Experiments To Determine Modes of Cohesive Sediment Transport in Salt Water[1]

H. A. EINSTEIN AND R. B. KRONE

Department of Hydraulic and Sanitary Engineering
University of California, Berkeley

Abstract. Laboratory measurements were made on properties of clay sediments from San Francisco Bay, in conjunction with field measurements, to ascertain the modes of transport and deposition existing in the bay. Laboratory measurements on sediment suspensions, settling rates, rheological properties, and deposition from flowing water showed a dependence of the mode of transport on the suspended sediment concentration and on flocculation kinetics. These qualitative relations are supported by tracer observations of sediment transport processes in the bay.

INTRODUCTION

Land drainage commonly terminates in an estuarial region. In this region, river flows pass through a transition from nearly steady unidirectional fresh water flow to quasi-periodic and littoral movements as they mix with salt water. Because of the unique hydraulic and chemical environment of an estuary, sediment transport is unlike that in other parts of land drainage systems. Coarse sediment, entering an estuary as bed load, encounters reduced transporting capacities of flow as velocities decrease and usually accumulates near the landward end of an estuarial region. Clay and silt particles that are efficiently transported in suspension in river flows are readily deposited in an estuary as a result of the changed hydraulic and chemical environment. Clay minerals remain dispersed in river water because of the repulsive surface forces that prevented aggregation. These forces are depressed by the saline environment of an estuary, and the particles form flocs as particle contacts occur. Fine sediments predominate in estuaries; they largely determine the shoreline and bottom configurations and are a primary problem in channel and harbor maintenance.

Transport processes of such sediments in estuaries are obscured by complex and changing currents and salinities and by the difficulty of observing the sediment directly. Detailed descriptions of sediment movements in an estuary are not practically obtainable. Qualitative information on modes of transport, deposition, and scour, however, is directly useful for describing local sediment behavior, and it logically precedes quantitative study. This paper presents laboratory observations that were made in conjunction with field measurements to establish the modes of cohesive sediment transport in San Francisco Bay. The laboratory experiments were begun for the purpose of determining the effects of suspended sediment on the fluid properties of the suspension and the effects of flocculation on the motion and deposition of suspended sediment. It was also desired to determine the characteristics of cohesive sediment that can easily be measured in the laboratory, to aid in the planning and interpretation of field measurements on estuarial sediment transport.

THE SEDIMENT

Samples of sediment, taken from widely distributed areas of shoaling in San Francisco Bay, uniformly contain more than half clay by weight, the remainder being nearly always less than 100 μ in diameter. The clay minerals are a mixture of illite and montmorillonite, with smaller amounts of kaolinite group minerals. The wide variety of mineral types originate in the variety of soils occurring in areas which drain into the bay. The sediments have a cation exchange capacity of about 30 milliequivalents per 100 grams. Organic matter in surface samples varies with bottom organism population, but analyses commonly run 2 to 3 per cent by weight.

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Modes of Transport

Cohesive sediment transport in the Thames estuary has been described as movement of a 'fluid mud' layer a few feet thick on the bottom, which moves as a result of tidal currents into regions that permit consolidation [*Hydraulics Research Station*, 1956]. The indication of a double bottom from fathometer readings on shoals in San Francisco Bay led those engaged in harbor maintenance to believe that similar transport occurred there. The occurrence of unconsolidated mud in a shoaling area does not necessarily indicate transport to the area in that form. Sediment enters an estuary in general suspension, and it appears probable that continued transport of suspended material occurs in the bay. The modes of transport of cohesive sediment from suspension in an entering stream to a shoal in the bay, or from shoal to shoal, depend on the rate of flocculation of suspended sediment particles, the nature of deposition of the dispersed or flocculent material from suspension, and the flow properties of suspended sediments. Some investigations of these aspects of San Francisco Bay sediment behavior are described.

Flocculation. The kinetics of rapid flocculation of suspended colloids have been derived by Smoluchowski, Tuorila, and Müller, whose works have been summarized by Overbeek [*Kruyt*, 1952]. Relations given by these authors can be used to identify the aspects of flocculation that are significant to estuarial transport. Under salinity conditions that depress the double layer sufficiently to allow the attractive surface forces to predominate, every collision between particles causes a lasting bond. Collisions between particles in suspension result from Brownian motion, local shear of the suspension, and different settling velocities of the particles.

The probability of collision of primary particles due to Brownian motion is

$$I = 4\pi\ D_{ij} R_{ij} \nu_0 \quad \text{per second} \tag{1}$$

where D_{ij} is the mutual diffusion coefficient, R_{ij} is the radius of collision (assumed here to be twice the particle radius), and ν is the number of particles per cubic centimeter.

