2D NUMERICAL SIMULATION OF WATER FLOW AND SEDIMENT TRANSPORT FOR SANDY AND GRAVEL SHOAL REACHES IN THE DOWNSTREAM OF TGP

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ABSTRACT

In this paper, the characteristics of water flow and sediment transport in a typical sandy and gravel watercourse of the middle reaches of Yangtze River is investigated using a 2D mathematical model. The major problems in this study include the following: the effective carrying capacity of suspended load, the incipient velocity and transport formula of non-uniform sediment, the thickness of mixed layers on the riverbed, partition of bed load and suspended load, etc. The model parameters are calibrated based on extensive field data. Water surface profiles, distribution of flow velocities and riverbed deformation are verified against field data. The present model has been applied to a sandy and gravel watercourse in the middle Yangtze River, with the Zhicheng-Dabujie reach as an example. Processes of sediment deposition and erosion, changes of water level and navigation conditions of the studied reach are predicted for the initial impoundment stage of Three Gorges Project(TGP).

1. INTRODUCTION

Applications of 1D mathematical models were reported as early as in the 1960s (Dou, 1963; Han, 1980；Lin, 1981；Chang, 1982；Holly-Rahuel, 1990；Lu et al, 1993). These models have been used to calculate long term sediment deposition and erosion for fluvial river channels. In the past few decades, 2D and 3D mathematical models for sediment transportation have been developed to predict river regime and riverbed deformation due to engineering projects (Dou et al., 1987, 1995；van Rijn, 1987；Li, 1989；Shimizu et al., 1990；Spasojevic-Holly, 1990, Olsen, 1999；Zhou, 1997；Lu et al., 1993, 2002, 2004；Minh Duc, 1998；Wu et al, 2000). The numerical models assume either equilibrium or non-equilibrium state of sediment transport. The models for suspended load transportation mostly assume the non-equilibrium sediment transport. The state of bed load transport (equilibrium or non-equilibrium) is essentially a key issue in the modeling of local sediment deposition and riverbed erosion.

The Zhicheng-Dabujie reach, with a length of 52km, is located 60 km downstream of the Gezhouba Dam (Figs. 1 and 2). It is part of the upper section in the middle Yangtze River, where the river plan forms are mostly meandering and island-braided. The river reach includes six shallow watercourses: Zhicheng watercourse, Guanzhou watercourse, Lujiahe watercourse, Zhijiang watercourse, Liuxiang watercourse and Jiangkou watercourse. The bed material consists of sand and gravel. The channel is wide with strong embankments.

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In this paper, a 2D mathematical model of water flows and sediment is developed to study the typical sandy and gravel watercourse in the middle Yangtze River, with the Zhicheng-Dabujie reach as an example. The model is first verified based on detailed field measurements, and then applied to study the navigation conditions of the Zhicheng-Dabujie reach downstream of the Three Gorges Project (TGP).

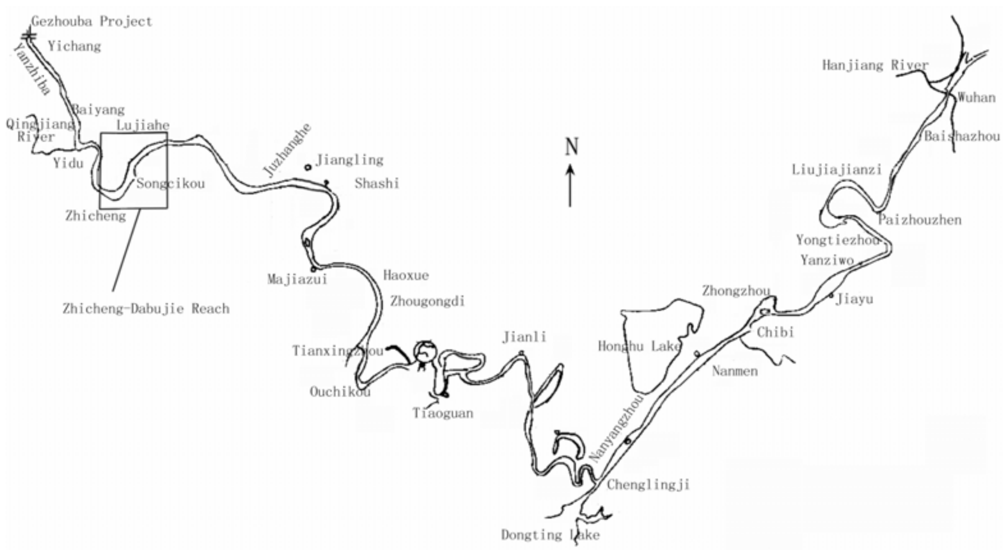

Fig. 1 Yichang-Wuhan reach of the middle Yangtze River and the location of the Zhicheng- Dabujie reach

