

Processes of small-scale tidal flat accretion and salt marsh changes on the plain coast of Jiangsu Province, China

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Abstract

Large-scaled reclamation modifies the coastal environment dramatically while accelerating the disappearance of salt marshes, which causes the degradation of the coastal ecosystem and the biodiversity function. In this study, we explored the changes of tidal flat and salt marsh coverage in a small-scale tidal flat with an area of ~160 000 m² in the plain coast of Jiangsu Province, China. Human activities (e.g., the construction of dikes) are a crucial contributor that benefits for the tidal flat accretions and the following changes of salt marsh coverage. Located in the front of the man-made “concave coastline”, the study area is suitable for sediment accretion after the dike construction in the end of 2006. On the basis of the annual tidal surface elevation survey from 2007 to 2012, the sedimentation rates in the human influenced tidal flat varied from a few centimeters per year to 23 cm/a. The study area experienced a rapid accretion in the tidal flat and the expansion of the salt marsh, with the formation of a longshore bar, and a subsequent decline of the salt marsh. Breaking waves during the flooding tide brought much sediment from the adjacent tidal flat to the study area, which caused burial and degeneration of the salt marsh. The vertical grain size changes within a 66 cm long core in the study area also demonstrated the above changes in the tidal environment. This study indicates that the responses of small-scale tidal flat changes to reclamation are significant, and the rational reclamation would benefit for the new salt marsh formation in front of the dikes. Further research about the evolution of small scale tidal flat as well as the spatial planning of the polder dike should be strengthened for the purpose to maintain a healthier coastal environment.

Key words: tidal flat, salt marsh, small-scale tidal flat, response to reclamation, plain coast of Jiangsu Province

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1 Introduction

In our time of rapidly increasing human uses of coastal zones, coastal wetlands were highlighted in science and the public because of their extraordinary character in terms of their environmental setting as well as their economic potential (Jennerjahn and Mitchell, 2013). Coastal wetlands provided important eco-functions such as nursery habitats for fish and crustaceans, resting and feeding areas for migratory birds; coastal wetlands also supported biodiversity, filtered contaminants, dissipated water energy, and offered intrinsic values such as aesthetics and education (Goodwin et al., 2001). Coastal wetlands were under increasing multiple pressures with the growth of population and urbanization in coastal zone (Belfiore, 2003). Coastal land has become the valuable resource. The need of land especially accelerated the embankment and reclamation, which significantly influences the coastal salt marshes.

Salt marsh represents an essential part of the coastal wetland which is covered by halophytic vegetation which is regularly food by the sea water. Salt marshes along the coast have long been interested by the researchers. Allen (2000) summarized the salt

marsh studies from the Atlantic and southern North Sea coasts of Europe in a multi-disciplinary view. Wang (1983) introduced the mud tidal flats, salt marsh and its formation in China. Salt marsh vegetations played an important role on physical processes in intertidal wetlands, such as hydrodynamics, sediment transport, sedimentation and geography (Li and Yang, 2007). The cycles of progradation and retreatment of the marsh edges were documented on a number of marsh and intertidal systems in a small scale (Cox et al., 2003; van der Wal and Pye, 2004). These cycles were related to changes in sea level, sediment supply, cliff morphology, intertidal sedimentation and changes in the location of the major tidal channel (van Proosdij et al., 2006). After qualitative comparison of British West-Coast estuaries, Allen (1989) has proposed that retreating salt-marsh cliffs response to the erosive attack of waves and tidal currents, mainly in the form of toppling failures and rotational slips. However the cliffs are also formed under accumulation conditions, the reason is the obvious difference accumulation rates in both sides of the cliffs (Gao and Collins, 1997). The marsh edge erosion was importance in “feeding” the marsh surface, quantified studies in the Danish Wadden