If D is

$$D = kT/6\pi\eta r \tag{2}$$

wherein k is Boltzmann's constant, T is the absolute temperature, η is the viscosity, and r is the radius of a particle, it can be found, by substitution of D into (1), that, at 20°C,

$$I = 4kT\nu_0/3\eta = 5.4 \times 10^{-12}\nu_0 \tag{3}$$

This shows that the probability of collision due

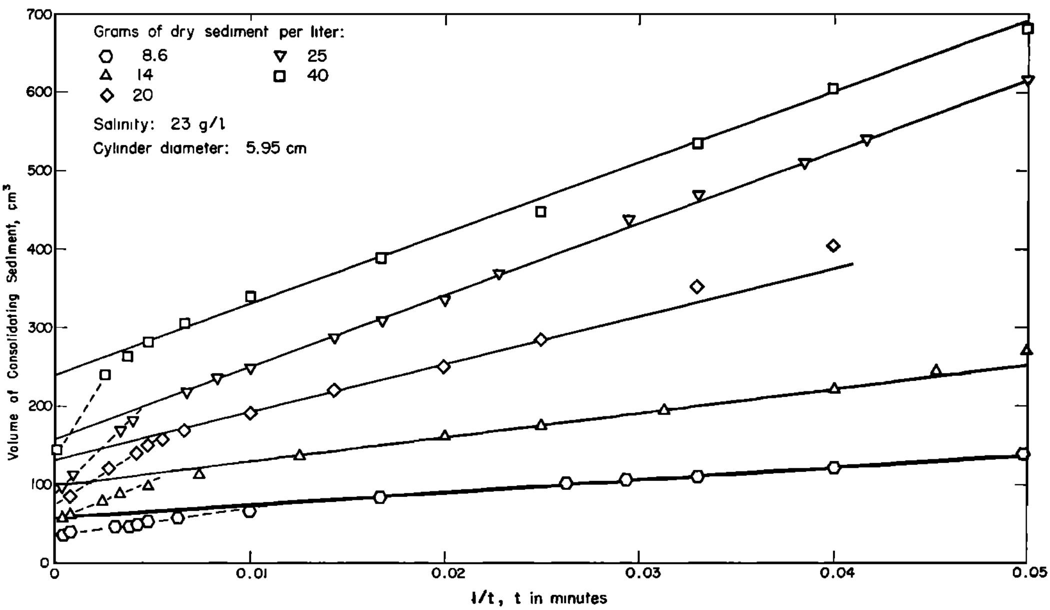

Fig. 1. Consolidation of sediment in 1-liter cylinder.

to Brownian motion depends directly on the number of particles per cubic centimeter.

The concentration of suspended sediment entering San Francisco Bay is usually less than 0.1 g/l. If the average particle diameter is 0.3 μ, ν_0 is 2.7 $\times$ 10^9/cm³, and I = 0.014/sec, or a collision on a primary particle at the start of flocculation every 69 sec. As flocs grow and the number of particles diminish, the collision rate decreases. The average diameter of bay sediment is probably larger than 0.3 μ, making this estimate conservative.

The total number of particles of all kinds, flocs and primary particles, at any time is

$$\nu = \nu_0(1 + t/t_c) \qquad (4)$$

where t is time during which flocculation has progressed and t_c (called the 'time of coagulation') is $1/I$. An estimate of the effect of flocculation by Brownian motion can be made by taking the primary particle density of 2.65, the floc density of 1.20, and the water density of 1.01 g/cm³. After 12 hours' coagulation, the approximate number of primary particles per floc is, ν_0/ν = 630, which is equivalent to a 5.4-μ spherical floc. If a 1-μ primary particle has been selected, ν_0 = 7.2 $\times$ 10^7, ν_0/ν = 17, and a 5.2-μ floc would result. These flocs have about the same settling velocity as a 2-μ primary particle, 3 $\times$ 10^{-4} cm/sec. If the floc has a density of 1.10, the settling velocity would be about 1 $\times$ 10^{-3} cm/sec. It is evident that flocculation resulting from Brownian motion would not prevent transport in general suspension during at least the first 12 hours, or about a tidal cycle in the bay.

The probability of collision of a particle due to local shear in the suspension is

$$J = (4/3)\nu(R_{ij})^3\, du/dz \qquad (5)$$

where du/dz is the local shear rate. It should be noted that if the flocs grow at a uniform rate the increase in R_{ij} is largely compensated by the decrease in ν. When a wide distribution of floc sizes occurs, however, the few large ones have a high probability of collisions with small flocs, because for these collisions both R_{ij} and ν are large. Under this condition, the larger flocs would tend to gather the smaller ones, further modifying the size distribution. The relative effectiveness of the two kinds of particle contact energies can be obtained from (3) and (5):

$$J/I = (\eta R_{ij}^{\,3}\, du/dz)/2kT$$

The relative effectiveness is 1 for a 2-μ particle and du/dz = 1/sec. As the flocs grow larger, however, the relative effectiveness increases very rapidly.

