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Numerical simulation of a horizontal sedimentation tank considering sludge recirculation

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Abstract

Most research conducted on the concentration distribution of sediment in the sedimentation tank does not consider the role of the suction dredge. To analyze concentration distribution more accurately, a suspended sediment transportation model was constructed and the velocity field in the sedimentation tank was determined based on the influence of the suction dredge. An application model was then used to analyze the concentration distribution in the sedimentation tank when the suction dredge was fixed, with results showing that distribution was in accordance with theoretical analysis. The simulated value of the outlet concentration was similar to the experimental value, and the trends of the isoconcentration distribution curves, as well as the vertical distribution curves of the five monitoring sections acquired through simulations, were almost the same as curves acquired through experimentation. The differences between the simulated values and the experimental values were significant.

Key words: concentration and isoconcentration distribution; suspended sediment transportation model; velocity field; vertical distribution.

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Introduction

Sedimentation tanks are widely used in water and wastewater treatment plants. Their design is primarily based on the ideal settling theory as they are able to remove the settled fraction of the suspended solids from water. Several numerical models have been developed to predict the concentration distribution of sediment in the sedimentation tank (Imam et al., 1983; Stamou et al., 1989; Zhou and McCorquodale, 1991; Zeng et al., 2002). Most research on this concentration distribution assumes that the sediments in the sedimentation tank are "perfect". Real conditions are, however, very complex. The disturbance of the suction dredge on the suspended sediment and its influence on the surrounding water change the flow regime and the concentration of the suspended sediment (Qin et al., 1986; Tang and Pang, 1999; Xu and Long, 2000; Zhang, 1990; Zhou and Sui, 2004). As a result, large errors can be introduced when designing sedimentation tanks according to the ideal settling theory.

This article analyzed the concentration distribution of sediment in the sedimentation tank taking into account the existence of a suction dredge. Our results made a significant contribution to the theory of sedimentation tank design.

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1 Sediment transport model

The sediment transport model is also called the suspended solid mass conservation equation. As well as convective and diffusion motions, the suspended sediment in the sedimentation tank has the setting velocity against fluid. The mass conservation equation is as follows:

$$\frac{\partial C}{\partial t} + \frac{\partial uC}{\partial x} + \frac{\partial vC}{\partial y} = \frac{\partial}{\partial x}\left(\Gamma \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(\Gamma \frac{\partial C}{\partial y}\right) + V_s \frac{\partial C}{\partial y} \quad (1)$$

where, C (kg/m^3) denotes the concentration of the suspended sediment, t (hr) denotes time, u (m/sec) and v (m/sec) denote the velocity components in the horizontal and vertical direction of water flow, respectively; x and y denote the horizontal and vertical direction, respectively; Γ (m/sec) is the diffusion coefficient, and V_s is the setting velocity of the suspended sediment.

1.1 Setting velocity of suspended sediment

There are many empirical equations describing solid concentration and setting velocity. In this instance, the exponential equation proposed by Vesilimd (Tang, 1994) was used:

$$V_s = V_0 e^{-nC} \quad (2)$$

where, V_0 and n are empirical parameters.

1.2 Water-flow velocity

1.2.1 Traditional settling theory

When analyzing particle sediment in an ideal sediment tank, water quantity is presumed to be Q, such that inflow and outflow are both set to Q. According to ideal sediment tank assumptions, the horizontal flow rate of sewage u (the rate at which the sewage moves uniformly along the horizontal direction) is:

$$u = \frac{Q}{A} \quad (3)$$

here, A is the cross-sectional area of the sediment tank. This deduction, however, does not take into account the influence of sludge recirculation. When considering sludge recirculation, the horizontal flow rate accelerates in the sediment area between the water inlet and the location of the suction dredge, as does the velocity component in the horizontal direction of the suspended particles (Zhou and Sui, 2004). Sludge recirculation, therefore, has great impact on the sedimentation effect in the tank, so it is of practical significance to calculate the horizontal flow rate considering sludge recirculation.

1.2.2 Settling theory considering sludge recirculation

As stated above, sludge recirculation impact the horizontal flow rate. Because the suction dredge sucks sludge simultaneously from the surroundings of the dredging tube, the flow in the sedimentation tank changes gradually from $Q + RQ$ to Q. To analyze the changing process of the flow, the sedimentation tank is divided into three parts in the horizontal direction (Fig. 1). The first part is the area between the inlet and section r, the second part is the area between section r and the location of the suction dredge, and the third part is the area between the location of the suction dredge and the outlet.

