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Modern changes of tidal troughs among the radial sand ridges in northern Jiangsu coastal zone*

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Abstract Using satellite images taken on different dates, GIS analysis of aerial photos, bathymetric maps and other field survey data, tidal troughs and major sand ridges in the northern Jiangsu coastal area were contrasted. The results show that there have been three types of movement or migration of tidal trough in this area: (1) Periodic and restricted, this type of trough usually developed along the beaches with immobile gully head as a result of the artificial dams and the swing range increased from gully head to the low reaches, so they have been obviously impacted by human activity and have longer swing periods; (2) Periodic and actively, this kind of trough, which swung with a fast rate and moved periodically on sand ridges, were mainly controlled by the swings of the host tidal troughs and hydrodynamic forces upon tidal sand ridge and influenced slightly by human constructions; (3) Steadily and slowly, they are the main tidal troughs with large scale and a steady orientation in this area and have slow lateral movement. The differences in migration mode of tidal trough shift result in different rates of migration and impact upon tidal sand ridges. Lateral accumulation on current tidal trough and deposition on abandoned tidal troughs are the two types of sedimentation of the tidal sand ridges formation. The whole radial sand ridge was generally prone to division and retreat although sand ridges fluctuated by the analysis of changes in talwegs of tidal troughs and shorelines of sand ridges.

Keyword: radial sand ridges; tidal trough migration; remote sensing; GIS; Northern Jiangsu Province

1 INTRODUCTION

There are about 10 sand ridges formed in an area of more than 20 000 km^2 within a 90 km long belt from the east to the west along the northern coast of Jiangsu Province, and extending continually outwards in NNE and NE (Fig.1). At the same time, under the strong actions of tidal current there are extraordinary well developed tidal creek systems, which can be divided into 4 grades by their scales and the effects on the development of radial sand ridges (Zhang et al., 1992).The formation and development of these sand ridges or tidal troughs have received great attention from many researchers and significant progress has been made in the study of the radial tidal sand ridge system (Li et al., 1981; Zhu et al., 1986; Zhang et al., 1992; Huang et al., 1998; Wang et al., 1999; Zhang et al., 1999; Li et al., 2001; Liu et al., 2004; Wu et al., 2007). The main tidal troughs, such as Xiyang, Chenjiawucao, Kushuiyang, Huangshayang, Lanshayang and so on, distributed irregularly between radial sand ridges are the dominating factor during the change of radial sand ridge system (Zhang et al., 1992; Wang et al., 1999; Yang et al., 2003). Both the speed and direction of the tidal trough migration control the stabilization and activity of sand ridges directly. One important characteristic in this area is that the most of sand ridges are submerged and only a small proportion are above sea level, so it is inconvenient to ravel the changes of the whole sand ridges. The characteristics of these changes, however, can be provided indirectly by detecting the migration of tidal troughs.

In the study area there are abundant secondary tidal troughs distributed diffusely along the beaches

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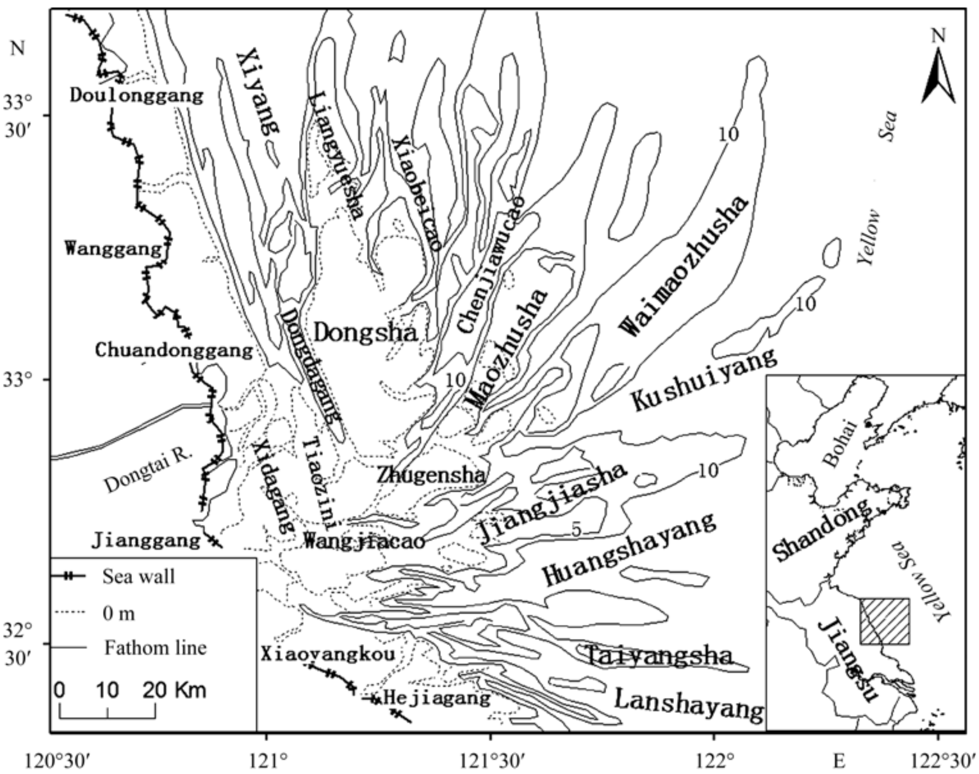

