CHAPTER 72

ON THE DEPOSITIONAL PROPERTIES OF ESTUARINE SEDIMENTS

by

Ashish J. Mehta[1] and Emmanuel Partheniades[2]

ABSTRACT

The depositional characteristics of flocs of fine cohesive sediments in a turbulent flow field differ distinctly from those of a cohesionless material such as sand. This difference exists because the floc size and shear strength distributions depend on the sediment type as well as the flow condition itself; consequently, the problem of the depositional behavior of these flocs is rather complex, and not easily amenable to analytic treatment.

The present basic experimental study was carried out in a specially designed annular channel. The derived laws of deposition in relation to the time-rates as well as the steady-state concentrations are described and discussed. The reanalyzed results of other limited investigations agree well with the result of the study.

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[1] Assistant Research Scientist, Coastal and Oceanographic Engineering Laboratory, University of Florida, Gainesville, Florida 32611.

[2] Professor of Hydraulic Structures, Aristotelian University of Thessaloniki, Thessaloniki, Greece; Professor, Department of Civil and Coastal Engineering, University of Florida, Gainesville, Florida 32611.

INTRODUCTION

Shoaling of fine cohesive sediments is often of considerable importance in characterizing the hydraulic as well as geomorphic regimen of such coastal features as tidal entrances, bays and estuarine navigation channels, where the presence of relatively high salinity and low flow velocities results in the deposition of flocculated fine-grained sediments carried by the flow. The sediment itself may be derived from upstream river sources, or it may be transported into the estuary or bay through the ocean entrance by the upstream salinity currents. When the sediment load is heavy, dredging becomes necessary and, in general, a costly operation. This and other problems, such as locating a safe area for dumping of fines from dredge spoils,has created a significant interest in investigating the laws governing the depositional behavior of cohesive sediments.

Until recently, most basic investigations dealing with elucidating the laws of sediment transport were confined to studying cohesionless, or coarse materials such as sand and gravel. Such was the case partly because coarse particles have relatively well-defined physical and mechanical characteristics and therefore their behavior in a given flow field is well-suited to an analytic description and experimental varification, as for example the bed-load function theory formulated by Einstein (1950) indicates. Unfortunately, in contrast to coarse sediments, fine cohesive sediments exhibit a much more complex behavior in a flow field, as the sequel points out.

Nature of Cohesive Sediments - The predominant constituents of cohesive sediments are silt and clay, consisting of particles of sizes less than about 60 microns. A significant characteristic of these particles, particularly those in the less than 2 micron range (clay fraction) is their plate-like structure, with a large specific surface area (surface area per unit weight) as compared with cohesionless particles, such that the physico-chemical surface force acting on any such particle is in general orders of magnitude stronger than the gravity force represented by the submerged weight of the particle. Under the influence of certain minimum amounts of ionic constituents such as salt, in an ambient medium such as water, the physico-chemical forces become strongly attractive, and cause the particles to cohere into aggregates, or flocs, when brought together by collisions, in a turbulent shear flow field. The flocs often are orders of magnitude larger than the individual particles, and are much more prone to settlement in a given flow field, because of their relatively large settling velocities.

Inasmuch as flocculation depends on the physico-chemical surface forces of the cohesive material, the ionic medium and on the flow condition, the floc size and shear strength distributions are expected to vary with the type of sediment-water suspension, as well as the flow itself. This makes the problem of the depositional behavior of flocculated cohesive sediments rather complex. Thus Partheniades (1971), in discussing the differential sediment continuity equation derived by McLaughlin (1961), has noted, that it is difficult to integrate this equation to obtain an analytic solution for the law of deposition, because the free surface and bottom boundary conditions are unknown functions involving the floc settling velocity and the turbulent diffusivity. As a consequence, studies on the depositional behavior of cohesive sediments have mainly been experimental.

Previous Studies - Krone (1962) conducted an important but limited series of tests on the measurement of rates of deposition of Bay mud from the San Francisco Bay in a straight flume, and essentially correlated his results with the bed shear stress. For suspended sediment concentrations less than 300 ppm, his measurements indicated an exponential decrease in the suspended concentration with time. For concentrations between 300 ppm and 10,000 ppm, a logarithmic relationship between concentration and time was obtained, whereas for concentrations in excess of 10,000 ppm, another logarithmic relationship was obtained, and the rate of deposition was found to be relatively slow. Krone also observed that there exists a critical shear stress τ_c above which no deposition can take place, while at lower shear stresses, all sediment must eventually deposit. From experimental measurements, τ_c, for the Bay mud suspension was found to be in the range of 0.60 to 0.78 dynes/cm^2.

The deposition tests of Partheniades (1965) were adjunct to his erosion studies on the Bay mud; he observed that in a given test, after a period of relatively rapid deposition, the suspended sediment eventually approached an apparent "equilibrium value". It was noted that two deposition runs, one of high and one of low initial suspended concentration resulted in nearly the same ratio of the apparent "equilibrium concentration" to the concentration at the beginning of the run. From this observation it was concluded that for a given flow condition, a constant proportion of the total initially suspended cohesive material (silt and clay) is always carried in suspension. Mehta (1973) used the data of Partheniades to derive a critical shear stress τ_c of 0.65 dynes/cm^2 which is consistent with the values obtained by Krone.

It is noteworthy that Partheniades obtained an "equilibrium concentration" for runs with shear stresses greater than τ_c whereas most of Krone's tests were conducted at shear stresses less than τ_c; therefore Krone did not observe the phenomenon associated with the equilibrium concentration, and erroneously postulated, as noted earlier, that no sediment deposition can take place for bed shear stress greater than τ_c.

