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CONTEMPORARY EVOLUTION PROCESS OF THE HANGZHOU BAY

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Abstract : Large amount of field data shows that sediment deposition is the main factor for contemporary evolution process of the Hangzhou bay. During recent forty years, the total volume of sediment deposition is about 2.12 billion m^3. The net water and net sediment transport is positive in the waters around the north bank. The area is controlled by flood tide and is scouring area, so that the deep channel is formed. At the same time, the net water and net sediment transport is negative in the waters around the south bank. The area is controlled by ebb tide and is deposition area, so that the Andong flat has been developed. It analyses the contemporary evolution process of the two areas and the dynamical mechanism.

Key words: Funnel-shaped bay, Scouring area, Deposition area

1. PREFACE

Hangzhou bay, which is a typical funnel-shaped bay, is out of Qiantang Estuary, adjoin the Changjiang Estuary. In 1960's Chen Jiyu, who is an academician of China, has full-scale lucubrated the form and historical changes of Hangzhou bay. According to the large amount of field data it analyses the contemporary evolution process of Hangzhou bay. Not only is it helpful to establish the planning of Hangzhou bay, but also it is valuable in scientific field.

2. PLANE SHAPE AND WATER SEDIMENT MOVEMENT OF HANGZHOU BAY

2.1 PLANE SHAPE

The total catchment area of Hangzhou bay is about 5,000km^2. It is bay head that is the connect from Ganpu in north side of Hangzhou Bay, to Xisan gate at the common boundary of Yuyao and Cixi., about 20km wide. It is mouth of the Hangzhou bay that links the Nanhuizui of Shanghai in north coast with Dayou mountain in Yongjiang estuary along southern coast, about 20km wide. Hangzhou bay is typical funnel-shaped bay. Change of the area's width can be expressed by Eq.(1):

$$B_{(x)}=B_0 e^{ax} \tag{1}$$

where origin of coordinate of x situates the center of mouth section of the bay, positive coordinate direct to bay head of the bay, B_0 is the width of bay mouth (100km), $B_{(x)}$ is the width of the section which coordinate is x. Coefficient of contraction α =-0.016.

2.2 WATER AND SEDIMENT MOVEMENT

2.2.1 The distributing rule of tidal range

From mouth to bay head of Hangzhou bay, the high tidal level jump up and the low tidal level decreases. So tidal range from mouth to bay head of the bay increases gradually. The distribution of contour is shown in Fig. 1. For the smoothness in base and large depth (8-10m), the bottom friction can be neglected during the tidal wave propagates to Hangzhou bay. Then according to the conservation equation, change of tidal range can be expressed as :

$$\frac{\Delta H(x)}{\Delta H_0} = \mathrm{e}^{-\frac{1}{2}\alpha x} \tag{2}$$

where ΔH_0, $\Delta H_{(x)}$is the tidal range of flood tide and ebb tide in the section which coordinate is x, coefficient of contraction α =-0.016. Eq.(2) is the famous Green's Law, namely effect of funnel. The tidal rang in axis of Hangzhou bay in Fig.1 merge the result of the Eq.2.From mouth to bay head of Hangzhou bay ,the reason for tidal rang increase linear is the tidal wave of open sea influenced by contracted bank when propagate into bay, so energy congregated , just as mentioned above—effect of funnel.

