capacity continued to decrease. In 2001-2006, the capacity increased slightly. But in 2006-2008, the capacity dropped drastically by $0.06 \times 10^9 \text{ m}^3$, and then gradually gained back slightly. Overall, between 1987 and 2012, the volume capacity of SP lost about 13% (Fig. 5). Comparing to the 0.1% volume decrease of the Mersey Estuary in the past 150 yr (Lane, 2004), the decrease at SP is considerable.

3.3 The Deposition/Erosion of the SP

Visual comparisons of the depth changes in 3-4 yr increments (Figs. 6a-6h, 7) indicate that the stages of erosion/deposition patterns of the SP were identical to the 2 stages described earlier. In the first stage (1987-1997) the SP was more or less in erosion/deposition equilibrium, having slight tendency of deposition. Because of the conjoining of the spit of Jiangyanan Shoal and the Jiudian Shoal, the upstream part of the SP turned from erosional (by 1 m) to depositional (by 1 m) (Figs. 6b, 6c). But the overall deposition was of about 0.2 m.

In the second stage (1997-2012), SP was firstly in the state of adjustments during 1997-2003 (Figs. 5d, 6e, 7). This is strongly reflected by the deposition around the upstream opening of the SP. Compared to the previous period of 1994-1997 (Fig. 6c), in the period of 1997-2000 the entire SP experienced slight net erosion. The erosional rate was over 5 cm/yr of (Fig. 7). In 2000-2003, the total accumulation around the upstream opening of the SP was over 4 m. In contrast, around the seaward opening near Jiudian Shoal, the total accumulation was over 3 m in 1994-1997; and yet, in 1997-2000, the erosional rate was over 6 cm/yr (Fig. 7). But in 2000-2003, slight accumulation rate of about 10 cm/yr occurred again (Fig. 7). From 1997 to 2003, the

net change at SP was from having an erosion rate of 5 cm/yr to an accumulation rate of about 10 cm/yr (Fig. 7).

In the subsequent years during 2003-2012, the SP was in a state of strong deposition that had a net accumulation rate over 10 cm/yr (Fig. 7). Within this trend, localized strong erosion and deposition also occurred (Figs. 6f, 6g, 6h). These areas included the continued accumulation at the upstream opening of the SP by 1-2 m. The southern end of the SP on the other hand, was in the state of erosion by about 1-2 m. Deposition also occurred in the center section of the SP, on average about 1 m. Since 2003-2009, the deposition area in the center-channel gradually moved upstream (Figs. 6f, 6g). In 2009-2012, the entire SP was in a general state of accumulation (average rate of 10 cm/yr) except for a narrow zone of erosion over 1m along the center section of Jiuduan Shoal (Figs. 6h, 7). Thereafter, between 1997-2003, the SP went through another period of erosion/deposition adjustment during which the opening of the SP developed a two-channel morphology (Fig. 7), which stabilized and showed infilling during 2003-2012 (Fig. 7). In this entire period (1997-2012) the changes included eastward spit formation and westward shoal incision of the short-cut-channel, eastward spit formation and westward shoal incision of the cross-channel.

3.4 EOF analysis of the bathymetric changes

The results of EOF analysis on the water depth data from 1987 to 2012 show that the first two eigenmodes can explain over 75% of the standardized covariance of the data (Fig. 8). Since all higher modes explain less than 10% of the data, only the first two modes are presented and discussed.

The first eigenmode explains 59% of the water depth co-variability, which is the most important form of morphological changes. The contour plot of the eigenvectors of this mode shows the spatial co-variability in the SP including the accretion at the

center of the northern opening of the channel (the area of highest positive values) due to the sediment load input from upstream and along the south side of the Jiudian Shoal (Fig. 8a). Also, along the northern edge of the SP bordering the Jiuduansha there is an elongate area having the values of 0~0.05. These are the areas of aggradation whose temporal pattern shows increasing trend as indicated by the eigenweighting curve of this mode (Fig. 8b). This mode also shows the formation of the thalweg in the center of the channel. The temporal pattern of this mode is expressed by the eigenweighting curve of this mode (Fig. 8b), which shows an increasing secular trend, which resembles the inverse trends of the decreasing mean water depth max. depths (Figs. 4a, 4b) and the decreasing volume capacity (Fig. 5). Therefore, this mode describes the increasing spatial gradients in sediment transport into the SP whose most significant effect is shown by the major deposition in the upstream opening of SP depicted by the eigenvectors (Fig. 8a).