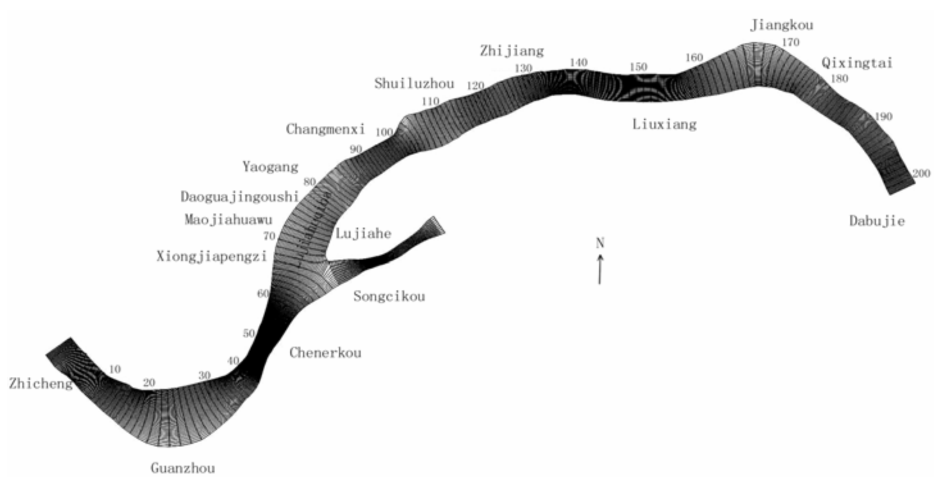

Fig. 2 Sketch and computational domain of Zhicheng-Dabujie reach

2. TREATMENT OF SOME KEY PROBLEMS

The mathematical model is based on the boundary-fitting coordinate system (Willemse et al., 1986). Details about development of the governing equations of 2D mathematical model for water flows and sediment transport as well as their numerical solutions can be found in the literature (Lu, 1998 ; Lu et al., 2002). The treatment methods of some key problems in the mathematical model are presented as follows.

2.1 Effective suspended load carrying capacity of flow on riverbed

The bed material of Zhicheng-Wuhan reach consists of medium and fine sand with the grain size less than 0.5 mm. Most part of the suspended load is with the grain size range of 0.025～0.18 mm, i.e., bed load with sizes larger than that will not participate in suspend motion. He and Han (1990) reported that the carrying capacity of suspended load (S_L^*) of group L consists of 3 parts: (1) the medium and fine particles of suspended load, which does not exchange with bed material, i.e., the so-called wash load, $SP_s^{'}$; (2) the coarse particles of suspended load, which deposit on the bed after exchanging with the bed material. Part of them can be lifted up and become suspended load, which is expressed as $SP_s^{''}S^*\left(\omega_2^*\right)/S^*\left(\omega_1^*\right)$; (3) the erodible particles of bed material, which can also be partially lifted up, expressed as $[1-\frac{P_s^{'}S}{S^*\left(\omega_1\right)}-\frac{P_s^{''}S}{S^*\left(\omega_1^*\right)}]P_1S^*\left(\omega_{11}^*\right)$. Therefore, one has

$$S_L^* = SP_s P_{SL1} + SP_s^{''}P_{SL2}\frac{S^*(L)}{S^*\left(\omega_1^*\right)} + \left[1-\frac{P_s S}{S^*\left(\omega_1\right)}-\frac{P_s^{''}S}{S^*\left(\omega_1^*\right)}\right]P_1P_{SL1}^*S^*\left(\omega_{11}^*\right) \tag{1}$$

in which $P_{SL1}=\begin{cases}P_{SL}/P_S^{'} & (L\le k)\\ 0 & (L>k)\end{cases}$; $P_{SL2}=\begin{cases}0 & (L\ge k)\\ P_{SL}/P_S^{''} & (L>k)\end{cases}$, $P_S^{'}=\sum_{L=1}^{k}P_{SL}$, $P_S^{''}=\sum_{L=k+1}^{n_0}P_{SL}$, k is the grain size dividing wash load and bed load;

$$S^*(\omega_1)=[\sum_{L=1}^{n}\frac{P_{SL1}}{S^*(L)}]^{-1}=K_0[\frac{V^3}{h}]^m\sum_{L=1}^{n}\frac{P_{SL}}{\omega_L^m}\omega_L$$

is the suspended load carrying capacity of the whole riverbed material ;

$$S^*(\omega_1^*)=\sum_{L=1}^{M}P_{mL}S^*(L)=K_0(\frac{V^3}{h})^m\sum_{L=1}^{M}\frac{P_{mL}}{\omega_L^m};$$

and $S^*(\omega_{11}^*)$ is the suspended load carrying capacity by the suspended part of riverbed material.

