Dynamics Characteristics and Topographic Profile Shaping Process of Feiyan Shoal at the Yellow River Delta

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Abstract: Feiyan Shoal is a sub Yellow River Delta, which was formed from Jan. 1964 to May 1976, when the Yellow River entered sea via Diaokou Channel. Since the terminal reach shifted to Qingshuigou channel in 1976, Feiyan Shoal has been experiencing severe erosion and retreat. This paper explains the evolutionary characteristics of the typical profile of Feiyan Shoal from the perspective of dynamical force and sediments' characteristics. All this is on the basis of the data of topographic profiles observed since the 1970s and the samples of hydrology and sediments collected in situ in Apr. 2004, the analysis of the retreating distance, and the tidal and wave friction velocity distribution. Feiyan Shoal topographical profile has experienced a course of "fast erosion and retrogression - slow eroding modulation - fluctuate triggering change" in recent 30 years, which is also the gradual disappearing process of the delta front. The different intensity of sediment erosion resistance is the main reason for the erosion speed changes. Due to the hydrodynamic force changes, the water depth range of maximum retreating distance and between erosion and progradation became shallow. It indicates that the storm tide will still be the triggering force of seashore topographic profile evolutions in the future.

Keywords: The Yellow River Delta; Feiyan Shoal; erosion; wave and tidal co-action; topographic profile; sediment transport

Introduction

In the 20th century, about 70 % beaches were in recession while the silting coasts only accounted for less than 10 % in the world [1]. 24.4 % of the coasts eroded severely in the U.S.A. [2]. Coastal erosion has become a world problem, especially the erosion and retreating speed of mud and silt coasts, which is up to hundreds of meters each year, is much faster than that of rocky coasts. The sediment load of the Yellow River and the Yangtze River has been declining sharply since 1980s in China, and a large number of coasts are in erosion [3-9]. Since the Yellow River course changed to Shandong province and entered into the Bohai Sea in 1855, the modern Yellow River Delta between Bohai Bay and Laizhou Bay has formed, whose area is 9 380 km^2, including a land area of 5 880 km^2 and an underwater area of 3 500 km^2 [9]. Meanwhile the terminal reach shifts frequently. Up to now, it has greatly changed for 10 times, and correspondingly 10 sub-delta lobes have been formed [10, 11]. The abandoned sub-delta lobes

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without sediments supply fell into the state of eroding one after another. Coast erosion not only causes the disappearance of land resources, but also influences the development of resources along the coast. For example, Shengli Oil Field (the second largest oil field in China), located in Feiyan Shoal, has numerous oil wells and oil field facilities severely destroyed because of the coastal erosion. The economic benefits of Shengli Oil Field have suffered from direct loss. The area of coastal wetland is reducing constantly, and it weakens the ecological function of the littoral zone. The present status and reasons for coastal erosion are paid close attention to by numerous scholars [6, 7, 12-15]. However, past studies mainly focus on the space variation of the silting and eroding and the time-varying. Based on the field data, this paper discusses such dynamics as tide and wave, the characteristics of sediments, how the dynamics influence the silt and erosion process, and the shaping process of the profile, which provides some useful theoretical foundation for coastal protection engineering.

