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Research Article

Simulation for Fine Sediment Flocculating Settlement in Flowing Water and Its Influencing Factors

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Abstract: The aim of this study is to simulate the growth process of fine Sediment flocculation fractal, which based on DLCA and three graphics technology. With the simulation, we analyze the effects of particle effective collision probability, initial concentration and particle diameter on sedimentation distance and distribution. The flow fractal structure was analyzed by graphic technology. Researches in this study have some theoretical and practical value on the control and treatment of Yellow River high turbidity flow.

Keywords: Effective collision probability, flocculation in moving water, sedimentation, setting velocity

INTRODUCTION

When fine sediment is dispersed in water, its characteristics compared with coarse particle mud and ion solution dispersion system are concerned; there is a big difference in characteristics. The flocculation and sedimentation of cohesive fine sediment is important and complex in the study of sediment movement mechanics theory. Many characteristics of High silt-laden water has a close relationship with viscous fine sediment flocculation, such as array flow phenomenon, plasma river phenomenon, the bottom phenomenon, the formation of non-Newtonian fluid, huge sediment-carrying capacity, etc., (Jin *et al*., 2003; Maks, 1999). At present, the efficient observation method for the flocculation and settlement of viscous fine particle is still lacking, especially the study on the flocculation process of flowing water have a lot of difficulties.

Both at home and abroad, Owen (1971), Allen (1973) and Zhao (1995) have studied the flowing water flocculation mechanism and the results of the study shown that the flow velocity of flowing water flocculation have a significant impact on flocculation. The research of Hai Zhou showed that the flow rate has an influence on the sediment particles flocculation via the flocculation crushing probability. On the basis of DLCA (Diffusion Limited Cluster Aggregation) model, namely floccules gathered model of limited diffusion (Yang *et al*., 2005; Hong and Yang, 2006), the flocculation model in the models in this paper study the flocculation growth of sediment floccules from the three dimensional angle. In DLCA model, the influence of velocity on the flocculation is mainly adjusted through the effective collision probability.

THE SIMULATION

Theory: The finer silt particles, the larger specific surface area, the physical chemistry reaction between the particles between particles can cause the microscopic structure, with the increase of the content in this fine silt, adjacent some fine particles with adsorbed water film connect together to form a flow, this phenomenon is called flocculation phenomenon (Wang *et al*., 2009). In the rivers with a higher content of fine particles, flocculation phenomenon is always accompanied by the movement of water flow and silt deposition.

The processing of Brownian motion: The classic Einstein brown displacement formula was used for the processing of Brownian motion (Hu *et al*., 2002):

$$\bar{x}_{\mathrm{i}} = \sqrt{\frac{2RT}{3\pi N_{\mathrm{A}} \mu_0 d_{\mathrm{f}}}} \bullet \sqrt{t} \quad (\mathrm{i} = 1, 2, 3) \tag{1}$$

$\bar{x}_1, \bar{x}_2, \bar{x}_2$ = The average displacement along the x, y, z axis of the particle whose diameter is denoted as r, m
R = Molar gas constant, J/moL·K
NA = Avogadro constant, moL^{-1}
μ_0 = Water dynamic viscosity, Pa·s
T = Absolute temperature, ^{o}C

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d_f = The diameter of particle or floc, m
t = The time, m

To compute the Brownian motion displacement of the floc, the diameter of floc is computed by Feder Fractal formula (Yang *et al.*, 2003a):

$$d_\text{f} = d_0(N)^{\frac{1}{D_\text{f}}} \tag{2}$$

d_0 = The diameter of particle, m
N = The number of particle in floc
D_f = The floccules fractal dimension

The selection of settling velocity formula: For the computation of single particle, its settling velocity is computed by the Stokes formula:

$$\omega_1 = \frac{1}{18}\frac{\gamma_\text{d} - \gamma}{\gamma} g \frac{d_0{}^2}{\upsilon} \tag{3}$$

ω_1 = The sedimentation rate of particle, m/sec
γ_d = The density of Floccules bulk, N/m^3
γ = The density of water, N/m^3
υ = The kinematical viscosity of water, m^2/sec

To calculate the settling velocity of floc, Suppose the floc is balanced under the common function of Gravity (G), buoyancy (f) and viscous Force (Fr) under the balance, the momentum conservation equation is:

$$\frac{dw}{dt} = g - \frac{f}{m_\text{f}} - \frac{Fr(\text{t})}{m_\text{f}} \tag{4}$$

