Mouth Bar Formation in Yangtze River Estuary

Intermediate Report

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1 Introduction

1.1 General Condition

The coastline of the world is about one million-km (Bird and Schwartz, 1985). Estuaries are common features in most world coast. Emery (1967) estimated that 80~90% of the Atlantic and Gulf coasts and 10~20% of the Pacific coasts of the United States are occupied by estuaries.

An estuary is a semi-enclosed coastal body of water that extends to the effective limit of tidal influence, within which sea water entering from one or more free connections with the open sea, or any other saline coastal body of water, is significantly diluted with fresh water derived from land drainage, and can sustain euryhaline biological species from either part or the whole of their life cycle. (Perillo, 1995)

The surroundings of an estuary are usually densely populated area, and they are favourite locations for the development of important cities. The cities are usually port cities, which means that navigation has a great effect on their economic development.

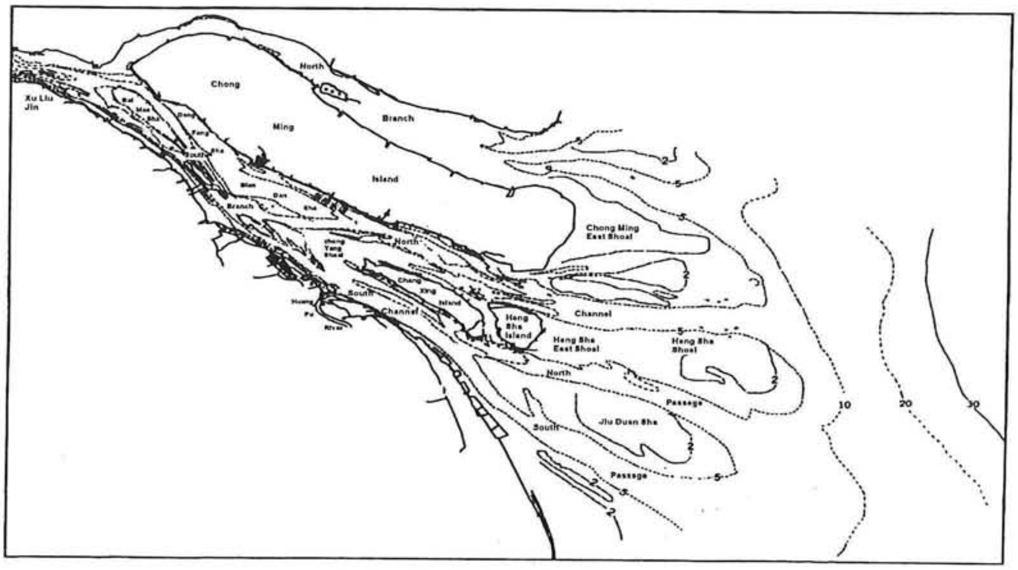

Fig. 1.1.1 The Yangtze River

In China the coastline amounts up to 32,000 km, including the islands, bays, etc. (Yan Kai et al, 1986) More than 500 rivers with a drainage area of more than 100 km^2 discharge into the Yellow Sea, the East China Sea, or the South China Sea. Yangtze River is the longest river in China. Its length amounts to 6300 km, passing 6 provinces and Shanghai City. The Yangtze River Estuary is one of the most important estuaries in China because of its special location and its effect on the economic development of the whole drainage area. The estuary is compared to the throat of the river.

The estuary expands considerably downstream Xuliujing. At Xuliujing, the width of the river is about 5 km, whereas at the sea entrance between Nanhuizhui and Subeizhui, the distance amounts to about 90 km. Since the development of channel above Xuliujing does not affect the channel downstream after the reclamation of Jiangxin Shoal, Xuliujing now is taken as the start point of the Yangtze River Estuary.

The Yangtze River Estuary is not a single waterway to the sea. In fact four waterways connect the river and sea. The estuary is bifurcated into the North Branch and the South Branch. The former undergoes serious sedimentation and the latter is now the main passage for runoff and navigation. The South Branch is further bifurcated by intertidal sandbanks and the Changxing Island into the North Channel and the South Channel, and the latter is again divided into the North Passage and the South Passage. (See fig. 1.1.1) Yangtze River Estuary is a typical example of coastal plain estuary.

1.2 Problem Description

Generally speaking, two main problems exist in the Yangtze River Estuary. One is the instability of the navigation channel. The other is the existence of shoal at all the entrances in the mouth bar section and the limited water depth above them. (Huang Sheng et al, 1981)

The periodic shifting of the bifurcation point of the North Channel and South Channel is very important in the estuary. The North Channel is bifurcated from the South Branch by cutting a channel through the submerged sandbanks. Once a bifurcation channel is formed, the differences in flow conditions of the two waterways make it change rapidly and very unstable: the bifurcation point shifts gradually downstream and the bifurcation channel rotates conterclockwise, thus increasing the flow resistance to flow and accelerating the process of channel sedimentation. The range of migration of bifurcation point may reach 20 km or more. When the channel is silted up to such an extent that it is impossible to accommodate the river flow, a new bifurcation channel will be formed at a certain distance upstream. Such changes in the flow field and the channel pattern bring much trouble to navigation.

The two channels, as well as the North Passage and South Passage, are all very wide, ranging from several km to more than ten km, and shoals can be found here and there in the passages and channels. The periodic shifting of the bifurcation point influences all these waterways.

So the stability of the estuary is very important.

Mouth bar is a kind of swollen section in the estuary-locating seaside of the estuary entrance.

The position of the estuary entrance is defined as the point of intersection of mean sea level and mean longitudinal water level of the estuary. If a line is drawn between the mean bed elevation of upper section and down section of the estuary, i.e. if the longitudinal section of the estuary is drawn, one swollen section can be found. If this section is inside the entrance, it is called sand threshold. If this section is outside the entrance, it is called mouth bar. Sometimes no apparent swollen section exists and this is the transition pattern (Yuan Ying, 19__). Huge mouth bar group exists in theYangtze River Estuary. They are Chong Ming East Shoal, Heng Sha East Shoal, Jiu Duan Shoal, Nan Hui Bank-attached Shoal (Yun Caixing, 1983 and Wang Guqian, 1999). The lower part of the North Channel, the North Passage and the South Passage are mouth bar stretches. For some reasons, other small shoals may be formed and superimposed on the mouth bar. In Yangtze River Estuary, Tong Sha Shoal and

Jiang Ya are two typical examples. (Yuan Ying, 19__, Yun Caixing, 1983, Wang Guqian, 1999)

Although estuaries all over the world are quite different in hydrodynamic and morphological features, mouth bars popularly exist in the tidal estuaries. In a review paper, Dalrymple and Rhodes (1995) proposed to classify estuarine bars into 'repetitive barforms' (i.e. alternate, point and braid bars occurring in tidal channels and creeks of estuaries), ' elongate tidal bars' (which are formed in the outer part of macrotidal estuaries but are also observed at the estuaries with smaller tidal ranges) and ' delta like bodies' (isolated features typically forming where a channel widens considerably). (Also see Seminara & Tubino, 1998) The mouth bar in the Yangtze River Estuary maybe regarded as delta like bodies.

Mouth bar is an obstacle to navigation and is only hindrance for the vessels to Shanghai Port and other ports located along lower reach or even middle reach of the Yangtze River. Because of the limitation of the mouth bar section, natural navigation depth of the estuary is only 6 m. Through dredging, 7-m depth can be maintained and vessels over 10,000 tonnage have to save the tide or unload part of the cargo before passing the channel. It may also have some effect on flood control. It is necessary to study its morphological development.

The mouth bar is characteristized not only by its height but also its length, its mild slope and its complex variation. The length of the mouth bar in North Channel is 39.6 km while in South Channel 64.2 km (mean value of 100 years). The reasons of such length are the fine grain size of the sediment and high water content.

In the mouth bar area, under the comprehensive action of runoff, tide, wind, wave and salt water, many phenomenons such as circulation, null point and turbidity maximum exist there.

The mouth bar system is very complex and is morphologically quite active, whence they are difficult to be controlled by engineering measures. The ability to understand and predict the morphological behaviour of the mouth bar including channels and tidal flats, is therefore an important issue in estuary management.

1.3 Objectives:

The objective of this study is to enhance our understanding of formation and variation of mouth bar not only under normal condition but also under extreme condition

In the past, much research has been done based on field survey and physical scaled model. Mathematical model with its flexibility is now used as one effective method. To be specific, the software Delft 3D will be used in this study to explain the observed phenomenon and to study the potential mechanism under normal condition, extreme condition and engineering construction. Based on mathematical model, the effect of different combinations of factors can be studied.

The objectives of this report are to review what have been done by many researchers and the possible mechanisms and factors put forward. The most important mechanisms and factors are dentified. With delft 3D, pilot calculaiton is carried out to simulate the phenomenon of erosion in dry season and deposition in flood season at the mouth bar area in the estuary.

2. Nature Condition of Yangtze River Estuary

2.1 Tide

The tide is an important factor in the morphology development of the estuary. The tidal affect limit is between Tongling and Wuhu. Generally Datong Station which is 640 km from the sea, is taken as the start point of Yangtze River Estuary at extensive scale. The tidal flow limit is between Jiangyin and Zhenjiang, which is about 200 to 300 km from the sea. The tidal period is 12 hours and 25 minutes and the mean tidal range is 2.67 m.

2.2 Runoff

The runoff of the Yangtze River is large and seasonally variable. The annual discharge is about 925000 million cubic meters. The yearly mean discharge, mean discharge of flood season and mean discharge of dry season are 29300 m^3/s, 40000 m^3/s and 18000 m^3/s respectively.

2.3 Wind

In the estuary, wind is an important dynamic factor. Seasonal variation of wind direction in the Yangtze River Estuary is quite apparent. In spring, summer, autumn and winter the dominant directions are SE~SSE, SSE~S, NE and NNW~N respectively. The strongest directions in summer, autumn and winter (larger than 6 scale) are SSE, NE and NW~NNW. The duration of SE wind is longer but the strength is weaker. The duration of NE wind is shorter but the strength is stronger.

2.4 Wave

Wind waves are predominant in the estuary and the directional spectrum coincides basically with wind. Mean wave height at Gaosheshan and Yingshuichuan are 0.9 m and 3.7 m respectively.

2.5 Sediment

The sediment in the estuary comes from both drainage area and sea, but mainly from drainage area. The mean sediment transported amounts to 486 million ton per year. Seasonal variation of sediment from upstream is significant. The sediment concentrations in flood season and in dry season are 1.0 kg/m^3 and 0.1 kg/m^3 respectively. The yearly mean value is 0.54 kg/m^3. About 86 % of the total is transported in flood season (May~October). From the mean monthly statistics, the maximum value (more than 20% of yearly transport) is in July and minimum value (less than 0.7% of the total value) occurs in February.

The composition of the sediment is fine. More than 98% of the total sediment is transported in the form of suspended load (Li Jiufa and Ji Zhong, 1988). In the South Passage, the median grain size of bed material is 0.023 mm and the median size of suspended load is 0.014 mm. The difference between bed material and suspended load is not much. (Li Jiufa and Ji Zhong, 1988)

The mean grain diameter of suspended load is 0.009 mm. For the bed material, the mean diameter differs from place to place. It is 0.093 mm in the North Branch, 0.084-mm in the South Branch, 0.061 mm in the North Channel, 0.059 mm in the North Passage, and 0.029 mm in the South Passage. (Zhou Jifu et al, 1999)

The median diameter d50 of suspended load in mouth bar section is 0.01 ~ 0.02 mm. (Wang Guqian et al, 1999)

Different location and time of data collection may cause the different results by different researchers.

