NUMERICAL SIMULATION STUDY ON DEPOSITION DOWNSTREAM ESTUARINE SLUICE

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In order to resist tides and salt intrusion, there have been more than 300 tidal gates built at many river estuaries in China since 1960s. However, the serious deposition occurred at a lot of gates due to the changes of hydrodynamic and sediment conditions and lack of discharge from the rivers. At present, the research is mainly to analyze the reasons for siltation downstream gates and the measures of dredging. It is not enough for study on distribution simulation of deposition downstream sluice. Studies have shown that 2D numerical model cannot reflect the distribution of sediment siltation downstream gates. Therefore, it needs to develop 3D sediment numerical model for deposition prediction. In this paper, combined the feasibility study of a tidal gate at Mulanxi River, a physical model and 3D numerical model of sediment siltation downstream gate are conducted.

Keywords: tidal estuary; sediment deposition; numerical model

OVERVIEW OF MULANXI RIVER

Mulanxi River, located in the eastern coastal of Fujian Province, China, flows through Putian City into the bay of Xinghua (Fig.1). The river basin area of Mulanxi River is1732km^2 and the main stream length is 105km. There is a weir named Mulanbi where is 34.1km from the estuary. Mulanxi River is an important river runs through the centre area of Putian city. The downstream of Mulanxi River suffers floods frequently due to low embankment of the river. A flood control project has been started at the end of 1998. The project was divided into four phases to construct (Dong et al 2001 and 2002). The reach has been shorted 8.7km, the bank has been heighted at the 9.8km long and the embankment has been built at the 7.2km long. The first and second phase has been finished in 2004. In order to control flood, store fresh water and improve the environmental landscape of the urban, a tidal gate at the estuary is proposed where is located at about 6km upstream the estuary.

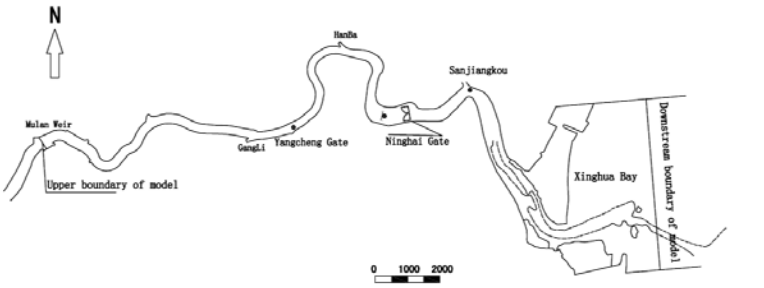

Figure 1. Mulanxi River and the proposed tidal gate at Mulanxi Estuary.

HYDRO-SEDIMENT CHARACTERISTIC OF MULANXI RIVER

The mean discharge of Mulanxi River is 30.9m^3/s. The mean flood discharge is 1550m^3/s and the maximum is up to 3820m^3/s which measured in Oct. 1999.

The estuary is in Xinghua Bay where the tide is a non-regular semidiurnal. The multi-year average high tide level is 6.78m and the low tide level is 1.58m. The maximum tide level is 7.68m which measured on July 31, 1996 and the minimum is -1.06m which measured on July 9, 1996. The mean tidal range is 5.32m. The mean tidal range of spring tide is 6.47m and neap tide is 3.51m. The

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maximum tidal range is 7.54m. The mean quantity of suspended load is 289,000t. The mean sediment concentration from the upstream is 0.30kg/m^3. The concentration is higher during flood and the maximum one measured is 8.88kg/m^3.

There is a large deposition on the beach at the two sides of the estuary that has been accumulated by the sediment load from the river in long term. So, the sediment concentration is higher at the downstream of the River due to the actions of tidal currents and wind waves. From the measured data during spring tide in dry season in April, 2000, the mean concentration of one tidal period is 2.6kg/m^3 at the position of Ninghai Bridge (800m upstream the proposed sluice). From the data measured in Nov., 2002, the bed materials in the most part of the reaches are silt, in which most of them are clay and the diameter is less than 0.005mm. The silt in the surface of bed has small density and easy to move. The density of the silt below the bed surface of 0.3 ~ 0.5m can up to 1.5kg/cm^3 and this kind silt need larger incipient velocity.