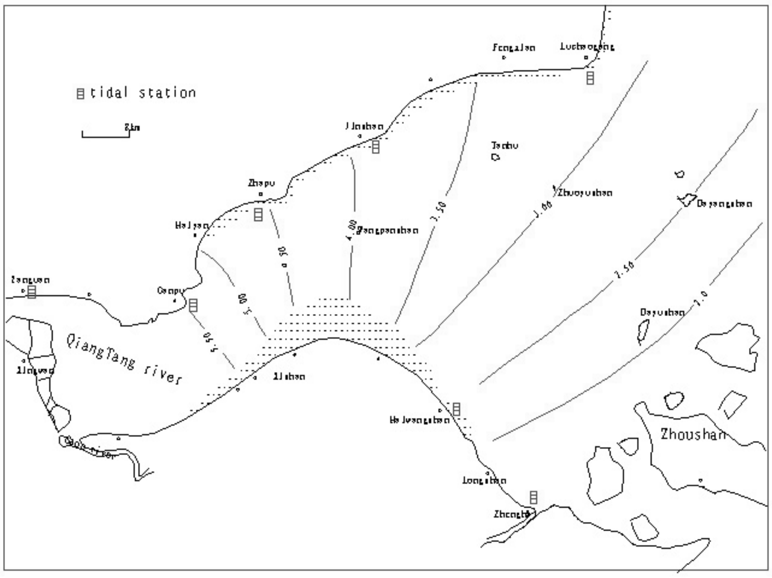

Fig. 1 Map of average tidal range in Hangzhou bay

2.2.2 Characteristic of water transport and sediment transport

According the hydrological date of Hangzhou bay (accumulate 30 points), we can get the character of water transport and sediment transport in Hangzhou bay. The isoline of parameter (v_f/v_e) and (q_{fs}/q_{es}) can be shown as Fig.2 and Fig.3.Where v_f refer the maximum average velocity of flood tide, v_e refer the maximum average velocity of ebb tide; q_{fs} ,q_{es} refer the sediment transport in per width of flood tide and ebb tide. The following should be noticed in Fig.2, 3. North of Wanpan mountain(upside central line) , velocity of flow and sediment transport in per width of flood tide is larger than ebb tide, namely v_f/v_e >1, q_{fs}/q_{es} >1; south of Nanpan moutain ,it's opposition ,namely v_f/v_e <1, q_{fs}/q_{es} <1.As mentioned above ,the dynamical axes of flood tide and ebb tide is different, the path of water and sediment transport of flood and ebb tide is different too. The north area controlled by flood tide, net water and net sediment transport is positive, south area controlled by ebb tide, net water and net sediment transport is negative. The result of two-dimensional tidalmodel shows there will be a influx at bay mouth from different way. And it extruded by the Andong flat and the force of gravitation when wave to bay head of bay, so main current of flood tide moving northward .The area in south of mouth bay controlled by ebb tide, slope become big, the main current moving south.

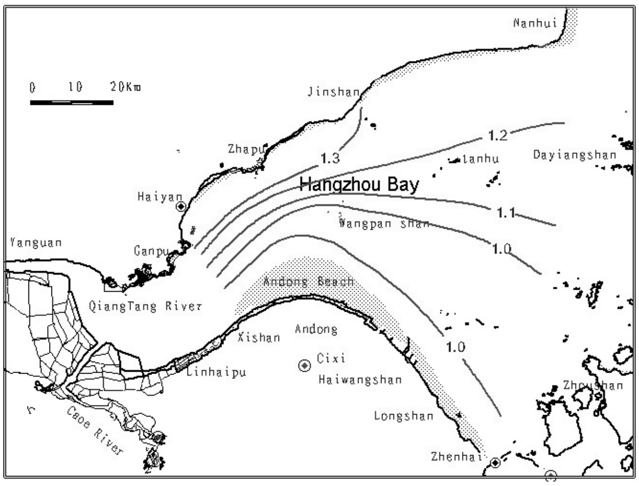

Fig. 2 The isoline of parameter (v_f/v_e) in Hangzhou bay

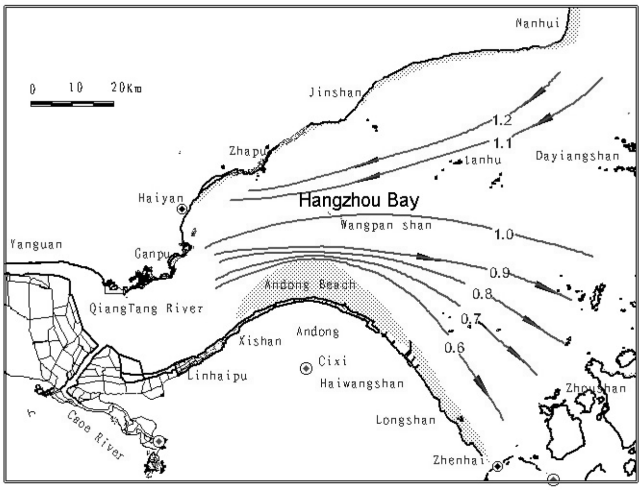

Fig. 3 The isoline of parameter (q_f/q_e) in Hangzhou bay

3. THE CHARACTER OF DEPOSITION UPSIDE HANGZHOU BAY AND ORIGIN OF SEDIMENT

The water area from Ganpu to Jinshan upside Hangzhou bay is about 1,600 square kilometers, about 1/3 of the whole bay area. After 1959's, there are 2 or 3 topography measurement in this area. More than one hundred charts have been got. All that is the credibility bases for analyze the course of evolution and the character of erosion-deposition.