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Sea showed that the deposition rate across the salt marsh platform decreased in an exponential manner away from the salt marsh edge at a lower rate than that found on salt marsh (Pedersen and Bartholdy, 2007). Taking the tidal salt marshes of Jiangsu Province as example, Wang et al. (2006) found that the original patterns of tidal flat accretion had been modified since the introduction of *Spartina alterniflora Loisel*, this “invasive plant” caused rapid accretion rate about 4.3 cm/a. In the Changjiang (Yangtze River) Estuary and Jiangsu coastal region, researchers interested in tidal flat morphological changes and the sedimentation process and its response to storm surge, large-scale reclamation, catchment hydrologic dam construction especially the Three Gorges Dam (Ren et al., 1985; Yang, 1999; Yang et al., 2001, 2003; Xie et al., 2013). The source of the tidal flat sediment indicated the complexity along the coast tidal flat of Jiangsu Province and the Changjiang Estuary (Zhang et al., 2012). Most studies concentrated on morphological changes and the vertical accretion rate but few researches related the tidal environmental changes based on annual continuous observation.

Salt marshes and associated environments influenced by complex natural controls and human exploitation (Allen, 2000). Salt marshes were valuable yet fragile, disappearing globally at an alarming rate (Möller et al., 2001). In the past decade, the reclamation activities along the coast of China came in to a rocketing development period. Large scale reclamation strongly changed the natural features of the tidal flat environment and accelerated the disappearance of the salt marsh, which caused the degradation of the coastal eco-environment and the biodiversity functions (Qiu, 2011).

The salt marsh vegetation dominated by *Spartina Alterniflora Loisel* was introduced and cultivated from the United States to Jiangsu Province in the 1980s. Subsequently, in the 1990s, *Spartina Alterniflora Loisel* was introduced and cultivated in along the coast tidal flat of Qidong City (Fig. 1a). Due to the suitable environment and strong ability of reproductive growth, *Spartina Alterniflora Loisel* rapidly expanded and formed a unique ecological landscape on the muddy tidal flat. The development strategy of “Marine Qidong” was carried out in the past decades, subsequently the reclamation and embankment along the coast of Qidong City was accelerated dramatically (Yuan and Zhang, 2003). Tidal flat reclamation could change salt marsh eco-environment, and the pattern of the salt marsh expansion differs in response to the reclamation rate and stages (Zhu and Gao, 2014). Human activities strongly changed the original coast morphology and the marine environment. The study area has been experiencing the multiple pressures and rapidly variations of the

tidal flat and salt marsh environment in the past decade.

Annual continuous observation and quantitative study of deposition rate are very important for small-scale processes and changes in tidal flat. Earlier researches on Allen Creek marsh found seasonal and annual variations based on the data from 1996 to 2002 (van Proosdij et al., 2006), which indicated the sensitivity of tidal flat to human and nature interactions. Yet few studies in China based on annual continuous observation of the tidal flat environment. In this study, processes of tidal flat accretion and related salt marsh changes on the plain coast of Qidong City were analyzed in the back ground of coastal embankment finished in December of 2006. The object of this study was to analyze the sedimentation process of tidal flat and salt marsh changes based on the annual field survey and core sediment analysis after the coastal dike construction in 2006.

2 Geographical settings and methodology

2.1 Physical environment of the study area

Qidong City is located in the northern part of the Changjiang River Delta. Before the Qing Dynasty, the region of Qidong was the part of the river mouth of the Changjiang River (Yangtze River) at that time with shallow water environment, scattering with sandy shoals or bars. Because of large amount of sediment supply and the rapidly deposition process, the scattered shoals and bars were enlarged and combined with each other. The general distribution pattern of present Qidong region appeared in the beginning of the last century and managed by the Nantong City and Haimen County. In the year of 1928, Qidong County was established as the new administrative district on the new land in the northern part of the Changjiang River Delta. The study area is located in the eastern coast of Qidong City (Fig. 1a). The local people started to embankment the higher tidal flat for agriculture, salt manufacturing, and aquaculture in the early time of last century. In the year of 2006, the recent embankment dike was finished (Fig. 1b). Before the embankment construction in December of 2006, the tidal flat is about 2 km in width and composed of the upper salt marsh tidal flat and the lower bare sandy tidal flat. The salt marsh was mainly composed of *Spartina Alterniflora Loisel*. On the seaside of the newly built dike, a continuous survey in a small triangle-shaped (Fig. 1b) tidal flat highlighted that a rapid changes of tidal flat-salt marsh in the micro-tidal settings. A section in the study area with five sites (A, B, C, D and E) were the key points for detailed investigation (Fig. 1b). One borehole named Core YH was collected with 66 cm long on August 21, 2011.

