Experimental Investigation on the Settling Properties of Muds

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SUMMARY

The settling properties of sea bed sediments were investigated experimentally to clarify the mechanism and process of the formation of tideland. The settling phenomenon of the sea bed sediments was considered to be affected by the type of sediments, the concentration of suspended sediments (SS), the salinity and the physio-chemical composition of sea water.

In this paper the settling and deposition of the sea bed sediments in the quiescent sea water were examined in the laboratory. The sea bed sediments and sea water tested were collected on the near shore region in the Ariake sea.

According to the experiment, the settling curve and settling velocity were affected significantly by the type of the sediment and sediment concentration, while being not much affected by the salinity in the range of 1.7%-7.5%. The flocculation and the hindered settling were considered to play an important role in the settling of sea bed sediments. Furthermore the relationship between interface settling velocities and particle sizes were expressed by a power-law equation.

Key word: deposition, flocculation, hindered settling, sea water, sediment, segregation, settling velocity, suspended sediments (SS)

INTRODUCTION

The most characteristic features of the shallow sea region are exhibited by cohesive sediment spreading over the region close to shore. At low tide, vast tidelands are exposed along the coastal and regions close to shore. The tideland sediments are suspended by current and wave agitation. The suspended sediment of transported by tidal waters and drain systems has commonly gone through physical, chemical, and biological processes such as flocculation, settling, deposition, consolidation, scour resuspension, and decomposition. Since these multi-dependency relationships have complicated structures, a clear explanation has not been given, but there have considerable practical importance.[1, 2, 3, 4]

In intense sea water conditions, the transport process of sea bed sediments is cyclic. In calm sea conditions, the current velocity reduces sufficiently to allow for settlement, thus the transported sediments deposit and accumulate on the sea bottom. This results in the gradual acceleration of tidelands growth.

The growth of tidelands leads to a number consequences both favorable and unfavor-

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able. These positive consequences include movement of organic matter, provision of nutrients, control of water quality, maintenance of a drain system, and preservation of the balance of the aquatic ecosystem. Negative consequences include the accumulation of pollutants and the siltation of harbor entrance, all of which are affected by transport circulation in the shallow sea region. Therefore, the nature of settling and recognition of the settling properties of sea bed sediment is of great practical and theoretical importance to comprehend deposition state and resuspension behaviour in hydraulic and coastal engineering.

Many attempts have been made to provide theoretical approximations, and a great deal of attention has been given to developing and comparing formulae for settling properties such as Kynch's and Two-phase flow Theory et al.[5, 6, 7] Measurement of laboratory experiments have been reported by Work & Kohler[8], Michaels & Bolgar[9], and Been[10]. However, the settling properties are believed to be affected by a number of complicated factors, such as the type and size of sediment, the concentration of SS, the salinity, and the physio-chemical composition of sea water. These properties make it difficult to present the relationships among the characteristics of flow, the settling velocity, and the particle size. Thus, a reliable clarification of the settling phenomenon of sea bed sediments has not been made at present.

Therefore, in these experiments the settling properties of sea bed sediment at rest in sea water was investigated in the laboratory. The results obtained are discussed to present the relationships among settling velocity, sediment particle size, and concentration of suspended sediments.

EXPERIMENT

The sea water on the estuary or bay greatly fluctuate according to the role of water current and wind. Water current velocity shows a range from zero at slack water to high during the intermediate periods on the shallow sea area. The sea bed sediments undergo a physio- chemical process involving suspension, transport, settling, resuspension, deposition, scouring, and decomposition. These relationships are plotted in Fig.1. The settling and deposition of sea bed sediments during high or low tide are considered to be predomi-

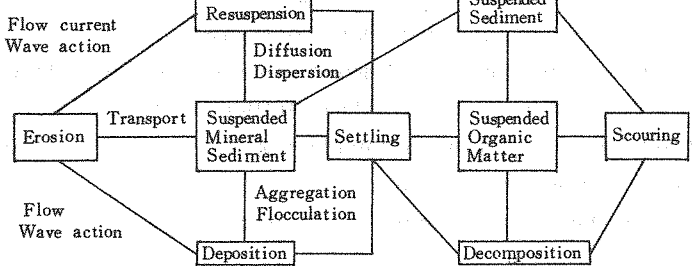

Fig. 1 General model structure of physio-chemical process.

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The purpose of the experiments, settling in idealized and controlled conditions, was to quantitatively measure the flow and transport characteristics of bed sediments in a shallow sea area. Their values in solving engineering problems depend on how well they represent the state of materials in the field. When used with the field conditions taken into consideration, the laboratory test methods can be very valuable.

SAMPLE.- Fig. 2 shows the bottom topography and location of sampling stations in the Ariake sea. The depth of sea water is takes into account mean depth at the high tide. Sea bed sediment from station A was obtained beneath the water with a dredger. The other three station samples of the top 5cm of sediment (for physio-chemical and sediment size analysis) and surface sea water were taken. The predominant materials from Station A on the estuary region were the sand and silt materials. Those of the other three stations (B, C, and D) were predominantly silt material. All of them were collected in the near shore region with a mean depth of 200cm in the Ariake sea.

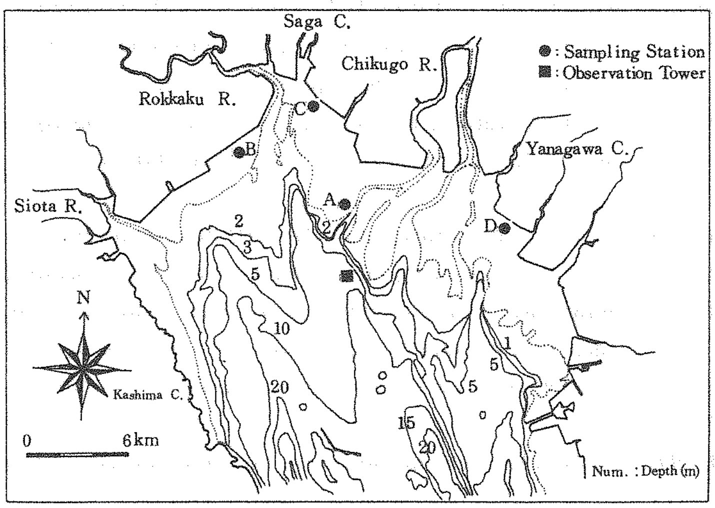

Fig. 2 Bottom topography and location of sampling stations in the Ariake sea.

