# **CHAPTER 238**

# SETTLING PROPERTIES OF COHESIVE SEDIMENTS IN A COOLING WATER INTAKE BASIN

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## ABSTRACT

In the present study, with the ultimate objective of developing a numerical model of siltation in a cooling water intake basin of a power plant, the settling velocities of non-uniform sediments are investigated using the settling tube tests. The critical shear stress for deposition of suspended silt and the vertical concentration profile of suspended sediments are investigated on the basis of field data. The depositon rate as well as the grain size distribution of deposited sediments were reproduced satisfactorily by a one-dimensional model.

#### INTRODUCTION

In a power plant basin used for both the intake of cooling water and the navigation channel, siltation usually occurs and a silty area is created inside the harbor, even if the basin is sited in a sandy coast. Cohesive fine sediments are suspended by the wave action outside the harbor under the severe wave conditions and transported by the intake flows through the entrance into the harbor. Most of the inflow fine sediments are settled and deposited on the bottom in a tranguil area inside the harbor.

Figure 1 shows the location map and the layout of the investigation site. The

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investigation site is the harbor basin of Fukushima No.2 Nuclear Power Plant and is located in Fukushima Prefecture, Japan, facing directly the Pacific Ocean. The spatial distribution of the median grain diameters of deposited sediments in the basin is also shown in this figure. A large portion of the basin is occupied by fine sediments with the median diameter below 100  $\mu$ m, although the surrounding coast consists of fine sands with the median diameter of approximately 200  $\mu$ m. The median grain diameters decrease along the streamline of the intake flow. In the course of transportation and deposition, sediment sorting due to difference of settling velocities occurs because the suspended fine sediments are composed of a wide range of grain sizes approximately from 1 to 100  $\mu$ m. Consequently, the median grain sizes of deposited sediments show a wide range of spatial distribution from about 200  $\mu$ m in the sandy area around the entrance to 20  $\mu$ m in the tranquil area near the intake channel.

In developing a numerical model for simulating siltation in such a cooling water intake basin, detail understanding of the depositional properties of nonuniform cohesive sediments is the first subject to be solved. In this study, we aim to discuss about a proper method for estimating the deposition rate by taking into account the effects of flocculation and nonuniformity of the grain size on the basis of the laboratory experimental data and the field measurement data.



#### DEPOSITION RATE

One of the well-known expressions for the deposition rate D is described as follows (e.g. Nicholson and O'Conner, 1987) :

$$D = C_b w_b (1 - \frac{\tau}{\tau_d}), \qquad for \ \tau < \tau_d \tag{1}$$

where  $C_b$  is the near bottom concentration,  $w_b$  the near bottom settling velocity,  $\tau$  the bottom shear stress, and  $\tau_d$  the critical shear stress for deposition. According to this expression, the deposition rate is regarded as the product of three factors; 1)the suspended sediment concentration near the bottom, 2)its settling velocitiy and 3)the probability of particles sticking to the bed which is described as ( $1 - \tau/\tau_d$ ) in eq. (1).

It is well recognized that the settling velocity of cohesive fine sediments is influenced sensitively by the suspended sediment concentration owing to the effect of flocculation. In the present study, the laboratory experiments in a settling tube were carried out in still water to examine the influence of concentration on the settling velocity of non-uniform sediments.

In depth-integrated models which are widely used for simulating the behavior of suspended particles, the near bottom concentration is to be evalueted from the depth-averaged concentration. Therefore, the vertical concentration profile should be determined for numerical calculation. Also the critical shear stress for deposition  $\tau_d$  is a very important parameter for estimating the depositional rate. In this study, the vertical concentration profiles for different grain sizes and the critical depositional shear stress are evaluated through comparisons between the calculated results and the field data.

#### SETTLING VELOCITY

The settling velocities of non-uniform sediments were investigated by the settling tube tests. The sediments used in the tests were sampled from the seabed in the tranquil area of the investigation site. The median grain diameter was 23  $\mu$ m after passing through a sieve with 106  $\mu$ m openings. The cation exchange capacity was 27 (meq/100g), and a large portion of absorbed cation was occupied by Ca<sup>2+</sup> and Mg<sup>2+</sup>.