Because of the fine sediment, flocculation is common phenomenon in the estuary. The settling velocity of flocs is 0.0003~0.0007 m/s.

2.6 Saltwater Mixing

The variation of the runoff is significant. The maximum discharge maybe 14 times larger than that of the minimum value. The tidal ranges also differ remarkably. The maximum tidal range is 27 times larger than the minimum. Under the different combination, different mixing may appear. For neap tide in flood season, highly stratified situation may appear. For spring tide in dry season, well-mixed situation may appear. Anyway the dominant situation is partially mixed one (Huang Sheng, 1981).

The salinity of mouth bar area is 5‰ ~ 15‰. (Wang Guqian et al, 1999)

2.7 Morphology

Under the action of run-off, tide, wave, wind and salt water, the dynamic condition of the estuary is very complicated and variable.

Although the morphological development of the estuary is very complicated, general pattern of the development during the last 2000 years may be described as (Chen Jiyu, 1981):
(1). Gradual growth of shoals nearby the south bank;
(2). Attachment of shoals and island to the north bank:
(3). Narrowing of the estuarine reach;
(4). Formation of a normal channel;
(5). Deepening of the channel

For the mouth bar area, general pattern of erosion in dry season and sedimentation in flood season is noticed by many researchers through analysing the field survey data.(e.g. Yun Caixing, 1983, Zhang Dongliang & Yao Jinyuan, 1993, Li Jiufa & Ji Zhong, 1988, Ji Lan et al, 1999)

The water depth above Tong Sha Shoal and Jiang Ya Shoal varies frequently. The long-term annual variation range of water depth is from 5.8 m to 7.3 m. The maximum difference is 1.5 m and the mean value is about 0.5~0.9 m. Generally speaking, the water depth in August and September is the minimum and in April and May is the maximum. (Yun Caixing, 1983)

In flood season, with the increasing runoff, the sediment supply from upstream increases too. In dry season, the situation is the opposite. So erosion in dry season and sedimentation in flood season are the general patterns in the mouth bar area. (Zhang Dongliang and Yao Jinyuan, 1993, also Qian Ning et al, 1987). Zhang Dongliang and Yao Jinyuan (1993) also specifically pointed that erosion in dry season and sedimentation in flood season are quite obvious in the lower part of the North Passage as well as in the South Passage.

Erosion in dry season and sedimentation in flood season in the lower section of the North Passage was identified by Ji Lan et al (1999) based on field survey data analysis. Null point was used to explain the phenomenon.

Li Jiufa and Ji Zhong (1988) divided the bank line of the estuary into 3 types, erosion section, stable section and sedimentation section. The sedimentation section such as Nan Hui Bank-attached Shoal is the most active part in the morphology development of the estuary. Concerning yearly variation, the bank attached shoal show apparent seasonal variation, sedimentation in flood season and erosion in dry season. In flood season, larger sediment supply from upstream leads to the sedimentation. In dry season, sediment supply is less and tide dynamic action is stronger. Increased sediment carrying capacity is leads to the erosion.

According to the analysis of the long period data, one statistical model between monthly mean sediment discharge of Da Tong Station and the erosion and sedimentation distance of -5 isoline at Zhong Jun in the Nan Hui Shoal is established by Li Jiufa and Ji Zhong (1988).

Concerning short-term variation, storm typhoon and strong cold storm and anthropogenic inputs are main factors leading to relative larger erosion and sedimentation. (Li Jiufa and Ji Zhong, 1988).

Since 1984, the navigation channel in the mouth bar area has been moved to the North Passage. The channel is divided by the trench in Hen Sha Shoal into the upper (landside) part and lower (seaside) part. Zhang Dongliang and Yao Jinyuan (1993) studied the sedimentation pattern of the upper part. Generally speaking, 3 sedimentation peaks can be observed yearly according to field survey data. They happened in April ~ May, July ~ August and October ~ November. The third peak is relatively small. For the upper part, sedimentation generally happens in the whole year, especially in the middle section of upper part. For the lower part, the annual development pattern is quite similar to the South Passage. Erosion in dry season and sedimentation in flood season are quite obvious. Sedimentation starts from April ~ May and reaches the maximum in August. The water depth keeps stable or slight sedimentation in September ~ November. Erosion starts in December and continues to March of the next year and water depth rehabilitates. (Also see Wang Guqian, 1991)

3 Processes and Mechanisms Relevant to Mouth Bar

Concerning the formation of the mouth bar, generally speaking, it is the result of sediment deposition under the action of fluvial dynamics and ocean dynamics. Some mechanisms were put forward.

3.1 Relative Strength of Runoff and Tide

The formation, the scale, the position and the development of mouth bar, are mainly related with relative strength between runoff and tide (Yuan Ying, 19__). It is generally regarded that sediment will be taken out of the estuary by runoff and brought back into the estuary by tide. Let us use Q1 to stand for the formative discharge of runoff:

$$Q_1 = \left(\sum_{i=1}^{n} Q_i^m / n \right)^{1/m}$$

In which:

n: days of statistics

m: index of sediment transport formula, i.e. $G=KQ^m$

Q2 is mean flood tide discharge. The position of shoal is related with the ratio between Q1 and Q2 (Also see Xie Jianheng et al, 1990).

For the estuary of $Q1/Q2 < 0.02$, which means runoff is weaker than tide, swollen section will be formed inside of the entrance of the estuary and sand threshold is formed. For the estuary of $Q1/Q2 > 0.1$, which means that runoff is stronger than tide, swollen section will be formed outside the entrance of the estuary and mouth bar is formed. For the estuary of Q1/Q2 between these two values, transition state will appear.

For the Yangtze River Estuary, because Q1/Q2 is greater than 0.1, mouth bar comes out.

3.2 Tidal Asymmetry

The residual sediment transport is a determinative factor to the morphological development in the estuary where tidal action is an important dynamic factor. An important factor causing residual sediment transport in estuaries is tidal asymmetry. Tidal asymmetry and its effects on the sediment transport and morphological development in estuaries have been studied in the last few decades and the results were summarised by Wang Zhengbing et al (1999).

Tidal asymmetry is the distortion of the tidal wave that makes the flood period unequal to the ebb period. When the duration of tide flooding is shorter than tide ebbing, the tide is called flood-dominant and it is called ebb-dominant in the opposite case. Tide is further divided into horizontal tide and vertical tide when different tide characteristics is considered. Residual sediment transport is the local averaged sediment transport within a tidal period. For the residual sediment transport, the tide asymmetry refers to the horizontal tide, which generates residual sediment transport. The difference between maximum ebb and flood velocities tends to cause residual transport of coarse sediment while the difference between the period of slack water before ebb and the one before flood, affects the residual transport of fine suspended sediment. When residual sediment transport considered, flood-dominant situation refers to the situation that the residual sediment transport is in the flood direction and vice versa.

Non-linear interactions between tidal components and non-linear interaction between the tide and extreme currents, e.g. due to a river flood or a storm surge can give rise to asymmetries in the tidal velocity. Some other mechanisms of asymmetry are the propagation of tidal components in the estuary associated, topography-induced, and the shape of the lateral flow boundaries related. Tidal asymmetry will result in a net sediment flux or a net deposition or erosion of sediment.

The morphology and the tidal asymmetry in the estuary affect each other. The influence of morphology on the tidal asymmetry is clear in the sense that the tidal motion and thus also the tidal asymmetry in the estuary is determined by the external forcing.

For the bed load transport, Kreeke and Robaczewska (1993) give clear insight into the effect of the asymmetry of the horizontal tide on the residual transport. Assuming the flow velocity to be dominated by M_2 tide and the bed-load transport to be proportional to a power of the local current velocity, they show that the long-term mean bed-load transport only depends on the residual flow velocity M_0, M_2 components and its over-tides (M_4, M_6).

For the suspended transport, this mechanism is also applicable. Also there is an additional one which is illustrated by Groen (1967) by using the one simple model for the relaxation effect in the sediment concentration.

In Yangtze River Estuary, the tide asymmetry is obvious. This may be one of the affecting factors to the formation and variation of mouth bar and should be studied further.

3.3 Salt Water Intrusion and Null Point Effect

For the formation mechanism of the mouth bar in the Yangtze River Estuary, based on the data of field survey and the data from the experiment of fine sediment, Huang Sheng et al (1981) found that salt water intrusion is one important factor.

The variation of the runoff is significant. The maximum discharge maybe 14 times larger than that of the minimum value. The tidal ranges also differ remarkably. The maximum tidal range is 27 times larger than the minimum. Under the different combination, different mixing may appear. For neap tide in flood season, highly stratified situation may appear. For spring tide in dry season, well-mixed situation may appear. Anyway the dominant situation is partially mixed one.

Because of the longitudinal and vertical salinity gradients owing to salt-water intrusion, velocity profile is changed. During flood period, salinity gradient has the tendency to increase the flood velocity. Because salinity gradient near bottom is larger than the value near water surface, the increase of the velocity near bottom is larger than the increase near surface. During ebb period, salinity gradient has the tendency to reduce ebb velocity. Because the resistance is larger near the bottom than near the surface due to the difference of salinity gradient along water depth and the discharge must be released, the water goes towards sea through the surface layer causing the velocity to increase in the upper layer. During slack period, salinity gradient plays a leading role. Velocity in the upper layer is towards seaside and velocity in the lower layer is towards landside. In one tide period, the mean net discharge near the surface is towards seaside while the mean net discharge near the bottom changes from towards landside to towards seaside. Null point exists where the net bottom mean discharge is zero.

Under the physical and chemical action, flocculation appears leading to the increase of settling velocity of flocs. The salinity, sediment concentration and temperature are the main factors to the settling velocity of flocs. According to experiment result (Han Naibing, 1974), settling velocity increases significantly with salinity from 3 ‰ till 20 ‰. Settling velocity increases with sediment concentration till 15 g/l~20g/l and decreases later. Settling velocity increases with temperature because the water viscosity is reduced.

Because of salt-water intrusion and the modification of the velocity profile, the sediment concentration distribution is changed too. According to the data of field survey, the net sediment transport of upper layer is towards sea. For the bottom layer, the net sediment transport is toward seaside upstream of the null point while toward landside downstream of the null point. So the concentration in lower layer is significantly larger than the concentration in upper layer. Because of flocculation, sediment concentration also increases in the bottom layer. This leads to one high concentration area around null point accelerating the settlement of flocs. The sedimentation of suspended load in flood season is one of the main reasons to the sedimentation of mouth bar.

Under different combination of run-off and tide, the position of the null point may change while the position of mouth bar is quite stable. For example, In flood season, the long-term flood discharge is 45500 m^3/s. The position of null point is around Tong Sha Shoal, i.e. the mouth bar area. In dry season, the discharge is about 10000 m^3/s. The null point may reach upstream to Xiao Jiu Duan in the South Channel. So Huang Sheng et al (1981) supplemented that the effect of null point is essential but not full. The sedimentation of mouth bar also depends on the magnitude of sediment from upstream and water temperature, etc. Because in dry season, the sediment from upstream is less and water temperature is lower, the sedimentation around null point is not severe, and erosion happens in the mouth bar area.

So the deposition of suspended load in flood season under the effect of salt-water intrusion is reason of mouth bar formation.

Null point effect is also used by other researchers to explain the variation of mouth bar, such as Ji Lan et al (1999), Li Jiufa et al (2000).

Yun Caixing (1983) and Shen Huanting et al (1986) also pointed that salt-water intrusion reduces the release of the suspended load in the lower layer.

