STUDY ON THE BEHAVIORS OF COHESIVE SEDIMENT IN THE YANGTZE ESTUARY

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Abstract

In order to study the deposition and erosion behaviors of the cohesive sediment in the navigation channel through the bar of the Yangtze Estuary, a series of experiments have been made with a standard settling tube and Ubbelodhe viscometer. The tests show that the flocculation and rheological behaviors of the cohesive sediment differ from the clay mineral contained in the fine sediments. Different clay mineral aggregates or flocs have their apparent volume due to the thin layer of water surrounding the aggregates or water entrained in the flocs. The Bingham relative viscosity and yield stress are obtained: $\mu_r = (1-KC_v)^{-2.5}$, $\tau_y = 0.13K\exp(7kc_v)$. The suspended load transport rate and depositional behavior of the cohesive sediment have been studied with rotating annular channel. It is shown that there is a certain silt carrying capacity for a certain flow condition. The equilibrium silt concentration can be expressed: $C_{eq}=A(\tau_b-\tau_1)$ and the concentration-time relation is $C=C_{eq}+(C_0-C_{eq})\exp(-\alpha\omega t/2H)$. Using the above formulas and tidal velocity analysis the yearly average dredging amount in the the navigation channel can be calculated.

Introduction

The Yangtze River is the largest river of China. It carries annually 924×10^9 m^3 of runoff and 470×10^6 t of sediment

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into the sea. The yearly average suspended concentration is 0.544 kg/m^3. The grain size of suspended load is generally greater than 5 ϕ, 30% of which are clay particles. Most of the sediment is deposited on the estuarine area, causing shoaling of navigation waterway, thus greatly affecting the traffic capability of port Shanghai and other port along the lower reaches of the River. The grain size of the materials deposited in the navigation channel is of the same order magnitude as that of suspended sediment (Chang Zhizhong, 1981). Extensive dredging has to be carried out to maintain the required water depth of the navigation channels, particularly the approach channel to the sea. Therefore regulation works have to be carried out in combination with dredging to copy with such adverse situation. For this purpose study was made, among others, on the behaviors of cohesive sediment of the Estuary, which is necessary for the planning and design of the regulation works, as well as for the disposal of the dredged materials in the dredging operation. The deposition and erosion of the cohesive sediment of the navigation channel in the Yangtze Estuary is affected by various factors, such as tidal current, runoff, wave, salinity, ph value etc.. The floc size and floc strength of cohesive sediment are important factors affecting deposition and erosion. In this paper the rheological behaviors of the cohesive sediment are studied from the test results with Ubbelodhe viscometer for different clay mineral composition and mediums. Transportion and deposition tests for Yangtze Estuary clay were conducted in the annular rotating channel. For deposition the concentration versus time relationship is obtained and could be used for calculating dredging amount in the navigation channel.

Experimental Study on the Rheological Behavior of Cohesive Sediment

On silty coast and estuaries the fine sediment usually consists of mixture of clay, silt, fine sand and occasionally some organic matters. Previously it was taken that there is no difference in behaviors between the clay minerals and he primary minerals except their grain size. In reality, the clay particles of the cohesive sediment carry electric charge which which causes flocculation and deflocculation of the sediment. Size distribution analysis with a setup of settling tube is shown in Table 1. Different clay mineral particles have different ratio of width to thickness and the flocculation sized of different clay mineral varies appreciably from each other in different mediums, but for fine silt particles of quartz there is no significant difference in the flocculation size d_{50} in different mediums. For example, kaolinite can be flocculated in distilled water but montmorillonite cannot.

Table 1. d50 of quartz, kaolinite and montmorillonite in different mediums

Minerals Mediums	Non clayey sediment	Clay minerals		Remarks
	Quartz silt	Montmorillonite	Kaolinite	
Distilled water	0. 010	0. 0024	0. 038	1. Unit : mm 2. Quanitity of $[NapO_3]_6$ added: 0. 5N. 1c. c. / g.
Water with salinity 10‰	0. 015	0. 027	0. 040	
Distilled water+ $[NaPO_3]_6$	0. 011	0. 0021	0. 0032	

The modes of particle(aggregate) association are of great importance to the essential behaviors of the flocs, such as settling, shearing, swelling etc., and are affected by by factors such as ph value, concentration of electrolyte and and sediment as well as composition of mineral etc. . Under normal conditions edge to face association is the principal mode of association, which leads to voluminous card- house structures and entrains a large amount of water. The aggregates or flocs will increase their apparent volume due to the thin layer of water surrounding the aggregates or water entrained in the flocs. The degree of association will change with different mediums. Along coast of China, the major clay minerals are illite, kaolinite, montmorillonite and in the Yangtze Estuary the clay mineral consits mainly of illite. The optium salinity for flocculation is about 10~15‰. With this salinity the apparent volume and settling velocity of the flocs attain a maximum.

