International Conference on Estuaries and Coasts
November 9-11, 2003, Hangzhou, China

SEDIMENTATION PROBLEMS RELATED TO REGULATION OF DEEP CHANNEL IN THE YANGTZE ESTUARY

Xiping DOU
Nanjing Hydraulic Research Institute, Nanjing 210029, China
E-mail: xpdou@njhri.edu.cn

Abstract: The deepwater navigation channel is a great project in China. The project is divided into three stages. The target water depths are -8.5m, -10m and -12.5m respectively. The total investment is 15,500,000,000 RMB yuan and the duration of construction is 9 years. The one-stage project started to be built in January 1998 and was completed in March 2000. The two-stage project started to be built in October 2003. In this paper, the dynamic conditions and sedimentation of the Yangtze Estuary are introduced. According to the similarity conditions of tidal currents and bed loads, a movable bed physical model of the Yangtze Estuary is designed to study the layout of regulating project of the deep channel and simulate bed load movement. In order to predict the siltation in the channel after regulation, a 2D numerical model is presented, in which total sediment transport, the actions of tidal currents and wind waves, the effect of salinity are considered. The annual siltation and short-term siltation in one-stage channel are calculated and compared with the dredging volumes in prototype.

Key words: Yangtze Estuary, Physical model, Numerical model, Sediment, Channel

1. INTRODUCTION

Yangtze Estuary, the mouth of Yangtze River, is located in the east part of China. Under the conditions of rich water and sand, the pattern of multilevel bifurcated channel is form in the process of evolution to the sea. The longitudinal length of Yangtze Estuary is above 164km and the width at the entrance is about 90km(Fig.1).

The seaway in Yangtze Estuary crosses the river mouth bar. In nature situation, the reach with depth of less than 9m is over 40km in length and the shallowest depth is only 6m. Since 1975, the man-made channels have been opened in South Passage and North Passage in turn by dredging, and their depth has been maintained to 7m. Annual dredging volume is about 12,000,000 m^3. The maximum annual volume is up to 24,000,000 m^3.

Due to the economic development along the Yangtze River and in Yangtze Delta, it is impatient to construction a deep navigation channel. However, the navigation depth is difficult to be greatly increased purely depended on dredging due to the changeable river situation. Sediment siltation is key problem in the deep-water channel project. In past the siltation prediction in harbor and navigation channel depends mainly on the siltation measured in the dug channel on the spot. In 1980's it obtained by the empirical formula according to the variation of velocity before and after the construction from physical model or numerical model of flow. Since 1990, physical model and numerical model of sediment transport have been used to study the siltation with the development of sediment movement simulation technical. However the sediment movement is very complicated in Yangtze Estuary. There are both suspended load and bed load. They are influenced not only by runoff but also by tidal currents, wind waves and salinity. Because it is difficult to consider the above factors in one physical model, the physical model is aim to study the layout of the regulation project and the effect of the bed load movement on deepwater channel (Chen, 1998). The numerical model is used to deal with the sediment siltation (including suspended and bed load) and optimize the layout of the project (Dou, 1999a).