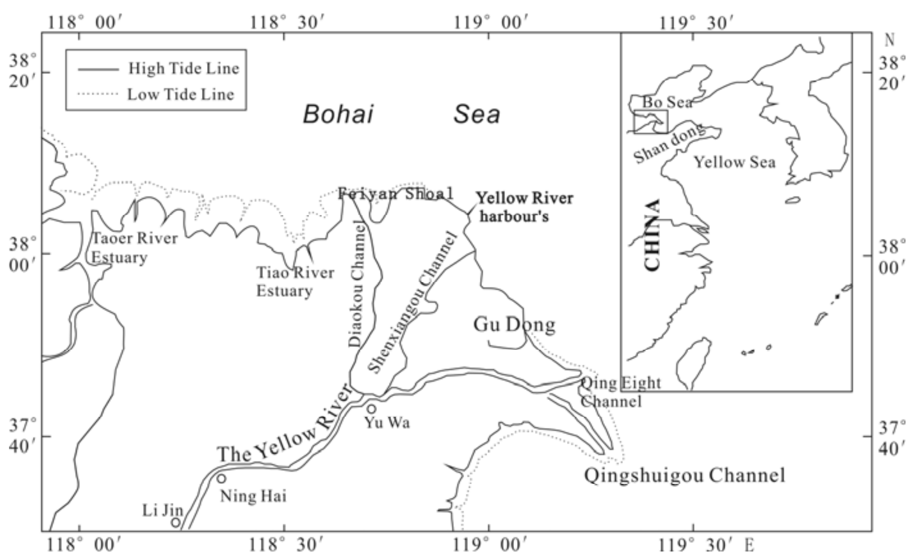

Fig. 1 Map of the Yellow River delta

1 The study area and data

1.1 The study area

Located at the northern Yellow River Delta (Fig. 1), Feiyan Shoal is a sub-delta lobe that was formed by about 71×10^8 t sediment from the Yellow River from Jan. 1964 to May 1976 [16, 17]. The coastal profile has the three zones of delta geomorphological structure, which consists of pro-delta, delta front and subsided delta platform [6]. The terminal reach shifted to Qingshuigou channel in 1976, and the effect of sediment diffused from the Yellow River is limited, and it’s diffusion influence extension toward north can’t exceed the Yellow River Harbour [18, 19]. Besides, sedimentation flux caused by sediment diffused from Qingshuigou channel is below 1 mm/a [20]. Therefore, after Feiyan Shoal was abandoned, there was no influence of sediment supplied by the Yellow River basically. With the hydrodynamic action of tide, wave and storm tide etc., the seashore eroded constantly with the sediment diffusing to open sea. It is found that about 35.9 % of the sediment from the Yellow River, amounting to 40.67 × 10^8 t from 1964 to 1973, diffused to the open sea probably [16]. It indicates that on condition of sufficient sediment supplied from the river, sediment diffusing ability is up to 4×10^8 t/a in this sea area. It is inevitable that seashore erodes in circumstances of strong sediment diffusion and little sediment supply.

1.2 Data

Since the 1970s, coastal profiles have been observed regularly in the sea area of the Yellow River Delta by the Hydrology and Water Resource Investigation Institution of the Yellow River. The observation is arranged and implemented after flood season of the Yellow River generally. A temporary tidal level station is set up to revise the measured water depth during the observation period. Typical profiles data are selected from those of 1976, 1977, 1980, 1985, 1989, 1990, 1991, 1993, 1996, 1998, 1999, 2002, altogether amounting to 12 years (the positions shown in Fig. 2). The profile data is interpolated with the step water depth of 0.1 m, and the range of the water depth is decided to be 2.4 - 17 m due to the difference of water depth range in different years.

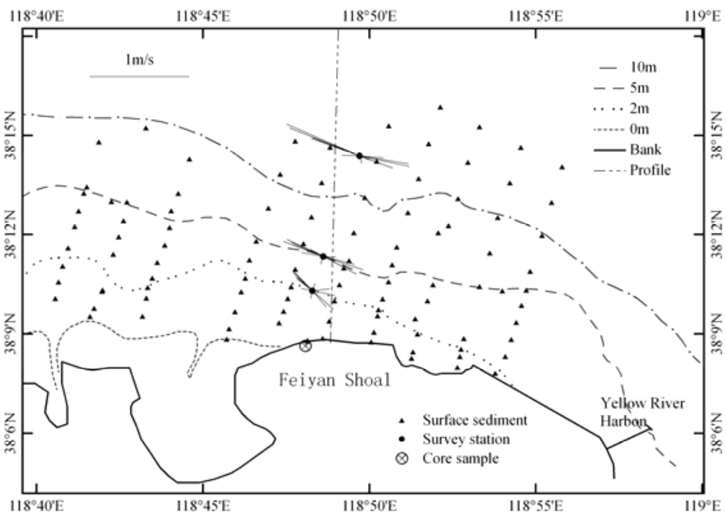

Fig. 2 Vector graph of field tidal flow and survey sites in the Feiyan Shoal

From Apr.19th to Apr. 27th of 2004, hydrology and suspended sediment surveys were carried out at 3 sites synchronously in the studied area. Surficial sediments and a core sample had been collected (the sites are shown in Fig. 2). The hydrology data was measured by the SLC-9 type current meter manufactured by Chinese Marine University. Sampling depth of surficial sediment was less than 5 cm. The core sample was collected from the high tidal flat (118°48′08″E, 38°08′37″N) by a truck borer, whose length was over 30 m with the diameter of 9 cm. It was cut into 1m sections and kept in PVC pipes hermetically. Sediment grain size was obtained by LS100Q laser particle size analyzer, manufactured by

American Coulter Corp., whose testing range is 0.000 4 - 0.9 mm and the error is less than 1 % for the same grain size. With a straight uni-directional flume with high speed flow at the Environmental Fluid Mechanics Laboratory in the Institute of Mechanics, Chinese Academy of Science in Beijing, the core sample was utilized in erosion resistance testing of undisturbed soil.