3.4 Sediment Exchange between Channel and Flat

In the estuary broad tidal flats generally exist. The erosion and sedimentation of the flats is not only related with shore and beach protection and usage but also closely related with the maintenance of navigation channel. Interaction between the shape of a mudflats and the hydrodynamic forcing leads to morphology development of mudflats. The mediator of this relationship is the movement of sediment. Tidal flats as part of the overall estuary shape also attracts much attention of many researchers, such as Yun Caixing (1983), Li Jiufa and Ji Zhong (1988), Shi Zhong and Chen Jiyu (1996).

According to field survey, Yun (1983) found periodic variation of the flats in Yangtze River Estuary. It may be divided into long-term (several years) variation, seasonal (one year) variation and short-term (such as under the action of storm) variation.

The seasonal variation is mainly affected by wind direction and bank direction. Seasonal variation of wind direction in the Yangtze River Estuary is quite obvious. In spring, summer, autumn and winter the dominant directions are SE~SSE, SSE~S, NE and NNW~N respectively. The strongest directions in summer, autumn and winter (larger than 6 scale) are SSE, NE and NW~NNW. The duration of SE wind is longer but the strength is weaker. The duration of NE wind is shorter but the strength is stronger. Because the water depth above the flat is relatively shallow, the whole water body maybe disturbed under the action of wind generated wave and wind generated flow, leading to the seasonal erosion and sedimentation of flat. According to field survey at Nan Hui, the NE wind leads to erosion and SE~S wind leads to sedimentation. So spring and summer are the main sedimentation seasons. Autumn is the main erosion season. In winter though the strength of NW wind is strong but the fetch is limited. So no large waves can be generated on the flat and only slight erosion can be observed.

The water and sediment in the channel and on the tidal flats exchange directly. The modification of water and sediment in the channel can be reflected by the erosion and sedimentation of the flats, and vice verse. (De Vriend et al, 1989, Yun Caixing, 1983)

In April and May, while sedimentation popularly happens on the Nan Hui Bank-attached Shoal, erosion happens to Tong Sha Shoal and Jiang Ya Shoal in the channel. In July, August and September when typhoon is active, the storm exert destructive effect on the Nan Hui Bank-attached Shoal, the water depth of Tong Sha Shoal is reduced correspondingly. Yun Caixing (1983) noticed this phenomenon.

After analysing the morphology development of both the channel and the flats, Yun Caixing (1983) concluded that the Nan Hui Shoal and Jiu Duan Shoal adjust the sediment transport into the sea. If the sediment is transported onto the flats and deposited there, the sediment concentration is reduced and erosion happens in the channel. If the flat is eroded, a large amount of sediment will be brought back into the channel, leading to sedimentation in the channel.

The sediment exchange between channel and tidal flats is realised through horizontal circulation. (Yun, 1983) Under ordinary weather, the net water and sediment transport in the channel is towards seaside because the current velocity and discharge in ebb tide is larger than the corresponding value in flood tide. While the net water and sediment transport on the flats is towards landside because the larger resistance of the flats. So one net circulation appears. This phenomenon is affected by wind direction. If large wind and storm happen, waves may resuspend the sediment on the flats and bring it back to channel. Yun (1983) also mentioned that fluid mud was a good demonstration of the sediment exchange. Fluid mud usually happens in flood season and neap tide. If windy weather happened first and calm weather followed, fluid mud can be observed in the channel. It can be concluded that the source of the sediment is from the flats.

3.5 Seasonal Variation of Sediment Supply from Upstream and Water Carrying Capacity

Seasonal variation of sediment supply from upstream is significant. The sediment concentrations in flood season and in dry season are 1.0 kg/m^3 and 0.1 kg/m^3 respectively. The yearly mean value is 0.54 kg/m^3. About 87 % of the total is transported in flood season (May~Octumber). From the mean monthly statistics, the maximum value (more than 20% of yearly transport) is in July and minimum value (less than 0.7% of the total value) occurs in February (Li Jiufa and Ji Zhong, 1988).

Seasonal variation of sediment from upstream is used to explain the variation of mouth bar by many researchers, such as Li Jiufa et al (2000). In flood season, because the sediment from upstream is larger than the water carrying capacity, sedimentation happens. In dry season, because the sediment from upstream is less than the water carrying capacity, erosion happens.

3.6 Flocculation at the Mouth Bar Area

Because the sediment of the estuary includes some fine clay and silt, current, but also the physical and chemical action between particles do not only control the movement of the sediment.

Under the physical and chemical action, flocculation appears leading to the increase of settling velocity of flocs. The salinity, sediment concentration and temperature are the main factors to the settling velocity of flocs. According to experiment result (Han Naibing, 1974), settling velocity increases significantly with salinity from 3 ‰ till 20 ‰. Settling velocity increases with sediment concentration till 15 g/l~20g/l and decreases later. Settling velocity increases with temperature because the water viscosity is reduced.

Many researchers, such as Huang Sheng et al (1981), Yun Caixing (1983), Sheng Huanting et al (1986), Li Jiufa et al (2000) notice the effect of flocculation. Because of salt-water intrusion, flocculation accelerates the sediment settling leading to the sedimentation of mouth bar, especially in flood season. In dry season, because the mixing area is moved upward, under the stronger action of tide, erosion happens in the mouth bar area.

3.7 Bed Load Effect

Since there is no field data on the bed load available, from the morphology development of other shoals, Huang Sheng et al (1981) deduced that the bed load is active and may have certain effect on the mouth bar, but very slow. Wang Guqian et al (1999) also mentions this phenomenon. If there is large amount of local bed load from upstream, the water depth of the mouth bar area may be reduced about 1 m temporarily. After 5 ~ 7 years, it may be transported to the sea and water depth is restored.

Li Jiufa and Ji Zhong (1988) pointed out that more than 98% of the total sediment is transported in the form of suspended load, which means under normal condition suspended load is much more important than bed load.

3.8 Detachment between Flood Tide and Ebb Tide

The detachment between flood tide and ebb tide is noticed by many researchers, such as Huang Sheng et al (1981), Wang Guqian et al (1999).

Concerning the stability of the shoal in the mouth bar area, Huang Sheng et al (1981) proposed another reason. That is due to the detachment between flood tide and ebb tide.

3.9 Boundary Condition

Boundary condition mainly refer to the plane geometry of the estuary, i.e. expanding rate dB/dx, in which B is width and x is longitudinal distance. If Q1/Q2 is relatively small, dB/dx is relatively large and sandbank will appear. If Q1/Q2 is relatively large, delta estuary and mouth bar will appear. (Yuan Ying, 19__)

Concerning the sedimentation around the entrance, Yun Caixing (1983), Shen Huanting et al (1986) gave a schematic explanation. At the entrance because of geometry expanding leading to the reduction of flow velocity, the water carrying capacity for sediment is reduced. So deposition happens.

Seminara and Tubino (1998) used the critical value of control parameter β (width to depth ratio) to study the formation of free bars in estuarine channels with width slowly varying in the longitudinal direction.

3.10 Sediment Source

Sediment condition includes source and direction of the sediment. If the sediment comes from seaside and tide is strong, much sediment may be carried into the estuary. If the run off is not strong enough to wash it out, sand threshold may appear. If the sediment comes from inland, mouth bar may appear. (Yuan Ying, 19__)

According to field survey, Yun (1983) found periodic variation of the flats in Yangtze River Estuary. It may be divided into long-term (several years) variation, seasonal (one year) variation and short-term (such as under the action of storm) variation. The affecting factors for the long-term cyclic variation is the magnitude of sediment from river, the wandering of main channel, and the discharge distribution between different waterways. The dominant factor is the increasing and reducing of sediment supplying.

3.11 Sediment Deposition and Resuspension

The variation of the mouth bar area indicates the frequent exchange between suspended load and bed material. Some researchers such as Shen Huanting et al (1986), Li Jiufa et al (2000) studied the process, the mechanism and affecting factors of the sedimentation and resuspension of the sediment at the mouth bar area based on field survey and flume experiment.

Concerning the vertical distribution of sediment concentration, generally speaking, the value of upper layer is less than the value of middle and lower layer. The vertical gradient of ebb tide is larger than that of the flood tide. The vertical gradient of neap tide is larger than that of the spring tide. The vertical gradient in flood season is larger than that of dry season. (Shen Huanting et al, 1986) During the maximum of flood and ebb tide, the distribution is uniform. During slack tide, the gradient is significant and sediment is easier to settle down to the middle and lower layer. (Li Jiufa et al, 2000)

Concerning the concentration distribution among the 4 entrances, due to the different characteristics of each entrance, different situation appears. The North Branch is flood-dominated waterway. The North Channel and the North Passage are ebb-dominated waterways. The South Passage is flood-dominated waterway in dry season and ebb dominated waterway in flood season. For the spring tide, the order of mean concentration of the 4 entrances from high value to low value is the North Branch, the South Passage, the North Passage and the North Channel. (Li Jiufa et al, 2000)

Concerning the longitudinal distribution the concentration of the mouth bar area is higher than the value of upstream and downstream. (Shen Huanting et al, 1986)(Li Jiufa et al, 2000)

Shen Huanting et al (1986) and Li Jiufa et al (2000) identified periodic nature of sediment concentration in tidal cycle. For flood and ebb cycle, two situations can be distinguished.
1) The concentration of ebb tide is larger than the concentration of flood tide for ebb dominated situation.
2) The concentration of flood tide is larger than the concentration of ebb tide for flood dominated situation.

For spring and neap tide cycle, the concentration of spring tide is larger than that of neap tide.

Seasonal variation of the concentration at the estuary is also identified. The magnitude of sediment from upstream shows seasonal variation. The sediment concentration in the estuary also shows seasonal variation, i.e. high in flood season and low in dry season. Li Jiufa et al (2000) further studied the process of sediment concentration. For spring tide, about 0.5 hour after the slack, the velocity exceeds the critical value, so the sediment is resuspended and concentration increases with the current and reaches the maximum at about 2-3 hours after the slack. Then the concentration reduces with decrease of current speed. Flocculation accelerates the sedimentation. The concentration of upper layer is smaller than that of low layer. Generally 2 high peaks and 2 low peaks can be observed. But sometime 3 or 4 high peaks can also be observed. They explained that the reason was the collision between ebb flow and flood flow around slack tide resulting upward and downward movement of water. This increases the turbulence and resuspends the sediment.

3.12 Sediment Nature

According to Shen Chenlie and Ruan Wenjie (1986) the bed material of the estuary mainly is composed of silt and clay. Concerning the sediment composition, the grain size of about 88% of the composition is finer than 0.05 mm, including 13% of clay (diameter less than 0.005 mm). The sediment of the estuary is fine, cohesive ununiform particles. The movement of the fine cohesive sediment is not only controlled by current but also affected by the physical and chemical action between the particles.

Based on the experiment, 2 types of bed material can be distinguished: slowly erosion type and suddenly erosion type. Slowly erosion refers to the one when water velocity increases exceeding erosion velocity, part of the material is suspended. If the velocity is fixed at certain value, the concentration increase slowly tending to a stable value, which is called stable concentration and the erosion stops. Suddenly erosion type refers the bed material when the shear stress on the bed surface increases to exceed the shear strength of the bed material, blocks of sediment suddenly suspended into water. The concentration increases sharply. If the water speed keeps constant, stable concentration may be reached in a very short time.

The sediment nature was used by Li Jiufa et al (2000) to explain erosion of mouth bar in dry season. Because the density of material in the area is lower and its water content is higher, the sediment is easier to be eroded in dry season.

