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EXPERIMENTAL STUDY OF SEDIMENT SETTLING VELOCITY IN CITANDUY RIVER, WEST JAVA

Wati Asriningsih Pranoto[1]

ABSTRACT

Accumulation of sedimentation in the downstream of Citanduy River has caused the aggradation on Segara Anakan estuary and therefore impacting on the alteration of estuary morphology. This sedimentation affects some aspects of humankind activities, such as shipping, fishing, and the surrounding. This phenomenon must be anticipated in order to stabilize and normalize the aspects of human activities. To anticipate this, a sediment characteristic research about the settling velocity of the sediment which affected by concentrated sediment and salinity was done in Fluid Mechanic and Hydrodynamic Laboratory of Bandung Institute of Technology by using bottom withdrawal tube. Research result showed two general equations, which were the flocculation settling equation and hindered settling equation. The limit for both equations is 4.25 gram/l. From 7 salinities used in the research, the 15‰ salinity proved to be most influential in obtaining the value of maximum sediment settling velocity and used as the salinity limit.

Keywords: Cohesive sediment, Settling velocity, Concentration of sediment, Salinity.

INTRODUCTION

Background

Indonesia is an archipelagic nation that has many rivers with estuaries. River downstream is part of the river that flows to the sea, which often called estuary. Everything that flows in the river will be carried to the downstream. If there are many erosions in the upstream caused either by the logging or lack of knowledge regarding environmental sustainability, then the river will carried many sediments to the downstream. Thus, resulting the estuary aggradation (usually occurs on cohesive sediment which is easier to get carried in river flow as the suspended sediment).

Many cases of aggradation happened in the rivers and estuaries in Indonesia, creating disturbance on the sailing activities in some rivers located in Java island such as Citanduy River, especially on the estuaries that functioned as the entrance of ships to the river (used either by fishermen or water transportations). Aggradation also changed the environment, particularly on river morphology or estuary morphology. This impact mostly affects the flora and fauna that can only live on its own habitat, such as Segara Anakan estuary that has lagoon. Segara Anakan waters only consist of 500 hectare area now, which is in contrast with the area before, 6,450 hectare. The narrowed estuary also put impacts on the destruction of mangrove forest, disturbance in the breeding of fishes, shrimps, crabs, oysters, and also job turnover from fishermen to farmers.

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To prevent those cases, investigation on the characteristics of sediment is needed. This research investigates the characteristics of cohesive sediment, particularly the settling velocity sediment of Citanduy River with laboratory experiment.

Research Objective

This research was aimed to investigate the characteristics of cohesive sediment, especially sediment settling velocity which affected by concentrated sediment and salinity. Case study for this research was Citanduy River sediment.

Research Methodology

This research was an experimental research conducted in laboratory with cohesive sediment from Citanduy River and artificial concentrated sediment. To determine the settling velocity of cohesive sediment, bottom withdrawal tube was used (Berlamont et al. 1993).

Research Hypothesis

The research result of sediment settling velocity is expected to have the highest salinity value for maximum settling velocity with hypothesis as follows: What is the adequate salinity value to obtain the maximum settling velocity? Based on the theory, salinity adds the flocculation on cohesive sediment to increase the settling velocity.

SEDIMENT

Processes in Motion Cycle of Sediment

Sediment is fragmental material, primarily formed by the physical and chemical disintegration of rocks from the earth's crust. Such particles range in size from large boulders to colloidal size fragments and vary in shape from rounded to angular. They also vary in specific gravity and mineral composition, the predominant material being quartz. The variety of size, shape, density, and the composition of material determine the process in motion cycle of sediment.

Water that flows in the surface of sediment applies forces on the particles that move it. The forces used to restrain flowing water force are usually differs, depend on particles size and distribution size of sediment. For coarse sediment, such as sand and gravel, the movement restrain forces are caused by the weight of particles. Fine sediment that contains mud or clay tends to be cohesive and restrains the movement with its cohesiveness rather than the weight of particles. Thus, fine sediment is usually called cohesive sediment while coarse sediment is called non-cohesive sediment.