Fig.1 The location map of research area (modified from Zhang et al., 1992)

in the west of the Xiyang trough and the inner Wangjiacao trough, while others lie on off shore sand ridges in small scale. Most of the beachy secondary tidal troughs in this area have a main same characteristic showing that the head of trough is quite stationary (tidal barrier), but the middle and lower reaches swing freely. There are significant variations between the basin areas of tidal troughs. As a result of its growth and change that control the regional frame work of geography, these tidal troughs have great influence on the evolution of the whole Tiaozini sand ridge, which is not only the centre of the radial tidal sand ridges, but also the joint other large sand ridges such as Dongsha, Zhugensha and Jiangjiasha (Zhang et al., 1992). In this paper, we present our study results of the Oscillatory motion of the secondary beachy tidal troughs, which are adjacent to the Tiaozini sand ridges and have biggish effect on its development, using satellite images from different dates. The migrations of major troughs and sand ridges were also examined using aerial photos, SAR images and bathymetric maps. Finally, the development characteristics of the whole tidal sand ridges were analyzed.

2 MATERIALS AND METHOD

The configurations and changes of beaches, troughs and tidal sand ridges above sea level can be recognized by high resolution satellite images acquired at low or near low tides. Multi-period satellite images taken at low or near low tides, aerial photos from the 1980's and bathymetric maps (1:100 000) from the 1960's and late 1970's were collected. Additionally, 5 SAR images from 1995 to 2000 (Table 1) were used as auxiliary data for detecting the tidal trough system in radial tidal sand ridges. All these bathymetric maps, aerial photos and satellite images were analyzed using Map/info.

Table 1 Parameters of collected satellite data

No.	Time of image	Type of image	Resolution (m)
1	1988-04-09	Landsat TM	30×30
2	1993-12-19	Landsat TM	30×30
3	1996-04-07	SPOT	20×20
4	1997-05-20	Landsat TM	30×30
5	1999-01-20	SPOT	20×20
6	2000-03-09	Landsat TM	30×30
7	2007-01-24	Landsat TM	30×30
8	1995-07-08	ERS-1	26×30
9	1997-11-14	Radarsat-1	28×35
10	1998-07-08	Radarsat-1	25×28
11	1999-12-05	ERS-2	26×30
12	2000-09-10	ERS-2	26×30

Geometrical calibration and contrast of images in different dates and from different sources require choosing a proper number of ground control points (GCPs) and a well-proportioned distribution pattern of GCPs that can has a significant influence on the calibration precision (Huang et al., 2002). There are only a few clear GCPs available in the east and north of the study area because of rapid formation and deformation of sand ridges. However, there were many easily distinguished GCPs in the west side of the studying area. These control points with a lopsided distribution pattern make it difficult to well calibrate the images. The differences of root mean square (R.M.S) errors resulted from the two distributions of GCPs could reach two or three times. Using geometrical continuity of Landsat image and locating GCPs accurately by field validation, geometrical calibration of the images was well made and experimental results showed the adaptability of this method.

Additionally, error would be also possible when the sand ridge outlines were compared between different images acquired at different tides, but the minor discrepancies caused by different tidewater height in each image can be neglected without influencing the overall net bias on analysis quality.