3.13 Extreme Condition

Under the action of extreme meteorology such as typhoon, cold storm, the morphology of the estuary maybe changed significantly. Sediment in the mouth bar area may be eroded and resuspended. After the wind, large amount sediment may settle down in the navigation channel leading to sedimentation. If the extreme meteorology coincides with spring tide or flood discharge, the effect is severer. In recent 50 years, the one, which has the greatest effect on the estuary is typhoon No. 8310. In 1983, the typhoon No. 8310 went past through the estuary and coincided with spring tide. Although the wind speed was only 16 m/s, waves more than 3 m were generated and water set up amounted to 2 m, (Dou Xiping, 1999), leading to the severe sedimentation of navigation channel in the South Passage. The whole 25 km -7 m elevation dredged channel was completely filled. In 10 days the maximum sedimentation height was 1 m, i.e. 100 mm per day. The mean sedimentation height is 0.5 m. The whole sedimentation amounted to 3.2 million m^3 and the channel could not be maintained. In 1984, new navigation channel had to be set up in the North Passage. In 1986, the same situation happened again. The typhoon 8615 coincided with spring tide again, The wind speed was higher but wave height was only 1~2 m. After the typhoon, the sedimentation in the whole 16 km channel amounted to 900,000 m^3 with maximum sedimentation 0.6 m and maximum sedimentation rate was 20 mm per day on the average. (Dou Xiping, 1999)

The morphology development of channel under the action of extreme meteorology attracts the attention of many researchers, such as Guan Xuwei and Gu Weihao (1992), Dou Xiping (1999), and Ding Pingxing et al (2000).

Guan Xuwei and Gu Weihao (1992) analysed the sedimentation of the North Passage under the action of cold storm in 1990 based on the data of field survey. Significant effect on the navigation channel sedimentation can occur only when the wind is larger than 7 scale. If it coincides with spring tide, the sedimentation effect is more remarkable.

Based on the non-equilibrium suspended load and bed load transport equations and the sediment transport capacity formula (suspended load and bed load) derived by Dou Guoren(1995), a 2 DH numerical model of total sediment transport was established by Dou Xinping et al (1999) to predicate the morphology development of the estuary after the deep navigation channel construction. In the model, runoff, tidal current, wind wave and salinity gradient was included. Special attention is concentrated on the model validation. The result showed that the sediment concentration, topography variation and sedimentation in the channel caused by tropical storm could be successfully simulated. (Dou Xiping et al, 1999)

One Mathematical model was developed by Ding Pingxing et al (2000) to study the effect of typhoon on the morphology development in the estuary. Typhoons No. 8913, No. 9711 and Jelawat were studied. For the typhoon No. 9711, two sedimentation peaks were found in the North Passage. Peak No. 1 was in the middle of upper section of the passage. The maximum sedimentation height is about 30 cm. The sedimentation was mainly caused by bed load. Peak No. 2 was in the middle to the lower section of the passage and was mainly caused by suspended load. They postulated that the sediment resuspension from the tidal flats might be the reason. They also studied the effect of Jelawat. Overall sedimentation happened in the North Passage. Two peaks appeared again. One located about 10 km from the upper end. Maximum sedimentation height was 57 cm. Bed load is the main factor. The other severer peak was around the middle and lower section of the passage, about 40-km from the upper end. Suspended load is the main factor. Maximum sedimentation height was 1 m. The significant difference compared with typhoon No. 9711 was the difference of the two peaks. Peak No. 1 was less than Peak No. 2. They mentioned that the construction of deep navigation project, phase I may effectively stop the sediment from the tidal flats. Groin restraint action may reduce the sedimentation in the channel.

They simulated the coincidence of Jelawat with spring tide. They found the sedimentation caused by bed load in the upper part increased while the sedimentation caused by suspended load in the middle and lower part reduced. The reason was the enhanced hydrodynamics due to the spring tide. This is favourable to the transport of bed load. On the other hand, the water set up leads to larger water depth thereby reducing the effect of waves on the shoals. The sediment resuspension is reduced thus the sedimentation in the channel was reduced.

They also simulated the coincidence of Jelawat with flood discharge. The position of the suspended load sedimentation was moved downward about 10 km. The sedimentation caused by bed load in the upper section increased not only the range but also the magnitude. The sedimentation caused by suspended load was reduced in the middle and lower section. The reason may be the increase of sediment capacity in flood season and movement downward of null point.

One statistical model was also developed to calculate the sedimentation (Ding Pingxin et al, 2000).

Generally speaking, the strength and path of typhoon are affecting factors. The path of typhoon determines the fetch, which is an important factor to the waves in the estuary. If it blows from the outside to the inside, larger wave may be generated, causing a large amount of silt to be resuspended and sever sedimentation of the channel. If the direction is the opposite, the sedimentation is less severe.

The local morphology development tendency of the channel is another important factor. The intensive movement of the tail of Jiuduan Shoal southward then was another reason why the typhoon No. 8310 caused serious sedimentation.

Tide situation is an important factor, too. The sedimentation concentration of spring tide is about 7 times that of the neap tide. The sediment may be suspended easier under the action of typhoon and spring tide. After the typhoon, the neap tide comes and much sediment may settle down causing severe sedimentation in the channel.

According to field survey, Yun (1983) found periodic variation of the flats in Yangtze River Estuary. The short-term (such as under the action of storm) variation was caused by storm. Morphological development of flat under the action of storm is severe although the duration is short. The erosion types depend on flat patterns.

3.14 Deep navigation channel project (Anthropogenic Input)

The construction scheme of deep navigation channel in the North Passage is put forwarded based on scientific research. The purpose of the project is to deepen the navigation channel to -12.5 m or even deeper to accommodate large vessels through dredging and regulation.

The construction of the project consists of the north and south training jetties, spur dikes inside the jetties and a diversion bulwark. The whole work is divided into 3 stages. For the first stages, 16.5 km of north training jetty, 20 km of south training jetty, 6 spur dikes and the diversion bulwark was constructed, together with $45*10^6$ m^3 of sediment dredging. The channel depth reaches 8.5 m. For the second stage, 32.5 km of the north jetty and 28.0 km of south jetty will be constructed and another 13 spur dikes will be built. The dredging material is estimated at about $56*10^6$ m^3 and the proposed water depth is 10 m. For the third stage, the channel will be dredged and the proposed water depth is 12.5 m. The dredging volume is about $150*10^6$ m^3.

The first stage was completed in June 2000. Container vessels of the 4^{th} generation carrying 4000 TEU now only need to unload 1000 TEU to enter the channel instead of 2000 TEU. The ship speed is increased from 8 knots to 12 knots.

The original intention and the end-result of the deep navigation channel project are to reduce the sedimentation. (Dou Guoren, 1999)

In order to construct deep navigation channel, one of the four natural channels, which connect the river and the sea, should be selected. The studies show that North Passage is the best choice(Dou Guoren, 1999). The change of upper stretch has the least effect on the North Passage; the diversion ratio of water is steady and rising. The diversion ratio of sediment is less than its diversion ratio of water. It is the most prospective one. However, the dredging volume amounts to 10 to 12 million cubic meters per year in order to deepen the channel from -6 m to -7 m. Its daily deposition rate is more than 6 mm. It is impossible to construct the deep navigation channel without other engineering measurers. The combination of dredge and regulation is the only practical method.

Based on the non-equilibrium suspended load and bed load transport equations and the sediment transport capacity formula derived by Dou Guoren (1995), a 2D numerical model of total sediment transporting in the Yangtze River Estuary is established by Dou Xiping et al (1999). In this model, the actions of tidal currents, wind waves and the effect of salinity on the sediment transport are considered. This model is used for the feasibility study to compare the two deepwater channel project schemes, phase one. The discharge ratio between the North Passage and South Passage and the annual maintenance dredging volumes of the North Passage are calculated. The flow field of the North Passage and the South Passage is also obtained. For the pre-feasibility study, only suspended load model is used to predict the annual maintenance dredging volume.

Yan Yixin et al (2001) studied the morphology development of Jiu Duan Shoal after the deep navigation channel project. Non-linear 3D mathematical model with σ co-ordinate system was used. The mechanisms of northward movement of lower-section Jiu Duan Shoal was studied. The sources of sediment are the groin section, the north part along the north jetty and Heng Sha East Shoal trench area.

3.15 Combination

In fact, the formation and variation of mouth bar may result from not only one factor but also the combination of several factors. This is also the subject, which should be studied further. Some researchers started to study the combination.

Zhang Dongliang and Yao Jinyuan (1993) studied the reasons for the three deposition peaks in one year in the upper part of North Passage. They found the mechanisms of different peak are different. They are the synthesis of several factors. For the first peak, the position of null point, the position of the sediment and water exchange between channel and flats, and the position of sediment and water transferring from the South Passage is relatively concentrated. So the first sedimentation peak reaches the maximum value. For the second peak, these positions are relatively dispersed. So the sedimentation is relatively disperse. For the third peak, sediment comes from the lower part of the North Passage and it is the adjustment of sediment in the lower part.

3.16 Synthesis

Several possible mechanisms and factors have been postulated. The formation and variation of the mouth bar in the Yangtze River Estuary may result from not only one factor but also the combination of many factors and mechanisms. One of the advantages of numerical model method is its flexibility. Different factors and mechanism can be studied separately and comprehensively through numerical model method.

Null point effect may be the most important factor to the formation and variation of mouth bar. Fluvial discharge and tide are two basic dynamic conditions in the estuay. The fluvial discharge varies seasonally. Every year flood season and dry season occurs in turn. Tide can also be divided into spring tide and neap tide. Under different combination of the two basic dynamic factors, the position of null point changes seasonally. In flood season, the null point is around the mouth bar area. The salinity condition and temperature favourite the forculation, leading to accelerate the deposition of mouth bar area. In dry season, the null point moves upwards. Although mixing phenomenon is still exists, because the sediment from upstream is less and the temperature is lower, sedimentation around the null point is not severe.

The sediment exchange between tidal flats and channels is also an important factor. Under normal weather, sediment may be brought from channels to flats. Under the action of large wave and wind, the water body above flats is severely disturbed and sediment on flats may be resuspended and brought back into channel. Tidal flats and channel are closely related and they should be regarded as one integrated system.

The sediment in the estuary varies significantly from fine sand to clay. Since the content of clay is high, the cohesive nature of sediment is an affecting factor.

The sediment transport can be divided into suspended load and bed load. If there is no significant change in the upper part of the estuary, suspended load plays the major role in the morphology development of the mouth bar area in the estuary.

Deep navigation channel project is the latest and the largest engineering construction in the estuary. The original intention and the end-result of the project are to reduce sedimentation so that the navigation channel can be maintained deep enough to accommodate larger vessels. Such influence is significant and should be studied further.

Typhoon as the destructive dynamic factor also plays an important role in the morphology development of the estuary. The affecting factors of typhoon on the morphology development of the estuary should be studied.

4 Numerical Model Analysis

4.1 Model Set-up

4.1.1 MOR Module

The morphological development of the estuary concern the fully coupled activities of waves, flow, sediment transport and bed level variation. The MOR module of Delft 3D fully integrates these effects and these are included in separate module which are operated sequentially but use each others results.

MOR module uses the process tree to control the complete process simulation: it starts the process, activates and de-activates process controllers and modules, arranges the data communication between the modules and stops the process simulation.

