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RESEARCH ON GENESIS AND REGULATION MEASURES OF SILTING IN THE LOWER REACH OF THE EAST SLUICE IN YUNZAOBANG RIVER, SHANGHAI

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Abstract: The Yunzaobang River is a seaward artificial river. After two sluices (the East sluice and the West sluice) were built on this river, the silting of the river channel took place in the seaward lower reach of the East Sluice. In this paper, the basic rules of erosion and deposition, along with the reasons of deposition in this reach were analyzed by observed hydrologic data and two-dimensional tide numerical simulation. The regulation measures for reducing deposition, hydraulic sluicing, were suggested. The effects of silting reduction for 5 levels of draw-off discharge and different draw-off time process were compared.

Key words: Yunzaobang, Sluice silting, Regulation measures for reducing deposition, Hydraulic sluicing

1. INTRODUCTION

Yunzaobang River, located in the north of Shanghai, which links up to the Suzhouhe Canal and down to Huangpujiang River, is an artificial river with a length of 34 kilometers. It traverses Jiading and Baoshan industrial regions. It is not only the leading inland channel for the water transport of Shanghai city, but also the main channel for flood storage and drainage of Jiading and Baoshan districts.

In 1979, the construction of East and West sluices in Yunzaobang River, which changed the upper reach (between the East and West sluices) from tidal river channel into artificial canal, brought about the silting in the lower reach (between the East sluice and the estuary of Wusong town, generally called the lower reach of the East sluice, see Fig. 1).

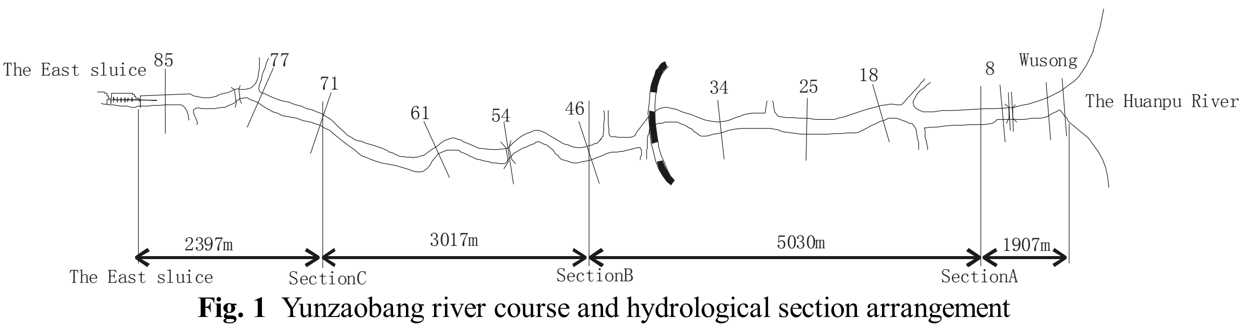

Fig. 1 Yunzaobang river course and hydrological section arrangement

In this paper, the hydrology, bathymetry and deposition in this lower reach were analyzed. And a two-dimensional tide numeric model was established for this 11.4 km long watercourse. The hydraulic sluicing as a regulation measure for reducing the deposition was suggested. The effects of silting reduction for 5 levels of draw-off discharge were calculated. The variations of river sectional configurations as the draw-off discharge is equal to 35 m^3/s were presented by analyzing the river facies relation of Yunzaobang River.

2. BASIC RULES OF EROSION AND DEPOSITION

By analyzing available data, the following erosion and deposition rules for Yunzaobang River were obtained:

2.1 SEDIMENT COMING FROM THE SEA AND DEPOSITING IN WHOLE RIVER

Owing to the construction of the regulation sluices at the upstream of the trunk and all branches of Yunzaobang River, there are little sediments transported into the lower reach. The sediments are mainly imported from the estuary of Yangtze River through the Huangpujiang River by floodtide. By analyzing the data of five whole tide surveys at the section A (Fig. 2) in different seasons during one year, the average sediment concentration is worked out to be 0.20kg/ m^3, which is close to the mean annual sediment concentration 0.26 kg/ m^3at Huangpujiang estuary. So, it is reasonable to consider the value (0.20 kg/ m^3) as the representative average sediment concentration. According to the measured flood tide volume and the relation curve between the average flow velocity and tidal level during floodtide, it is derived that the mean annual flow velocity of floodtide at section A is 31 m^3/s and the tide volume is 2,100,000 m^3on the basis of annual average tidal range 2.32m. these estimated values are very close to the average measured data of 5 whole tide surveys (flow velocity $V\uparrow$ =30 m^3/s, tide volume $W\uparrow$ =2,180,000m^3). Subsequently, the amount of sediment removed from sea into the Yunzaobang River per year can be obtained by:

$$S = 706 \cdot \rho\uparrow \cdot W\uparrow = 300{,}000(ton)$$

Here, $W\uparrow$ is the average floodtide volume and $\rho\uparrow$ is the average sediment concentration.

