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SEDIMENT TRANSPORT OF SEA-ENTERING WATERWAY IN THE CHANGJIANG ESTUARY

Caixing YUN, Qing HE & Yuanye WANG
State Key Laboratory of Estuarine and Coastal Research, Shanghai, China, 200062

Abstract: As is known to all, the mouth bars reach is a key section to the deep waterway improvement in the Changjiang Estuary with sediment erosion and deposition. Evolution of the mouth is very complicated i as it is located at the mixing area and affected by many factors such as interaction of runoff and tidal current, mixing of the salty and fresh water and sediment resuspension action by wave and current. On the basis of the evolution laws of the river channels in the Changjiang Estuary summarized, this paper centers on characteristics of bed-load transportation, mechanism of suspended sediment deposition and resuspension and effect of sediment exchange between flat and channel on the waterway silting in the sea-entering from the South Channel to North Passage in the Changjiang Estuary, by using satellite remote sensing information and regional corrective analyzing of sediment composition. From this, the paper further expounds the theoretical basis of decision-making plan for the deep waterway improvement in the Changjiang Estuary.

Key words: Changjiang Estuary, Sea-entering waterway, the Basic Laws of Sediment Movement

1. APPLICATION SETTING

Located at the middle part of Chinese coast, the Changjiang estuary is a intersection point of the Changjiang River valley and the coastal economic zones (Fig.1). Since the 1990's,with acceleration of construction steps in the Pudong new area, in Shanghai as a big internationalized city, an across century project connecting to the international shipping, the deep waterway improvement in the Changjiang estuary had been put into operation on 27 January, 1998 at the same time of considering promoting the economic and social development of the Changjiang River valley and constructing Shanghai into the international economic, financial and trade center as soon as possible. The general target of construction is that under direction of the principle of combining realignment and dredging with reclamation, through efforts about ten years, the water depth of the sea-entering bifurcation from the south channel to the north passage in the Changjiang estuary will be increased to 8.5 m, 10.0 m and 12.5 m by stages from 6 m at present to meet the need of whole day in and out of the international fourth generation container ship and the need of entering into the channel by tide for 10 thousand tonnage cargo ship and the fifth and sixth generation container ships (Fig.2). In recent 10 years, based on comparison and selection of a lot of schemes, many scientists and engineering experts with a great deal of the theoretical and practice experience at home have chosen the section from the south channel to the north passage in the Changiang estuary as the sea-entering deep waterway. This new bifurcation formed in 20th century 50's has become a good waterway with the stronger carrying sediment capacity, good separating water and sediment state, a little silting amount at mouth and basically stable river state.