The process tree used in this study is as follows:

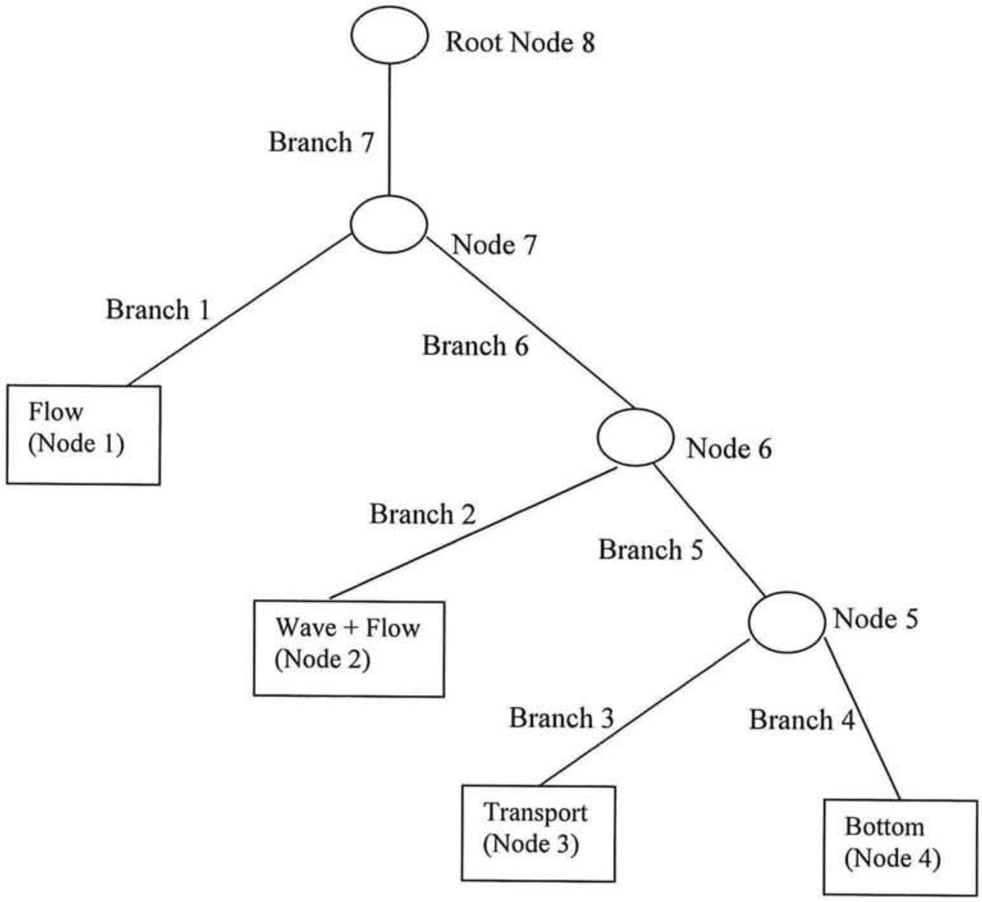

Fig. 4.1.1 Process tree

This process tree is executed in the following order:

1. A flow simulation is made in Node 1. This node is executed once to prepare water level and current data for the Wave model.

2. The Wave and Flow model are executed in Node 2. This node automatically will use the hydrodynamic data from Node 1. Node 2 can be executed a fixed number of times or can be controlled by an accuracy check.

3. The Transport and Bottom modules are executed consecutively in Nodes 3 and 4. These nodes are always executed together via Controller 5. An intermediate update of the hydrodynamics is made automatically (via the continuity correction) if Node 5 is executed more than once. The <Stop Criterion> for Node 5 is usually a pre-set number of executions or an accuracy check.

4. Controller 6 controls the actual morphological process tree. This node can be executed a fixed number of times, but usually a maximum simulation time is prescribed here.

5. Controller 7 only exists to allow the one time execution of Node 1, it is executed once.

The time management of the whole process tree is specified as follows:

The start types for hydrodynamic and transport modules (Controller 1 to 3) are reset to Starting Time (Record 4) by using the start time of Controller 7. The Central Time is not changed.

Controller 4 contains the Bottom module, which runs in morphological time. Therefore its starting time is updated by taking the Running Time of Controller 5 as Starting Time. The Running Time of Controller 4 is updated after each check and when execution ends (Update Type is 1) by taking the maximum relative end time encountered in the last executed <End-Node> (Update Item is 3). This implies that the End Time of the Bottom module in Node 4 is used to update the Running Time.

Controller 5 controls the Transport and Bottom modules. The Transport module is running over a constant interval. However, the Bottom module runs in the morphological time frame and therefore the <Central Time> should be updated. When Controller 5 is activated it should take over the Running Time of Controller 6. As Controller 4 has already updated the Running Time it is not necessary for Controller 5 to carry out a time update.

Controller 6 manages the actual morphological simulation and is executed a number of times. The Starting Time should not increase and is obtained from Central Time.

Controller 7 is executed once, as it is only present to facilitate a preliminary run of the flow model it should start with a Starting Time (Record 4) and not update running time.

The composition (i.e. selection of a set of physical processes) of each <End-Node> is defined as follows:

<End-Node> 1 contains only a Flow simulation over a period of 1500 Tscale.

In <End-Node> 2 the Wave and Flow modules are active. The relative time interval for the Wave module is always set from 0 to 0. The relative time period for the Flow module is set from 0 to 750 Tscale. The first time Flow (<End-Node> 1) is executed the simulation period is set to 1500 Tscale to allow the model to let the initial disturbances damp out. If flow data is available on the communication file, the Flow module will use a selected flow field (selection is based on time) as an improved estimate of the initial flow field. This enables an efficient model execution without the necessity for the model to have a significantly extended interval in which the initial disturbances are damped out at each execution.

<End-Node> 3 contains the Transport module in suspension mode (Version 3).

<End-Node> 4 contains the Bottom module.

4.1.2 Flow Module

Flow module is a multi-dimensional (2D or 3D) hydrodynamics simulation program, which calculates non-steady flow that result from tidal and meteorological forcing on a curvilinear, boundary fitted grid. In 3D simulation, the vertical grid is defined following the sigma co-ordinate approach.

The depth averaged continuity equation is given by:

$$\frac{\partial \zeta}{\partial t}+\frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\left[(d+\zeta)U\sqrt{G_{\eta\eta}}\right]}{\partial \xi}+\frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\left[(d+\zeta)V\sqrt{G_{\xi\xi}}\right]}{\partial \eta}=Q$$

The momentum equations in ξ- and η-direction are given by:

$$\frac{\partial u}{\partial t}+\frac{u}{\sqrt{G_{\xi\xi}}}\frac{\partial u}{\partial \xi}+\frac{v}{\sqrt{G_{\eta\eta}}}\frac{\partial u}{\partial \eta}+\frac{\omega}{d+\zeta}\frac{\partial u}{\partial \sigma}+\frac{uv}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\xi\xi}}}{\partial \eta}-\frac{v^2}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\eta\eta}}}{\partial \xi}-fv$$
$$=-\frac{1}{\rho_0\sqrt{G_{\xi\xi}}}P_\xi+F_\xi+\frac{1}{(d+\zeta)^2}\frac{\partial}{\partial \sigma}(v_v\frac{\partial u}{\partial \sigma})+M_\xi$$

$$\frac{\partial v}{\partial t}+\frac{u}{\sqrt{G_{\xi\xi}}}\frac{\partial v}{\partial \xi}+\frac{v}{\sqrt{G_{\eta\eta}}}\frac{\partial v}{\partial \eta}+\frac{\omega}{d+\zeta}\frac{\partial v}{\partial \sigma}+\frac{uv}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\xi\xi}}}{\partial \eta}-\frac{u^2}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\xi\xi}}}{\partial \xi}+fu$$
$$=-\frac{1}{\rho_0\sqrt{G_{\eta\eta}}}P_\eta+F_\eta+\frac{1}{(d+\zeta)^2}\frac{\partial}{\partial \sigma}(v_v\frac{\partial u}{\partial \sigma})+M_\eta$$

In which:
Q: the contributions per unit area due to the discharge or withdrawal of water, evaporation E and precipitation P:

$$Q=H\int_{-1}^{0}(q_{in}-q_{out})d\sigma+P-E$$

q_{in} , q_{out}: the local sources and sinks of water per unit of volume (1/s) respectively.

Pξ, Pη: gradient hydrostatic pressure in ξ, η direction ($kg/m^2/s^2$)

Fξ, Pη: turbulent momentum flux in ξ, η direction (m^2/s^2)

Mξ, Mη: source or sink of momentum in ξ, η direction (m^2/s^2)
ζ: water level above some horizontal plane of reference (m)
t: time co-ordinate (s)
Gξξ, Gηη: coefficient used to transform curvi-linear to rectangular co-ordinates (m)
ξ,η: curvilinear spatial co-ordinates
u, v: velocity in ξ, η direction (m/s)
б: scaled vertical co-ordinate
f: Coriolis coefficient (1/s)

In the calculation, curvilinear grid is used to fit as closely as possible the land boundaries. Since the estuary area is large, general latitude 32° is selected. The simulation is carried out in dry season and flood season separately. January and September are used as the representative months. The calculation time step is 60 s. The salinity and temperature processes are included in the pilot simulation. The gravity acceleration is 9.81 m^2/s. Water density is 1000 kg/m^3. K-ε turbulence model is used in the simulation. Uniform Chezy roughness 100 $m^{0.5}/s$ is used for both U and V direction. Harmonic water level is used for the sea boundary and harmonic discharge is used for the fluvial boundary. The representative discharges in flood season and in dry season are 44000 m^3/s and 11000 m^3/s.

For this module, data is from Dr. Wang Zhengbing's calibrated flow module.

4.1.3 Transport Module

The transport module determines the sediment transport for 2DH area at a set of times. It uses the time dependent wave and flow data from the communication file. A fixed bed level is assumed when the transport is calculated.

As the Flow module is by far the most expensive module in terms of computational cost, the Transport module can apply a so-called continuity correction. The continuity correction methodology is based on the assumption that the velocity patterns are not significantly influenced by the small bed level changes. By using the discharge components from Flow data group on the communication file, the Transport module approximates the velocity field at each sediment transport calculation.

The transport of sediment can be in the form of bed load and suspended load, depending on the size of the bed material and the low condition.

The transport module has three options:
1. total mode
2. suspended mode
3. silt mode

In Suspended Mode, the time dependent development of the suspended sediment concentration are determined with an advection-diffusion equation. The suspended sediment transport components are derived from these concentrations. In this mode only the algebraic sediment transport formulas can be used that distinguish between bed load and suspended load as the suspended load is used to derive the equilibrium concentration which is used in the advection-diffusion equation.

The advection-diffusion equation to model the depth averaged the suspended sediment concentrations is derived from a 3D advection-diffusion equation by assuming algebraic approximations for vertical diffusion coefficient and having a concentration imposed as a boundary condition at the bed.