As a result of the weak sediment carrying capability of ebbtide, incoming sediments are partly deposited on the riverbed. The evolution of the topographic profiles during 1986-1988 shows that silting took place in the lower reach of sluice from the section 2 of estuary (Fig. 1) to the section 87 near the West sluice, except a few river segments.

2.2 SCOURING DURING FLOODTIDE AND DEPOSITING DURING EBBTIDE

According to the measured sediment concentrations at the three sections of A, B and C (Fig. 2), it can be derived:

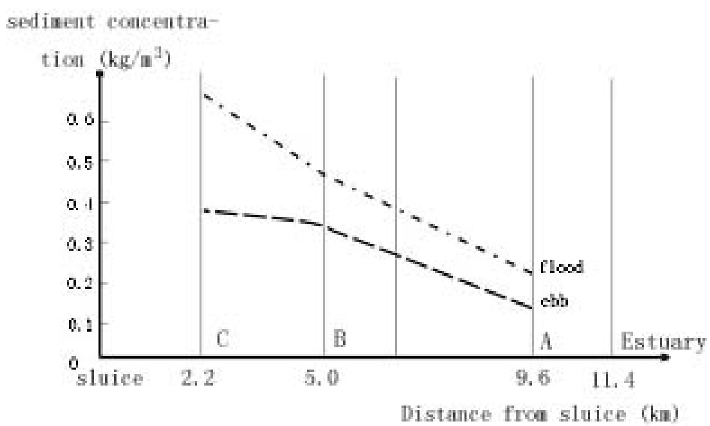

Fig. 2 Measured average sediment concentration

During floodtide, the increasing progressively of sediment concentration means that the riverbed is scoured along river channel. However, during ebbtide, the decreasing progressively of sediment concentration means that sediments were deposited along river channel, i.e. scouring during floodtide and depositing during ebbtide. During floodtide, the scouring effect and transporting sediment upstream indicate that the silting in some lower reaches of the East sluice is not only caused by tide, but also depended on the 're-moved' effect of sediment.

At every section in question, the sediment concentration during floodtide is always greater than that during ebbtide. It discloses that water body is turbid during floodtide and adverse while ebbtide. So, the rule of sediment transport can be described as: turbid water coming in and clear water going out.

2.3 THE NEARER TO THE SLUICE IT IS, THE HEAVIER THE SILTING WILL BE

Judging by the topographic variation in the river channel during 1986−1988, it is clear: There coexisted depositing and scouring effects in the lower reach of the section 34#. However, in the upper reach of this section, only the former existed. Furthermore, the deposition thickness increased gradually as approaching the East sluice and the maximal thickness was 0.62m. It can also be found from the 1988-1989 record, which shows that there existed scouring generally in the downstream reach and depositing in the upstream reach of section 61#. That made the deposition intensity (maximum is 0.30m) increase gradually as approaching the sluice.

2.4 SCOURING WHEN RUNOFF IS STRONG, DEPOSITING WHEN IT IS WEAK

For a river channel where sediments mainly come from the sea, the following rule exists consequentially: scouring when runoff is strong, depositing when it is weak. According to the five measured hydrologic data, it can be found that sediments were removed into the river channel through section A in the first four surveys that made the river deposited, while sands were transported out sea in the fifth (1989.8) that made the river scoured. The fact to be responsible for above results is that the runoff in the fifth survey is stronger than those in the other fours is.

3. REASONS FOR DEPOSITION

As everyone knows, a river channel slowly comes into the relatively steady state in the long course of interaction of fluid with riverbed. Flow and riverbed are two main parts influencing the formation of river channel. The deposition occurring in the lower reach of the East sluice obviously resulted from the changing hydraulic conditions that caused the imbalance between sediment supply and output. By analyzing the obtained data, the variations of the hydraulic conditions in Yunzaobang River can be summed up as follows:

3.1 THE CHANGE OF RUNOFF CONDITION

For the lower reach of sluice where sediments are mainly imported from sea, runoff is the vital element. Without runoff, it can be inferred that the amount of incoming sediments is always greater than that of outgoing sands and bed is gradually silted up to drying up. Only with the erosion of runoff, the lower reach of sluice is able to retain a certain discharge area. Since the East and some branch sluices were built, runoff was partly intercepted especially in rainless year or drought period. Moreover, artificial control on runoff modified the natural process of draw-off. Thus it can be concluded that: both the decrease and the change of the distribution of runoff greatly cause the silting in the lower reach of East sluice.

