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A numerical simulation of suspended sediments flocculation in the estuary*

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Abstract: A steady state numerical model has been developed in order to investigate the behavior of suspended sediments in a partially mixed estuary. The model includes the flocculation process of suspended sediments, that is, suspended sediments change their radius and density in the model. The turbidity maximum of suspended sediments in the middle layer at the central part of the estuary is formed only in the case where the model includes the flocculation precess. The age and residence time of each suspended sediment are also discussed.

1. Introduction

It has been well known that suspended sediments play important roles in the material transport process from the land to the sea. Suspended sediments in the river water usually change their electric property and flocculate to settle in the estuary when they come in contact with saline water. Furthermore they often form the turbidity maximum above the halocline in the estuary. The flocculation and the turbidity maximum of suspended sediments were observed in detail at the St. Lawrence Estuary by KRANCK (1979). FESTA and HANSEN (1978) showed by use of a steady state numerical model that the estuarine dynamics is primarily responsible for the occurrence of the turbidity maximum in partially mixed estuaries. That is, the turbidity maximum is formed at the place where the settling velocity of suspended sediment balances the upward velocity of estuarine circulation. However, their model does not include the flocculation process. As suspended sediments change their settling velocities by the flocculation, it will be interesting to investigate the relation between the formation of turbidity maximum and the flocculation process.

In this paper, we shall show at first the distribution of suspended sediments and their formations of turbidity maxima in the Yoshino River estuary, Japan. Moreover we shall investigate the detailed behavior of suspended sediment in a partially mixed estuary with a Euler-Lagrangian numerical model which includes the flocculation process of suspended sediments.

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2. Field observations

The field observation was carried out at the Yoshino River estuary on 27 May 1980 (Fig. 1). Station 1 in Fig. 1 is situated upstream of the tidal weir and is occupied with only freshwater and Stn. 9 is situated in the sea. The salinity was observed continuously from surface to bottom by a conductivity meter. Water sampling was carried out every 50 cm from surface to bottom with a magnet pump. The concentration of suspended sediments was determined after shipboard filteration through 0.45 μm Millipore filter. Then the size distribution was measured by an Elzone particle counter (Model 190XY, Particle Data Inc.). The results of the observation are shown in Fig. 2. The distribution of salinity is near the weakly mixed state. Turbidity maxima are seen at three regions; one is near the river head, another in the intermediate layer at the central part and the other in the bottom layer at the river mouth. Moreover, large size particles are accumulated in the turbidity maximum regions.

Another observation shows that the tidal changes of such distributions are small because the maximum tidal range is only 1.0 m at the

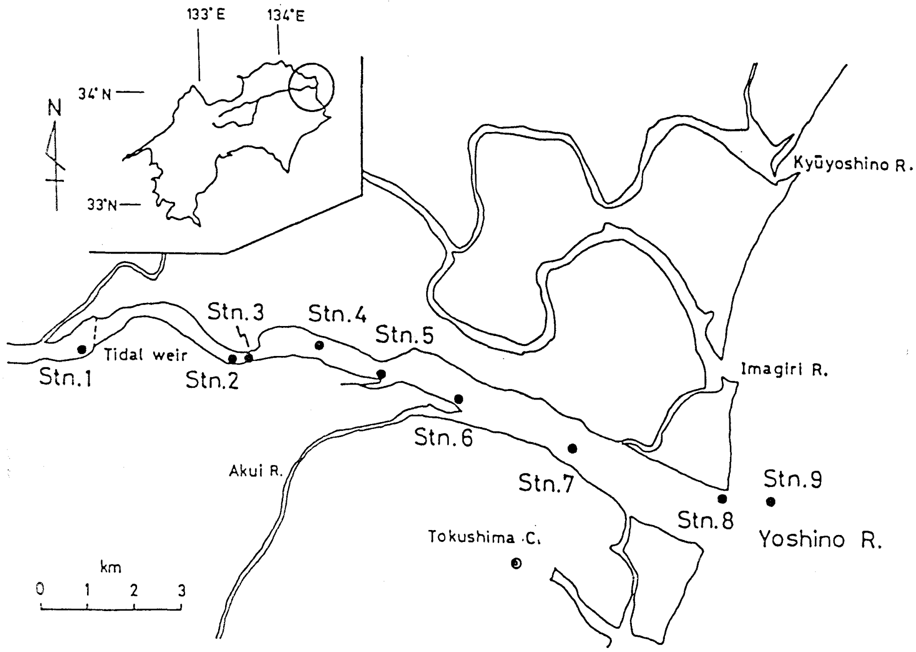

Fig. 1. Map of the Yoshino River estuary.

river mouth (HONDA *et al.*, 1985). Therefore, such distributions of salinity and suspended sediments can be considered as in quasi-steady state.