The second mode explains the 18% of the water depth co-variability. The eigenvectors of this mode indicate that the morphological changes related to the growth, decay and movements of the spit of the Jiangyanan Shoal, which is the second most important factor contributing to the water depth changes in the SP (Fig. 8c). The 'W' shaped temporal pattern suggests a somewhat recurring pattern, if not cyclical. From 1987 to 1995, the descending trend in the eigenweighting curve reflects the retreat of the spit of the Jiangyanan Shoal (Figs. 8d, 3). On the other hand, the rapid downstream elongation of the spit caused the ascending trend between 1995 and 1998 (Figs. 8d, 3). Between 1999-2002 the spit retracted and became shorter. In the meantime, it migrated towards the Jiudian Shoal, making the tidal cove narrower (Figs. 8d, 3). Beginning in 2003, the spit began to lengthen again, which is accompanied by the erosion and the head-ward retrogression of the cove, making it

more resemble a narrow and long channel (Fig. 3f). This development is reflected by the ascending part of the eigenweighting curve after 2003 (Fig. 8d).

4. Discussion

4.1 The changing sediment load of Changjiang

The average water discharge of Changjiang exceeds $900 \times 10^9 \text{ m}^3/\text{yr}$. The runoff of the Changjiang did not show noticeable change in the period between 1954-2011 (Fig. 9a). The mean sediment load of the Changjiang is $420 \times 10^6 \text{ m}^3$. In the period of 1954-2011 there was a decreasing trend, which was more pronounced in the period of 1987-2011 (Fig. 9b). In the case of the NP (Fig. 1a), the accumulation is on the order of hundreds of million tons despite the sediment load reduction (Jiang et al., 2012; Dai et al., 2013a). This is largely attributed to the engineering works (Dai et al., 2013a). The regions shallower than the -5-m isobath on the submerged delta of the Changjiang was still in the state of accretion (Yang et al., 2011). Controversy continues regarding whether or not the shores around the mouth of Changjiang will start to erode (Chen et al., 2010; Yang et al., 2011; Dai et al., 2012, 2013a; Wang et al., 2013).

Sediment supplied by the Changjiang determines the seaward progradation of its river mouth (Chen et al., 1985). Since the 12th century, the shoals on the south bank of the Changjiang have prograded seaward at the pace of 1 km per 40 yr. In the last half century, the rate accelerated to 1 km per 23 yr (Chen et al., 1985). Since the SP is the major seaward conduit of the riverine sediment (Milliman et al., 1985), it should show responses to the load reduction. The relations among the max. water depth, mean depth, and the whole capacity below 0 m isobath of the SP and the sediment load of Changjiang into the estuary in the period 1987-2011 show statistically significant ($p < 0.001$, except for the max. water depth) positive correlations (Figs. 10a, 10b, 10c).

These patterns indicate that the decrease in mean and max. water depths and the volume capacity of the SP are associated with the reduction of the sediment supply, which is counter-intuitive. Meanwhile, the value of mean grain-size of the Changjiang sediment was 0.0017 mm (1976-2000) and that of the medium diameter in 2012 was of 0.011 mm. The fining trend corresponds with the deposition trend in the SP., attesting to the deposition in the SP. On the other hand, reduction of sediment supply should have induced erosion, which in turn would have caused deepening of the SP and an increase of the volume capacity. However, the above relations point to factors other than these direct distal effects of the reduction of sediment supply upstream of the Changjiang Estuary. This is consistent with the recent discovery that the despite of the reduction of the distal sediment source, the submerged delta of the Changjiang still showed aggradation (Dai et al., 2014) due to proximal and local factors.–

4.2 Local influences

Engineering works in the NP have affected the Jiangyanan and Jiudian Shoals. The construction of the south jetty and dike system in the NP stabilized the northern rim of these two shoals. From the second stage to the end of the third stage of the navigation channel improvement and maintenance project the flow dominance coefficient measured at the two stations in the SP first showed decreasing and then increasing trends (Fig. 11). The min. ebb dominance was 60%, which reached 70% during the flood season of 2010. These trends indicated the engineering practices of the project strengthened the ebbing flow, which enhanced the channel's ability to transport sediment seaward (Fig. 11). Furthermore, the engineering structures blocked the sediment exchanges between the NP and SP (Yang et al., 1998; Li et al., 2006). This is reflected by the disappearing of the short-cut-channel before the early 1990s (Figs. 3a-3c). In 1997-2006, during slack transition from flood to ebb, the suspended

sediment in the NP was still able to move over the submerged dike and enter the SP (Liu et al., 2010). Since the peripheral groin field of the NP trapped sediment, this could be a local source for SP. The depositional pattern along the Jiuduan Shoal illustrated by the 1st mode eigenvectors (Fig. 8a) could be the effect of this source. Yet, this sediment input from NP did not fully fill in the tidal cove, which remained stable (Figs. 3d-3g). Rather, sediment could probably bypass the cove and enter the main channel of SP. In 2012, the cove almost cut Jiangyanan Shoal in the form of head-ward erosion, which was potentially caused by the cut-off of spill-over sediment from the NP.