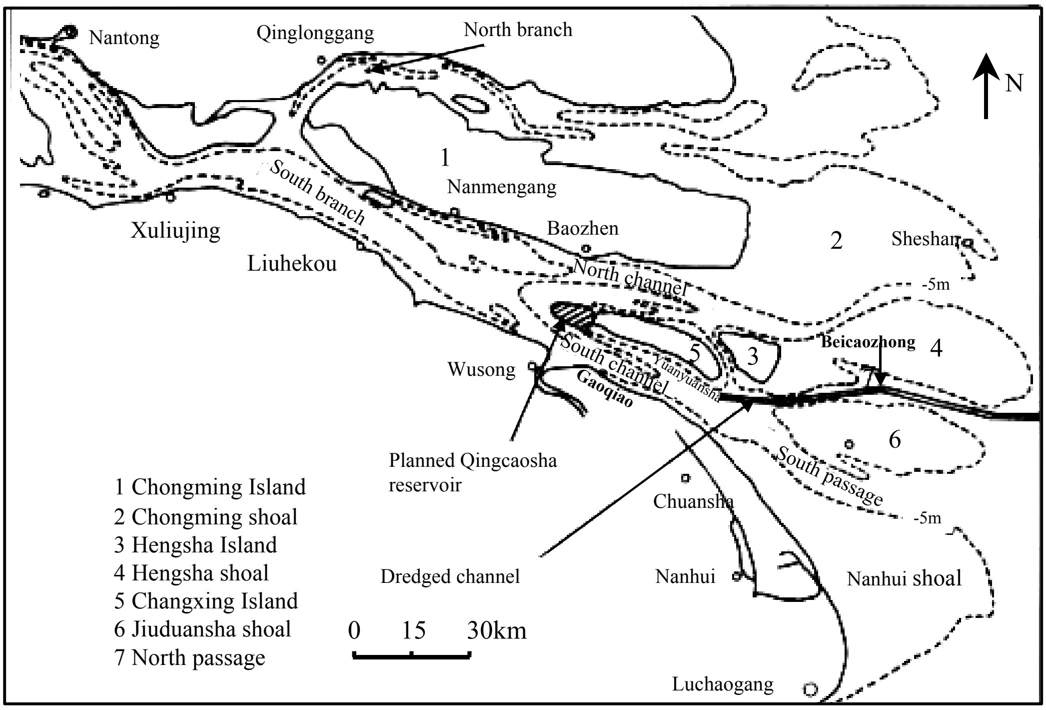

Fig. 1 The situation of Yangtze Estuary

2. THE DYNAMIC CONDITIONS AND SEDIMENTATION

2.1 RUNOFF

The annual average runoff in Datong gauge station (640km to the estuary) is 29,600m^3/s and the volume is 9,250,000,000,000m^3. The mean runoff is 40,000m^3/s in flood period (from May to October) and 18,000m^3/s in dry period (from November to next April) respectively. The statistics shows the discharge of flood is almost 70% of whole year.

2.2 TIDE

The tide in Yangtze Estuary belongs to non-regular semi-diurnal tide and the tide power is moderate. Tidal wave is mixed and progressive wave mainly. The duration of rise gradually shorten and that of fall gradually increase when tidal waves propagate from out to inside of the estuary. The tidal limit is about 640km and the tidal current limit is about 240km from the estuary.

In Beicaozhong (in the middle of North Passage), the highest high-water level is 5.20m and the lowest low water level is -0.58m, the mean high tide is 3.34m and the mean low water is 0.63m.

In South Channel and North Channel, the currents are to-and fro flows and the velocity of ebb current is larger than that of flood current. In South Passage and North Passage, the tidal currents transfer from to-and-fro to rotary flow with clockwise. The tidal currents are clockwise flow outside the estuary.

2.3 WIND AND WAVE

In this region, the prevailing wind direction is SE-SEE. The strong direction is NW~NNW. In one year, the wind scale that is greater than 6 is 11%. The windy days are the most in December and January and the lest in June and May.

The wave is principally deduced by wind. The frequency of wave direction is basically as the same as that of wind direction. The wave height is decreased gradually when waves propagate from the out to the inside of the estuary. The mean wave height is 0.9m in Sheshan and its period is 3.7s. It reduces to 0.35m in Gaoqiao and the period is 2.4s. The maximum wave height measured during typhoon is 5.2m in Sheshan and 3.2m in Gaoqiao respectively. The maximum wave period is 12s in Sheshan and 4.5s in Gaoqiao respectively.

2.4 SEDIMENTATION

The sediment in Yangtze Estuary is mainly from Yangtze basin. According to the records of Datong gauge station, the annual average sediment discharge is 486million tons before 1985 and 357million tons after 1986. The silt discharge in flood season is 86% of whole year. The mean sediment concentration is 1.0kg/m^3 in flood season and 0.1kg/m^3 in dry season. The annual average concentration is 0.54 kg/m^3. The sediment transport is mainly in suspended style. The silt discharge in the form of bed material is roughly estimated 10% of total silt discharge.