Table 1 Physical characteristic and sediment size distribution

Sample	G_s	ω (%)	Sand	Silt	Clay	D_{16}	D_{50}	D_{84}	D_m	L.L	P.L	I.L
A	2.60	56.63	69.9	14.7	15.4	6	149	253	187	32.2	—	- -
B	2.60	305.11	0.2	68.4	31.4	0	18	44	31	106	52.0	10.6
C	2.63	271.33	0.2	69.5	30.3	1	23	61	41	110	51.1	10.9
D	2.60	310.65	0.8	61.7	37.5	0	14	46	29	106	49.6	10.1

G_s: Gravity, ω(%): Water content, Sand(%), Silt(%), Clay(%), D_{16}(μm): 16% of the particles are smaller than that size, D_{50}(μm): Middle particle size, D_{84}(μm): 84% of the particles are smaller than that size, D_m(μm): Mean parcicle size, L.L: Liquid limit, P. L: Plastic limit, I. L(%): Ignition loss

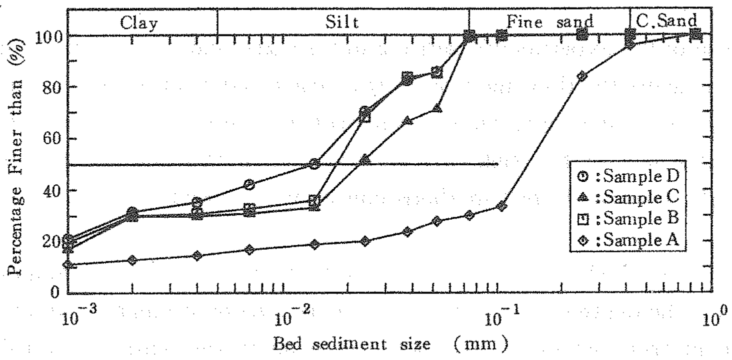

Fig. 3 Bed sediment size distribution.

The distribution curves of bed sediment size are plotted in Fig. 3. A summary of their physio-chemical characteristics and the distribution of bed sediment size is shown in Table 1. The curves of sea bed sediments along the estuary and near shore region show not uniform but different distribution respectively. As for the distribution of bed sediment and the physio-chemical characteristics, station B, C, and D have shown similar features, while station A showed different characteristics. Significant differences are due to geological reasons and the flow characteristic on the deposition surface. In order to investigate representative properties in the future, we focused our attention primarily on station A and C sediments. The experimental values are summarized in Table 2.

APPARATUS.- A schematic drawing of the settling column is shown in Fig. 4(a). The settling column, with the measuring device built as a trial, consists of a cylindrical acrylic column 200cm long with an inside diameter of 10cm. Sampling taps were prepared on the outside wall of the settling column at given points (at distances of 5cm, 15cm, 30cm, 70cm, 110cm, 150cm, and 190cm from the bottom of the settling column).

PROCEDURE.- A detailed description of the experimental procedure is available as

Table 2 Experimental values

Sample	Soil weight (g)	Salinity (%)	Water gravity	pH	Tem. (°C)
A	300	4.4	1.036	7.5	20
B	300	4.4	1.036	7.5	20
C-1	100	4.2	1.035	7.5	20
C-2	300	1.7	1.017	7.5	20
C-3	300	3.0	1.025	7.5	20
C-4	300	4.4	1.036	7.5	20
C-5	300	5.0	1.041	7.5	20
C-6	300	7.5	1.060	7.5	20
C-7	500	4.2	1.035	7.5	20
D	300	4.4	1.036	7.5	20

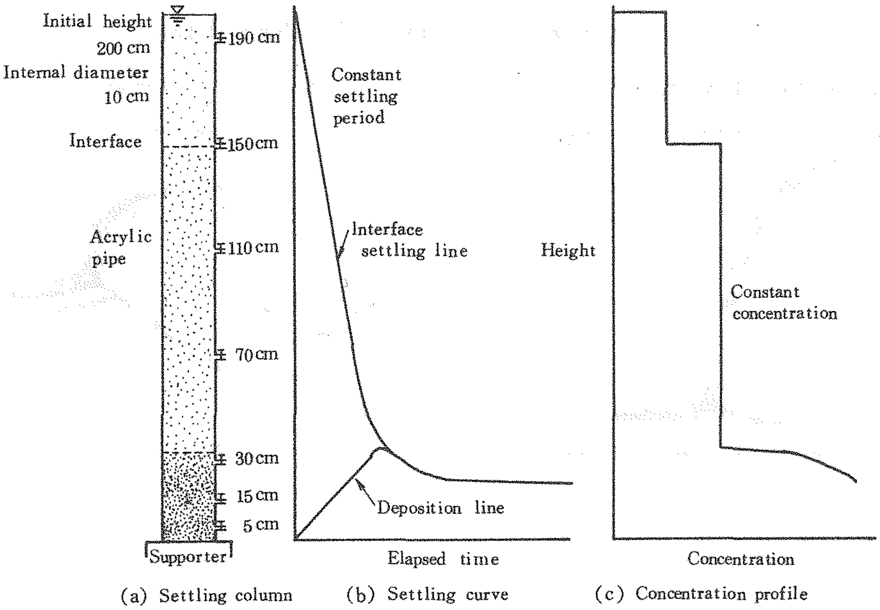

Fig. 4 Schematic drawing of settling column-settling curve-concentration profile.

follows; Four sea bed sediments were sampled from specific stations in the Ariake sea basin. Sampled sediments were natural-air-dried and sieved through a 0.425mm sieve to get rid of second source particles, trash, and other materials. Next, sea water with preselected salinity was added to the sieved-sample which prepared the unit weight of sediments. These mixtures were well stirred for an hour in a Maruto Blender. Next, we poured the agitated sample into a container filled with controlled water. The sample was mixed for 5 minutes by hand just before being poured into the settling column. The experiment started as the mean concentration of SS was determined. The top of the settling column was opened to introduce dispersion mixture. In making the run, the sample was poured into the settling column. A series of settling tests was run twice for each concentration. For one, the movement of an interfacial plane between the solid and water was read and a photograph taken at a specified time. For the other, small samples of mixture were extracted by a sampling tap, which is located on the outside wall of the settling column at a given height. In these experiments, the final settling state was defined as the time after 7200 minutes had elapsed. The particle size analysis for extracted samples was conducted by the Micronphoto Sizer and Centrifuge Methods, and the concentration of SS measured by the Filtration Method. Careful handling was required in conducting the particle size analysis because the flocculated sample requires as little disturbance and damage as possible to analyze particle size accurately. Sedimentation data were obtained in a 20°C constant temperature room.

ANALYSIS OF EXPERIMENTAL RESULTS.

SETTLING CURVE.- The settling process was studied by observation of the inter-

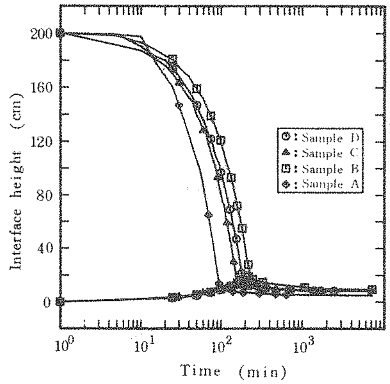

Fig. 5 Settling curve for sampling station difference.