Rosillon and Volkenborn (1964) studied the depositional behavior of Maracaibo sediment. They noted the effects of depth, initial suspended concentration and salinity on the rate of deposition. In two of their runs, the suspended sediment concentration apparently reached an "equilibrium" value; however, an examination of their data reveals that some of their runs were not carried out for long enough periods to determine whether equilibrium concentrations would be attained; this fact limited the possibility of a systematic analysis of their measurements.

The various studies described above were able to isolate some important factors affecting the rates of deposition, such as the bed shear stress, depth of flow, type of sediment, initial suspended concentration and salinity. However, the ranges of these variables studied were limited, and therefore, no generalized conclusions could be drawn from the results. It was further realized that straight flumes tend to disrupt the flocs when they pass through the return pipe and diffusers. Primarily to obviate this problem, a special annular rotating channel-ring assembly was constructed at M.I.T. and experiments were conducted using kaolinite clay in distilled water (Partheniades, Cross and Ayora, 1968). A major advantage of this type of apparatus is that it can essentially generate a flow that is uniform at every section, and is free from any floc-disrupting elements. The present investigation was also carried out in a similar but larger apparatus constructed at University of Florida and its attributes will be discussed in the sequel.

OBJECTIVES

The investigation described here was to a certain extent a continuation of tests initially conducted at M.I.T., but with a much broader scope. The following were its main objectives:

1. A study of the effects of flow parameters on the rates of deposition of flocculated fine sediments under turbulent flow conditions, and derivation of quantitative relationships describing these effects.

2. Generalization of the law relating the "equilibrium concentration" to flow parameters.

3. Identification of physico-chemical parameter(s) which may be used to characterize the cohesive characteristics of a given sediment.

EQUIPMENT AND TEST PROCEDURE

The components of the basic experimental equipment consisting essentially of a system of rotating ring and annular channel (Fig. 1) are briefly described below; a detailed description may be found elsewhere (Mehta and Partheniades, 1973b).

The two main components were: (a) an annular fiberglass channel, 8 in. wide, 18 in. deep and 60 in. in mean diameter containing the sediment suspension and (b) an annular plexiglass ring of the same mean diameter as the channel but slightly less than 8 in. wide. The ring could be positioned

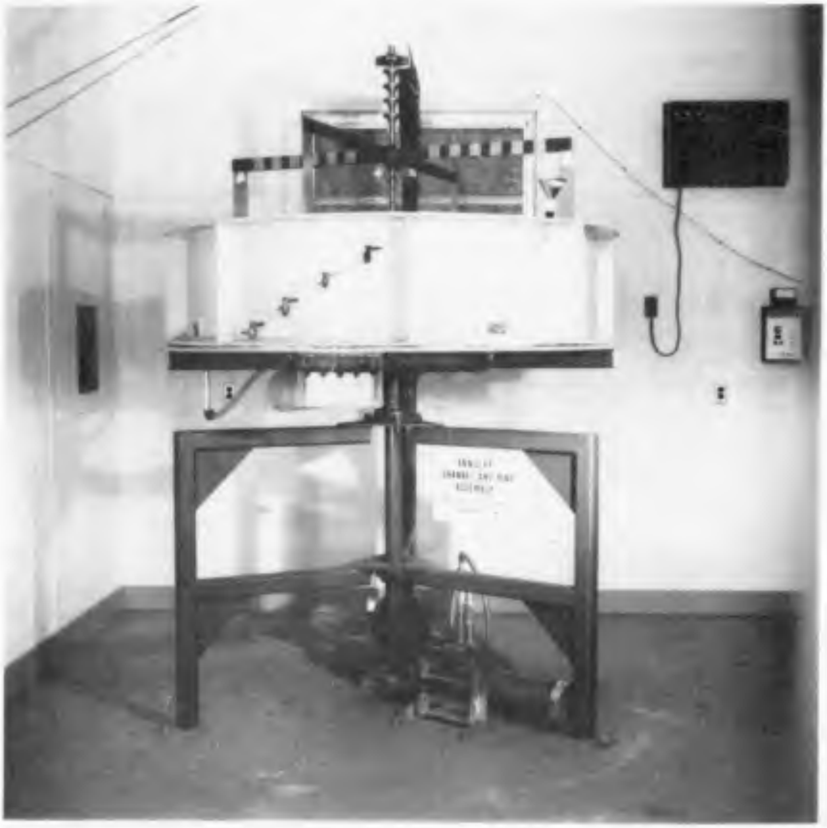

Fig. 1 Annular Channel and Ring Assembly.

within the channel so as to remain in contact with the water surface. A uniform turbulent shear flow field could be generated by a simultaneous rotation of the channel and the ring in opposite directions at a given "operational speed" at which the radial secondary currents generated by the channel were counter-balanced by corresponding currents caused by the ring, in the opposite sense. An operational speed was determined by selecting a channel speed, and then varying the ring speed until a number of 3/8" plastic beads with a specific gravity of 1.04 placed at the bottom of the channel moved uniformly without shifting either towards the outer wall or towards the inner wall of the channel. Later, the same procedure was repeated using kaolite clay, and the uniformity of the deposited material across the width of the channel was checked by measuring the depth of the deposited bed. Four sample taps at different elevations were provided, as shown in Fig. 1, to withdraw suspended sediment samples into bottles on the rack attached below the channel. Water lost due to sample withdrawal could be replenished from a funnel at the top of the channel. Because the ring had to stay on the water surface to generate flow, the channel bed shear stress was measured by introducing a false annular plexiglass bottom which was attached to the channel bottom by means of steel blades with strain gages. Through proper calibration the bending of the blades produced by a given shear stress on the false bottom was registered by the strain gages on a meter outside the channel.