2 Hydrodynamic characteristics near shore

2.1 Tide flow

The tidal character is controlled by the amphidromic point of M_2 component tide (E119°04′, N38°04′) in the Northeast. The flood direction is westward. From the amphidromic point westward, the tide range increases, and the largest tidal flow speed reduces gradually. The max tide range of spring tide was 1.42 m in April 2004 (the lunar calendar was 1^{st} March), and the minimum was 0.65 m. The vector graph of field tidal flow (Fig. 2) shows that the tidal flow in the form of rectilinear current is parallel with isobaths approximately. Suppose that the flow velocity is 0 at the 0 m water depth approximately, thus in a certain range, the deeper water depth, the higher tidal flow velocity. By means of the logarithmic equation the transverse distribution of the tidal-period and depth average velocity is:

$$\overline{V_y} = 0.1445 \times \mathrm{Ln}(y+1) - 0.0014 \quad (1)$$

Where y is water depth, $\overline{V}_y$ the tidal-period and depth average velocity at 'y' water depth, correlation coefficient R^2=0.9914.

During the tidal period T, the relation between the tidal-period and depth averaged velocity $\overline{u}$ and maximum depth-averaged velocity $\overline{u}_{max}$ can be expressed as the equation below:

$$\overline{u} = \frac{1}{T}\int_0^T \overline{u}_{max}\sin(\omega t)dt = \frac{2}{\pi}\overline{u}_{max} \quad (2)$$

Assuming that the flow is steady, the depth-averaged flow can be described as:

$$\overline{u} = \frac{1}{n}R^{2/3}i^{1/2} \quad (3)$$

The maximum bed shear stress by current can be expressed as $\tau = \rho gRi$.

$$\text{So} \quad U_* = \sqrt{\frac{\tau}{\rho}} = \sqrt{gRi} \quad (4)$$

Through equation (3) and (4), the correlation between $\overline{u}$ and friction velocity U_* is:

$$\frac{\bar{u}}{U_*} = \frac{1}{n} R^{1/6} g^{-1/2}$$

Using water depth ‘d’ to stand for hydraulic radius R, $U_* = n\sqrt{g} d^{-1/6} \bar{u}$ (5)

Where n is 0.025.

Based on the field data, the maximum friction velocity of tidal flow can be calculated, and the result is shown in Fig. 3.

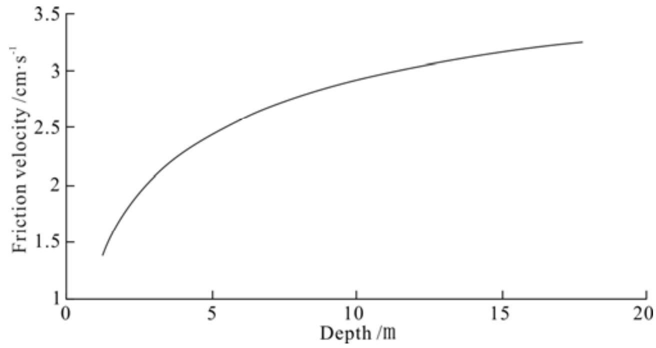

Fig.3 Distribution of friction velocity of tidal flow

2.2 Wave

The Bohai Sea is a semi-closed inland sea, and communicates with open sea only via the Bohai strait. The tidal wave is difficult to enter the Bohai Sea from Huanghai Sea, so the wind wave is preponderant in studied region. The direction of the strongest wave is NE-NNE, and that of the second strongest wave is N-NNW. The wave characteristics are listed in Tab.1 (Wu, 1989). The storm with 5.3m wave height and NE direction was observed at 14 m water depth on Nov. 22nd, 1985.