Under these conditions, the inflow of the sedimentation tank is $Q + RQ$, the outflow is Q, and the sludge flow of the suction dredge is RQ. The flow taken up by the suction dredge from the area between the water inlet and the dredge is denoted by Q_1. The flow in the sedimentation tank changes gradually from $Q + RQ$ to $Q + RQ - Q_1$, and finally to Q. Based on the above conditions, the horizontal flow rate u_1, u_2, and u_3 can be calculated as: $u_1 = \frac{Q+RQ}{A}$, $u_2 = \frac{Q+RQ+Q_1}{A}$, and $u_3 = \frac{Q}{A}$, respectively. Both Q and RQ are measured directly, while Q_1 is calculated.

A fluid dynamics model must be built to calculate Q_1.

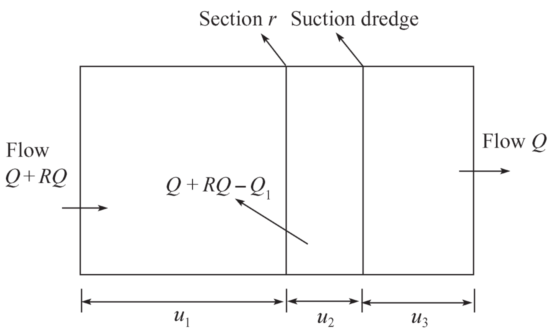

Fig. 1 Sedimentation tank diagram.

An analysis of the suction dredge's mechanism shows that the fluids near the sludge blanket possess different concentrations and show clear interfaces. As a result, the suction issue of the dredge can be treated as watering issues about stratified waters (Yu, 1998). The energy formula is as follows:

$$\frac{\rho_1(h - h_r)}{\rho_2} + h_r = \frac{\rho_1(h - z)}{\rho_2} + z + \frac{V^2}{2g} \quad (4)$$

where, ρ_1 and ρ_2 denote the concentrations above and below the sludge blanket, respectively. V is the horizontal flow rate of the sludge sucked by the suction dredge, z is the height of the sludge near the suction dredge, hr is the height of the sludge in section r, h is the height of the water surface, and g (m/sec^2) is the acceleration of gravity.

According to Eq. (4), h_r can be obtained as follows:

$$h_r = z + \frac{V^2}{2g\left(\frac{\rho_2-\rho_1}{\rho_2}\right)} = z + \frac{V^2}{2\varepsilon g} \quad (5)$$

where, $\varepsilon = \frac{\rho_2-\rho_1}{\rho_2}$ is the concentration difference between the fluids within the range of (0, 0.02) and b is the width of the sedimentation tank, such that $V = \frac{Q_1}{bz}$, and it is put into Eq. (5).

$$Q_1 = \sqrt{2\varepsilon g b^2 z^2 (h_r - z)} \quad (6)$$

2 Boundary conditions

2.1 Tank bottom

Takamatsu (Imam et al., 1983; Cai et al., 2003) proposed the boundary conditions that simulate the sediment and scouring of the suspended particles at the bottom of the sedimentation tank, that is:

$$\Gamma\frac{\partial C}{\partial y} + KV_sC = 0 \qquad (y = 0) \quad (7)$$

where, K is the scouring coefficient and is dependent on the degree of scouring.

When K is larger than one, the scouring motion dominates the settling motion. When K equals one, there is a balance between settling and scouring. When K is smaller than one but larger than zero, settling dominates. When K equals zero, the particles only settle. The scouring coefficient is usually determined by the empirical equation proposed by Takamatsu (Imam et al., 1983; Cai et al., 2003):

$$K = ae^{-m/\Gamma} \quad (8)$$

where, a and m are constants, and set at 1.17 and 8.05, respectively.

2.2 Water inlet

The horizontal flow rate u and the vertical flow rate v are zero. The concentration of the suspended solid C equals C_0, which is the concentration in the inlet of the sedimentation tank.

2.3 Water surface

The normal gradient of the horizontal flow rate and the vertical flow rate v are zero (Yao, 2005; Stamou et al., 1989). The concentration of the suspended solid is $\frac{\partial C}{\partial y} = \frac{V_s C}{\Gamma}$.