The reach from Mulanbi Weir to the estuary is affected by tide. It is mainly scour during flood season and siltation during dry season. From a longer time period, the tidal reach maintains the balance of scour and deposition that is suit to the hydrodynamic condition. From the measured topography in 2000 and 2007, there were scouring and silting at different reach (Fig.2). The river is in the state of deposition. The total siltation is 1,200,000 m^3.

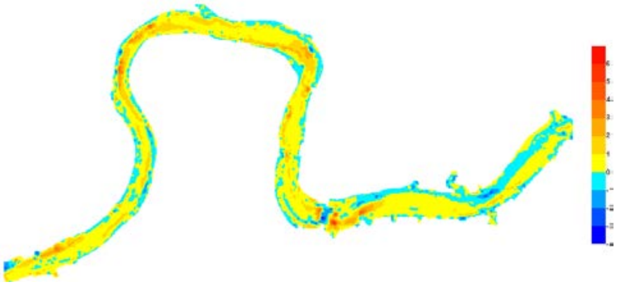


Figure 2. Thickness of silting and scouring at Mulanxi River from 2000 to 2007.

PHYSICAL MODEL OF MULANXI RIVER

A physical model is built for the feasibility study of the proposed tidal sluice at Mulanxi River (Zhao et al, 2011). The horizontal scale is 335 and the vertical scale is 65.

Physical model design

First, the model should meet similarity conditions of geometry, gravity and resistance.

Geometry similarity:

$$\lambda_L = L_P / L_m,\ \lambda_H = H_P / H_m \tag{1}$$

Gravity similarity:

$$\lambda_V = \lambda_H^{1/2} \tag{2}$$

Resistance similarity:

$$\lambda_n = \lambda_H^{2/3} / \lambda_L^{1/2} \tag{3}$$

On the basis of flow similarity, the model should meet similarity conditions of sediment transportation including suspended load, bed load, silting and scouring.

The main scales of the physical model are listed in Table 1.

Table 1. The main scales of the physical model.

Name	Scale	Name	Scale
Horizontal scale	335	Roughness scale	0.88
Vertical scale	65	Dry density scale	1.45
Velocity scale	8.06	Sediment concentration scale	0.21
Flow time scale	41.6	Suspended load transport time scale	287

The tidal level in the physical model is measured by automatic track water level meter. The accuracy of the level meter is 0.1mm. The total measurement error is about ±0.5 mm due to the influence of water temperature and quality that is equivalent to 3.25cm in the prototype. The tidal current is measured by photoelectric propeller flow meter that the measuring ranges from 3cm/s to 120cm/s. The topography is measured by needle and underwater topography instrument. The accuracy of the topography instrument is 0.1mm that is equivalent to 6.5cm in the prototype. Fig.3 is the physical model of Mulanxi River.

Figure 3. Photo of physical model of Mulanxi River.

The boundary control

The upstream boundary of the physical model is in Mualnbi Weir where the weir cut off the effect of tide on the upper reaches. The downstream boundary of the model is in a lighthouse named Tazaiyu at the estuary. The tidal level process of the downstream boundary is provided by the value calculated by a large scale numerical model due to the boundary affected by flood.

The tidal currents verification experiment is conducted (Zhao et al, 2011) and the measured data including spring and neap tide from Aug. 7 to Aug. 15, 2007. The verification results of the tidal levels and velocities at Yangchenzha, Ninghai Bridge and Sanjiangkou are in good agreement with those measured in prototype (Fig.4 and Fig.5).