Tab.1 Wave Feature in the Northern Yellow River Delta

Direction	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total / %
$0 \le H < 0.5$	2.3	1.8	2.7	1.5	2.4	3.5	3.5	3.5	3.7	4.6	4.3	3.3	3.9	3.1	5.2	1.8	51.1
$0.5 \le H < 1.5$	2.1	1.9	4.0	2.5	4.1	2.3	3.8	2.1	1.4	1.7	0.9	0.9	1.0	1.4	2.5	3.7	36.3
$1.5 \le H < 3.0$	0.4	1.4	3.4	3.0	1.2	0.7	0.8	0.2	0.2	0.7	0.1	0.1				0.2	11.8
$3.0 \le H < 5.0$	0.1		0.2	0.1		0.1											0.5
Total / %	4.9	5.1	10.3	7.1	7.7	6.6	8.1	5.8	5.3	6.4	5.3	4.3	4.9	4.5	7.7	5.7	100
$H_{l/10}$ / m	3.0	2.5	3.1	3.3	2.5	3.0	2.8	2.6	0.8	2.0	1.5	2.4	1.1	1.0	1.4	2.1	

The relationship between average period and average wave height at Yellow River Delta can be expressed as [22]:

$$\overline{H} = 0.0338\overline{T}^2 \text{, convert } \overline{H} \text{ to } H_{1/10}\text{: } \overline{T} = 3.82\sqrt{H_{1/10}} \quad (6)$$

When it propagates from deep sea to nearshore, due to the shallow water effect, refraction and bottom friction action, the wave gradually declines.

$$\frac{H}{H_0} = K_r K_s K_f \quad (7)$$

Where K_r is shoaling coefficient, K_s is refraction coefficient and K_f is bottom friction coefficient. According to micro amplitude wave theory, K_c and K_s can be expressed respectively as follows:

$$K_r = \frac{\cos^{0.5}\alpha}{\left[1 - \sin^2\alpha \, th^2(kd)\right]^{0.25}} \quad (8a)$$

$$K_s = \left[\frac{2ch^2(kd)}{2kd + sh(2kd)}\right]^{0.5} \quad (8b)$$

When $h/L_0<0.1$, K_s should be calculated based on Cnoidal Wave Theory [23]:

$$K_s = K_{s0} + 0.0015\left(\frac{h}{L}\right)^{-2.8}\left(\frac{H_0}{L_0}\right)^{1.2} \quad (8c)$$

Where $L = \frac{gT^2}{2\pi} th(kd)$ and $k = 2\pi/L$

K_f is calculated in accordance with the Bretschneider-Reid method [24]:

$$K_f = \frac{H_2}{H_1} = \left[1 + \frac{64\pi^3 f H_1 X K_s^2}{3g^3 T^4 \sinh^3(kd)}\right]^{-1} \quad (8d)$$

Where X is the horizontal distance from water depth H_1 to H_2. L is wavelength; T is wave period; d is water depth; f, the frictional coefficient, is 0.015.

In a wave period, the peak value of bed shear stress is [25]: $\tau_w = \frac{1}{2}\rho f_w u_w{}^2$

Linear wave theory shows that the maximum horizontal velocity of water particle at the bottom can be expressed as:

$$U_{max} = \frac{\pi H}{T\sinh(kd)}$$

The maximum friction velocity at the bottom:

$$U_{*max} = \sqrt{\frac{\tau_{max}}{\rho}} = \sqrt{\frac{f_w}{2}} \times U_{max} \tag{9}$$

The wave propagates to nearshore, enduring a remarkable topographical bottom friction effect. Feiyan Shoal experienced an erosion process of 26 years from 1976 to 2002, and the topography has changed enormously. The process of wave damping varies on different topographies, and distribution of the friction velocity takes on different characteristics. Therefore, based on the topography data of 1976 and 2002, the wave friction velocity is calculated separately. The result is drawn in Fig. 4. It is found that the wave friction of the two years is dissimilar regarding the wave height over 1 m. The energy consuming speed on the topography of 2002 is slower than that of 1976, and the peak of friction velocity moves landward; the friction velocity in 2002 is greater than that in1976 only at the shallow area; at the area with water depth more than 4 m, friction velocity in 1976 is greater than that in 2002.

