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VERTICAL DISTRIBUTION OF SUSPENDED SEDIMENT AT THE YANGTZE RIVER ESTUARY

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Abstract: The vertical distribution regulations of flow velocity and the suspended sediment concentration play a key role in revealing the flow characteristic, which is very important in studying the intrinsic mechanism of sediment transportation and riverbed evolution. In natural rivers, suspended sediment is usually the dominating part of sediment transportation. Based on the data obtained from the survey of the north-trough and south-trough at the Yangtze River Estuary, vertical distribution of the suspended sediment concentration is calculated with the application of 1-D vertical numerical model of the suspended sediment, and compared to the measured data. As a result, the calculated data have a pretty good coherence to the measured data.

Key words: The Yangtze River Estuary, Suspended sediment, Vertical distribution, Modeling

INTRODUCTION

The Yangtze River Estuary is the path where the water of the Yangtze River flows into East China Sea. By thrice bifurcated from Xuliujing below, four passages have been formed. The Yangtze River Estuary covers roughly 145kms from Xuliujing to the estuary gateway, and it is the transition area from inland to ocean. It has characteristics of inland rivers and of oceans as well. What's more, the phenomena that the salty-water blends with the fresh-water, and that the salty-water encroaches occur at the Estuary. Influenced by the runoff flow, tidal current, wave, salt wedge, set-up and set-down, and Coriolis force, the kinetic regulation and distribution of sediment are very complicated at the Estuary.

The Yangtze River Estuary is the estuary of medium intensity tide. According to the data obtained from Zhongjun tide station that locates at the Yangtze River Estuary, the minimum tidal difference is 0.17m, the maximum tidal difference is 4.62m, and the mean tidal difference is 2.66m. Comparatively speaking, the tidal discharge is dominating, and it is about 8 times of runoff flow discharge. Based on the data of the discharge of runoff flow and sediment at Datong gauging station, at the Yangtze River Estuary the minimum discharge is 4,620m^3/s, the maximum discharge is 92,600m^3/s, and the mean discharge is 29,300m^3/s. The minimum sediment concentration is 0.306kg/m^3, the maximum sediment concentration is up to 0.697kg/ m^3, and the mean sediment concentration is 0.547kg/ m^3. The minimum sediment discharge of a year is 2.39 $\times 10^8$t, the maximum sediment discharge of a year is 6.78 $\times 10^8$t, and the annual mean sediment discharge is 4.86$\times 10^8$t.

Transportation courses of fine sediment at the Yangtze River Estuary have been researched theoretically and experimentally by researcher on estuary and coast. Numerical modeling researches on the transportation of fine sediment and the variation of riverbed erosion and deposition, such as 1-D vertical numerical model, 1-D horizontal numerical model, 2-D vertical numerical model , 2-D horizontal numerical model,3-D numerical model and mathematical statistic model, have been achieved prodigious progresses. In the channel improvement projects on sea-route of deep water of the Yangtze River Estuary, researches on fine sediment are very important.

The vertical distributions of the suspended sediment at the north-trough and south-trough of the Yangtze River Estuary are calculated with the application of 1-D vertical numerical model in this paper.

1. 1-D VERTICAL NUMERICAL MODEL OF SUSPENDED SEDIMENT

1.1 1-D VERTICAL NUMERICAL MODEL OF SUSPENDED SEDIMENT

The suspended sediment transportation at the estuary is mainly used to study the vertical distribution and the unbalanced problem of the suspended sediment. The vertical distribution can be researched with turbulent theories.

After neglecting the horizontal convection diffusion effect and the vertical flow velocity, 1-D vertical numerical model of suspended sediment is:

$$\frac{\partial S}{\partial t} = \frac{\partial}{\partial z}\left(\omega_s S\right) + \frac{\partial}{\partial z}\left(\varepsilon_{sz}\frac{\partial S}{\partial z}\right) \tag{1}$$

where: S — suspended sediment concentration, ω_s —settling velocity of suspended sediment, ε_{sz}—vertical diffusion coefficient, z—water depth.