We try to reproduce two turbidity maxima near the river head and at the central part of the estuary in a numerical model because they should play important roles in the material transport from the land to the sea. The turbidity maximum at the river mouth is considered to be formed by the sea-born suspended sediments.

3. Numerical model experiment

Here we try to develop a numerical model to investigate the behavior of suspended sediments in the estuary. The present study is concerned with not only the Lagrangian behaviors of suspended sediments but also the Eulerian concentration distributions, so that the method of Euler-Lagrangian numerical model (YANAGI and OKAMOTO, 1984) is used. Such approach is suitable for studying the flocculation, deflocculation and absorption processes of pollutants in the estuary. Here the partially mixed state estuary is dealt with in order to study the flocculation process, because it is the intermediate state between the strongly mixed and weakly mixed states.

3.1. Salinity and velocity distributions

A steady state, two-dimensional, laterally homogeneous estuary is set up. The co-ordinate system is Cartesian in x and z, where z is positive downward from the water surface and x increases from the river head toward the sea. A linear equation of state is assumed,

$$\rho=\rho_f(1+\delta S)\,, \qquad (1)$$

where ρ is the density of water, ρ_f the density of freshwater, δ the coefficient of salt contraction and S the salinity. The horizontal momentum balance, continuity of flow and concentration of salinity with use of the Boussinesq approximation are given by

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial P}{\partial x}+A_h\frac{\partial^2 u}{\partial x^2}+A_v\frac{\partial^2 u}{\partial z^2}, \qquad (2)$$

$$\frac{\partial u}{\partial x}+\frac{\partial w}{\partial z^2}=0, \qquad (3)$$

$$P=g\int_0^z \rho dz, \qquad (4)$$

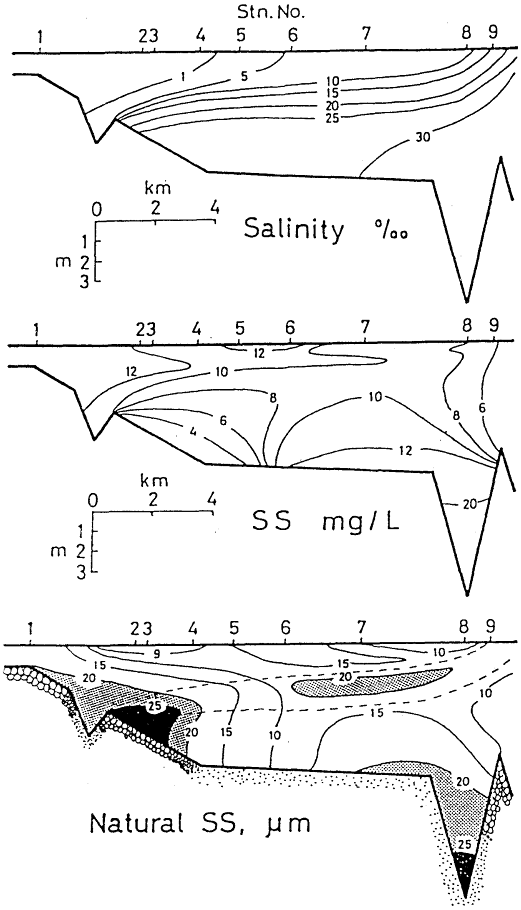

Fig. 2. The longitudinal vertical distributions of salinity (top), mass of suspended sediments (middle) and mode of grain diameter of suspended sediments (bottom) in the Yoshino River estuary on May 27, 1980.

$$\bar{\rho}=\frac{1}{H}\int_0^H \rho dz, \tag{5}$$

$$\frac{\partial S}{\partial t}+u\frac{\partial S}{\partial x}+w\frac{\partial S}{\partial z}=K_h\frac{\partial^2 S}{\partial x^2}+K_v\frac{\partial^2 S}{\partial z^2}. \tag{6}$$