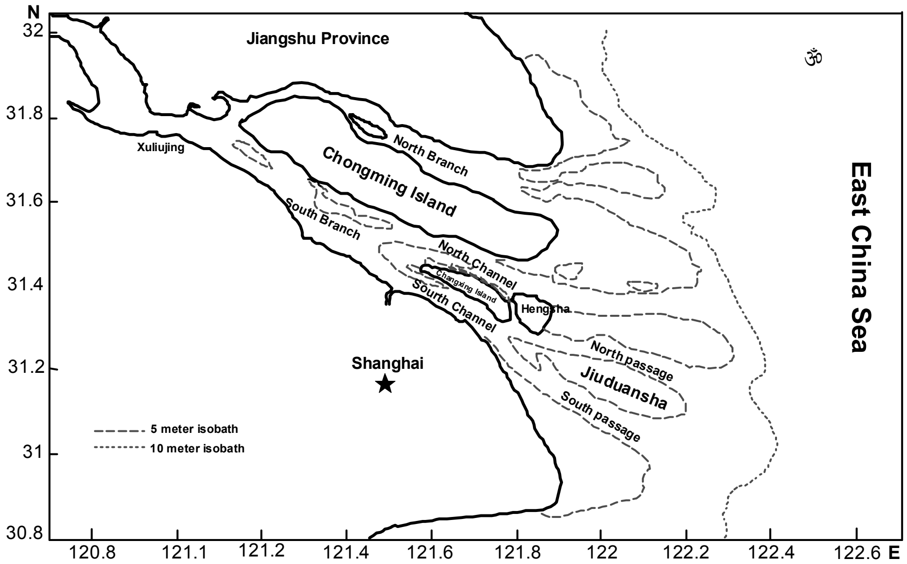


Fig. 1 The situation map of Changjiang Estuary, China

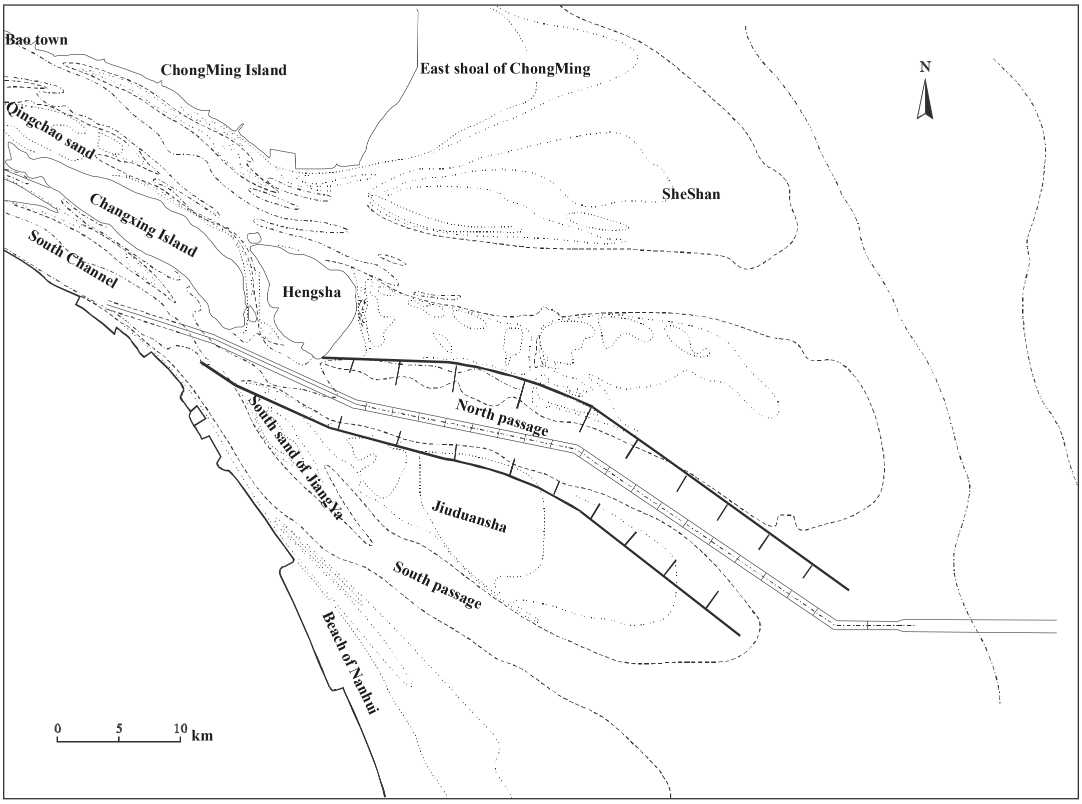


Fig. 2 Layout plan of Deep Water Navigation Improvement Project in Chang jiang Estuary, China

According to the improvement experience of the southwest waterway in the Mississippi estuary in U.S.A. and the actual situation of the Changjiang estuary, the implementation plan of the double guide dikes plus spur dike engineering will be used for the deep waterway improvement in the Changiang estuary. In the feasible study of the project there are three problems mostly concerned as follows

1. Where the vigor of the new bifurcation from the south channel to the north passage in the Changjiang estuary lies;

2. The desired results of the double guide dikes –spur dike engineering;

3. The possible effect of meeting of flood, astronomical spring tide and storm surge at the Changjiang estuary on waterway silting.

The heart of the three problems mentioned above is to clearly recognize the sediment movement laws in the process and suddenly silting at the river section of the mouth bars in the Changjiang estuary.

2. BED-LOAD TRANSPORTATION AND BED BIFURCATION

The early study of Wuhan University of Hydraulic and Electric Engineering shows that the pattern of sediment movement in the lower reaches of the Changjiang River and the estuary is dominated by suspension. That is to say, only 1% of 424.5 million tons of the annually averaged sediment discharge at Datong station transports to the estuary as a bed-load form. The grain size of the sediments ranges from 0.12 mm to 0.30 mm, that of the bed sediments in the southern branch of the Changjiang estuary and the main channel of the south channel ranges from 0.11mm to 0.15 mm. And the average grain size of the suspended sediment in the water body ranges from 0.01mm to 0.031 mm. In other wards, the suspended sediments are little involved in bed-forming process in the main channel of the finished-form channels in the Changjiang estuary.

During the feasible demonstration of the realignment plan of the sea-entering waterway in the changjiang estuary, the effect of the river changes in the upper reaches on the engineering section has been mentioned. Through analyzing the bed evolution data in recent hundred years, especially the alluvial and silting changes of the topography in the south channel and the northern and southern passages since 1958, it is discovered that the main factors causing unstability of the river channel are both bed-load transportation and cutting the beach by transversal gullies. And its form of expression is that the active sediments produce one after another at center bars and sand spits, with unstable down up movement of the division gap. The evolution results in becoming the double channels of the southern branch, the south and the north channels in the Changjiang estuary, which increases the differentiation of the dynamic axis of the rising and falling tide and the cutting bank ratio of the transversal throw.

The typical examples that bed-load transportation makes river bed bifurcate are the Ruifeng sand spit at the south channel and the southern sand sand of Jiangya at the diversion gap between the southern and northern passages in the Changjiang estuary (Fig.3 and 4). The silting period for the waterway in the south channel was between 1958 and 1972, and the sediments were mainly from the drastic changes of the central section in the southern branch. From 1959 to 1961 the Xincongming waterway at the western end of the Changxing Island developed toward the east and scoured stone and sand. And 660 thousand squaremeters of 670 thousand square meters of sediments scoured was silted in the channel of the south channel and the silt body, as a form of the Ruifeng sand spit, continuously down moved. After the Xinbaoshan channel to south of the central beach formed from 1962 to 1963, the central beach at the diversion gap between the south and the north channels retreated in succession at about 600 m of scouring velocity. About 0.604 billion m^3 of sediments scoured entered into the south and the north channels, and 0.320 billion m^3 in the south channel and 0.275 billion m^3 in the northern channel. Most of these sediments moved as a form of bed-load body, with 500-1500 m of bed-load velocity a year. Both development of the Ruifeng sand spit and forming of the southern sand of Jiangya are related to it. For example, since 1960 when the Ruifeng sand spit in the south channel was formed, the area and volume enclosed by 5 m isobath have increased by 1.3 times and twice respectively. The southern sand of Jiangya belongs to the central beach at the diversion gap between the southern and the northern passages, which had been formed since 1965. The area and the volume evolved by 5 m isobath increased to 53.98 km^2 in 1996 from 8.955 km^2 in 1971, and since 1995, the area and the volume of the sand body decreases gradually and the the average water depth maintains at about 2.5m(Table 1).