The inner diameter of the settling tube was 27 cm, and the available water depth was 95 cm. Saline water with a temparature of 20°C was used as the settling medium. Sediments were initially stirred to create a state of homogeneous susupended sediment concentration in the tube. The water samplings and the concentration measurements were conducted six times after 3, 8, 25, 90, 180 and 420 minuites from the start of the test, and the sampling mouth was set at the water depth of 60 cm.

The time series of concentration were transformed to the settling velocity curve. The grain-size distributions were also analyzed by the laser diffraction method after breaking the flocs. Then, the settling velocity curves were obtained for every grain-size class.

Figure 2 shows the relationships between the median settling velocity  $w_{50}$  of each grain-size class and the initial total concentration. It is recognized that in the case of low concentration, C < 200 mg/l, the settling velocity is independent of concentration and can be evaluated by the Stokes law. In the case of 200  $\leq C \leq 2000 \text{ mg/}l$ , the settling velocity increases exponentially with concentration and the following general formula can be used :  $w = kC^m$  ( k : empirical constant, m : empirical exponent ). The settling velocity reaches the equilibrium value of 0.19 (cm/s) for each grain-size class at a concentration of approximately 2000 mg/l.

These tendencies are observed only for the grain-size classes with the median diameter below 48  $\mu$ m. For the larger grain-size classes, dependence of settling velocities on concentration can not be observed. According to these results, the settling velocity of suspended sediments is formulated as a function of grain size and total concentration as shown in Figure 3. The critical median diameter, 48  $\mu$ m, above which flocculation is negligible, corresponds to the equilibrium settling velocity of 0.19 cm/s. It should be noticed that these quantities are regarded as local factors which are inherent in the sediment properties of the investigation site. The range of concentration for flocculated settling obtained in this study corresponds to the results of the previous studies (e.g. Ross and Mehta, 1989).

# VERTICAL CONCENTRATION PROFILE AND PROBABILITY OF DEPOSITION

The vertical concentration profile and the probability of deposition were investigated on the basis of field data. The critical shear stress for deposition and the reference level at which the near bottom concentration was defined were evaluated through comparisons between the cummulated depositional fluxes calculated from the measured time histories of concentration and the measured weights of the deposited sediments in the traps.







Fig. 3. Formulation of settling velocity as a function of median grain diameter and total concentration.

## **Outline of Field Data**

An intensive field investigation was carried out in the harbor basin of Fukushima No.2 Nuclear Power Plant over a peroid of approximately two months from July to September in 1989 (Shimizu et al., 1990). Figure 4 shows the arrangement of observation points. Among them, three points are concerned in the discussion here. They are point A-2 in the sandy area at the harbor entrance with a median grain diameter of about 150  $\mu$ m, point A-6 in sand-silt coexisting area with a median grain diameter slightly below 100  $\mu$ m and point A-8 in the silty area with a median grain diameter of approximately 50  $\mu$ m.

A synchronized combination of an ultrasonic wave gauge and an electromagnetic current meter with a pressure gauge and a turbidity meter were placed at each of the above three obserbation points. Hourly time histories of suspended sediment concentration at 1.5 m above the bottom together with the wave height and near-bottom flow velocity were measured simultaneously. At point A-8, another turbidity meter was set at 3.0 m above the bottom in addition to the one at 1.5 m, so that the ratio of concentrations measured at these two elevations could provide the information about the vertical concentration profile.



Fig. 4. Location of observation points.

Two types of silt traps were set at points A-6 and A-8, to obtain direct measurements of the weight and the grain-size distribution of newly deposited silt. The photograph of silt traps are shown in Figure 5. Type-A has a trapping mouth at almost the same elevation as the sea bottom, and Type-B has its mouth at 0.3 m above the bottom. The traps were set in pipe lattices so as to trap only the suspended silt falling down into the bed.