3.1 THE COURSE AND CHARACTER OF AGGRADATION AND SCOUR IN UPSIDE

After studying the filed measurements data, we gain the change of cubage under average high tidal level of Hangzhou bay, from the parameter, the character of aggradation and scour can be presented in Table 1.

Table 1 Change of cubage under average high tidal level and the volum of scour-deposition of Hangzhou bay **unit:billion –stere**

Year	1959	1972	1980	1985	1990	1995	2000	Total
cubage	18.23	18.135	19.286	18.055	17.68	17.184	16.801	
Volumeof scour-deposition		-0.095	+1.151	-1.231	-0.375	-0.496	-0.38	-1.426

Note: cubage minish “-”indicate deposition, cubage increase “+”indicate scour

From this table, the accumulative total of deposition is about 1.426 billion-stere, thickness of deposition is about 0.90m.In this table, from 1959 to 1972,change of cubage is small, indicated that deposition balance to scour; from 1972 to 1980 ,the cubage is increased, riverbed be scoured, after 1980, cubage reduce gradually , deposition happened in riverbed. The topography charts of April and November in the same year indicated that cubage of April larger than November, tested riverbed in upside of Hangzhou bay scour in winter(November of last year to March of this year); deposition in summer(April to October), extent between scour and aggradation about 0.2-0.3 billion-stere.

Runoff in Qiangtang river have seasonal change, the riverbed of Qiangtang Estuary upside of Ganpu deposition in winter and scour in summer. Qiangtang water area has the exchange of sediment with Hangzhou bay, as showned in fig.4.Which indicated that the character of scour-deposition in riverbed of Qiangtang water area and Hangzhou bay is opposite, exchange of the two water area is frequent.

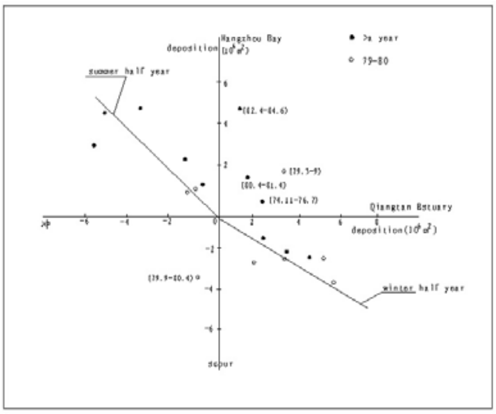

Fig. 4 Sediment exchange between Qiangtan estuary and Hangzhou bay

3.2 THE DISTRIBUTING OF SCOUR AND AGGRADATION

The deep coast bank of trough and Andong flat in south bank are two important resources in Hangzhou bay. The request for using resource of water area, sediment transports and circumstance is different. So it is the most basis for using the two resource is the distributing of scour and deposition and mechanism.

The accumulative total of deposition is about 1.426 billion-stere, distributing chart shown as fig.5. From Ganpu to Changqian present deposition, thickness of deposition is about 1.0-3.0m,1/3 of the area from Changqian to Jinsahn present scour, range of scour from 1.0-3.0m,near the bank it can reach 3.0-5.0m, 2/3of south area present deposition ,scope reach 1.0-2.0m. The maximal scope of deposition in Andong flat reach 4.0-5.0 m. Therefor during lately 40 years ,from 1978 to 1980 Qiangtang jiang water area be dry year ,riverbed upside Ganpu present deposition ,Ganppu downside present scour, in Table 2, 1980 the volume increase, compare with 1978,the amount of scour about 0.958 billion-stere, the amount of scour about 0.32 million stere per year. During this time, most sediment from estuary is head off for inning. In 1981-1984,Qiangtang river runoff become abundance, based on filed measurement, the amount of sediment of scour from estuary is small, but back sediment deposition from upside of Hangzhou bay is about 1.23 billion-stere. The average back sediment deposition is about 0.31 million-stere per year. This sediment comes from out of Hangzhou bay.