Moreover, the SP has not been significantly affected by land reclamation, which was carried out on the tidal flat of Nahui on the south bank of the SP in 1994-2003 (Fig. 1b, Fig. 12) (Li et al., 2007). At present, the reclaimed area above the -2 m isobath exceeds 15, 000 hm² (Li et al., 2010). Although the geomorphology of SP in 1987-2012 has shown appreciable changes (Fig. 3) in the river channel, but the positions of the -5-m isobath on both sides of the SP remained unchanged and relatively stable. This suggests that reclamation-engineering projects at the seaward end of the SP had little influence on the SP morphology, although there may have been an impact on shallower areas.

4.3 Spit morphodynamics of the Jiangyanan Shoal

The EOF analysis points out the most important mode of morphological change is characterized by the deposition around the northern opening of the SP. To further illustrate a possible proximal sediment source, the development and evolution of the Jiangyanan Shoal is expressed by the 0-m isobath at discrete time points from 1994 to 2009 (Fig. 13).

In 1994, only a few small-scattered sand bodies were present at the general

location of the present Jiangyanan Shoal following its orientation (Fig. 13a). In 1997, the size of the sand bodies increased and they continued to develop along the orientation of the Jiangyana Shoal (Fig. 13b). In 1999 the small bodies merged into one large body forming the Jiangyanan Shoal (Fig. 13c). In the meantime, the southern limit of the shoal moved 990 m downstream compared to the 1997 location. In 2002 Jiangyanan Shoal moved downstream by another 3000 m, whose southern tip was separated from the main body to form a small sand body (Fig. 13d). In 2006 the Jiangyanan Shoal moved farther downstream by 1990 m as one body (Fig. 13e). In 2009 the Jiangyanan Shoal moved again by 1700 m and the elongated spit was well formed (Figs. 3g, 13f). These historic changes suggest the development and downstream movements of the Jiangyanan Shoal also contributed to the infilling of the SP.

The downstream movement was probably associated with the lateral expansion of the Jiangyanan Shoal into the subaerial SP channel, which also can be reflected by the 0-m isobaths (Fig. 13). The downstream movement of the shoal was facilitated by the bed material along the SP. In the Changjiang Estuary, shoal movements are a major form of bedload sediment transport that amounts to 350×10^6 t/yr (Li, 1993; Li et al., 2010). This amount is equivalent to the amount of sediment delivered by the Changjiang to the sea, which on a large degree, results in the shoaling of estuary channels (Li, 1993; Li et al., 2010). Generally these shoals comprise of fine sand having the medium diameter of 0.16 mm (Zhou, 1983). Under strong ebbing flow (average velocity: 1-1.5 m/s) the sediment transport in shallow part of the Changjiang Estuary is in the form of sand wave movement, whose migration rate could reach 300-2000 m/yr in the flood season (Zhou, 1983; Li, 1993; Gong et al., 2003). Li (1993) described the mechanism of the sand wave migration. This implies that the sediment

on the Jiangyanan Shoal could move into SP via sand waves. Thereafter, the temporary trend of the 1st eigenmode thus, could also reflect the enlargement of the Jiangyanan Shoal, which is reflected by the deposition next to the shoal.

The second most important pattern of morphological changes was caused by the slow accretion, recession, and lateral migration of the spit of the Jiangyanan Shoal (Figs. 3a-3h). In 1997-2000, the spit extended into the SP channel by 6430 m. The extension caused the single-channel thalweg to become a double-trough channel (Figs. 3d, 3e, 3f). Moreover, the spit also displaced the thalweg and made it shift laterally (Fig. 3). A critical time point in the spit-morphodynamics is 1998 when historically the second most severe flooding in Changjiang occurred (Fig. 9). The river discharge exceeded $120 \times 10^9 \text{ m}^3$. The strong river flow and extra large amount of sediment load probably triggered the spit of the Jiangyanan Shoal to extend downstream, causing the mean water depth to decrease noticeably between 1998-2000 (Fig. 4). Once this spit is in place, in the ensuing years, the spit-building process continued with fluctuations.

At present the dikes along the south side of the navigation channel stabilized the northern rim of the Jiangyanan Shoal. Jiudian Shoal is in the state of equilibrium (Jiang et al. 2012). As the reduction in the sediment load from the upstream continues, and the strength of the river flow remains unchanged (Fig. 11), the spit in the SP might not continue to extend downstream. The SP might revert back to a single trough channel and the seaward extension of the Jiangyanan Shoal might slow down or stop, and the Jiudian Shoal might undergo erosion.