Fig. 5. Photograph of silt traps (Type A and Type B).



Fig. 6. Photograph of remote water sampling system.

At point A-2, remote water samplings were conducted during severe wave conditions by a newly developed apparatus shown in Figure 6. Figure 7 shows the grain size distribution of suspended silt measured at point A-2 by this apparatus. This will be used as the boundary condition for simulation of grain size sorting, to be discussed later.



Fig. 7. Grain size distribution of suspended silt at harbor entrance.

# Vertical Concentration Profile

The vertical concentration profile should be determined in order to evaluate the bottom concentration  $C_b$  from the measured concentration at 1.5 m above the bed. In the present study, the vertical concentration profile is assumed to have an exponential form as shown in Figure 8:

$$C(z) = C_{\delta} \exp\left(-\frac{w}{u_*\kappa\delta}(z-\delta)\right)$$
(2)

where C(z) is the concentration at elevation z above the bed,  $C_{\delta}$  is the concentration at the reference level  $\delta$ , w the settling velocity of suspended sediment corresponding to the depth averaged concentration, and  $\kappa$  the Karman constant. The bottom concentration is assumed to be equal to  $C_{\delta}$ . In this expression, the eddy viscosity  $u_*\kappa\delta$  is regarded as vertically constant and proportional to the friction velocity.

By assuming this profile, the concentration related to each grain-size class at 1.5 m above the bed can be estimated using the corresponding settling velocity, and the total concentration at this elevation can be also estimated as the sum of the contributing components. Then,  $C_{\delta}$  can be determined by comparing the estimated total concentration with the measured one at 1.5 m elevation. However, in estimating the total concentration, the information is needed about the grain size distribution of the susupended sediments at the point of interest.



Fig. 8. Assumption of vertical concentration profile.

In the present study, the grain size distributions at points A-6 and A-8 were estimated by a simple numerical model of sediment sorting along the streamline as introduced in the following section. It should be mentioned that in the above calculations, the measured concentration at 1.5 m above the bed has been used as the depth-averaged concentration for estimating the settling velocity in eq.2).

#### Sediment Sorting Simulation by One-dimensional Model

In this study, a one-dimensional depth-integrated model is employed for calculation of sediment sorting. The harbor is regarded as a simple channel along the streamline of intake flow as shown in Figure 9. The channel is divided into 23 grids with an interval of 50 m on the main streamline. Assuming the quasi-equilibrium state and neglecting the diffusion term, the mass conservation of suspended silt for a certain grain-size class is described as follows.

$$u\frac{\partial C}{\partial x} = -\frac{w_b C_\delta}{h} \left(1 - \frac{\tau}{\tau_d}\right) \tag{3}$$

where C is the depth-averaged concentration, h is the water depth and u is the current velocity.



Fig. 9. One-dimnsional modelling of harbor along streamline.

The near bottom concentration  $C_{\delta}$  is evaluated from the depth-averaged concentration C by using eq. (2). At each grid, the value of  $C_{\delta}$  calculated for its preceeding grid is used. The settling velocity  $w_b$  on the bottom (exactly at the elevation  $\delta$ ) is evaluated by the relationship between the diameter of each grainsize class and the total concentration as indicated in Figure 3.

The wave height at each grid is computed by multiplying the diffraction coefficient, calculated in advance, by the measured incident wave height at the harbor entrance. The depth-averaged current velocity is estimated by dividing the intake discharge by the cross-sectional area of each grid. The bottom shear stress at each grid is then evaluated by the friction law for the wave-current coexistent field proposed by Tanaka and Shuto(1981). The measured time history of concentration is given as the boundary condition at the grid No. 3 which corresponds to point A-2. The concentration for each grain-size class at the boundary is given according to its ratio based on the grain size distribution measured at point A-2 during the severe wave conditions as shown in Figure 7.

# Determination of Critical Shear Stress and Reference Level

According to the above procedure, the deposited weights and their grain size distributions at points A-6 and A-8 can be estimated by using the assumed values of  $\tau_d$  and  $\delta$ . The objective here is to find the appropriate values for these parameters which provide the best agreement between calculations and measurements.