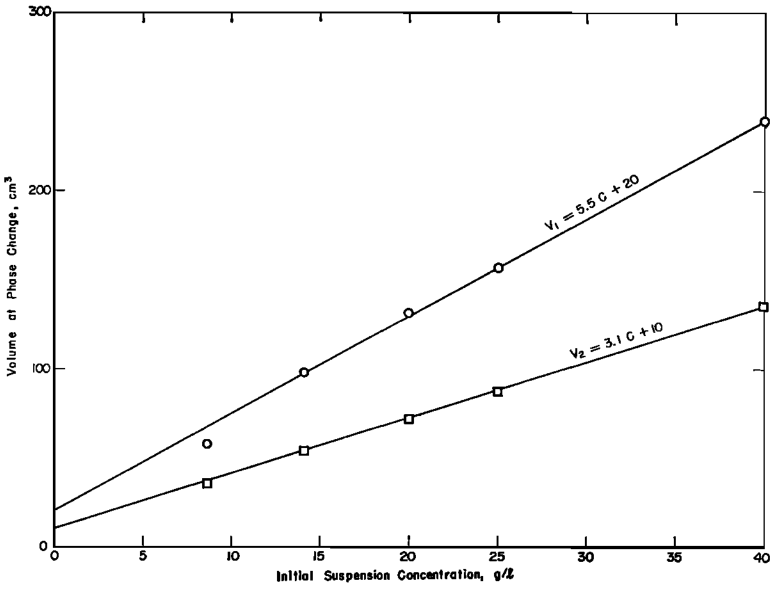

Fig. 2. Volumes of sediment at phase changes, obtained by extrapolation using relation $V/V_\infty - 1 = K/t$.

Similar arguments apply to contacts caused by differential sedimentation rates. It is evident that large flocs will tend to gather smaller flocs in the suspension through which they pass and will thereby grow larger.

These relations indicate that clay sediment can remain in suspension in salt water for considerable periods of time, during which slow growth of flocs occurs due to Brownian motion and local shear in the suspension. After an appreciable size is obtained, internal shear in the suspension can produce (by combining flocs) a condition of rapid increase of the floc sizes. Such an increase in particle size should adversely affect the transport capacity.

Destruction of flocs by high rates of shear, such as that near the bottom at appreciable flow velocities, can also occur. Breaking of flocs near the bed would tend to maintain particle suspension.

Sedimentation. Sedimentation velocities are of direct importance to the transport of sediment by water. The fall velocities of dispersed particles are the basis of particle size distribution measurements and are easily measured in terms of weight of sediment. The fall velocity of well-separated flocs can similarly be observed and, for present needs, can be calculated from Stokes' relation, if the densities are known. The fall velocities of flocculent material in the 'fluid-mud' concentration range, however, are limited by the proximity of adjacent suspended sediment, which restricts the upward flow of displaced water.

It was found that when about 10 grams of sediment or more were uniformly suspended throughout a 1000-cm³ cylinder filled with salt

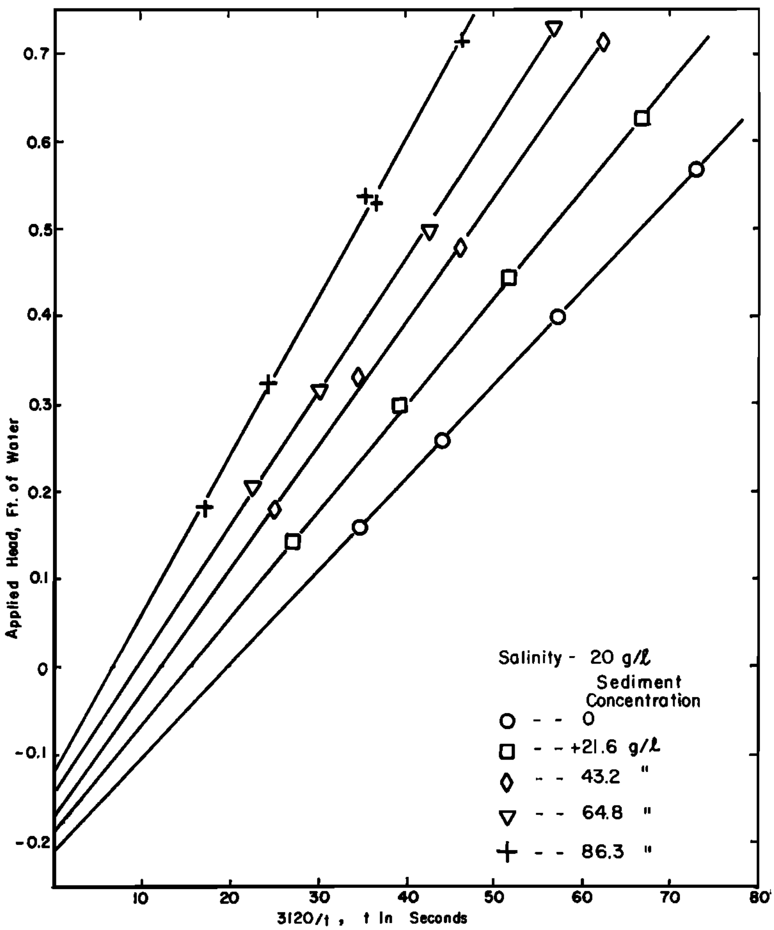

Fig. 3. Viscometer data obtained on bay sediment suspensions.