The above expressed suspended load concentration should not be larger than the suspended load carrying capacity, that is $S_L \le S_L^*$. When $S_L > S_L^*$,

$$S_L^* = P_{SL}S^*(\omega) \tag{2}$$

2.2 Initiation and transport rate of non-uniform bed load

(1) Probability of non-uniform sediment initiation

For non-uniform bed material, particles with different grain sizes are of different degrees of exposure, resulting in complex effects on their motion. Different positions of particles on the riverbed lead to different forces acting on particles by water flows. Coarse particles on bed are subject to relatively larger actions, while the fine particles are “hiding” under the larger ones or in their wake flow areas. This paper employs a parameter ξ to denote the exposure and hiding effects of particles. By using the geometric mean grain size D_m of bed material as the characteristic size, regression analysis of test data from Little-Mayer, Gessler, Ashida-Michiue, Liu Xingnian, Lu

Yongjun et al., and field data of the San Lus River yields the following equation for the exposing-hiding coefficient (Lu, et al, 1992)

$$\xi_L = \begin{cases} 10^{0.55\lg^2(D_L/D_m)-0.204(D_L/D_m)-0.112} & (D_L \le 0.5D_m) \\ 0.895(D_L / D_m)^{-0.16} & (D_L > 0.5D_m) \end{cases} \tag{3}$$

Critical Shields number for sediment particles with the grain size of D_L is obtained as

$$\theta_{crL} = 0.031\xi_L \tag{4}$$

Substituting Eg.s (3) and (4) into Gessler's probability formula of sediment staying on the riverbed yields the probability of initiation of group L:

$$p_L = 1 - q_L = 1 - \frac{1}{\sigma\sqrt{2\pi}}\int_{-\infty}^{\xi_L\frac{0.031(\gamma_S-\gamma)D_L}{\tau}} \exp\left(-\frac{t^2}{2\sigma^2}\right)dt \tag{5}$$

(2) Sediment transport rate for non-uniform bed load

In this study, the following non-uniform bed load transport formula is employed, which was developed based on the stream power theory (Lu, et al., 1991)

$$g_{bL} = K_b \frac{\gamma_s}{\gamma_s - \gamma}\tau_0 u_* P_{mL}\left(1 - 0.7\sqrt{\frac{\theta_{crL}}{\theta_L}}\right)(1 - q_L) \tag{6}$$

in which $\tau_0 = \gamma RJ$ is the boundary shear stress, C is Chezy coefficient, $C = h^{1/6}/n$; $u_* = \sqrt{\tau_0}/\rho$ is the shear velocity; P_{mL} is the percentage of size group L in the bed material; q_L is the probability of size group L staying on the riverbed, which is obtained by the modified Gessler's Eg. (5); θ_{crL} is calculated by Eg. (4) ; $\theta_L = \tau_0 / [(\gamma_s - \gamma)D_L]$.

$$K_b = \begin{cases} 11.6 & (\theta > 0.25) \\ 10^{0.2256-2.5348\lg\theta-1.896\lg^2\theta} & (0.06 < \theta < 0.25) \\ 10^{12.8719}\theta^{10.1319} & (\theta \le 0.06) \end{cases} \tag{7}$$

For bed material with uniform size, Eg. (6) is simplified to

$$g_b = K_b \frac{\gamma_s}{\gamma_s - \gamma}\tau_0 u_*\left[1 - 0.7\sqrt{\frac{\theta_c}{\theta}}\right](1 - q) \tag{8}$$

Comparisons between the results of Eg. (8) and those by Samage et al., the test data by Gilbert, and the measured sediment transport rate of sandy bed load at the No. 2 station of Xinchang on the Yangtze River indicate that 90% of the predictions are within the error range of 0.5～2.0, in terms of the ratio of the calculated to the measured values (Lu et al., 1991).

2.3 Coefficient K_o and exponent *m* in the formula for the carrying capacity of suspended load

Coefficient K_o and exponent m in the Zhang Ruijin formula, $S = K_o\left[Q^3B/A^4w\right]^m$, for the suspended load carrying capacity for saturated suspended load concentration, are determined according to verification calculation of sediment deposition and erosion in the middle reaches of Yangtze River. The results show that K_o = 0.014～0.017. The value of m = 0.92 is the same as that given by Han (1987).