3 RESULTS

The changes of secondary tidal troughs distributed diffusely on the beaches and the changes of the sand ridges for analyzing the shift tendency of the whole radial tidal sand ridges, were analyzed using the satellite images from 1988 to 2007 combined with bathymetric maps (1960's–1970's) and data from field surveys.

3.1 The Chuandonggang tidal trough

It branched at the upper reaches of tidal trough from 1996 to 1999. The middle reach had moved 1.4 km southward from 1988 to 1993, and then continued moving southward, reaching its most southerly point in 1996. After that, the tidal trough retreated significantly (2 km) northward to a position further north than that in 1988 during 1999 and continued to move northward before 2000, but it retreated back to the position of 1988 in 2007. The range of swinging from the north to the south was about 2.5 km in total during these years, while the trough mouth kept basically the same but narrowed.

3.2 The Chuanshuigang tidal trough

Middle and upper reaches of this tidal trough wiggled significantly southward with the increased curvature from 1988 to 1993, and then moved northward slowly. The position of the tidal trough in 2007 was different from that of 1988 by several hundred meters. The swinging period of tidal trough went on about 15 years. The estuary has moved continually northward from 1988, and reached its most northerly position in 1999, with a position 2.5 km further north than that in 1988. The channel of the tidal trough moved 5–6 km southwards in 2000 when curvature developed rapidly. The swinging period of the tidal trough was estimated to be about 20 years with a scale of 6–7 km (Huang et al., 2001). The trough mouth retreated westward about 2.5 km in landscape orientation from 1993 to 2007 with the coastline near the Chuandonggang moved seaward 4–5 km. The differences of swinging period and scale between tidal trough middle and lower reaches showed the impact of the main tidal trough-Xiyang trough on its branches.

3.3 Liangduohe dam estuary tidal trough (The Sishenggang trough)

The Liangduohe Dam tidal trough (Sishenggang trough) is an approximate N-S direction tidal trough which separates the radial tidal sand ridges from the mainland. The middle and lower reaches shifted approximately 5 km northwestward between 1949 and 1970, 5 km northwestward during the 1970's, and an approximate 4 km northwestward between 1979 and 1981, showing an accelerated shifting rate towards the northwest. After it united the Dayazigang tidal trough in 1980 and the Chuanshuigang tidal trough estuary in 1984 (later separated) along with human activity in 1980's, the shifting rate of trough from the Dam was slowed down (Zhang et al., 1992). There was an obvious cut-off event in the upper reach of the tidal trough between 1988 and 1993 with a maximum 2 km eastward shift, and then retreated about 800 m until 1996 when the trough began to branch off (Fig.2). The trough swayed eastward and westward from 1993 to 2007, while the position of the trough head also varied slightly in different images and showed no extension trend from 1988 to 2000; however it retreated northward about 3 km from 1988 to 2007 as a result of the artificial coastline went seaward and the trough head was cut off. Some changes in position were caused by the differences in the space resolution of images or tide condition. The middle reach of the trough swayed eastward and westward in a range of 300–800 m from 1988 to 2007.

The lower reaches of the trough moved straight into the Xiyang trough. The extension direction of lower reaches changed and its channel was divided. The centerline of the trough mouth moved 4.17 km northwestward from 1988 to 1993. It shifted back northeastward and the mouth moved 2 km southward from 1993 to 1997. It moved northeastward to a position similar to that of 1988, and it then divided into a major south branch and a smaller north branch in 1999. In 2000 the two branches merged and the trough became narrower and increasingly bended, and up to 2007 the centerline of the trough mouth moved westward 2.5 km compared with that of 1993 going with the artificial coastline went seaward 3−5 km from Liangduohe dam to Chuangshuigang area. Between 1988 and 2007, the lower reach of trough swayed in a fan-shaped area with the width of about 5 km from south to the north (Fig.2).

3.4 The inner Wangjiacao trough-Xiaodengzhuang-gang tidal trough

The inner Wangjiacao trough shrank since 1984. The estuarine channel was captured by the Xiaodengzhuanggang trough in 1987 and became one branch of this tidal trough system (Zhang et al., 1992). The lower reaches of the inner Wangjiacao trough splayed out in multi-channel flow into the sea in 1988. Channels of the tidal trough were small and labile in scale. At the same time the Xiaodengzhuanggang moved laterally westward and the ability to transport water and sediment from the western Tiaozini beach flat was lost. The small tidal troughs merged into a wide channel extending in the north-south, northwest-southeast directions at the upper reaches and the head extended significantly northward in 1993 (Fig.3). The position of the trough in 1996 was similar to that in 1993 with a small-scale shift southwestward. Upper and middle reaches of tidal trough shifted significantly westward and meandered in 1999. Furthermore, the tidal trough deviated westward and the whole sandbank shrank in 2000. The tidal trough was narrower than that in the 1990's and the trough head retreated southeastward with some branches died away in 2007.