Here u and w are the horizontal and vertical components of velocity, respectively, $\bar{\rho}$ the vertically average density, P the hydrostatically reduced pressure, H the depth, A_h, A_v and K_h, K_v the horizontal and vertical exchange coefficients of momentum and salt, respectively, and g the gravitational acceleration. Tidal fluctuations have been averaged out, while the tides are considered to be the primary source of energy for turbulent mixing. The exchange coefficients are, therefore, a measure of the strength of tidal mixing. For simplicity, these coefficients are chosen to be constant as tabulated in Table 1. The magnitude of each coefficient is within commonly used one. It is confirmed that the principal results of the numerical experiments are not sensible to small changes in their magnitudes.

Table 1. Parameters used in the numerical model.

ρ_f:	1.0	g :	980 cm sec^{-2}
δ :	7.75×10^{-4} ‰$^{-1}$	μ :	0.0115 cm^2 sec^{-1}
Ah:	10^4 cm^2 sec^{-1}	U_f:	50 cm sec^{-1}
A_v:	5 cm^2 sec^{-1}	S_B:	30 ‰
K_h:	10^4 cm^2 sec^{-1}	$H_{\max}$:	6 m
K_v:	1 cm^2 sec^{-1}	L:	12 km
D_h:	10^3 cm^2 sec^{-1}	α:	0.01 ‰$^{-1}$ sec^{-1}
D_v:	0.1 cm^2 sec^{-1}		

The boundary conditions to be satisfied at the river head, which is occupied with only the freshwater, are zero salinity and the constant river flow U_f. At the bottom boundary, the no-slip condition and zero vertical flux of salt are specified. At the top boundary, the slip condition and zero vertical flux of salt are specified. These are expressed by

$$S=0,\ u=U_f \quad \text{at} \quad x=0 \text{ and } z=0, \tag{7}$$

$$\frac{\partial S}{\partial z}=0,\ \frac{\partial u}{\partial z}=0 \quad \text{at} \quad z=0, \tag{8}$$

$$\frac{\partial S}{\partial z}=0,\ u=0 \quad \text{at} \quad z=H. \tag{9}$$

The remaining boundary conditions to be specified are those at the mouth of the estuary. The salinity at the bottom of the seaward boundary is fixed to be S_B and horizontal diffusive fluxes of salt and momentum are required to be constant, but unspecified after FESTA and HANSEN (1976). These are expressed by

$$S=S_B \quad \text{at} \quad x=L \text{ and } z=H, \tag{10}$$

$$\frac{\partial^2 S}{\partial x^2}=0,\ \frac{\partial^2 u}{\partial x^2}=0 \quad \text{at} \quad x=L. \tag{11}$$

Here L is the length of the estuary and is 12 km in this case. The maximum depth H_{max} is 6 m. Equations (2) and (6) are approximated by finite difference with a time step of 10 seconds

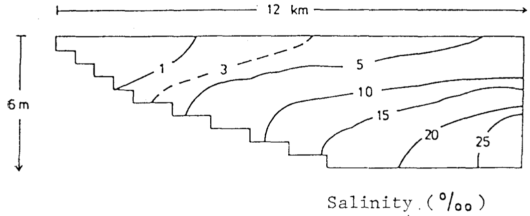

Fig. 3. Calculated salinity distribution in the numerical model.