Four types of sediments were studied, namely a) a kaolinite clay from Bath, South Carolina, mined by Dixie Clay Company; this clay immediately flocculates even in distilled water, b) San Francisco Bay mud, whose predominant clay mineral constituent is montmorillonite, followed by illite, kaolinite, halloysite and chlorite, as well as organic matter, c) Maracaibo sediment from Venezuela, which contains an abundance of quartz in the silt size range, and illite, followed by Kaolinite, montmorillonite and chlorite in the clay fraction; it also contains organic matter, which, as in the case of Bay mud, imparts a greyish color to the sediment, and finally d) a 50/50 mixture of kaolinite and Bay mud.

Distilled water as well as salt water at sea water salinity were used for tests with kaolinite, whereas the other three sediments were tested in salt water only. The initial suspended sediment concentration C_o was varied from approximately 1,000 to 26,000 ppm, while the bed shear stress τ_b was varied from 0 to approximately 11 dynes/cm^2. Flow depths of 6, 9, 12 and 13 in. were selected. The test procedure essentially consisted in stirring the suspended sediment at a high speed, to break up any chunks of sediment, and then rapidly lowering the speed to an "operational" value, to allow deposition of the material to commence. From time to time the suspended material was then withdrawn and its concentration determined through vacuum-filtration of the sample.

TEST RESULTS

The first extensive sets of tests were carried out with kaolinite in distilled water. The primary purpose of these measurements was to investigate the hydrodynamic interaction between the settling flocs and the flow, by keeping the sediment type and water quality constant.

Fig. 2 shows a typical set of time (t)-concentration (C) runs. These are all at C_0 = 1,005 ppm with a flow depth of 6 in., and τ_b varying from 0 to 3.55 dynes/cm^2. It is clearly observed from this figure that in each case, after a period of relatively rapid deposition, the suspended concentration C attains a constant steady-state value, which was previously referred to as "equilibrium concentration", C_{eq}. In what follows, these two aspects, namely, the time dependent part of the runs and the steady-state part of the runs represented by C_{eq}, are discussed.

Degree of Deposition - In Fig. 3, the ratio C_{eq}/C_0, such as may be obtained from Fig. 2, is plotted against the bed shear stress τ_b, for all the tests carried out with kaolinite in distilled water. Here, although runs at different values of C_0 have not been separated by different symbols, it was found, that the data points fall randomly about a single line; this for instance is clearly observed with respect to data taken at different depths of flow. This very interesting observation has the implication that for a flow at a given bed shear stress and sediment type, the ratio C_{eq}/C_0 remains constant, and is independent of the depth of flow or C_0. Thus for example, at τ_b = 3.1 dynes/cm^2, if C_0 is 2,000 ppm, then C_{eq} will be 1,000 ppm. If on the other hand, C_0 is 20,000 ppm, then C_{eq} will be 10,000 ppm. In other words, the amount of sediment that can be maintained in suspension at steady-state depends not on the flow condition, but is contingent upon the available initial quantity of suspended sediment. This behavior contrasts with the transport process for coarse cohesionless sediments, whose bed material transport is governed by an exchange of the sediment particles between the bed and the suspension, such that in a state of equilibrium the number of particles depositing per unit area per unit time equals the number eroding per unit area per unit time. Consequently, the equilibrium concentration of the coarse suspended bed material, depends not on the availability of suspended material of the same kind, but solely on the flow condition itself, inasmuch as the exchange rates themselves depend on the latter.

C_{eq} is thus not an equilibrium concentration but rather represents a constant amount that indefinitely remains in suspension at steady-state, at a given flow condition. This further implies that any exchange of particles between the bed and the suspension, as occurs in the case of cohesionless materials must be precluded for cohesive sediments; this is a fundamental difference between the hydrodynamic behavior of cohesionless and cohesive sediments. Partheniades, Cross and Ayora (1968) confirmed this conclusion directly by flushing the annular channel of the suspended material at steady-state. They found that, in this condition the bed exhibited no erosion and the flowing water above the bed remained clear.

Another interesting feature of Fig. 3 is the existence of a well-defined minimum shear stress, τ_{bmin}, below which no amount of material can remain in suspension indefinitely. This shear stress is the same as τ_c obtained by Krone (1962), but contrary to his postulation, it does not represent a shear stress above which no amount of material can deposit. From Fig. 3, τ_{bmin} = 1.80 dynes/cm^2 for the suspension of kaolinite in distilled water.

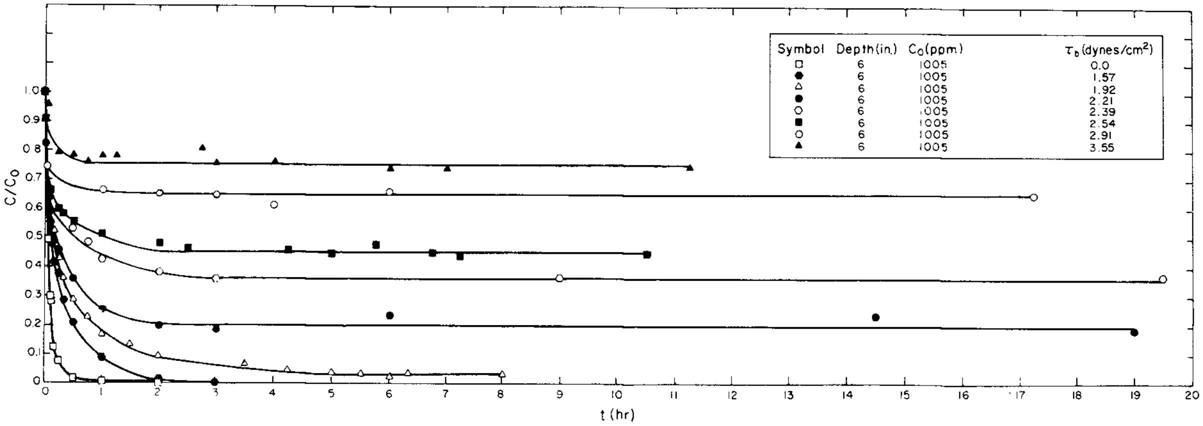

Fig. 2 Ratio C/C_0 of Instantaneous to Initial Suspended Concentration versus Time t for Tests using Kaolinite in Distilled Water.