The sediment discharge in South Channel is same as that in North Channel. The sediment discharge in South Passage is greater than that in North Passage. From the measured data, the mean concentration is 1.0−2.0kg/m^3 in North Passage during flood current and 0.1−0.2kg/m^3 during neap current. In North Passage, the concentration increases from upstream to downstream and the concentration inside the estuary is greater than that in the outside. The median diameter of suspended load is between 0.0065−0.0301mm and the average median diameter is 0.01−0.02mm in North Passage.

The salinity is between 5‰−15‰in river mouth bar. The salinity decreases from the sea to the upstream. The distances of salt intrusion are different in flood and dry season. Under the influence of salt water, suspended load may flocculate and the flocculent settling velocity is about 0.0003−0.0007m/s. The mean median diameter of bed material is 0.093mm in North Branch, 0.084mm in South Branch, 0.061mm in North Channel, 0.059mm in North Passage and 0.029mm in South Passage respectively.

3. THE PHYSICAL MODEL

There are two physical models of the whole Yangtze Estuary. One is in Nanjing Hydraulic Research Institute and another is in Estuary and Coast Research Center (Shanghai). In the paper, the work done in Nanjing model is introduced.

3.1 THE MODEL DESIGN

3.1.1 Similarity conditions of tidal currents

From the equations of flow movement, the conditions of similarity for the tidal currents between model and prototype are expressed as follows:

$$\lambda_u = \lambda_v = \lambda_h^{1/2} \quad (1)$$

$$\lambda_c = \left(\frac{\lambda_l}{\lambda_h}\right)^{1/2} \quad (2)$$

Where λ is the scale ratio between the value in the model and that in prototype, with the footnote representing the relevant value; *u* and *v* are the depth-averaged components of velocity; *h* is water depth; *l* is the length in horizontal plane; *C* is Chezy coefficient.

3.1.2 Similarity conditions of bed load

The study of movable bed model is mainly on the scouring effect of the regulation project. The similarity of bed load movement should satisfy the similarities of incipience movement, bed load transport discharge, bed deformation, bed load deposition and suspension (Dou, 1997). According to the formula of the bed load transport volume derived by Dou Guoren

$$q_b = \frac{\gamma\gamma_s}{\gamma_s - \gamma}\frac{k_2}{C^2}\frac{U^3}{\omega_b}\left(U - U_C\right) \tag{3}$$

where q_b is the value of the bed load transport volume; ω_b is settling velocity of bed load; γ_0 is the dry volume weight of bed material; γ and γ_s are the unit volume weight of sea water and sediment particles respectively; U_c is the critical velocity for incipience of bed load particles; $U = \sqrt{u^2 + v^2}$; K_2 is a coefficient.

The following relationships are the similarities of initial movement, bed load transport, scouring time and deposition respectively:

$$\lambda_U = \lambda_{U_c} \tag{4}$$

$$\lambda_{q_b} = \frac{\lambda_{\gamma_s}}{\lambda_{\gamma_s - \gamma}}\frac{\lambda_{U^4}}{\lambda_C^2 \lambda_{\omega_b}} \tag{5}$$

$$\lambda_{t_b} = \lambda_{\gamma_0}\frac{\lambda_h}{\lambda_{q_b}}\lambda_l \tag{6}$$

$$\lambda_{\omega_b} = \lambda_U \lambda_h / \lambda_\ell \tag{7}$$

According to the analysis of similarity and the condition of testing hall, the horizontal scale was 2000 and the vertical one was 150. The area of movable bed is downstream of Gaoqian in South Channel, North Passage and part of South Passage. The model sand is asphalt powder. The unit volume weight is 1,180kg/m^3 and d_{50} is 0.32mm. The tide time scale is 163.3 and one day is 8′48″in the model. The scale of bed load discharge and the scale of bed deformation time were determined by the experiments of the seabed verification. The detail scales are shown in Table 1.