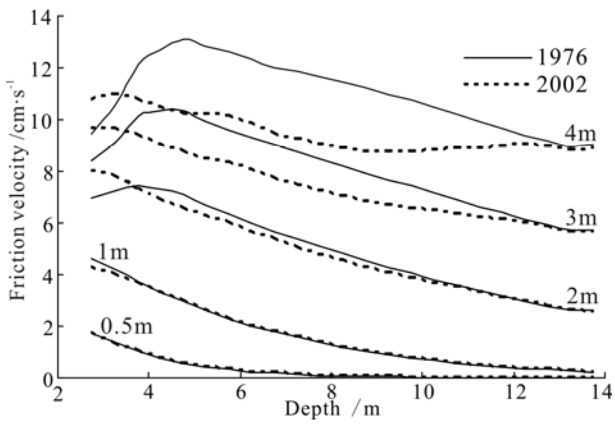

Fig.4 Distribution of near-bed wave generated friction velocity

2.3 Interaction of wave and tidal current

Vector sum principle is used for calculating the interaction of wave and tidal flow. Suppose at the moment of the largest tidal flow, the maximum wave-current friction velocity is calculated. Take the topography of 2002 for example (Fig. 5): in shallow water the wave-current friction velocity is higher than that in deeper water. When the coming wave height is 4 m, the maximum value is over 12 cm/s. At the moment of slack tidal flow, the maximum wave-current friction velocity is the same to that in Fig. 4. The velocity of tidal flow declined after 1976 [26], and the majority of wave friction velocity in 1976 is higher than that in 2002 in the depth range of study. Thus the friction velocity of wave-current is considered to have decreased since Feiyan Shoal was abandoned in 1976.

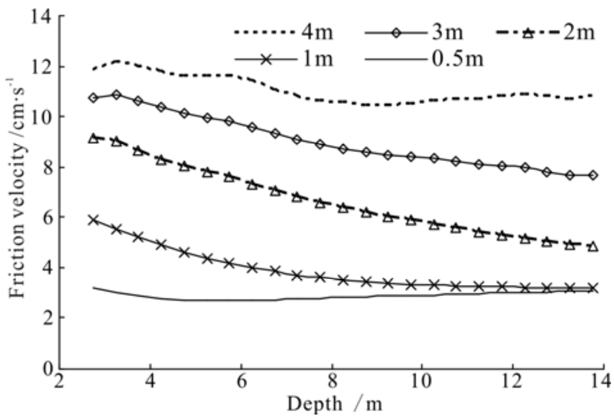

Fig.5 Distribution of tidal and wave co-action generated friction velocity

3 Sediment characteristics

3.1 Newly deposited sediment

High sediment concentration and concentrating sediment transport result in the rapid deposition of sediment from Yellow River at the river mouth, which is a high water content and low soil compactness delta deposition body. When Feiyan Shoal was abandoned in 1976, the shallow layer of seashore was newly deposited sediment. The dry bulk densities of deposits in the top 0.5 m give an average of 0.750 g/cm^3, and those of deposits buried below 0.5 m are 0.908 g/cm^3 on average [17]. The relation between threshold shear stress and dry bulk density adopts the result of sediment test of top layer done by Huhe (Huhe Aode. Scouring equipments of scatula originalis soil and surficial sediment of Yangtze Estuary Deepwater Channel, 1998)

$$\tau_c = 2.069 \times 10^{-9} S^{2.71}$$

Here S is dry bulk density. The threshold shear stress of deposits in the top 0.5 m is 0.128 N/m^2, and that buried below 0.5 m is 0.908 g/cm^3, which are 1.13 cm/s and 1.47 cm/s after being conversed to threshold friction velocity respectively.

3.2 Surficial sediment at present

One hundred and four surficial sediment samples were gathered in Apr. 2004. According to 2 m, 5 m and 10 m water depth, they are divided into 4 groups, and the characteristics are listed in Tab. 2.

Sediment grain becomes finer and finer from nearshore to sea, which is the result of seashore erosion and sediment sorting. Nearshore erodes and the fine sediment is transported to deep sea, then coarser grain sediment is left on the nearshore. The sorting coefficient increases within 10 m, while it decreases at deeper than 10 m. This phenomenon is due to the fact that at depth of about 12 m is the boundary of delta front and prodelta of sub-Yellow River Delta [15]. The deposit is mainly made up of fine sediment during the period of delta construction. Part of the fine sediment that is eroded from nearshore silts up in areas deeper than 12 m. Therefore, the deep sea area lacks the component part of coarse particle all the while, thus the sorting coefficient is better. From Tab. 2, it is found that the deeper water depth is, the finer the grain is, and the greater threshold friction velocity for sediment motion is.