3.2 DECREASE OF TIDE VOLUME

The overall length of Yunzaobang River is 34km. The East sluice was built at 12km away from the estuary and shortened the tide-received prismatic body for 22km. Since the sluice was built, the tide volume decreased markedly in the lower reach of the East sluice. By analyzing the measured data for Yunzaobang River, it can be found that currently the average incoming flood volume at section A (as the representative section of estuary) is 2,180,000m^3 per tide. Although there is no measured data about incoming flood volume before the buildings of sluices, the decreasing value of tide volume can be obtained as following.

(1) Incoming tide volume (W_1) in the river reach between the East and West sluices

The span between the East and West sluices is 22km while the width of river channel is 40m. Let the descend rate per-kilometer of the tidal range be (2.22-1.44)/12=0.065 (referred to the measured tide range at two stations with distance of 12 km before construction of the sluices), the tidal range is close to zero near the West sluice. Now, the incoming tide volume can be figured out as:

$$W_1 = 22000 \times 40 \frac{1.44}{2} = 633600\,\mathrm{m}^3 \approx 633{,}000\,\mathrm{m}^3$$

(2) Increasing tide volume (W_2) due to the wave deformation in the lower reach of sluice

Comparing the tidal eigenvalues of the two stations at the estuary and near the East sluice before and after construction of sluices, it is clear that in the lower reach of sluice, the tide volume increased due to the increasing tidal range after construction of sluices. Calculated by the length, width and increased tidal range of this river reach, the tide volume increased 180,000m^3, 80,000 m^{3}and 40,000 m^3 respectively at the three sections of A, B, C.

(3)The tide volume before construction of the sluices

The tide volume before construction of the sluices (W_{pre}) can be formulated as:

$$W_{\mathrm{pre}} = W_{\mathrm{hind}} + W_1 - W_2$$

Here, W_{hind} is the current tide volume, W_1 is the incoming tide volume of the river reach between the East and West sluices, W_2 is the increasing tide volume due to the increased tidal range.

(4) ΔW The decreasing tide volume: $\Delta W = W_{\mathrm{pre}} - W_{\mathrm{hind}}$

Table 1 shows the computed results: the incoming tide volume decreases markedly in Yunzaobang River since the sluices were built. Furthermore, the nearer to the sluices it is, the less tide volume it will be, which causes the more serious silting in the end.

Table 1 calculating table for decreasing tide volume due to the buildings of sluices

Calculating Item	Data source	A	B	C
W_{hind}	Surveyed	218	92	39
W_1	Calculated As A Tidal Prismatic Body	63	63	63
W_2	Deformation of tidal wave	18	8	4
W_{pre}	$W_{\mathrm{pre}} = W_{\mathrm{hind}} + W_1 - W_2$	263	147	98
ΔW	$\Delta W = W_{\mathrm{pre}} - W_{\mathrm{hind}}$	45	55	59
$\Delta W / W_1$ (%)	$\Delta W / W_{\mathrm{pre}}$	17	37	60

3.3 DURATION OF FLOOD SHORTENED AND THAT OF EBB EXTENDED

The variation of duration of flood and ebb tide before and after construction of sluices shows different feature at the estuary and near the East sluice. The change is not obvious at the estuary station, the duration of flood tide only shortened for 2 minutes and that of ebb tide extended for 1 minute. However, at another station, the variation is large relatively that the duration of floor tide shortened for 23 minutes and that of ebb tide extended for 22 minutes. Consequently, the variations of durations caused the flow velocity of tide flood to increase and that of tide ebb to decrease. It results in the enormous difference of the ability to carry sediment between flood tide and ebb tide (induced from the relation of positive proportion between the ability of carrying sediment and the 2-3 power of flow velocity). The former increased incoming sediments while the later decreased the outgoing silts that led to serious silting in the river channel.

4. REGULATION MEASURES

On the basis of the experiences to reduce the silting in a lower reach of sluice and the stuation involved in the deposition of Yunzaobang River discussed above, hydraulic scour was stressed as the main measure for reducing silting.