Table 1 The statistics of characteristic changes of southern sand of Jiangya

year	Southern sand of Jiangya					
	Average depth(m)	Aera (km^2)	Volume (m^3)	Annual variation of thickness (m)	Annual variation of area (km^2)	Annual variation of volume (m^3)
1988	2.82	50.35	141,987,000			
1989	2.82	52.34	147,598,800	0	1.99	5,611,800
1990	3.78	55.68	210,470,400	0.96	3.34	62,871,600
1991	3.25	55.91	181,707,500	-0.53	0.23	-28,762,900
1992	2.76	51.62	142,471,200	-0.49	-4.29	39,236,300
1993	3.33	55.1	183,483,000	0.57	3.48	41,011,800
1994	3.1	53.2	164,920,000	-0.23	-1.9	-18,563,000
1995	2.57	53.98	138,728,600	-0.53	0.78	-26,191,400
1996	2.56	52.93	135,500,800	-0.01	-1.05	-3,227,800
1997	2.49	45.88	114,241,200	-0.07	-7.05	-21,259,600
1998	2.49	45.88	114,241,200	0	0	-
1999	2.36	41.77	98,577,200	-0.13	-4.11	-15,664,000
2000	2.59	42.18	109,246,200	0.23	0.41	10,669,000

Note: negative represent increase of the water depth of the shoal face, decrease of area of the shoal face and volume decrease of sand body.

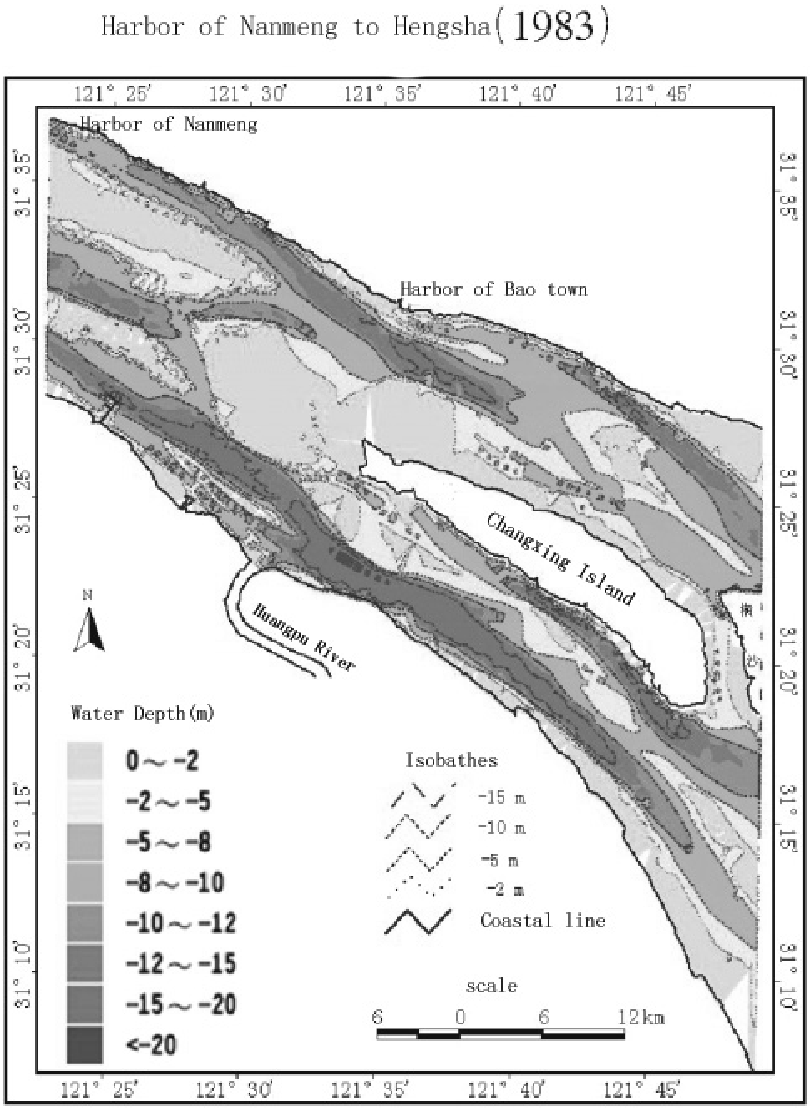


Fig. 3 The dune ridge distribution in the south channel of Changjiang Estuary, China

