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VARIATION OF TIDES AND RIVER REGIME AFTER RIVER TRAINING IN THE QIANTANG ESTUARY

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Abstract: The Qiantang estuary is situated in Zhejiang province along the coast of East China sea. Its large tidal range, spectacular tidal bore and frequently drastic change of river bed are not only matchless in China but also rarely found around the world. In the last half century, large-scale river contraction and reclamation works have been carried on in the estuarine reach (transition reach) of the Qiantang estuary. Up to date, the river width has been narrowed down by one-half to three-quarters and 73,000 ha of tidal flat has been reclaimed in the 106km stretch from Hangzhou to Ganpu， tremendous comprehensive benefits have thus been achieved. The large-scale river training and reclamation project results in the obvious changes of tides and river regime. This article relates a brief retrospect of the past regulation plans and practice; emphasizes the variation of tides, including high/low tide stages, tidal range, tidal flow, flood/ebb duration, etc., as well as the variation of river regime, such as the deduction of shifting range of the main channel， the tidal volume, cross-sectional area and the change of longitudinal profile, etc.. Some variation mechanisms were studied by means of numerical simulation or regime theory analysis.

Key words: Qiantang estuary, Regulation, Tide, River regime

1. HISTORICAL RETROSPECT OF REGULATION IN QIANTANG ESTUARY

The drainage area of the Qiantang river is 55,558km^2 with a total length of 668km, in which the length of its estuary is 282km from the tidal limit to its outlet into the East China Sea. The estuary is divided into three reaches: The upper river flow dominated reach from the tidal limit Lucipu to Wenyan, 78km long; the transition reach (estuarine reach) from Wenyan to Ganpu, 122km long; and the lower tidal flow dominated reach Hangzhou Bay from Ganpu to Lucaogang, 82km long (Fig.1.1). The upper and lower reaches are comparatively stable, the transition reach is a wandering reach with swift tidal flow, strong tidal bore and drastic aggradations/degradation of the river bed. The estuary is flanked by Taihu-lake plain on the north and Ningbo-shaoxing plain on the south. These plains are among the most flourish and the principal revenue collecting districts in China. However, the ground level is lower than the ordinary high tide by 2–4m, the plains are protected against flooding by seawall. Great attention were paid for seawall construction in past dynasties, nevertheless, the seawall was ruined and rebuilt repeatedly owing to the strong dynamic actions. Great flooding disasters recorded since Tang dynasty attains 125 times in nearly one thousand years. During the Ming and Qing dynasties, (14th–19th century), vast money has been invested in the construction of the elaborate and massive masonry seawall over 200km in length (Fig. 1.2); about 70km of it is still standing on the front line guarding against the violent tide. However, the foundation is too shallow limited by the technical conditions then and it is the most troublesome hidden danger against foot scouring.

In 1930's, suggestions were initiated to stabilize the wandering channel and to exploit the resources of tidal flat and navigation apart from passive defending by building seawall.

Because of financial and technical limitations, few achievements were attained till 1950's. Professional organizations of surveying, research, designing and administration were successively established to launch year round hydrological observation of tides and to carry out topographical survey of the river. large amount of field data was thus collected. Fluvial process analyses based on field data reveals the following characteristics of the Qiantang estuary (Dai Zeheng and Li Guangbing,1958).

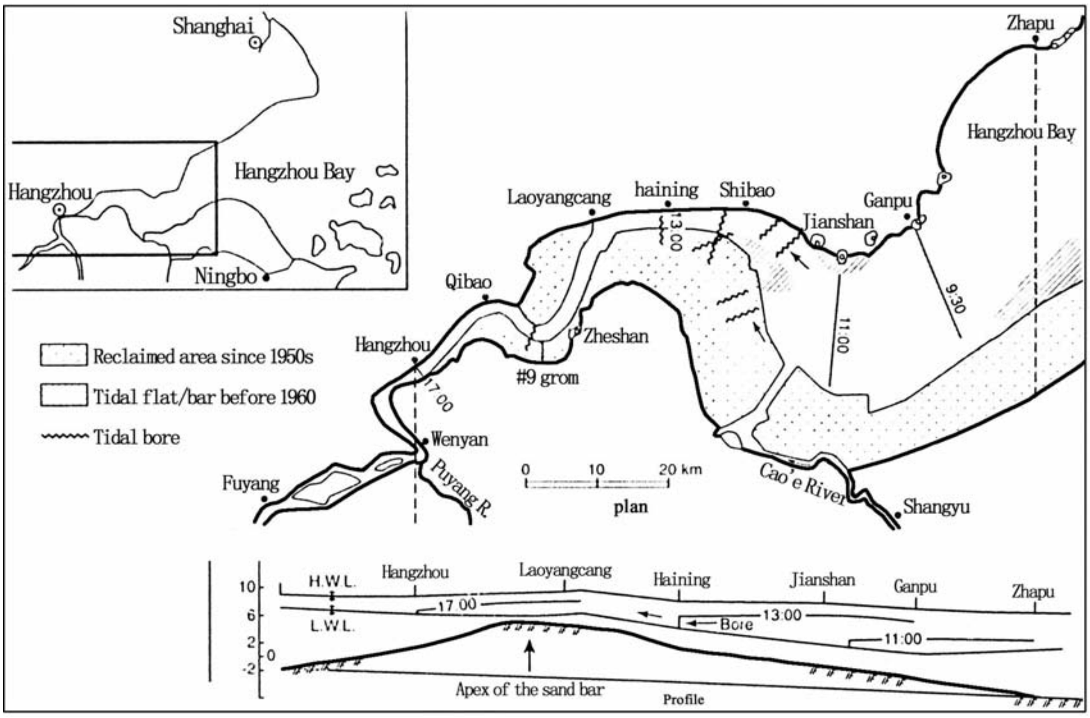

Fig. 1.1 Sketch of the estuarime reach of Qiantang Estuary

1. Strong tide with swift current–the maximum tidal range being 9.00m at Ganpu, the vertical mean velocity at spring tide usually being 3–5m/s, the height of the tidal bore being 2–2.5m。

2. Very wide and shallow in the estuarine reach, width/depth ratio $\sqrt{B}$/H>20–45, larger than that of the typical wandering river in China–Yellow River.

3. Bed material is the well sorted uniform silt (d_{50}=0.02–0.04mm with clay content less than 5–10%), liable to be scoured. The main channel is constantly shifting, so that the tidal flat come and go from time to time, maximum record of bank retreating rate being 245m/d. Fig. 1.3 shows a typical example of channel shifting.