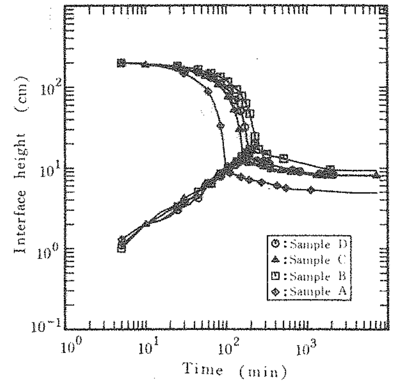

Fig. 8 Logarithmic plot of settling curve as a function of sampling station.

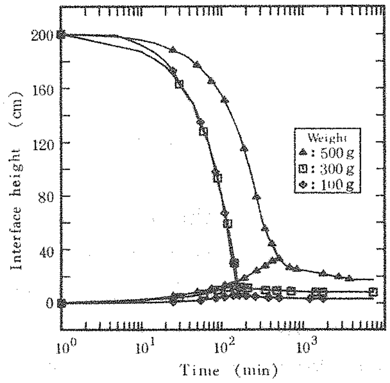

Fig. 6 Settling curve for initial weight difference at station C sediment.

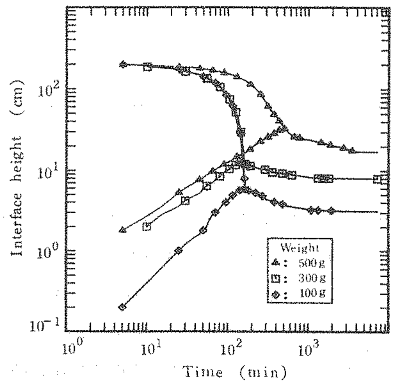

Fig. 9 Logarithmic plot of settling curve as a function of initial weight.

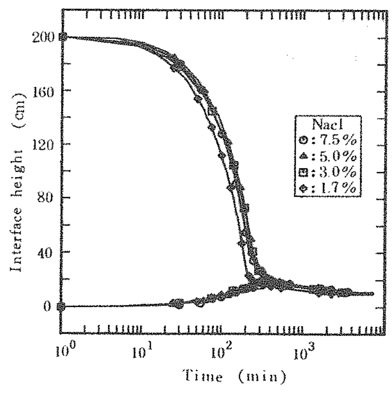

Fig. 7 Settling curve for salinity difference at station C sediment.

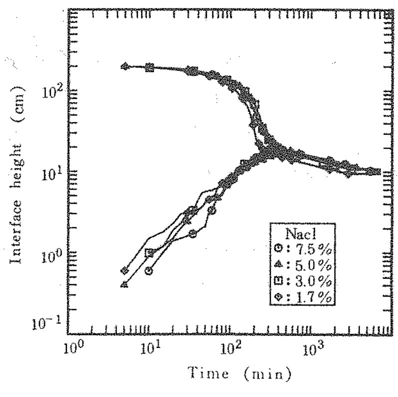

Fig. 10 Logarithmic plot of settling curve as a function of salinity at station C.

face changes as well as the amount of concentration. The interface reading was taken continuously until the final settling was virtually complete. The settling tests were run on natural-air-dried sediments at three unit weight of dried-sediments (ranging from 100g -500g) and four salinities (ranging from approx. 1.7-7.5% Nacl) with fixed height, 200cm. For all of the tests, because of the frequency of the readings and regularity of the interface settling, the settling velocity was determined by plotting the height of interface at a certain time. The one-dimensional settling phenomenon progressed as described in Fig. 4. The typical settling curve illustrated by Fig. 4(b) shows the process of settling and deposition.

As time passes, on the upper part, the supernatant water fraction increases and interface falls at a constant speed, while on the other, the deposition of sediments increases toward a specific settling volume. These relationships are represented by two lines. The upper line, which begins to decline with a constant settling velocity, indicates a plane of interface settling in the initial stage. The lower line represents a depositional plane of the sediments on the bottom of the settling column. Two lines join near the end point of the constant settling period, and join after the settling velocity is rapidly reduced. These represent consolidation periods. To easily understand the constant settling period, the experimental results are expressed by semilogarithmic plots, as in Fig. 5 to 7. Fig. 5 shows four settling curves concerning four sediments, in which the initial salinity and unit weight of solids is held constant. Fig. 6 illustrates the settling height-time behavior compared to the relationship of slopes on the three settling curves of station C sediment. Fig. 7 presents four curves which have different initial salinities for the settling of station C sediment. These expressions would not be represented by any relationship commonly available to consolidation periods.

In usual consolidation period, the relationships were obtained by logarithmic plots as Fig. 8 to 10. The relationship between interface height and time shows that the slope changes rapidly with the lapse of time and then reaches inflection point. Thereafter a gentle slope line results. This behavior refers to a steep slope part as a constant settling period in the early part of settling and to a gentle slope part as a consolidation period in the latter part of settling, respectively. There is no theoretical equation, but any empirical equation such as the 3 or 4 order of polynomial equation can be used;

$$y = a_0 + a_1x^1 + a_2x^2 + \cdots + a_nx^n \tag{1}$$

in which y is interface height (cm), x is the elapsed time (min), n is the order of regression, and a, n are empirical parameters. The values of the two empirical parameters (a and n) obtained by regression analysis for each samples are presented in Table 3, which include the functional relationships and the values for correlation coefficients.

SETTLING VELOCITY OF INTERFACE SETTLEMENT.- Generally, the equation of settling velocity is obtained by the slope of the height-time curve at any point. Empirical relations for sea bed sediments were plotted as log settling velocity against log elapsed time in Fig. 11 to 13. In all of the cases, all initial settling and accumulating velocities maintain constant settling and accumulating rates within initially finite time. This

Table 3 Relationships between interface height and time.

Sample	Settling Part Height ($y=x/y$) vs. Time($x=x$)						
	n	a_0	a_1	a_2	a_3	a_4	γ
A	3	-8.06	0.19	9.38×10^{-6}	-9.38×10^{-10}	—	0.99
B	4	-4.03	0.05	5.54×10^{-5}	-1.64×10^{-8}	1.35×10^{-12}	0.99
C-1	4	-16.82	0.25	8.79×10^{-5}	-3.00×10^{-8}	2.65×10^{-12}	0.99
C-2	4	-3.77	0.06	3.01×10^{-5}	-6.39×10^{-9}	4.26×10^{-13}	0.99
C-3	4	-4.00	0.05	2.75×10^{-5}	-5.79×10^{-9}	3.83×10^{-13}	0.99
C-4	4	-6.62	0.11	2.15×10^{-5}	-7.96×10^{-9}	7.28×10^{-13}	0.99
C-5	4	-3.89	0.05	1.68×10^{-5}	-2.03×10^{-9}	6.68×10^{-9}	0.99
C-6	3	-4.52	0.06	1.29×10^{-5}	-9.78×10^{-10}	—	0.99
C-7	4	-2.59	0.03	1.35×10^{-5}	-2.02×10^{-9}	9.65×10^{-14}	0.99
D	4	-6.80	0.10	2.71×10^{-5}	-8.33×10^{-9}	6.99×10^{-13}	0.99