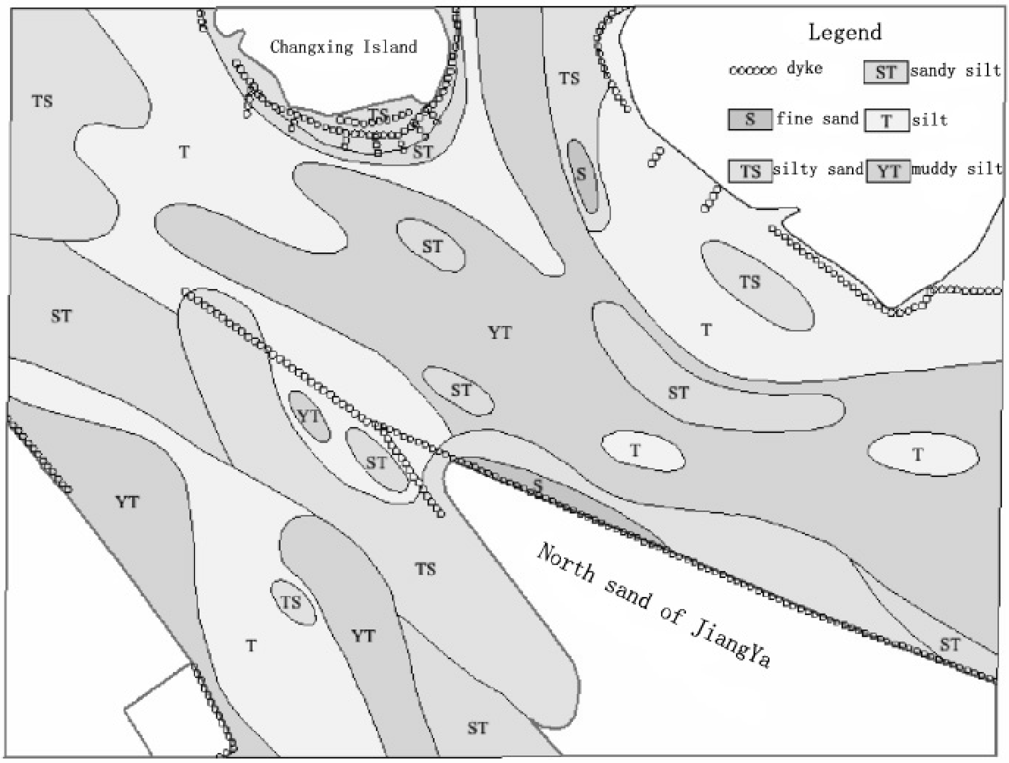


Fig. 4 The distribution of sediment types in bifurcation of south and north passages of Changjiang Estuary, China

The forming and development of the southern sand of Jiangya is the main source of the severe adjustment dividing water and sediments in the southern and the northern passages and that of failing of the sea-entering bifurcation in the southern passage. In 1965 the central part of the location of the southern sand of Jiangya was only a sand dune, with 0.0225 mm of grain size of the bed material. It, however, becomes a central beach continuously enlarged, and the grain size of the bed material coarsens to 0.15 mm, showing that the bed-forming action of the runoff in the Changjiang estuary has moved down. For the Tongsha shoal in the original southern passage, the grain size of the bed material has also continuously coarsened. In 1965 the average grain size was 0.006 mm, of which the fine sediments smaller then 0.01 mm took up over 65%. But in the bed material the coarse one increases, with 0.0115 mm of the median grain size. It is shown that the bed-load transportation in the south channel in the southern branch of the Changjiang River has mainly moved into the southern passage, which is also proved by the comparison results of the erosion and deposition and physical model experiment results. Besides, the change process of the flow-diversion and sand-diversion ratios can further indicate the role of the bed-load transportation in the estuary evolution. From 1964 to the times before the flood season in 1971, the south passage in the south channel in the Changjiang estuary was a main channel discharging water and sand and its flow-diversion and sand-diversion ratios took up about two-third of the total amount of the southern and northern passages. On the basis of field measurement in September 1971,the flow-diversion and the sediment-diversion ratios in the nortern passage started to be dominant. During the flood season in 1978 the water and sediments in the southern passage backwashed into the northern passage. From 1982 to 1987 the southern deep channel of Jiangya was deeply scoured and the southern sand of Jiangya was cut into the central sand of Jiangya from the form of side beach. And the flow-diversion and sediment-diversion ratios in the upper mouth of the southern passage were a little increased, backwashing of water and sediment into the northern passage was also disappeared. At present, the southern sand of Jiangya trends to be combined with the Jiuduan beach and the diversion gap mouth between the southern and northern passages has been up to the sand section of Yuanyuan. Thus it can be seen that controlling the diversion gap, stabilizing the diversion gap and the sediment-diversion ratios of the southern and northern passages and limiting the bed-load transportation body into the northern passage are the key to make the south channel link up the northern passage in the deep waterway in the Changjiang estuary.

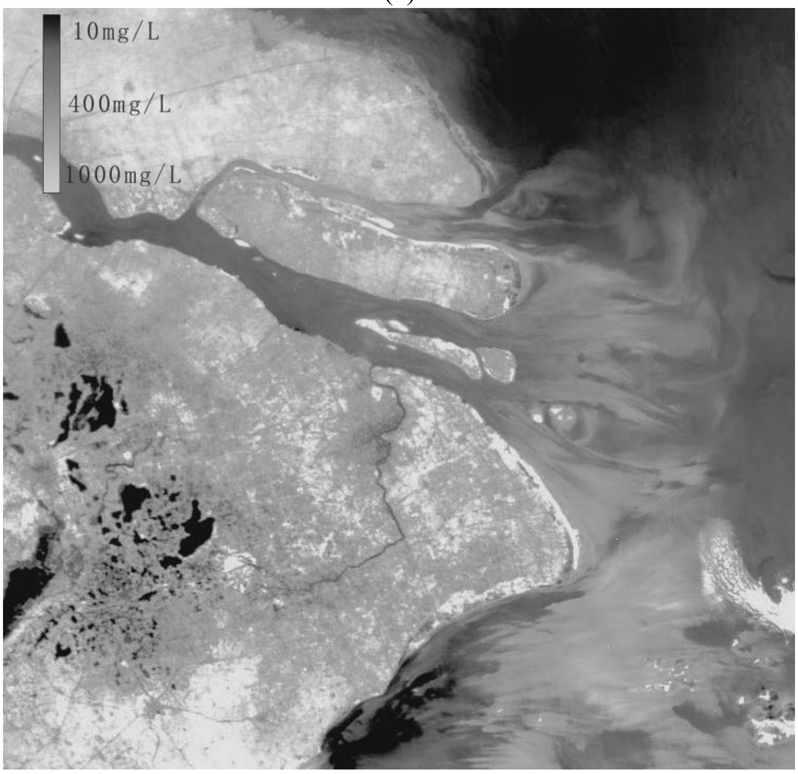
3. SUSPENDED SEDIMENTS DEPOSITION, RESUSPENSION AND THE TRUBIDITY MAXIMUM IN THE ESTUARY