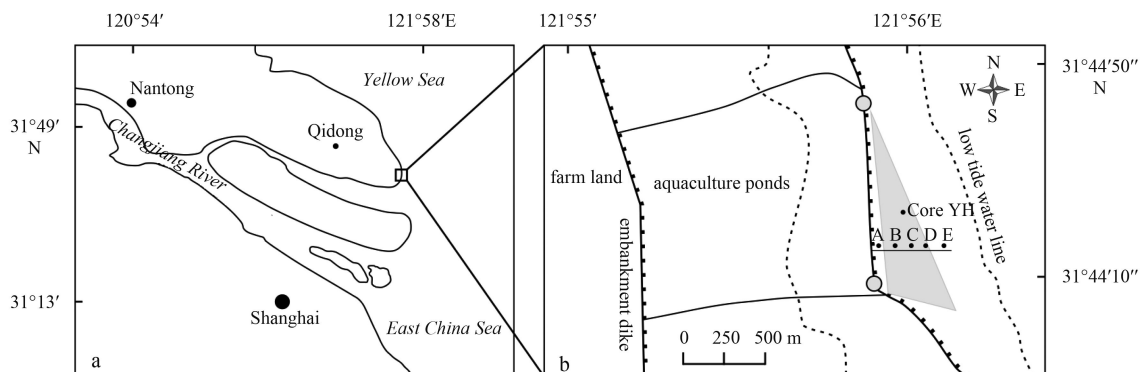


Fig. 1. Location and geographic settings of the study area after the dike construction in 2006.

The tides at the study site are of an irregularly semi-diurnal type, with the range of two successive tides being unequal. The tidal parameters of Lianxing Harbor, neighboring to the study area, was obtained in March 2007 (Li et al., 2011). The average tidal range was 2.94 m, and durations of flood tide and ebb tide were 5.38 h and 7.08 h, respectively.

The wind was strong in the study area and mainly controlled by the monsoon. In addition, a significant correlation was present between the wind speed and significant wave height (He et al., 2010). According to the Qidong Weather Station observation data from 1979 to 2009, the annual average wind speed is about 3.5 m/s. In the spring and summer season, the main wind directions are SE, ESE and SSE. In the autumn and winter seasons, the dominated winds are from the NE, NNE, NW and WNW directions.

2.2 Field survey

For the purpose to reveal the annual changes of tidal flat accretion and salt marsh coverage, field surveys were carried out every year and topographic survey used precise leveling instrument of DS03 (accumulated error is 0.3 mm). Although RTK was efficiency and reliability for quick investigation in field morphological survey (Martín et al., 2015), we found the RTK-GPS results was not better than the precise leveling instrument when measuring tidal elevations. A section in the study area was selected and five sites in the section were the key points for detailed investigation (Fig. 1b). From 2007 to 2012 the trans-section topographic data and the coverage of salt marsh in the study area were obtained. Because it was difficult to calculate the precise area of the scattered salt marsh, the percentages of salt marsh coverages were estimated in the field. Five shallow cores named A, B, C, D and E with the length of one meter, were collected by semicircular gravity sampler in January 4, 2013. The annual topographic elevation data were collected using precise leveling in-

strument of DS03 from 2007 to 2012 during the ebb tides. The increase of annual topographic elevation in Sites A, B, C, D, and E indicated the tidal flat accretions. In the studying period, the landscape especially the sand spits and the salt marsh changes in the study area were also observed and recorded in the field survey.

2.3 Grain size analysis

Grain sizes of all samples from Core YH were analyzed using Mastersizer 2 000, with the measurement range of 0.02–2 000 μm and relative error of being less than 2% for replicated measurements. Grain size parameters were calculated using the method by McManus (1988).