Sample	Accumulating Part Height($y=x/y$) vs. Time($x=x$)						
	n	a_0	a_1	a_2	a_3	a_4	γ
A	4	-1.48	0.16	3.42×10^{-5}	-8.12×10^{-9}	5.92×10^{-13}	0.99
B	4	5.58	0.03	7.66×10^{-5}	-2.22×10^{-8}	1.82×10^{-12}	0.99
C-1	4	10.01	0.15	1.89×10^{-4}	-6.20×10^{-8}	5.41×10^{-12}	0.99
C-2	4	8.05	0.03	5.44×10^{-5}	-1.23×10^{-8}	8.62×10^{-13}	0.99
C-3	4	8.69	0.02	4.75×10^{-5}	-1.04×10^{-8}	7.23×10^{-13}	0.99
C-4	4	1.71	0.08	4.76×10^{-5}	-1.60×10^{-8}	1.42×10^{-12}	0.99
C-5	4	10.54	0.02	3.82×10^{-5}	-6.91×10^{-9}	4.17×10^{-13}	0.99
C-6	4	11.85	0.02	3.59×10^{-5}	-5.76×10^{-9}	3.19×10^{-13}	0.99
C-7	4	10.94	0.003	3.17×10^{-5}	-6.18×10^{-9}	3.96×10^{-13}	0.99
D	4	2.93	0.07	5.02×10^{-5}	-1.48×10^{-8}	1.22×10^{-12}	0.99

shows a horizontally constant linear mode as constant settling and accumulating rate at logarithmic plot. When more time elapses, the settling and accumulating velocity reaches an inflection point, and thereafter interface settling and accumulating velocity gradually decreases with the lapse of time. The shape of the interface settling or accumulating velocity-time curves suggest that the settling and accumulating velocity is a polynomial equation as a function of time. For the Ariake sea bed sediments, the settling and accumulating velocity were found to be correlated with time, the relations being given by

$$y=a_0+a_1x^1+a_2x^2+\cdots+a_nx^n \quad (2)$$

in which y is the velocity of interface settling and accumulation (cm/min), x is the elapsed time (min), and a, n are empirical parameters as functions of salinity as well as concentration of SS. These functions for experimental conditions and values for correlation coefficients are tabulated (Table 4).

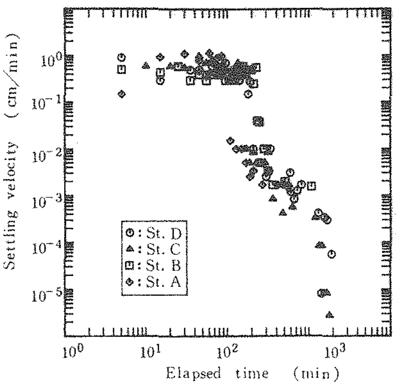

Fig. 11 Plot of settling velocity vs. height for sampling station difference.

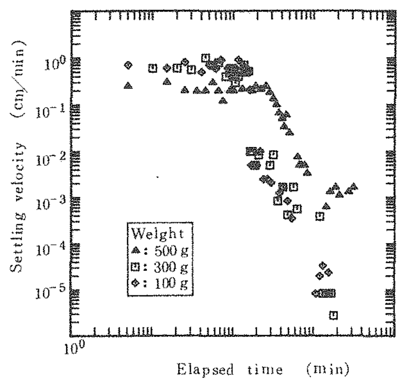

Fig. 12 Plot of settling velocity vs. height for initial weight difference.

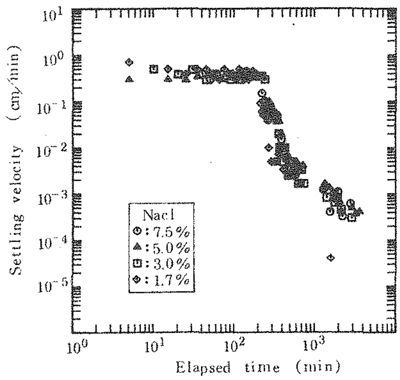

Fig. 13 Plot of settling velocity vs. height for salinity difference at station C.

The settling of sea bed sediments is closely related with bed sediment distribution, concentration of SS, and salinity. It was found that the settling curve and settling velocity were independent of salinity in the range of 1.7%-7.5%, but dependent on the type of sediments and concentration of SS. The settling velocity increased with a decreasing initial concentration of SS, fine particle size, and salinity that has relatively little variance compared to the other properties.

RELATIONSHIP BETWEEN SETTLING VELOCITY AND POROSITY.- From the two-phase flow view point, sedimentation in the settling column is considered relative motion. With regard to solids, it was continuously deposited on the bottom of the column to form a bed of loose structure, which gradually consolidated as a result of the weight of the accumulated solids, thus porosity decreased as time passed. Contrary to solids, water leaves the bed through the pore spaces and later as the settling velocity progressively decreases. Then, the water eliminated by compression is expelled via a much smaller line, and thereafter supernatent flow slowly stops, after which no further water flow occurs. Since the variation of porosity seems to be an important factor in explaining the two-phase flow, we considered that porosity and settling velocity are closely related. Therefore, the relationship is shown from the log of porosity against log of settling velocity. Fig. 14 shows that interface settling velocity is linearly correlated to porosity with an r of 0.97. The relationship lines were expressed as

$$y=\exp(ax^2+bx+c) \tag{3}$$

in which y is the interface settling velocity (cm/sec), x is porosity (%), and a, b, and c are empirical constants. The relationship of settling velocity and porosity has been

Table 4 Relationships between settling or accumulating velocity of interface and time.

Sample	Settling Part							
	Settling velocity (y=log y) vs. Time (x=log x)							
	n	a_0	a_1	a_2	a_3	a_4	a_5	γ
A	5	−0.753	−9.082	8.987	−2.778	0.336	−0.014	0.95
B	5	−1.188	−0.174	0.237	0.063	−0.032	0.0024	0.95
C-1	4	−3.365	1.088	0.855	−0.307	0.021	—	0.95
C-2	4	−2.884	0.367	0.911	−0.273	0.018	—	0.95
C-3	4	−0.476	−2.169	1.596	−0.329	0.018	—	0.96
C-4	4	0.295	−2.777	2.101	−0.462	0.028	—	0.95
C-5	4	−1.568	−2.067	1.845	−0.401	0.024	—	0.97
C-6	4	−1.279	−2.410	1.963	−0.417	0.025	—	0.97
C-7	4	−0.256	−3.604	2.148	−0.401	0.022	—	0.96
D	4	−4.858	1.799	0.687	−0.278	0.020	—	0.96

Sample	Accumulating Part							
	Accumulating velocity (y=log y) vs. Time (x=log x)							
	n	a_0	a_1	a_2	a_3	a_4	a_5	γ
A	4	−1.222	−1.535	0.899	−0.205	0.013	—	0.96
B	5	0.958	−1.859	−0.234	0.312	−0.061	0.0034	0.90
C-1	4	−3.089	−2.173	1.444	−0.287	0.016	—	0.96
C-2	4	−2.067	−1.365	0.829	−0.163	0.009	—	0.91
C-3	4	−2.066	−0.723	0.335	−0.055	0.0016	—	0.93
C-4	4	−1.462	−2.938	1.746	−0.340	0.019	—	0.95
C-5	4	−2.512	−1.426	0.936	−0.185	0.010	—	0.93
C-6	4	−4.402	−1.329	1.163	−0.235	0.013	—	0.83
C-7	4	−3.346	−1.094	0.991	−0.207	0.012	—	0.91
D	5	0.114	−1.723	−0.089	0.270	−0.059	0.0035	0.96

proved a good linear relationship; the results are correlated by a single line. A summary of the experimental values is given in Table 5.