The sediments silted in the waterway of the mouth bars in the Changjiang estuary are thoroughly supplied by the runoff. As the complexity of the dynamic conditions and geomorphic shape at the mouth area, there takes place differentiation in the movement pattern, diffusion form and deposit location. The information from the satellite image can basically indicate the basic laws of suspended sediment transport and deposit in the Changjiaang estuary.

The total transport sediment amount from the Changjiang estuary into the sea is 0.486 billion tons a year, of which that during six months from May to October takes up 87.2% of the total amount and that both in July and August when the flood peak takes place frequently, takes up 54%. The sediment transport pattern during the flood season is that it, like a tongue shapes of turbid water, mainly discharges off the estuary through the main channel of the sea-entering bifurcation. Taking the MSS image of land satellite on 9 August, 1978 as an example, the imaging time was at thirteen minutes to ten in the morning when it was just in the flood season, the ordinary tide fell fast to the low tide, on an average, the tidal range at the Zhengjun Station was 2.99 m and the average flow at the Datong Station was 29,900 m^3/s in that month. The image shows that the north channel is a main way of draining off floodwaters, the north passage is the middle one and the southern passage is a flood channel with tidal backwashing. According to hydrographic surveying data on the land in-phase with the land satellite, the three areas may be divided for the concentration distribution of the sea-entering suspended sediments: the high turbid water area, with 0.5-0.9kg/m^3 of surficial sediment concentration, 0.25-0.5 kg/ m^3 of surficial sediment concentration in the middle turbid water area corresponding to the underwater delta area between 5 m and 15m isobaths and the surficial sediment concentration in the low one sharply decreases to 0.08-0.25 kg/ m^3, which is a sediment fast deposit area corresponding to the shallow sea area between 15m and 30m water depths (Fig. 5(a), (b) , Fig. 6(a),(b)). The similar suspended sediment distribution can be somewhat seen on the meteorological satellite image taken at 7:30 am on 13 August , 1988 (19 June in the lunar calendar). The flow pattern of the turbid water tongue in the north channel, the northern and southern passages can be obviously seen in the image. The outside of the southern passage mouth is the converging area of sediments transported by runoff, where the fine sediments deposited and formed a silting center. This has been verified by the figures of the alluvial and silting changes and the deposition rate in the Changjiang estuary.

Through a comprehensive analysis to the information shown by many satellite images, it is discovered that in the shallow water area of mouth bars to east of the Hensha Island in the Changjiang estuary (121°50″−122°15″E) the water body around 3120km^2 is usually in a turbid state, its sediment concentration is higher than that of the main channel inside the mouth as well as that of the sea area off the mouth. It is also the moving range of the largest turbid zone in the estuary generally called. The two images mentioned above represent two kinds of tidal state respectively. The former was imaging on 18 may, 1987 (21 April in the lunar calendar), representing the lowering situation of the ordinary tide, the latter on 12 November, 1988 (4 October in the lunar calendar), belonging to the flood tide state of spring tide. And the sediment concentration of the latter is larger than that of the former with a more obvious sediment front, reflecting turbulence and sediment-stir action of the tidal current and wind waves at the mouth bars area and the effect of sediment resuspension. Also, it can be verified by the in-situ surveying data on the land, in which the sediment concentration of spring tide is larger than that of neap tide and that of flood tide is more than that of ebb tide.

(a)



(b)

Fig. 5 Remote sensing image of suspended sediment distribution in Changjiang Estuary on June 1, 2002