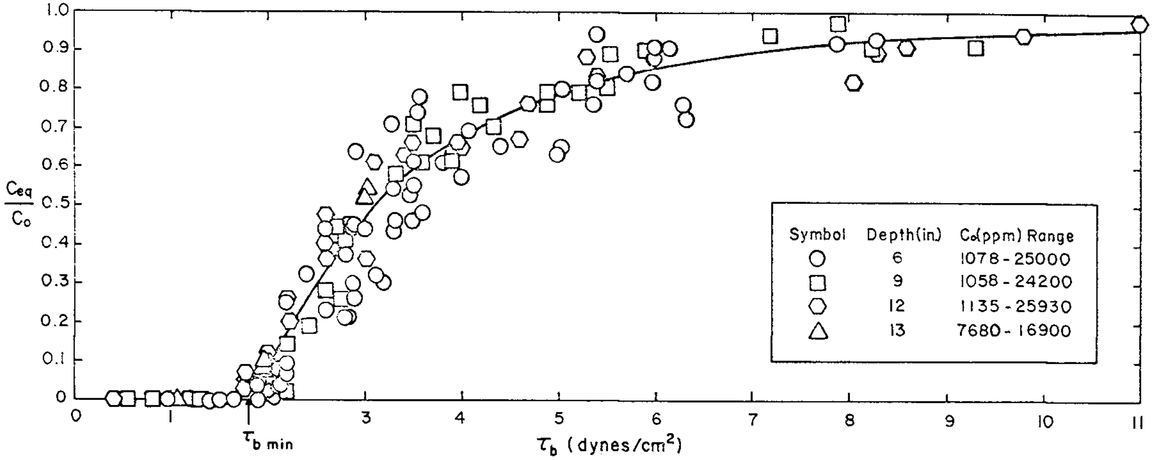

Fig. 3 Ratio C_{eq}/C_o of Steady-State to Initial Suspended Concentration versus Bed Shear Stress τ_b.

It should be noted that the fraction $1 - C_{eq}/C_o$ represents the degree of deposition at steady-state. In Fig. 4, the data of Fig. 3 are plotted on a log-normal paper, in terms of $C^*_{eq} = C_{eq}/C_o$, in percent, as a function of the dimensionless parameter $\tau^*_b - 1$, where $\tau^*_b = \tau_b/\tau_{bmin}$. The straight line on the plot is represented by the expression

$$C^*_{eq} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{y_a} e^{-w^2/2}\, dw \qquad (1)$$

where

$$y_a = \frac{1}{\sigma_1} \log[(\tau^*_b - 1)/(\tau^*_b - 1)_{50}] \ . \qquad (2)$$

Here, σ_1 is the standard deviation, $(\tau^*_b - 1)_{50}$ is the geometric mean of the log-normal relationship and w is a dummy variable. For the data of Fig. 4, $\sigma_1 = 0.49$ and $(\tau^*_b - 1)_{50} = 0.72$.

The plot of Fig. 5 is similar to Fig. 4, except that it is normalized with respect to the geometric mean $(\tau^*_b - 1)_{50}$. Here, Series A (at a depth of 6 in. and $C_o = 6{,}140$ ppm) and Series B (at a depth of 9 in. and $C_o = 10{,}270$ ppm) correspond to measurements using kaolinite in salt water in the annular apparatus. Series C is for the 50/50 mixture of kaolinite and Bay mud in salt water and Series D is using Bay mud in salt water. Measurements of Partheniades, Cross and Ayora (1968), Partheniades (1965) and Rosillon and Volkenborn (1964) are also included.

An interesting aspect of Fig. 5 is that even though values of τ_{bmin} and $(\tau^*_b - 1)_{50}$ are different for different suspensions, the value of $\sigma_1 = 0.49$ for the standard deviation is seen to hold for all the data; thus suggesting a universality of this coefficient. This implies that C^*_{eq}, and therefore, the degree of deposition is uniquely determined by the ratio of $(\tau^*_b - 1)/(\tau^*_b - 1)_{50}$, irrespective of the values of $(\tau^*_b - 1)_{50}$ or τ_{bmin}.

It has been shown elsewhere (Mehta and Partheniades, 1973a) that for measurements taken in salt water, $(\tau^*_b - 1)_{50}$ and τ_{bmin} are related, and therefore, only τ_{bmin} need be measured to obtain the degree of deposition of a given sediment. Further, it appears that under certain conditions, τ_{bmin} can in turn be related to the cation exchange capacity (CEC) of the sediment, which is a measurable quantity, and is representative of the cohesive property of the sediment itself.

Rates of Deposition - Since C_{eq} represents the amount of sediment that does not deposit, $C_o - C_{eq}$ represents the amount that gets deposited, and the fraction $C^* = C_o - C/C_o - C_{eq}$ is the fraction of depositable sediment $(C_o - C_{eq})$ which is deposited at any given time. C^* of course varies from zero when $C = C_o$, to unity, when $C = C_{eq}$.