The initial interface height, z, falls to some final height, z_f, at some final time, t_f, which was defined as after 7200 minutes had elapsed. The final settling volume, $s_0=z_f/z$, is considered the ratio of the final height and initial height. According to the experiment, the relationship of the final settling volume and the concentration is plotted on the double logarithmic scale in Fig. 15. The results are correlated by a curvature line with the equation

$$y=ax^2+bx+c \tag{4}$$

where y is the final settling volume, x is the initial concentration (mg/l), and a, b, and c are experimental constant. The experimental values are shown as Table 6.

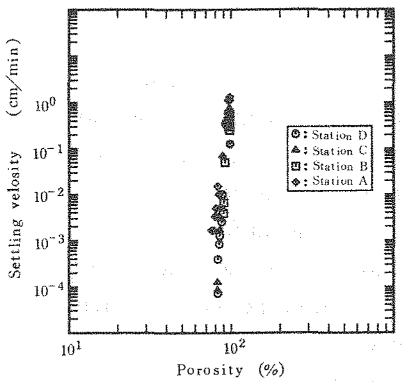

Fig. 14 Relationship between settling velocity and porosity.

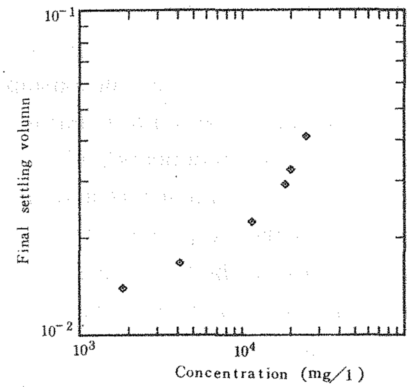

Fig. 15 Relationship between initial concentration and final settling volumn.

Table 5 Relationships between interface settling velocity and porosity.

Station	Settling velocity (y) vs. Porosity (x)			
	a	b	c	γ
A	−0.007181	1.55573	− 83.011	0.97
B	−0.022106	4.57617	−236.656	0.97
C	−0.053947	10.38870	−499.594	0.97
D	−0.022007	4.50000	−229.594	0.98

Table 6 Relationships between final settling volume and initial concentration.

final Settling volume (y) vs. concentration (x)			
a	b	c	γ
5.531×10^{-9}	7.461×10^{-5}	2.79143	0.99

CONCENTRATION PROFILE MEASUREMENTS FOR SEA BED SEDIMENTS.- To elucidate settling process, experimental investigation, i.e. a series of concentration profiles are obtained using the SS filtration method, was done to make a quantitative evaluation. It has been developed to describe the variation of SS concentrations against the time and height in settling column. Fig. 16 (for station A sediment) and 17 (for station C sediment) respectively, are a schematic comparison of the consequence of height against concentration profiles of the settling and consolidation period. Concentration profiles of station A and C respectively, are shown in chart form. These data are typical of moderate concentrations of SS with settling velocities. The variation of concentration decreases with rising height, except the bottom side in an essentially linear fashion. To show a detailed relationship with the station C sediment, Fig. 18 (a) and 18 (b) show the concentration profiles during the 360 minutes with an initial concentration of 11,500 mg/l and 4,150 mg/l respectively. Fig. 19 (a) (for station A sediment) and 19 (b) (for station C sediment respectively, show the variation of concentration at a given time and height (C_0= 20,000mg/l and 11,500mg/l respectively).

As is clear from the relationship curve of the time-concentration-height, the settling and consolidation period are characterized by the relative movement of solids and water. Cohesive sea bed sediments , which are subject to surface electrochemical forces because of their various components and small size, tend to group into clusters of flocs. At the beginning of the experiment, the distribution of concentration is uniform at every height. As time goes by, the flocs joined together and coalesced to form extended networks. Also, this structure of networks changes with time. The flocculation period is thought to be finished early, but it affects settling velocity. At this time, the settling rates are restricted and the flocs networks closely packed forming an interfacial plane at the top of the dispersion. The local concentration decreases with an increase in height; an upper part gradually decreases concentration, a central part uniformly maintains constant concentration, and a bottom part accordingly decreases concentration. This is caused by the bedding down of flocs and the squeezing out of water. Whereas the flocs of the bottom part are

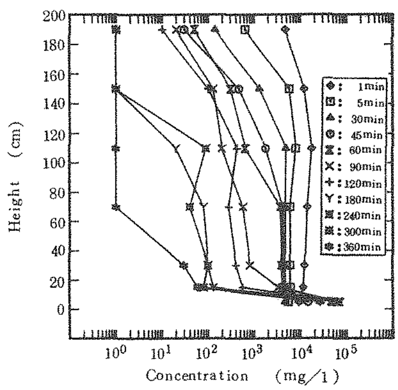

Fig. 16 Variations of concentration with height for station A sediment (C_0= 20,000 mg/l).

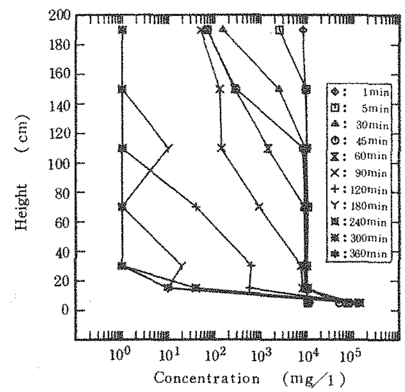

Fig. 17 Variations of concentration with height for station C sediment (C_0= 11,500 mg/l).

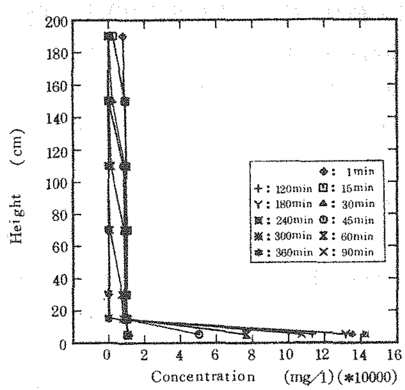

Fig. 18 (a) Variation in the concentration and the height on the station C sediment (C_0=11,500 mg/l).