Table 1 Scale values of Yangtze Estuary model

Scales	Calculated Values	Adopted Values
Horizontal λ_l		2000
Vertical λ_h		150
Flow velocity λ_v	12.25	12.25
Roughness λ_n	0.63	0.63
Tide time λ_t	163.30	163.30
Settling velocity λ_{ω_b}	0.92	0.21
Particle diameter λ_d		0.125
Dry unit weight λ_{γ_0}		2.02
Incipient velocity of current λ_{U_c}	12.27	12.73~15.47
Bed load discharge λ_{q_b}	450	246
Bed deformation time λ_{t_b}	1600	2920

3.2 THE BED LOAD VERIFICATION

In order to predict the bed load movement after the regulation project, the variation of seabed in North Passage from 1978 to 1980 was used to verify due to the seabed undisturbed by dredging during this period. The experiment conditions are that the upstream discharge is 30,000m^3/s and a middle tide circulates in the out sea. At the beginning of the experiment, the bed of model was made according to the topography in 1978. When ebb current, 1.0kg sands were added in South Channel. After 6 hours, the bed of model was same as that of 1980 in nature. The comparison of siltation and scouring are shown in Table 2. The results show the similarity can be obtained by the choice of dynamic factors and model sand.

Table 2 Comparison of siltation and scouring in North Passage

Bed Elevation	Scoring Reach				Siltation Reach			
	Length (km)	Scouring Volume			Length (km)	Siltation Volume		
		Prototype (10^3m^3)	Model (10^3m^3)	Relative Error		Prototype (10^3m^3)	Model (10^3m^3)	Relative Error
-2m	20.8	73,120	63,600	13 %	12.8	27,992	19,840	29 %
-5m	24.0	66,640	64,320	3 %	9.6	14,640	7,600	48 %

3.3 THE MOVABLE BED EXPERIMENT

The bed of South and North Passage is cover with silt and mud. These materials are easy to be suspended and transported between the shoals and deep channel under the action of tidal currents and wind waves. It is necessary to construct regulated structure because the deepwater way cannot be maintained merely by dredging. The diversion of South Passage and North Passage should be firm firstly to prevent it drawing back.

Through different plans associated experiments, a regulation plan was presented that include diversion fish lips, leading jetty and spur dikes (Fig. 2). The experiment shows that -8m isobath was joined up and -9m isobath was formed in North Passage after 9 hours experiment when one stage regulation project was built in the model.