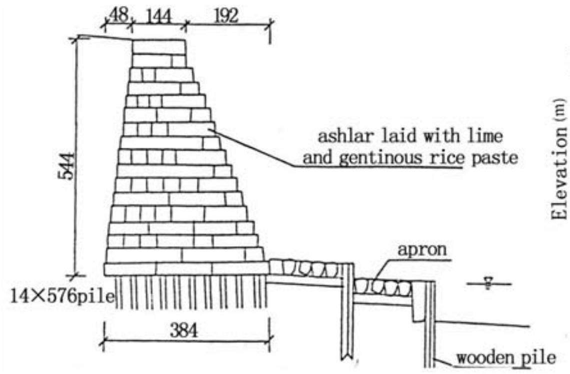

Fig. 1.2 Fish-scale-shaped ashlar aeawall with a single line of capping blocks

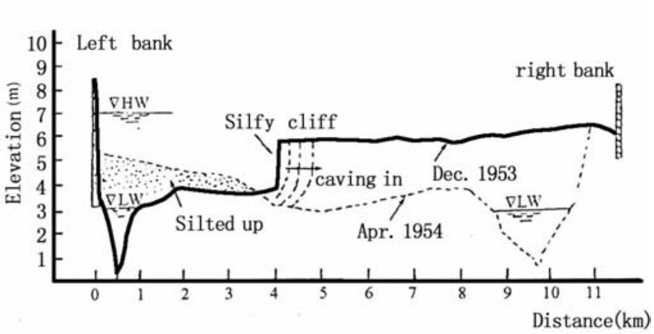

Fig. 1.3 Shifting of main channel from left side to right side

The river runoff from the river basin is rather small except during high freshets, the ratio of river flow/tidal flow (at Ganpu—the lower boundary of the transition reach) is only 0.01; hence, large amount of sediment is carried in by the flood flow and could not be carried out by the weaker ebb flow of longer duration. The inner long sand bar is thus formed which leads to the formation of extra wide-shallow channel, violent tidal bore, frequently shifting main channel, and unstable tidal flat (Chien Ning, Li Guangbing, et al. 1964).

Aiming at the basic reason of the formation of the above mentioned characteristics, it was decided to increase the ratio of river flow/tidal flow by decreasing the tidal volume as the regulation principle of the Qiantang estuary. Since 1960’s, three principal kinds of regulation plans were studied by means of 1D/2D numerical modeling and fixed bed/movable bed physical modeling, i.e., building tidal barrage and sluice somewhere to exclude the intrusion of salt water and sediment, building a submerged dam near the lower end of the transition reach to decrease the tidal flow and to contract the entire river course to lessen the tidal volume from Hangzhou to Ganpu. The former two plans were rejected mainly because of the heavy deposition occurred downstream of the barrage/submerged dam causing seriously unfavorable effects. The latter plan of river contraction combined with reclamation was chosen to be carried on at the first stage.

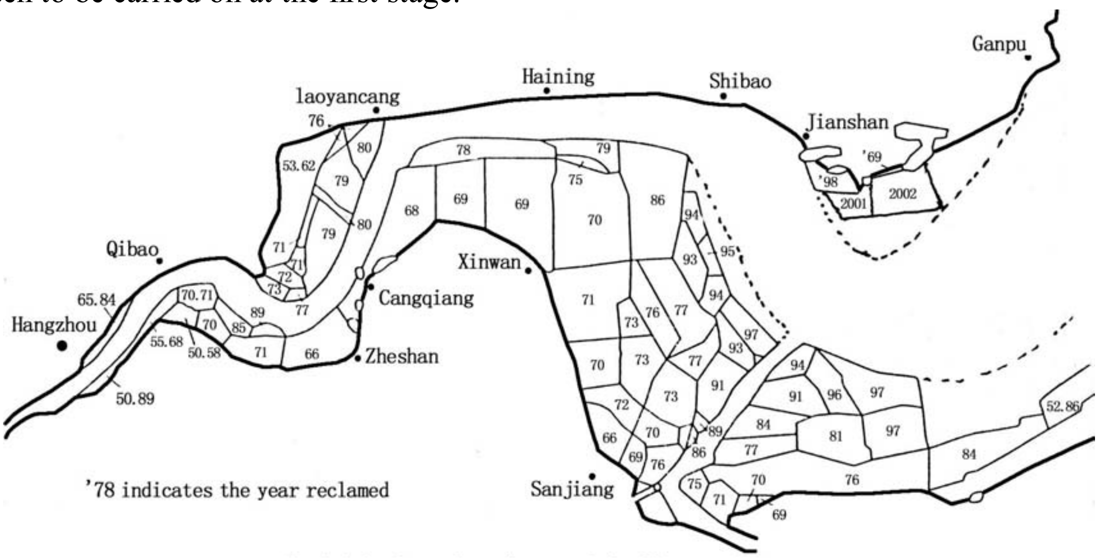

Fig. 1.4 Reclamation phases of the Qiantang Estuary

The river contraction (training) project was worked out by means of regime analysis and mathematical/physical modeling techniques with a view to compromise the requirements of flood prevention, draining, fresh water diversion, navigation and reclamation, etc.. The alignment was designed along the natural route and by possibly full use of the old seawall in order to lessen engineering works. In the course of implementation, short groin systems were used in the upper narrower stretch during 1950’s, long spur dykes and longitudinal dykes were built to promote deposition at first in the concave bank of Zheshan bend and then encircling dyke was built to contract the river and also to reclaim the silted flat area during 1960’s. Since 1968, large tracts of high flat area inside the designed alignment were easily encircled by earth dykes where tide is rather weak and then gradually reinforced. The cost of this kind of work is very cheap and the progress of river training and reclamation was speeded up in middle stretch from Cangqian to Jianshan. Till the end of 1980’s, 74km stretch upstream of Jianshan has been narrowed to the designed width and consequently 60,000 ha tidal flat has been reclaimed. The tidal flat downstream of Jianshan is lower, long spur dykes/longitudinal dykes were again built during 1990’s to promote deposition before encircling dyke could be built. Fig. 1.4 shows the progress of river training and reclamation works.

After the regulation practice in recent half century, the following benefits have been gained (Han Zengcui. Dai Zeheng, 2002).

1. The river course has been narrowed down by one-half to three-quarters with a total reclaimed area of 73,300 ha which was used mainly for agriculture and aquatic breeding before 1980's, then gradually transformed for industrial use to form new economic growth sources.

2. The main channel of 74km long has been stabilized and the comparatively short dangerous sections along the 200km embankment were fixed and could be reinforced in advance for flood prevention.