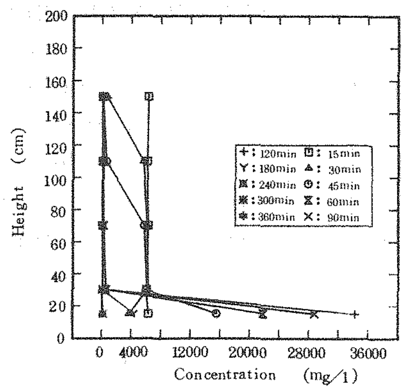

Fig. 18 (b) Variation in the concentration and the height on the station C sediment (C_0=4,150 mg/l).

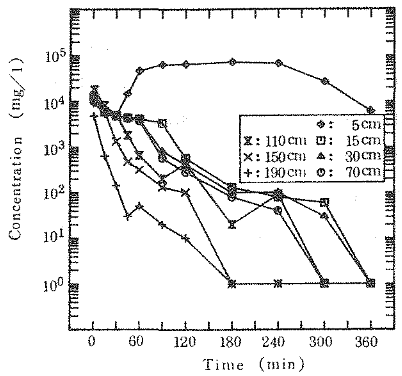

Fig. 19 (a) Variation in the concentration and time on the height (C_0=20, 000mg/l: Station A).

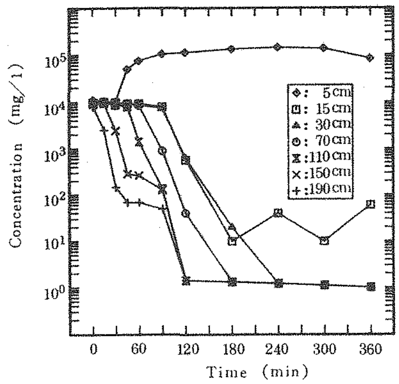

Fig. 19 (b) Variation in the concentration and time on the height (C_0=11, 500mg/l: Station C).

forced and compressed by the weight of the overlying flocs, the supernatent is isolated in the upper part. Thereafter, the movement of the interface begins slowly downward. As more time goes by, the interface settling rate decreases with increasing retardation. The water is eliminated by porosity and vertical drainage wells from a bed. Given enough time, the concentration increased remarkably near the bottom (such as 5cm height) and the water was displaced by compression and overburden weight. If the time elapsed too close to the final settling state, the settling abruptly stopped, after which no further consolidation occurs. The following became clear after the experiment continued: first, the relationships between SS and water are shown in the hindered settling effects. Second, the concentration profile of the bottom part is obtained for the path by a number of flocs layers of various thickness which occurs over time. For the near shore region of Ariake sea (especially station A and C), the mean concentration (mg/l) of settled sediment at 5cm height in the settling column is given by

$$y = a_0 + a_1 x^1 + a_2 x^2 + \cdots + a_n x^n \qquad (0<t<360 \text{ min}) \text{ in minutes} \qquad (5)$$

where y is mean concentration (mg/l), x and t are elapsed time (min), and n is the order of polynominal. The experimental values are shown in Table 7.

SEGREGATION OF PARTICLE SIZES DURING SETTLEMENT.- To investigate flocculation, one of the most important process of settling, a suitable experimental method is required. The major factors affecting flocculation could be: segregation of particle sizes, similarity of particle size distribution, and variation of average particle size, which are attributed to the differential settling of different size distribution. A representative sample was extracted through the wall of the settling column, and the particle size analysis of samples obtained at a given height and time was performed.

Our first attempt to determine segregation of particle sizes and similarity of particle size distribution was to use the particle size analysis. This method helps to understand the influence of those factors described above. The experimental results account for the particle behavior of initial concentration (C_0=11,500mg/l) in station C sediment. A detailed comparison of the particle size distributions with the height at a given time are shown in Fig. 20 (a) to 20 (f). During the initial settling period such as shown on Fig. 20 (a), the particle size distribution indicates similar settling features at every height. Consequently, there is not very much change. The distribution confirmed that the mixture concentration should be almost the same at all points, but should not yet develop settling. Fig. 20 (b) and 20 (c) describe that after 15 and 30 minutes respectively, the particles

Table 7 Relationships between mean concentration and time.

Station	Mean concentration ($y=y$) vs. Time ($x=\log x$)						
	n	a_0	a_1	a_2	a_3	a_4	γ
A	4	9202.69	227552	−192736	51644	−4332.25	0.98
C	4	11351.6	230976	−199840	54496	−4554.5	0.98

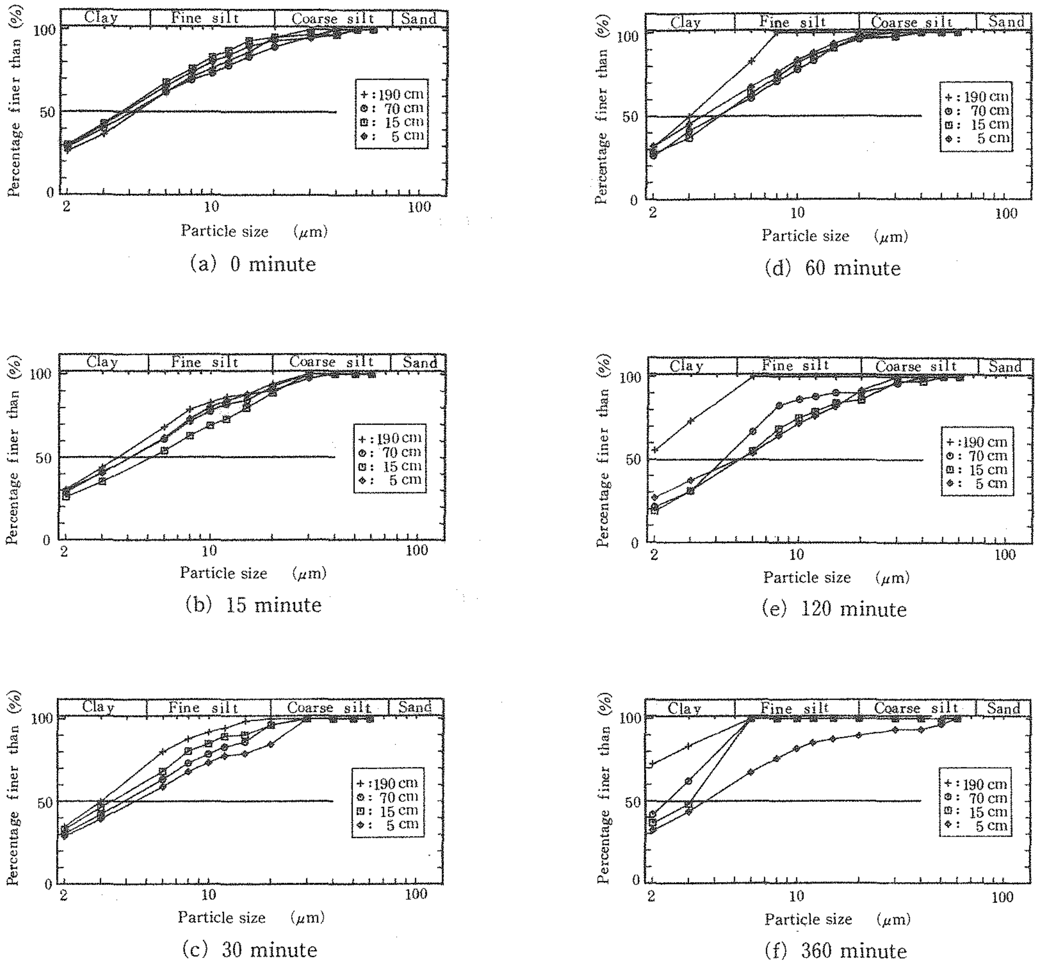

Fig. 20 Particle size distribution as a function of height.