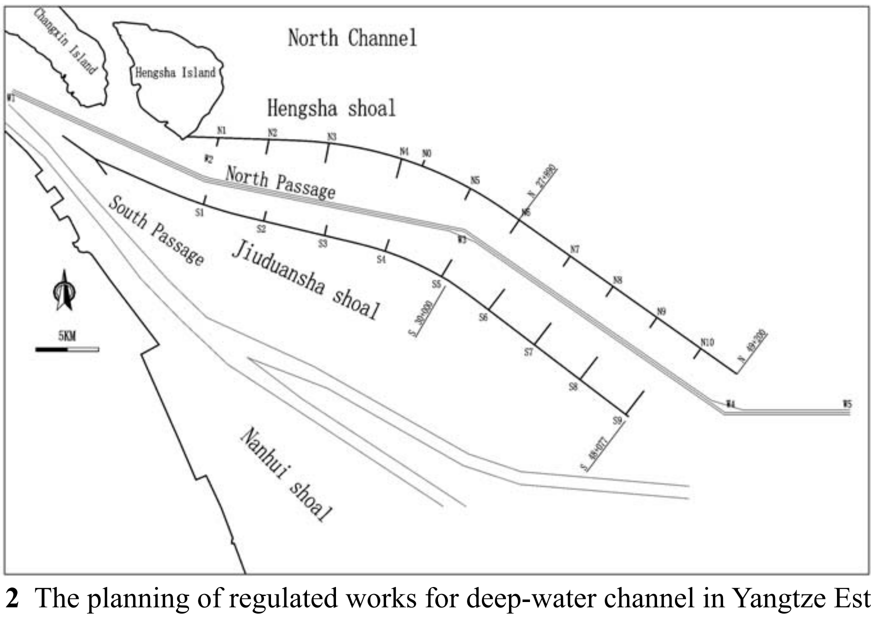

Fig. 2 The planning of regulated works for deep-water channel in Yangtze Estuary

3.4 SAND MOVEMENT EXPERIMENT

In order to know the influence of bed load transport on the deepwater channel after the regulation, two situations were simulated in the model.

One is putting some red sands in the front of Changxing Island just as the shoal suffered scouring seriously and a great quantity of bed load moved down in the middle of 1970s. The experiment conditions are that the upstream discharge is 60,000 m^3/s and a spring tide circulates in the out sea. After 30 min (three months in prototype), the bed load arrived Yuanyuansha. In the process of ebb current, a large part of the sands entered the entrance of North Passage and some of them silted in the channel. The silted sands removed with the flood current to the upstream and a few entered South Channel. The sand silted less in the main channel through the diversion fish lips adjusted.

Another is putting some green sands in the south part of the main way of South Channel just as a new way formed and a large number of sands transported down at the beginning of 1960s. The experiment conditions are the same as that mentioned above. The experiments showed that the sands were transported along South Passage by the ebb currents and did not make a direct influence on North Passage.

4.THE NUMERICAL MODEL OF TOTAL SEDIMENT TRANSPORT

In order to predict the siltation volume in the deepwater channel after training project, a horizontal 2D numerical model of suspended load and bed load was presented (Dou 1999b). A boundary-fitted grid with orthogonal curvilinear coordinate is applied to fit the boundaries of the estuary and the regulation project. The length (in east- west) of the calculated area is 200 km and the width in (north- south) is 130 km. The spatial steps are from 50 m to 4,000 m and the grids are densely added in the project region. The action of tidal currents, wind waves and the effect of salinity on the suspended load are considered.

4.1 THE EQUATIONS OF SUSPENDED AND BED LOAD TRANSPORT

The basic equation of 2-D suspended load transport established by Guoren Dou is

$$\frac{\partial(hS)}{\partial t}+\left[\frac{\partial(huS)}{\partial x}+\frac{\partial(hvS)}{\partial y}\right]+\alpha\omega(S-S_*)=0 \tag{8}$$

where S is depth-averaged concentration of suspended sediment; α is a coefficient which can be determined by verification calculation; ω is the settling velocity of sediment particles; S_* is the sediment transport capacity of flow.

According to Dou's formula (Dou, 1995), the sediment transport capacity of tidal currents and wind waves is:

$$S_*=\alpha_0\frac{\gamma\gamma_s}{\gamma_s-\gamma}\left[\frac{(u^2+v^2)^{3/2}}{C^2h\omega}+\beta_0\frac{H_w^2}{HT\omega}\right] \tag{9}$$

H_w is mean wave height and T is mean wave period. From the fields data and wave flume data, $\alpha_0=0.023$ and $\beta_0=0.0004$.

The Non-equilibrium bed load transport equation derived by Dou Guoren is

$$\frac{\partial(\beta hN)}{\partial t}+\frac{\partial(\beta hNu)}{\partial x}+\frac{\partial(\beta hNv)}{\partial y}+\alpha_b\omega_b(N-N^*)=0 \tag{10}$$

where βh is the thickness of bed loads transport layer; N is the quantity of bed loads in the unit volume; α_b is the settling coefficient of bed load; ω_b is the settling velocity of bed load particle; N^* can be determined by

$$N^*=\frac{q_b^*}{\beta h\sqrt{u^2+v^2}}$$

where q_b^* is the bed loads transport capacity per unit width in unit time and can be determined by Dou's formula of bed load transport capacity