Once the sediment particles are detached, they may be transported. The process of moving and removing from their original source or resting place is called erosion. In a channel, the water flow erodes the available material in the bank or the stream bed until the flow is loaded with as much sediment particles as the energy of the stream will allow it to carry.

When the value of bed-shear velocity just exceeds the critical value for initiation of motion, bed material particles will be rolling or sliding in continuous contact with the bed. For increasing values of bed-shear velocity, the particles will be moving along the bed by more or less regular jumps, which is called saltations. When the value of bed-shear velocity begins to exceed the settling velocity of the particles, the sediment particles can be lifted to a level at which the upward turbulent forces will be of comparable or higher order than the submerged weight of the particles and as a result the particles may go into suspension. Generally, the transport of particles by rolling, sliding, and saltating is called bed-load transport, while the suspended particles are transport as suspended load transport. The suspended load may also include the fine silt particles brought into suspension from the catchment area rather than from the streambed material and is called the wash load. A grain size of 50 μm is frequently used to make the separation between bed material load and wash load. Sometimes, a value of 63 μm is used in USA.

Transport of sediment by flowing water is strongly linked to surface soil erosion and sedimentation. All of them depend on the flow velocity. Sedimentation process is the process in which sediment materials are suspended into the water that filled the bed channel and thus become bed sediment due to the decrease in flow velocity. The whole process can be seen as a continuous cycle of: soil erosion → sediment transport → sedimentation.

CHARACTERISTICS OF COHESIVE SEDIMENT

Cohesive sediment is the sediment that tends to be cohesive due to electro-statical forces comparable to or higher than the gravity forces. Therefore, the sediment particles do not behave as individual particles, but tend to stick together forming aggregates known as flocs. Flocs have larger size and settling velocity than those of the individual particles.

Beside its cohesiveness, cohesive sediment also has other important characteristics, such as size, mineral composition, deposition rate, and settling velocity.

Size and Mineral Composition

Cohesive sediment is fine sediment that classified from coarse silt to very fine clay, with the size of particles smaller than 62 μm. The classification of fine sediment is based on the particles size, as issued by American Geophysical Union (AGU).

Most of the minerals contained in cohesive sediment or mud are illite, montmorillonite dan kaolinite. There are other mineral content such as holloysites, chlorites, and vermiculites but in a very small contents.

Those minerals are the smallest and discreted particles that formed mud. Mud is a substance with solid phase from chemical element or compound formed by organic processes, has a certain chemical composition, and elements as the crystal structure (Graf 1984).

Mineral characteristics are always associated with its length, thickness, specific surface, and cation exchange capacity (CEC). CEC is the characteristic that draws cation or anion. Later, it turns that kaolinite has smaller specific surface and CEC compared to illite and montmorillonite.

Variations of factors between one mineral to another made the chain reaction in mud mineral very complex, resulting in no CEC value on the group of mud mineral to be single CEC. However, CEC values can be used as the more accurate comparator when it is obtained through the same standard procedure.

Deposition Rate

General equation of deposition rate for cohesive sediment (Winterwerp 1989) is as follows:

$$D_{ep} = \left(1 - \frac{\tau_b}{\tau_d}\right) w_s c_b \quad \text{for } \tau_b \leq \tau_d \tag{1}$$

where:

D_{ep} = deposition rate (kg/m^{2}s)
w_s = sediment settling velocity (m/s)
c_b = sediment concentration in bed (kg/m^3)
τ_b = applied bed-shear stress (N/m^2)
τ_d = critical bed-shear for deposition (N/m^2)

Deposition process is the process in which suspended load in water filled the bed channel and becomes cohesive bed sediment. Deposition process of cohesive sediment depends on the combination of various factors, including size of particles, settling velocity, and forces from particle units. These units may consist of single particle, flocculation that might settled together in one unit. Critical bed-shear stress for deposition is the bed-shear stress that occurs when the bed sediment is deposited (Winterwerp 1989).