In order to investigate the erosion of sediment and movement of fluid mud, the rheological behavior tests of cohesive sediment are conducted with Ubbelodhe viscometer for different clay mineral suspension and mediums (Yen, Kai, et al, 1989), as shown in Fig. 1 . It is clear that for the same concentration the relative viscosity of montmorillonite suspension is larger than that of kaolinite suspension with salinity of 10‰. For the same clay mineral, the relative viscosity in salinity medium is larger than that of suspension with peptizer. The degree of volume expansion K, which can be expressed by the ratio of the volumes after and before expansion , may be obtained from the formula

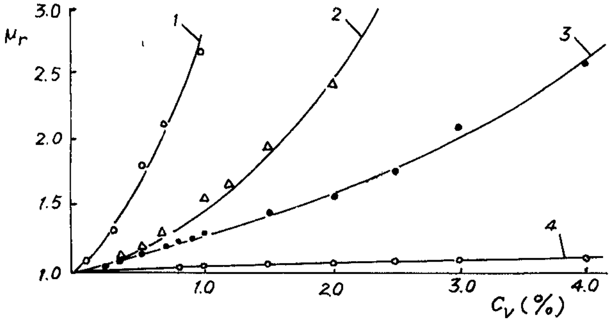

Fig. 1 μ_r-C_v curves of montmorillonite and kaolinite suspended in different mediums: 1-montmorillonite suspension witb salinity of 10 ‰. 2-montmorillonite suspension with peptizer. 3-kaolinite suspension with salinity of 10‰. 4-kaolinite suspension witb peptizer.

$$\mu_r=(1-KC_v)^{-2.5} \qquad (1)$$

In this formula μ_r is the relative viscosity cofficient and C_v the volumetric concentration. The volume expansion K for different clay mineral and mediums are given in Table 2.

Table 2 Value K obtained by Ubbelodbe viscometer

Minerals	Saline water with salinity 10%	Distilled water + peptizer of $[NaPO_3]_6$	Remarks
Montmorillonite	37.0	15.3	Quantity of $[NaPO_3]_6$ added: 0.5N, 0.5c.c./g
Kaolinite	7.8	1.5	

The Bingham yield stress is a measure of the number and the strength of the links in card-house (Van Olphen, 1977). The magnitude of Bingham yield stress is closely related to the size of flocs and to volume of the entrained water in the flocs, as shown in Fig. 2. When peptizer is added into the suspension, the card- house structures are completely dissociated, and the Bingham yield stress will tend to disappear. The formula of Bingham yield stress for Yangtze Estuary clay is:

$$\tau_y=0.13K\exp(7KC_v) \qquad (2)$$

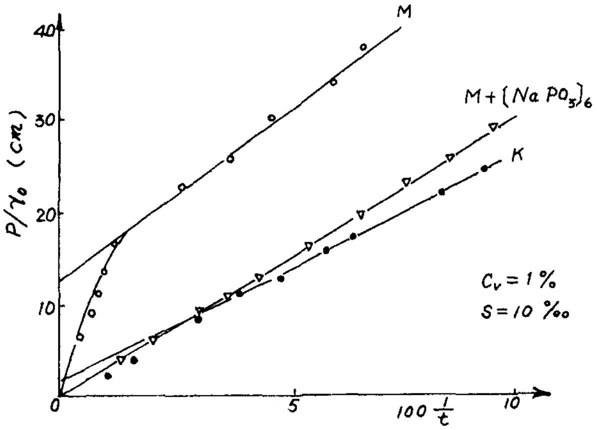

Fig. 2 Equivalent yield stress of montmorillonite and kaolinite suspension

For the Yangtze Estuary clay, which consists mainly of illite, the values of volume expansion K in Equ. (1) and Equ. (2) are given in Table 3.