water, flocculation would occur rapidly, and a well-defined interface between the upper surface of flocculent material and overlying relatively clear water was formed. This fits the descriptions of 'fluid mud.' The height of the upper surface of the flocculent sediment could easily be followed during the hindered settling. Plots of log time against log height (or volume of settling flocculent material) showed, after an initial forming period, two successive well-defined straight lines with a short transition region between. Similar plots are presented by *Work and Kohler* [1940], who worked on slurries. They labeled the initial forming period the 'constant rate period' and the two straight log-log lines the 'falling rate period.' These authors showed that various initial concentrations of suspension gave parallel lines during the falling rate period. A number of relations have been proposed and demonstrated to describe the hindered settling [*Robinson*, 1926; *Powers*, 1939; *Steinour*, 1944]. A dimensionless relation proposed by *Bosworth* [1956] is

$$h/h_\infty - 1 = k/t \qquad (6)$$

where h is the height of the surface of the flocculent material, h_∞ is the surface-height of the final consolidated sediment at infinite time, t is the elapsed time of settling, and k is a constant that includes a reference time. The observed volumes of flocculent bay sediment in graduated

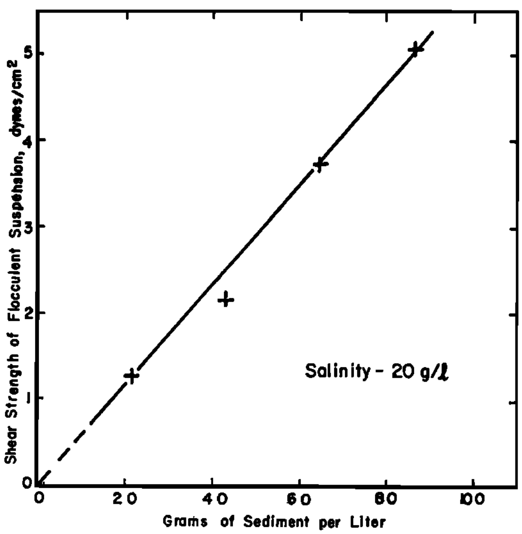

Fig. 4. The increase in shear strength with concentration of connected bay sediment suspensions.

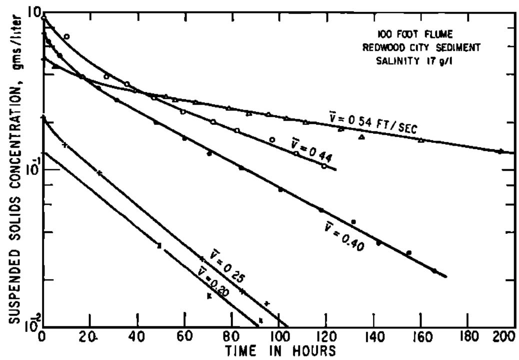

Fig. 5. Deposition of sediment from flowing water.

cylinders are plotted against $1/t$ in Figure 1, which shows that the data fit (6) on both phases of consolidation.

As hindered settling nears the end of the first phase, the lower parts of the suspension begin the second phase of consolidation first, and a transition period persists until the entire column is in the second phase. The fit of the data to (6) facilitates extrapolation of each phase to infinite time by continuing the lines in Figure 1 to the ordinate. The intercepts are the extrapolated volumes of the flocculent material at the end of the consolidation phases.

A plot of the intercept volumes is shown in Figure 2. These volumes are linearly related to the amount of sediment in the cylinder and have slopes of 5.5 and 3.1. The slopes can be explained as the relative volumes of roughly spherical packed flocs and compressed flocs with the inter-floc water removed. If these are the terminal conditions, the inter-floc porosity is 0.44 and the density at the end of the first and second phases is 1.11 and 1.19 g/cm^3, respectively. Suspended floc densities are probably nearer the former value. The concentration at the end of the first phase was 167 g/l of sediment. This concentration appears to be the limiting concentration of bay sediment that can be called 'fluid mud.' If during the first stage the cylinder is tipped, the surface of the sediment responds quickly. During the second stage, the sediment appears to consolidate slowly. The fluid mud phase lasts only about 2 hours in still water, which is a short time in terms of consolidation.

Viscous properties. Sediment transport by flow of fluid mud depends on the viscous properties of suspensions in the fluid mud concen-