3 Results

According to the observation and records in the field survey, rapidly environmental changes happened from 2007 to 2013 in the small triangle-shaped tidal flat including the accretion, tidal landforms and salt marsh coverage evolution (Fig. 2). The process of tidal flat accretion and salt marsh changes were controlled by the coastal dynamics and the reproduction of the salt marsh in the background of embankment construction in December of 2006. In the October of 2013, a new jetty in the south of the study area was built (Fig. 2d).

3.1 Surface sediments and morphological changes of the tidal flat

The embankment dike in December of 2006 separated the tidal flat into two parts (Fig. 1). The landward part was mostly covered by the salt marshes and later the salt marsh used for aquaculture fishery. The seaside of the dike was the triangle-shape area with bare tidal flat at the beginning and the surface sediments was composed of fine to medium sand. In March of 2007, there was a strong storm surge and caused the strong accumulation in the study area. Much of the sandy mud materials accreted on the tidal flat especially the area closed to the embank-

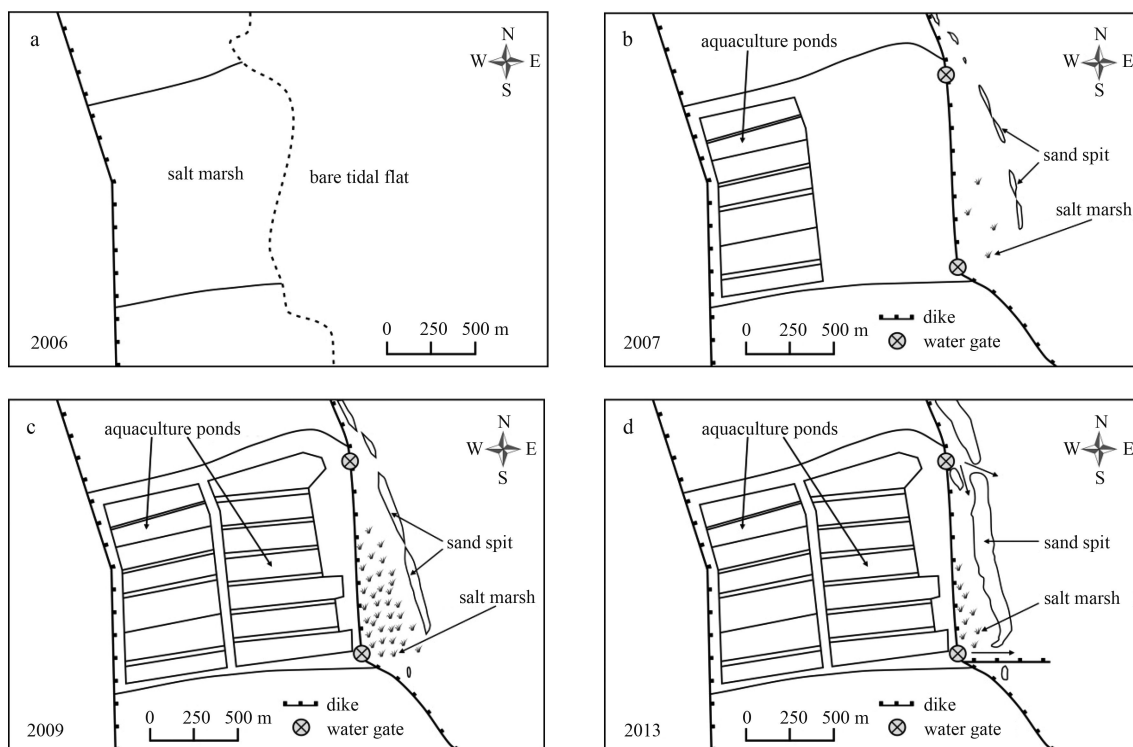


Fig. 2. The tidal flat salt marsh and morphological change in study area.

ment dike. Field survey revealed a deposition layer in 2007 of over 20 cm thick, with a maximum thickness of 30 cm in the central part of the study area.