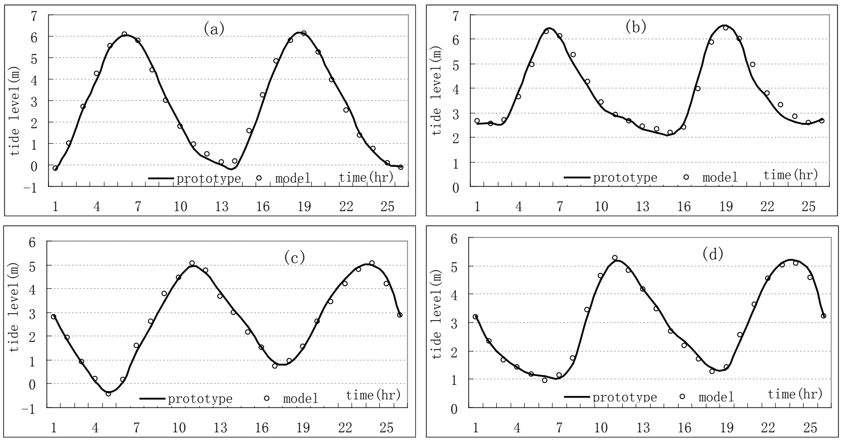


Figure 4. Verification of tide levels: spring tide at Sanjiangkou(a) and Yangcheng Sluice (b), neap tide at Sanjiangkou(c) and Yangcheng Sluice (d).

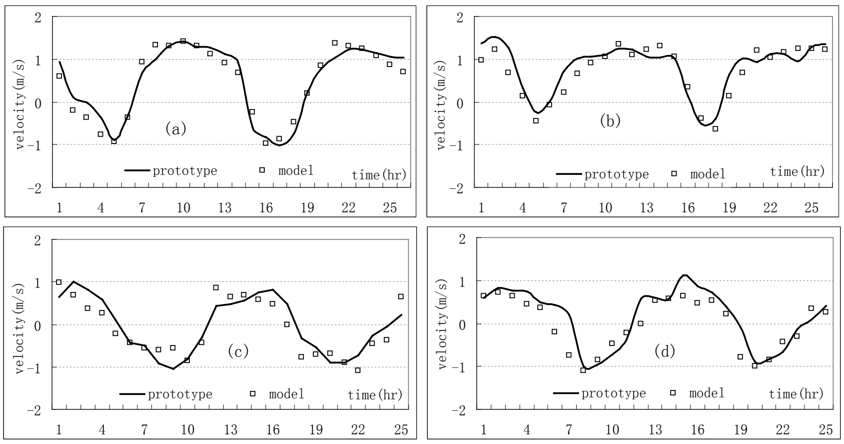


Figure 5. Verification of velocities: spring tide at Sanjiangkou(a) and Yangcheng Sluice (b), neap tide at Sanjiangkou(c) and Yangcheng Sluice (d).

The model sand is wood flour and D_{50} is 0.065mm. The siltation verification experiment is conducted using the measured topography from August to October, 2010. The positions of the section for siltation verification are in Fig. 6. The comparison results between the model and the prototype at each cross-section are in agreement (Fig.7).

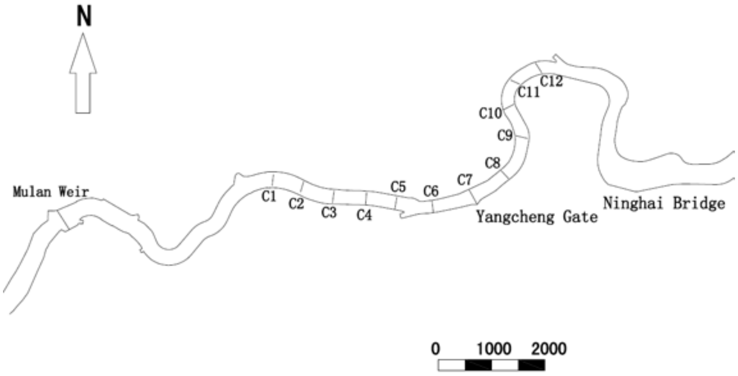


Figure 6. The positions of the section for siltation verification (c1~c12).