3. The sluicing condition of 2,000−3,000km^2 farm land was improved because no siltation will block the free discharge of the sluice gates which could be located at the sites nearby the fixed channel.

4. The navigation channel is fixed and the tonnage of sea-going ships were increased from 50 t to 300 t, annual freight volume increased from 100,000 t to 400,000 t as the result of increasing depth in the upper stretch near the apex of the sand bar.

2. VARIATION OF TIDE AFTER RIVER TRAINING (HAN, 2003) (HAN ET AL, 1998)

Variation of Tide includes tidal stage, tidal range, tidal volume, flood/ebb duration, flood/ebb mean velocity and maximum velocity, etc.. Because it is very difficult to measure velocity by boat in the wide river subjecting to the action of tidal bore twice a day, the data of velocity, tidal flow and tidal volume is rather few, particular attention is laid on the analyses of tidal stages and tidal ranges.

2.1 VARIATION OF MEAN HIGH/LOW TIDE STAGES AND TIDAL RANGES

In selecting the years for comparison between before and after river training, similar conditions of river runoff (wet or dry) and the channel route (straight or curved) should be taken into consideration which exert obvious influence on the high/low stages. Average values of three years before 1961 and after 1989 of similar conditions were chosen for comparison of the general case between before and after river training. Average values of one year (1955/1992) were chosen for comparison of specific case, while the river course in 1955was heavily eroded and enlarged by the recorded maximum river runoff in 1954 and the maximum flood discharge in 1955 notwithstanding the yearly runoff and the channel route are similar in 1992 and 1955, hence the high/low stages are extremely low in 1955 and the rise of high/low stages in 1992 are very large. The rising/lowering (+/-) of stages and increasing/decreasing (+/-) of tidal ranges were listed in Table 2.1.

Table 2.1 Increments of mean high/low tidal stages (HW/LW) and tidal ranges (ΔH) after river contraction

Unit:cm

Station	Average of three years						Average of one year					
	Straight			Curved			Straight			Curved		
	HW	LW	ΔH	HW	LW	ΔH	HW	LW	ΔH	HW	LW	ΔH
Zhakou	41	25	16	-01	-37	36	83	94	-12	02	-10	12
Qiao	40	21	19	-09	-52	43	74	96	-22	03	-13	17
Cangqian	27	29	-02	-16	-73	57	58	134	-76	-07	-38	31
Yanguan	32	71	-42	-23	-95	73	59	158	-99	-26	-123	97
Ganpu	31	04	27	17	0	18	41	-07	48	17	03	14
Zhapu	29	-01	30	22	0	22	28	-05	34	20	02	19
Zhenhai							18	09	09			

As seen from the above table, the general rising (average of three years) of high stages after river training for the straight river course are 27–41cm, the rising of low stages are larger in middle stations than that in upper/lower stations, hence the tidal ranges are decreased in middle stations and increased in upper/lower stations. For curved river course, both the high and low stages are lowered; however, the lowering of low stages are larger than that of the high stages, hence the tidal ranges are increased. The general tendency is that the high stages are raised and gradually increased upstream when the river course is straight, the low stages upstream of Jianshan varies with the erosion/deposition of the river bed, hence the tidal range increase or decrease accordingly. The low stages at Ganpu and Zhapu are not influenced by the bed deformation of the upstream river bed, while the hight stages are raised by reflection of the upstream narrowed channel, hence the tidal ranges are increased.

2.2 VARIATION OF TIDES AT SPRING TIDE

During spring tide, the dynamic action on the seawalls and salt water intrusion are much more stronger than that during medium tide. The rising of stages and increasing of tidal ranges related to the spring tide of frequency 90% and the medium tide of frequency 50% of the three years mean value in September (the tides is generally highest in a year) after river training are listed in Table 2.2.

As seen from the table, increments of mean high/low tidal stages and tidal ranges are larger at spring tide than that at medium tide after river training. These are owing to the greater flood velocity and the consequent stronger reflection of tidal wave.

Table 2.3 lists the occurrences of high stage higher than/between different elevations in a year of straight river course before/after river training (1955/1995).

Table 2.2 Increments of tidal stages after river contraction. Unit:cm

Station	HW		LW		ΔH	
	Spring tide	Medium tide	Spring tide	Medium tide	Spring tide	Medium tide
Zhakou	75	39	24	22	51	17
Qibao	88	44	20	-03	68	47
Cangqian	71	32	59	44	12	-11
Yanguan	74	48	134	119	-60	-81
Ganpu	48	34	33	18	15	16
Zhapu	53	37	0	-06	53	42

Table 2.3 Occurrences of high stages in various stations

Station	Zhapu		Ganpu		Yanguan		Cangqian		Qibao		Zhakou	
High stage (m)	>5.5	5–5.5	>6.5	6.0–6.5	>6.5	6–6.5	>7.0	6.5–7.0	>7.5	7–7.5	>8	7.5–8.0
1955(before)	18	89	2	31	30	121	65	102	7	27	7	8
1995(after)	44	137	6	61	181	141	163	120	92	127	26	65
after/before	2.4	1.54	3	2	6	1.16	2.5	1.18	13.1	4.7	3.7	8.1

After river training, the occurrences higher than/between same high stage are 1.16–13.1 times of that before river training. It is the largest at Qibao and smaller in downstream stations.

2.3 VARIATION OF TIDAL VOLUME (HAN ZENGCUI, 2003)

Tidal volume is an important parameter of the characteristics of tides, however, it is difficult to measure velocities and the tidal volume could not be accurately calculated by a few vertical data, calculation of tidal prism using data of tidal stages and river cross sections as well as calculation by numerical simulation were used combined with that of velocity measurements to get the empirical relation of tidal volume and tidal range at various stations.

The correlation curves of tidal volume vs. tidal range of several stations both before and after river training are quite different from that before. The tidal ranges and tidal volumes of spring/medium tide (frequency=90%/50%) before/after river training are listed in Table 2.4.

As listed in the table, During medium tide of frequency 50%, the tidal volumes after river training are decreased by 16%, 40%, 35% respectively at station Ganpu, Yanguan and Cangqian, and increased by 25% and 46% at Qibao and Zhakou respectively. The tidal volume after river training of the curved channel are only 37%, 40%, 47% and 63% at Yanguan, Cangqian, Qibao and Zhakou respectively that of the straight channel. The Variation related to different stations are because of the difference of the degree of river contraction and the variation of tidal ranges in different stretches.