The viscous force calculation formula of particles in the static water is:

$$Fr\,(t) = 3\pi g \upsilon \gamma d_\text{f} \cdot \omega \tag{5}$$

As the force equilibrium, the settling velocity formula of floc is deduced as:

$$\omega_2 = \frac{1}{18}\frac{\gamma_\text{f} - \gamma}{\gamma} g \frac{d_\text{f}{}^2}{\upsilon} \tag{6}$$

γ_f is the density of floc, N/m^3. Bring the fractal formula (2) into the density composition formula of mud, the density of floc can be expressed as:

$$\gamma_\text{f} = (\gamma_\text{d} - \gamma)(\frac{d_\text{f}}{d_0})^{D_\text{f}-3} + \gamma \tag{7}$$

The movement displacement of sediment: Flow speed and the flocculation effect is complicated, for simplification, we selected laminar flow, we denoted the directions along the water's flow, width of water surface, depth of water as x, y, z direction and set the flow velocity as V1, then the three-direction displacements of the sediment particles within the unit time step are:

$$L_\text{X} = V_1 \cdot dt \pm \overline{x_1} \tag{8}$$

$$L_\text{Y} = \pm \overline{x_2} \tag{9}$$

$$L_\text{Z} = \omega \cdot dt \pm \overline{x_3} \tag{10}$$

L_X, L_Y, L_Z = The displacement at x, y, z direction respectively of the sediment particles within the unit time, m
dt = The unit time step, sec

Initial boundary conditions: Time step size is calculated in accordance with the single particle settling velocity and the spatial scale of the simulation area, each iteration of the time step is taken as 1 sec, the simulation area is long (1 mm) ×width (1 mm) ×height (2 mm), The flow rate of imported water in analog area is 0.1 m/sec. The initial position of sediment particles has a random uniform distribution, according to the input sediment concentration, the model of particle density and particle density of the actual suspension is roughly identical, its calculation formula is:

$$N_\text{p} = \frac{g \cdot S_0 \cdot a \cdot b \cdot c}{6 \cdot \pi \cdot \gamma_\text{d} \cdot (d_0)^3} \tag{11}$$

N_p = The number of particle in simulation area
S_0 = The initial condition of sediment particles in the import, kg/m^3
a, b, c = The long, width and height respectively in the simulation area, m

Parameter selection: The density of sediment particles is 25996.5 kg/m^3, the fractal dimension of sediment floccules is taken as 1.78 according to the existing material (Yang *et al.*, 2003a; Yang *et al.*, 2003b), the Avogadro constant is 6.02×10^{23} moL^{-1}, the temperature is 298 K, at this temperature, the dynamic viscosity and motion viscosity of water is 0.894×10^{-3} Pa·sec and 0.897×10^{-6} m^2/sec, molar gas constant is 8.31 J/moL·K.

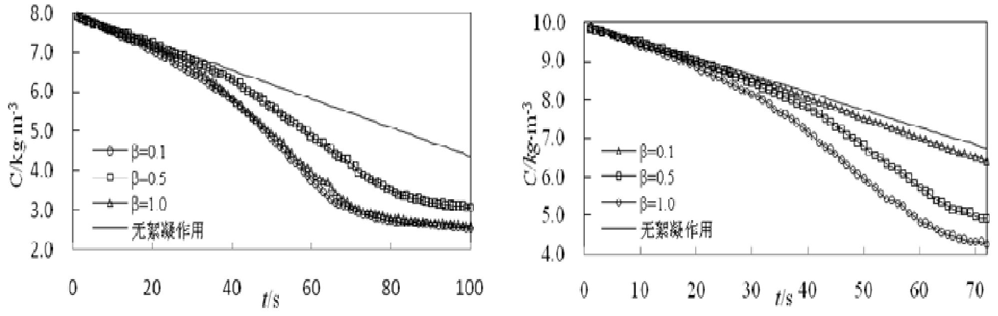
METHODOLOGY

The impact of effective collision probability on the settling velocity: The shift of sediment transport, flocculation and sedimentation effects each other in the sediment movement. According to the stokes settling speed theory, the main factor in the influence of sediment settling velocity is the proportion of water and the sediment particles (floccules) and its size. For floccules, effective collision probability is the main factor to decide the growth rate of the size and at the same time, effective collision probability is also an important intermediate factor for the impact of flow velocity on the sediment settling velocity (Zhou *et al*., 2007), so the impact of effective collision probability of sediment on the settling velocity is particularly important, the effect on the sediment settling down is mainly produced through the flocculation way.