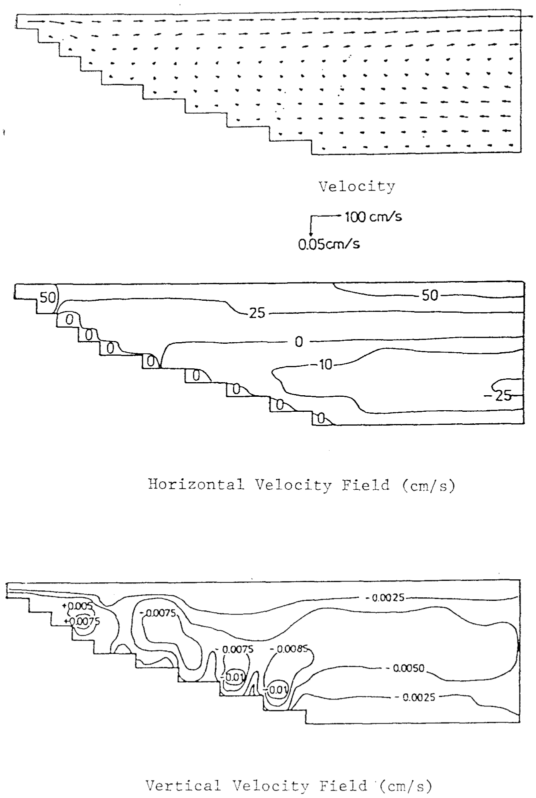

Fig. 4. Calculated velocity distributions in the numerical model.

and a grid size of $\Delta x=500$ m and $\Delta z=60$ cm and are solved by the primitive method with boundary conditions (7) to (11). The initial conditions are set up in such a way that the salinity, horizontal and vertical velocities are zero throughout the area. We considered that the steady state was achieved when the time change rate become less than 1 % in magnitude of other terms in Eq. (2). The partially mixed state is reproduced as shown in Fig. 3 and the gravitational circulation pattern is reproduced as shown in Fig. 4.

3.2. Suspended sediments behavior

Some assumptions are needed to study such complex phenomenon as suspended sediments flocculation in the estuary. It is assumed that 1) suspended sediments are composed of many elementary particles with their own radius and density, 2) the principle of superposition for the movement of each particle due to the gravitational circulation, their own settling velocity and the turbulence is valid, and 3) resuspension of settled suspended sediments from the bottom is not considered. The movement of a labeled particle is traced. Imagine that a labeled particle exists at a point (x^n, z^n) at time n. Position of the labeled particle (x^{n+1}, z^{n+1}) at time $n+1$, Δt time after, is traced by the following formula,

$$x^{n+1}=x^n+u(x^n, z^n)\cdot\Delta t+R_x, \qquad (12)$$

$$z^{n+1}=z^n+[w(x^n, z^n)+w_s(\rho^n, r^n)]\cdot\Delta t+R_z, \qquad (13)$$

where R_x and R_z are the movements due to the turbulence in x and z direction, respectively. The original Lagrangian expression for tracing the particle has more terms than Eqs. (12) and (13), but the spatial gradient terms of velocity are neglected because the velocity field is steady and the time step used for calculation is too short to "feel" critically the spatial gradients of velocity. Horizontal velocity $u(x^n, z^n)$ and vertical velocity $w(x^n, z^n)$ are interpolated from Eulerian velocities at four grid points surrounding the particle.

The dispersion coefficients D_h and D_v for suspended sediments are defined by the time derivative of the variance of positions of suspended sediments as follows,

$$D_h=\frac{1}{2}\frac{dx^2}{dt}, \quad D_v=\frac{1}{2}\frac{dz^2}{dt}. \qquad (14)$$

Therefore, the movements of suspended sediments due to the turbulence are given by the following equations,

$$R_x=\gamma_x\times\sqrt{2\times\Delta t\times D_h}, \qquad (15)$$

$$R_z=\gamma_z\times\sqrt{2\times\Delta t\times D_v}. \qquad (16)$$

Here γ_x and γ_z denote the random numbers whose mean values are zero and whose variances are 1.0. ρ^n and r^n are the density and radius of the particle, respectively. $w_s(\rho^n, r^n)$ denotes the settling velocity of the particle itself given by Stokes' law,

$$w_s(\rho^n, r^n)=\frac{2}{9}g\,\frac{\rho^n-\rho}{\mu}r^{n2}, \qquad (17)$$

where ρ and μ are the density and viscosity, respectively, of the surrounding water. The flocculation process is formulated by KRANCK (1973) as follows,

$$r^n(t, s)=r_\infty-(r_\infty-r_0)e^{-\alpha st}, \qquad (18)$$

where r_0 denotes the grain radius of original particle and r_∞ that of flocculated particle related by

$$r_\infty=2.80\times r_0^{0.772}, \qquad (19)$$

and α is a numerical constant determined to complete the flocculation process in half an hour with a salinity of 3‰ after an experiment by KRANCK (1973). When the elementary particles aggregate to the flocculated particles, its density decreases due to water contained in the flocculate. The change of particle density by the flocculation is given, in analogy of radius increasing, by

$$\rho^n(t, s)=\rho_\infty+(\rho_0-\rho_\infty)e^{-\alpha st}, \qquad (20)$$

where ρ_0 denotes the density of the original particle and ρ_∞ that of flocculated particle related by

$$\rho_\infty=\frac{\frac{4}{3}\pi r_0{}^2\rho_0{}^3+\frac{4}{3}\pi(r_\infty{}^3-r_0{}^3)\rho}{\frac{4}{3}\pi r_\infty{}^3}=(\rho_0-1)\left(\frac{r_0}{r_\infty}\right)^3+1, \qquad (21)$$

