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MIXING OF SALT WATER AND FRESH WATER IN THE CHANGJIANG RIVER ESTUARY AND ITS EFFECTS ON SUSPENDED SEDIMENT

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ABSTRACT: Using field hydrological data, the relationship between the mixing of salt water and fresh water and the tidal range/ high tidal level in the Changjiang (Yangtze) River estuary is discussed, and the transporting and concentrating of suspended sediment in the estuary were also analysed in respect to the circulation, flocculation and stratified interface resulting from mixing.The calculation results by two–dimentional box model have confirmed the effects of the circulation on the concentrating of suspended sediment in the estuary. The conclusions derived from this work have deepened the understanding on the mixing in the Changjiang River estuary and are of significance in both theory and practice.

KEY WORDS: mixing of salt water and fresh water, suspended sediment, circulation, flocculation, the Changjiang River estuary

I. INTRODUCTION

The Changjiang River estuary is a large and complicated estuary. Downstream from Xuliujing, the estuary branches at Chongming Island, Changxing Island and Jiuduan shoal. And the runoff discharged into sea through the four outlets–North Branch (NB), North Passage (NP), North Channel (NC) and South Channel (SC). Complicated topographic conditions affect current structure. This causes the differences in mixing processes among channels and in mixing types between upper– and lower–reaches in the same channel. The hydrological conditions of the Changjiang River estuary are also complicated. the runoff varies in different years and different seasons. The tidal current varies in half a month, a day and half a day. The combination of different runoff and different tidal current enable mixing intensity at the same location to vary with time. Spacial difference and temporal variation of the hydrological conditions enable several mixing types to exist in the Changjiang River estuary. Using field hydrological data, this paper analysed the mixing characteristics and the regularities of its spacial and temporal variations in each channel of the Changjiang River estuary, its dynamical mechanisms, as well as the effects of mixing on the concentrating and transportation of suspended sediment. Fig.1 shows the surveying stations.

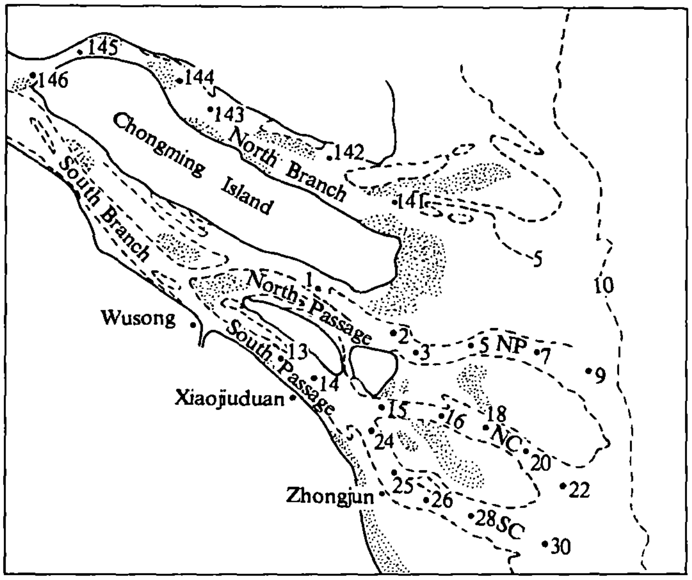

Fig.1 The Changjiang River estuary and hydrographic stations

II. RELATIONSHIP BETWEEN TIDAL PHASES AND MIXING OF SALT WATER AND FRESH WATER

We must consider the variation of the mixing rate with time when we study mixing of salt water and fresh water. If we merely consider the time mean distribution of velocity and salinity, it may lead to misunderstanding on the mixing effect and its mechanisms in a tidal cycle. The study on mixing rate varying with time by Bowden[1] indicated that when current velocity reached its maximum, the vertical eddy diffusion coefficient also reached its maximum and is 3—5 times of its time mean value. Haas study[2] indicated that vertical mixing was related to tidal range and was also closely related thigh tidal level. Byrne et al.[3] pointed out that in the estuarine area the relation between tidal regime and tidal level was logarithmic instead of linear. In the Changjiang River estuary, the existence of shoals make the tidal regime enlarge more at higher tidal level than at lower tidal level. Therefore, the height of high tidal level has greater influences on the current velocity and much greater influence on the mixing degree than the magnitude of tidal range.