2.4 Selection of recovery saturation coefficient α

Numerical tests show that the value of α in the non-equilibrium sediment transport Eg.s may not change with grain sizes. Generally, for the situation when all size groups of suspended load deposit and erode, α = 0.25； in the case when the coarse particles of the suspended load do not deposit and all the erodible particles of bed material are partially eroded, α = 1.0； for a situation when the coarse particles of suspended load deposit and the medium and fine particles of riverbed material are eroded, α = 0.5.

2.5 Thickness of the mixed layer of the bed, E_m

E_m is related to the characteristics of bed material. Calculations show that for sandy and gravel riverbed, E_m = 1.0～2.0 m during the initial period of erosion, and E_m = 0.5～1.0 m during the later stage; for the sandy riverbed, E_m is equivalent to the height of sand waves, and generally it is 2.0～3.0 m.

2.6.6 Partition of bed load and suspended load

Partition of the bed load and the suspended load is achieved by using the definition of the suspension index ω/ku_*. Particles with $\omega/ku_*\geq 5$ are bed load, otherwise they are suspended load.

3. MODEL VERIFICATION

The Zhicheng-Dabujie reach, a sandy and gravel shoal reach, downstream of TGP includes Zhicheng watercourse, Guanzhou watercourse, Lujiahe watercourse, Zhijiang watercourse, Liuxiang watercourse and Jiangkou watercourse (Fig. 2). Scientific Research Institute of Yangtze River Watercourse Bureau observed instantaneous water surface, velocity, sediment concentration, components of bed material and riverbed topography of the Zhicheng-Dabujie reach during 1988～1997. The calculated roughness by use of the measured water surface profiles is in the range of 0.016～0.030, and it is larger during the low-water period and smaller during the flood period. The calculated water levels corresponding to the discharges of 4961 m^3/s, 14679 m^3/s and 18656 m^3/s by use of mathematical models are basically in agreement with the measured instantaneous values of the Zhicheng-Zhijiang reach in 1988, and those corresponding to the discharges of 5380 m^3/s, 12200 m^3/s and 49000 m^3/s are in good agreement with the measured instantaneous values of the Zhicheng-Zhijiang reach in 1997, with the error being smaller than 0.1 m(Lu, 1997). The maximum elevation of Guanzhou is about 46 m, and generally it won't be submerged by water flows. During the low-water period the left channel of Guanzhou becomes a branch channel, and its confluence ratio is small. During the middle and flood period, the left channel of Guanzhou becomes the main channel, and the confluence ratio is larger than 50％. Comparison between the calculated confluence ratios corresponding to discharges of 4740 m^3/s, 19940 m^3/s and 28500 m^3/s and the measured values by Jingjiang Water Resources Bureau of Changjiang Water Resources Commission in 1995 shows (Table 1) that the calculated confluence ratio of Guanzhou is close to the measured one. The calculated distribution of velocities along the river width by use of mathematical models is basically in agreement of the measured one by Scientific Research Institute of Yangtze River Watercourse Bureau. The calculated flow fields for various discharges by use of mathematical models can better reflect that with the increase of discharges water flows gradually submerge Guanzhou, Shuiluzhou and Jiangkouzhou, and that the dynamic axis of water flows of the Lujiahe watercourse shifts toward the right bank from the left bank during flooding and returns the left bank during receding, and diffluence situation of Songcikou.

The Gezhouba Project is a run-of-river power plant, and the discharged water flows and sediment processes are nearly in agreement with that under the natural situation. Under the existing conditions, the annual evolution law of sediment deposition and erosion of the Lujiahe watercourse is characterized by deposition during flooding and erosion during receding . The calculated amount of deposition and erosion shows that during the period from the end of January to the first ten days of May 1988, there is some erosion on the riverbed, with the amount of erosion being 2.0×10^6 m^3; from the middle of May to the end of June, there is slight deposition on the riverbed, from July to the last ten days of September there is large quantity of deposition, with the maximum thickness being about 9.0 m and the amount being up to 11.0×10^6 m^3; Afterwards, as the water levels begin to decrease, the riverbed is gradually eroded, however, accompanied by small flood peaks and sand peaks, the amount of erosion is not large. From the middle of February to the last ten days of October the total amount of deposition is 10.07×10^6 m^3, while the measured one is 8.38×10^6 m^3, showing a close relationship between, and the calculated distribution of locations of riverbed deposition and erosion is in good agreement with the measured one (Fig.3). From the last ten days of October to the end of December, the study reach is characterized by obvious erosion, with the amount of erosion being 9.64×10^6 m^3 within 2 months, the measured one is 7.29×10^6 m^3, and the calculated distribution of locations of riverbed deposition and erosion is in good agreement with the measured one. Comparison between the calculated and measured amount of deposition and erosion for the Zhijiang-Jiangkou reach from November 1994 to March 1995 (Table 2) shows that during the receding period, an amount of erosion of 5.62×10^6 m^3 is washed away, and the calculated one