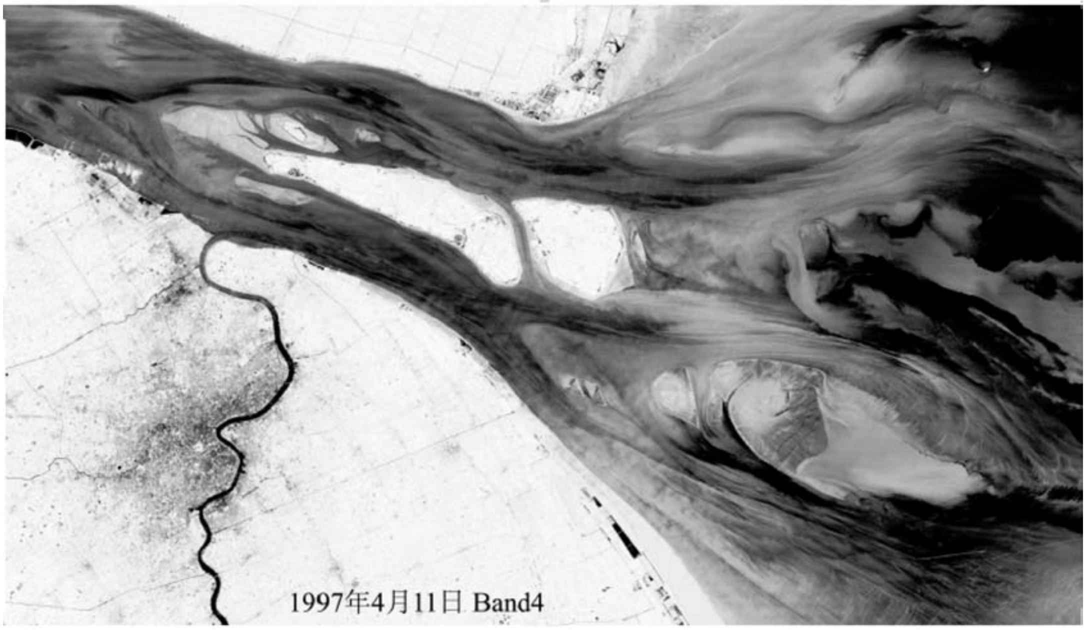


Fig. 6(a) Flow state of the sediment exchanges between the shoal and the channel in the north passage of Changjiang Estuary

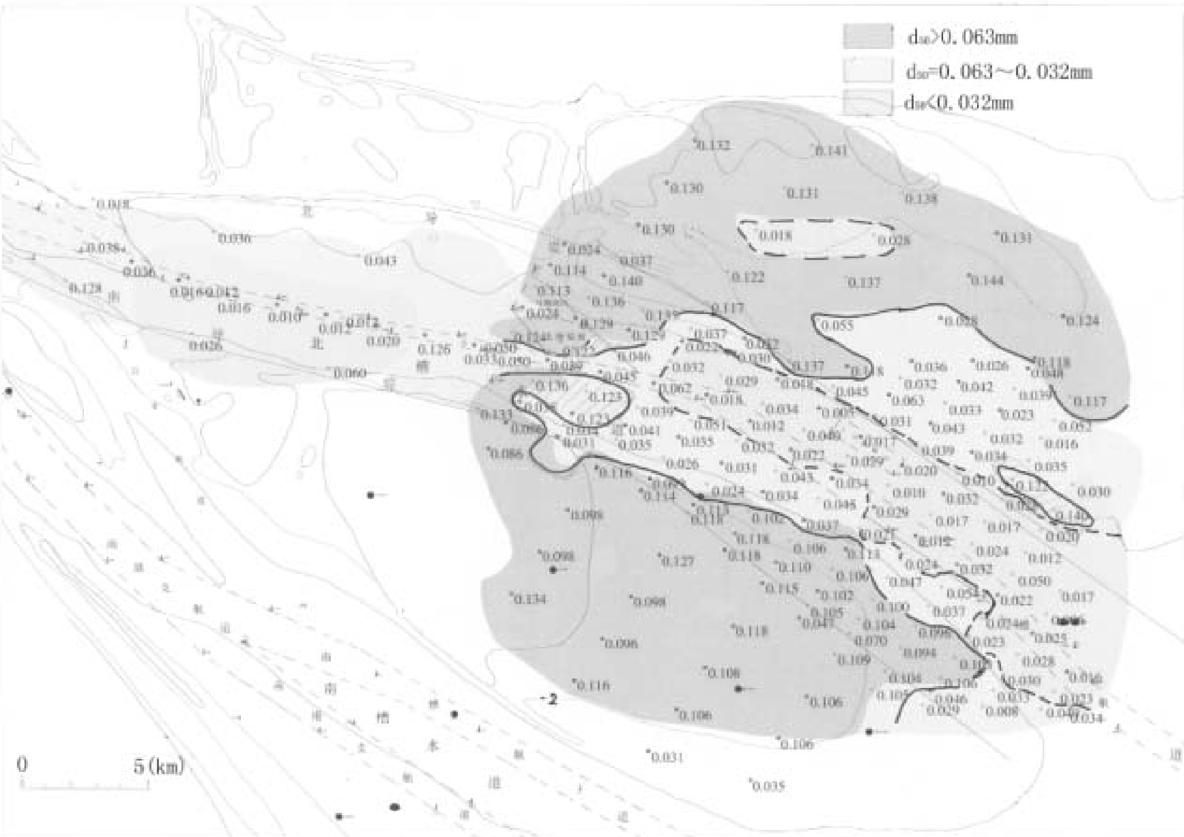


Fig. 6(b) The particle size distribution of bed material in north passage of Changjiang Estuary

That there repeatedly occurs the silting process of the fluid mud in the southern passage in the Changjiang estuary is manifestation of frequent exchange of bed sediments with suspended ones at the mouth area. The requisition for this exchange is that the grain size of the bed sediments is similar to that of the suspended matters and that it is dominated by viscid particles. For example, the viscid particles smaller than 0.01 mm takes up over 78%in the bed sediment composition in the southern passage in the Changjiang estuary. The sufficient condition of deposition is effect of flocculation. And the sufficient conditions of resuspension is that the newly silted materials have not been consolidated and compacted and that the critical shear stress of the bed surface is larger than the resistance shear strength of the bed surface. This shows that the turbidity maximum in the Changjiang estuary must be located at the frequent exchange area between bed sediments and suspended matters.

