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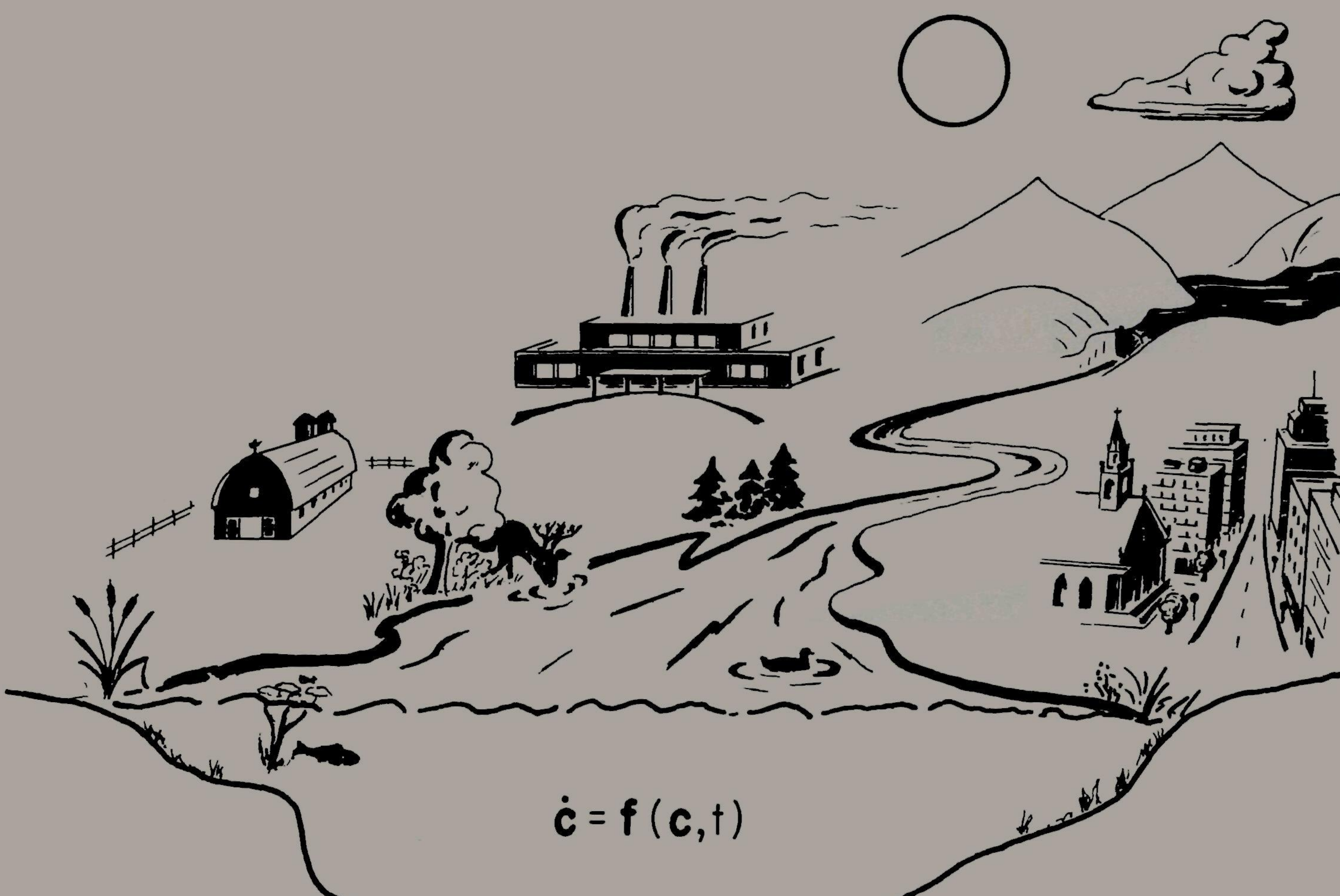
DEPOSITION OF FINE SEDIMENTS IN TURBULENT FLOWS



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DEPOSITION OF FINE SEDIMENTS IN TURBULENT FLOWS

by

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for the

Office of Research and Monitoring

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ABSTRACT

Basic laboratory investigations were carried out to study the role of flow parameters on the deposition of fine cohesive sediments in a turbulent flow field. The study utilized a special apparatus consisting of a system of a rotating annular channel and ring. The results obtained have confirmed earlier conclusions that the percentage of the total sediment that a given flow can maintain in suspension depends only on the bed shear stress and is independent of the initial sediment concentration.