2.4 Sidewall of the tank

The horizontal flow rate u and the vertical flow rate v are zero. The concentration of the suspended solid is $\frac{\partial C}{\partial x} = 0$ and $\frac{\partial C}{\partial y} = 0$ (Yao, 2005; Stamou et al., 1989).

3 Application

3.1 Initialization

The initial conditions of a secondary horizontal sedimentation tank in a sewage treatment plant in Guangzhou, China are provided as an example. The water quantity Q was 550 m^3/hr. The sludge flow of the suction dredge RQ was 950 m^3/hr. The inflow ($Q + RQ$) was 1500 m^3/hr, and the outflow Q was 550 m^3/hr. The concentration C_0 in the inlet of the sedimentation tank was 2658 g/m^3. The length L of the sediment tank was 50 m, the width b was 10.9 m, and the height H was 5 m. The diffusion coefficient Γ was one and the suspended sediment was presumed to be eliminated when it fell onto the bottom of the tank.

Equation (2) was converted into: $\ln V_s = \ln V_0 - nC$, and the parameter V_0 and n were calculated using linear regression as 8.7 m/hr and 0.0005, respectively.

Q_1 was calculated by Eq. (6). The parameters used in Eq. (6) were set as follows: $z = 0.3$ m, $h_r = 0.5$ m, $g = 9.8$ m/sec^2, $\varepsilon = 0.01$. From this, Q_1 was calculated to be 213.8 m^3/hr, and $u_1 = \frac{Q+RQ}{A} = 28$ (m/hr), $u_2 = \frac{Q+RQ+Q_1}{A} = 24$ (m/hr), and $u_3 = \frac{Q}{A} = 10$ (m/hr), supposing that the vertical flow rate in the secondary sediment tank was zero.

3.2 Simulation results

The differential equation was discretized and the square lattice was used to solve the equation. The sedimentation tank was presumed to be a rectangular container and Matlab software (Zhang, 2003) was used for simulation and analysis.

The simulated value of the outlet concentration of the sediment tank was 10.1 g/m^3 and the average value of the values observed from the experiments was 12.2 g/m^3. The two values are very close.

The location of the suction dredge was fixed at a distance of 17 m from the inlet to the dredge to analyze the simulated value. Figure 2 shows the concentration distribution of the sediment tank at the analysis point. The role of the suction dredge in the sedimentation tank is to remove all or part of the sludge settling at the bottom of the tank to the aeration tank. After the suction dredge takes up the sludge, the concentration of sludge near the dredge should decrease. As seen in Fig. 2 near the 17 m point, the curve presents a concave trend whereby the concentration decreases. This is in accordance with theoretical analysis.

We also analyzed the isoconcentration distribution curves acquired through simulations and experiments, as well as the vertical concentration distribution curves of the five monitoring sections. Figure 3 shows the isoconcentration distribution curves when the suction dredge was 17 m away from the inlet. As seen in Fig. 3a, b, the trend of the isoconcentration distribution curves acquired through simulations were almost the same as that acquired through experiments. The curves which are drawn by experimental values suppose that the concentrations of the sludge at the two adjacent monitoring points is linear relation. When the concentration was above 4000 g/m^3, the

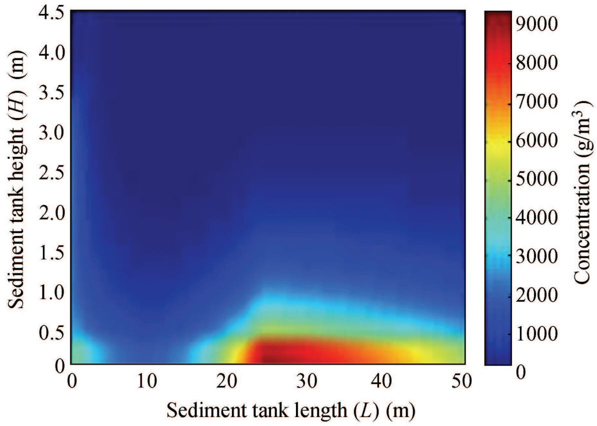

Fig. 2 Concentration distribution when the suction dredge is 17 m away from the inlet. 0 in the X- and Y-axis are inlet of tank and the bottom of tank, suspectively.