1.2 BOUNDARY CONDITIONS AND INITIAL CONDITIONS

With the assumption that sediment doesn't exchange at free surface, that is, the diffusion effect of suspended sediment is equal to the settlement effect, the free surface condition can be expressed:

$$\omega_s S + \varepsilon_{sz}\frac{\partial S}{\partial z} = 0 \qquad (z = \zeta + h) \tag{2}$$

Where: ζ—water level, h—mean water depth.

Treatment method of bottom boundary condition is relatively complicated. In this paper, the bottom boundary condition is determined using suspended sediment concentration obtained from survey of the Yangtze River Estuary with six-point method:

$$S|_{z=a} = S_a\left(t\right) \tag{3}$$

The initial conditions are determined using suspended sediment concentration of vertical line at beginning time:

$$S|_{t=0} = S_0(z,0) \tag{4}$$

Because of the influence of the tide varying according to time, the space scope of the model is not invariable. After transforming the relative water depth at vertical coordinate, the un-dimensional water depth is adopted:

$$z^* = \frac{z-\zeta}{H} \tag{5}$$

Where: $H = \zeta + h$.

After coordinate transformation, the settling velocity of a single grain suspended sediment is:

$$\omega_s^* = \frac{\omega_s}{H} \tag{6}$$

The numerical model of suspended sediment is:

$$\frac{\partial S}{\partial t} = \frac{\partial}{\partial z^*}\left(\omega_s^* S\right) + \frac{1}{H^2}\frac{\partial}{\partial z}\left(\varepsilon_{sz}\frac{\partial S}{\partial z^*}\right) \tag{7}$$

The boundary condition of the free surface is:

$$H\omega_s^* S + \varepsilon_{sz}\frac{1}{H}\frac{\partial S}{\partial z^*} = 0 \tag{8}$$

1.3 DETERMINATION OF DIFFUSION COEFFICIENT AND SETTLING VELOCITY OF SUSPENDED SEDIMENT

The diffusion coefficient of suspended-sediment:

$$\varepsilon_{sz} = \alpha\left(\frac{z}{H}\right)^{\beta} \tag{9}$$

Where: α, β —constants, in the estuary area can be taken: $\alpha = 0.6, \beta = 0.06$.

The settling velocity of suspended sediment:

$$\omega_s = \omega_{50}\frac{1 + c_2 S^{m_2}}{1 + c_1 u^{m_1}} k_s^{'} \tag{11}$$

Where: c_1, c_2, m_1, m_2 —data gained from experiment, taking value as: $c_1 = 0.06, c_2 = 4.6,$ $m_1 = 0.75, m_2 = 0.6$. u —flow velocity, $k_s^{'}$ —coefficient relating with salt concentration, $k_s^{'} = 3.8$, ω_{50}—settling velocity of single grain suspended sediment of medium diameter d_{50}, can be solved with Stokes equation:

$$\omega_{50} = \frac{1}{18} g d_{50}^2 \frac{\rho_s - \rho}{\rho \nu} \tag{12}$$

ρ_s —bulk specific gravity of suspended sediment, $\rho_s = 2650 kg/m^3$. ν —coefficient of kinematic viscidity, $\nu = 1.007 \times 10^6\ \mathrm{m^2 \cdot s}$.

2. FINITE DIFFERENCE EQUATION OF THE NUMERICAL MODEL OF SUSPENDED SEDIMENT

Solve equation (1) using implicit difference scheme:

$$\frac{\partial S}{\partial t} = \frac{S_i^{n+1} - S_i^n}{\Delta t} \tag{13}$$

$$\frac{\partial(\omega_s^* S)}{\partial z^*} = \omega_s^* \frac{S_{i+1}^{n+1} - S_i^n}{\Delta t} \tag{14}$$

$$\frac{\partial}{\partial z}\left(\varepsilon_{sz}\frac{\partial S}{\partial z^*}\right) = \varepsilon_{sz}\frac{S_{i+1}^{n+1} - 2S_i^{n+1} + S_{i-1}^{n+1}}{\left(\Delta z^*\right)^2} \tag{15}$$