Table1 Verification of confluence ratio of Guanzhou watercourse (%)

Discharge (m^3/s)	Time	Confluence ratio of left channel		Confluence ratio of right channel	
		Calculated	Measured	Calculated	Measured
4740	1995.1.17	78.30	76.16	21.70	23.84
19940	1995.10.21	47.20	48.85	52.80	51.15
28500	1995.8.25	56.10	58.24	43.90	41.75

Table 2 Comparison between the calculated and measured amount of deposition and erosion at Zhijiang-Jiangkou reach (10^6 m^3)

Reach	Changmenxi ～ Zhijiang	Zhijiang ～ Jiangkou	Jiangkou ～ Qixingtai	Zhijiang ～ Qixingtai
Calculated (1994.11～1995.03)	－1.54	－2.49	－1.51	－5.54
Measured (1994.11～1995.03)	－1.51	－2.45	－1.67	－5.63
Error (％)	2.46	1.55	－9.66	－1.5
Calculated (1995.03～1995.09)	3.51	1.55	－1.84	3.22
Measured (1995.03～1995.09)	3.91	1.47	－2.27	3.11
Error (％)	－10.0	5.0	－19.1	3.70

is 5.54×10^6 m^3, showing a close relationship. The calculated distribution of locations of riverbed deposition and erosion is in good agreement with the measured one. Comparison between the calculated and measured amount of deposition and erosion for the Zhijiang-Jiangkou reach from March to September 1995 shows that during the flood period, deposition amounts to 3.11×10^6 m^3 for Zhijiang-Jiangkou reach, and the calculated one is 3.22×10^6 m^3, among which, 0.39×10^6 m^3 for Changmenxi-Zhijiang reach, a slight deposition of 1.47×10^6 m^3 for Zhijiang-Jiangkou, a slight erosion of 0.23×10^6 m^3 for the Jiangkou-Qixingtai reach, and the calculated distribution of locations of deposition and erosion is in good agreement with the measured one(Lu, 1997).

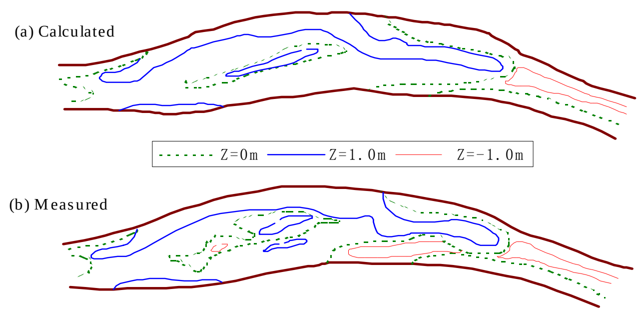

Fig. 3 Comparison between the calculated and measured distribution of locations of deposition and erosion for Lujiahe watercourse

4. EFFECT OF THE INITIAL IMPOUNDMENT OF TGP

The operation of the TGP significantly changes the hydrological conditions in the middle and lower reaches of the Yangtze River, particularly the sediment concentration and gradation of suspended load. This will have a great influence on the fluvial processes in the affected reach.

4.1 Change of flow conditions

TGP is an annually regulating reservoir, i.e., the mean inflowing and outflowing runoffs within the same hydrological year are basically equal. However, the discharged flow may be different due to the dispatching of the Reservoir within the same year.

- During the flood period (June~Sept.), there is no impoundment in the Reservoir, and the discharging ratio is 100%. Only if the discharge of Zhicheng becomes larger than 56700 m^3/s, or the discharge of Yichang becomes larger than 55000 m^3/s, will there be impoundment in the Reservoir. However, this probability is very small.
- During the impoundment period (Oct. ~ Nov.), the discharged flow will decrease. This will change the pattern of fluvial processes in the middle and lower reaches of the Yangtze River, i.e., depositions during the flood season will not be washed away in time, therefore the navigation conditions will deteriorate.
- During the dry season (Jan. ~ Apr.), the discharged flow will increase. The water level will rise and the depth of the navigation channel downstream of the reservoir will be increased.

4.2 Changes of sediment transport conditions

Changes of sediment transport conditions after the construction of TGP are mainly as follows:

(1) Change of sediment concentration and sediment load

After the construction of the Reservoir, the sediment concentration and the suspended load inflowing into the middle Yangtze River will be significantly smaller than before. During the first 10 years of impoundment, the sediment outflow ratio of the Reservoir is only 30%, i.e., about 70％ of the sediment from upstream will be deposited in the Reservoir. During the first 20 years of impoundment, the outflow sediment concentration and sediment load of the reservoir will maintain a constant low level. During the high-flow years, its annual mean sediment load is still less than 0.2 billion tons, which indicates that the reservoir sedimentation takes a sufficiently long time to reach its equilibrium.