4. EFFECT OF SEDIMENT EXCHANGE BETWEEN SHOAL AND CHANNEL ON DEPTH OF WATERWAY

In the Changjiang estuary there occurred a gale by north with a magnitude of 5-6 on 27 to 28 October 1976. The aerial photograph taken above the east shoal of Hensha on 29 there occurs the landscape of the large wavemark with 8-20 m of wavelength. The wavemark run from ENE to WSW, perpendicular to the wind wards direction. As braking and losing energy of wave through the shallow water area, the wavemark size gradually decreases from north to south. Thus it can be seen the north gale in the Changjiang estuary can carry the sediments on the east shoal of Hensha into the waterway of the northern passage.

On the landsatellite TM images, taken respectively on 31 May, 1986 (23 April in the lunar calendar), 18 May, 1987 (21 April in the Lunar calendar) and 12 November, 1988 (4 October in the Lunar calendar), there all shows a vast sheet of sediment cloud with the high suspended sediment concentration in the river section of mouth bars in the northern passage, which is not directly related to distribution of the suspended sediment concentration in the upper and lower reaches but to the flow path and sediment concentration field in the shallow water area of the east shoal of Hensha.

To further confirm the effect of the east shoal of Hensha on the waterway of the northern passage, based on the conservation of sediment mass, taking light and clay mineral composition as a tracer, the authors regard the river section of mouth bars in the northern passage as a sediment convergent area and the surrounding water area as a supply area. The supply area of the east shoal of Hensha is located at the northern side of the waterway of mouth bars in the northern passage. Five bed material samples are evenly collected according to the distance from the dredge and fill dock in west to the galley ditches on the east shoal of Hensha in east. The supply areas of the Jiuduan sand and the southern sand of Jiangya are located at the southern side of the northern passage from which four samples are collected. The coming sediment state from the upper reaches is controlled by the supply area in the waterway of the south channel and seven samples are collected from Wusong mouth to the south mouth of Xiaogang of Hensha. On an average, the median grain size of its bed material is 0.051 mm. The supply area of the lower section of the northern passage represents the sediment state from the sea, from which four samples are taken, and the average median grain size of its bed material is 0.001 mm, belonging to clay. The geographical coordinates of the sediment converging area range from 31°15′54″to 31°12′20″N and from 121°58′23″to 122°07′12″E. Through a comparability examination it is discovered that there is good representiveness for the average percentage of mineral composition in the area, with 0.053 mm of the median grain size of the samples. Suppose the sediments in the four supply areas mentioned above were all involved in bed-forming process of the river section of mouth bars of the northern passage, then the percentage content analysis of the light mineral composition from 27 samples (Table 2) shows that 57.72 % of coarse sediments in the silting area of the upper northern passage comes from the east shoal of Hensha, next from the south channel, with 22.04 % of converging amount, 15.71% from the Jiuduan sand and the northern waterway of the southern sand of Jiangya and the least from the lower northern passage, only 5.47 % .

Table 2 The afflux percentage of light mineral of the bed material of the up reach of the north passage in the Changjiang Estuary

Source area and afflux area	Percentage of light mineral(%)					Percentage of afflux
	quartz	plagioclase	potash feldspar	calcite	clay mineral	
East shoal of Hensha	62.33	13.5	6.59	8.56	9.02	57.72
Jiuduan sand and Navigation of Jiangya	61.45	14.22	5.15	8.51	10.67	15.71
Navigation of south channel	62.73	11.4	4.41	9.21	12.33	22.04
Down reach of north passage	59.4	9.97	4.26	13.93	12.4	5.47
The affux region of Up reach of north passage	62.83	13.05	5.17	9.14	9.8	100.94

The statistics of clay mineral composition percentage in the Changjiang estuary may fully reflects the transport state and deposit location of fine sediments in suspended sediments (Table 3). From percentage correlative calculation of clay minerals in the converging and the supply areas, it differs greatly from the coarse sediment distribution. From Table 3, it can be obviously seen that 52.16 % of sediments comes from the waterway of the south channel, the northern waterway of the southern sand of Jiangya and the Jiuduan sand, showing that the sediments in the silting area in the upper northern passage are mainly from the runoff in the upper reaches and the sediment backwashing of the southern passage. The transport sediment amount by tidal current in the lower northern passage takes up a considerable proportion (43.34 %) and the effect from the east shoal of Hensha is the least, with 4.11 % of content. The regional differences and correlative analysis of clay mineral composition further indicate that the sea-entering suspended sediments from the Changjiang River are considerably active at the mouth area. They can directly enter into the region of mouth bars through transporting sediments by the runoff in the upper reaches, and with ebb current also they can be transported off the mouth, resuspended after deposition and carried back inside the mouth. For the bed-forming process of the silting area in the upper northern passage, however, there is a limited effect of fine sediments in suspended sediments on silting of the mouth bars waterway in the northern passage, since clay grain size is only up to 9.8 % in the bed sediment composition in the upper northern passage, and a large amount of silt, fine grain size and its mineral composition is similar to that from the east shoal of Hensha. The practices prove that after the first phase of the project of the deep waterway improvement in the north passage in the Changjiang Estuary, the effect of the guiding flow, stopping up a bifurcation, holding up the sediments and decelerating the deposit rate of the north guide dike are great obvious.