Fig.2 shows the variation of mixing in a tidal cycle at the stations which are located at

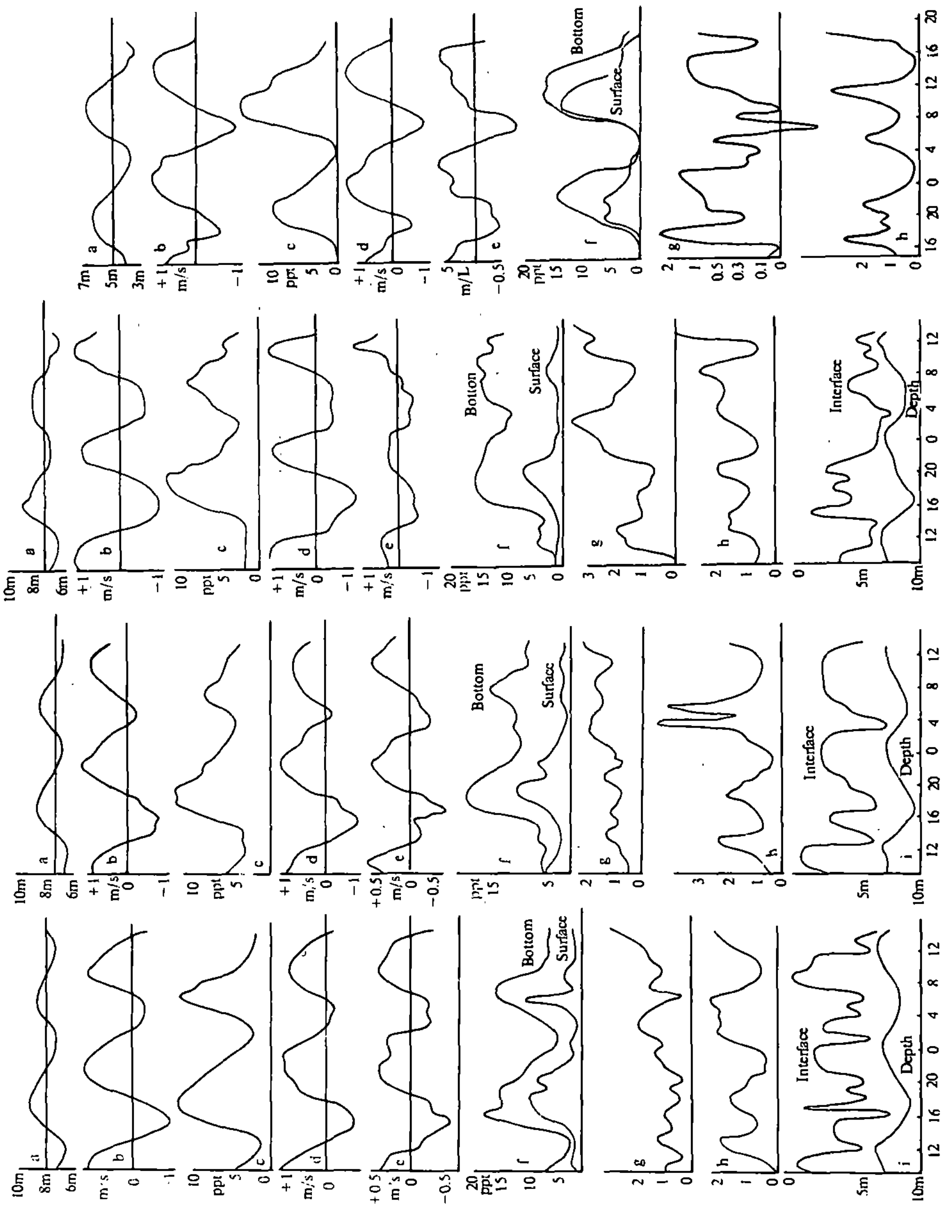

Fig.2 Mixing variation in a tidal cycle

a. tidal level, b. vertical mean velocity, c. vertical mean salinity, d. surface velocity, e. bottom velocity, f. surface and bottom salinity, g. stratification coefficient, h.stratified index, i. depth of interface the salt water and fresh water confront (Fig.2). From figures 2a and 2b, we can find the common characteristics of these stations: in the two tidal cycles a day, the tidal ranges are not equal, and neither are the high tidal levels. This has a little influence on ebb current, i.e. ebb current velocity increases at higher high tidal level. Furthermore, this affects greatly the flood current, i.e. flood current velocity increases remarkably at high tidal level. This is a dynamical cause of the different mixing degrees due to different high tidal levels. From the figures we can also see that the time lag between the ebb/ flood current shifting and low tidal level, and between flood/ ebb current shifting and high tidal level is less than 1 hour at 5# Station NP, 2—3 hours at 24# Station in SC and 1—2 hours at both 16# Station in NP and 142# Station in NB. Figure 2c shows mean vertical salinity. Comparing with figures 2a and 2b, we can see that the varying tendency of salinity accords with that of tidal level, in other words, higher high tidal level accords with maximum of salinity, lower high tidal level accords with hypomaximum of salinity, lower low tidal level accords with minimum of salinity and higher low tidal level accords with hypo—minimum of salinity. The time lag between the maximum of salinity and high tidal level and between the minimum of salinity and low tidal level is very short at 5# Station, and longer at 24# Station, the other two stations are between them. That is to say that the variation of salinity is related much closer to the tidal current phase, i.e. the maximum of salinity appears at flood slack and the minimum of salinity at ebb slack.

Figures 2d and 2e show the variation of surface and bottom velocity with tidal phase. Generally, flood current begins earlier at bottom than at surface, and ebb current begins earlier at surface than at bottom. This means that flood period is longer at bottom than at surface, and ebb period is shorter at bottom than at surface. When current shifts its direction, there will appear the phenomenon that the upper layer water flow downstream and the lower layer water flow