Table 3. Value d in Different Salinity Mediums

Salinity	2‰	5 ‰	10‰	20‰	25‰
n	5. 9	6. 3	5. 0	6. 0	5. 6

Comparison of μ_r values between experimental and calculated by Equ(1) is shown in Fig. 3 and comparison of Bingham yield stress between experimental and calculated by Equ. (2) is shown in Fig. 4. It shows that Equ. (1) and Equ. (2) conform with experimental data.

All the above tests show that the composition of clay minerals is of great importance to the essential properties of flocs.

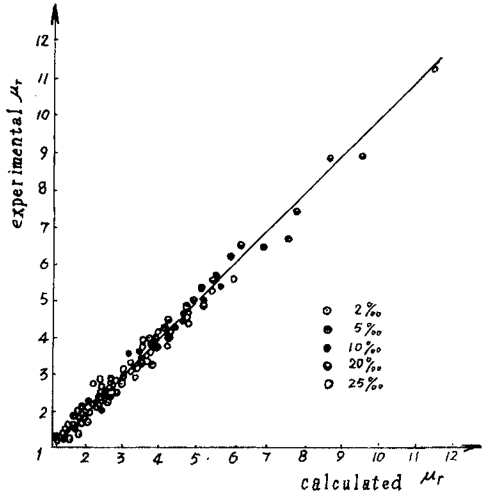

Fig. 3 Comparison between experimental and calculated μ_r values

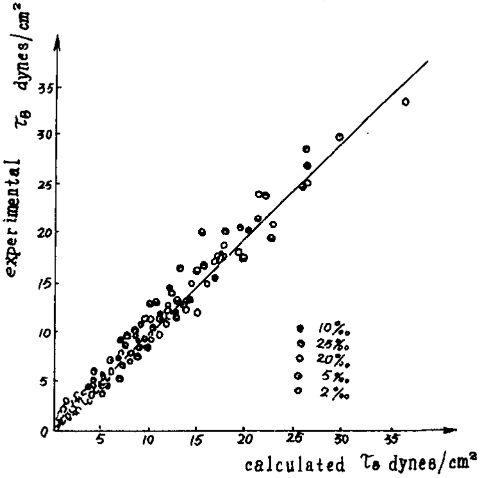

Fig. 4 Comparison between experimental and calculated Bingham yield stress

Deposition Behavior of Cohesive Sediment

A series of deposition tests with different clay mineral composition and the Yangtze Estuary clay in sea water were conducted in an annular rotating channel to study the relation between the deposition behavior of cohesive sediment and the bed shear stress (Zeng Xiaochuan, 1985). Fig. 5 shows the results of test for kaolinite. It can be seen that there is a critical critical shear stress τ_1 below which the flocs of the cohesive sediment will be all deposited on the channel bed, and when the bed shear stress τ_b is greater than the critical shear stress τ_1 the suspended sediment will attain a state of equilibrium with concentration Ceq. The relation between equilibrium concentration Ceq and bottom shear stress τ_b for differdent initial concentration C_0 can be divided into single-valued stage (along τ 1) and the multi-valued stage (on the right of τ_1 p) respectively. At the single valued stage C_{eq} versus τ_b is independent on the initial concentration C_0. That is, there is a certain silt carrying capacity for a certain flow condition. At this stage Ceq varies with τ_b in a straight line relation. For a give water depth it can be written

$$C_{eq}=A(\tau_b - \tau_1) \qquad (3)$$

where A is a coefficient and τ_1 the critical shear stress, both depend on the salinity of water and kind of clay mineral. On the right of curve τ_1P, the values of Ceq vary with initial concentration C_0 for a constant flow condition. At this stage there is no marked siltation on the bed. On the bare fiber glass channel bed there could be no exchange between bed load and suspended load. When a large amount of sediment is deposited on the bed, free exchange between suspended load and bed load occurs, thus obtaining the relation as shown by the curve τ_1P.