The percentage C', of the depositable sediment deposited at time t has been found to vary with time according to the law $C' = \alpha \log t + \beta$, where the coefficient α appears to be independent of the flow conditions and sediment concentration, while the coefficient β is a function of the bed shear stress only. Both α and β are expected to depend on the physico-chemical properties of the sediment and the water environment. It follows that the deposition rates are proportional to the depositable sediment concentration and inversely proportional to time.

This report was submitted in fulfillment of Project Number 16050 ERS, under the sponsorship of Environmental Protection Agency.

CONTENTS

FIGURES

SECTION I

CONCLUSIONS

The following are the main conclusions of that part of the present study supported by the EPA.

1. For given geometry, sediment, water quality and flow conditions, the suspended sediment concentration reaches, after a period of relatively rapid deposition, a constant value C_{eq}, herein called equilibrium concentration. This equilibrium concentration is found to be a constant fraction of the initial concentration, C_o, at the start of each test; i.e. the ratio C_{eq}/C_o is independent of C_o and is a function of flow conditions only, which implies that each flow can maintain in suspension a constant percentage of the total initial sediment.

This very fundamental conclusion is in agreement with the earlier preliminary results obtained by Partheniades (11) in an open flume with a natural silty-clay sediment taken from the San Francisco Bay.

2. The relative equilibrium concentration, C_{eq}/C_o is found for various depths to be strongly related to the bed shear stress, τ_b by a logarithmic-normal relation.

3. The percentage C' of the depositable sediment deposited at time t is found to vary with time according to the law

$$C' = \alpha \log t + \beta$$

where the coefficient α appears to be independent of the initial suspended concentration C_o for C_o less than 10,000 ppm, which corresponds to the maximum sediment concentration encountered in most estuaries. For higher concentrations, α seems to decrease with concentration, suggesting a reduction in the deposition rates. 10,000 ppm thus seems to mark the concentration above which the settling of particles is hindered. A slight variation of α with depth is also observed; however no conclusive law for the dependence of α on depth has yet been obtained.

The coefficient β appears to be independent of both the concentration and depth and seems to depend on the bed shear stress only.

The law described above pertains to measurements corresponding to the bed shear stress greater than the minimum bed shear stress

τ_{bmin}, at which C_{eq} becomes equal to zero

SECTION II

RECOMMENDATIONS

The present study was carried out to investigate the role of flow parameters on the deposition rates of a commercial kaolinite clay, suspended in distilled water, in a turbulent flow field. A significant extension of this study is required before a complete knowledge of the behavior of cohesive sediments depositing under turbulent conditions is acquired. Various sediments, under various ambient environments need to be studied. Also, the effect of secondary currents generated in the flow field need to be analyzed. To this end, the following objectives and recommendations are in order:

1) An important objective is an investigation of the effect of bed roughness on the equilibrium concentration and on the deposition rates. The strong dependence of these two important depositional characteristics on the bed shear stress raises the question as to whether the way in which the shear stress is transferred from the boundary to the fluid is also of importance to sedimentation. Such a transfer may take place either by molecular viscous action in the case of a smooth bed, or by the drag resistance of the roughness elements. It should be mentioned at this point that recent results of turbulence studies, conducted by Partheniades and Blinco (14) showed conclusively that the turbulence intensities in open channel flows depend on the bed shear stress, the distance from the boundary and on the kinematic viscosity of the fluid, but not on the roughness.

The effect of roughness on deposition must be studied experimentally by inserting in the channel plexiglass annular bottoms with roughness elements glued on them. Three or four roughness sizes should be used.