Tab.2 Surficial sediment character in 2004

Depth rang / m	0-2	2-5	5-10	10-14
Median diameter / um	75.1	59.3	52.8	47.7
Sorting coefficient	1.73	1.90	1.95	1.79
U^*_c / cm.s^{-1}	1.60	2.18	2.87	3.51

3.3 Core samples

Shi et al. [27] have utilized the core samples to do erosion resistance testing of undisturbed soil. It is found that threshold friction velocity of sediment is 3.6 - 3.8 cm/s, which is at the 3 - 7m depth of the core samples. Due to the compaction effect of sediment above, sediment compactness of over 7 m increases, water content declines, and viscous force between fine sediments enhances, and correspondingly, threshold friction velocity of sediment also increases. It increases sharply to 10 - 14 cm/s at depth of 9 - 13 m of core samples, which is the largest part in the depth range of study.

4 Profile change

4.1 General features

Before Feiyan Shoal was abandoned, the coastal profile had the three zones of delta geomorphological structure, which was composed of pro-delta, delta front and subsided delta platform. From beach to sea, the slope of profile was soft-steep-soft, which was the typical topographty of reversed ‘S’ shape. After course diversion in 1976, the coast eroded and retreated backward rapidly (Fig. 6).

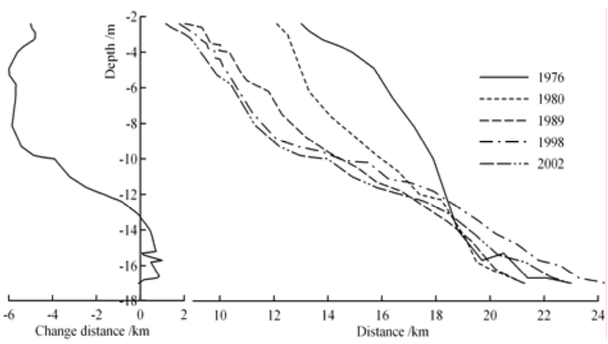

Fig.6 Erosion of coastal profile and corrosive distance

(The left is the eroding or silting-up change distance in the 26 years, and the right is the process of profile change)

From 1976 to 2002, the erosion volume per unit width in the depth range of 2.4 - 17 m is over 4.7 × 10^4 m^3. The depth range of the most backward distance is 3.5 - 9.5 m water depth; the depth-average value amounts to 5.7 km, with 319 m/a; the depth of the most backward is 4.9 m, amounting to over 5.99 km. It can be seen in Fig.6 that with water depth deeper than 9.5 m, the retreat distance reduces. At 13.3 m depth, it becomes net silt-up. The amount of silt-up is minor in the 26 years, just about 1km. The profile slope becomes softer and softer, from 0.150 % in 1976 to 0.098 % in 2002. With the reduction of the pro-delta's horizontal distance and the gradual disappearance of the delta front, the shape of profile changes to sunken from upper-convex.

4.2 Period characteristics

Based on the character of profile change, the profile change can be divided into 4 periods. Fig. 7 and Tab. 3 show that the profile erodes backward at a high retreating speed before 1980. In this period, the profile retreated intensively and integrally. The max retreat took place at 6.2 m water depth, which was up to 2 940 m; while there was a soft silting at the depth range of 13.5 - 14.6 m, which was less than 100 m. In the period of 1980 - 1989, the profile development started the process of upper erosion and down silting. The threshold depth between erosion and silting was about 14.2 m, and the depth of the maximum retreating distance became shallower with retreating speed slowing down. The years of 1989 - 1998 were a fluctuating adjustment period. The most backward distance at each depth hadn't exceeded 1.2 km in the 10 years. Water depth 10.1 m was the threshold depth of this period. The amount of progradation at deep water was high; all the progradation distance below 11.7 m water depth was over 1.2 km, and what's more, the progradation distance was 3.0 km at 17 m depth. After 1998, the profile transferred to integral erosion again, and the erosion amount at deep water was higher than that at shallow water.