Table 2.4 Variation of volume before/after river training. Unit: m/10^6m^3

Station			Ganpu		Yanguan		Cangqian		Qibao		Zhakou	
			ΔH	$\bar{v}$	ΔH	$\bar{v}$	ΔH	$\bar{v}$	ΔH	$\bar{v}$	ΔH	$\bar{v}$
Straight channel	Medium tide	Before ①	5.45	3140	4.09	290	1.87	84	0.90	24	0.60	13
		After②	5.72	2650	3.67	175	1.85	55	1.09	30	0.76	19
		②/①=③		0.84		0.60		0.65		1.25		1.46
	Spring tide	Before ④	6.62	4040	4.53	355	2.33	126	1.27	45	0.88	25
		After⑤	6.90	3320	4.33	250	2.41	100	1.55	54	1.26	42
		⑤/④=⑥		0.82		0.70		0.79		1.20		1.68
Curved channel		After⑦	5.67	2610	2.43	65	1.07	22	0.68	14	0.56	12
Curved/straight		⑦/②		0.98		0.37		0.40		0.47		0.63

2.4 NUMERICAL SIMULATION OF THE RISING OF THE HIGH TIDAL STAGES

The rising of high tidal stages could be simulated by the coupling math model of 1-D & 2-D, various factors affecting the rising could then be analyzed separately.

The region of the model should be large enough to avoid the effect of river training. The upper boundary is the tidal limit at Lucipu (now the Fuchunjiang Hydropower station) and the lower boundary is at the mouth of the Hangzhow bay crossing from Lucaogong to Zhenhai. Upstream of Zhakou, the river width is 500–1000m， 1-D model is used, while downstream of Zhakou, the width is 1–100km，2-D model is used (Fig. 2.1). The basic equations may be written:

For 1-D model,

$$\frac{\partial z}{\partial t}+\frac{1}{B}\frac{\partial Q}{\partial X}=0 \tag{2.2}$$

$$\frac{\partial Q}{\partial t}+2u\frac{\partial Q}{\partial X}+Ag\frac{\partial z}{\partial x}=u^2\frac{\partial A}{\partial X}-bg\frac{u|u|}{c^2} \tag{2.3}$$

and for 2-D model,

$$\frac{\partial z}{\partial t}+\frac{\partial (uH)}{\partial x}+\frac{\partial (vH)}{\partial y}=0 \tag{2.4}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+g\frac{\partial z}{\partial x}-fv+gu\frac{\sqrt{u^2+v^2}}{c^2H}=\frac{\partial}{\partial x}(\varepsilon_x\frac{\partial u}{\partial x})+\frac{\partial}{\partial y}(\varepsilon_y\frac{\partial u}{\partial y}) \tag{2.5}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+g\frac{\partial z}{\partial y}+fu+gv\frac{\sqrt{u^2+v^2}}{c^2H}=\frac{\partial}{\partial x}(\varepsilon_x\frac{\partial v}{\partial x})+\frac{\partial}{\partial y}(\varepsilon_y\frac{\partial v}{\partial y}) \quad (2.6)$$

In which, u, v = the depth integrated velocities in x,y directions respectively; z = water stage; H=water depth; $\varepsilon_x,\varepsilon_y$ =eddy viscosities; c = Chezy's coefficient; q = water discharge; A= cross-sectional area. These equations could be solved by coupling methods: ① The characteristic oriented scheme for 1-D and characteristic cone for 2-D are coupled at the junction section; ② an overlapping region is set near the junction section of 1-D and 2-D, solution is made by finite element method with the boundary condition of 1-D given by the calculated results of 2-D and vice versa.

Times of Verification have been carried out in Qiantang estuary. Once with eight tidal stage stations and sixteen velocity measuring verticals, the discrepancies are less than 20% within the 80% measured data of the mean velocity and direction of flood/ebb current; The discrepancies of high/low stages are less than 0.2m.

With a view to separate the factors causing the rising of high tidal stage, calculations with three different topographies of the river course were made.

Chart 1: the alignment of embankment and the topography were surveyed in October of 1959 (the earliest chart of the estuary including Hangzhou bay), the tidal ranges at Zhapu are 5.43m and 6.12m, both corresponding to spring tides;

Chart 2: The alignment of embankment is the case of 1995 (after river contraction) and the topography remain the case of 1959.

Chart 3: Both the alignment and topography are surveyed in 1995—after river Contraction and bed deformation.

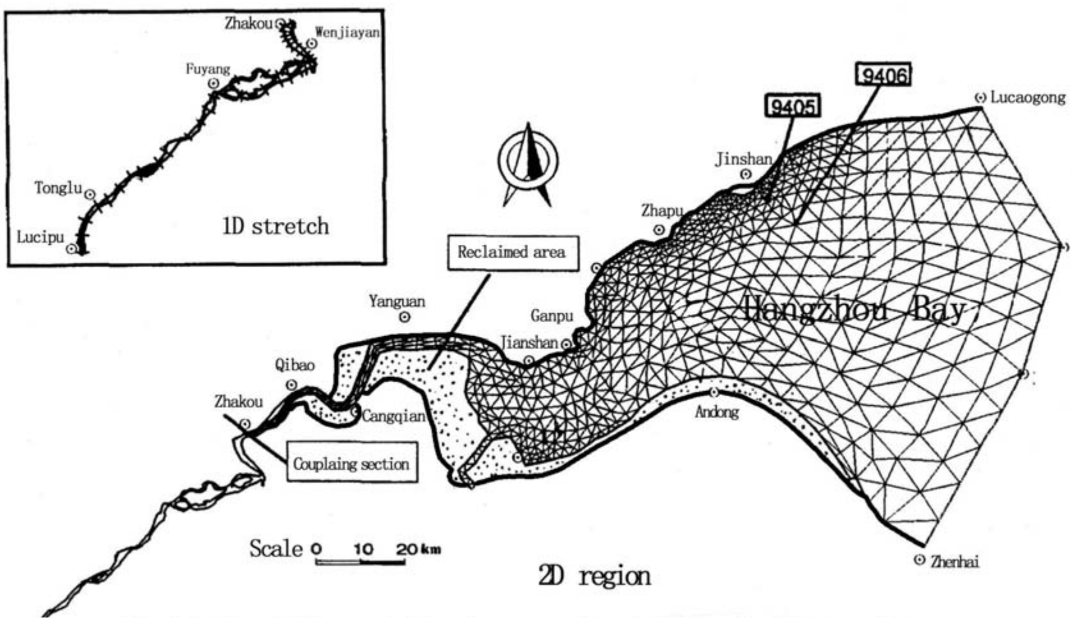

Fig. 2.1 1D and 2D computational areas and mesh points for Qiantang Estuary

The difference of the calculated high tide stage based on chart 1 and 2 is the result caused by river contraction named as case A; the difference based on chart 2 and 3 is the result caused by bed deformation named as case B; the difference based on chart 1 and 3 named as case C is the result caused by both river contraction and bed deformation. Only case C reflects the actual rising of high tide stages. The calculated results and the observed values are listed in Table 2.5.