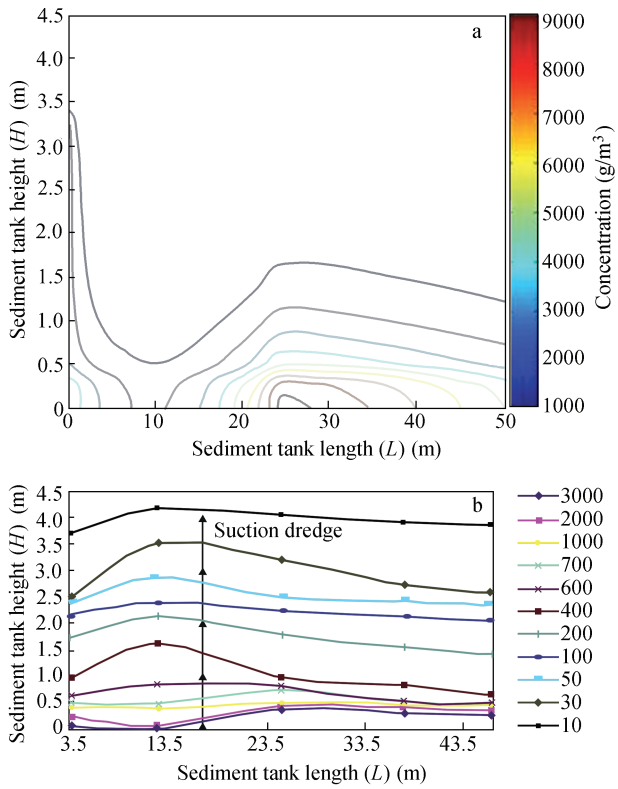

Fig. 3 Isoconcentration distribution curves when the suction dredge was 17 m away from the inlet. (a) isoconcentration distribution curves of simulated value; (b) isoconcentration distribution curves of measured value. 0 in the X- and Y- axis are inlet of tank and the bottom of tank, suspectively.

isoconcentration distribution curve was very close to the X-axis. As a result, the curve with concentrations higher than 4000 g/m^3 is excluded in Fig. 3. However, there are some differences between the simulated and experimental values. The isoconcentration distribution curves with a concentration of 1000 to 2000 g/m^3 are below 1 m in Fig. 3b, but curves with a concentration of 1000 to 2000 g/m^3 are above 1 m and below 2 m in Fig. 3a.

Figure 4 shows the vertical concentration distribution curves of the five monitoring sections. The curves were acquired by simulation, and the dots show the experimental values. As seen in Fig. 4, there are some differences between the simulated and experimental values. In the first two sub-figures, which show the vertical distribution curves of the monitoring sections at 3.5 and 12.5 m, the differences between the simulated values and the experimental values are smaller than the differences in the other three sections. The concentrations of the sludge at the bottom in the first two sub-figures were low (< 3300 g/m^3), which resulted in a small difference.

3.3 Discussion

As seen in Figs. 3 and 4, the differences between the simulated results and the observed values are significant. The reasons for this are as follows:

(1) The accuracy of the sampler: This has a direct impact on the experimental results. When the experimental data were collected, the water collected by the traditional water sampler was different from the theoretical value. After analyzing the sampler based on fluid dynamics, we found that the water sample gathered by the traditional water sampler was not the real water sample of the monitoring point. As a result, the sampling method was changed to increase accuracy, although the new method was prone to human influence and difficult to control. During the sedimentation tank setting process, the water inlet and outlet of the traditional water sampler always stayed open, so the water sample at the specified points was influenced by an upper-layer liquid of lower concentration, and the vertical concentration of the sedimentation tank could be reduced. However, a liquid sampler designed to sample and open the water inlet at specified points could solve this problem and improve accuracy.

(2) Velocity field issues: Our research presumed that the vertical rate was zero and the horizontal rate was uniform. These assumptions simplified velocity distribution in the sedimentation tank. In practice, velocity distribution is very complex and directly influences the transfer of the suspended particles. Such simple assumptions influenced the accuracy of the simulated results. If the vertical rate is not zero, the setting velocity of the sludge would be faster and the vertical concentration distribution curves would be much steeper. If the velocity field of the sedimentation tank is simulated by fluid dynamics and combined with