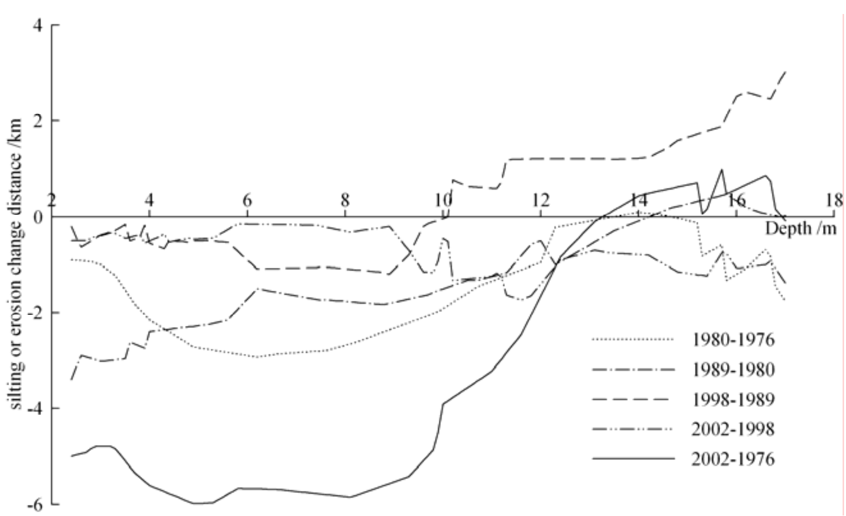

Fig.7 Change of profile in different periods

Tab.3 Distance change of recession and progradation at different depth

Water depth	1976-1980		1980-1989		1989-1998		1998-2002	
/ m	Amount / km	Average / m	Amount / km	Average/ m	Amount / km	Average/ m	Amount / km	Average/ m
2.5	-0.91	-228	-3.13	-348	-0.43	-43	-0.5	-135
5	-2.74	-685	-2.28	-253	-0.5	-50	-0.46	-125
10	-1.92	-480	-2.07	-230	-0.04	-4	-0.45	-112
13	-0.09	-23	-0.59	-66	1.20	120	-0.73	-182
16	-1.20	-300	0.34	38	2.51	251	-1.08	-270

5 Discussions

5.1 Relationship between sediment erosion resistance and profile retreat speed

5.1.1 Weak erosion resistance at earlier periods of abandonment

The sediment from the Yellow River deposited near bank constantly, which resulted in the new incompact deposition without the cover load of sediment above. The dry bulk density of deposit in the top 1m was under the average value of 0.908 g/cm^3 [17]. Erosion resistance of the incompact deposition was very low, whose threshold friction velocity was not over 1.47 cm/s. It was easy to be started and transported by the tidal flow. At the earlier periods of abandonment, the seashore entered the state of quick erosion, and the profile retreated backward wholly. In the first 4 years, the retreating speed was the fastest with 735 m/a at 6.2 m water depth.

5.1.2 Increase of sediment resistance

After the new incompact sediment of shallow water eroded and disappeared, the sorting effect made the sediment resistance strengthen. On the other hand, sediment resistance enhanced with deposit compaction increasing along depth gradually. It is found that the threshold friction velocity of core sampling sediment of the range of 3 - 7 m depth was about 3.7 cm/s, which was similar to the threshold friction velocity of surficial sediment in 2004. The tidal friction velocity was lower than the sediment threshold friction velocity in 2004, so it is concluded that the erosion active force became interactive of wave and tide. Wave is to move the sediment and tidal flow is to transport sediment mainly. With sediment resistance enhancing, the main eroding force changed to the interaction of wave and tide from the single tidal flow, while the speed of retreating slowed down gradually.

5.1.3 Vertical differences of deposition and profile shaping

The net retreating curve of profile takes on the figure of ‘soup ladle’ during the period of 1976-2002 (Fig. 7). About 9.5 m depth is a mutation point; the backward distance is over 4.8 km at shallow water, retreating amount is reduced to 3.8 km suddenly at 10 m depth, and then declines gradually until it turns into the net silt. According to the erosion resistance test of the core samples, from 9 m depth the clay content increases rapidly, and water content declines, and the threshold friction velocity increase to 10 - 14 cm/s that is the max value of the core sample. The depth ranges of high sediment resistance and the retreating distance change are consistent.

5.2 The illustration of profile shaping

The coastal erosion profile shaping process has the following characteristics: (a) The eroding speed slows down gradually from the initial periods of abandonment; (b) The depth ranges of max backward distance in different periods become shallower and shallower; (c) The topographical profile presents a phenomenon of up erosion and down accumulation, and the slope becomes soft gradually.