(2) Gradation of grain sizes of the suspended load

During the initial stages of impoundment, the median particle size of suspended load discharged into the downstream is less than 0.01 mm, while that before the impoundment was 0.03 mm, a 28％ reduction which results in a corresponding reduction of the settling velocity, only about 10％ of the previous value. The sediment carrying capacity is fairly larger than the sediment concentration downstream of the reservoir, leading to serious erosion of the fluvial channel.

5. CALCULATION OF DEPOSITION AND EROSION AND SITUATION OF NAVIGATION CHANNEL In ZHICHENG-DABUJIE REACH AFTER THE COMMISSION OF TGP FOR 20 YEARS

5.1 Calculation of deposition and erosion in Zhicheng-Dabujie reach after the commission of TGP for 20 Years

During the initial impoundment of TGP, the sediment outflow ratio is only 30％, that is, the discharging sediment concentration is only 30％ of that before its construction, and the median diameter of discharging suspended load is only 0.0088~0.012 mm, or only 31％~43％ of that before its construction. Thus, the sediment carrying capacity by water flows in the downstream reaches is fairly larger than the sediment concentration, and the water flows need sediment from the riverbed so as to erode the riverbed and make the sediment concentration in the water flows gradually recover their saturation. After the riverbed is eroded, the bed material becomes coarse and restricts the downcut of riverbed. The largest erosion period for Zhicheng-Dabujie reach is during 2003~2008, after erosion of 6~8 years, that is, till 2010, the study reach reaches its equilibrium of deposition and erosion (Fig. 4), and the bed material obviously becomes coarse. Afterwards, the increase of amount of erosion becomes slow, and the depth of riverbed erosion decreases. Change of the mean erosion areas with time for various reaches is different, with the alternative deposition and erosion phenomenon (Fig. 5), among which, the Zhicheng-Chenerkou reach, the Chenerkou-Changmenxi reach and the Changmenxi-Zhijiang reach, there is rapid erosion before 2007, after 2008, especially after 2009, equilibrium of deposition and erosion is reached, and sediment from the upper reaches deposits at the Zhijiang-Jiangkou reach. After 2010, the Zhijiang-Jiangkou reach will not deposit and erode. As for the Jiangkou-Dabujie reach, alternative deposition and erosion will occur, showing an tendency of erosion in general.

Fig. 6 shows isolines of 1 m and 3 m of erosion in the Zhicheng-Dabujie reach after 10 years. It is seen that the depth of erosion in the Zhicheng watercourse is 1~2 m and 3 m locally; as for the Guanzhou watercourse, its head is basically not eroded, and the left and right branches are eroded about 2 m in depth, and its rear is eroded 3~4 m in depth; the Songcikou-Songci is eroded 1~2 m in depth; as for the Lujiahe watercourse, the left channel is eroded 2~3 m in depth, the right channel about 2 m in depth, there is only erosion of 0.2~0.5m in depth for the Lujiaheqiba. The

Maojiahuawu-Yaogangjian reach (Daoguajingoushi) is eroded about 1 m in depth (left side), an the right side is eroded 2~3 m in depth; the deep channel of Yaogang-Changmenxi reach is eroded about 3 m in depth, and the right shoal is eroded 1 m in depth. As for the Zhijiang water, the gravel shoal at the head of Shuiluzhou in Dongshi is eroded 0.5~1.0 m in depth, the rear is eroded 3~4 m in depth, and the right branch of Dongshi is eroded 1~2 m in depth. The Zhangjiataoyuan shoal at the opposite side of Zhijang is eroded 1~2 m in depth, while the deep channels at the left side are all eroded about 2 m in depth. There is a small depth of erosion for the Liuxiang watercourse and the Jiangkou watercourse, only 0.5~1.0 m in depth. The head of the Jiangkouzhou is eroded 0.5~1.0 m in depth, and its rear is eroded 2~3 m in depth. The Qixingtai-Dabujie reach has a mean depth of erosion about 2 m.