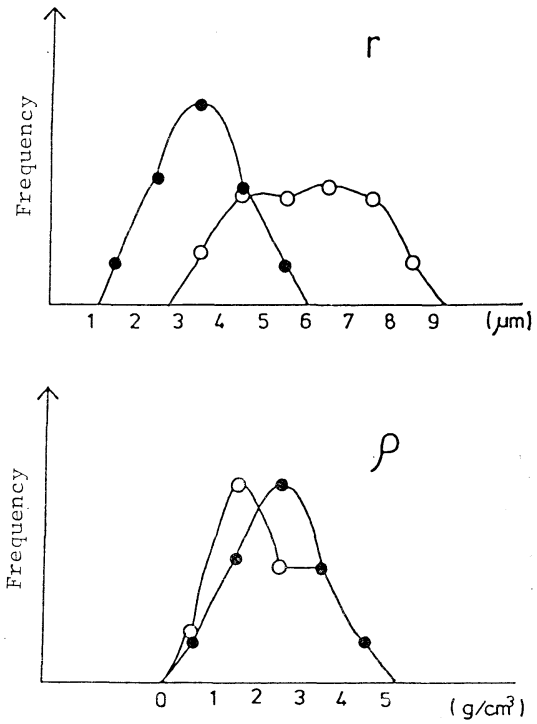

Fig. 5. Grain radius (r) and density (ρ) distributions of particles injected at the river head (solid circle) and those flown out of the estuary or settled down to the bottom (open circle) in Case III.

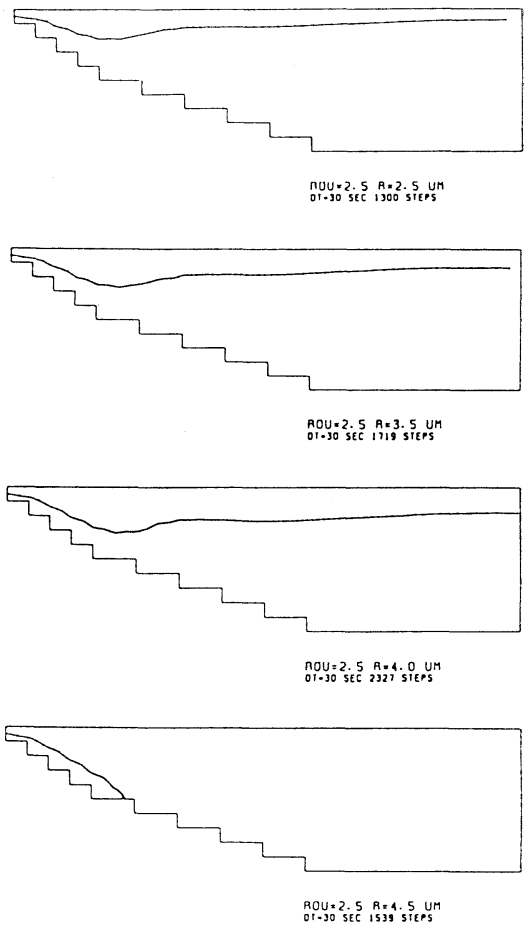

Fig. 6. Loci of particles with a constant density of 2.5 g cm^{-3} and variable grain radius of 2.5 to 4.5 μm (top to bottom) without the flocculation process.

where ρ is 1.0.

The original grain radius and density distributions of injected particles at the river head are shown in Fig. 5. The modes of grain radius and density of the original particles are 3.5 μm and 2.5 g cm^{-3}, respectively. The time step Δt for tracing each particle is 30 seconds, which is chosen from the viewpoint that it will take more than twenty time steps at least for a particle to pass through one mesh.