Figs. 6, 7, and 8 show some of the experimental data (from Mehta, 1973) for kaolinite in distilled water, plotted in terms of C^* in percent versus t/t_{50}, where t_{50} is the time at which C^* is 50%. The data points indicate

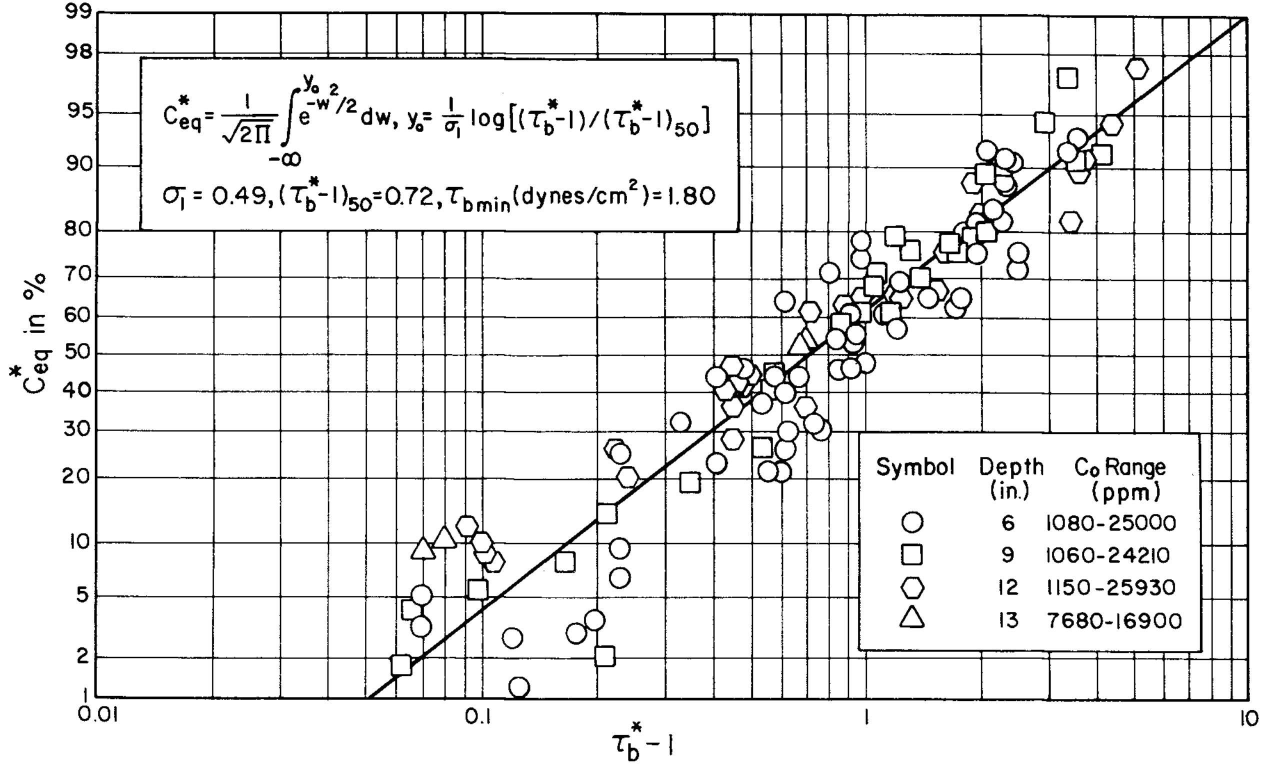

Fig. 4 Relative Steady-State Concentration $C_{eq}^* = C_{eq}/C_0$ versus Shear Stress Parameter τ_b^*-1 for Kaolinite in Distilled Water.

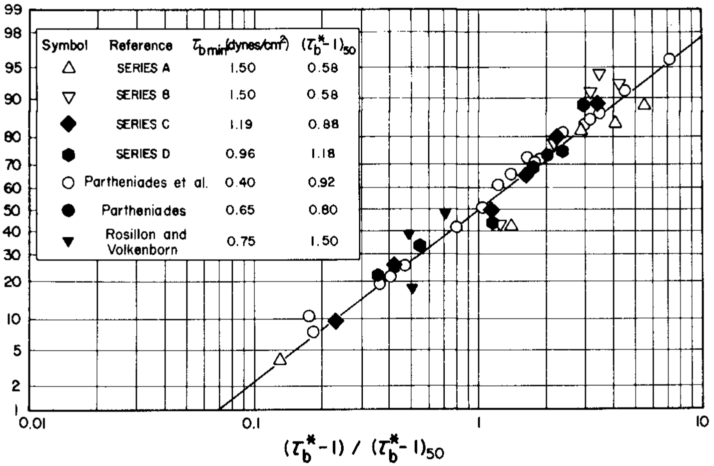

Fig. 5 C_{eq}^* versus Normalized Bed Shear Stress Parameter $(\tau_b^*-1)/(\tau_b^*-1)_{50}$. Data Points are from Different Types of Suspensions (Series A to D) and other Investigations.

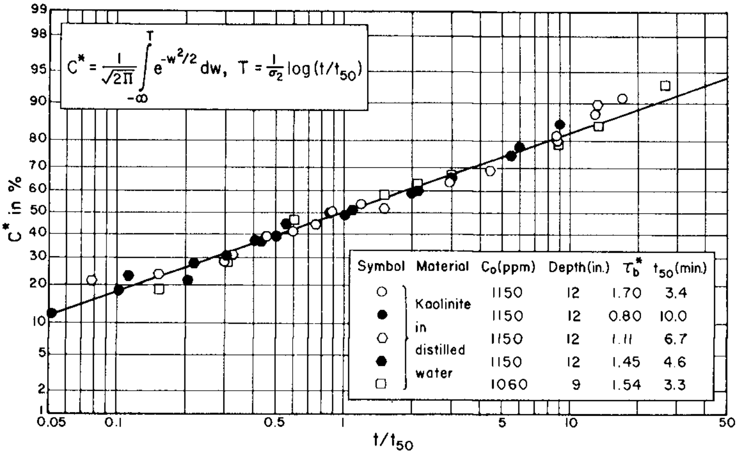

Fig. 6 Fraction of Depositable Suspended Concentration, C^*, versus Normalized Time t/t_{50}, for Kaolinite in Distilled Water.