The Xiaodengzhuanggang tidal trough extended in the north to northwest direction and combined with the Sishenggang and Xidagang trough. The tidal trough swung slightly from the west to the east, but the trough head moved mainly in the northward and southward directions from 1988 to 2007 (Fig.3). The tidal trough extended toward the northwest to the north during the middle and low tides in 1993. During 1996 the trough became smaller and narrower and shrank further with multi-channel entering the sea in 1997. Images showed that in 1999 the Xidagang tidal trough had three branches: the east

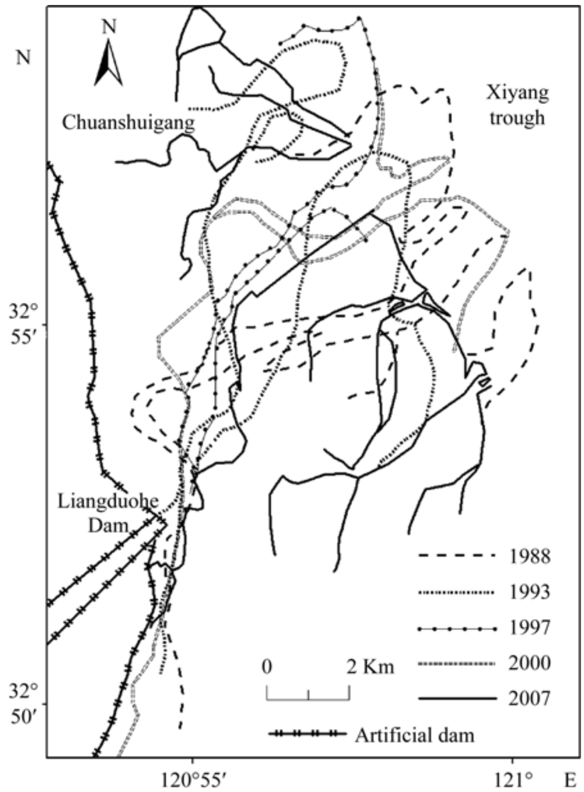

Fig.2 The sketch map of migration of the Sishenggang trough interpreted from TM Images between 1988 and 2007

tidal trough, middle tidal trough and west tidal trough. The middle branch extended southwestward and become closely positioned to Tiaoyugang trough network, which had extended northeastward and they tied together in 2000. While the west and middle trough shrank and only the east trough was still hearty with moving sideward to the east a long way in 2007.

3.5 The southern Xidagang tidal trough

From 1988 to 2007, the trough distribution pattern had changed greatly, including the width, length, number of tidal troughs and even the outspread direction (Fig.3). Beijianzi sand ridge, in northern Tiaozini sand ridge, showed another scenario of evolution. The main body of the Beijianzi detached from Tiaozini in 1988, and a new sandbank-the Xibeijianzi sand ridge formed on its southwest. In addition, many minor sandbanks formed in the west and southwest of the Beijianzi and merged into the Beijianzi sand ridge later. At the same time, the head of Tiaozini sand ridge retreated and moved southwards significantly. Hence the main Xidagang tidal troughs merged eventually, combining the south branch which joined the Tiaoyugang during a wide tide in 1993. The Xidagang trough moved eastward in 1997, in west of which there appeared a new sand