This phase should also involve detailed velocity profiles taken by a 4 mm miniature propeller meter listed in Section V and considerable turbulence measurements with a hot-film anemometer for smooth and rough boundaries. The average bed shear stress should be directly measured by an instrumented false bottom as described in Section V. The main objective of these measurements would be to compare the structure of flow, particularly in the neighborhood of the bed, with that in an open channel and in a closed rectangular duct. The experiments of this phase should be conducted at the operational speeds of the channel and ring so that the sediment deposits unifromly. In (17) it was explained how the simultaneous rotation of the channel and ring generate two cells of opposing secondary currents cancelling each other's effect on the distribution of deposited sediment across the width of the channel. Although preliminary experiments at M.I.T. have indicated the existence of an almost constant bed shear stress distribution at these speeds, the question as to the effect of these secondary currents on the turbulence characteristics and the velocity distribution near the bed, i.e. on the overall flow structure near the boundary, remains open. It is expected that the recommended measurements will answer this question and will indicate how closely an endless straight conduit or a turbulent Couette flow is approximated at the operational speeds.

2) A systematic study of the effect of secondary motion on the distribution of the boundary shear and on the depositional characteristics should be next conducted. The first step of this phase would be a study of the transfer of the shear stress from the ring to the channel bottom for various relative speeds and depths. The false annular bottom, described in Section V, must be used for the measurement of the average bed shear stress. Velocity profiles and local bed shear stresses should then be measured by a micro-propeller meter, a Prandtl tube and a Preston tube in order to determine the secondary flow effect on the spacial shear stress distribution, and on the velocity profiles.

This recommendation is motivated by the following previous observations. It has already been stated that any deviation from the operational speeds strongly affects the depositional characteristics. This is indicative of a strong effect of the unbalanced secondary currents on deposition. Surprisingly however, the early M.I.T. experiments indicated that the ring shear stress depends only on the algebraic difference of rotational speed between the channel and the ring but is little affected by the absolute speed of either component. This conclusion was verified in the experiments in University of Florida. This means that the secondary currents may have a weak effect on the total boundary shear force on either the ring or the channel; however, they may strongly alter the spacial distribution of the bed shear stresses. In the light of the strong dependence of deposition and erosion on the boundary shear stress, it appears that the secondary currents affect deposition by creating zones of low local shear stresses. However, no measure of secondary flows nor any quantitative relationships between secondary flow and shear stress distribution have been established to date. It is the long range purpose of this phase of the recommended project to provide a relevant quantitative measure for the secondary current effect on boundary shear stress distribution and to investigate the relationships between the local shear and the velocity profile near the bed. It is realized that this is a very difficult task since it involves essentially a three-dimensional turbulent flow. For this reason, it can only be hoped to approach the problem in terms of correlation of gross flow variables. Substantial turbulence measurements should also be carried out for a preliminary study of the effect of secondary currents on turbulence characteristics, in combination with phase 1. Moreover, the three-dimensional aspects of the flow should be investigated using a triaxial array hot-film probe for measurements of turbulence intensities and time-average local velocities in the three directions.

3) The third recommended objective deals with an investigation of the role of sediment properties on deposition. Very little is known about the role of the physico-chemical characteristics on the hydrodynamic behavior of fine cohesive sediments. A rigorous literature review by Partheniades and Paaswell on the erodibility of channels with cohesive boundary showed that certain commonly used soil mechanics parameters, such as cohesive shear strength, compression index and Atterberg limits, for the prediction of the behavior of a dense clay mass to an external load, do not sufficiently describe the soil resistance to erosion (9,18,19). At this point, however, the rather limited state of knowledge does not permit a forecast of detailed experimental procedures. The project should start with pilot observations of deposition of various commercial clays, mixtures of pure clay materials and natural cohesive soils for constant flow conditions. Techniques should then be tried for obtaining an index or indices representative of the average magnitude of the interparticle physico-chemical forces, to be correlated with the depositional characteristics of the sediment.

4) In addition to the above, a number of short duration problems may be investigated. The following are a few examples:

a. Hydrodynamic behavior of very fine sand and cohesionless silt.

b. Depositional characteristics at very high concentration.

c. Detailed measurements of grain size distribution of suspended sediment at equilibrium concentration.

d. Pilot sedimentation experiments in an open flume and in a closed rectangular duct.

SECTION III

INTRODUCTION

The importance of investigating phenomena related to the deposition of fine cohesive sediments in turbulent flows is clearly evident from the usefulness of the results of such an investigation in engineering practice. Challenging situations in this context arise in the problem of shoaling in estuaries, channels, and in irrigation canals, due to geological sediments carried by the flow. Frequently the control of such shoaling is important, as for example when the question of maintaining a navigable waterway or of sustaining a specific environment for aquatic life is involved (21). Other situations where the hydrodynamic behavior of cohesive sediments plays an important role include the design of stable channels, and the transport of industrial effluents through flows, carrying with them various chemical pollutants.