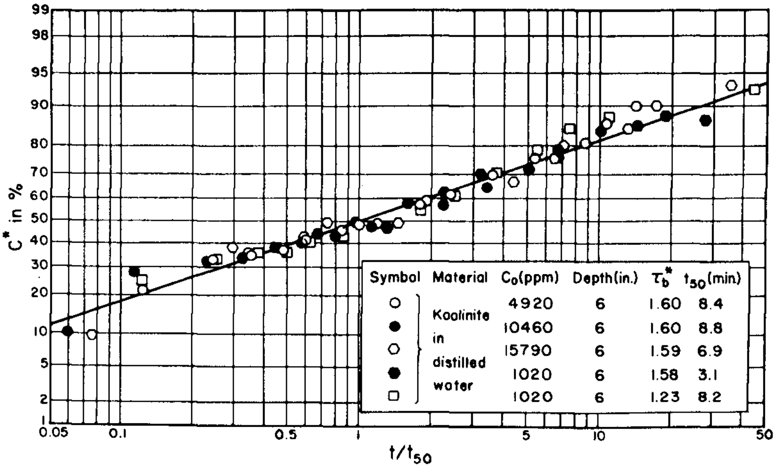

Fig. 7 Fraction of Depositable Suspended Concentration, C*, versus Normalized Time t/t_{50} for Kaolinite in Distilled Water.

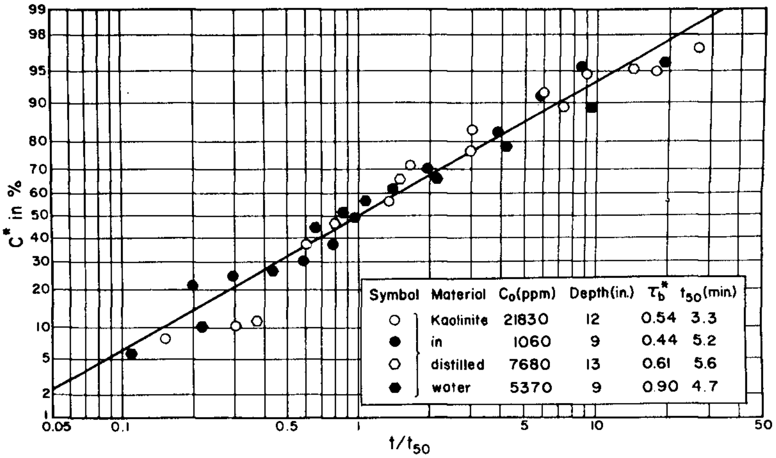

Fig. 8 Fraction of Depositable Suspended Concentration, C*, versus Normalized Time t/t_{50} for Kaolinite in Distilled Water.

the following log-normal relationship for the decrease of suspended concentration with time:

$$C^* = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{T} e^{-w^2/2}\, dw \qquad (3)$$

where

$$T = \frac{1}{\sigma_2} \log[t/t_{50}] \quad . \qquad (4)$$

Here, σ_2 is the standard deviation, t_{50} is the geometric mean and w is a dummy variable. It can be seen from the plots that the log-normal relationship holds for τ_b^* less than unity, i.e., $\tau_b < \tau_{bmin}$, as well as for τ_b^* greater than unity, i.e., $\tau_b > \tau_{bmin}$. From Eqs. (3) and (4), the following expression can be derived for the time-rate of deposition:

$$\frac{dC^*}{dt} = \frac{0.434}{\sqrt{2\pi}\sigma_2} e^{-T^2/2} \frac{1}{t} \quad . \qquad (5)$$

Figs. 9 and 10 show examples of variations of the parameters σ_2 and t_{50} with τ_b^*, depth of flow and initial concentration C_0, for kaolinite in distilled water. In general, the trends are somewhat obscured by the scatter of data points; however, the following broad conclusions may be derived from these and other similar plots obtained by Mehta (1973):

1. The variation of σ_2 and t_{50} with τ_b^* is such that for a particular τ_b^*, the rate of deposition reaches its lowest value. For kaolinite in distilled water, this value of τ_b^* was found to vary between 1 and 2 dynes/cm^2, depending on the value of C_0 and the depth of flow. As τ_b^* decreases below this particular value, the rates become higher, while as τ_b^* increases above this value, the rate also increases, but less significantly.

2. The effect of depth for τ_b^* less than unity is such that increasing the depth tends to increase the rate of deposition. For τ_b^* greater than unity, the effect is less significant and less distinct.

3. The effect of C_0 is such that in general, increasing C_0 decreases the rate of deposition.

Fig. 11 shows examples of some of the rates measured for kaolinite in salt water (from Series B). These also indicate the law given by Eq. (5). The rates are, however, in general slower than for kaolinite in distilled water. Fig. 12 shows two sets of reanalyzed data of Rosillon and Volkenborn (1964) which indicate remarkable consistency with the log-normal law. The rates were, however, much lower than those measured in the annular channel, as indicated by the relatively much higher values of t_{50}. Finally, Fig. 13 shows reanalyzed data of Partheniades (1965) and Krone (1962) which also agree with the log-normal law.