$$q_b^*=\frac{k_2}{C^2}\frac{\gamma\gamma_s}{\gamma_s-\gamma}m\frac{(u^2+v^2)^{3/2}}{\omega_b} \tag{11}$$

where

$$m = \begin{cases} \sqrt{u^2+v^2} - U_c & U_c \le \sqrt{u^2+v^2} \\ 0 & U_c \le \sqrt{u^2+v^2} \end{cases}$$

k_2 is a coefficient; U_c is the critical velocity for the incipience of bed load particle.

4.2 THE VERIFICATION OF BED LOAD

To total sediment model, the verification of bed load transport is necessary. Because the data of bed load are difficult to measure in Yangtze Estuary, the results from the physical model of movable bed are used to verify the numerical model. Taking the same conditions of the physical model, the bed load movement was calculated by the numerical model. The results show the longer the experiment is taken, the larger the width and the depth of scour in the channel increase. -8.0m equivalent lines are joined up and -9.0m equivalent lines are formed in the channel after 9h experiment in numerical model. This situation is just like that observed in experiment of the physical model.

4.3 THE VERIFICATION OF DREDGING VOLUME

Generally, the seabed scouring and siltation in Yangtze Estuary are caused by the movement of suspended load and bed load. Therefore, total sediment transport model is needed. The survey of geography figures shows that the variation of seabed is almost undetected in the South-North Passage area. Only the upper part of North Passage has to be dredged to maintain -7.0m bed elevations. The quantity of dredging is about 12,000,000m^3 each year.

The calculation of the variation of the seabed is performed from 1995 to 1996. In the model wave height and period in the out-sea boundary are take as 0.9 m and 3.7 s respectively, which are the mean values for 30 years on the spot. The calculating conditions are the surveying data in September 1996 and March 1996 that were taken as typical hydrology conditions. The calculated siltation in North Passage is 11,750,000m^3 in one year that is near to the actual one.

4.4 THE SILTATION DURING TYPHOONS

Every year, typhoons pass Yangtze estuary and meet spring tides frequently. At this moment, rough water and setup of water level occur. The sediment loads are re-suspended from the underwater shoals under the action of wind waves, and then the sediment concentration is high. After typhoon, tidal currents carry a part of suspended loads into the channel and lead to a large amount of silt in it.

In recent some ten years, the largest typhoon affected on Yangtze Estuary is No.8310 occurred in the late of September 1983, which came across the spring tide. Although wind speed of No.8310 typhoon is, about 16m/s, not very large, the wave heights and the setup of water are as high as 3m and 2m respectively. The typhoon caused heavy silt in South Passage. The dredged place was almost silted back to the original elevation. The highest thickness of silt was 1m and the highest intensity of it was 10cm/d. The total silt quantity was about 3,200,000m^3.

Another typhoon No. 8615 took place in the late of August 1986. The wind speed was as high as 20m/s but the wave height was only between 1m and 2m. The largest thickness of silt in North Passage was 0.6m. The largest intensity of silt was 2cm/d and the total quantity of silt was about 900,000m^3.

The siltations caused by No.8310 and No.8615 typhoon are verified by the total sediment transport model. The wave factors in the calculation are the measured value in that time. The seabed in South Passage was surveyed on Sep.22−23, 1983 and Oct.2−3, 1983 which was before and after No.8310 typhoon. The same measurement was carried in North Passage before (on Aug.11, 1983) and after (on Sep.13, 1983) No.8615 typhoon. The silt during 10 days and 33 days are calculated respectively. The thickness and distribution of sediment silt along the main channels are in good agreement with actual ones (Fig.3).