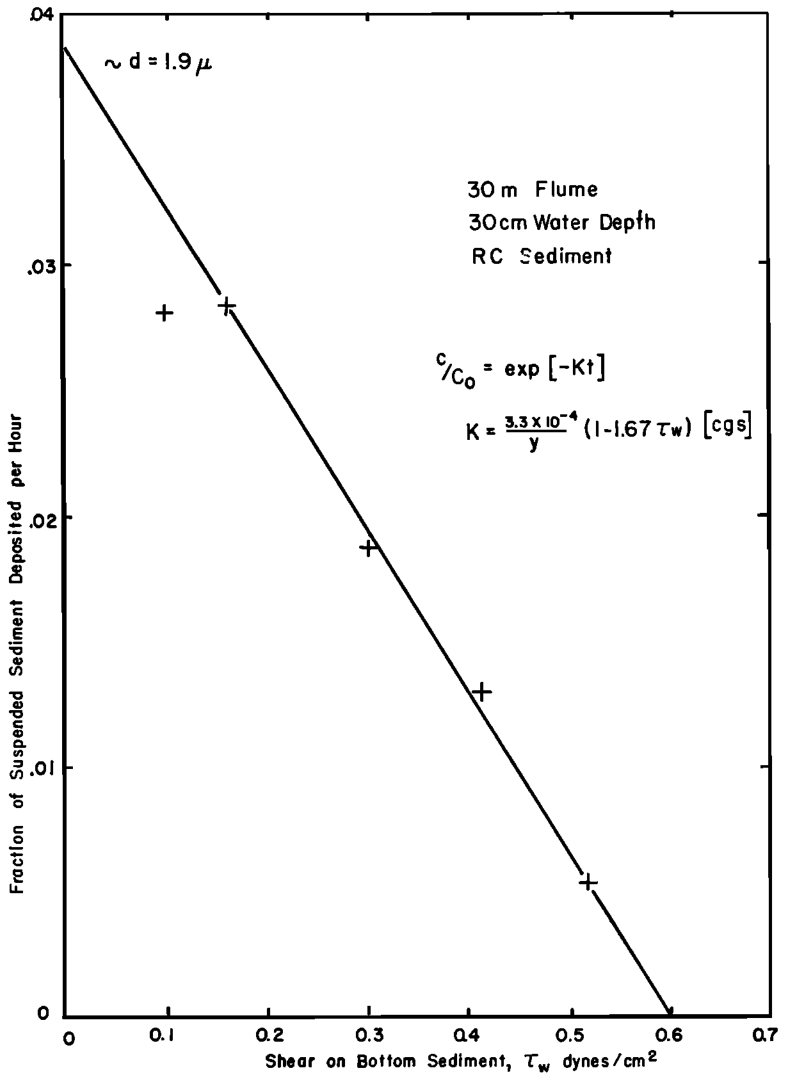

Fig. 6. Net deposition rate of bay sediment in flowing water.

tration range, roughly above 10 g/l of suspended sediment.

Viscous properties of concentrated sediment suspensions were measured by means of an Ostwald capillary viscometer equipped to provide variable driving pressures, as described by *Einstein* [1941]. Samples were screened to remove bits of wood and other organic matter and were diluted to four suspended sediment concentrations by water containing 20 g/l of sea salts. The times for a measured volume of each sample to pass through a capillary were determined at each of four driving pressures. These data are presented in Figure 3.

Poiseuille's relation for flow through a capillary can be rearranged to give

$$H = K\mu/t - H_0$$

where H is the applied driving head, μ is the differential viscosity of the fluid, t is the time for a measured volume to pass through the capillary, H_0 is the average head in the viscometer, and K is a constant that includes the terms describing the geometry of the system. This

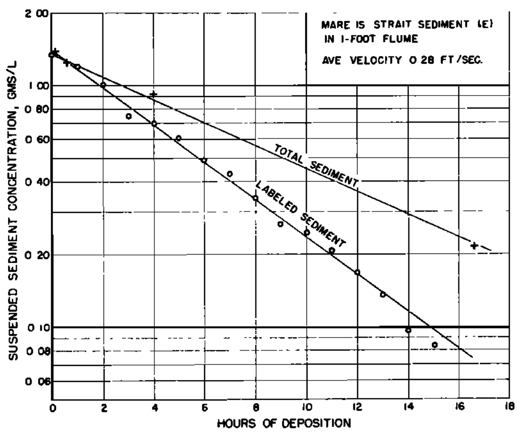

Fig. 7. Suspended sediment concentration in flume during deposition.

constant was found to be 3120 by passing distilled water through the capillary at several driving heads. The points in Figure 3 fit straight lines whose slopes and intercepts on the $K/t = 0$ ordinate change with the concentration of suspended sediment. The differential viscosities taken from the slopes are given on the curves. These data show that bay sediment suspended in salt water has the character of a Bingham fluid.

Intercepts of the lines on the ordinate are the extrapolated values of driving head that the suspensions should resist at zero flow. Taking the differences between the suspension and the salt water intercepts as the head necessary to overcome the yield stress at the capillary wall, the Bingham yield stress values were calculated. These values are plotted in Figure 4, which shows a linear relation between calculated yield stress values and suspended sediment concentrations. The line is extended to zero suspended sediment concentration to show that the relation is a direct proportionality. A system of connected flocculent particles should not exist below about 10 g/l of sediment, however, and static resistance to shear should not be possible. Measurement of sediment at concentrations of more than 90 g/l was not feasible with the Ostwald viscometer, but there is no reason to doubt the existence of the relation to 170 g/l of sediment, considered an upper limit to the fluid mud description.

The observation of shear strength and viscosity shown by sediment in the range of concentrations greater than 20 g/l is the basis for a preliminary qualitative description of estuarial transport modes:

(*a*) Connected, fluid mud gravity flows down slopes of an estuary bottom can certainly occur. The distribution of upward shear into the flow from the lower boundary is probably limited by static resistance to shear, and the differential viscosity of such a fluid is greater than that of water. Gravity flows are limited to slopes sufficiently steep to start and maintain flow. Transport in a typical estuary by this means is limited to short distances. It can be of significance, however, because distribution of high concentrations of suspended sediment into a channel is facilitated from zones of rapid deposition along the channel edges.