Table 3 The afflux percentage of the clay mineral in the up reach of north passage in the Changjiang Estuary

Source area and afflux area	Percentage of clay minneral(%)				Percentage of afflux
	montmorillonite	illite	kaolinite	chlorite	
East shoal of Hensha	6.4	62.34	15.56	18.16	4.11
Jiuduan sand and the Navigation of Jiangya	4.45	67.2	14.16	14.19	52.16
The navigation of south channel	4.96	69.61	10.2	14.82	43.34
Down reach of north passage	5.5	67.87	12.5	14.21	99.61
The afflux region of up reach of north passage	6.4	62.34	15.56	18.16	4.11

5. THE THEORETICAL BASIS TO DETERMINE DEEP WATERWAY IMPROVEMENT PLAN

As mentioned above, the silting of the sea-entering waterway in the Changjiang estuary results from many factors such as bed-load movement, suspended sediment deposition and horizontal exchange of sediments between shoal and channel. The silting location and deposit process of sediments can be divided into three expression forms. The first is the bed-load movement body near the diversion gap, which are sand spit and the central shoal in a geomorphological form, the second is the detention area of sediments with a high concentration near the bottom around the shoal head of mouth bars and the third is the accumulated area of the fine sediment deposition at the shore off mouth (Fig. 7).

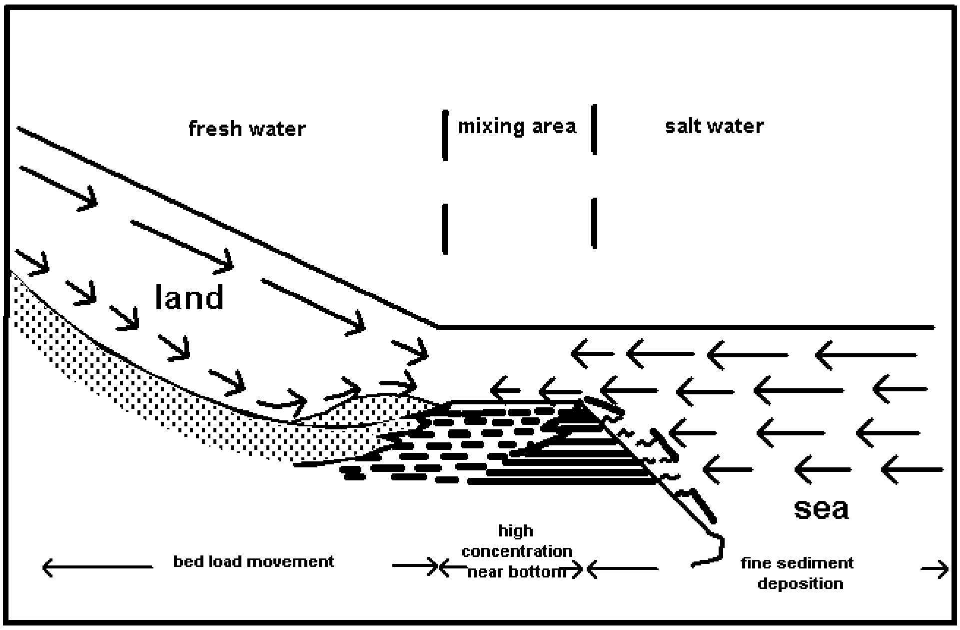


Fig. 7 A silting model of the Changjiang estuary

Aiming at the three silting body forms mentioned above there are three sections of the upper, the middle and the lower, which will be respectively dealt with, in the project arrangement of the deep waterway improvement plan in the Changjiang estuary. The upper section, diversion gap project of Yuzui, is located near zero m isobath at the upper end of the southern sand of Jiangya in the diversion gap between the southern and northern passages. A buried dike, about 3.2 km long extending to the upper reaches, is set up over Yuzui along the shoal ridge line. (The elevation of the original shoal surface ranges from 0 m to 8.0 m. The top of the buried dike bottom is +2 m high and that the dike head is –2 m high.) , like a underwater wall damming a river and holding up sediments, this shallow structure with a slope change will play a role in stabilizing the river state of the diversion gap between the southern and northern passages, controlling flow-diversion and sediment-diversion ratios of the channels and holding up some bed load to transport into the northern passage. Since the east shoal of Hensha and the Jiuduan sand are located on both sides of the middle section from the south channel to the northern passage there is a good basis to construct an artificial waterway there. In the project plan the northern guide dike, 49.16 km long, (The elevation of the dike summit is +2.0 mm) is arranged on the east shoal of Hensha and the southern guide dike, 48.08 km long, (The elevation of the dike summit is +2.0 m) is arranged on the Jiudum sand and the southern sand of Jiangya, which play a multiple role in guiding flow, stopping up a bifurcation, holding up sediments and decelerating the deposit rate. The aim is to construct a formed channel in the open water area by an artificial dike according to the laws of channel forming, narrowing and deepening, which makes exchange of water and sediment between the shoal and the channel be artificially controlled. After the project construction, water body with a high suspended sediment concentration in the middle and low layers below half tidal level will be held up the outside of the double guide dikes, decreasing the effect of stiring sediments by wind wave on the tidal bank on the channel. And the water body with a low suspended sediment concentration will still cross the dikes and converge into the main channel, increasing scouring capacity of ebb current to the channel. For the engineering of spur dike group arranged in the inside of the double guide dikes, a somewhat curve and symmetric river pattern will be used. The aim is to bound water and guide flow, and with adjustment of the flow velocity in the cross-section of flood and ebb tide, to increase the scouring capacity of flow to the partial riverbed. The mouth section beyond the double dike project belongs to an open sea area without engineering shield and the diffusion and deposition of suspended sediments and resuspension in windy days are all active. The transport path and deposit location is controlled by the scouring fresh water path. In view of strong revolving of the tidal current in the northern side of the northern passage mouth there is a stronger silting area of sediments off the southern passage mouth, the waterway out the mouth is arranged by 30 degree to the east in order to facilitate treatment of dredged sediments and to decrease re-silting amount by digging the channel.

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