As seen from the Table:

1, For case C, the calculated values are rather close to the observed values except in station Cangqian where the discrepancy is greater, however, it is within the variation range.

2, The cause of the rising of high stage is owing to the river contraction as shown in case A; case B shows a lowering of high stage which is because of the increase of resistance caused by the deposition of channel. The combined effect of river contraction and deposition reflects the actual change. The rising of high stage is really the transform of dynamic energy to potential energy with large velocity during spring tide; while during neap tide, the rising will be much smaller.

Table 2.5 Increment of HW and flood tide durations

		High water level (m)					Flood duration min.	
		Ganpu		Cangqian	Qibao	Zhakow	Ganpu	Yanguan
Calculated	Case A	0.73	0.93	1.07	1.18	1.03	-0:17	-0:02
	Case B	-0.20	-0.19	-0.31	-0.8	-0.46	-0:00	-0:04
	Case C	0.53	0.73	0.76	0.80	0.57	-0:17	-0:33
Observed	Mean	0.52	0.76	0.55	0.88	0.71	-0:15	-0:45
	Range	0.64-0.39	0.64-0.89	0.34-0.76	0.74-1.02	0.59-0.83		

3, The transformation of tidal wave would be naturally greater after river contraction, hence the flood duration was shortened as shown in Table 2.5 both by calculation and observation with a similar amount.

From the above analyses related to the variation of tides after river contraction, there exist both general and particular characteristics:

1, The high tidal stages(HW) are risen, greater in spring tide and smaller in medium tide; greater for straight channel and smaller (even lower) for curved channel.

2, The variation of low tide stage (LW) is related to the amount and location of deposition. Owing to the heavy deposition in the stretch from Cangqian to Jianshan, the rising of LW at Yanguan and Cangqian may be 1−2m for straight channel. Since the change of tidal range is the result of changes in HW and LW, the tidal ranges at Cangqian and Yanguan in the middle heavily deposited stretch are lessened, while in stations of the upper and lower stretches, the tidal ranges become larger.

3, The river contraction work did not impair the excellence of Qiantang bore， the fascinating scenery was protected and improved, because the development of tidal bore is related to flood discharge per unit width and the water depth with no relation to the total tidal volume.

4, The regulation principle of the Qiantang estuary is to increase the ratio of river flow/tidal flow by lessening tidal volume. The river contraction work helps to stabilize the channel and to lessen the tidal volume; mean while, the channel alignment should be curved to some degree in order to raise the river bed and the low tide stage thus to lessen the tidal range and tidal volume as well.

5, The contraction of river course will inevitably deduct the tidal volume, however, the deduction will be lessened somewhat by virtue of the self adjustment ability of the river-feedback by raising the high tide stage to increase the tidal volume which might be the indication of the equilibrium tendency of the river.

3. VARIATION OF THE RIVER REGIME (HAN, 2003)(HAN & LOU, 1995)

Since 1953, more than three charts (1：50,000 scale) in the estuarine reach were surveyed each year which recorded the macroscopic changes of the river course in the progress of river training and reclamation. Analyses were made based on these data as follows.

3.1 REDUCTION OF CHANNEL SHIFTING RANGE

The bed material is composed of fine silt (d_{50}=0.02–0.04mm) easily to be scoured and the space between both banks is very wide， mostly 5–20km， which provides a wide movable boundary for the channel to shift. After river contraction, the main channel was controlled by the new embankments and its shifting range is largely reduced. Fig. 3.1 shows the thalwegs before and after river contraction.

Table 3.1 lists the frequencies occurred of different distances between thalweg and north bank at several sections before and after river contraction.

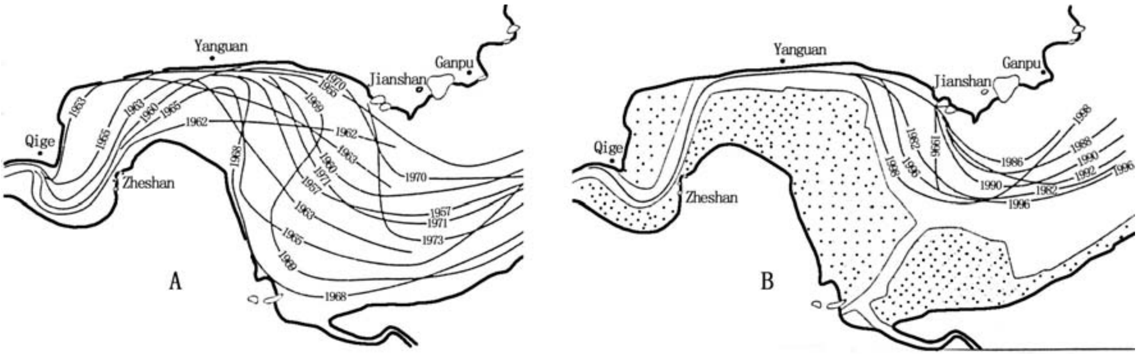

Fig. 3.1 Thalwegs in Qiantang Estuary: A) before and B) after reclamation

Table 3.1 Frequency of different distances of the thalweg departed from north bank

Distance Frequency / Station	≤1000m		≤500m		≤250m	
	Before	After	Before	After	Before	After
Mamugong	27.5%	100%	37.5%	100%	31.3%	75%
Yanguan	50%	87.5%	43.8%	87.5%	31.3%	50%
Xincang	25%	100%	12.5%	87.5%	6.3%	37.5%

The frequencies are obviously increased after river contraction and the thalweg was mostly controlled within a distance of 500–1,000m departed from the north bank. This is beneficial to draining of sluicing gates, to stabilize the navigation channel and to fix the dangerous sections of seawall which could be reinforced with focusing attention.

Fig. 3.2 shows the channel volume below 6.0m (about the mean high stages at spring tide) from Zhakou to Ganpu during 1955–1999, the tidal flat area above 5.0m (about the mean high stages) and the yearly mean river flow at Lucipu (the drainage area is about 67% that at Ganpu—downstream boundary of the estuarine reach).