upstream. This will contribute to salt water to convey upstream. At surface, ebb current velocity is larger than flood current velocity. And at bottom, flood current velocity is larger than ebb current velocity. The velocity difference between surface and bottom is larger at ebb period than at flood period. This means that in the flood current period the bottom shearing force is larger, causing vertical diffusion mixing stronger, and in the ebb current period the shearing velocity between the upper and lower layers is larger, causing entrainment more active.

Figure 2f shows the variation of surface and bottom salinity with tidal phase. The difference of salinity between surface and bottom layers is larger at lower high tide than at higher high tide. This is mainly due to variation of surface salinity, while the variation of bottom salinity is small. The surface and bottom salinity at 142# Station in NB approaches to zero at slackwater, i.e. there fresh water dominates. With current shifting to flood, surface and bottom salinity increase gradually at the same time. Till floodswift period, the salinity difference between surface and bottom is little all along. This means that at this period, vertical mixing is very strong and the salinity gradient appears mainly at horizontal direction. After current shifting to ebb, the stratification phenomenon appears. The salinity difference between surface and bottom reaches its maximum before ebb swift current. Till ebb slack, as fresh water flow downstream, 142# Station is gradually dominated by fresh water again. From this we can see that vertically homogeneous mixing type and partial mixing type occur alternatively in a tidal cycle. With reference to the conditions of other three channels in South Branch (SB), salinity difference between surface and bottom can not represent vertical mixing degree because under the condition of different vertical mean salinity, the same salinity difference represents different mixing degree. Therefore, it is proper to use stratification coefficient $N=(S-Ss)/S$ to indicate stratification degree. Figure 2g shows the value of N varying with the tidal phase. N reaches its maximum at ebb slack and minimum at flood slack, and decreases gradually in the flood period and increases gradually in the ebb period. This means that both the bottom salinity diffusion and advection are the important factors affecting mixing process. The figure also reflects that the stratification is somewhat better at lower high tide than at higher high tide.