5.2 Situation of navigation channel of the Zhicheng-Dabujie reach after the commission of TGP for 20 Years

5.2.1 Scale of navigation channels

During the construction of TGP at the impoundment levels of 135 m and 156 m, the scale of navigation channel of the study reach is considered according to the current low-water period, that is, 3 m× 100 m×1000 m (depth×width×bend radius). At the impoundment of 175 m, the scale of navigable employs that required by vessels of 10^4 t, that is, 3.5 m×100 m×1000 m. The navigation channel of the Maojiahuawu-Yaogang reach and the Zhijiang watercourse with a 3 m depth can not be satisfactorily run through. After the commission of TGP, mathematical models are employed to calculate the navigable surface at discharge of 3200 m^3/s and to observe change of navigable depths, till the end of 2004, the 3 m-navigable depth of the left channel on Lujiahe and rear of Jiangkouzhou can not be run through. The left channel on Lujiahe still in a state of shortage of navigable depth during the back trough period nearly the same as the current state. Till the end of 2008, deposition of suspended load at the left channel on Lujiahe obviously decreases, and its navigable depth will not be in a state of shortage during the back trough period. However, as the depth of erosion at the Maojiahuawu-Yaogang reach is limited and its downstream water levels are of large amplitude of decrease, here the 3 m-navigable depth can not be run through. In addition, as for the Jiangkou watercourse, the 3 m-navigable depth cannot be also run through, having a direct effect on navigation. After 2009, the discharge increases to over 5000 m^3/s (the mean value during the low-water period provided by the design units), and the corresponding water depth has an increase of about 1.2 m, the 3.5 m-navigable depth required by vessels of 10^4 t can not be run through in the upstream and downstream. It should be pointed out that during the low-water power period when daily regulation is performed, there are 7 hours for the discharge of about 1050 m^3/s each day, after regulated by Gezhouba Project it is only about 4300 m^3/s, and at this time the navigable depth also does not meat the requirements.

5.2.2 Velocity and gradient

Under the current conditions, the local gradient of the Chenerkou-Dabujie reach is 2/10000~3/10000 and its velocity is 2.2 m/s when the discharge of the Maojiahuawu-Yaogang reach and the Zhijiang watercourse is 5380 m^3/s, and the navigable depth for vessels of 10^4 t can be satisfied. Through erosion for 8~10 years, the sand bed in the Zhicheng-Dabujie reach is basically washed away, and the depth of erosion is very small (<1m) for the head of Guanzhou, Lujiaheqiba, Daoguajingoushi, head of Shuiluzhou and head of Jiangkouzhou with exposed gravels, resulting in worse local velocity and gradient compared with those before the construction of TGP (Table 3). With the increase of erosion in the Jingjiang River and decrease of water levels, the local steep gradient of the

Table 3 Local gradient and velocity of Lujiahe-Jiankou reach after impoundement of TGP ($Q = 5000\sim5500\ m^3/s$)

Year	Daoguajingoushi (C.S.76)		Zhijiang watercourse (C.S.116)		Jiankou watercourse (C.S.169)	
	J (10^{-4})	V (m/s)	J (10^{-4})	V (m/s)	J (10^{-4})	V (m/s)
2003	2.82	2.21	2.26	2.16	0.77	1.34
2005	2.89	1.72	2.48	1.91	2.21	1.52
2006	3.48	2.10	2.47	1.94	2.56	1.81
2007	5.24	2.39	3.12	1.97	2.64	1.90
2008	7.12	2.57	3.20	2.04	3.11	1.93
2009	7.72	2.60	3.20	2.04	3.09	1.97
2012	7.80	2.97	3.59	2.11	3.22	2.18
2017	9.15	3.09	3.70	2.20	4.55	2.45
2022	9.42	3.17	3.84	2.30	4.54	2.45