As mentioned above, during lately 40 years, influence by runoff of river-basin, riverbed upside of Hangzhou bay present scour and deposition. The result of river harness and polder is deposition, and it is irreversible process. The plane charts of scour-deposition indicate that deposition present in north trough from Ganpu to Chanqian, scour present in north trough from Chanqian to Jinshan, deposition present in floodplain of Andong. So the analysis of the contemporary evolution process of Hangzhou bay and the character of scour-deposition is helpful for using the north port, resource of sea-route and south floodplain.

3.3 CHANGE OF AGGRADATION AND SCOUR ABOUT DOWNSIDE OF HANGZHOU BAY

Area of downside from Jinsan to Wankou about 3,400km^2,about 2/3 Hangzhou bay area, riverbed is smoothness, average depth about 8-10m.the influence of Qiangtan estuary for water area is small, controlled by dynamical of sea, the change of aggradation and scour is slowness .Landform measurement and hydrological date scarcity. This paper choose the detailed date of 1959\1989\1997 (lack the date of south of Qijiebamei island) analyze the face of aggradation and scour of riverbed ,as showed in Table 2.

Table 2 character of scour-deposition of downside Hangzhou bay during lately 40 years

year	1959	1989	1997	Total
cubage below 0m	23.671	23.054	22.98	
Volumeof scour-deposition	-0.617	-0.074		-0.691

From Table 2,in this area riverbed aggradation during lately 40 years is about 7.0 million stere ,average depth of aggradation about 0.26m.the ration of average aggradation is 6.8mm/a. According to the filed measurement from 1920 to 1959, ration of average aggradation is 5.4mm/a,the two ration is closed .so sediment in downside of Hangzhou bay is deposition, and the velocity is slow. The first reason is the fine silt, the second reason is sediment transport and the high wind power .

3.4 SOURCE OF SEDIMENT

According to the historical information, Chen ji-yu considered that the volume of sediment in Qiangtang Estuary is about 425 million-stere, this sediment comes from the sea. According to abundance filed measurement of landform, this paper considered that the volume of sediment in Qiangtang Estuary during lately 40 years is about 20.2 million-stere. Deposition upside of Hangzhou bay is about 14.3 million stere, downside is about 7.0 million stere. During lately 40 years, accumulate of deposition in the three area is about 41.5 million-stere, the average deposition per year is about 1.0 million stere. The average amount of sediment from Qiangtang river (include Caoe river) is 890 ten thousand ton (amount to 740 ten thousand stere)per year ,7% of the total. So the sediment deposition in Qiangtang estuary and Hangzhou bay comes from outside of the bay.

4.THE MODERN PROCESS AND ITS MECHANISM OF DEEP CHANNEL IN NORTHERN BANK AND ANDONG FLAT IN SOUTHERN BANK

The deep channel that is in northern bank of Hanghzou Bay and Andong flat that is in southern bank of Hangzhou Bay, are the most important two kinds of topography cell in the bay. The former is harbor and waterway resource and the later is land resource potentially. Analyzing the modern process and dynamic mechanism is the scientific reference to the development and planning.

4.1 THE DEEP CHANNEL IN NORTHERN BANK

From Ganpu in Haiyan to Jinshanju in Shanghai, the deep channel in northern bank is 65km in full length and the water depth is16−15.0m. The evolution of the deep channel is divided into two steps. The amount of sediment from Yangtse Rive increasing leads to the sand spit in southern bank of Yangtse River silting quickly. So the mouth of Hanghou bay moves outside and the mouth width increases, which strengthen the effect of trumpet-shape and makes the tidal range larger. According to equation 2, the tide range of Ganpu, Zhapu, Jinshan has increased by 85%, 60%, 45% since 1500, and the tide current velocity increased correspondingly at the same time. The tide wave arrives at bay mouth from different direction outside and gathers around bay mouth. The main current of flood tide turns right for Coriolis force when it propagates to bay head. In addition to the erosion of SE stormy wave shoreline in northern bank collapsed and reversed in history. The collapse of shoreline in northern bank was not controlled until 14 century because the seawall was built along the shoreline.