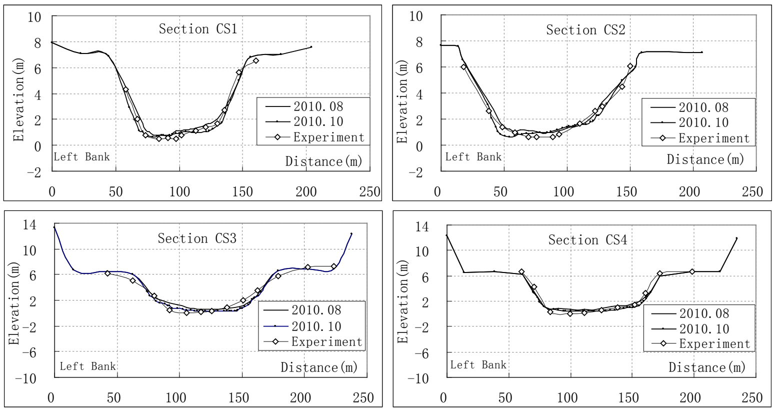


Figure 7. verification of siltation (c1~c4).

Siltation experiment

In siltation experiment, the disadvantageous condition is considered that the sluice is always closed. The spring and neap tide are alternated in the experiment. The model sand is added in the outside of the estuary and the concentration is controlled by photoelectric measuring sand meter.

Tidal waves are reflected by the sluice when they are propagating from the estuary into the river. Along the downstream to the upstream of the river, the high level is increased and the low level is reduced, at the same time the tide difference is increased. The duration of flood is shortened and the duration of ebb is increased. The sediment concentration during flood tide is greater than that during ebb tide. So, net flux of sediment load to sluice is greater than zero.

The sediment concentration in spring tide is greater than that in neap tide. The tidal influx of spring tide is larger than that of neap tide. Therefore, the sediment discharge during spring tide is larger than that during neap tide.

The experiments were conducted in the conditions of the sluice continuous closed 45 days, 90days and 135 days respectively. The results (Fig.8) show that the rate of siltation is slower at the beginning of the sluice construction. With the sluice closing time prolonging, floods and ebbs make suspended load exchange with the bed load and move to the sluice. The siltation thickness at the downstream of the sluice increase gradually. If the sluice closed 10 months continuously, the average siltation thickness is up to 1~ 2m and the siltation thickness at the deep ditch of Sanjiangkou river bend can up to 3~4m.

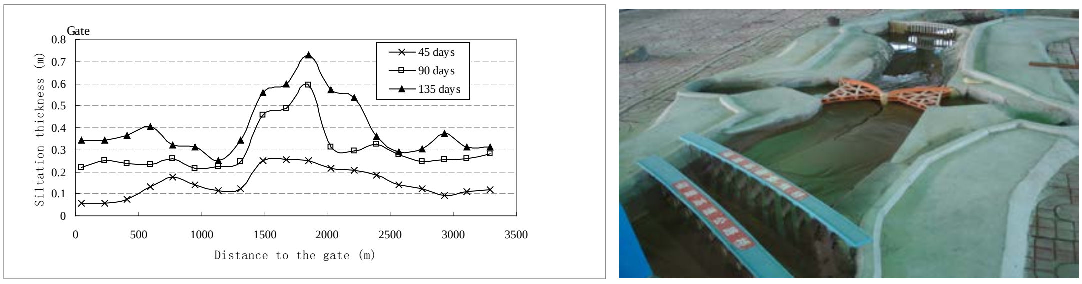


Figure 8. Thickness of Siltation downstream the sluice.

Sluicing experiment

After the sluice built, there will occur siltation downstream the sluice. So it is necessary to open the sluice on time to wash away the siltation. The experiment of scouring is to study the capacity of wash the siltation away and the form of bed after scouring.

In the average year, the 50% discharge at the section of Mulanbi Weir is 28.9m^3/s and the water volume is 9.11×$10^8 m^3$. In the dry year, the 50% discharge at the same section is 22.7m^3/s and the water volume is 7.15×$10^8 m^3$.

According to statistics of runoff at Laixi Hydrometric Station in the upstream of the river, 1987 is chose as an average year and the 90% discharge of 1991 as a dry year. In 1987, the number of day runoff over Mulanbi Weir is 190 days and no runoff is 175 days. The longest time that is no runoff over the weir is 99days from Dec. 6, 1987 to Mar. 15, 1988. In 1991, the number of day runoff over Mulanbi Weir is 80 days and no runoff is 285 days. The longest time when no runoff over the weir is 121days from Ocb.21, 1991 to Mar. 4, 1991.