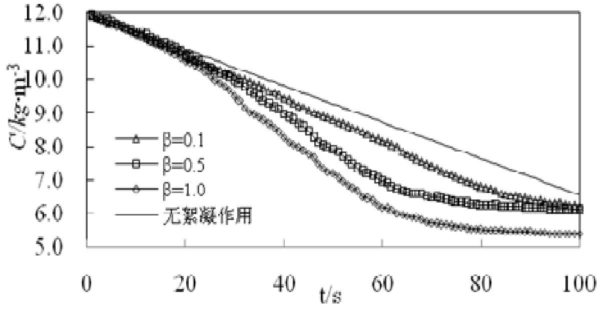
Figure 1 is the influence of flocculation on the silt sediment deposition, from this figure, we can see the flocculation speed up the deposition of the sediment at these three initial concentrations and the speed of deposition will increase with increasing the sediment effective collision coefficient. This is due to in the process of sediment deposition, part of the sediment particles flocculate to floc, the particle sizes have an increase, the settling velocity is accelerated, leading to the silting process of overall sediment be faster. The increase of effective collision coefficient accelerated the growth rate of floc particle size and the rate of sediment deposition. Higher content of sediment at the initial time, more times of particle collisions per unit volume, floc size increased faster, shown a accelerating trend, with the sediment deposition, the concentration of sediment decreased, falling silt slowed down and this phenomenon is consistent with the actual (Zhao, 1995).

The distance of deposition: The on-way deposition distance of sediment is mainly effected by the flow velocity and the sediment size, Fig. 2 is the quality profile of on-way deposition of the sediment in unit group (d_0 = 0.003 mm), the flow rate is u = 1.0 m/sec, as the diameter of single particle is smaller, the influence of Brownian movement of particle is larger, the on-way deposition distance present a Guassian distribution. As the Fig. 2 shown, as the increase of effective collision probability, the particle of sediment have a chance to form lager floc and induce the acceleration of deposition, to cause the earlier deposition finally, decrease the distance of deposition. As the increase of initial silt concentration, the silt particle per unit has an increase and more time and longer distance is needed for the deposition. This result is consistent with the former (Zhou *et al*., 2007; Zhang, 2001).

Due to the flocculation effect, the value of average on-way deposition distance of sediment is not stable, but in a certain range, in this range, the sediment deposition quantity fell a gaussian normal distribution, it can be presented by the following statistical formula:

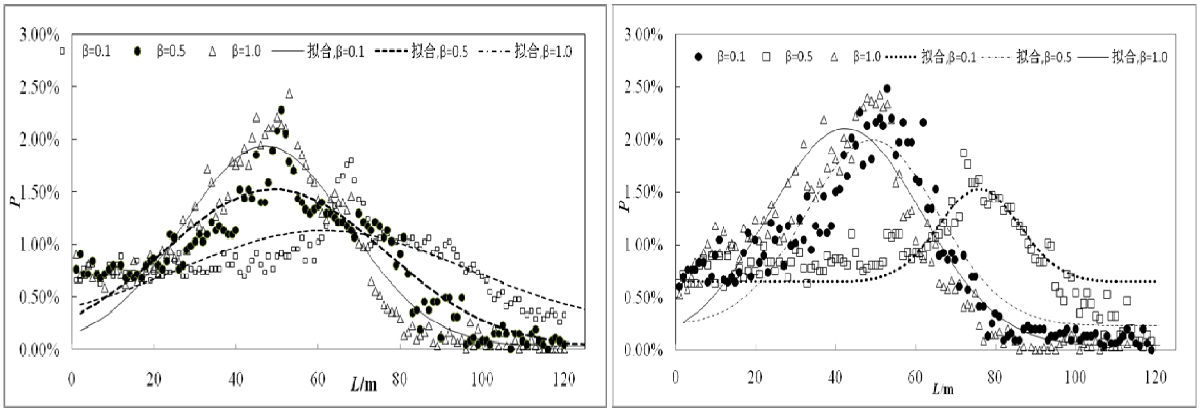


(a) $C_0 = 8.0$ kg/m^3 (b) $C_0 = 10.0$ kg/m^3

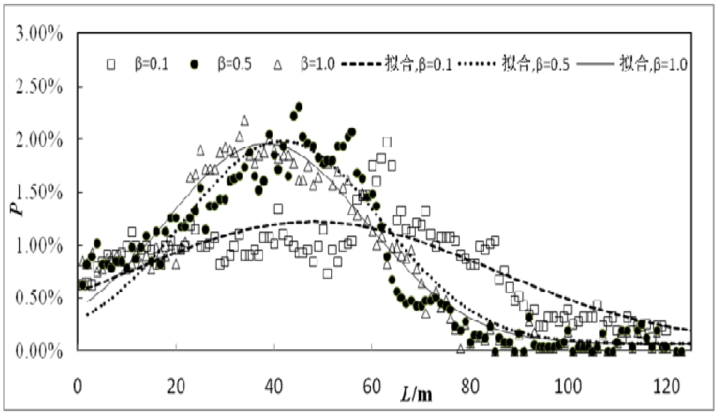


(c) $C_0 = 12.0$ kg/m^3

Fig. 1: Variation of sediment concentration with time



(a) $C_0 = 8.0$ kg/m^3 (b) $C_0 = 10.0$ kg/m^3



(c) $C_0 = 12.0$ kg/m^3

Fig. 2: Quality distribution of uniform sediment along flow direction

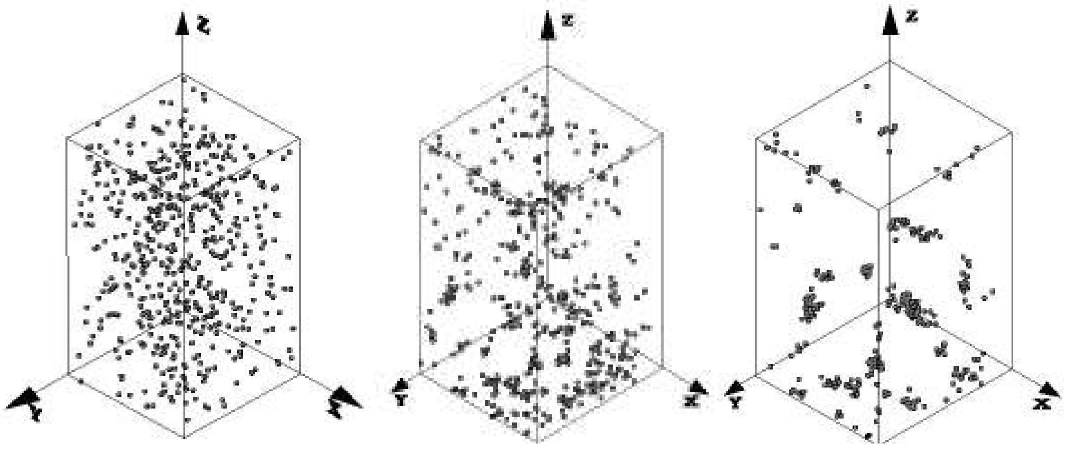
Table 1: Sediment deposition distance

			L (m)			
C_0 (kg/m^3)	β	μ (m)	p≤25%	p≤50%	p≤75%	p≤100%
8.0	0.1	63.1	34.1	63.1	93.1	≥135.1
	0.5	48.1	26.8	48.1	85.2	≥127.6
	1.0	45.5	23.2	45.5	72.5	≥123.4
10.0	0.1	74.2	50.3	74.2	87.2	≥147.9
	0.5	49.2	31.4	49.2	70.2	≥129.8
	1.0	43.8	24.3	43.8	66.7	≥125.4
12.0	0.1	47.6	34.5	47.6	83.2	≥162.5
	0.5	43.2	25.1	43.2	64.7	≥138.7
	1.0	39.2	24.6	39.2	62.8	≥132.6