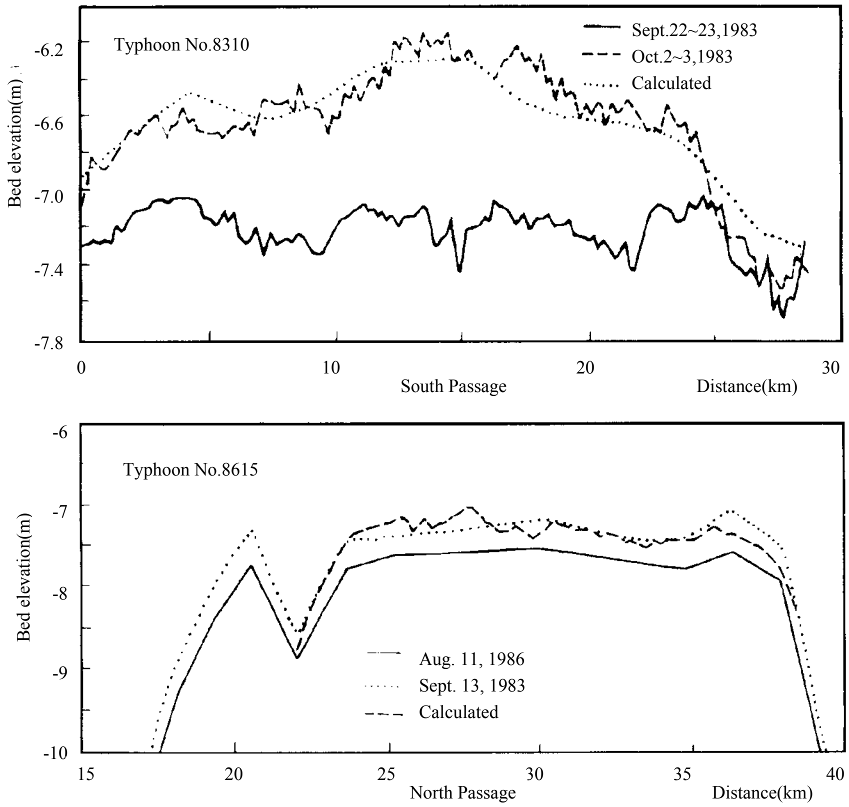

Fig. 3 The silt verification in south and north passage before and after the tropical storms

5. THE SILTATION OF THE DEEPWATER CHANNEL

5.1 THE SILTATION PREDICTION OF THE DEEP WATER CHANNEL

The main dimensions of the regulation project of deepwater navigation channel are listed in Table 3.

Table 3 Main dimensions of the project

Items	One Stage	Two Stage	Three Stage
Length of North Dike (km)	16.5	16.5+32.7	49.2
Length of South Dike (km)	20	20+28.077	48.077
Length of South Diversion (km)	1.6		
Length of Under Water Sand Fence (km)	3.2		
Spur Dikes Number	6	13	
Channel Width	300−350m	350−400m	350−400m
Length of Dredged Channel	49.1km	60.62km	79.5km
Target Water Depth	-8.5m	-10.0m	-12.5m

5.1.1 The silation in normal year

Based on the numerical model of total sediment transport, the annual siltations in the channel at different stages of regulated project are calculated. It is found that the spur dikes should be cut down due to the resistance increasing. Through the comparison of siltation, half of the design length of spur dikes is suggested. When the influence of adverse weather and hydrographic condition such as typhoon is neglected, the siltations in the channel are calculated (Table 4).

Table 4 Siltation of deep navigation channel in each stage

Stage	Water depth (m)	Annual siltation (10^4m^3)	Length (km)
One	-8.5	1,200	North dikes 16.5km South dikes 20.0km
Two	-10.0	1,700	North dikes 49.2km South dikes 48.077km
Three	-12.5	2,400	North dikes 49.2km South dikes 48.077km

5.1.2 The siltation in adverse conditions

No.8310 typhoon is the strongest one in recent 50 years. The siltation created by it can be taken as the siltation caused by typhoon came across spring tide. On the basis of the verification mentioned above, the sudden siltation volume of channel was calculated further in the situation of meeting with storm surge and catastrophic flood (Table 5). The results show that the silting is about 6cm/d and the thickness is about 0.6m during the period of typhoon (10 days).