(*b*) Movement of connected fluid mud along a channel bottom by flow of the overlying water alone probably does not occur. The concentration of sediment at the bottom of such a layer is no lower than that anywhere above. Consolidation during slack periods reduces the water content in the lower parts of a fluid layer first, causing a gradient of increasing sediment concentration from the upper surface downward. In view of the increased strength with increased sediment concentration shown in Figure 4, shear applied to the top of such a layer would result in movement at the upper surface first. Mixing would then occur with the water flowing above, and the moving particles would be carried into suspension by turbulence.

(*c*) Bay sediment transport by estuarial water movement is largely by transport in general suspension, that is, as particles entirely supported by water. This argument follows from (*b*) and is supported by observation in the estuary.

Concentrations of bay sediment that can resist a given shear by flowing water can be calculated from the extrapolated strength values. As an illustration, the shear applied to the bottom of a 30-foot channel was calculated from the friction velocity, obtained by von Karman's relation, and the resistant sediment concentrations were obtained by means of Figure 4. These concentrations are listed in Table 1, showing that fluid mud can easily consolidate at flow velocities commonly found in docks and estuarial channels.

An estuary is a zone of varying salinities. The effect of salinity on the viscous behavior of sediment was observed by varying the salinity

TABLE 1. Shears Resisted by Sediment in a 30-Foot Channel

Average Velocity, ft/sec	Shear, dynes/cm²	Sediment Concentration, g/l	Bulk Density, g/l
1	0.98	17	1011
2	3.43	59	1051
3	7.37*	127	1092
4	12.6*	217	1148

* Extrapolated values.

of a 54-g/l suspension and measuring its flow rates through the viscometer. The differential viscosity remained unchanged, but the shear strength increased from zero at no salt to its maximum value at 1 g/l of salt. The salinity of sea water is about 35 g/l, and it can be anticipated that the variations of salinity in most of an estuary have only a small effect on the apparent bond strength.

Transport in flowing water. Observations of suspended sediment transport were made in two laboratory flumes, each of which consisted of rectangular channels equipped with propeller pumps and return lines for recirculating sediment suspensions. The dimensions of the channel and the return lines were chosen to minimize deposition in the return lines. A 3-foot-wide channel, 100 feet long, was filled to a 1.0-foot depth of water for the observation described next, and 15-inch and 12-inch lines in parallel were used for the return.

Suspended sediment concentrations observed in San Francisco Bay are usually less than 0.1 g/l. Transport of bay sediments in suspension near this concentration was observed by measuring concentrations of sediment suspended in salt water while the suspension was continuously circulated at uniform velocities. Measured concentration changes with time for transport at several velocities are presented in Figure 5. These data show that at low flow velocities and at less than 300 ppm suspended sediment the concentration of suspended sediment falls logarithmically with time. The deposition rates shown in Figure 5 are slow. At the velocity (in the channel) of 0.20 ft/sec the deposition rate was less than 3 per cent per hour, and at 0.5 ft/sec it was 0.5 per cent per hour.

These deposition rates are plotted against the shear applied by the flow to the bottom sediment, calculated from the friction velocity in Figure 6. There appears to be a linear relation that indicates no deposition at bottom shears exceeding 0.60 dyne/cm². The intercept on the zero shear axis (zero flow velocity) corresponds to the average settling of particles having a Stokes diameter of 1.9 μ, or of small flocs having a low

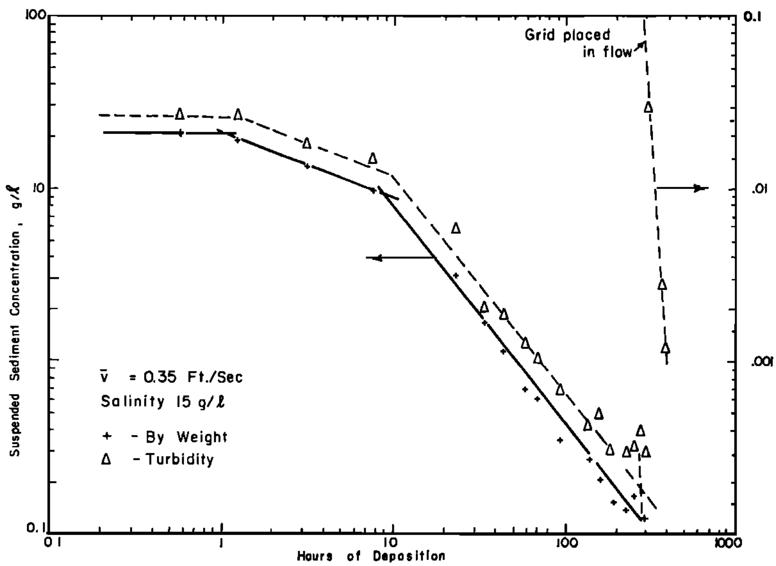

Fig. 8. Deposition of flocculated sediment in flume.