In the outside of the triangle-shaped tidal flat, a long-shore bar shaped as sand spit emerged in 2007 and extended from the north to the south (Fig. 2b), which coincided with the coastal current (known as the Subei Coastal Current) flowing from the north to the south. The formation of the sand spit is influenced by the tides, wave and the coastal current (Yang, 2003). The man-made concave coastal line of the embankment dike provided a suitable space for the formation of the longshore bar (or sand spit). During the spring tide period, the over-wash and the coastal current bring much sand into the inner part of the tidal flat. The sediments transportation trend indicated the sand spit grew up and migrated to the salt marsh area based on the annual surveys (Figs 2c and d).

3.2 The accretion of the tide flat

Field investigation from 2007 to 2013 indicated the quick accretion in the study area after the embankment construction finished. According to topographic elevation data in the study area, the accumulation rates were calculated along the survey section (Fig. 3 and Table 1).

The basement of the tidal flat in the study area is sand layer. The elevation survey used as the basis for the next year, and the elevation was measurement each year by high precision leveling

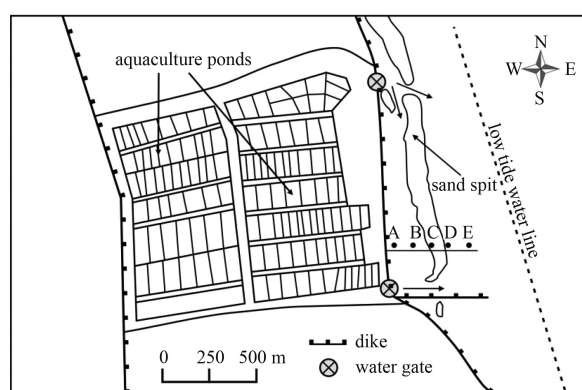


Fig. 3. The triangle-shaped tidal flat and sand spit changes in the study area.

Table 1. Results of tidal flat elevation and accretion in the study area

Date	Elevation/Accretion	A	B	C	D	E
2006-07-28	E (cm)	181	166	166	177	152
	A (cm/a)	-	-	-	-	-
2007-09-22	E (cm)	204	189	187	189	158
	A (cm/a)	23	23	21	12	6
2008-08-16	E (cm)	215	200	194	202	162
	A (cm/a)	10	10	7	12	4
2009-08-20	E (cm)	225	210	204	214	168
	A (cm/a)	10	10	10	13	6
2010-08-18	E (cm)	233	216	211	226	176
	A (cm/a)	8	6	6	12	8
2011-08-10	E (cm)	239	221	216	238	183
	A (cm/a)	5	5	5	13	6
2012-08-16	E (cm)	243	222	219	248	187
	A (cm/a)	4	1	3	10	4

instrument. The elevation of embankment dike is constant and as standard objects. Therefore, annual elevation changes of five sites along the section indicated the changes of sedimentation rates (Table 1).

The accretion process was very quickly because of the concave coastal settings (Fig. 1b). The cores of A, B, C, D and E indicated that in the early few years the sedimentation was very high and maximum sediments layer reached to 23 cm because of the storm surge in 2007; After 2009 the annual sedimentation rates in the salt marsh area decreased to below 10 cm/a (Fig. 4). In the inner part of the triangle-shaped tidal flat, the sandy mud accreted in Sites A, B and C from the year of 2007 to 2009. The record of strong storm surge event of March 22–23, 2007 severely influenced the study area.

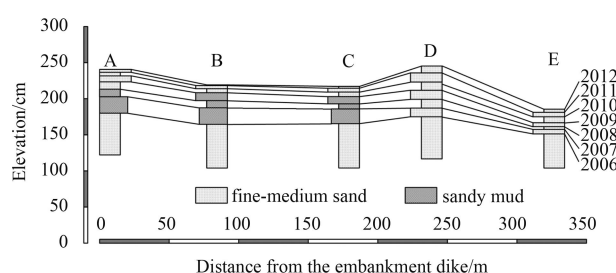


Fig. 4. Annual accretion in the tidal flat from 2006 to 2012.

3.3 Salt marsh evolution

After the embankment finished in December of 2006, the salt marsh in the triangle-shaped area experienced the complex process of changes. There are two stages for the evolution of the salt marsh. The first stage is the expansion of salt marsh on the bare tidal flat. And the second stage is the degradation of the salt marsh vegetation, the reason is that the covering of the sand sheet transported by the over-wash from the adjacent lower sandy tidal flat. But sediment is constantly silting thickening for tidal flat beach surface.