Figure 2h shows the variation of stratification index $S=log_{10}(h/|Us|3)$ with tidal phase. The value of S reaches its minimum as the velocity reaches its maximum. The value of S is smaller at ebb swift current than at flood swift current because surface velocity is larger and the water depth is smaller at the ebb swift current period than at the flood swift current period. It should be noticed that in the flood period, the turbulence in the lower layer is strong and the energy is consumed through vertical diffusion caused by bottom shearing. Therefore, vertical mixing is much stronger at the flood swift current period although the value of S is smaller at the ebb swift current period. Obviously, this is due to that mixing action of diffusion is much stronger than that of entrainment. The advection at ebb period is also an important factor causing better stratification.

Figure 2i shows the variation of interface (maximum of vertical density gradient) height with tidal phase. Interface height is closely related with tidal level. It is high in high tide and low in low tide. The general tendency of interface height is extend from the lower layer of upstream to the upper layer of downstream although it may goes up and down longitudinally. With the maximum salinity gradient zone moving upstream and downstream along longitudinal direction in a tidal cycle, for a fixed station, interface reaches its highest at flood slack and lowest at ebb slack. Furthermore, in the flood period, turbulence in the lower layer of water is stronger, and in the ebb period, entrainment in the upper layer of water is more active. This is also a factor which affects the interface height. The phenomenon is especially obvious at 24# Station.

III. EFFECTS OF MIXING ON SUSPENDED SEDIMENT

Mixing of salt water and fresh water can cause the changes in the characteristics of particle setting and the estuarine current structure. Flocculation caused by mixing enable suspended sediment to set easier. Circulation is beneficial to bottom sediment moving upstream. Hence the effects of mixing are important mechanisms of promoting sediment accumulation in estuary.

The mean medium diameter of suspended sediment in the Changjiang River estuary is 8.6 μm. Fine silt (8 μm − 4 μm) is the dominant grain, and together with the clay particle (< 4 μm), its weight exceeds 70% of the total particles. The setting velocity of these particles is at the order of 10^{-3} — 10^{-4} cm / sec.[4] While the vertical upward advection velocity caused by mixing in the Changjiang River estuary, calculated from two—dimentional box model, reaches 10^{-3} cm / sec order. That is to say that the majority of suspended sediment in the Changjiang River estuary can not sink as single particle. The component of these particle is mainly illite, kaolinite and montmorillonite. After entering the confrontal area of salt water and fresh water, because of flocculation, their diameter increases and can reach 30 μm, and the setting velocity of the particle can increase 1—2 orders. The material of fluid mud in the Changjiang River estuary is mainly coarser silt with a medium diameter of 20—30 μm,[5] which is much larger than that of suspended sediment. This verifies that flocculation is the main factor for the siltation of suspended sediment in the Changjiang River estuary. The turbidity maximum exist at middle and lower layers in each channel of the Changjiang River estuary. Their central locations, during the investigation period, where at 7# Station in NP, 18# Station in NC, 24# Station in SC and 141# Station in NB, which accord with confrontal area of salt water and fresh water. Sediment flocculation and setting are very active in this area.

Fig.3 shows that in each channel there is a circulation with the net flow seawards in the upper layer. The active range and the intention of circulation are different in each channel. The circulation in NP occurs at downstream of 5# Station. The downstream current in the upper and middle layers is very strong while the upstream current in the lower layer is weak. This accords with the fact that the runoff in NP is large. The circulation in the NC occurs at downstream of 16# Station. Its downstream current in the upper and middle layers is weaker than that of NP, and its upstream current in lower layer is stronger than that of NP. This is due to the runoff being smaller in NC than in NP. In SC, the downstream current in the upper layer is very weak, while the upstream current in the middle and lower layers is very strong, and the circulation develops upstream to enter SE. The circulation in NB is limited at the downstream of 142# Station.