3.3. *Results*

Some examples of particle movement with fixed density, variable grain radius and without the flocculation process and turbulence are shown in Fig. 6. Small particles flow out of the estuary in 10–14 hours, because their settling velocities are smaller than the water upwelling velocity in the estuary. On the other hand, large particle settles down near the river head in 12 hours, because its settling velocity is larger than the water upwelling velocity there. If the flocculation process is introduced in the model, a particle with a moderate grain radius, flowing out of the estuary without the flocculation process, can settle down to the bottom in 22 hours as shown in Fig. 7.

Fifty particles are successively injected at each time step from the river head. The grain radiuses and densities are determined by random selection from the normal distributions (Fig. 5) and the steady state distribution is obtained.

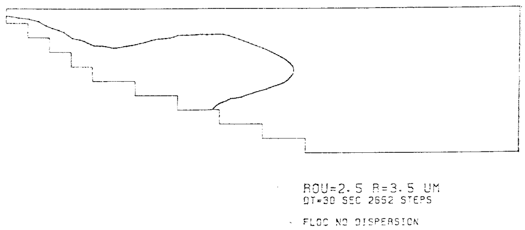

Fig. 7. Locus of a particle with an original grain radius of 3.5 μm and a constant density of 2.5 g cm^{-3} with the flocculation process of grain radius increasing only.

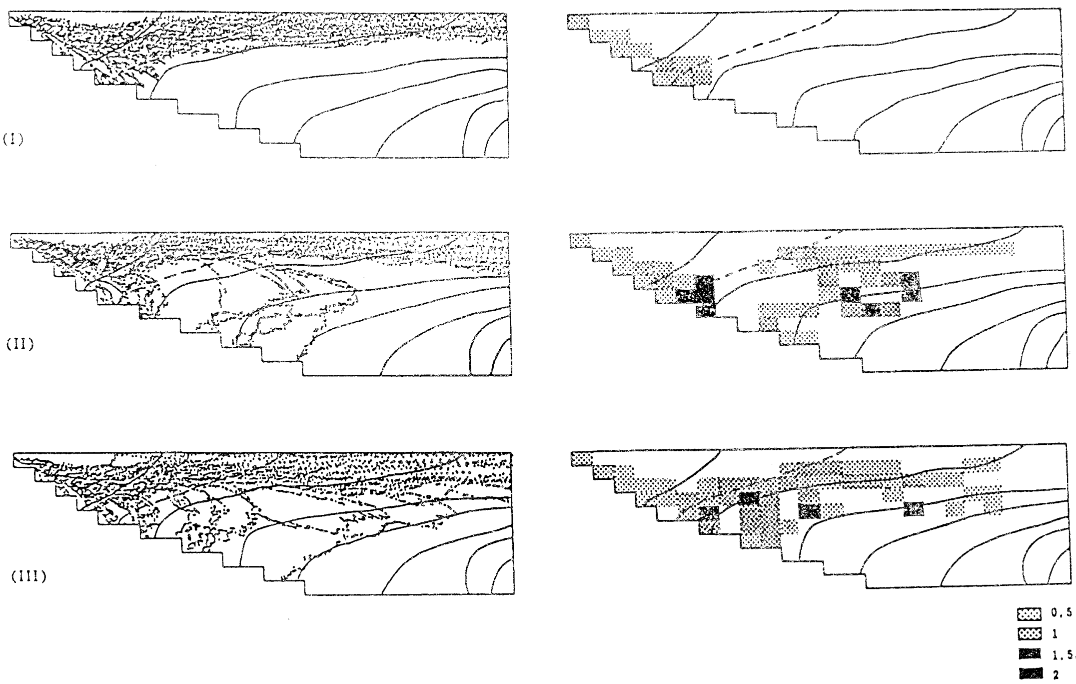

Fig. 8. Distributions of particle position (left) and normalized mass concentration (right) of suspended sediments in the case of no flocculation (Case I), the case of grain radius increasing only (Case II) and the case of grain radius increasing plus density decreasing (Case III).