4.1 WATER SOURCES

Undoubtedly, water resource is the basic element for hydraulic scour. Well then, which sources the water resource of Yunzaobang River comes from:

(1) Runoff. The drainage area of Yunzaobang River is more than 700 km^2. Let the catchment area ratio be 5 percent, the catchment area is to be 35km^2. On the basis of the measured flood or ebb tide volume and runoff volume resulted from five hydrologic tests during 1988−1989, the ratio of (runoff volume)/(tide volume) for each hydrologic section is listed in Table 2.

Table 2 Runoff volume during 1988-1989 Unit: $10^4\ m^3$

Sections	Floodtide Volume	Ebbtide Volume	Runoff Volume	(Runoff Volume)/(Tide Volume)
A	218	272	54	20%
B	92	130	38	29%
C	39	74	35	47%

Obviously, there still is considerable proportional runoff effusing down from the East and other branch sluices under current natural condition. However, judging by the slight silting status in this period, it is inferred that runoff volume during 1988−1989 might be greater than those of ordinary years.

(2) Drawing water from Liu River. Making reasonable adjustment and management of the sluice system, it is possible to draw water from Liu River, a adjacent river, into Yunzaobang River.

(3) Collecting and storing tide water. The measured data indicates that the sediment concentration in Yunzaobang River is changing along with seasons (less in winter and more in summer). Moreover, even in the same season, there exist huge differences among the sediment concentrations of different tides. Thus, it is a good practice to store water on suitable occasions for the sake of scouring.

4.2 DRAW-OFF DISCHARGE

The other key factor with respect to hydraulic scour is the draw-off discharge. What is the appropriate discharge for retaining no-silting in the lower reach of sluice? Therefore, the relation between runoff volume and net sediment transport discharge (transport direction) was worked out on the basis of flood/ebb tide volume and sediment discharge listed in Table 3. The minimum runoff volume for sediment transport balance at section A, B and C can be found in Table 3.

Section C: When runoff volume >210,000m^3, outgoing sediment > incoming sediment and this runoff volume is 54 percent of the average tide volume.

Section B: When runoff volume >550,000 m^3, outgoing sediment > incoming sediment and this runoff volume is 60 percent of the average tide volume.

Section A: When runoff volume >1,310,000 m^3, outgoing sediment > incoming sediment and this runoff volume is 60 percent of the average tide volume.

Therefore, for retaining no-silting in the lower reach of sluice, the gross draw-off discharge has to reach 50−60 percent of local tide volume per tide. However, owing to varying tide volume along river, the different draw-off discharge should be determined in response to different river reach. For retaining no-silting in the whole Yunzaobang River, the gross draw-off discharge must be 1,000,000−1,300,000 m^3 per tide that would cause apparent erosion to the whole river. Owing to the average ebbtide duration is eight hours and six minutes, the due draw-off discharge should be 35−40 m^3/s or so.

Table 3 The relation between runoff volume and sediment transport direction

Time \ Item \ Section	C		B		A	
	Q	ΔS	Q	ΔS	Q	ΔS
1988.8.	8	-526	-10	-841	51	-313
1988.11.	21	46	14	-59	39	-112
1989.1.	5	-202	3	-147	9	-105
1989.5.	48	518	55	344	41	-47
1989.8.	93	221	130	679	131	173

Note: Q=runoff volume(10^4 m^3); ΔS=net sediment transport discharge（ton）,“-” refers incoming, “+” refers outgoing.

4.3 PREDICTION OF THE EFFECT OF HYDRAULIC SCOUR

Practically, it is highly effective to use the method of hydraulic scour to settle the silting. But it is also very important to choose the draw-off discharge and occasion. Consequently, it is necessary for people to conduct adequate draw-off tests to optimize the draw-off plans. Through computing of the flow velocity field by numeric model and analyzing the fluvial facies relationship, the effects of hydraulic scour for Yunzaobang River in five given draw-off conditions will be compared.

5. CALCULATING IN TERMS OF DIFFERENT DRAW-OFF DISCHARGE

For exactly simulating the shape and trend of river channel in question, both the topography and main streamline should be considered. So, the arbitrary quadrilateral grid along topography and fluid was employed in the two-dimensional tide numerical model. After the accuracy of calculating results was verified, different combined designs in terms of the draw-off discharge and time process of the East sluice were simulated and computed.

(1) Draw-off discharge=35 m^3/s: sluicing for 2 hours from beginning of ebbtide, or 2 hours from the maximum ebb, or sluicing during whole ebbtide.

(2) Draw-off discharge=40 m^3/s: sluicing during whole ebbtide.