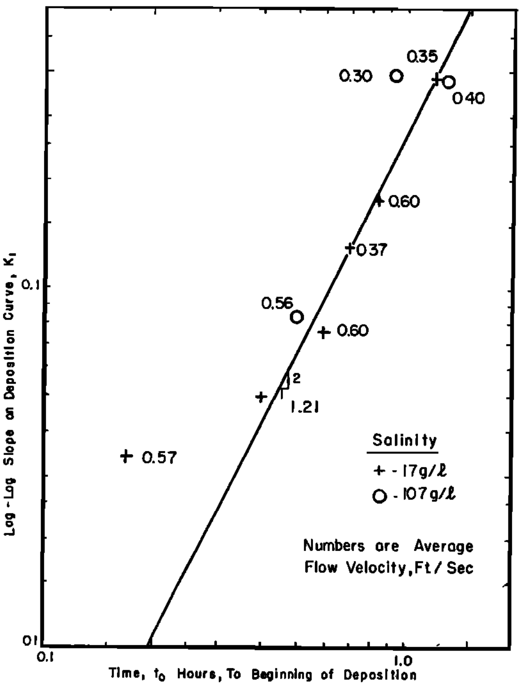

Fig. 9. Initial deposition exponent as a function of flocculation time.

density. It appears that at suspended sediment concentrations lower than 300 ppm very little flocculation occurs in salt water during flow down a simple rectangular channel.

Additional information on deposition from dilute sediment suspensions was obtained by labeling a fraction of the suspended sediment with gold-198 [*Krone*, 1960] and comparing the total and tracer suspended sediment concentrations. These data, obtained in a second flume, are presented in Figure 7. The fact that the labeled sediment deposited more rapidly than did the total suspended material, indicated by the two curves in Figure 7, shows that an interchange between suspended and deposited sediment occurs during transport.

The data in Figures 5, 6, and 7 can be explained in terms of individual particle or small floc transport as follows: At a given concentration of suspended particles, the frequency of particle-bed collisions is probably independent of the velocity below 0.6 ft/sec. The fraction of colliding particles that stick to the bed depends on the shear, as indicated by Figure 6. When a colliding particle is torn from the bed, it will detach itself or the particles to which it is stuck will be torn off with it, depending on the weakest bond. This process accounts for the falling resuspension rate with suspended particle concentration shown in Figure 7. This interpretation can be presented as

$$dc/dt = -m_0 \nu_0 v_s p/y \tag{7}$$

where c is suspended sediment concentration, t is elapsed time, m_0 is the mass of an individual particle, ν_0 is the number of primary particles per cubic centimeter, v_s is the settling velocity with which the particles approach the bed in a region close to the bed, y is the water depth, and p is the over-all probability of a particle sticking to the bed. p does not distinguish between bed particles deposited and replaced in suspension by another scoured particle and deposited particles that do not stick. $m_0\nu_0$ is c, and, if v_s is nearly independent of c and t,

$$c/c_0 = \exp\left[-ptv_s/y\right]$$

The data in Figure 4 give $v_s = 3.3 \times 10^{-4}$ cm/sec, and $p = (1 - 1.67\tau_w)$, where τ_w is the bottom shear in dynes/cm². The relative resuspension rate is $1.67\tau_w$.

Transport of suspensions at concentrations above 0.3 g/l was also observed in the flume. At these concentrations, interparticle contacts are frequent and floc sizes can become large in reasonable times, as is shown by (1) and (5). To observe deposition from sediment suspensions in a concentration range that includes part of the fluid mud range, an initial sediment concentration of 20 g/l was selected. An example of deposition with time from a suspension having this initial concentration is shown in Figure 8. The suspension was stirred at a flow velocity of 3 ft/sec; the velocity was then reduced to a constant 0.35 ft/sec, and the suspension concentration was measured. These concentrations, as determined by weight and as indicated by turbidity, are plotted on log-log coordinates in Figure 8, and straight-line slopes are indicated. Closer examination of portions of these slopes during similar experiments indicates log-log relations in each of the concentration ranges above 0.3 g/l. This figure was selected to show changes over a wide concentration range.

As is shown in Figure 8, little deposition occurred during the first hour, presumably while an initial sediment cover formed on the floor

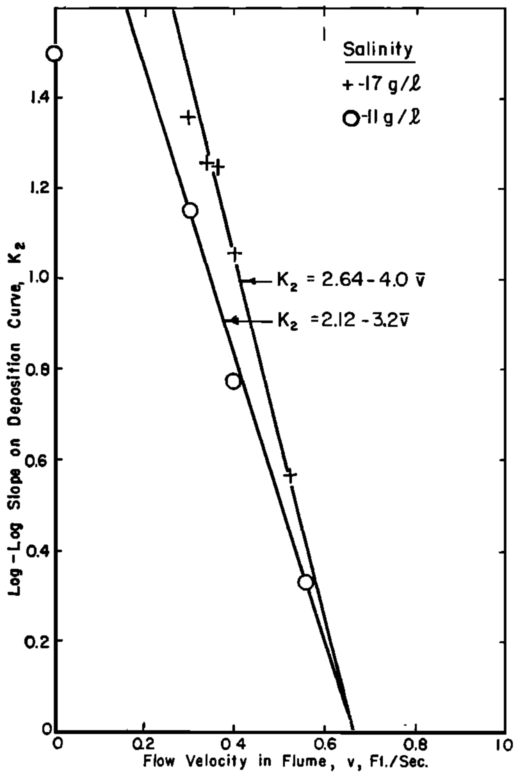

Fig. 10. Exponent of deposition curve 10 to 0.3 g/l.

and initial flocculation progressed. At about 1 hour after the velocity was reduced, flocculation in the suspension became unstable, as described above, and a rapid deposition of flocculent material occurred.