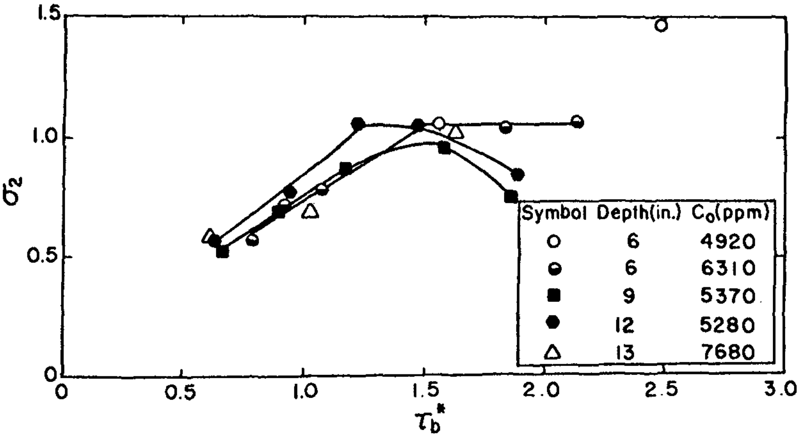

Fig. 9 Examples of Variation of σ_2 with τ_b^* for Kaolinite in Distilled Water.

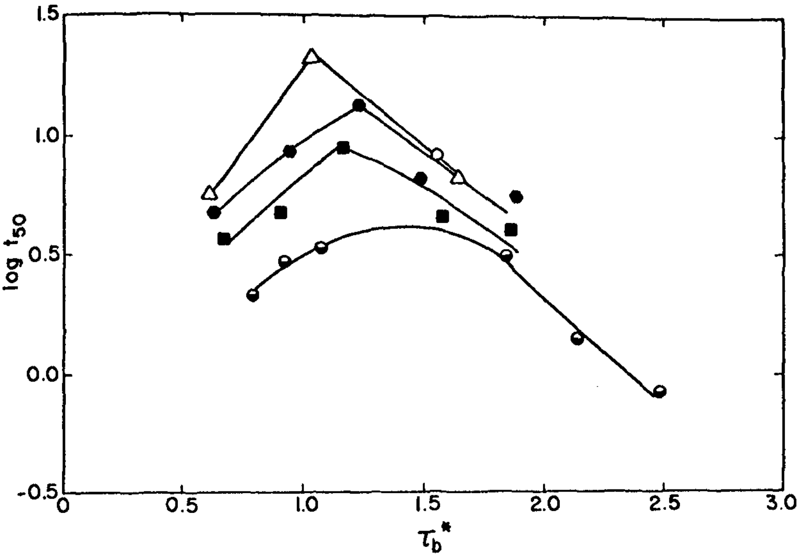

Fig. 10 Examples of Variation of Log t_{50} with τ_b^* for Kaolinite in Distilled Water.

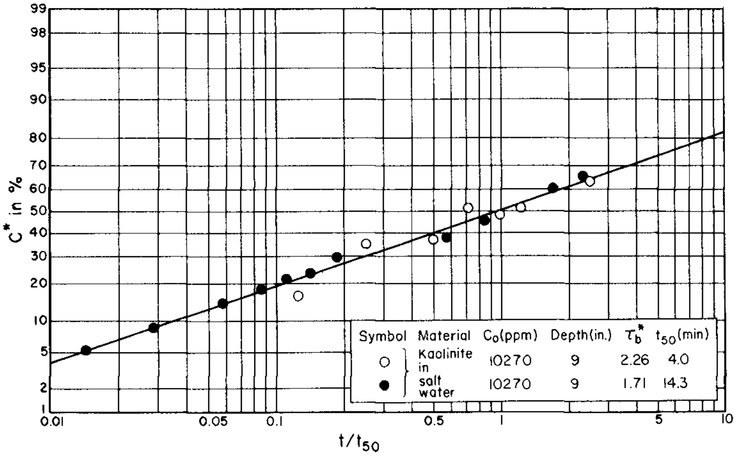

Fig. 11 Fraction of Depositable Suspended Concentration, C*, versus Normalized time t/t_{50} for Kaolinite in Salt Water.

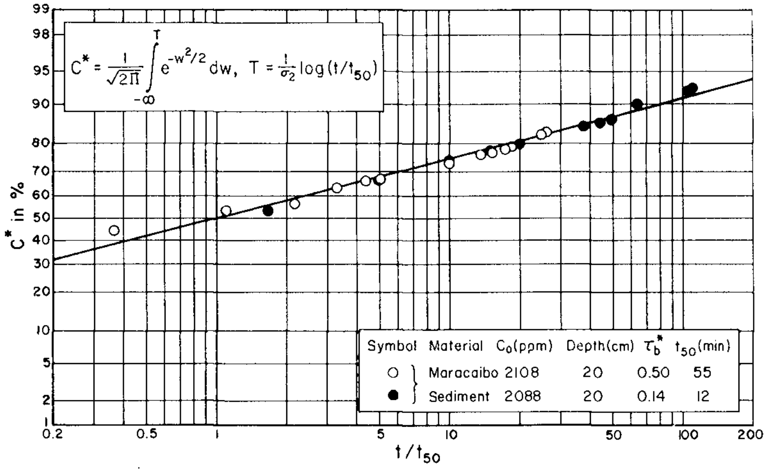

Fig. 12 Fraction of Depositable Suspended Concentration, C*, versus Normalized time t/t_{50} for Maracaibo Sediment.

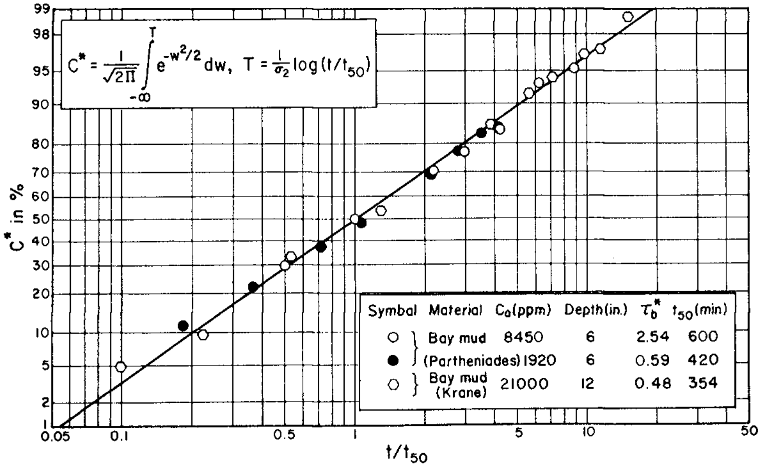

Fig. 13 Fraction of Depositable Suspended Concentration, C*, versus Normalized Time t/t_{50}. Data of Krone (1962) and Partheniades (1965).