In textual research, there was an old Yi city that was 1.5 km away from southern Zhapu, and the old Yi city collapsed into sea in 1381. It is said in *Zhapu Mark* that Yi city cropped out four times in early Qing dynasty (1647,1683,1697 and 1730). That is to say there was no deep channel in northern bank. After the collapse of northern bank was controlled, the bed in northern bank was scoured by flood tide and became deeper, which led to the formation of deep channel in northern bank. By the analyst of chart, deep pool around Zhapu was scoured about 13.0−15.0m deeper since recent 100 years.

After the establishment of the People's Republic of China, the amount of tide in the cross-section of Ganpu decreased by 15%−20% for the reclamation of Qiangtang Estuary, which is the main reason for the siltation of Hangzhou bay. In order to study the siltation which has effect on the deep channel in the northern bank, based on the observed topographic map given 2−3 times for one year from 1972−1988 , Han Zengcui etc analyzed the siltation of deep channel in northern bank which was about 3km long. The average bed from 1972 to 1977 represents the bed before reclamation and the average bed from 1991−1998 represents the bed after reclamation. The result of analysis shows that the siltation happened from Ganpu, where is the deep channel in northern bank to Changqian which is 3km away from the bank, and the average water depth decreased 1.5−2.5m, the bed was scoured from Changqian to Jinshan where the average water depth increased about 3.0m, the result showes good agreement with Fig.5. In order to control the development of the deep channel in northern bank, 2-D numerical simulation and moving bed physical model were applied to study the work of regulation and reclamation of Jianshan river reach in Qiangtang River.

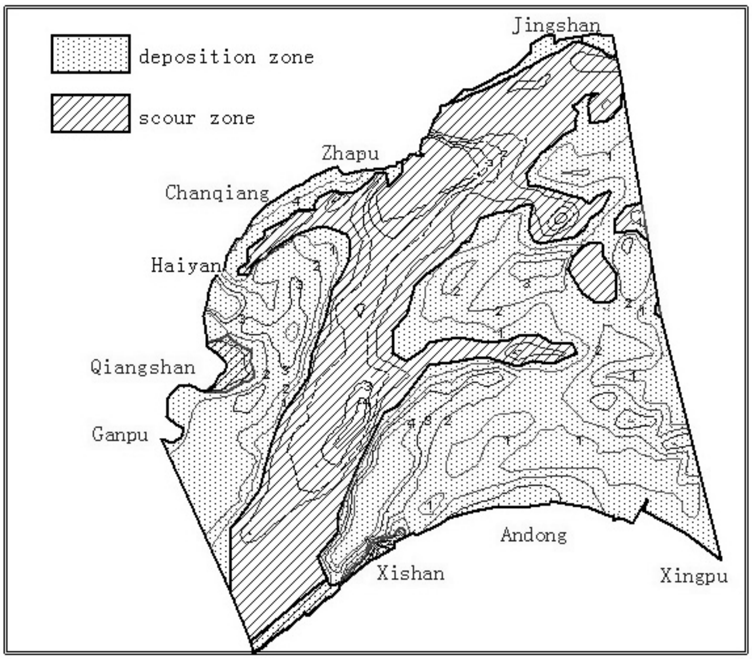

Fig. 5 Map of scour zone and deposition zone in Hangzhou bay
(the topographty map of 2000's comapre with 1959's)

In order to study the dynamic mechanism of the formation of deep channel in northern bank, the ratio of sediment concentration (s_0) to sediment carrying capacity (s_*) is defined to the siltation-judged index, which is applied to judge siltation:

$$\psi = \frac{S_0}{S_*} \tag{3}$$

where s_0 is sediment concentration of inlet cross-section, s_* is sediment carrying capacity of study domain. Siltation will happen on the bed when $\Psi > 1$,on the contrary ,Scour will happen on the bed when $\Psi > 1$.The sediment carry capacity equation of Hangzhou bay is applied to equation (3), then equation (4) is:

$$S_* = 0.008\frac{V_0^2}{h\omega} \qquad m=0.95\sim1.10$$

$$\psi = \frac{V_0^2 h_i}{V_i^2 h_0} \tag{4}$$

Where h is water depth, v is the maximum mean velocity in vertical, subscript "0", "i" are the inlet corss-section and study cross-section. By the analysis of observed hydrologic data, Fig .6 shows the maximum mean velocity of flood tide and ebb tide in northern bank of Hangzhou bay. Fig.6 shows that the velocity of flood tide is more than the velocity of ebb tide. Combined with the topography change of the deep channel in northern bank, according to equation 4 was got Ψ=0.63, which is less than 1, shows that the deep channel in northern bank of Hangzhou bay is an area scoured, which lead to the formation of deep channel near to the bank. The deep channel in northern bank from Zhapu to Qingshan is a branch one. Fig.6 showes that the velocity in the branch deep channel is small but the velocity of flood tide is also more than that of ebb tide. The velocity of flood tide is also more than that of ebb tide from Qingshan to Ganpu. The siltation happened for the effect of reclamation of Qiantang estuary.

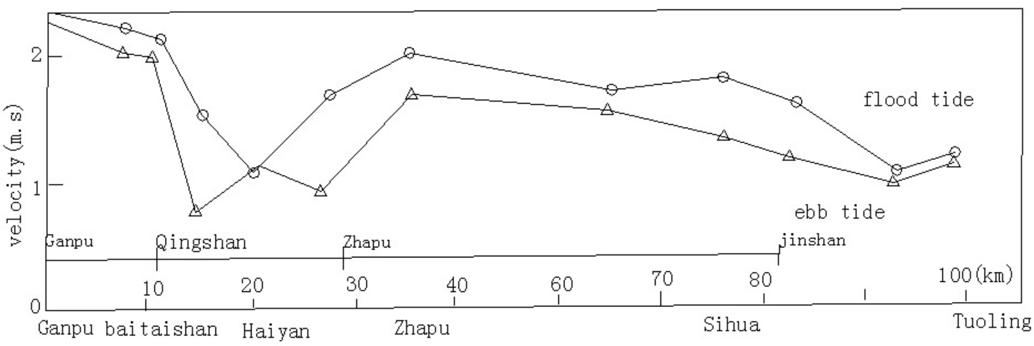

Fig. 6 The maximum mean velocity of flood tide and ebb tide in north deep channel

4.2 ANDONG FLAT IN SOUTH

The alluvial plain between Xisan Sluice and Haiwangshan Sluice along south Hangzhou Bay named Andong flat with 4−4.7 hectare area. It is the largest continuous alluvial plain in Zhejiang province. Many scientists have been studying on its formation, evolution characteristics, sediment source and development and utilization. This paper focuses on its contemporary evolution process and dynamic action.

Andong flat is a deposit shore and its shoreline extended outside owing to beach reclamation. The widest distance extended outside is about 15.5 kilometers in 600 years, and grew 560 square kilometers area. The contemporary evolution process of Andong marginal bank is illustrated in Table 3 and Fig. 7.

Table 3 Area change of Andong marginal bank in recent 40 years unit:km²

Sector marginal bank area	1959	1972	1979	1984	1990	1994	1998	Increment area before and after 1979	
								before	after
83#(Xisan Sluice)−91#(Andong) (west part)	75.0	107.8	101.2	114.5	122.6	128.3	115.8	26.2	14.6
91#（Andong）−99#(Xinpu)	89.2	101.3	123.9	156.8	158.2	147.6	165.5		
91#(Andong) −Haiwangshan (east part)	105.9		143.4	200.6			21.66	37.5	73.2
83#(Xisan Sluice) − Haiwangshan	180.9		244.6	315.1			332.4	63.7	87.8