3.2 DEPOSITION OF RIVER, CHANNEL VOLUME REDUCTION AND INCREASING OF TIDAL FLAT AREA

The figure shows:

1, The channel volume reduced greatly after successive dry years during 1963–1965 and 1978–1980. If the tidal flat area had not been reclaimed after dry years, it would have been eroded during wet years to recover its lost channel volume. Since the tidal flat was reclaimed and never be eroded, the reduction of channel volume is thus not reversible.

The average channel volume in 1950's is 7.05 billion m^3, while in 1990's, it is only 4.77 billion m^3, deduced by 2.28 billions, about 32% of its original volume.

2, Before reclamation, the flat area is about 600,000 mu (15 mu=1 ha); till 1976, the reclaimed area attained 600,000 mu and another 200,000 mu was silted up.

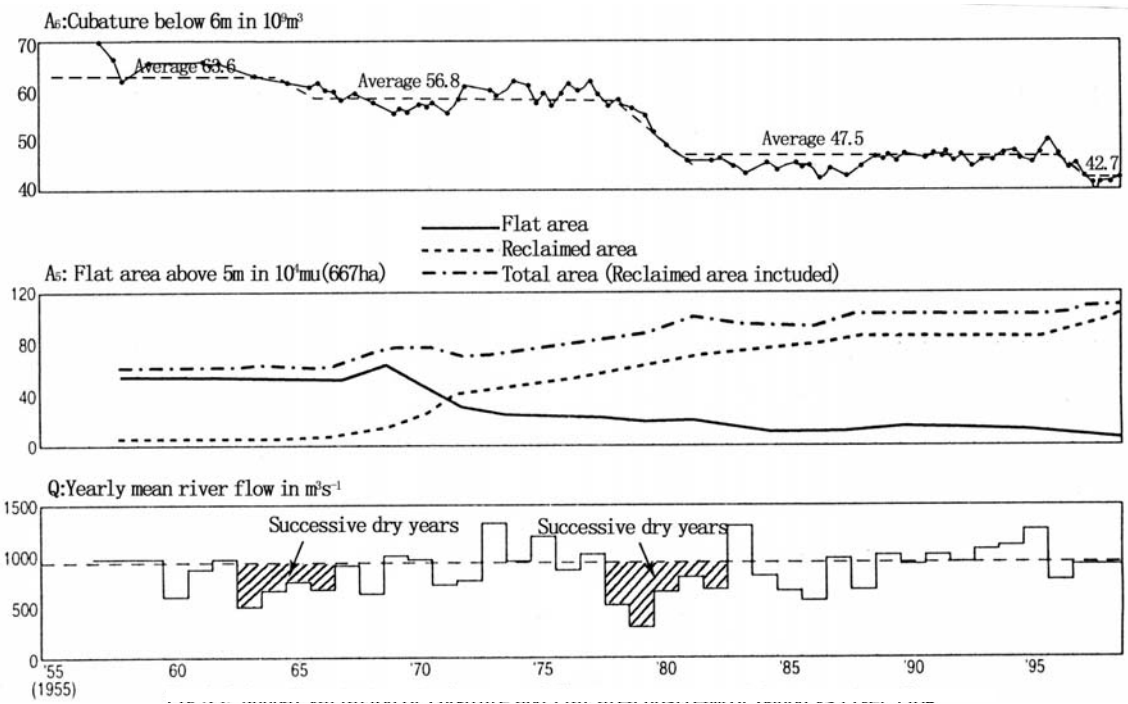

Fig. 3.2 Annual variation of cubature and flat area upstream of Ganpu vs river flow

3, Fig. 3.3 shows the longitudinal and vertical distribution of the amount of erosion/deposition in the seven stretches of the estuarine reach. The percentages are calculated based on the total amount of deposition/erosion below HW of each stretch after reclamation. Two stretches upstream of Cangqian (#27) were eroded and the middle and lower stretches were deposited. The percentages of deposition in the four middle stretches are greater than that in the lower stretch and mainly in the region between high stage (HW) and mean stage (MW).

3.3 THE VARIATION OF LONGITUDINAL PROFILE

There exists a long sand bar from Wenyan to Zhapu about 130km in length with its apex usually located between Qibao to Cangqian. This is one of the main factors forming the unstable channel. It was desired to lower the elevation of the sand bar thro river contraction.

Fig. 3.4 shows the longitudinal profiles (mean bed elevation below mean low tide) of July (the end of wet season in a year) of 1956–1958 and 1994–1996 which represent the similar hydrological condition of straight channel before and after river contraction respectively. Upstream of Yanguan, the river bed is eroded down by 1–2m， where down stream of Yanguan, deposited by about 1m. From July to November, the river flow is small and the tidal flow is predominant, deposition takes place. The comparison of the profiles of November (not shown in the figure) show that the river bed upstream of Yanguan after river contraction is only lowered by 0.5–1.5m than that before. When in April during the end of the dry winter season, the lowering of river bed after river contraction is even lessened to smaller than 0.3m. Fig. 3.5 (a & b) is the relation of the ratio of river flow/tidal flow vs. the elevation/location (distance from Zhakou) of the apex of the sand bar plotted based on the data before 1962.