For clay suspension in the Yangtze Estuary, equilibrium C_{eq} versus differential motor speed Δn between ring and channel is shown in Fig. 6. This could also be seen from Equ. (3). The values A and τ_1 in different salinity mediums are shown in Table 4. Making use of equation (3) , we analysed sediment

Table 4. Value A and τ_1 in Different Salinity Mediums

Salinity	A	τ 1 (dyne / cm^2)
5‰	11.28	0.72
10‰	10.67	0.90
20‰	10.99	0.76
30‰	10.79	0.82

concentration data (average over semitidal period) in Yangtze Estuary during spring or neap tide in both high flow and low flow seasons. Both laboratory test and field data show that equation (3) well discribes the relationship between suspension concentration and bed shear stress.

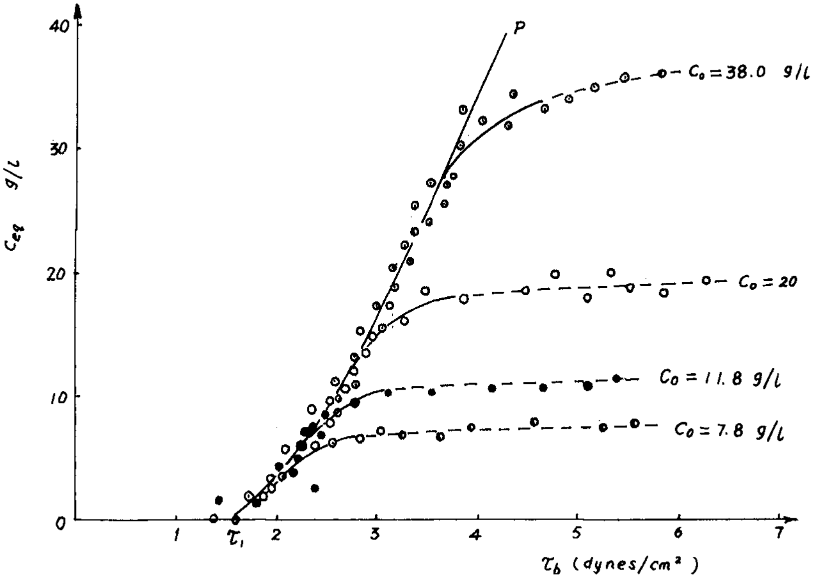

Fig. 5 Equilibrium concentration C_{eq} versus bed shear stress τ_b for kaolinite

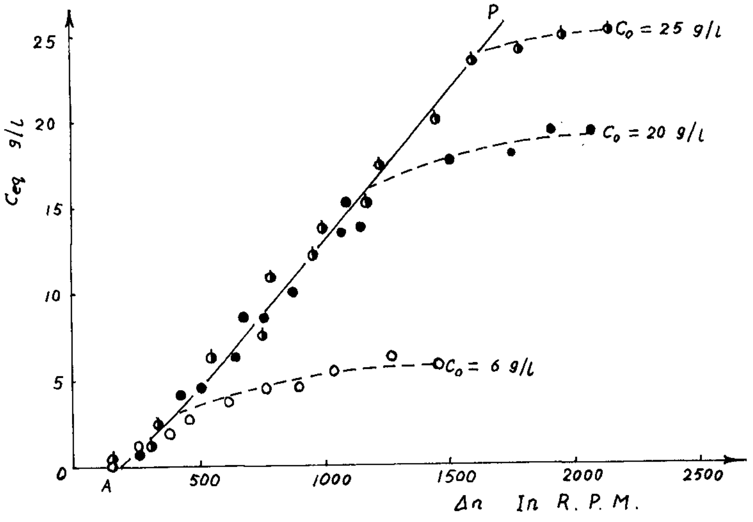

Fig. 6 C_{eq} versus differential motor speed $\triangle n$ between ring and channel for Yangtze Estuary Clay

No matter at which stage, the vertical concentration distribution can be expressed by the diffusion equation (Ren, Ru-shu et al, 1987), from which the setting velocity can be calculated. The curve ω_s versus τ_b can be expressed by equation

$$\omega_s = \omega_0 \exp\left[-b(\tau_b - \tau_1)\right] \qquad (4)$$

ω_0 and b depend on salinity and depth of water and kind of clay mineral. It can be seen that the settling velocity of the flocs decreases exponentially with increase of the bed shear stress, indicating that cohesive sediment is very sensitive to the dynamic actions of flow, as shown in Fig 7. For Yangtze Estuary clay, the settling velocity in turbulent flow is much smaller than that in still water and reduces with increasing bed shear stress, the values ω_0 and b in different salinity water are shown in Table 5.