The species of the salt marsh is dominantly composed of the *Spartina Alterniflora Loisel*. On September 22, 2007 the percentage of the salt marsh coverage was less than 10% (Fig. 5a), and the groups of the *Spartina Alterniflora Loisel* were dispersedly distributed on the sandy mud tidal flat (Fig. 5a). Earlier researches indicated the individual *Spartina Alterniflora Loisel* was characteristic with the rapid reproduction. Seeds and rhizomes were the main reproduction vegetative forms (Gallagher et al., 1984; Plyler and Carrick, 1993; Davis et al., 2004; Wang, 2011). With the expansion of the salt marsh, the ground was almost fully covered with the marsh plants, except for the tidal channels, in August of 2011 (Fig. 5b).

In the triangle-shaped study area, the percentages of the salt marsh coverage were about less than 10%, 40%, 90% (all estimated during field investigation) in the sandy mud tidal flat in 2007, 2008 and 2009, respectively, in the central part of the salt marsh, which indicated that the reproduction of the salt marsh was rapid. One interesting finding in the study area was the decline of the salt marsh along the zone between the salt marsh and the sand spit in 2011. Sandy sediment from the sand spit moved to the salt marsh edge and covering part of the salt marsh. Hence, the salt marsh coverage increased with the sandy mud accretion and shrunk with the landward movement of the sand spit in a few years in the study area. In 2011, the sand spit was about 0.4–0.5 m higher than the salt marsh in the southern edge of the study area. The salt marsh edge was covered by the sand from the sand spit (Fig. 6).

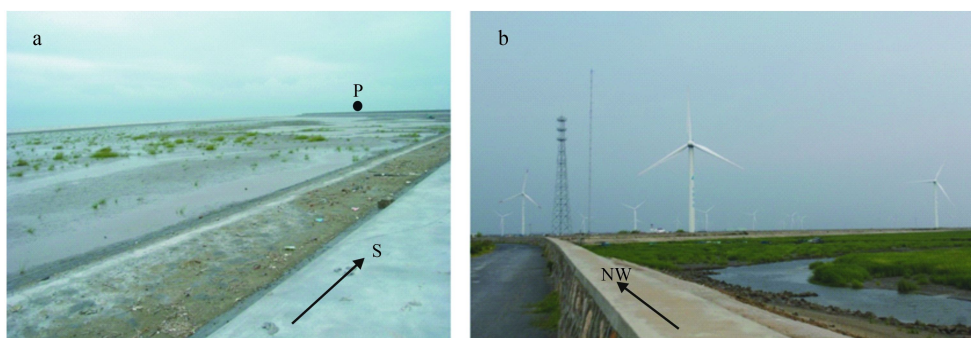


Fig. 5. Salt marsh coverage evolution in the study area.

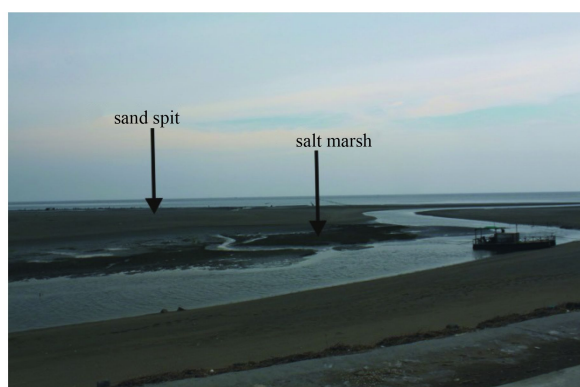


Fig. 6. Sand spit and salt marsh in the southern part of the study area (photo on August 16, 2008).

3.4 Grain size changes in Core YH

Using the grain size analysis results of Core YH, the vertical changes of the grain size parameters were shown in Fig. 7. In the bottom of Core YH the sediment type is sandy silt, and indicated the quickly accretion after the sea dike construction in the end of 2006. With the coastal longshore bar enlargement and the landward sediment movement in the study area the upper part of Core YH was composed of medium sand and fine-medium sand layers, which indicated the sand sediments covered the edge of the salt marsh (Fig. 6).