The advection-diffusion equation to be solved for C_s reads:

$$\frac{\partial c_s}{\partial t} + \alpha_u \left(u \frac{\partial c_s}{\partial x} + v \frac{\partial c_s}{\partial y}\right) - \frac{\partial}{\partial x}\left(\varepsilon_x \frac{\partial c_x}{\partial x}\right) - \frac{\partial}{\partial y}\left(\varepsilon_y \frac{\partial c_s}{\partial y}\right) = \frac{(c_{se} - c_s)}{T_s}$$

where:

$$\alpha_u = 1.0$$

$$T_s = \frac{h}{1.01 w_s} T_{sd}$$

In which:

w_s: settling velocity of suspended sediment.
C_{se}: equilibrium concentration of suspended sediment.
T_s: adaptation time for vertical sediment concentration profile.
The equilibrium suspended sediment transport, as computed by a user specified algebraic sediment transport formula, will be used in Suspended Mode to derive the local equilibrium concentration (C_{se}) by the expression:

$$C_{se} = \frac{S_{se}}{\alpha_s u_s h}$$

In which:

S_{se}: equilibrium suspended sediment transport
u_s: depth averaged velocity
h: water depth
α_s: parameter

The adaptation time T_{sd} can be determined in two ways:
1. Assuming a concentration as a bed condition for the 3-D case.
2. Assuming a concentration gradient as a bed condition for the 3-D case.
(For detail, see Galappatti, 1983)

In the simulation, concentration bottom boundary and algebraic relations are used. The time step of transport computation is 600 s and tidal cycle is 12 hours and 25 minutes. Secondary flow effect is included for suspended transport components. The correction coefficient for shields number is 1.0. Bed slope correction coefficient is 1.5 and power is 0.5. Since the concentration of upstream changes seasonally, 0.1 kg/m^3 and 1 kg/m^3 are used for dry season and flood season respectively. For the sea boundary, the concentration 0.1 kg/m^3 is used. The dispersion coefficient 0.5 is used. Sediment density is 2650 kg/m^3 and kinematics viscosity of water is 1.0 E-6. Since the grain size in the estuary changes from place to place, several grain sizes such as D50 0.00007 m, D90 0.00008 m are used. Bottom condition for concentration is applied at the position 0.2+0.01H. H is the water depth. Van Rijn (1984) formula is used as sediment transport relation. If wave effect is added, Bijker formula will be used. Bottom roughness is 0.03 m. Fixed layer is not present. The physical slope effect is taken into account through a correction parameter. The coefficient to include the effect of bed slope on the magnitude of bed load transport and the coefficient to include effect of slope on magnitude of suspended load transport are 0.5. The porosity is 0.4.

If the silt option is selected, it is assumed that all deposition and erosion is due to suspended sediment (bed load is irrelevant and is not modelled).

The Silt option uses the following advection-diffusion equation:

$$\frac{\partial hc}{\partial t}+\frac{\partial uhc}{\partial x}+\frac{\partial vhc}{\partial y}-\frac{\partial}{\partial x}(D_x h\frac{\partial c}{\partial x})-\frac{\partial}{\partial y}(D_y h\frac{\partial c}{\partial y})=E-D$$

where:

$$E=\begin{cases}0 & \text{if } \tau_{\text{bs}}<\tau_{\text{e}}\\ M(\frac{\tau_{bs}}{\tau_e}\text{-}1) & \text{if } \tau_{\text{bs}}\geq\tau_{\text{e}}\end{cases}$$

$$D=\begin{cases}w_s c(1-\frac{\tau_{bs}}{\tau_d}) & \text{if } \tau_{\text{bs}}<\tau_d\\ 0 & \text{if } \tau_{\text{bs}}\geq\tau_d\end{cases}$$

w_s is the settling velocity:

$$w_s = w_{s0} + \alpha_w c^n$$

and τ_{bs} is the effective shear stress:

$$\tau_{bs}=\beta_s\tau_b=\beta_s\rho g(\frac{u_s}{C})^2$$

where:

τ_d : critical shear stress for sedimentation
τ_e : critical shear stress for erosion
n: concentration power
w_{s0} : constant in settling velocity relation (m/s)
M: coefficient
α_w : factor in settling velocity relation
β_s : reduction coefficient for shear stress

In dry season, the critical shear stress for sedimentation, the critical shear stress for erosion and M parameter are 0.4 N/m^2, 0.7 N/m^2, and 0.0000001 respectively. In flood season, the critical shear stress for sedimentation, the critical shear stress for erosion and M parameter are 0.4 N/m^2, 1.2 N/m^2, and 0.00000005 respectively. The constant in settling velocity relation is 0.0001 m/s. The factor in settling velocity relation is 1. The power on concentration in settling velocity relation is 1.5.

4.1.4 Bottom Module

In the Bottom module the bed level variation are determined based on the (gradients in) the sediment transport fields as calculated by the Transport module. The module will execute one time step, being the time interval imposed by steering module Morsys. Similar to the transport module, it operates on the Flow grid. As a consequence, it has the same open boundaries as the Flow module.

The Bottom module is a sediment budget model that solves bed level continuity equation:

$$(1-\varepsilon_{por})\frac{\partial z_a}{\partial t}+\frac{\partial S_x}{\partial x}+\frac{\partial S_y}{\partial y}=T_d$$

where:

(S_x, S_y): the sediment transport components
Z_a: the bed level
ε_{por}: the bed porosity
T_d: the deposition or erosion rate

$$T_d=-\frac{\partial S_{sx}}{\partial x}-\frac{\partial S_{sy}}{\partial y}$$

where (S_{sx}, S_{sy}) represents the suspended sediment or silt transport components.

The porosity used in Bottom module is 0.4. As the bottom module operates on the flow grid, the number of boundary segments follow the specification of the Flow module. Constant bed level is used as boundary condition.

4.1.5 Model Adaptation

For this version of Delft 3D used in TU Delft, some mechanisms and processes can be simulated. For example the fluvial discharge and tide can be included in the model. The upstream sediment concentration in flood season and dry season can be specified in the model to study the effect of the sediment supply. The position of null point due to salt water intrusion can be studied under different combination of fluvial discharge and tide. Wind effect and wave effect can be included. The sediment exchange between channels and tidal flats can be also identified under different conditions.

But still some situations can not be simulated by this version of the software, such as floculation. Because of the mixing of salt water and fresh water, floculation will occur under certain salinity and temperature leading to acceleration of the deposition. This is very important in the Yangtze River Estuary but cannot be simulated now.

The dynamic condition of the Yangtze River Estuary is complicated. Fluvial discharge, tide, wind and wave are all important factors. The sediment of the estuary is very special too. The application area of different sediment transport formula is obvious. If the transport formula put forward by Dou Guoren, which is mainly based on the research work on Yangtze River Estuary and around coastal area and wave effect can be included, can be added to the transport formula option, better results may be obtained.

4.2 Pilot Application

The process-based numerical model, Delft 3D, is used to simulate the seasonal variation of the mouth bar in the Yangtze River Estuary.

The sediment in the estuary is very complex. In different entrance, the sediment composition is different. According to Zhou Jifu et al (1999), the mean diameter are 0.093 mm in the North Branch, 0.084-mm in the South Branch, 0.061 mm in the North Channel, 0.059 mm in the North Passage, and 0.029 mm in the South Passage. The difference is significant. So two transport modes, i.e. suspended mode and silt mode, are used to compare the results.

The affecting factors both in dry season and in flood season are used as input parameters.

For flow module, the mean discharge of 11000 m^3/s in dry season and the mean discharge of 44000 m^3/s in flood season are used for upstream boundary condition.

For transport module, the sediment concentrations of 0.1 kg/m^3 in dry season and 1 kg/m^3 in flood season are used as upstream boundary condition. For the seaside sediment concentration, 0.1 kg/m^3 is used as boundary condition.

The model is used to run 2 tide cycles both in flood season and in dry season.

The suspended mode is used first to simulate the morphology development of the estuary. The results are shown in fig. 4.2.1 and fig. 4.2.2. From the results, we may find sedimentation happens in the mouth bar area in the lower part of the North Passage in flood season. This is reasonable. But in dry season, sedimentation can still be observed in that part, although the sedimentation degree is reduced. In the South Passage the sedimentation and erosion patterns in dry season and in flood season are similar although the degrees are different.

Since the sediment in the mouth bar area is fine and suspended load plays a major role in the estuary under normal condition, which means no large instability of shoals in the estuary, silt mode can be reasonably selected to simulate the morphology development of the estuary.

If the silt mode is used, the results are shown in fig. 4.2.3 and fig. 4.2.4. In dry season, erosion occurs in the South Passage and in the lower part of the North Passage. In flood season, sedimentation occurs in the lower part of the North Passage and parts of the South Passage.

In fig. 4.2.1 ~ 4.2.4, minus value stands for sedimentation and positive value stands for erosion.

Comparing the simulation results with field observation, we may conclude that silt mode is better than suspended mode to be used to simulate the morphology development of the mouth bar area of the Yangtze River Estuary.

The sediment exchange between channels, i.e. the North Channel, the North Passage and the South Passage and tidal flats, i.e. Jiu Duan Shoal, Heng Sha Shoal, Nan Hui Bank-attached Shoal in the mouth bar area, is clearly shown in fig. 4.2.5 and fig. 4.2.6. Also the sediment exchange between waterways can be clearly identified.

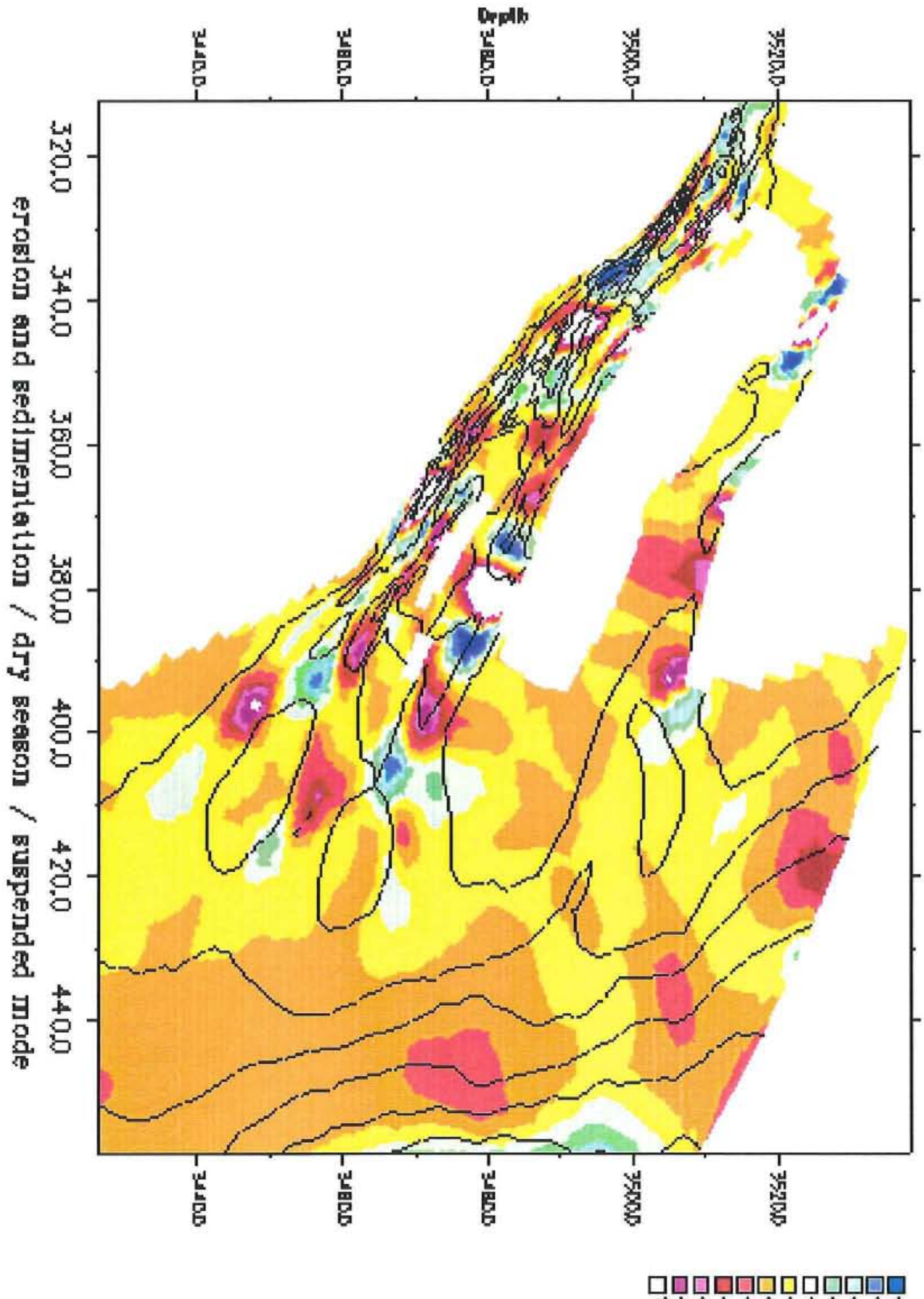

Fig. 4.2.1 erosion and sedimentation in dry season (suspended mode)