$$\overline{L} = \langle L \rangle, \sigma^2 = \langle L^2 \rangle \tag{12}$$

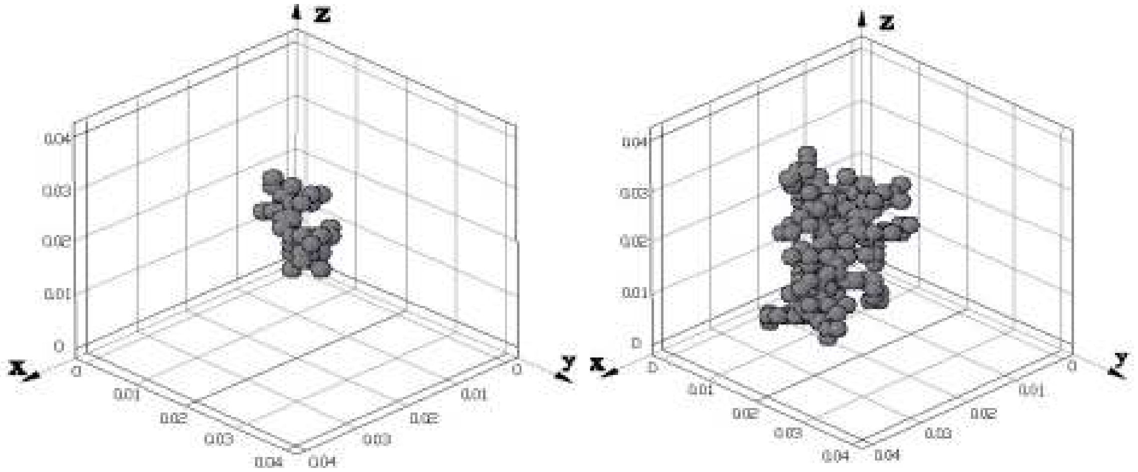
The statistics data under every parameter is shown in Table 1, after the analysis, we can see the rule of sediment deposition volume is almost consistent in every probability scope, along with the increase of effective collision coefficient and the decrease of silt initial concentration. But the distance for deposition of all silt is long, as the silt concentration in the silt deposition process is decreasing, the final residual fine sediment has a stronger random Brownian movement, this is also the reason of that the sediment in reservoir which can move to the dam is smaller.

The change of floccules structure: The internal structure change of floccules is more complicated and due to its strong dynamic nature, microscopic sport scale, leading to the dynamic observation of floccules still stays in the qualitative description stage. This study discussed the floccules structure by the simulation method.