(3) Draw-off discharge=70 m^3/s: sluicing for 2 hours from the beginning of ebb, or 2 hours from the maximum ebb, or sluicing during whole ebbtide

(4) Draw-off discharge=140 m^3/s: sluicing for 2 hours from the beginning of ebbtide, or 2 hours from maximum ebb.

(5) Draw-off discharge=200 m^3/s: sluicing for 2 hours from the beginning of ebbtide, or 2 hours from the maximum ebbt.

5.1 VARIATION OF FLOW VELOCITY

The above computation gave the results of the variations of average flood/ebb tide flow velocity, flow velocity for every hour and the distribution of average velocity along river channel. Three conclusions are derived from above outcomes.

For the cases of draw-off time for 2 hours with the same discharge, it is apparent that the average flow velocity when the beginning of draw-off is at the maximum ebb is greater than that at the beginning of ebbtide. What is responsible for the fact? Obviously, because of the lower water level and the less discharge area at the maximum ebb, the corresponding flow velocity is higher. This conclusion shows that sluicing is more effective when beginning of draw-off is at the maximum ebb than that at the early ebb.

Obviously, no matter what cases, the impact of draw-off is greater for upstream than for downstream. Therefore, the determination of draw-off discharge depends on the position of river section in question. The flux of $35m^3/s$ is the suitable value retaining no-silting in the whole valley of Yunzaobang River.

For the cases of sluicing during whole ebbtide, the flow velocity increases markedly. On the basis of the no-silting velocity obtained by circulating flume test, which is 32 cm/s, the discharge of 35 m^3/s is an appropriate value for hydraulic scour.

5.2 DIVERSITY OF SECTIONAL CONFIGURATION

By analyzing the relation of fluvial facies for current Yunzaobang River, the variations of river sectional configurations were obtained as following.

A) The relation of sectional discharge area A and ebb tide volume Q:

$$A = 6.2Q^{0.9} \quad \text{for whole river channel}$$

B) The relations among sectional average water depth $\overline{H}$, ebb tide volume Q, sediment concentration ρ and river width B:

$$\overline{H}_1 = \frac{3.98}{B}\left(\frac{Q^{0.5}}{\rho^{0.25}}\right)^{1.6} \quad \text{for sections 8 to 45}$$

$$\overline{H}_2 = \frac{2.88}{B}\left(\frac{Q^{0.5}}{\rho^{0.25}}\right)^{1.8} \quad \text{for sections 46 to 70}$$

$$\overline{H}_3 = \frac{2.69}{B}\left(\frac{Q^{0.5}}{\rho^{0.25}}\right)^{1.8} \quad \text{for sections 71 to 89}$$

C) The relation of max channel depth $H_{\max}$ and sectional average depth $\overline{H}$:

$$H_{\max} = 1.3\overline{H} \quad \text{for whole river channel}$$

Here, A, $\overline{H}$, $H_{\max}$, B all correspond to the case of mesotidal level.

Using the above formulas, the configurations of the given three hydrologic sections can be figured out when the draw-off discharge of the East sluice eq. 35 m^3/s, see Table 4.

Table 4 Sectional sizes for sluicing during whole ebbtide (draw-off discharge eq. 35 m^3/s)

Section	Discharge Area (m^2)		Average Depth (m)		Max Depth (m)	
	A_0	A	H_0	$\overline{H}$	$H_{0\max}$	$H_{\max}$
A	337	375	4.16	4.53	5.62	5.89
B	129	242	2.57	4.18	3.60	6.43
C	76	188	2.63	4.53	3.38	5.89

Here, A_0, $\overline{H}_0$, $H_{0\max}$ are the sectional sizes of the original river channel.

6. CONCLUDING REMARKS

1. The construction of the two sluices in Yunzaobang River, which partly intercept runoff volume and decrease incoming tide volume, brought about the silting in the lower reach of the East sluice. According to the current discharge area of river channel, the mean annual silting volume reaches about 200,000 m^3. The medium diameter of sediment is 0.02−0.034mm.

2. The sediments of Yunzaobang River mainly come from the estuary of Huangpujiang River. The mean annual volume concentration of sediment is 0.20kg/ m^3 at the estuary and the amount of incoming sediment from the sea reaches about 350,000 m^3. Moreover, there exist the following rules in the lower reach of the East sluice: scouring during floodtide/floodwater and depositing during ebbtide/lowwater; the nearer to the sluice it is, the heavier the silting will be; turbid water coming in and clear water going out.

3. By analyzing above rules and conditions, the hydraulic scour should be a suitable measure for settling the silting of Yunzaobang River.

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