The experiments were conducted in the case of the average year and the dry year. In dry year, the discharge at the upstream is 90% of flood process and the maximum discharge is near 600m^3/s. In average year, the discharge at the upstream is 50% of flood process and the maximum discharge is about 1300m^3/s (Fig.9).

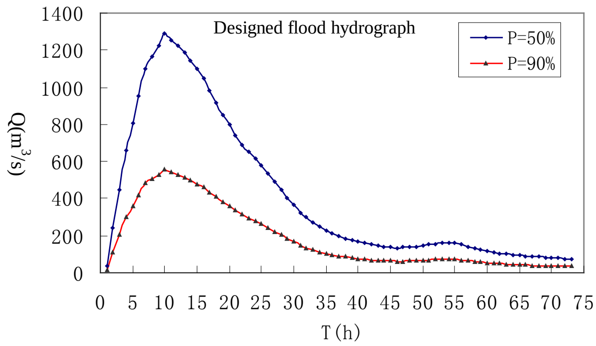
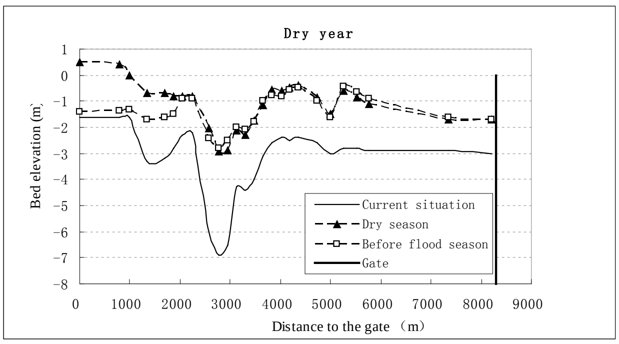


Figure 9. Design flood process for sluicing sand experiment.

It can be seen from Fig. 10 that the siltation thickness can be decreased by the sluicing before flood season, which is more obvious in the dry year. Therefore, it is necessary to select the appropriate time to open the sluice and wash off the siltation. That can reduce the siltation downstream the sluice and maintain a normal operation of the tidal gate.



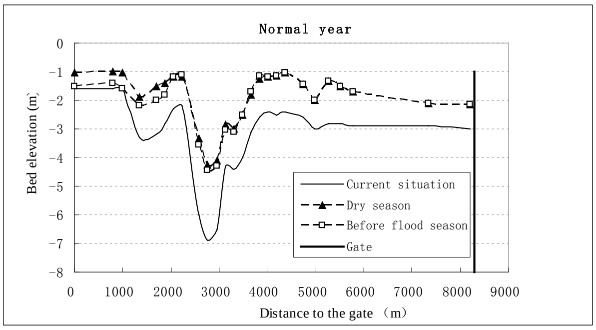


Figure 10. Comparison of siltation in normal and dry year.

NUMERICAL MODEL OF MULANXI RIVER

Density of water with sediment concentration

When tidal gate is closed, the flow velocity near the gate is almost zero. Because the sediment-carrying capacity is directly proportional to the 2nd~3rd power of the flow velocities, the capacity is also close to zero when velocity is close to zero. The sediment load from the estuary is difficult to be transported to the gate (QU, 2011).

However, it can be seen from the physical model experiment that there is a static water area downstream the gate and a relatively high sediment concentration near the bottom dives into and move to the gate. So, there must be some relationship between siltation downstream the gate with density flow movement.

If sediment concentration is *S*, the density of water with sediment concentration is

$$\rho = S + (1 - \frac{S}{\rho_s})\rho_w = \rho_w (1 + \frac{\rho_s - \rho_w}{\rho_s \rho_w} S) \quad (4)$$

in which ρ_s, ρ_w, ρ is the density of sediment, water and water with concentration respectively.