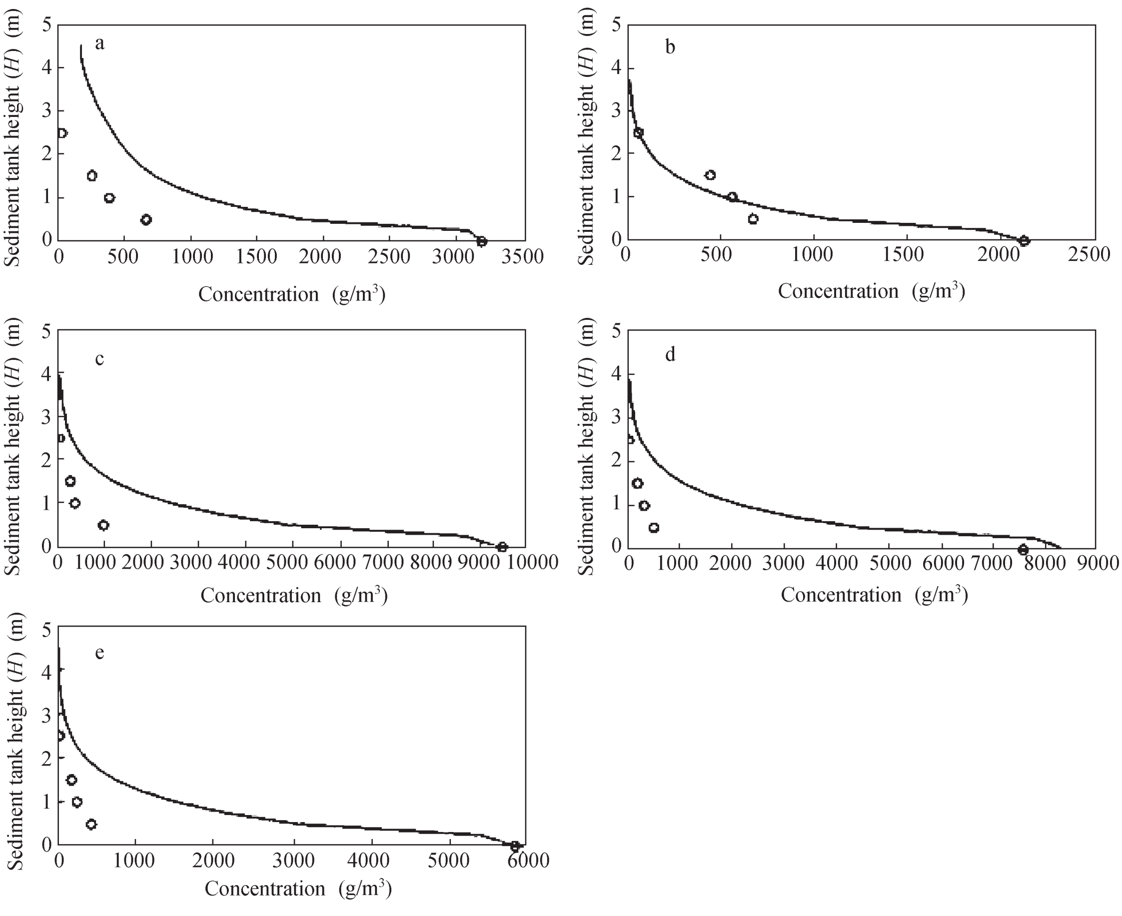

Fig. 4 Vertical concentration distribution curves of the five monitoring sections. When the suction dredge was 17 m away from the inlet, the point was 3.5 m (a), 12.5 m (b), 25 m (c), 37.5 m (d), and 46.5 m (e) away from the inlet. 0 in the Y-axis is the bottom of tank.

concentration distribution research, the simulation result would be much more accurate.

4 Conclusions

This article constructs and discusses a suspended sediment transportation model and calculates the flow taken up by the suction dredge from the inlet to its location based on fluid dynamics. Under the assumption that the horizontal rate is uniform, the velocity field was acquired using the calculated flow and the inflow and outflow. In addition, the concentration distributions were obtained when the suction dredge was fixed to different positions. The comparison between the simulated results and the experimental results shows that the simulated outlet concentration value was close to the experimental value. However, large differences were observed between the simulated and experimentation isoconcentration distribution curves and the simulated and experimentation vertical distribution curves of the five monitoring sections. The reasons for such differences include sampling inaccuracy and the simple assumption of the velocity field.

This article takes into account sludge recirculation to calculate the concentration distribution in the sedimentation tank. Results showed that distribution in practice followed theoretical analysis. The velocity field in the sedimentation tank greatly influences concentration distribution, based on the assumptions that the vertical rate was zero and the horizontal rate was uniform. However, future study and analysis of the velocity field is required to increase the accuracy of the simulation results.

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