Therefore, the finite difference equation of the partial difference equation (1) is:

$$\left(1 + \frac{\Delta t \omega_s^*}{\Delta z^*} + 2\frac{\Delta t \varepsilon_{sz}}{\left(H\Delta z^*\right)^2}\right) S_i^{n+1} = \left(\frac{\Delta t \omega_s^*}{\Delta z^*} + \frac{\Delta t \varepsilon_{sz}}{\left(H\Delta z^*\right)^2}\right) S_{i+1}^{n+1} + \frac{\Delta t \varepsilon_{sz}}{\left(H\Delta z^*\right)^2} S_{i-1}^{n+1} + S_i^n \tag{16}$$

Let:

$$A_i = \frac{\Delta t \omega_s^*}{\Delta z^*} + \frac{\Delta t \varepsilon_{sz}}{\left(H\Delta z^*\right)^2}$$

$$B_i = 1 + \frac{\Delta t \omega_s^*}{\Delta z^*} + 2\frac{\Delta t \varepsilon_{sz}}{\left(H\Delta z^*\right)^2}$$

$$C_i = \frac{\Delta t \varepsilon_{sz}}{\left(H\Delta z^*\right)^2}$$

$$D_i = S_i^n$$

Equation (16) can be rewritten:

$$-A_i S_{i+1}^{n+1} + B_i S_i^{n+1} - C_i S_{i-1}^{n+1} = D_i \tag{17}$$

The boundary condition of the free surface (equation 8) is dispersed to:

$$S_{n+1} = S_i \left(1 - \frac{\omega_s^* \left(H\Delta z^*\right)^2}{\varepsilon_{sz}}\right) \tag{18}$$

The coefficient matrix of algebra equations（17）is a triple diagonal matrix which diagonal elements hold advantage. TDMA method is the best solution method on the matrix.

Assuming that there are M layers on the vertical line, the equation of suspended sediment concentration using TDMA method can be solved:

$$\begin{cases} S_M^{n+1} = \dfrac{q_{M-1}\left(1 - \dfrac{\omega_s^* H\Delta z^*}{\varepsilon_{sz}}\right)}{1 - p_{M-1}\left(1 - \dfrac{\omega_s^* H\Delta z^*}{\varepsilon_{sz}}\right)} \\ S_i^{n+1} = p_i S_{i+1}^{n+1} + q_i \qquad i = M-1 \sim 1 \\ p_1 = \dfrac{A_1}{B_1} \qquad q_1 = \dfrac{D_1 + C_1 S_0^{n+1}}{B_1} \\ p_i = \dfrac{A_i}{B_i - C_i p_{i-1}} \qquad q_i = \dfrac{D_i + C_i q_{i-1}}{B_i - C_i p_{i-1}} \qquad i = 2 \sim M-1 \end{cases} \tag{19}$$

Because of using implicit difference scheme, difference dispersed equation (17) is always steady.

Because of surveying at integer hours, the densities of water-depth, bottom suspended sediment concentration and vertical suspended sediment concentration at temporal steps and spatial steps need to be increased. According to the data obtained from survey of the north-trough and south-trough at the Yangtze River Estuary, the densities are increased using Lagrangian three-point interpolation method.