The circulation structure change induced by mixing affects the distribution and transportation of suspended sediment. Circulation not only troubled river sediment to get into sea, but also capture the sediment moving upstream. Fig.4 shows the net sediment flux in each channel in the Changjiang River estuary. From the figure we know that in NP, downward sediment flux in the upper and middle layers is much larger than upstream sediment flux in the lower layer. While in SC, the upstream sediment flux in the middle and lowerlayers is much larger than the downstream sediment flux in the upper layer. And situation in NC is between that of NC and SP. It accords with the fact that the runoff in each channel is NC > NP > SP. Referring to Fig.3 we know that the sediment transport flux is related closely to longitudinal circulation, but the location of the converging zone of sediments and that of currents are not at the same point, and the location of maximum of sediment transport flux is not coincided with that of circulation. This is because there are differences between the vertical distribution of net current and that of suspended sediment.

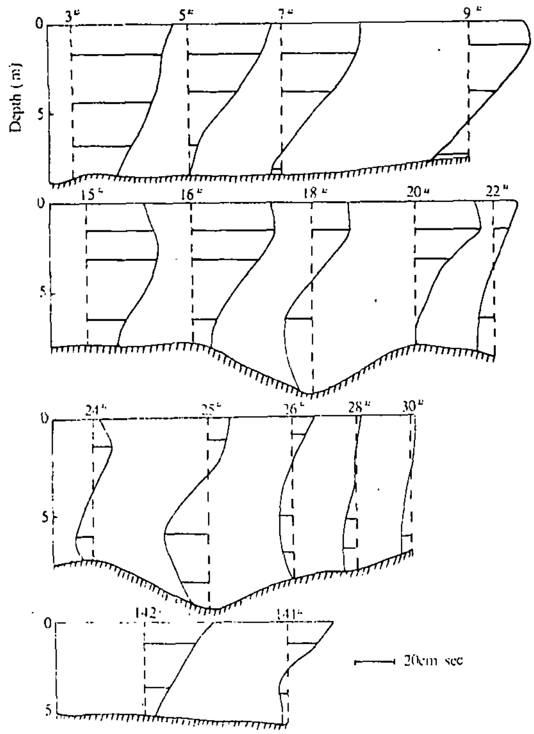

Fig.3 Net velocity

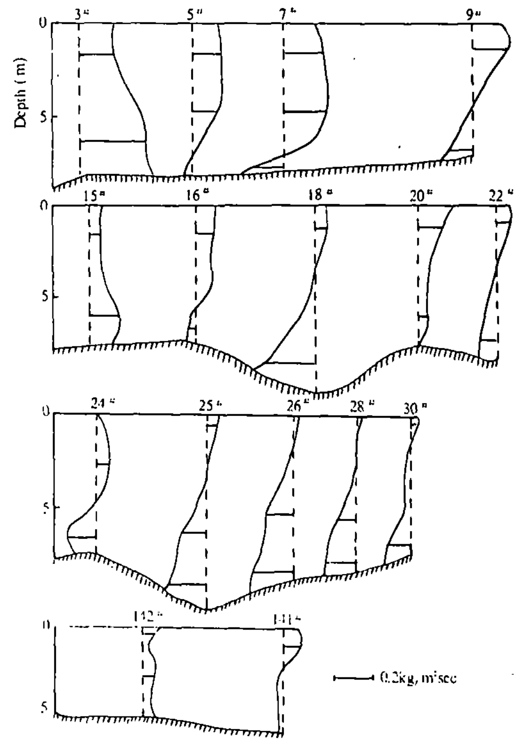

Fig.4 Net sediment flux

Fig.5 shows the relations among suspended sediment quantity, dominant current and dominant sediment flux. From the figure we know that the position of maximum content of suspended sediment at the lower layer is located at the downstream of null point. For example, the null point of NP is located between 5# Station and 7# Station and is somewhat close to 5# Station. But the maximum content of sediment is located at 7# Station. The reason is that downward from 5# Station, there is a confrontal area of salt water and fresh water, in which flocculation plays an important role in concentrating of suspended sediment at the lower layer although silted sediment in the Changjiang River estuary mainly comes from the river. Downward from null point, the bottom shearing force of flood current become strong and sediment resuspended. This also causes the increases of the sediment content in the lower layer. Thus, sediment content of upstream current in downstream of null point is more than that of downstream current in upstream of null point. Therefore, the center of high content of suspended sediment is often located the downstream of the null point. The concentration of suspended sediment are 2.7214 kg/ m^3 in NP, 2.0217 kg/ m^3 in NC, 2.0014 kg/ m^3 in SC. This is related to the fact that the turbulence of tidal shearing in bottom is NP> NC> SC and that the quantity of runoff and sediment supply is NP> NC> SC. From the figure we also know that the converging point of bottom sediment is located at the upstream of the null point. This is due to that bottom shearing force is stronger at flood period than at ebb period, and that sediment content is more at flood period than at ebb period.