increase in size and the curves of distribution themselves shift downwards. This is due to the solids of the mixture becoming gradually flocculated at the particle surface, and becoming large and heavy. Thus, the settling of sand-size as well as coarse-silt size particles was drawing to an end. These are ascribed to the results of the variation of self-weight. The coarse silt-size and sand-size as well as clay-size does not change with the height very much, but fine silt-size does. It paraphrases that the most of the change in the distribution occurs in the fine silt-size range, the equivalent size of about 5-20μm. The deposition profile of the bottom part being composed of a number of layers of various particle sizes is explained in terms of the segregation of particle sizes. At the bottom part, the coarse-size particles, aggregated heavy particles, and large particles are settled, with the result that the thickness increases sequentially. The results are very closely related to the accumulation plane of the settling curve in Fig. 5 to 10. As time goes by , the experiments show that after the elapse of 60 and 120 minutes respectively (Fig. 20 (d) and 20 (e)), the upper part curves shifting upwards, whereas the lower part curves downwards. This trend is due to the significant proportion of the aggregated sand size and coarse silt size particles which are settled in the bottom, so that the SS concentration as well as the particle size decreases stepwise with in increasing height and time. Fig. 20 (f) shows that after 360 minutes, the concentration of SS increased markedly near the bottom, such as 5cm height, while in the upper and middle part gradually decreased with the lapse of time, and then reached nearly zero. The obvious conclusion was that reaching a certain point (within the passage of 30 minutes), the coarse silt-size as well as sand-size particles segregated and settled on the bottom but the fine silt-size and clay-size consistently carried on a stepwise variation, except the bottom part. The various relationships characterizing the segregation as well as similarity of particle size are found in the experimental results. Subsequently, one of the factors affecting flocculation shall be considered variation of average particle size. Using the experimental values for station C sediment (C_0=11,500mg/l), the time and average particle size relationships in Fig. 21 was obtained.

The average particle size varies widely with the lapse of time. In the beginning of a period (such as from 0 min to 15 minutes), the average particle size varies consistently at every height but thereafter changes remarkably. It is believed the effect of the concentration variation appeared settling state. When the height was increased and time passed, the average particle size is reduced significantly. The flocculation of sea bed sediments plays an important role in understanding the relationships among the segregation and deposition state of particle

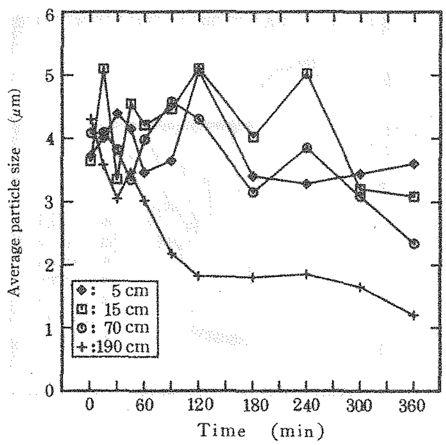

Fig. 21 Variations of average particle size with time for station C sediment.

size, the fluidity of the sea bed sediment, and the settling characteristics.

SETTLING VELOCITY.- In order to deduce the settling velocity equation, let us take x, y, and z axis respectively in the direction of wave propagation, perpendicular to the x axis in a horizontal plane, and vertically upward from the quiescent water level. The fundamental transport equation for the concentration of SS is expressed as

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}+(w-w_g)\frac{\partial C}{\partial z}=\frac{\partial}{\partial x}(D_x\frac{\partial C}{\partial x})+\frac{\partial}{\partial y}(D_y\frac{\partial C}{\partial y})+\frac{\partial}{\partial z}(D_z\frac{\partial C}{\partial z}) \qquad (6)$$

in which C is the mean concentration of SS (mg/l), w_g is the settling velocity of SS, and D_x, D_y, and D_z are the diffusion coefficients in the x, y, and z directions respectively.

In order to simplify conditions, the particle size of sea bed sediments throughout the near shore region of the shallow sea distributes itself uniformly. Thus, we assume the motion of water depth is uniform and the flow motion in the settling column is one -dimensional, $u=v=w=0$, and D_x D_y, and D_z are negligibly small, as a result, all derivatives with respect to x, y, and z (except w_g) are zero. Then the distribution of concentration in a one-dimensional flow is governed to a good approximation by the following settling equation;

$$\frac{\partial C}{\partial t}=w_g\frac{\partial C}{\partial z} \qquad (7)$$

By integrating the equation with respect to C we obtain

$$w_gC=\frac{\partial}{\partial t}\int_0^z Cdz \qquad (8)$$

To compute the settling velocity profile, it is necessary to obtain the variation of the

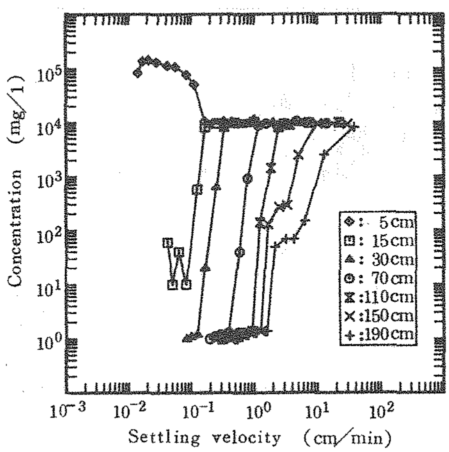

Fig. 22 (a) Relationship between settling velocity ($w_g=dz/dt$) and concentration.

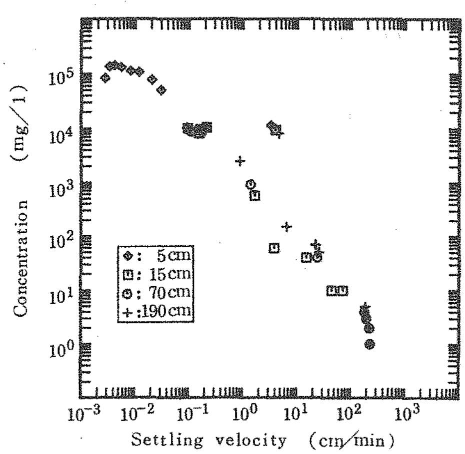

Fig. 22 (b) Relationship between settling velocity and concentration.

concentration during the course of time. We have mentioned this in accordance with Fig. 16 to 19 already given. The relationships between the settling velocity and the concentration were expressed as a function of time at a given height in Fig. 22(a) to 22(b). In Fig. 22(a), we assume that the settling velocity is proportional to the instantaneous time rate of change of the height i.e. $w_g = dz/dt$. Fig. 22(b) introduces the idea that the settling velocity was derived by the use of equation (8), and the experimental results were plotted as the log settling velocity against log concentration. The interpretation of the resulting settling velocity-concentration data yielded a description of the variation of the concentration at given height and an expression for the settling velocity with the passage of time. It turns out that the settling velocity decreases with increasing concentration at the initial stage, and thereafter the settling velocity of the bottom part decreases rapidly as concentration increases. On the other hand, the settling velocity of the middle and the upper part attains constant value and varies slowly. One of the reasons affecting it could be considered hindered settling, which increases with the increase of the SS concentrations, the dispersion rate of sea bed sediments, and the strength of the attractive force between particles. The settling velocity increases as the height increases at a given time; in the upper and middle part, settling velocity increases with height, whereas in the bottom part, it decreases significantly.