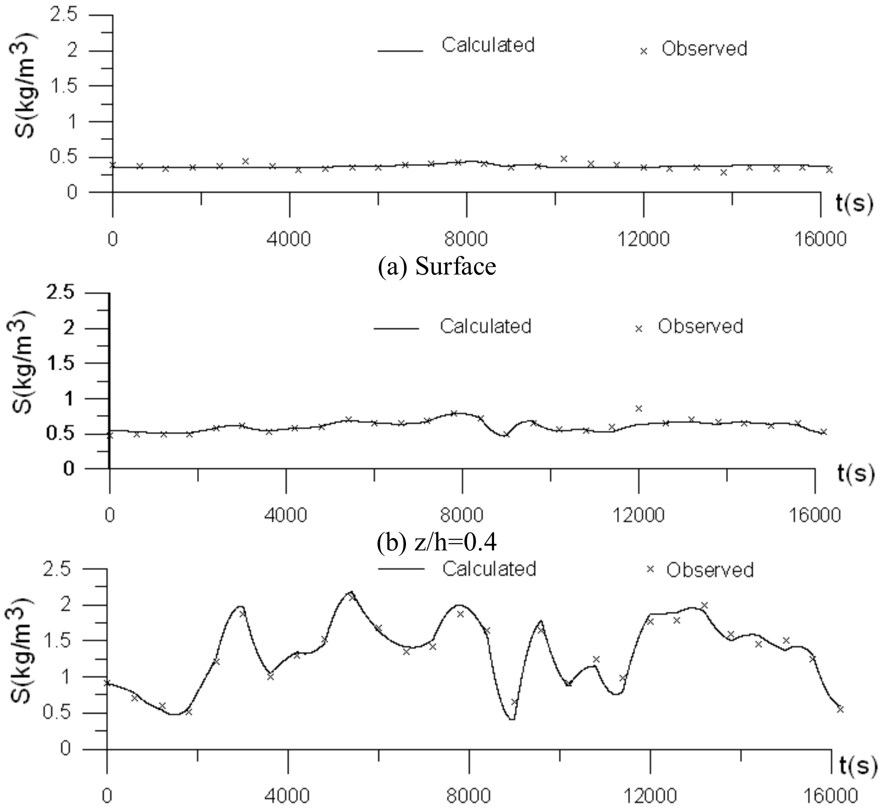
3. VERIFICATION OF MODEL

The water-depths, vertical suspended sediment concentrations and velocities obtained from April 9,2001 to April 20,2001 at the north-trough and south-trough of the Yangtze River Estuary are chosen. The vertical distributions of suspended sediment of A# vertical-line at the north-trough and B# vertical-line at the south-trough, on conditions of spring-tide, slack-tide, neap-tide, are calculated using 1-D vertical numerical model of suspended sediment which has been established above. The water-depths, velocities and suspended sediment concentrations at all layers are input into the calculation equation, and the calculated data are compared with the surveyed data.

Because of the paper length limit, the calculated data of A# vertical-line at the north-trough on Spring-tide condition are given only.

3.1 VERIFICATION OF SUSPENDED SEDIMENT CONCENTRATION AT VARIOUS LAYERS

Figure 1 is the comparison on suspended sediment concentration between calculated data and survey data at different layers at A# vertical-line in Spring tide.



(a) Surface

(b) z/h=0.4

(c) Bottom

Fig. 1 Verification of suspended-sediment concentration at various layers

From Fig.1, calculated data are close to surveyed data comparatively. Furthermore, calculated upper-layer data are closer to surveyed data than under-layer ones. The mean error between calculated data and surveyed data is less than 30% at all integer hours of survey.