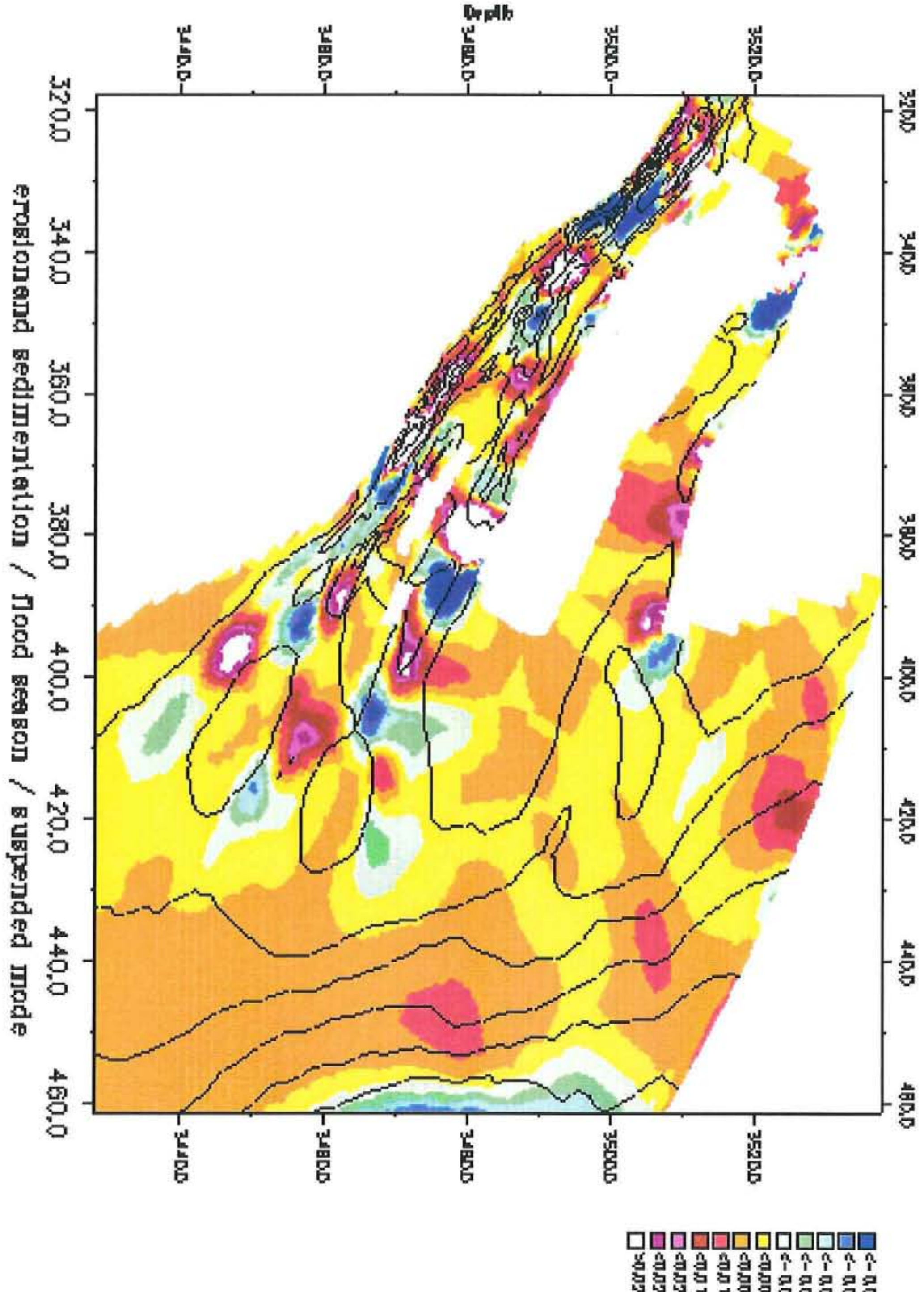

Fig. 4.2.2 erosion and sedimentation in flood season (suspended mode)

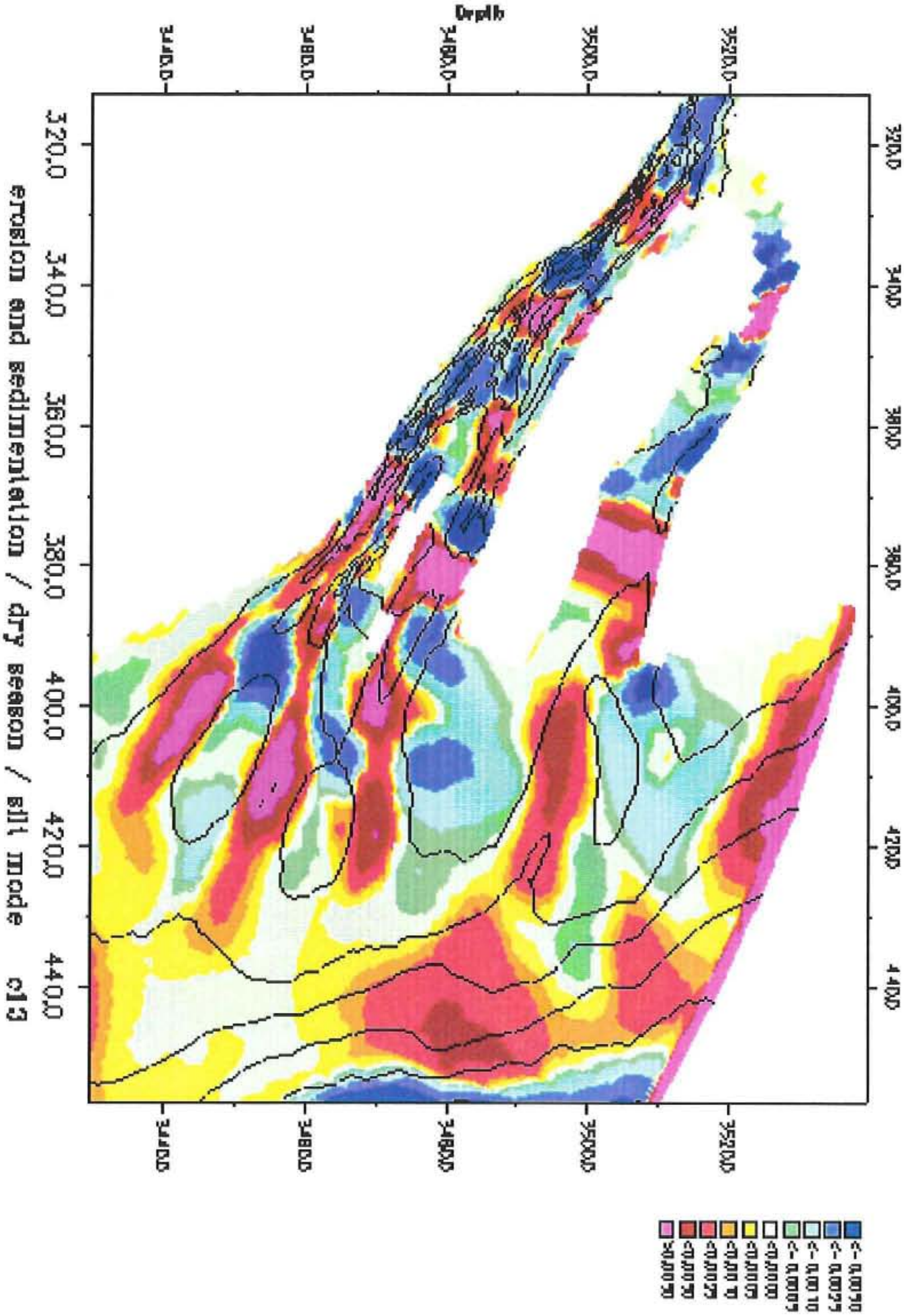

Fig. 4.2.3 erosion and sedimentation in dry season (silt mode)

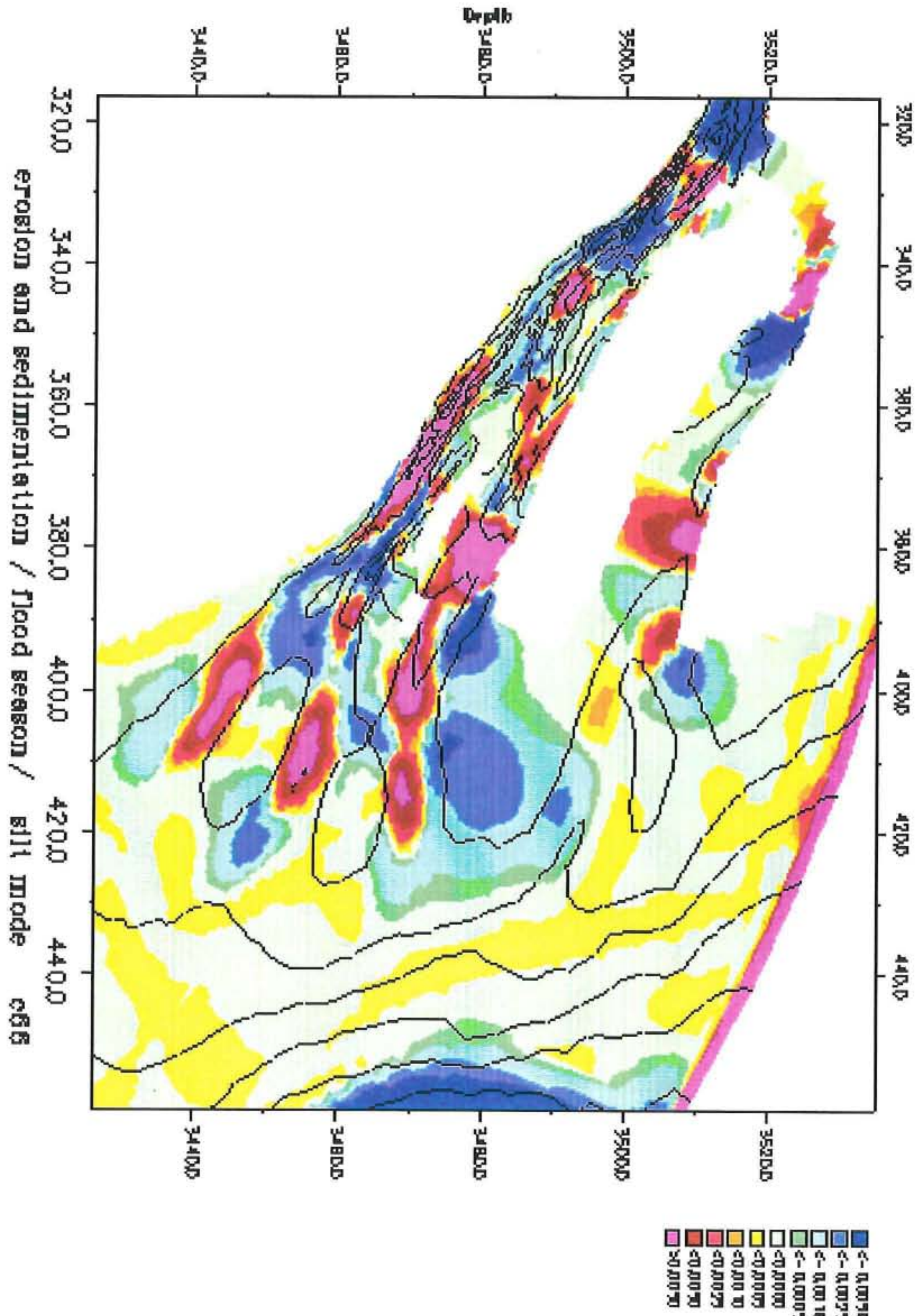

Fig. 4.2.4 erosion and sedimentation in flood season (silt mode)