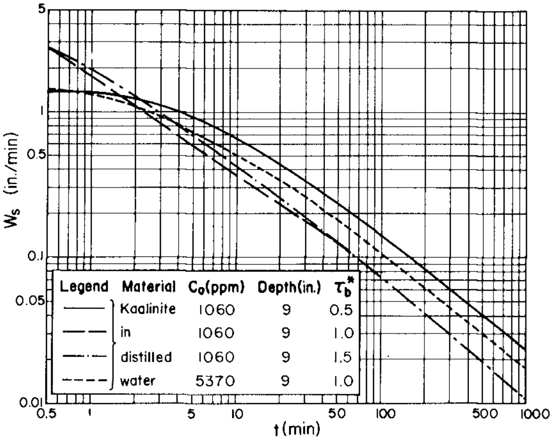

Fig. 14 Variation of Apparent Settling Velocity, W_S, versus time t for Kaolinite in Distilled Water.

It should be pointed out that inasmuch as it is desirable to be able to predict the rate of deposition of any given sediment under a given flow condition, the parameters σ_2 and t_{50} must be functionally related to τ_b^*, depth of flow and C_0, as well as a physico-chemical parameter such as the cation exchange capacity of the sediment. The scope of the present study was, however, limited to experimentally describing the relationships between σ_2 and t_{50} with τ_b^*, depth of flow and C_0 only.

Certain limits were observed in the applicability of the law of Eq. (5). Thus it was noted by Mehta (1973) that for high initial concentrations C_0 of the order of 25,000, Eq. (5) may still be used for $\tau_b^* > 1$, but for τ_b^* less than unity, significant deviations begin to appear. It may further be noted that for τ_b^* of the order of 0.25 and less, for all concentrations, the data may exhibit deviations from Eq. (5).

SETTLING VELOCITIES

The scope of this paper precludes an extensive discussion of the results; such a discussion may be referred to elsewhere (Mehta and Partheniades, 1973b). It suffices to note that the process of deposition of the flocs appears to be controlled by the stochastic turbulent processes in the zone near the bed. There, the strongest shear and lift forces prevail, and these in turn control the size and shear strength distributions of the flocs in suspension. Thus a floc which is strong enough to withstand the maximum shearing force acting on it near the bed will settle on the bed and will attach itself to the bed by cohesive bonds. On the other hand, a floc with a relatively low shear strength will be broken into two or more smaller units and these will be reentrained in the suspension by the strong hydrodynamic lift forces. This hypothesis in fact implies that the steady-state suspension represented by C_{eq} contains flocs that are too weak and small to be able to withstand the shear stresses near the bed and deposit.

The settling velocities of the depositing flocs are of signficance, particularly from an engineering point of view. It is obvious from the foregoing presentation, that inasmuch as the sediment floc size distribution depends not only on the type of sediment-water suspension but also on the flow condition itself, the settling velocities of the flocs can not be derived from extrapolation of results, to smaller particles, obtained for sand grains.

A simple finite volume continuity principle for the sediment in the annular channel may be written as

$$\frac{dC^{**}}{dt} = -\frac{W_s}{h} C^{**} \qquad (6)$$

where $C^{**} = 1 - C^* = C - C_{eq}/C_0 - C_{eq}$ represents the fraction of depositable sediment which is in suspension at any given time, h is the total depth of flow and W_s is the settling velocity. Since as noted the settling flocs are segregated by a stochastic selection process near the bed before some of them actually deposit on the bed, W_s may be viewed as an apparent settling velocity; it thus involves a probability of deposition, which depends on the time-distribution of the turbulent bed shear stress (Mehta, 1973). For a given test, the variation of C** and dC**/dt with time can ultimately be obtained through Eqs. (3), (4) and (5); Eq. (6) can therefore be utilized to determine the variation of W_s with time. Four examples of this nature are given in Fig. 14, where W_s(in/sec) is plotted against time t (min) for Kaolinite in distilled water suspension at C_o = 1,060 ppm, depth h = 9 in. and τ_b^* varying from 0.5 to 1.5 dynes/cm^2. An interesting observation is that for t greater than 10 minutes, the plots begin to exhibit an approximate exponential decrease of W_s with time. Clearly, the settling velocity can not be assumed to be a constant.

APPLICATION

A few brief comments on the applicability of the derived law of deposition in numerical models are in order.

1. Although the law itself may be assumed to be applicable under field conditions, the constants defining the log-normal relationships must necessarily be evaluated through calibration using field data, since the present state of the art does not permit ready determination of these constants from known relationships; the use of the cation exchange capacity is only a first step toward this direction.

2. Sediment dispersion was absent in the annular channel inasmuch as there was no concentration gradient dC/dx in the direction of flow; it is believed this term was also of secondary importance in the straight flume experiments with which the data have been compared. Field application of the law of deposition must be carried out in general in conjunction with the one-dimensional transport-diffusion equation. In this context it may be noted that although deposition is essentially a phenomenon associated with the bottom boundary, in the transport-diffusion equation, the law of deposition may be included as a sink term.

3. Care must be taken in applying the law of deposition derived under a steady flow situation to time varying flows.

ACKNOWLEDGEMENT

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