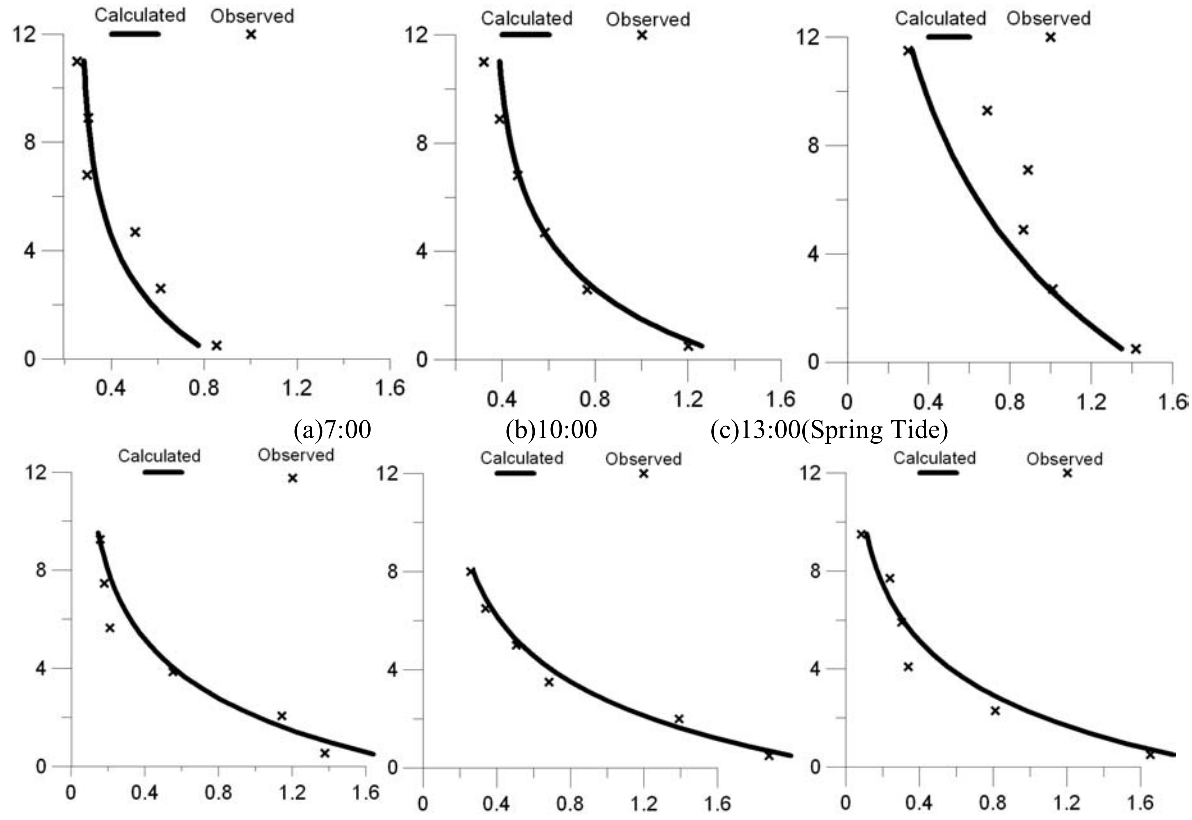
The maximum sediment concentration occurs at time when the water-depth is up to the highest depth, and the minimum sediment concentration occurs at time when the water-depth is up to the lowest depth.

3.2 VERIFICATION OF VERTICAL DISTRIBUTION OF SUSPENDED SEDIMENT

Fig. 2 is the comparison on suspended-sediment concentration between calculated data and survey data at different time at A# vertical-line in Spring tide.

From Fig. 2, the calculated data of vertical distribution of suspended sediment are closer to survey ones. As calculated data of suspended sediment concentration at different layers, calculated upper-layer data at vertical lines are closer to surveyed data than under-layer ones. The mean error between calculated data and surveyed data is less than 30% at all vertical survey-lines.

From Fig. 1 and Fig. 2, the calculated data of suspended sediment concentration are close to surveyed data. The errors of calculated data maybe caused by three causations:(1)the obtained values of diffusion coefficient and settling velocity of suspended-sediment;(2)the error caused by convection diffusion function that is ignored; (3)the influence of surveyed data errors.



(a)7:00 (b)10:00 (c)13:00(Spring Tide)

(d)16:00 (e)19:00 (f)22:00(Neap Tide)

Fig. 2 Verification of vertical distribution of suspended sediment

4. CONCLUSIONS

In this paper, the vertical numerical model of suspended sediment at the Yangtze River Estuary is established, which takes account of the influence of the instantaneous flow velocity on suspended sediment and which therefore has a closer consideration on settling velocity of suspended sediment to the practical fact in calculation. At the same time, the vertical distributions of the suspended sediment at integer time and layered temporal change of suspended sediment are given by solving the motion equation of suspended sediment. Then the mean values of the suspended sediment concentration are solved. Finally, the numerical model is verified using the ADCP flow velocity and suspended sediment concentration measured by 6-point method. As a result, the instantaneous variation of the suspended sediment at the Yangtze River Estuary is determined primarily by the vertical diffusion coefficient and settling velocity of suspended sediment. Moreover, the influence of horizontal function of convection diffusion on vertical distribution of suspended sediment is so little that it can be ignored.

In addition, because the established equation in this paper is solved using TDMA method, the equation stability is good.

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