If taking ρ_s as 2600kg/m^3 and ρ_w as 1000 kg/m^3, mixture density is ρ =1000+0.615*S*. The higher concentration, the more influence on mixture density.

A 3D numerical model of tidal currents and sediment transport is established. Equations of flow and suspended load transport are same as the usual, except the densities of water in the sediment equation are replaced by the densities of water with sediment concentration in the following equation (5).

$$\frac{\partial \rho s}{\partial t} + \frac{\partial(\rho u_i s)}{\partial x_j} = \frac{\partial}{\partial x_j}(\varepsilon_{sj}\frac{\partial s}{\partial x_j} - \rho\overline{u_j s}), \quad -u_j s = D_t \frac{\partial s}{\partial x_i} \quad (5)$$

in which, ρ is the density of water with sediment concentration; *S* is sediment concentration (kg/m^3); ε is sediment diffusion coefficient. In first-order closure model, D_t is turbulent anisotropic diffusion coefficient depends on turbulent property.

The verification of mixture density mode

In a generalized physical model of tidal sluice, sediment siltation experiment is conducted using spring tide (X.P. DOU, et al, 2011). The comparisons among the result of the experiment with the results of numerical model if considering the mixture density are in Fig. 11. That shows the numerical model using mixture density is valid to simulate the siltation downstream the sluice.

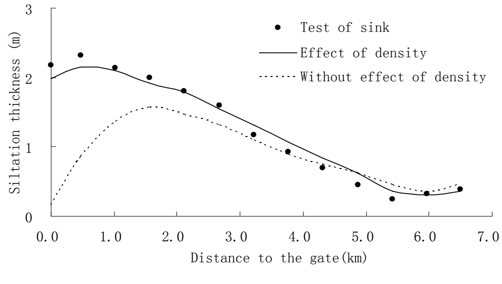


Figure 11. Verification of siltation along the downstream of the sluice

The verification of the numerical model

The range of the numerical model Mulanxi River is from Lanxi to the Jiangyin Island, which simulates the river about 45km in length. The geography of the model is measured in January 2007. Orthogonal meshes are adopted. The mash size is 16.2~203.4m and the mesh number is 407 in longitudinal. The mash size is 3.0~89.8m and the mesh number is 20 in transverse. There are 20 layers in vertical which the lowest grid elevation is -15m and the highest is 8m（Figure 12）.

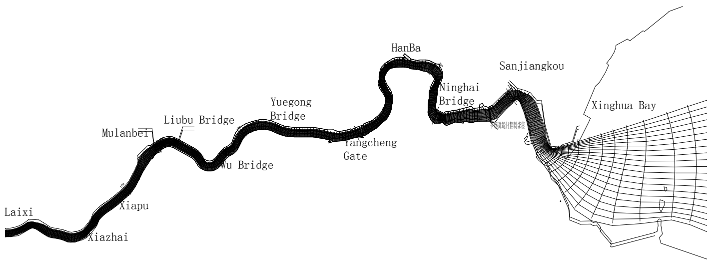


Figure 12. Mesh of the numerical model.

The roughness is 0.018 inside the estuary and $n = 0.013 + 0.01/h$. The time step of the current model is 1s and the sediment model is 5s. The verification data was measured on Augest 7-8, 2007 and Augest 14-15, 2007, which the former is neap tide and the latter is spring tide.

The sediment transport capacity formula in depth average is $S_* = K\frac{u^2}{gH}$, k =40~160.

The verifications show the results is better when k is taken as 80. Then the sediment transport capacity near the bottom can be obtained through integral.

The diameter of suspended load is 0.054mm and the flocculation settling velocity is taken as 0.55cm/s. The verification results of sediment concentration are in Fig.13.