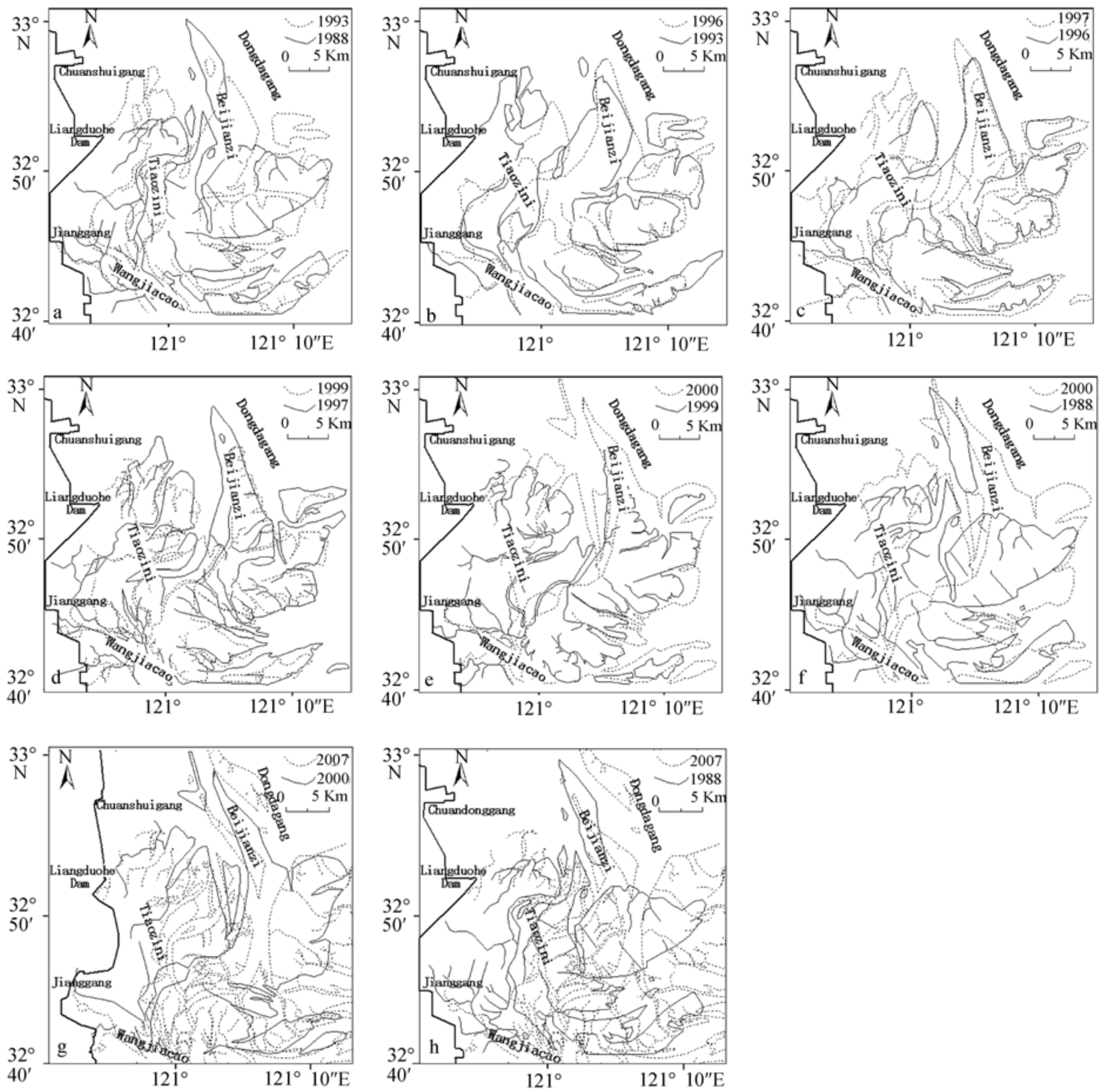

Fig.3 The changes of tidal troughs in Tiaozini sandbank interpreted from TM images between 1988 and 2007

ridge which was separated from beach flat by a small tidal trough in the S-N direction. Therefore the width of the Beijianzi narrowed, the length increased and it extended northward as the change of the Xidagang trough. The small sandbanks on both sides also disappeared because of further erosion in the west part of Beijianzi, the width of Beijianzi sandbank became much narrower. At the same time, its head retreated southwards, leaving only a small sandbank by 1999. On the other side, both the east and west sides of the Xidagang trough extended, especially the east side, so the width of tidal trough increased and the south of it divided into three tidal troughs.

3.6 The radial tidal sand ridge

(1) The area and the number of sand ridges

In the 1960's there were 17 offshore sand ridges (above sea level in bathymetric maps), and each of them with an area of 10.0 km^2 or less and the average area was 6.4 km^2. During the 1970's, the number of ridges increased to 21 with an average area of 5.8 km^2. The average area decreased 10% from the 1960's to the 1970's (Huang et al., 2001). Although the total number of radial sand ridges in Northern Jiangsu Province increased from 41 in the 1960's to 61 in the 1970's, the total area of sand bank decreased by about 230 km^2.