Table 5 The siltation in the channel when typhoon meeting spring tide

Stage	Water Depth (m)	10 days' Siltation (10^4m^3)	Length (km)
One	-8.5	290	North dikes 16.5km South dikes 20.0km
Two	-10.0	400	North dikes 49.2km South dikes 48.077km
Three	-12.5	530	North dikes 49.2km South dikes 48.077km

5.2 THE DREDGED VOLUME OF ONE-STAGE PROJECT

One stage regulation project was constructed in January 1998 and completed in March 2000. The depth of navigation channel was up to 8.5m. If the average depth of the channel is less than 8.7m, the maintenance should be carried out at once.

According to the records of dredged volume, the maintenance was 22,000,000m^3 in 2000 including the siltation caused by several times of typhoon. It was measured that the siltation volume produced by Jielahua typhoon and Qide typhoon was about 6,000,000m^3. The obvious erosion occurred in the upper reach of North Passage due to construction of regulated structures particularly spur dikes. The total quantity of scouring material on the bed was up to 100,000,000 m^3. The bed siltation was piled up in the reach below the exit of a pair of dikes. The bottom of the channel in the middle and lower reaches was raised 1−2m in comparison with the topography predicted by the numerical model of total sediment transport. It was estimated through habitual method the siltation volume increased about 5,000,000 m^3 due to the topography of the middle and lower reaches of the channel raised.

The siltation volume was 18,100,000m^3 in 2001 and 21,030,000m^3 in 2002. During 2002, there are two times of typhoon occurred and the sudden siltation was 6,280,000m^3. From January 2003 to May 2003, the siltation volume was 54,300,000m^3 (Table 6).

Table 6 One stage siltation since the project completed

Period	Mean depth	Total siltation	Siltation in typhoon
2000.3.22−2000.12.31	8.5m	23,700,000 m^3	6,000,000m^3
2000.12.31−2001.12.15	8.8m	18,100,000 m^3	
2001.12.15−2002.12.23	8.99m	21,030,000 m^3	6,280,000m^3
2002.12.23−2003.5.27	9.03m	5,430,000 m^3	

It can be seen that the siltations in one-stage deepwater channel gradually decrease after the seabed readjusted. The regulated project plays an important part in the deepwater navigation channel constructed.

6. CONCLUDING REMARKS

In Yangtze Estuary, sediment siltation is a key problem in the deepwater navigation channel development. Based on Dou's formula of sediment transport, the movable bed physical model was designed and total sediment transport numerical model was established. Through both physical model and numerical model, the regulated plans in multi-level bifurcated estuary were studied. The function of regulation project can be summarized into leading currents, preventing sediment and reducing siltation. The siltation volumes in normal year and in adverse conditions for each stage of the project were calculated. The measured data show that the target water depth of one stage has been achieved and the dredged volumes tend to the predicted value after the seabed readjusted.

REFERENCES

Dou G. R., Dong F. W., Dou X. B, 1995, Sediment Transport Capacity of Tidal Currents and Waves, *CHINESE SCIENCE BULLETIN*, Vol.40, No.13, pp.1096-1101.

Dou G. R., 1997, The Similarity Law of Total Sediment Model and Design Example, *Journal of Nanjing Hydraulic Research Institute,* No.3, pp.1-8.

Chen, Z. C., 1998. The Physical Model of Deep-water Regulation Project in Yangtze Estuary, *Report of Nanjing Hydraulic Research Institute*, No.9802.

Dou X. P., 1999a, Numerical Model Study on Deepwater Navigation Channel Project of Yangtze Estuary, *Report of Nanjing Hydraulic Research Institute*, No.9920.

Dou X. P., Li T. L., Dou G. R., 1999b, Numerical Model of Total Sediment Transport in the Yangtze Estuary, *CHINA OCEAN ENGINEERING*, Vol.13, No.3, pp.277-286.