(a) t = 0 sec (b) t = 30 sec (c) t = 60 sec

Fig. 3: Floc figures in different time



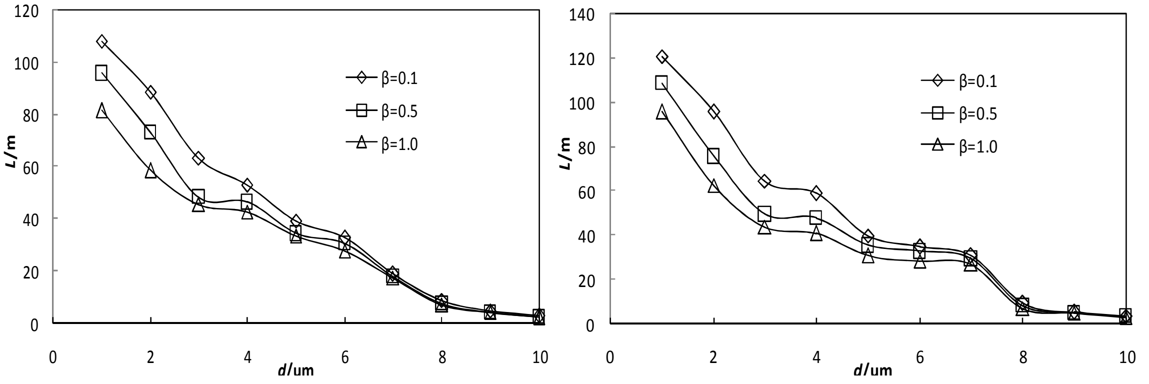
(a) N = 50 (b) N = 200

Fig. 4: Figures of floc structure

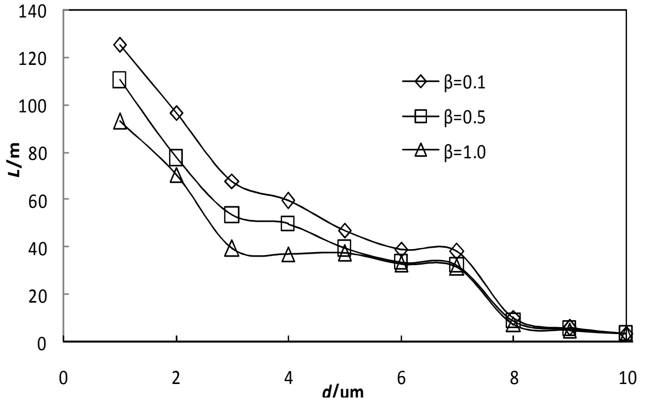
Figure 3a to c show the floc structure Figure at initial state, 30 and 60 sec in the deposition process, as the initial concentration is 10 kg/m^3, the initial particle size is 2 um, effective collision coefficient is 0.5, in order to avoid too many particles, the three dimension scheme for 0.1×0.1×0.2 mm area was chose in the center of the calculation area in Fig. 3. Figure 3a shows the initial state of the system, including the sediment particles in three dimensions are random uniform distribution, Fig. 3b is the distribution condition of sediment particles and floccules at 30 sec, in this moment, floccules obviously appeared, but sediment particles and floccules still has a average distribution, Fig. 3c shows that the sediment floccules have a further increase at t = 60 sec in the suspended liquid. Figure 4 is the internal structure for single floccules, after the careful observation to floccules structure, we will find floccules have the similar type features, this results is consistent with the literature (Zhang, 2001; Liu *et al*., 2012; Zhang *et al*., 2006).

RESULTS AND DISCUSSION

The effect of sediment particle size on the sediment deposition distance: In the natural channel, the effect of sediment size on the deposition is at the settlement rate firstly, secondly, the sediment size effect the floc deposition by the influence of the flocculating. At the same concentration, the decrease of the number of big size sediment particle also influence the particle collision. The sediment was divided into ten group with the same particle size (d_0 = 1~10 um) to calculate in this simulation. We assume that the average sediment deposition distance as the sediment deposition cumulative frequency $p \leq 50\%$, its change with the sediment particle size is shown in Fig. 5.



(a) $C_0 = 8.0$ kg/m^3 (b) $C_0 = 10.0$ kg/m^3



(c) $C_0 = 12.0$ kg/m^3

Fig. 5: Relation between sediment deposition distance and particle diameter

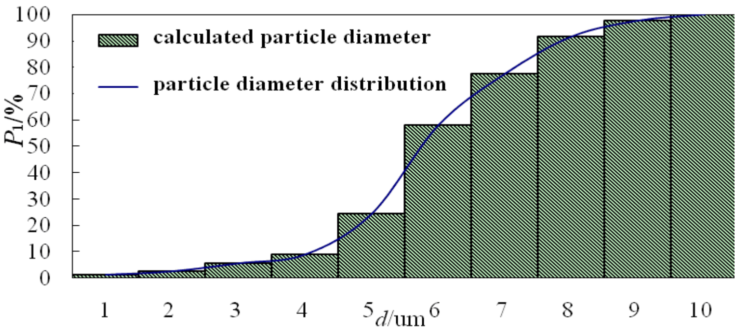
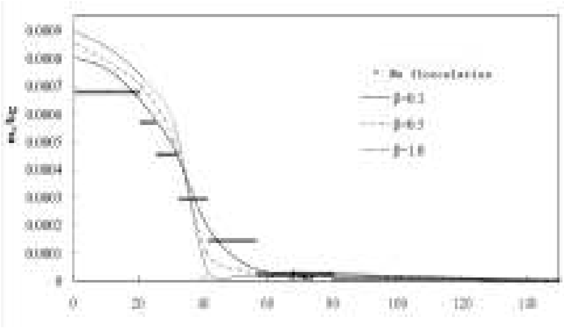


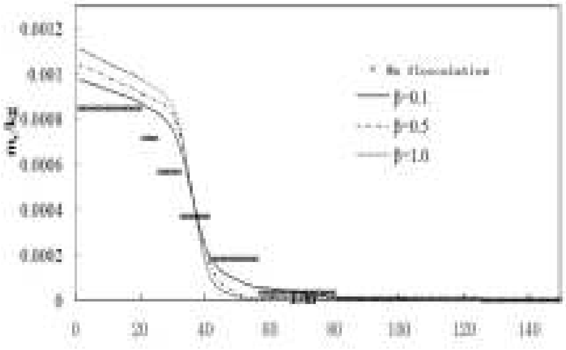
Fig. 6: Sediment particle diameter distribution