(2) The range of sand ridge

The shoreline at low tide on the northern and the eastern Northern Jiangsu offshore radial sand ridges retreated 20 km both south and west from the 1900's to 1979. The northern edge of Dongsha sand ridges retreated obviously to the south, about 5–6 km between the 1960's and the 1970's.

(3) The changes of small sandbanks

In the 1960's the area above sea level of the Xiaoyinsha sand ridge in the Xiyang trough was 3.2 km^2 and that of the Piaoersha was 0.9 km^2, but during the 1970's they became submerged shoal. Total areas of the Sanyazi and the Liangyuesha sand ridge were 6.4 km^2 and 60.0 km^2 in the 1960's, and 15.9 km^2 and 43.9 km^2 in the 1970's, respectively. The area decreased at an average rate of 1.2 km^2/yr, but the rate reduced to 0.2 km^2/yr from 1988 to 1993. The whole position of radial sand ridges in Northern Jiangsu moved obviously southwards.

4 DISCUSSIONS

The modern directional tendency of the radial sand ridges depends on three factors: (1) Prevailing storms which erode peripheral sand ridges; (2) Tidal currents which take sediments towards the center of sandbank (Huang et al., 2001); (3) The migration of tidal trough. Besides the three, human activities have become a major impact.

4.1 The influence of human construction on the movement of tidal trough

Examining the development of Sishenggang clearly demonstrates the great impact of human activities on the evolution of tidal troughs. The Sishenggang tidal trough was active, which moved towards northwest as a whole since 1949 and the fastest movement was from 1949. The data from 1970 to 1979 also showed a constant increase in length. Five rocky spurs in a line on soft-base were built in the south near the Liangduohe Dam (the south branch), and one spur was built in 1980 at the north side near the Liangduohe Dam (the north branch) when the Sishenggang trough united the Dayazigang trough near the Liangduohe Dam. After the completion of these constructions, the activity of the Sishenggang trough was weakened obviously, especially in the upper reaches. The southwest part of Tiaozini sand ridge joined with the Tiaoyugang trough in 1974. After the event the tidal trough and beach topography were adjusted to balance out the local hydrodynamic conditions.

It is clear that the natural processes have influenced on the trough and slowed down its movements at the upper reaches of Sishenggang. On the other hand, human activities also had great influence on the lower reaches and resulted in slower swing. For example, compared to the position of the tidal trough in Sept. 1979, the position in Feb. 1980 was 3 km further towards northwest. The tidal trough, however, retreated towards southeast by 2 km after 10 months, moved northwestward more than 3 km till June 1981 (Zhang et al., 1992). The speed of the trough change was between 2.4 km/yr and 6 km/yr with the trough shifting periodically.

4.2 The styles of tidal trough change

Increasing curvature and channel divulsion are two causes of trough change in the study area. The changing length of the waterway below the Liangduohe Dam controls the swing styles of the tidal trough. The total length of tidal trough below the Dam increased from 8 km at the beginning of Dam construction in 1972 to 15 km by 1988. The capability of transportation of water and sediment declined as curvature and length of trough waterway increased and the slope gradient decreased. After the middle reaches lost 1.4 km in 1996 because of a cut-off, the length of tidal trough shortened to 12.3 km. A cut-off occurred again in 1999, reducing the length to 10.5 km. Meander curvature increased again during 2000 with the trough length increasing to 13 km in TM image while the length decreased about 1.5 km in 2007 with the curvature decreasing, but the head went southwards about 2 km. The swing of the middle and lower reaches was periodic in the case of tidal trough with stable gully head. The swing cycle of the lower reaches was longer than that at the middle reaches. For example, the cycle for the middle reaches of the Chuanshuigang trough was 15 years, while it was about 20 years for the lower reaches.

There was another trough shift style differently from the trough movements mentioned above although the scale was small. The gully head was able to swing freely and the impact of human activities was undersized on troughs evolution, but the entire movement process was rapid alternation of advances and retreats. At Erfengshui in the Tiaozini sandbank near Jianggang Town，the swing range off the coastline was about 3.7 km from 4.8 km to 8.5 km (Zhang et al., 1992).