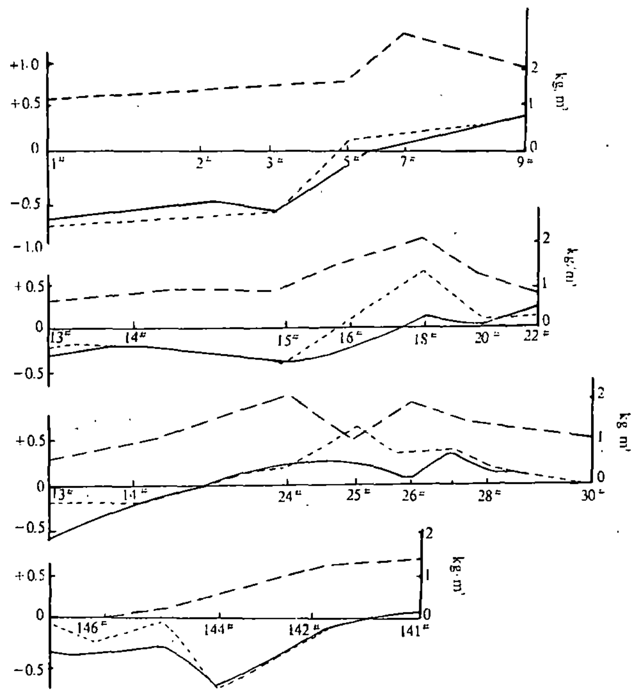

Fig.5 Sediment content (– • –), predominant flow (—) and predominant sediment flux (—)

The sediment transport flux is related to tidal range as well as to tidal phase. When tidal range is large, the vertical mixing is strong, suspended sediment content in the upper and middle layers is high, and the downward sediment flux at the downstream station is larger. When tidal range is small, the stratification is well developed, suspended sediment is retracted in the lower layer, and the downward sediment flux at the downstream station is smaller. For example, in NP, the sediment content at 3# Station and 5# Station at higher high tide is larger than that at lower high tide, and at 7# Station, downward sediment flux in the upper and middle layers at higher high tide is larger than that at lower high tide.

The calculation of two–dimentional box model has confirmed the effects of estuarine circulation. The calculated and surveyed suspended sediment contents coincide well in both value and location. The results of calculation also indicate that the vertical upward advection velocity caused by mixing of salt water and fresh water is at the order of 10^{-3} cm / sec.

IV. CONCLUSIONS

The main dynamical mechanisms controlling mixing of salt water and fresh water in the Changjiang River estuary are the bottom shearing turbulent diffusion caused by flood current and the advection caused by ebb current. The entrainment caused by velocity shearing between the upper and lower layers of water column is limited. There is an obvious variation in mixing process with tidal phase. The intensity of vertical mixing at flood period is greater than that at ebb period. The stratification develops better at smaller tidal range and lower high tidal level than at larger tidal range higher high tidal level. The stratified interface restracted the vertical diffusion of suspended sediment, thus changed the transportation process of suspended sediment in the estuary. The quantity of suspended sediment exported from the estuary at larger tidal range / higher high tidal level is much more than that at smaller tidal range and lower high tidal level. The bottom sediment converging point and the turbidity maximum are located at the upstream and downstream of the null point, respectively. Affected by estuarine circulation and flocculation, the confrontal area of salt water and fresh water is the position in which suspended sediment is detrained and pollutants are concentrated easier. The channel in which runoff is heavier and frontal zone is located downstream favours to export suspended sediment and pollutants from the estuary at larger tidal range / higher high tidal level.

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