Settling Velocity

Settling velocity of cohesive sediment is the velocity of particles or flocculation on its way to bed due to mass forces. Flocculation occurs because of the cohesiveness on cohesive sediment and influences the settling velocity of sediment. Flocculation also forms larger particles and will has larger mass to make it easier to settle.

Influence of Sediment Concentration

As explained above, flocculation occurs on cohesive sediment. It also influenced by sediment concentration. Larger concentration can forms flocculation with larger particles, which is also enlarging the settling velocity. However, for very large concentrations, particles of settling velocity become slower due to hindered settling effect.

Hindered settling is the effect that the settling velocity of the flocs is reduced due to an upward flow of fluid displaced by the flocs. At very large concentrations, the vertical fluid flow can be so strong that the upward fluid drag forces on the flocs become equal to the downward gravity forces resulting in a temporary state of dynamic equilibrium with no net vertical movement of the flocs. This state, which occurs close to bed, generally is called fluid mud (Van Rijn 1993). In saline suspensions with sediment concentration up to 1,000 mg/l, an increase of the settling velocity with concentration has been observed as a result of the flocculation effect, both in laboratory and in field conditions. When the sediment concentrations are larger than approximately 10,000 mg/l, the settling velocity decreases with increasing concentrations due to the hindered settling effect. Settling velocity in the two ranges was expressed by Van Rijn (1993), Mehta (1984), and Mehta (1993).

EXPERIMENT ANALYSIS

Laboratory experiment has been conducted using bottom withdrawal tube. Experiment on settling velocity used 7 salinities and 7 - 8 concentrations for each salinities.

Relation Between Settling Velocity and Concentration

The bond between the type of sediment with dynamic flow and salinity level needs to be noted. Settling velocity of cohesive sediment in Citanduy River, which was being observed, has the classification of silt and kaolinite mineral. It was observed when the flow was calm, making it easier to be observed and obtained the maximum settling velocity. Besides that, sedimentation is more optimum when the flow was lacking.

From the experiments, two general equations are obtained, which are:

1. Equation for flocculation area (flocculation settling)
   Flocculation area is the range of concentration in which flocculation occurs in the sediment, resulting the increase in settling velocity. In this range of concentration, settling velocity increases proportional with the increase in concentration.
2. Equation when the disturbance occurs on sediment settling (hindered settling)
   Hindrance on sediment settling occurs after the optimum flocculation phase. Optimum flocculation phase maximizes the settling velocity, but then it decreases due to the hindrance on flocculation that grows larger on its size but lacks of movement space. This hindrance decreases the settling velocity as the concentration increases.

Limit of General Equation

Two general equations have its own range and limit of concentration. From each salinity, various limit is obtained. Figure 1 can be used to determine the general equation and limit that applied to all salinities. The limit obtained in Figure 1 is 4.25 gram/l.

Equation for Flocculation Area (Flocculation Settling)

This equation applies when the value of C is between C_1 and C_2 = 0.1 gram/l < C < 4.25 gram/l.

$$w_s = k_1 C^{k_2} \tag{2}$$

where k_1 = constant value of 0.02 - 0.56; k_2 = constant value of 1.06 - 2.03; and w_s = sediment settling velocity (mm/s).

Equation When The Disturbance Occurs on Sediment Settling (Hindered Settling)
This equation applies when the value of C is between C_2 and C_3 = 4.25 gram/l < C < 18 gram/l.

$$w_s = w_{so}(1 - k_3 C)^{k_4} \tag{3}$$

where k_3 = constant value of 0.0045 - 0.025; k_4 = constant value of 3 - 4.65; and w_{so} = value of w_s on concentration C_2.

The obtained result shows the same tendency with the research on Citanduy River that was conducted by Umar (2005) with the value of k_1 = 0.0004 and k_2 = 1.7132. The range of concentration that applied from 0.03 to 1.1 gram/l indicates that it is still on flocculation settling limit.