From the shoreline change profiles taken from TM images on the west bank of Xiyang Trough, Dongsha sand ridge and Tiaozini sand ridge, lateral movement was another transformation characteristic of the main tidal trough in this area. The west bank of Xiyang trough retreated from 1988 to 2007; however, the east beach moved eastward, thus the Xiyang Trough broadened. Erosion rate decreased from the north to the south and small deposition happened at the south of Chuandonggang with changes of the small tidal trough mouth on the west bank of the Xiyang Trough. Concurrently, The movement pattern of the east bank of Xiyang Trough (the west bank of Dongsha sand ridge) was in a low erosion rate between 1988 and 1993 and followed by an increased rate between 1993 and 2007 in the northern Dongsha sand ridge. The southern Xiyang Trough showed a contrary way. The shift of shoreline in southern Dongsha sand ridge was great at the beginning as the eastward movement was significant and slowed to an insignificant rate later (Fig.4).

From 1988 to 1993, the southeast Dongsha sand ridge retreated shoreward to 5 km. A new sandbank 5–6 km from the east to the west and 4–5 km from the south to the north formed in the south of Dongsha sand ridge. The Dongsha sand ridge moved southwards and was intersected and shrank as a whole. As a fact, the northern part retreated while the south advanced with an average moving range of 1–2 km between 1993 and 2000, but the south retreated northward to a position further north of that in 1993 by 2007 (Fig.4). Some small sandbanks