5. Conclusions

Having a branching estuary, the Changjiang has one of the most complex river mouth in the world. In the face of declining sediment supply and extensive engineering practices, different channels of this branching estuary have displayed

differential morphological processes as followed as:

1. Between 1987-2012, the average, maximum, and the volume capacity below the 0-m isobath were all in a decreasing trend. The volume capacity in the last 30 years has decreased by 13%. The erosion/deposition patterns varied in time. In 1987-1997 the SP was in a state of equilibrium. The net depth change was 0.2 m. In 1997-2003, the SP was in a state of transition, which was followed by a state of infilling by the amount of 10 cm/yr between 2003 and 2012. The infilling is the most important mode of morphological changes indicated by the EOF analysis result, which is mostly attributed to the deposition in the northern opening of the SP.
2. There were two stages in the morphological processes at the SP. Between 1987-1997 the SP had a single channel with closure of the cross-channel. Between 1997-2012, the SP firstly transitioned from a single channel to a two-channel configuration from 1997-2003. From 2003 to 2012, the SP remained a two-channel branch. In this period SP showed eastward spit formation and elongation and westward shoal incision of the cross-channel. These two stages were controlled by the lengthening, retreat, and lateral migration of the spit of the Jiangyanan Shoal, which is the second most important mode of morphological changes indicated by the EOF analysis results.
3. The secular trend in the sediment load decrease cannot explain the opposing trends of water depth and volume capacity decrease at the SP. The morphological changes in the SP were mainly induced by the development, growth, and migration of the Jiangyanan Shoal into the SP and the morphodynamics of the spit of the Jiangyanan Shoal. Furthermore, the

engineering project north of the SP stabilized the river flow partition and constricted the ebbing flow to be stronger as shown by the high coefficient of ebb-flow dominance. This might help to transport sediment into SP from the upstream.

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676

Captions:

Fig. 1. Maps showing: a. the location of the study area in relation to the China; b. the morphological units at the mouth of the Changjiang based on the 2006 navigational chart; c. the location of the SP and the study area is marked by dashed red lines.

Fig. 2. Nautical charts of a. 1990, and b. 2006.

Fig. 3. Geomorphological changes of the SP and the two shoals as expressed by the -5-m isobath in 3-yr increments.

Fig. 4. Water depth changes of the SP in 1987-2012: a. yearly mean depths; b. yearly maximum depths.

Fig. 5. The volume capacity change below the 0-m isobath of the SP in 1987-2012.

Fig. 6. Erosional/depositional patterns of the SP (negative means erosion, positive means deposition) in different time periods.

Fig. 7. The net erosion/deposition values of the SP derived from Figure 6.

Fig. 8. The EOF analysis result of the time-space related water-depth changes Showing: a. the plot of the 1st mode eigenvectors; b. the 1st mode eigenweighting curve; c. the plot of the 2nd mode eigenvectors; and d. the 2nd mode eigenweighting curve.

Fig. 9. Yearly records of discharge (a), and suspended sediment load (b) at the Datong st. The black lines are the linear regression results for the period of 1954-2011 and the red lines are the linear regression results for the period of 1987-2011, respectively.

Fig. 10. Yearly mean sediment load at Datong st. verses (a) yearly max. water depth; (b) yearly mean water depth; and (c) volume capacity below the 0-m isobath of the SP.

702 Fig. 11. The measured flow dominance coefficients at two hydrographic stations at
703 different times

704 Fig. 12. Schematic plot of the land reclamation of the Nanhui Shoal (Modified from
705 Li et al., 2007).

706 Fig. 13. Time changes of the 0-m isobath of the Jiangyanan Shoal (0-m isobath: red
707 dotted line; the southern jetty of the navigational channel and dikes: blue line).

Table 1 Observed water depth data in the South Passage, Changjiang *

Surveyed date	Map title	Scale	Data sources
1987, 1988, 1989, 1990, 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000	Nancao Fairway	1:50000	MSBSMCR ¹
2001, 2002, 2003, 2004, 2005	Beicao and Nancao Fairway, Changjiang Estuary	1:25000	CJWAB ²
2006, 2007, 2008, 2009, 2010, 2011, 2012	Beicao and Nancao Fairway, Changjiang Estuary	1:10000	CJWAB

¹ MSBSMCR: Maritime Survey Bureau of Shanghai, Ministry of Communications of China

²CJWAB: Changjiang Estuary Waterway Administration Bureau (CJWAB), Ministry of Transportation of China.

Table 2 Hydrological gauging stations of the South Passage

Stations	Position	Surveyed periods
NC1	121.76° E, 31.27° N	8.2002, 8.2005, 8, 2007, 8.2010
NC2	121.85° E, 31.19° N	8.2002, 8.2005, 8, 2007, 8.2010