Research from Van Leussen (1988) gives the same equation where k_1 is the referenced settling velocity and k_2 varied from 0 to 2, depending on the type of sediment. Another research (Mehta 1984) divides 2 concentrations for the equation of settling velocity, which are concentration that ranged from 0.1 to 3.5 gram/l or flocculation settling (with the value of k_1 = 0.513 and k_2 = 1.29) and concentration above 3.5 gram/l or hindered settling (with the value of W_{so} = 2.6 mm/s, k_3 = 0.008, and k_4 = 4.65). The equation of flocculation settling and hindered settling shows the same type of equation, it only differs from the constant value obtained from empirical and from equation limit.

So does with the research from Mehta (1993) which stated that flocculation settling shows the same type, but hindered settling shows the type than rather different.

Both researches only stated the relation between settling velocity and concentration of suspended sediment, but didn't give any explanation about salinity, resulting the salinity for the applied equations is unknown.

Relation Between Settling Velocity and Salinity
Based on the experiment result, settling velocity on cohesive sediment was not only affected by concentration, but also by salinity. From 7 salinities used on the experiment (0‰, 5‰, 10‰, 15‰, 20‰, 25‰, and 30‰ salinity), 15‰ salinity proved to be the optimum salinity and the most influential salinity to obtain the maximum settling velocity of sediment. If salinity above 15‰ was used, the settling velocity of sediment started to decrease significantly as shown in Figure 1, 2, and 3.

Figure 2 depicts the relation between settling velocity and salinity on flocculation settling concentration. It shows that 15‰ salinity becomes the optimum salinity and started to influence from the concentration of 0.75 gram/l. Figure 3 depicts the relation between settling velocity and salinity on hindered settling concentration. It also shows that 15‰ salinity becomes the optimum salinity. Data in 0‰ - 15‰ salinities indicates that the settling velocity of sediment increases as the value of salinity increased, but then the settling velocity of sediment decreased when the value of salinity is over 15‰.

Salinity affects the double diffuse layer surrounding the particles. If salinity increases, double diffuse layer will decreases, then resulting on closer distance between particles and the occurance of Van der Waals force, making the cohesive characteristics become stronger and forming the bigger flocs that increase the settling velocity (Krone 1962).