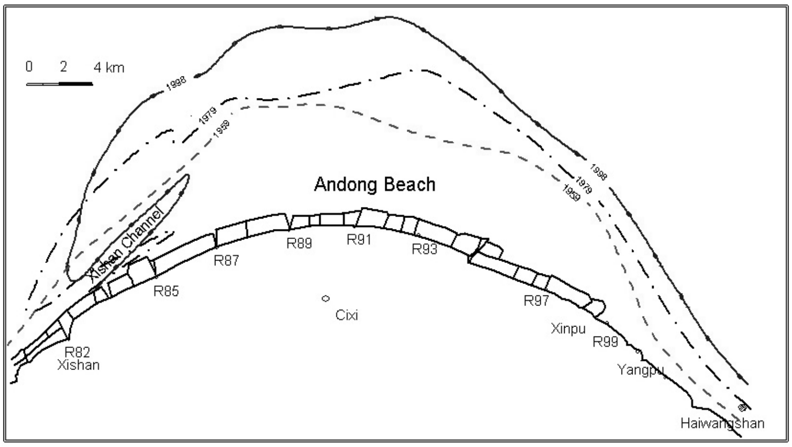

Fig. 7 The contemporary evolution process of Andong flat

Andong flat is divided into west part and east part taking Andong (91# pile) as the boundary. The area of west part (83#−91#) increased 26 square kilometers in the first 20 years from 1959 to 1979, and the area increased only 14.6 square kilometers in the later 20 years from 1979 to 1998. The deposition speed reduced 50 percent after year 1979. However, the area of east part (91#−Haiwangshan) increased 37.5 square kilometers in the first 20 years and increased 73.2 square kilometers in the later 20 years. The deposition speed accelerated 100 percent after year 1979. The above phenomenon discloses that the deposition speed of east part is faster than that of the west part and the deposition is from upstream to downstream with time.

Preamble analysis shows that the south water area of Hangzhou Bay and Andong flat is controlled by ebb flow, that is to say, the transported water and sediment in ebb period are larger than in rising tide period. Mean velocity in vertical, mean sediment concentration and grain size in flow and ebb period along Andong flat observed in year 1959 and year 1965 are illustrated in Fig.8. Mean velocity in vertical and sediment concentration in flow and ebb period reduced from west to east as showed in Fig.8, and grain median size changed from coarse to fine from west to east. The sediment transportation belongs to deposition environment. Velocity in ebb along Andong flat from west to east has the law $\frac{V_0^2}{V_i^2}>1$, but $\frac{h_i}{h_0}\cong 1$, so $\psi>1$ belongs to deposition environment based on Eq. 4.

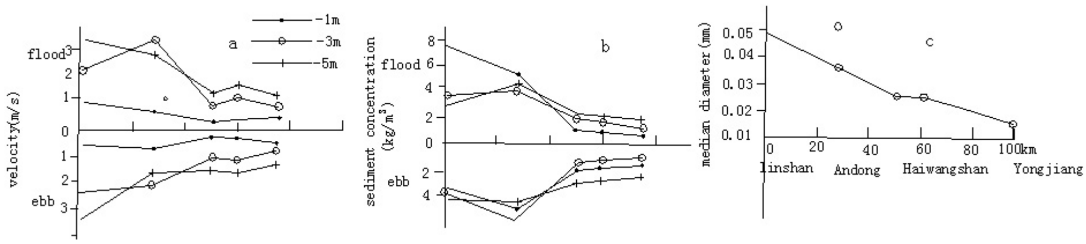

Fig. 8 Mean velocity ,mean sediment concentration and grain size along south bank

5. CONCLUSIONS

Hangzhou Bay is the seacoast of Qiantang Estuary with a typical horn shape, its contemporary evolution process is mainly deposition influenced by beach reclamation. The accumulated deposition volume is about 2.12 billion triple meter in recent 40 years and the sediment originating from Changjiang River. The sediment of bay head Hangzhou Bay exchanges frequently with the sediment of Qiantang Estuary. Evolution process of Hangzhou Bay is erosion (or deposition) in up reach and deposition (or erosion) in down reach, erosion in winter and deposition in summer.

The north deep of Hangzhou Bay is the seaport and navigation resource and the south Andong flat is the land resource. Observed data showed that the north water area is controlled by rising tide and flow velocity in this area increases from east to west, and transported water and sediment upwards is larger than downwards. According to erosion or deposition criterion number of bed surface, north water area is belong to erosion zone and formed the north quirk. Contemporary evolution process of north quirk is a erosion process except the reach from Ganpu to Changqian is deposited due to beach reclamation. South water area of Hangzhou Bay is controlled by ebb flow and flow velocity in this area reduced from west to east, and transported water and sediment upwards is less than downwards. According to erosion or deposition criterion number of bed surface, south water area belongs to deposition zone. Contemporary evolution process of Andong flat is mainly deposition. The conclusions of this paper provide scientific reference for implement development planning of Hangzhou Bay.