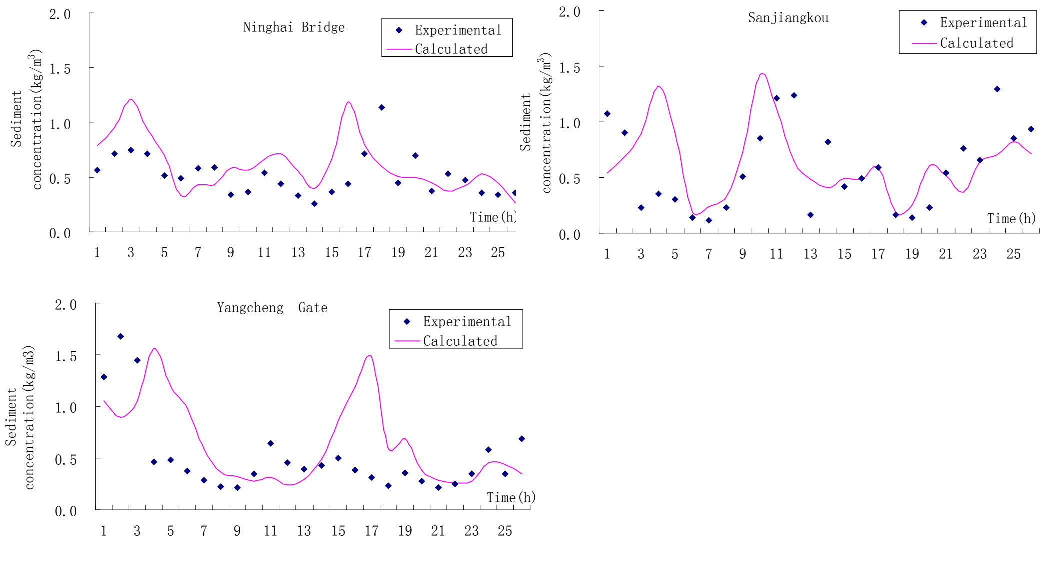


Figure 13 verification results of sediment concentration.

Simulation of siltation downstream the sluice

In dry year, the discharge at the upstream is 90% designed flood process and the maximum discharge is near 600m^3/s (Fig. 9). The distribution of the siltation downstream the sluice is calculated by the numerical model. The result shows (Fig. 14) that the thickness of siltation in the deep trough is largest. The maximum thickness is 3m and the average is above 2m. The measured data obtained from the physical model of Mulanxi River are basic same as that calculated from the numerical model.

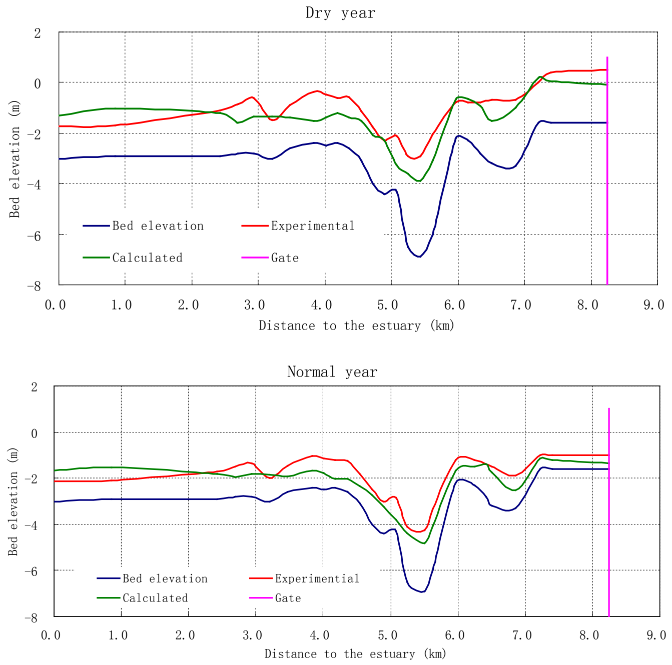


Figure 14. Siltation at the downstream of the sluice in normal and dry year.

CONCLUSION

There are different completely on siltation at tidal estuary with sluice and without sluice. After sluice built, the sediment load at the estuary is brought into the river by tide and silt at the downstream of the sluice. The 3D numerical model considering the mixture density is verified by the experiment of the generalized physical model. The simulation results can reflect the processes of siltation and scouring downstream the sluice in the physical model of Mulanxi River.

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