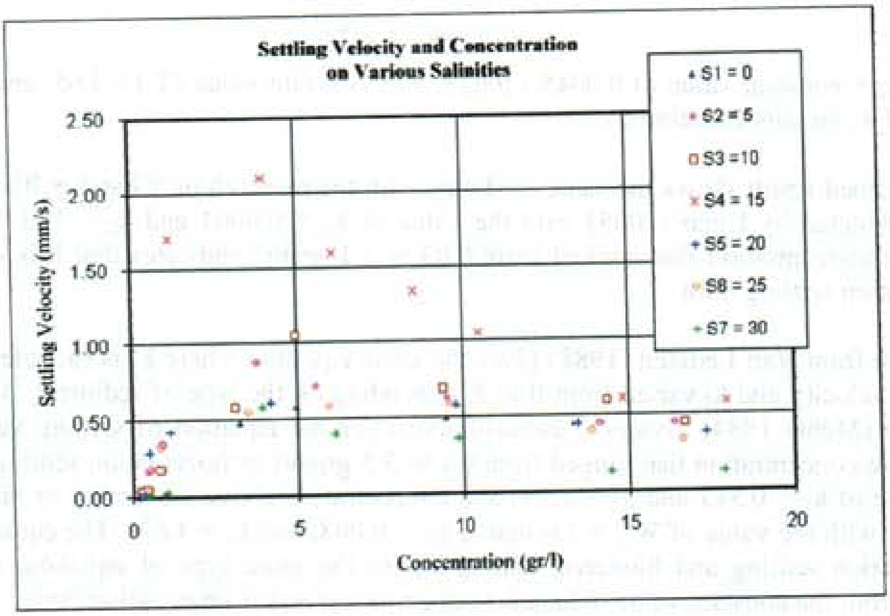

Figure 1. Settling velocity on various salinities

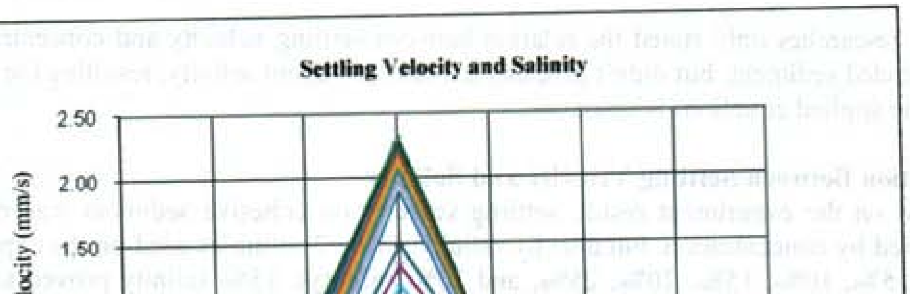

Figure 2. Relation between settling velocity and salinity on flocculation settling

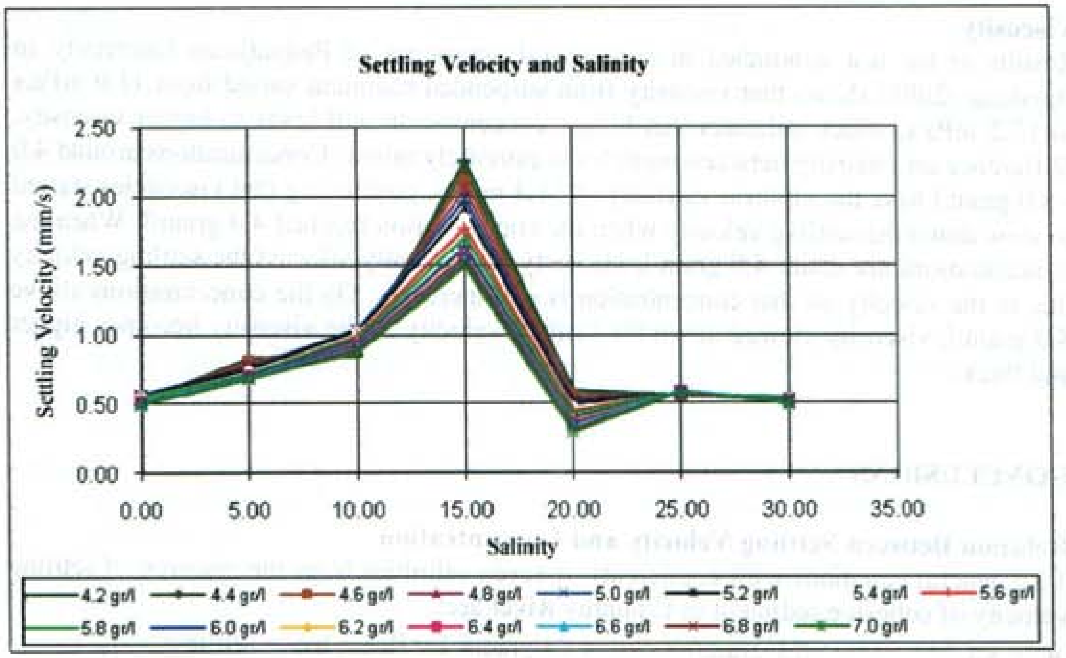

Figure 3. Relation between settling velocity and salinity on hindered settling

Experimental laboratory shows a clear effect of the salinity on settling velocity for salinities up to 10‰ when the sediment concentration is smaller than 1,000 mg/l (Krone 1962). When the sediment concentration is larger than 1,000 mg/l, an almost linear increase of the settling velocity with the salinity can be observed (Owen 1970; Allersma 1967). The highest concentration analyzed in this research was ± 18 mg/l and the maximum settling velocity obtained was on 15‰ salinity.