From Fig. 5, as the increase of sediment particle size, the overall deposition distance present a decrease trend. As the effect of Brownian motion on the sediment particle is mainly concentrated in the particle whose diameter is less than 5 um, the particle in this scope has a feature at the deposition, the deposition distance has a big change with the particle size, as the particle size is higher than 5 um, its deposition distance change slightly. At the same time because effective collision coefficient effect the deposition distance mainly through the flocculation, from Fig. 5a to c, we can obviously see that when the particle size is smaller, the effective collision coefficient has a bigger influence on the deposition and the effect is slight to the big particle. Under the same effective collision coefficient, the greater initial concentration of sediment, the farther deposition distance

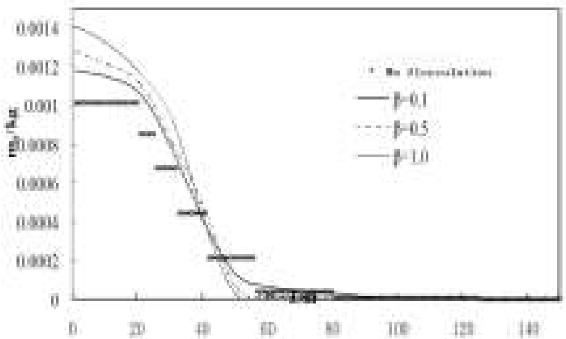
The distribution of on-way deposition of inhomogeneous sediment: After the retrieve of the



(a) $C_0 = 8.0$ kg/m^3



(b) $C_0 = 10.0$ kg/m^3



(c) $C_0 = 12.0$ kg/m^3

Fig. 7: Quality distribution of nonuniform sediment along flow direction

sediment samples, screening the sediment particle whose diameter is less than 0.01 mm, the particle size distribution curve is calculated by the laser particle size distribution instrument, the sediment particles is divided into 1~10 um ten group according to size, as shown in Fig. 6. According to the former method, we can calculate the sediment deposition respectively.

The condition of inhomogeneous sediment deposition at different concentrations is shown in Fig. 7, from the figure, we can see when the flocculation is not considered, the amount of flocculation is decreasing as the time, the deposition of particle present reverse S type as the deposition distance, the deposition is mainly concentrated on the former, this is due to the particle deposition of different diameter. After the consideration of flocculation, the time change trend is almost same as the former, but the different effective collision probability has a big influence on the on-way deposition form, the effective collision probability is bigger, the amount of flocculation nearer the front, the rate of deposition is faster, it suggest that the rate of deposition which due to the flocculation is enhanced. The condensation has a slight influence on the deposition shape, from the figure, we can see the higher condensation, the larger overall deposition distance and it is consistent with the deposition change trend that calculated former.

CONCLUSION

The three-dimensional flocculating sedimentation simulation of the viscous fine sediment moving water that based on the DLCA model, can display viscous fine sediment moving water flocculation settlement process to a certain degree.

In the simulation process, the flus is constantly formed as the collision between particles and it has a gradual developing and flocculating sedimentation in the factor of Brownian motion, gravity, buoyancy and viscous force, the flocculation speed up the sediment deposition and the rate of deposition is raising with the sediment effective collision coefficient. There is higher sediment content, more particle collision frequency per unit volume, faster growing of floc diameter with accelerating in the initial time and the sediment concentration is decreasing and the rate of deposition is slowing down with the sediment deposition.

Due to the influence of the particles Brownian motion, the on-way deposition distance of single particle size group present a Gaussian distribution. Effective collision coefficient increase speed up the sediment settling velocity and the increase of the initial concentration of sediment make the whole sediment deposition to need a long distance. As the non-uniform sediment deposition, the deposition mainly concentrate in the forepart, effective collision coefficient and initial silt concentration have the same influence on the no uniform sediment deposition and uniform sediment.

The flocculation settlement process of viscous fine sediment is actually affected by many factors, in addition to initial sediment concentration, sediment particle size and grading factors, the electrolyte concentration, flow turbulence intensity and so on also have a relationship with it. A simplified treatment is taken in this study, these factors are not considered and as the limitation of the current computer level, the simulation range is still small. At the same time, the microscopic test for dynamic flocculation will be provided more advanced technology equipment and complete test method, these are our further future work.

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