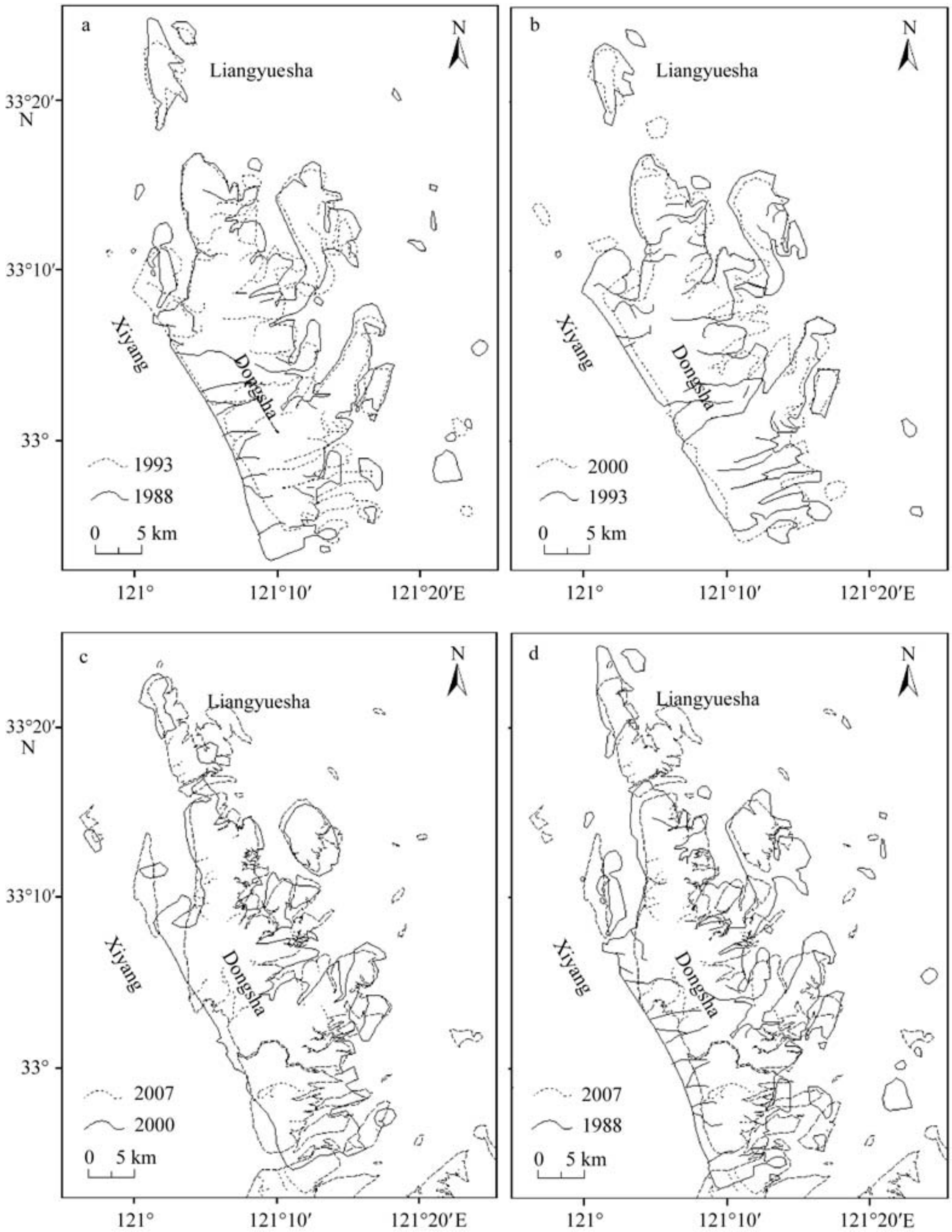

Fig.4 Shoreline changes of the Dongsha sandbank interpreted from TM images between 1988 and 2007

partitioned from the east side of Dongsha shrank and finally disappeared. The Tiaozini sand ridge showed obvious change due to the influence of tidal troughs which lay in the southern Xiyang and Tiaoyugang troughs; however, as a center of sediment accumulation, it extended as a whole.

As previously discussed, there were two main modes of tidal trough shift: curvature increase resulting in channel cut-off and lateral movement. Difference in migration mode result in different rates of migration and impact upon tidal sand ridges.

4.3 Analysis on the movement of the radial tidal sand ridge

From the results above, the area, the number and changes of the sand ridges show that the sand ridges have been atrophying. Field observations showed that the peripheral area of Dongsha sand ridge was being divided by new small tidal troughs which swung quickly. For example, an artificial structure staying on the sand ridge (near the Xiyang Trough) in the early 1980's lies in a branch of the Xiyang Trough now. Its foundation has been eroded down 4 meters in the last two decades, and the cemented ladder, which was buried in the sandbank previously, is now exposed in the air. The sand ridge has been also eroded and new tidal troughs moved quickly in the Dongsha sand ridge, even continually extended to the center of the sand ridge.

Although the radial sand ridges fluctuated, generally the trend was retreat. Evidence is the increasing width of the tidal troughs; the talwegs constantly moved eastward and the gully head extended southward. Furthermore, the east and the west part of sidelines of the Dongsha sand ridge had a tendency of bringing together, which resulted in sand ridge retreat. In the 1960's, the Xiaobeicao, Chenjiawucao troughs and so on, which lie to the east side of the Dongsha with a north-south direction extended constantly toward the inner Dongsha sand ridge significantly and their talwegs moved westward near the shoreline. Some deep troughs crossed through the upper part of the large sand ridge (such as the Maozhusha) and sand ridges in the edge side, such as Tiaozini, tended to be divided into small ones by stretching at the gully head of tidal troughs. The east, northeast and north parts of each radial sand ridge moved toward the center at a various range resulted in the radial sand ridges retreating landwards as a whole.

5 CONCLUSIONS

The results show three movement methods of tidal trough in the study area and these movements can be described as: (1) periodic and restricted, (2) periodic and actively, and (3) steadily and slowly. The majority of the first type was secondary tidal troughs and they usually developed in the estuary of the artificial channel with dams which were used to protect them from flood tide. Their shifts were influenced by both natural and human factors. The gully head of this kind of tidal troughs was immobile and the swing range increased from the gully head to the lower reaches, hence, the swing period was also longer. One instance is that the swing period in the middle reach of the Chuanshuigang was about 15 years but that at estuary was about 20 years with a swing range of about 6–7 km. The second type was also secondary troughs, which were mainly controlled by the swings of the host tidal troughs and hydrodynamic forces upon tidal sand ridge and influenced slightly by human constructions. This kind of trough swung with a fast rate and moved periodically on the sand ridge. The third type of trough has large scale, slow movement and a steady orientation.

Although these radial sand ridges are still accreting deposition, the whole sand ridge was prone to division and retreat. In so doing the number of sand ridge was constantly increasing, but the total area actually decreased. The atrophication speed of sand ridge tended to weaken from the 1960's; the rapid swing of the tidal troughs and erosion were main styles resulting in sand ridges to separate, whereas peripheral sand ridges moved obviously to the center of the whole radial tidal sand ridge system. The movement modes of the tidal troughs play an important role in the sedimentary environment of radial sand ridge and their interrelationships merit further study.

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