Mud Mineral Composition

Test results from the analysis of mud mineral in Segara Anakan estuary issued by the laboratory of mineral chemistry and environment, Department of Energy and Mineral Resources of Indonesian Republik (2004) are as follow:

Composition of mineral: Kaolinite, Anorthite, and quartz.
The composition consists mostly of kaolinite. The least mineral contented in the composition is quartz.

From the composition, surface area and CEC value can be obtained (Winterwerp 1989). Kaolinite has the lowest value of CEC and surface area compared to illite and montmorillonite, indicating that kaolinite has little drawing characteristic of cation and anion, thus needed bigger concentration to reach optimum flocculation for maximizing settling velocity compared to illite and montmorillonite. This result can make the concentration limit (4.25 gram/l) becomes bigger than the result from Mehta (1984) with the amount of 3.5 gram/l or Mehta (1993) with the amount of 3.0 gram/l.

Viscosity

Results of the test conducted in agricultural laboratory of Padjadjaran University in Bandung (2004) shows that viscosity from suspended sediment varied from 11.0 mPa.s to 12.2 mPa.s, which indicates that bigger concentration will leads to bigger viscosity. Difference on viscosity between particles is extremely minor. Concentrations around 4.0 - 8.0 gram/l have the uniform viscosity of 11.4 mPa.s, concluding that viscosities started to slow down the settling velocity when the concentration reached 4.0 gram/l. When the concentrations are under 4.0 gram/l, viscosity hasn't really affected the settling velocity due to the velocity on that concentration is still increases. On the concentrations above 8.0 gram/l, viscosity slowed down the settling velocity as the viscosity becomes bigger and thick.

CONCLUSIONS

Relation Between Settling Velocity and Concentration

Two general equations with coeficients of seven salinities from the research of settling velocity of cohesive sediment in Citanduy River are:

$w_s = k_1 C^{k_2}$ 0.1 gram/l $< C <$ 4.25 gram/l for flocculation settling;
w_s = settling velocity (mm/s); C = sediment concentration, gram/l; k_1 = 0.02 - 0.56; k_2 =1.06 - 2.03

$w_s = w_{SO}(1 - k_3 C)^{k_4}$ 4.25 gram/l $< C <$ 18 gram/l for hindered settling;
w_{so} = settling velocity on concentration C_2; k_3 = 0.0045 - 0.025; k_4 = 3 - 4.65

In general, after seven salinities were analyzed, the results obtained are as follow:

- flocculation settling (0.1 gram/l $< C <$ 4.25 gram/l):
  k_1 = 0.1353; k_2 = 1.4515
- hindered settling (4.25 gram/l $< C <$ 18 gram/l);
  w_{SO} = 2.1 mm/s; k_3 = 0.024; k_4 = 4.65

The change from flocculation settling to hindered settling occured in 4.25 gram/l concentration. Viscosity increases as the concentration also increases. In concentrations of 4.0 - 8.0 gram/l, uniform viscosity is obtained, which is 11.4 mPa.s. This research concludes that when the concentration reached 4 gram/l, viscosity starts affecting and slowing down the settling velocity. Whereas for the concentration under 4 gram/l, viscosity hasn't affected the settling velocity as the velocity still increases.

The equations obtained from the analysis are supported by the research of Umar (2000), Van Leussen (1988), and Mehta (1984).

Relation Between Settling Velocity and Salinity

Salinity affects the double diffuse layer surrounding the particles in an inverse proportional relation. If the salinity increases, the double diffuse layer surrounding the particles will decreases. This relation results on closer distance between particles and the occurance of Van der Waals force, making the cohesive characteristics become stronger and forming the bigger flocs that increase the settling velocity. This research obtained the optimum salinity value on 15‰ with concentration from 0.1 gram/l to 4.25 gram/l, then the settling velocity will decrease for concentration from 4.25 gram/l to 18 gram/l. Any increase of salinity value above 15‰ didn't affects the double diffuse layer and didn't strengthens the cohesive characteristics.

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