However, the effects of these parameters on calculation results are not so simple. The increase of  $\tau_d$  has both effects of increasing the deposition rate owing to the increase in probability of deposition and of decreasing it because of the increase in the deposition rate in the upstream region. The decrease of  $\delta$  has the same effects as those caused by the increase of  $\tau_d$ .

Table 1 shows the measured and the calculated results of deposited weights in the traps at points A-6 and A-8. Three couples of  $\tau_d$  and  $\delta$  listed in the table were selected in order to reproduce the deposited weight at point A-8. By using two of these couples, the deposited weight at point A-6 could also be well reproduced at point A-6.

Figure 10 shows the comparisons between the measured and calculated grain size distributions of trapped silt at points A-6 and A-8. The grain size distribution at point A-6 is reproduced well by setting  $\tau_d$  and  $\delta$  equal 0.4 (Pa) and 3.0 (cm), respectively. At point A-8, on the other hand, the grain size distribution could not be reproduced satisfactorily. In general, judging from these results, it is concluded that the most appropriate values for  $\tau_d$  and  $\delta$  are respectively 0.4 (Pa) and 3.0 (cm).

Figure 11 shows the time histories of the measured significant wave height, the estimated bottom shear stress, the measured concentration, the vertical ratio of concentration, the calculated mean grain diameter and the calculated weights of trapped silt at points A-6 and A-8 with  $\tau_d = 0.4$  (Pa) and  $\delta = 3$  (cm). During the observation period, storm waves attacked twice, with the peak significant wave heights of 5.0 m and 3.8 m, respectively. During these stormy periods, considerable deposition occurred. As shown in this figure, the trapped weight of Type-B which has the mouth at 0.3m above the bed could be also reproduced by considering the concentration at 0.3 m above the bottom as the bottom concentration. It is also observed that the calculted time history of the ratio of concentration at 3m above the bottom to that of 1.5 m at point A-8 agrees reasonably well with the measurements.

Table 1.Comparison between measured and calculated weights<br/>of trapped silt.

τ <sub>₫</sub> (Pa)	δ (cm)	Trapped	Weight(kg)
		A-6	A-8
0.7	2.0	2.6	4.0
0.4	3.0	3.5	4.3
0.2	2.5	5.4	4.0
Measurement		3.0	4.2



Fig. 10. Comparison between measured and calculated grain size distributions of trapped silt.



Fig. 11. Time histories of bottom shear stress, significant wave height, observed and calculated concentrations, calculated mean diameter of suspended silt and calculated weight of trapped silt.

# CONCLUDING REMARKS

The settling process of nonuniform cohesive sediments in a cooling water intake basin was investigated on the basis of laboratory experiments and field measurements. The settling velocity was formulated empirically as a function of the grain-size and the total concentration by taking into account the effect of flocculation. The critical shear stress for deposition and the vertical concentration profile were also evaluated through comparisons with field measurements. A numerical model was developed to simulate the transportation and deposition of nonuniform sediments in the basin. The deposition rate as well as the grain size distribution of deposited sediments were reproduced satisfactorily by this model.

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#### REFERENCES

- Nicolson, J. and B. A. O'Connor, 1986: Cohesive sediment transport model, Jour. Hydraulic Eng., Vol. 112, No. 7, ASCE, pp.621-639.
- Ross, M. A. and A. J. Mehta, 1989: On the mechanics of lutoclines and fluid mud, *Jour. Coastal Res.*, Special Issue, No. 5, pp.51-62.
- Shimizu, T., M. Banno, S. Kanayama, S. Sakauchi, K. Ueki and T. Sakakiyama, 1990: Field investigation of siltation in a cooling water intake basin, *Proc. Coastal Eng.*, Vol. 37, JSCE, pp.424-428 (in Japanese).
- Tanaka, H. and N. Shuto, 1981: Friction coefficient for a wave-current coexistent system, *Coastal Eng. in Japan*, Vol. 24, JSCE, pp.105-128.