The upper panel in Fig. 8 shows the distributions of particle position (left) and mass of suspended sediments (right), which is calculated by using particle's density and grain radius and is normalized to that at the river head mesh, in the case of no flocculation process (Case I). There is one turbidity maximum in the lower layer near the river head but no turbidity maximum in the intermediate layer at the central part of the estuary in Case I. The turbidity maximum in Case I is formed due to the balance of settling velocity of suspended sediments and the upward velocity of estuarine circulation which was already shown by FESTA and HANSEN (1987). When the flocculation process of grain radius increasing only is introduced in the model (Case II), the turbidity maxima are formed in the lower layer near the river head and in the intermediate layer at the central part of the estuary as shown in the middle panel of Fig. 8. Moreover, when the flocculation process of grain radius increasing and density decreasing are introduced in the model (Case III), the position of turbidity maximum at the central part of the estuary slightly shifts to the downstream of the estuary as shown in the lower panel of Fig. 8. The grain radius distribution of suspended sediments in Case III is shown in Fig. 9. Largest particles are seen in the lower layer near the river head and particles larger than ca. 14 μm in diameter are seen in the intermediate layer at the central part of the estuary. Comparing with Figs. 2, 8 and 9, the numerical experiment well reproduces qualitatively the results of field observation except the turbidity maximum in the lower layer near the river mouth. The turbidity maximum in the lower layer near the river mouth is formed by the sea-born suspended sediments which are not included in the model.

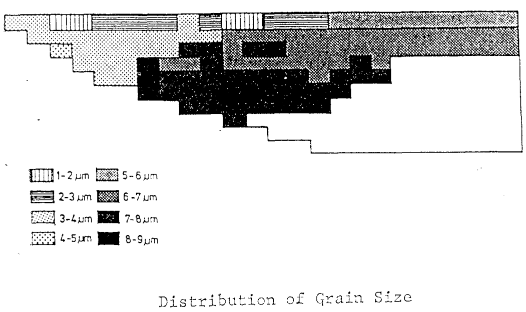

Fig. 9. Distribution of grain radius of suspended sediments in Case III.

4. Discussions

The turbidity maxima of suspended sediments in a partially mixed estuary are successively reproduced by use of an Euler-Lagrangian numerical model, which enables us to trace each particle and to investigate the time change of some properties of each particle. If chemical problems such as heavy metal behavior in the estuary are concerned with, this Euler-Lagrangian model will be more useful. In such cases the age and residence time of each particle will be important parameters (TAKEOKA, 1984). The distribution of age of particle (the elapse time from the injection) at the river head is shown in the upper panel of Fig. 10. The distribution of residence time of particle (the expected time in which the particle flows out of the estuary or settle down to the bottom) is shown in the lower panel of Fig. 10. They are in Case III. The particles in the intermediate layer at the central part of the estuary have long age and long residence time. The complex chemical or biological processes, which will take long time, may be carried out over the particles which have long age or long residence time. Such chemical and biological problems will be investi-

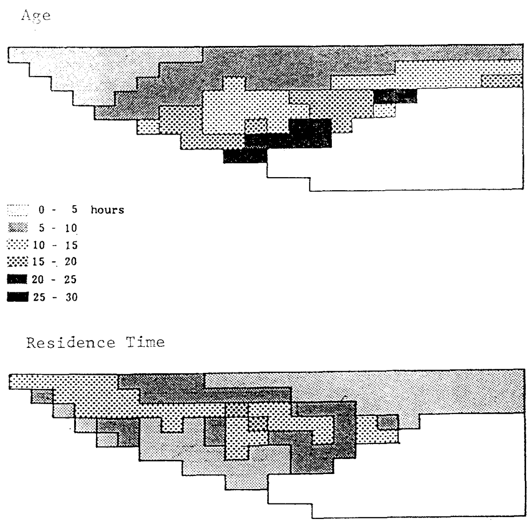

Fig. 10. Distributions of age of particles (top) and residence time of particles (bottom) in Case III.

gated by use of the present Euler-Lagrangian model in the near future.

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河口域における懸濁粒子のフロキュレーションの数値実験

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要旨: 緩混合の河口域における懸濁粒子の挙動を調べるための数値モデルを開発した。数値モデル内で懸濁粒子はフロキュレーションを起す。すなわち懸濁粒子の直径と密度は時間的に変化する。観測された河口域の中央部中層における濁度極大は,数値モデル内にフロキュレーション過程を取り入れた時のみ再現された。個々の懸濁粒子の年令と滞留時間に関する議論も行った。