Table 5 Value ω_0 and b in Different Salinity Mediums

Salinity	ω_0	b
5‰	2.17×10^{-2}	0.63
10‰	3.64×10^{-2}	0.90
20‰	3.45×10^{-2}	0.76
30‰	1.13×10^{-2}	0.46

In order to forecast the dredging amount in navigation channel, which is needed for the planning of regulation works and determining the required capacity of dredging equipment, the depositional behavior of the cohesive sediment in turbulent flow was studied in the annular rotating channel. For a given flow condition, the sediment movement equation can be written as:

$$\frac{\partial(AC)}{\partial(QC)} + \frac{\partial t}{\partial x} + \alpha\beta\omega(C - C_{eq}) = 0 \qquad (5)$$

where A is cross-sectional area, Q is discharge, B is channel width, and α is the probability of sediment siltation. For the annular rotating channel, $x=\bar{v}t$, where $\bar{v}$ is mean velocity, then Equ. (5) can be written as:

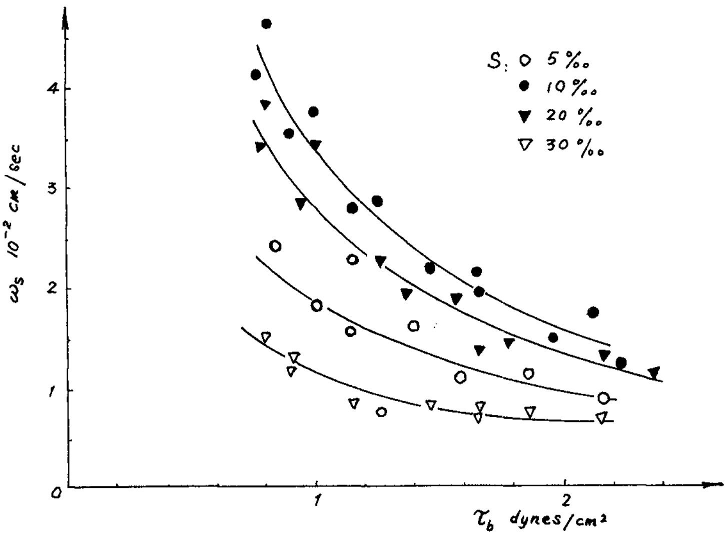

Fig. 7 ω_s versus bed shear stress τ_b (lower layer)

$$2\frac{\partial (HC)}{\partial t} + \alpha\,\omega\,(C - Ceq) = 0 \qquad (6)$$

where H is the water depth, we have

$$C = C_{eq} + (C_0 - C_{eq})\ \exp(-\alpha\,\omega\,t/2H) \qquad (7)$$

where C_{eq} can ω could be calculated by Equ. (3) and Equ. (4). Equ. (7) conforms well to the experimental data.

The siltation thickness p in the navigation channel for steady flow can be obtained from:

$$P = \frac{H}{r_0}(C_0 - C_{eq})\ (1 - \exp(-\alpha\,\omega T_d/2H)) \qquad (8)$$

where r_0 is the dry specific weight of deposited sediment, T_d is the time of current passing through the channle.

For unsteady flow, the thickness p of deposited sediment can be written as:

$$\bar{P} = \beta\frac{H}{r_0}(C_0 - C_{eq})\ (1 - \exp(-\alpha\,\omega T_d/2H)) \qquad (9)$$

where β is a cofficient.

Conclusions

a. The mineral composition and its content are of great importance to the hydrodynamic behaviors of fine cohesive sediment.

b. The transportation of cohesive sediment can generally be divided into three stages. At single valued stage Ceq is independent of C_o.

c. The vertical concentration distribution of sediment can can be expressded by diffusion equation. The settling velocity in turbulent flow is smaller than that in still water.

d. The relation of suspension concentration versus time in turbulent flow can be obtained from tests with an annular rotating channel, formula (7) could be used for calculating the yearly dredging amount.

Apart from the factors mentioned above, there are also many other factors affecting the hydrodynamic behavior of cohesive sediment.

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