RELATIONSHIPS BETWEEN SETTLING VELOCITY AND PARTICLE SIZE.- The settling velocity was obtained by timing the movement of the interface settling, i.e., the ratio of varied height to varied time. For the particle size analysis, sand-size particles were measured by the sieve method, and both silt and clay-size particles were measured by the hydrometer method. It was obtained referring to Fig. 3 in the last section. The relationships between settling velocity and particle size shown in Fig. 23 indicate that the settling velocity increased with an increase in particle size. An almost linear relation is obtained when the relationship is plotted on logarithmic scale. The relationship for these curves were described by the following.

$$
\begin{aligned}
w_i &= 0.549D^{0.11} \quad \text{sample A}\\
w_i &= 0.101D^{0.07} \quad \text{sample B}\\
w_i &= 0.263D^{0.05} \quad \text{sample C}\\
w_i &= 0.142D^{0.04} \quad \text{sample D}
\end{aligned} \qquad (8)
$$

where w_i is the settling velocity of interface (cm/min) and D is particle size (cm).

It can be observed that the relationship among the curves of sampling stations show the settling velocity in aggregates many times larger than the settling velocity of an isolated particle. This would have small size

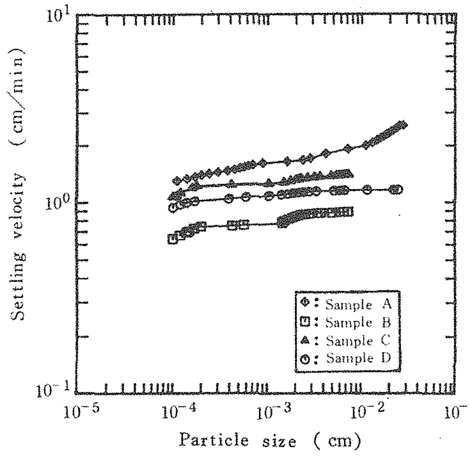

Fig. 23 Relationship between settling velocity and particle size.

particles changing in size as flocculation from a point of view described later, such as in Fig. 20, and it obviously could mean that most of the change in the particle size distribution occurs in the smaller particles. This is presumably a result of high flocculation in this size fraction.

CONCLUSIONS

This paper is concerned with settling properties in the settling column and showing the results of using an experimental laboratory for sea bed sediments in the Ariake sea. The results revealed the following settling properties of sea bed sediments:

1. The settling properties of sea bed sediments are closely related with the type of sea bed sediments, the concentration of SS, and the salinity of sea water. These relationships are shown in an obvious quantitative relation. The settling curve as well as settling velocity which depends significantly on the sea bed type and SS concentration, decreased with the increasing initial concentration, fine particle size, and salinity of the sea water.

2. The interface settling and accumulating velocity indicates a constant rate at the initial stage, and then attains an inflection point, thereafter decreasing.

3. The relationships among the settling velocity, the mean concentration of SS, and the particle size were investigated. There relationships are shown in chart form and explicitly expressed equations.

4. Flocculation as well as hindered settling is found to be suitable for describing the settling properties.

5. The segregation of particle size appeared in the silt-size range (i.e. 5-20μm) before and after 30 minutes.

6. The relationship between interface settling velocities and particle sizes are expressed by a power -law equation.

REFERENCES

1. K. Yano (1985): Properties of very soft ground reclaimed by dredged marine clay and their prediction. Trans. JSCE. **364**, pp. 1-14 (in Japanese)
2. M. Seguchi, K. Watanabe, O. Kato & J. H. Park (1991): Characteristics of the near-bottom flow in the shallow sea areas. Trans. JSIDRE. **152**, pp. 101-109, (in Japanese)
3. M. Seguchi, K. Watanabe, O. Kato & J. H. Park (1992): Resuspension of the sea-bottom sediment in the shallow sea areas of the interior parts of Ariake sea. Trans. JSIDRE. **157**, pp. 65-74, (in Japanese)
4. Mirbagheri, S. A., K. K. Tanji & R. B. Krone (1988): Simulation of suspended sediment in Colusa Basin Drain. ASCE. (EE12). Vol. **114**, No. 6, pp. 1275-1294
5. J. H. Park, K. Watanabe & M. Seguchi (1991): Settling and flow characteristics in the shallow sea areas. Proc., 72th Annual Meeting of JSIDRE. in Kyushu. pp. 179-180 (in Japanese)
6. Kynch,G.J. (1952): A theory of sedimentation. Trans. Faraday Soc. **48**, pp. 166-176
7. K. Otsubo (1983): Experimental studies on the physical properties of mud and the characteristics of mud transportation. Rep. NIFES., Japan, No. **42**, pp. 29-77, (in Japanese)
8. Work, L. T. & Kohler, A. S. (1940): Sedimentation of suspensions. I&EC. **32**, pp. 13-29.
9. Michaels, A. S. & Bolger, J. C. (1962): Settling rates and sedimentation volumes of flocculated kaolin suspensions. I & EC. Fundam. **1**, pp. 24-33
10. Been, K. & Sills, G.C (1981): Self-weight consolidation of soft soils; an experimental and theoretical study. Geotechnique 31, No. **4**, pp. 519-535

底泥の沈降特性に関する実験的研究

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（浅海干潟総合実験施設）

摘　要

干潟の形成メカニズムや過程を明らかにするために底泥の沈降特性について実験的に考察された．底泥の沈降現象には底泥の種類やその懸濁濃度，さらには海水の塩分濃度や物理化学的な成分などの要因が影響すると思われる．

本論文では，静止海水中での底泥の沈降と堆積特性について実験的に検討した．実験の試料は有明海沿岸域で採取した底泥と海水を用いた．

実験結果から，沈降曲線と沈降速度は底泥の種類や懸濁濃度によって大きく影響されるが，1.7%-7.5%範囲での塩分濃度ではあまり顕著な影響がみられなかった．凝集と干渉沈降は底泥の沈降に重要な役割を果たしていることが分かった．さらに，界面沈降速度と粒径との間にはべキ乗の関係が見出された．

Key words: 堆積，凝集，干渉沈降，海水，堆積物，分離，沈降速度，浮泥

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