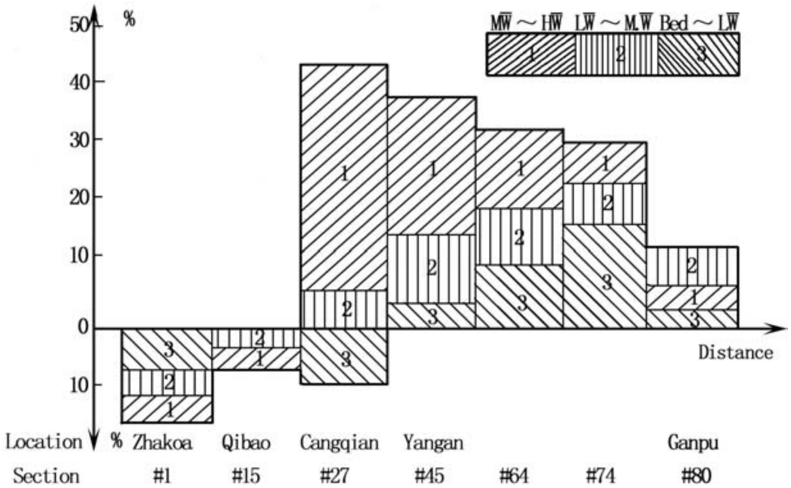

Fig 3.3 Vertical distribution of erosion/deposition

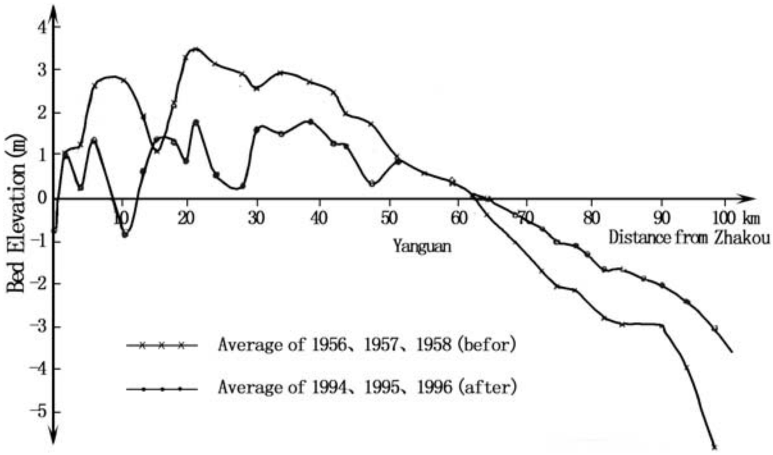

Fig 3.4 Average bed elevation below MLW before/after reclamation

3.4 VARIATION OF CROSS-SECTIONAL AREAS

Data of 1954–1963 and 1988–1996 were selected to represent the state before and after river contraction respectively for the similar straight river course. Average values of cross-sectional areas below mean high/low stages (A_H/A_L) and 6.0m (A6) at nine stations from Qibao (#15) to Ganpu (#80) were calculated, the ratio in terms of percentages of the area corresponding to after/before river contraction (Aa/Ab×100%) as well as the ratio of A_L/A_H×100% were listed in Table 3.2.

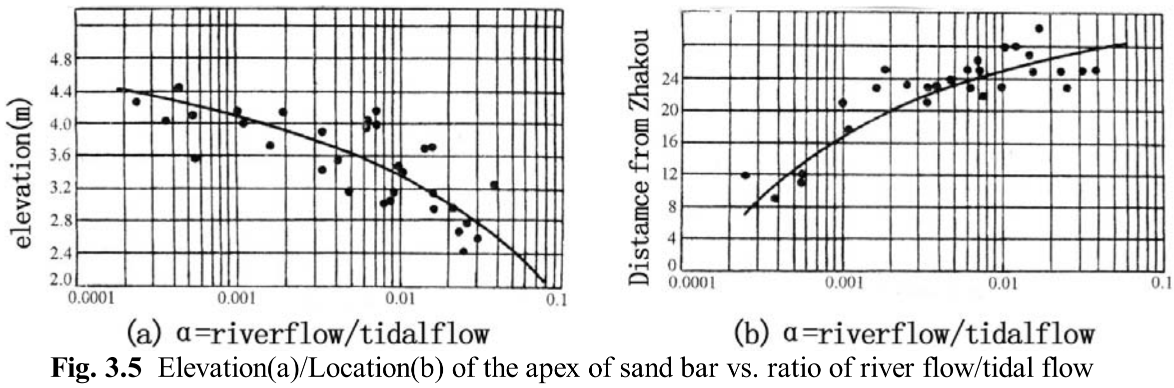

Fig. 3.5 Elevation(a)/Location(b) of the apex of sand bar vs. ratio of river flow/tidal flow

Table 3.2 Variation of cross-sectional area

Item \ Section no.		#15	27	37	45	54	64	68	74	80
$A_H^a / A_H^b \times 100\%$		98	84	70	57	37	60	81	92	98.6
$A_L^a / A_L^b \times 100\%$		82	98	108	69	42	67	53	68	85
$A_6^a / A_6^b \times 100\%$		90	80	54	50	33	56	76	90	95
A_L/A_H%	Before ①	80	36	19	17	18	22	38	40	50
	After ②	67	42	30	20	21	24	25	30	43
	②-①	-13	6	11	3	3	2	-13	-10	-7

As seen from the above Table:

1, After river contraction, the reduction percentage of A_H is the largest at the middle section #54, being 63% (=100–37), the reduction percentage decreases towards both upstream and downstream, being only about 2% (100–98) at #15 and #80. The longitudinal distribution of the reduction percentage is responding to the degree of contraction of river width along the river course.

2, The reduction percentage of A_L is also largest at section #54, being 58% (=100–42). The percentages at upstream sections are rather small and comparatively larger in downstream sections. This is because of that the area below low stage (A_L) in upstream stretch is governed mainly by river flow while A_L in downstream stretch is governed mainly by tidal flow which has been reduced by larger amount thro river contraction and greater deposition was resulted.

3, Because the HW/LW changes with the river bed in different periods, the reduction of A_H^a/A_H^b and A_L^a/A_L^b didn't represent the actual deposition state; The percentages of A_6^a/A_6^b referring to the area below a definite elevation of 6.0m do represent the actual deposition amount. The reduction percentages of A6 are mostly greater than that of A_H/A_L.

4, The ratio of A_L/A_H in sections #27–#64 were increased by 2%–11% from 17%–36% before river contraction to 21%–42% after contraction; this is resulted from the large reduction of A_H thro reclamation of high tidal flat. The percentages of A_L/A_H in the downstream sections #68–#80 were decreased by 13%–7% which was resulted from the lesser reclaimed high flat and the larger deposition below low stage.

5, Besides, the seasonal variations of A_H/A_L were also calculated, the maximum variation ranges after river contraction are decreased than that before, and the decrease is greater in upstream sections, smaller in downstream sections. The decreasing of variation ranges (of erosion/deposition) reflects the general tendency towards stabilization of the river course, and this as in accordance with the object of river training.

3.5 ELEMENTARY ANALYSIS OF THE REASON OF BED CHANGE (HAN ZENGCUI, FU NINGPING, XU YOUCHENG, 2001)

The cross-sectional area is related to the amount of water flow and sediment transport for a river in state of dynamic equilibrium. In an estuary effected by tides, the cross-sectional area (*A*), width (*B*) and mean depth (*H*) at the mid-tide stage are used as the cross-sectional parameters, the mean ebb discharges (*Qe*) and the mean sediment concentration (*Se*) during ebb flow are used as the water flow and sediment parameters. Data of fourteen estuaries in the world including eight in Zhejiang province of China were collected and the correlation graph was plotted in Fig. 3.6. Sections in upper, middle and lower stretches of the estuarine reach are chosen, the data used cover the range of $100\text{m}^3/\text{s} < Qe < 50,000\ \text{m}^3/\text{s}$, $0.2\text{kg/m}^3 < S < 10\text{kg/m}^3$, and bed material of $0.02\text{mm} < d_{50} < 0.16\text{mm}$.