3.5 Interaction of the physical and biological processes of the tidal flat-salt marsh system

In the study area, the embankment dike finished in 2006. The first response of the tidal flat was the physical sedimentation ac-

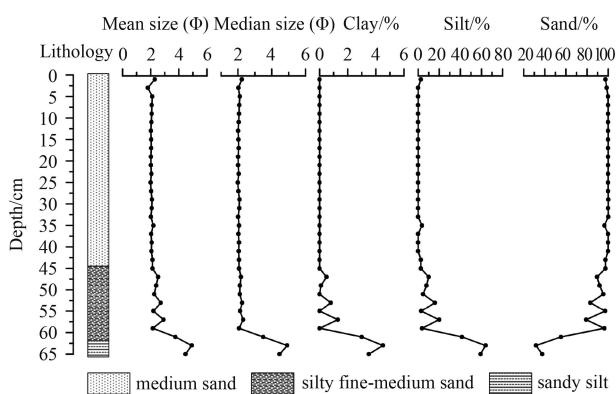


Fig. 7. Vertical changes of the grain size parameters in Core YH.

celerated in front of the dike. The triangle-shaped tidal flat with the concave artificial coast was suitable for the accretion of sandy mud. The sandy mud tidal flat was rich in nutrients and benefit for the growth of the salt marsh. The soil of mud is best for reproduction of *Spartina Alterniflora Loisel* (Allen, 2000). Because of the rapid reproduction of the *Spartina* plants, the percentage of the salt marsh coverage extended from less than 10% in 2007 to 90% in 2009 quickly in the central part of the triangle-shaped tidal flat with sandy mud deposits. At the outer edge of the triangle-shaped tidal flat was a sand spit developed after the embankment finished. During the time of storm surges and extreme wave with flood tide, the breaking surf zone was located in the outside of the sand spit and the over-wash brought sandy sediments into the triangle-shaped tidal flat. Thus, the surface of the edge of the triangle-shaped tidal flat was composed of the medium sand, which is not suitable for the reproduction of *Spartina Alterniflora Loisel*. With the landward movement of the sand spit, the salt marsh shrunk in the study area.

4 Discussion

4.1 Factors controlling the tidal flat-salt marsh ecosystem changes

4.1.1 Human activities

Human activities are rapidly changing the coastal environment through embankment, huge nutrients and sediments discharges from the river basin (Turner et al., 1996; Wolanski and De'ath, 2005). The embankment and reclamation in the study area plays important role for the tidal flat-salt marsh eco-environment changes. The concave artificial coast is suitable for the deposition of fine sediments. There are two water gates in the embankment finished in 2006 (Fig. 2). During the high tide time the sea water come into the aquaculture ponds, and during the ebb tide the water gates is the channel sometime discharging water from the polder. So in the seaside of the water gates, the erosion channel developed on the triangle shaped tidal flat with the intensified marine dynamics and no mud deposited and salt marsh cover in 2006. The study area was the typical tidal flat with salt marsh and bare tidal flat before the coastal embankment in 2006. However, coastline turned into the type of concave after construction of the dike. By contrast, embankment changed the coastline to concave type, and sediment accumulation was easier than before. Human activities, e.g., the construction of the dam, not only change the physical process of sedimentation, but also impact the biological processes of the salt marsh expanding. The water gates are the channel of transporting seeds from the original salt marsh in the polder to the triangle-shaped tidal flat. In the process of the original salt marsh in the polder changing to

aquaculture ponds, the fragments of the stems of the *Spartina Alterniflora Loisel* plant is also transported to the study area and reproduction in the tidal flat.