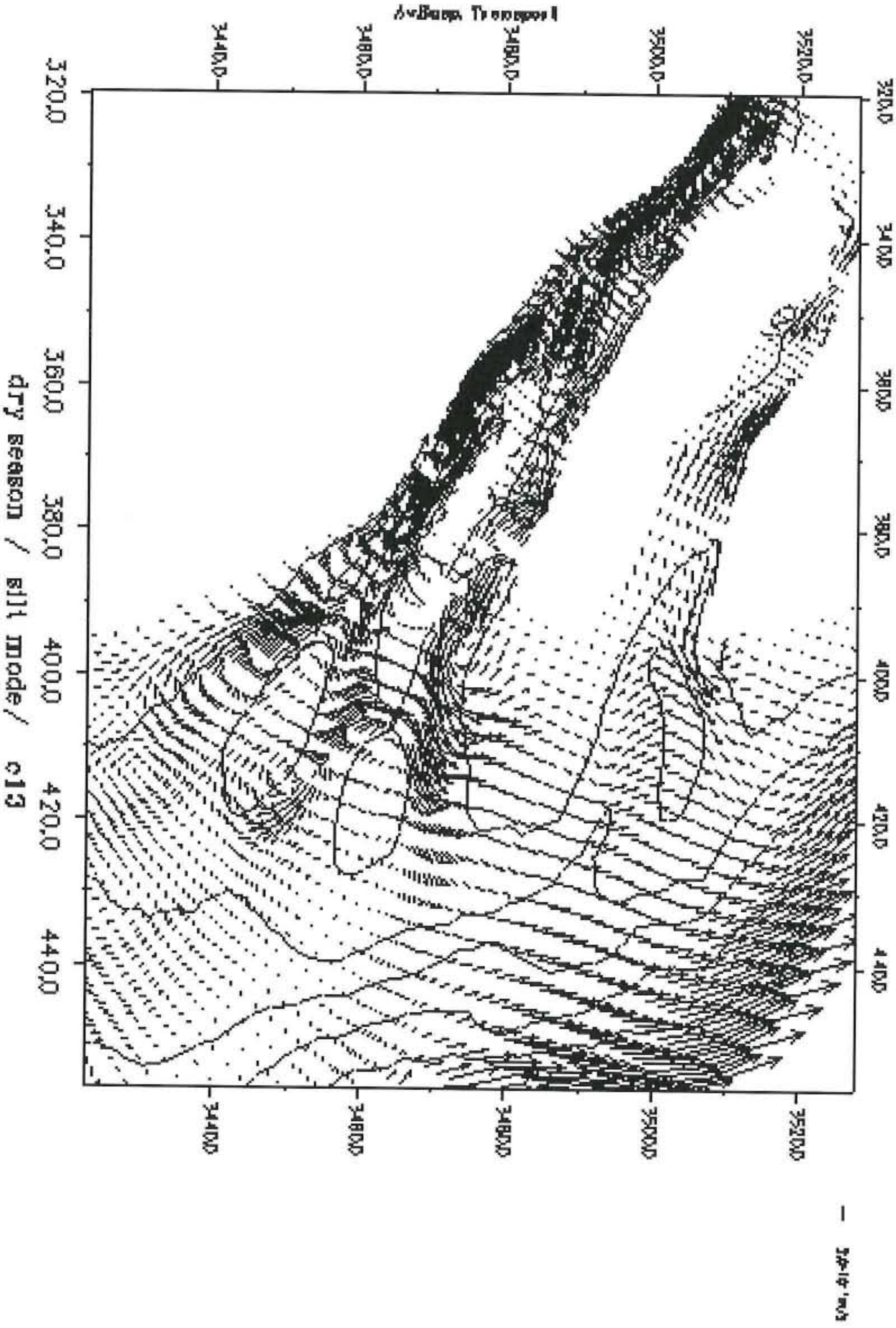

Fig. 4.2.5 Averaged sediment transport in dry season (silt mode)

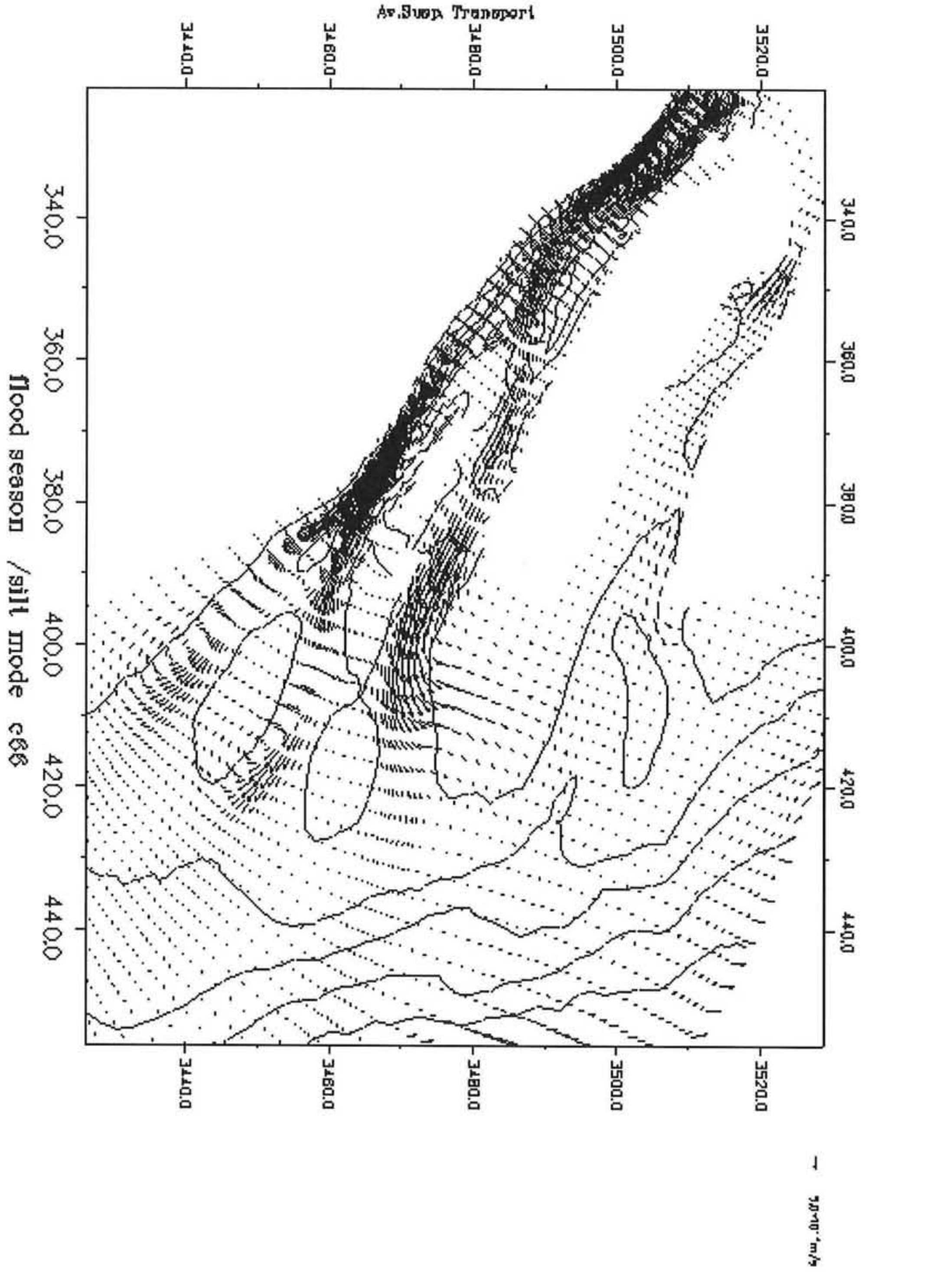

Fig. 4.2.6 Averaged sediment transport in flood season (silt mode)

5 Future Work

The ability to understand and predict the morphological behaviour of the estuary, including channels and tidal flats, is an important issue in estuary management.

In the past, physical model and field survey were mainly used to study the estuary. Recently mathematical models have come into the research area. Mathematical models are particularly attractive because of their flexibility and because the complexity of the system makes physical scale modelling very difficult, especially when it concerns long-term morphological evolution (De Vriend, 1989).

In 1980's the sedimentation in navigation channel is studied through the analysis of the flow field before and after the engineering construction through physical scaled model and numerical model. Since 1990's, with the development of numerical model, new method is available. Morphological models are used directly to investigate the effect of engineering construction. They have become possible to model many complex physical processes, such as waves, currents, sediment transport and morphological changes in estuary. Such models enable researchers to develop and test hypothesises on how an estuary works, and to identify the most important knowledge gaps. They also enable researcher to analyse the response of an estuary to proposed engineering measures.

Processes based mathematical model is an effective tool to investigate the relationship between hydrodynamics forcing, sediment transport and morphology development. Due to our knowledge level the methodology involves simplification of the extremely complex hydrodynamic and sediment transport processes, by identifying those which appear to be dominant. If main physical processes are properly involved in the model, it can be used to study the mechanisms of physical phenomena.

The relationship between numerical models and physical measurements is very close which gives a healthy progress in understanding. Numerical models give insights into what measurements need to be done, or which processes needed to be quantified better, and the measurements refines the model (Dyer, 1998).

Barforms are widely developed in estuaries. The mouth bar system is very complex. It is driven by partly unpredictable exterior forces, such as waves and storm surges. Its behaviour also involves a wide range of space and time scales. Variations of exterior force and response of the system to exterior forces impose this behaviour. Estuarine barforms are understudied as indicated by the absence of an adequate classification system. The understanding of bar genesis is limited. (Dalrymple and Thodes, 1995) At present, a lack of such understanding limits our ability to predict the response of mouth bar to changes in external circumstances, for example engineering works, sea level rise or changes in sediment supply.

Until now, most studies are concentrated on field survey and physical scaled model. Some numerical models have been developed to study the effect of deep navigation channel project. Generally speaking, less effort has been made on the systematic study on mouth bar system.

The main aim of this study is to enhance our understanding of the relationship between the observed situation of mouth bar area and the physical processes, which combine to create and mould them. The behaviour of morphology development of mouth bar under hydro-meteo conditions, such as flood season discharge and dry season discharge salt water intrusion, spring and neap tide, wind, wave, and typhoon will be studied through the process based numerical model. Since the grain size of the bed material is very characteristic and part of it is in the range of clay, cohesive nature should be taken into account. The relationship between hydrodynamic forcing, sediment transport and the morphology development (shape) in the mouth bar system including the mudflat and channel will be investigated using process-based mathematical model. General properties and mechanisms of the mouth bar area are expected to be indicated by the model results. Relative importance of the factors will also be identified. Mixing is very important in the Yangtze River Estuary and mixing occurs around mouth bar area. But the affecting factor leading to mixing around mouth bar area is not clear and should be studied further.

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