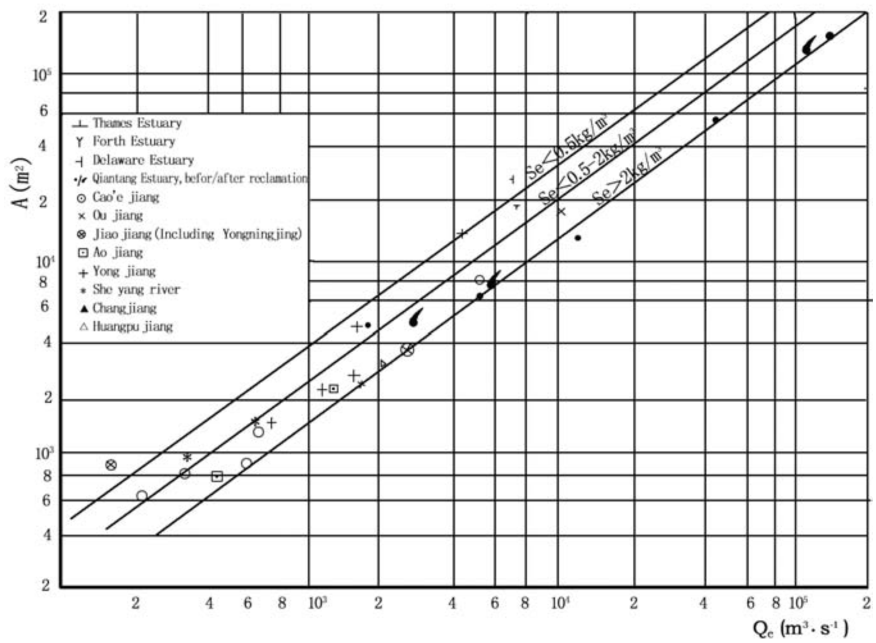

Fig 3.6 Relation between cross-sectional area at mean tide level and ebb tidal flow

The empirical relation can be written,

$$A = 4.7 Q_c^{0.9} / S_c^{0.22} \tag{3.1}$$

Since the data of sections effected by major human activities (e.g., large amount of river fresh water diverted outward in Yongningjiang and large scale river contraction in Qiantang estuary) are included in the graph, hence the relationship is verified both for before and after human activities and we obtain,

$$A_2 = (\frac{Q_2}{Q_1})^{0.9} (\frac{S_1}{S_2})^{0.22} A_1 \tag{3.2}$$

The subscription 1,2 represent the value referring to before and after human activities respectively. The change of mean water depth could be derived based on its relation with the mean ebb discharge per unit width (q), assuming the sediment carrying capacity is unchanged, we get,

$$H_2 = (\frac{q_2}{q_1})^{2/3} (\frac{S_1}{S_2})^{1/3} \cdot H_1 \tag{3.3}$$

The variations of A and H after river contraction and reclamation were calculated by eqs. (3.2) and (3.3) and verified by the surveyed data for three typical sections in Qiantang estuary as shown in Table 3.3. In the calculation, the changes of HW/LW and duration of ebb flow are took into consideration while the change of sediment concentration S is not considered owing to its small exponent and lack of field observation data.

Table 3.3 Verification of changes of A and H

Station	before / after	Observed mean value							Calculated			
		A	B	H	Tidal Range	Tidal Volume	Qe	q_e	A_2 by eq 3.2	error	H_2 by eq 3.3	error
		m^2	m	m	m	$10^8 m^3$	(m^3/s)	(m^2/s)	m^2	%	m	%
Cangqian	b	3688	2059	1.8	1.75	0.80	3625	1.76				
	a	3130	1802	1.74	2.01	0.70	3333	1.84	3410	8.9	1.81	4.0
Yanguan	b	11780	4097	2.87	4.15	3.0	10386	2.53				
	a	5440	1806	3.0	3.73	1.85	6915	3.82	5877	8.0	3.78	26
Jianshan	b	52180	16740	3.1	4.58	10.0	33000	1.97				
	a	28250	8415	3.35	4.42	5.0	17270	2.05	30.030	6.3	3.18	5

The error (discrepancy) of the calculated values of A_2 and H_2 from that of the observed mean except H_2 at Yanguan are less than 9%, which might be accepted as agreeable quantitative prediction results.

4. MAIN CONCLUSIONS

1, After the regulation of Qiantang estuary thro continuous field observation, investigation, planning, practice, and revision in the past half century, the frequently shifting channel and the drastic erosion/deposition of the river course have been greatly changed, the river tends to be gradually stabilized. Owing to the fixation of the main channel, The dangerous sections of seawall are fixed and could be reinforced in advance to ensure safety; the drainage and navigation conditions obviously improved; the scenery of Qiantang bore preserved; and in the mean while, 1.1 million mu (73300 ha) of tidal flat has been reclaimed with an annual production value largely exceeded the total input, thus to play an important role in enhancing the regional socio-economic development.

2，The Qiantang estuary is a renowned macro-tidal estuary, the regulation principle of its wandering estuarine reach was decided to increase the river flow/tidal flow ratio by lessening the tidal volume. This was achieved by large scale river contraction in the entire estuarine reach, and the proper curved alignment of the river course was designed to weaken the strong tide resulted from the reflection of tidal wave due to contraction. The engineering measures conform to the rule: "river training combined with reclamation and reclamation ought to be in accordance with (the alignment of) river training." The drastic erosion/deposition and the violent tidal bore bring about severe difficulties in construction. After unintermittent observation and research, the objective rules of ever-changing river regime were gradually grasped, different engineering measures suited to different stretches and different periods were adopted. Under the support of the reasonable policy and organization of governments of all levels and the enthusiastic participation of numerous riparian people, the river contraction project was performed with cheap cost and quick pace.

3, In the course of the regulation practice in Qiantang estuary, continuous hydrological and topographical data were collected, thus rendering us to examine the variation of river regime and the effect of regulation. Field data indicate that the sediment transported to and fro was largely reduced and the river course tends to become more stable, the sand bar was lowered and shifted downstream somewhat as predicted in early 1960's. The self adjustment of the river is by means of raising the high stage to increase tidal volume thus rendering some balance to the reduction of tidal volume thro river contraction. It might be an indication of the rule of the equilibrium tendency of a river.

4, The regulation work of the Qiantang estuary has not yet been completed and is going to proceed towards downstream. Many natural rules have to be tackled thro investigation and practice.

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