The intense erosion has made the slope of the profile soft. The softer topographical slope is, the longer distance wave propagates to nearshore from a certain water depth, and the energy consuming is more dispersive, and the corresponding wave friction velocity decreases, and the peak value wave friction velocity moves landward, and the depth range of the max retreating distance becomes shallower gradually. The sediment at the depth range of max retreating distance can be scoured by the interaction of tide and wave whose wave height is less than 1 m, while the scoured sediment needs the interaction of tide and wave whose wave height is over 1.5 m with the frequency of just 12.3 % at about 12 m water depth area. The deeper the water is, the less probability that the sediment starts up is. The coarser part of suspending sediment is easier to deposit when hydrodynamic force becomes weaker. The finer the sediment is, the greater difference value of threshold velocity and non-depositing critical velocity will be. Thus, the finer sediment can be transported farther. When the amount of deposit is more than the erosion amount, the profile takes on net accumulation. Thus, the profiles have the characteristic of up erosion and down accumulation in the eroding process.

Due to the storm tides took place in 1992 and 1997 at Yellow River Delta, the silting increased in regions of over 10 m water depth by a large margin in the 1990s. When the storm tidal takes place, on condition of backwater with high hydrodynamic energy, the materials of land area above low tidal flat are corroded and carried to the deep sea. It often makes the deep water area deposit fast, which happens frequently at the beach of the Yangtze River [28]. The fast storm tidal deposition is also of low soil compactness, which will be adjusted after the storm. The change of surficial sediment may result in the trend change of profile development: so the profile entered a new period of corroding again after 1998.

5.3 The threshold depth and dynamic strength

The hydrodynamic force varies, so the threshold depth is not the same at different areas. The stronger hydrodynamic force is, the deeper threshold depth is [29]. As illustrated in Section 4.2, the profile development has experienced 4 periods. At the period of incipient abandonment and the storm tides later, the profiles retreated rapidly, and the threshold depth did not exist. In the later two periods, the main character of profile retreating process was up erosion and down accumulation. With the weakening of hydrodynamic force, the threshold depth also reduced from 14.1 m to about 10 m water depth. It is concluded that if the hydrodynamic force is far greater than the sediment resistance, the profile retreating process takes on the character of eroding integrally; if the hydrodynamic force and the sediment resistance is comparable, the profile retreating process takes on the character of up erosion and down accumulation, and the threshold depth exists.

6 Conclusions

The essence of strong erosion process of Feiyan Shoal is that sediment transports and redistributes and delta deposition dwindles constantly under the control of marine dynamic. The development characteristics of topographical profile are decided by hydrodynamic force and sediment factors. The following are the characteristics of coastal profiles retreating at Feiyan Shoal:

a) At the initiative period of abandonment, the low sediment resistance of new incompact sediment is the main reason for the coastal profiles eroding and retreating backwards at a high speed. As the surficial sediment resistance strengthens, the main erosion action force changes from tide to the interaction of tide and wave. The feature of profile shaping becomes up erosion and down accumulation from integral erosion, and the retreat speed declines gradually.

b) With the decrease of tidal flow nearshore and landward distribution of peak value distribution of wave bottom friction velocity, the retreat distance and critical depth change less and becomes shallower gradually.

c) The high energy of storm tide may change the developing trend of profiles. It is still the triggering force of seashore topographic profile development in the future.

Acknowledgements

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黄河三角洲飞雁滩动力特征与地形剖面塑造

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摘 要：飞雁滩是 1964 年 1 月至 1976 年 5 月黄河尾闾由刁口流路入海形成的黄河亚三角洲。自 1976 年黄河改走清水沟入海后，飞雁滩岸滩发生强烈侵蚀后退。以 20 世纪 70 年代开始的地形固定断面观测资料、2004 年 4 月现场水文泥沙及沉积物取样资料为基础，地形剖面后退距离作为统计参数，并根据实测资料计算了潮流和波浪底摩阻流速的横向分布，从动力分布和沉积物结构方面解释了飞雁滩典型剖面的变化特征。30 a 来飞雁滩岸滩地形剖面经历了“ 快速后退侵蚀——慢速调整——波动触发 ”的变化过程，这也正是其三角洲前缘侵蚀逐渐消失过程。沉积物抗冲性强弱是剖面蚀退速度变化的主要原因，水动力条件的变化改变了不同阶段的地形剖面最大蚀退量水深范围与闭合深度。风暴潮仍是今后海滩地形剖面演变的触发动力。

关键词：黄河三角洲；飞雁滩；侵蚀；波流共同作用；地形剖面；泥沙输移