4.1.2 Storm surge, wave, tide and coastal current

Storm surge, wave, tide and coastal current are the main marine dynamics, which vary rapidly. In a short term period, the morphological change, erosion and accretion in the tidal flat or sand beach are sensitive to the marine dynamics (Wright and Short, 1984; Yang et al., 2003; Anthony et al., 2005; Masselink et al., 2006; Quartel et al., 2008). In the study area the morphological and biological changes are rapid on a small scale. Under normal conditions the tide and the wave bring sediments from the lower tidal flat to the tidal flat in front of the embankment dike, which result in the formation of the long shore bar migrating to the coast. The long shore bar in the study area coincided with the coastal current. The sand spit extends to the south-east direction corresponding with the Subei Coastal Current. Hence, the sediment source is not from the estuary of the Changjiang River, similar to the situation for in the north branch of the Changjiang River (Xie et al., 2013). On the other hand, siltation thickness of sediment was larger due to the storm surge in 2007 and reached to 23 cm/a.

4.2 The reproduction rate of *Spartina Alterniflora Loisel* in the muddy tidal flat

Reproduction of *Spartina Alterniflora Loisel* is primarily vegetative, but seed production also plays an important role. Rhizomes from a single plant spread outward in all directions, creating circular clones that eventually coalesce to form large extensive patches or meadows (Gallagher et al., 1984; Plyler and Carrick, 1993). The seeds in the muddy tidal flat grew and distributed dispersedly indicated the sexual reproduction was the important way of reproduction. Other studies have shown that biomass of *Spartina Alterniflora Loisel* had significant variations in deferent tidal flat habitats and different seasons (Chen et al., 2005; Leonard and Crof, 2006; Darby and Turner, 2008; Ren et al., 2010). In the study area the salt marsh mostly composed of *Spartina Alterniflora Loisel* expanded rapidly. According to the annual changes of the salt marsh coverage changes, annual expanding rate of the salt marsh coverage was above two times with that in the earlier year.

4.3 The implication of the small tidal flat-salt marsh evolution

In China, although wetland is little in area, its ecosystem service value was $26\ 737 \times 10^8$ RMB per annum, which was about one third of China's total value of ecosystem service (Chen and Zhang, 2000). In China, in recent years, efforts have been made to restore the coastal ecosystem including the salt marsh. With the development of urbanization and industrialization along the coastal region in China, the reclamation and landfill activities along the coast of China come in to a rapid development period. A report by the China Council for International Cooperation on Environment and Development (CCICED) showed that 57% of the country's coastal wetlands had disappeared since the 1950s, largely due to land reclamation. On the basis of development projects approved by the government, another 5 800 square kilometers of coastal area would be lost by 2020, eating away the remaining coastal wetlands (Qiu, 2011). How to find a balance between the reclamation and the protection of coastal wetlands is an urgent task in present China. In this study, the local scale tidal flat sedimentation and evolution of *Spartina Alterniflora Loisel* community in the background of embankment was dis-

cussed and the results indicated that the specific distribution of embankment dike (the artificial concave coast) would be benefit to the salt marsh evolution. So the rational planning of the embankment should be concerned. The best design of the embankment should be in a concave shape and benefit to the following growth of tidal flat and salt marsh.

5 Conclusions

Changes of the tidal flat and salt marsh coverage in the study area were rapidly varied after the construction of the coastal embankment, which created a suitable space for sedimentation and the salt marsh growth. The salt marsh coverage experienced two stages. The first stage was the expansion of salt marsh from bottom up corresponding with the sandy mud accretion of the tidal flat. And the second stage was the shrink of the salt marsh coverage corresponding with the landward sand movement from the longshore bar, which later became a sand spit connecting the dike. In the study area the tidal flat covered by salt marsh experienced the continuous accretion. Annual sediments rates varied sharply from a few centimeters to maximum 23 cm/a in the year of 2007. The salt marsh coverage annual expanding rate in the muddy tidal flat was above two times of the coverage than that of the previous year. The short and small scale changes of tidal flat accretion and salt marsh indicated the complexity controlled by the coastal physical and biological processes. The annual processes of tidal flat accretion and salt marsh changes in this study are the response and adaption to the coastal dynamics in the background of embankment.

This study provides an example of the small scale tidal flat processes and salt marsh changes in front of the embankment. The systematic analysis of tidal flat response to reclamation should be studied in the future. The rational spatial planning of the sea dike will benefit for the coastal salt marsh restoration.

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