About half of the sediment was deposited between 1 and 9 hours after the velocity decrease.

The deposition rate (slope of the log-log curve) during the first phase of deposition is plotted against time for deposition to commence in Figure 9. The points for deposition at several velocities show no apparent relation to velocity, but are more or less distributed along the line $K = 0.26t_0^2$. The scatter is typical of measurements of an instability phenomenon, but it might also result from undefined variables. The number of flocs composed of n particles per floc [*Kruyt*, 1952] is

$$\nu_n = \nu_0(t/t_c)^{n-1}/(1 + t/t_c)^{n+1}$$

which, for $t \gg t_c$, can be rearranged to

$$\nu_0/\nu_n = (t/t_c)^2$$

ν_0/ν_n is proportional to k, which is proportional to R^3. J was shown to depend directly on $(R_{ij})^3$, by (5), so that the larger R is before rapid growth due to shear and deposition begins, the more rapid the deposition. These arguments make the line $K = 0.26t_0^2$ in Figure 9 appear reasonable. Equation 7 cannot be applied here because the approach of sediment to the bed is a function of the concentration. It is encouraging to see the similarity of log-log settling rates for material at concentrations above 10 g/l observed in glass cylinders and the deposition rates at these concentrations in the flume. Flow in this concentration range corresponds to the fluid mud description, except that the sediment remained dispersed throughout the flow. Deposition in this concentration range might be viewed as simply discontinued flow near the bed as the local concentration reaches a value that can resist the shear.

The change in log-log slope shown in Figure 8 at about 10 g/l is believed to occur when flocs can independently settle to the bed and when resuspension is no longer interfered with by settling flocs. This view is supported by the apparent relation between slopes of the deposition curves and the flow velocity shown in Figure 10. The data for the two curves in Figure 10 are from deposition at two salinities, one of which was obtained by diluting the sediment suspension with tap water. This procedure also increased the depth and decreased the sediment concentration by the ratio of the values of K, so that the effect of these variables is not separated. The relation given by these lines,

$$K_2 = A - B\bar{v}$$

is analogous to the deposition rate found for deposition at low suspension concentrations, and it appears to have both a deposition and a scour part. These curves show also that net deposition ceases at a velocity of 0.63 ft/sec.

At about 0.2 g/l, the flocs or particles remaining in solution are too small and too widely separated to cause continued rapid deposition. To demonstrate the dependence of deposition on flocculation, together with the importance of internal shear on the instability, an industrial floor grid was inserted across the flow at midlength in the flume to provide increased internal shear throughout the water depth. The average velocity downstream from the grid was unchanged from that existing before the grid was inserted, so that the increase in deposition rate shown in Figure 6 is not due to better settling conditions but to larger flocs. Particles were rapidly deposited from an otherwise nearly stable suspension after insertion of the grid, as is shown in Figure 8.

Conclusions

There appear to be at least three kinds of deposition of clay sediments from flowing salt water. These kinds of deposition depend on flocculation and sedimentation characteristics of the suspension. At high concentrations, the particle collisions resulting from Brownian motion will make the suspension unstable in a short time, the internal shear encountered in simple open channel flow will cause rapid flocculation, and the sediment suspension appears to 'consolidate out' at low flow velocities. This material is probably that referred to as 'fluid mud.'

Below a suspension concentration of about 10 g/l a flocculent suspension continues to deposit, but an interchange of bed and suspended material occurs.

Below suspension concentrations of 0.2 to 0.3 g/l, suspended sediment deposits very slowly, even from slowly flowing water, unless additional internal shear in the suspension is applied. The stability results from the infrequency of particle contacts after initial flocculation.

Neither of the last two kinds of deposition was observed in the flume at flow velocities above 0.7 ft/sec, and it can be concluded that transport of these suspensions can be maintained at the moderate flow velocities commonly occurring in channels in the bay.

Flow properties of sediment suspensions at concentrations above 20 g/l were examined only by means of the viscometer. Viscometer measurements indicated that the suspensions have the properties of a Bingham fluid. The calculated shear strengths indicate that suspensions at high concentrations can resist shear by flowing water.

It can be concluded that long-distance transport in estuarial waters is by movement of particles in suspension, and that deposition is governed by flocculation and suitable levels of shear at the bed.

An illustration of these modes of transport obtained by means of sediment-tracing techniques in a harbor in San Francisco Bay has been published [*Einstein and Krone*, 1961]. It was found that labeled sediment released in suspension outside the harbor was transported several miles and was deposited from water flowing under docks supported by pilings, and beyond similar flow-disturbing objects. Little deposition occurred in other parts of the harbor. The average flow velocities in this area seldom exceed 4 ft/sec. Once deposited, the trace sediment showed no evidence of movement, except in the region of highest deposition rate, where slight changes in distribution occurred during consolidation.

The flume observations do not include measurements which include wide ranges of salinities and depths or quantitative measures of the effects of flow disturbing objects on sedimentation. Flume measurements made to date, however, together with the viscometer and sedimentation observations, indicate the usefulness of these tools for studying the modes of estuarial sediment transport.

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