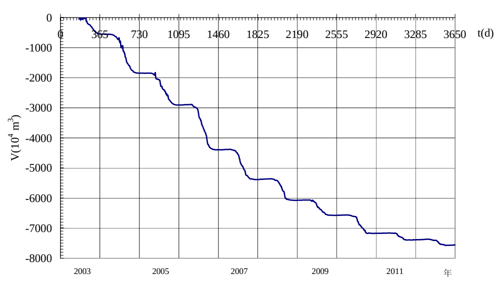

Fig. 4 Change of amount of erosion in Zhicheng-Dabujie reach with time

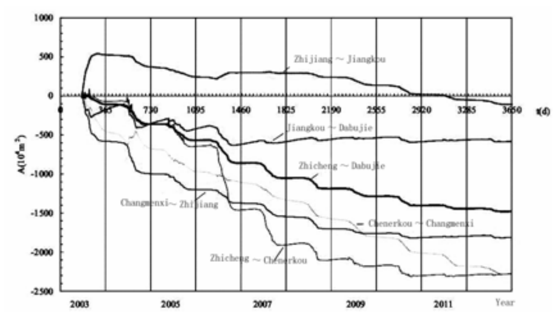

Fig. 5 Change of erosion area of Zhicheng-Dabujie reach with time

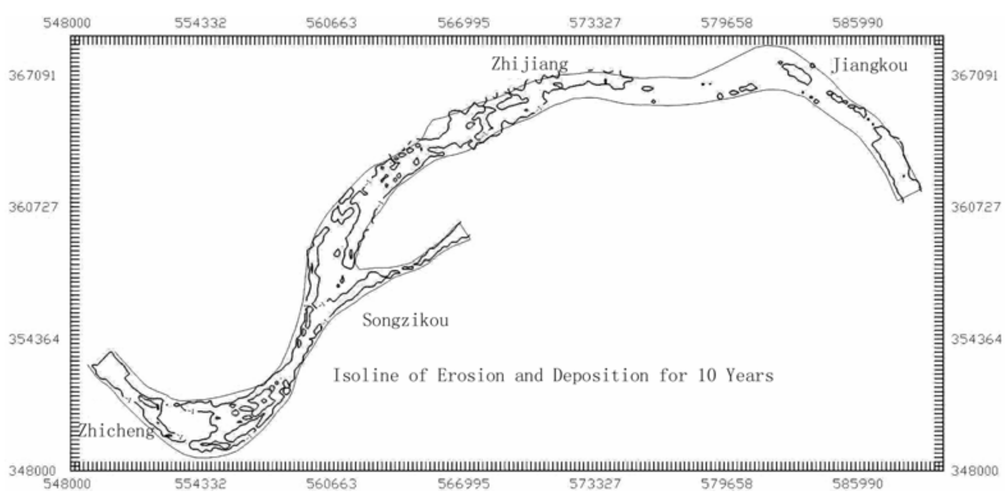

Fig. 6 Isolines of 1 m and 3 m of erosion in Zhicheng-Dabujie reach after 10 years

navigation channel gradually increases. That of the Daoguajingoushi (C.S.76) reaches 7.72/10000 in 2009, and its velocity is up to 2.6 m/s; till 2017, that is, with the impoundment of TGP for 15 years, its local steep gradient is up to 9.15/10000, and the velocity is 3.09 m/s; till 2022, it is 9.42/10000, and the velocity is 3.17 m/s. As for the right branch (C.S.116) of the Zhijang watercourse, till 2009 the local steep gradient ratio reaches 3.2/10000, and the velocity is up to 2.04 m/s; till 2017, it is up to 3.7/10000, and the velocity is 2.2 m/s; till 2022, it is 3.84/10000, and the velocity is 2.3 m/s. With regard to the Jiangkou watercourse (C.S.169), till 2009 the local steep gradient is up to 3.09/10000, and the velocity is 1.97 m/s; till 2017, it is 4.55/10000, the velocity is 2.45 m/s; afterwards, the velocity and gradient are of little change. It should be indicated that the above mentioned velocity is transformed into surface velocity by use of mean velocity of a vertical line (×1.16). It is seen that after the construction of TGP the Lujiahe, Zhijiang and Jiangkou reaches will become dangerous low-water shoals from the current shallow watercourses, directly affecting navigation.

6 CONCLUSIONS

Numerical simulation of flow and sediment transport has been performed with a 2-D model using the non-equilibrium equations of suspended load and bed load, the sorting equation of bed material and the riverbed deformation equation. The navigation channel of Zhicheng-Dabujie reach in the middle reaches of Yangtze River is taken as a case study in this paper. Model verification shows that the calculated water surface profiles, velocity distribution and riverbed deposition and erosion distribution are in good agreement with the field measurements.

As for the impoundment levels of 135 m and 156 m of TGP, during the first 3 years, the navigable depth less than 3.0 m will occur with regard to the left channel of Lujiahe. Before 2009, the discharging amount can not be regulated, as at this time the Jingjiang River has been violently eroded, and the low-water level has a decrease of about 1 m, resulting in that the Mojiahuawu-Yaogang reach on the Lujiahe and Jiangkou watercourse can not satisfy the requirements of the current navigable depth of 3.0 m.

Under the current conditions, the gradient and velocity of the Lujiahe-Dabujie reach can basically satisfy the requirements of navigation for vessels of 10^4 t. After the commission of TGP, there is limited erosion (<1 m) with regard to local reaches. Furthermore, decrease of the water level in the Jingjiang River increaeses the local steep gradient of Daoguajingoushi in Lujiahe reach to 9.42/10000 and the velocity to 3.17 m/s; the local steep gradient in Zhijiang watercourse is up to 3.84/10000, and the velocity is 2.30 m/s, the local steep gradient of the Jiangkou watercourse is 4.54/10000, and the velocity is 2.45 m/s. Therefore, there is a problem of large gradient and rapid water flows in the Lujiahe-Jiangkou reach.

ACKNOWLEDGEMENT

The project is financially supported by the National Basic Research 973 Program of China (No. 2003CB415206) and the National Natural Science Foundation of China (No. 50379027).

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