Fine sediments are composed predominently of silt and clay and range in size from a fraction of a micron up to a few microns. Particles in that size range are strongly subjected to the effects of the interparticle physico-chemical forces, which may far exceed the effect of the gravitational forces. Some of these inter-particle forces are attractive while others are repulsive (22). Their net effect may be either repulsive or attractive depending on the physico-chemical properties of the water environment and the adsorbed ions. In the first case the individual fine particles remain dispersed, so that the finer portion, smaller than one micron, may remain indefinitely in suspension due to Brownian motion, whereas a very slight degree of agitation could prevent even the heavier silt particles from settling. In the second case, which is more common of the two, the particles tend to attach themselves to each other forming agglomerates, or flocs, whose sizes and settling velocities may become several orders of magnitude higher than those of the individual particles. This phenomenon, known as flocculation, is the main cause of rapid deposition of suspended fines, a well-known occurrence of which is due to the presence of a slight salinity in water (6,13).

Estuaries, and especially deep estuarial channels are favorable sites for the deposition of fine sediments coming from either landward or seaward sources. The two main factors that enhance such a deposition are the low flow velocities, or low bed shear stresses, and the increased salinity. The latter contributes to the deposition by favoring the process of flocculation and also by generating slow upstream salinity currents which are associated with stratified as well as mixed estuaries (3,4,12).

In the last three decades, there have been significant contributions to the development of important theories leading to semi-theoretical equations relating the rate of transport of coarse sediments to the flow conditions and to the mechanical properties of the sediment. These theories are based on the phenomenological laws of turbulence. The validity of these theories, the most important of which describes Einstein's bed-load function (1), is limited to the transport of bed-material load, i.e. to sediment sizes adequately represented in the bed of the channel, and to uniform flows in channels in equilibrium.

The state of knowledge of fine sediments is much more limited. The hydrodynamic behavior of fine cohesive sediment suspensions is complicated by the flocculation effect, since the basic settling unit is a floc rather than an individual particle. The floc size-distribution depends not only on the physico-chemical properties of the sediment but also on the flow conditions themselves. This dual dependence makes the processes of erosion, transport and deposition of fine sediments rather complex and quite distinct from the corresponding processes of a coarse sediment. It is necessary therefore, to discover the important flow parameters and soil properties, which control the initiation, degree and rates of deposition and erosion and to establish quantitative functional relationships among these variables.

Extensive investigations conducted by Partheniades and co-workers during the past several years have revealed important and conclusive information regarding the effect of flow parameters on deposition, and about the physical mechanism of erosion and deposition of cohesive soils. These results, contained in ref. (2,9 to 16) are summarized in Section IV. The present experimental phase is essentially a continuation of the earlier studies and is concentrated on investigating the role of flow parameters on the time-deposition rates. The results obtained to-date are reported and discussed in this report.

SECTION IV

PREVIOUS INVESTIGATIONS

In order to understand the process of shoaling in navigable channels and attempts to control it, basic research on the depositional behavior of fine sediments was begun in the late fifties. The sequel is a summary of the approach taken by various investigators, dealing with the transport of fine sediments, and leading to the present study.

Erosion, transport and deposition of sediment is controlled by two groups of variables: a) the flow parameters, describing the hydraulics of the system, and b) the sediment properties.

McLaughlin (8) derived the general fundamental equation for the transport of fine sediments based on the conservation of sediment mass. For one-dimensional flow, this equation reduces to the following form:

$$\frac{\partial C}{\partial t} + U \frac{\partial C}{\partial x} = D_y \frac{\partial^2 C}{\partial y^2} + \left(\frac{\partial D_y}{\partial y} - w\right) \frac{\partial C}{\partial y} + D_x \frac{\partial^2 C}{\partial x^2} \quad (1)$$

where C = the total concentration of sediment, U = U(y) = the time average flow velocity as a function of the vertical distance y from the bottom, D_x, D_y = the turbulent diffusion coefficients in the x and y directions respectively, x = the Cartesian coordinate in the direction of flow and w = the average settling velocity of the sediment. The solution of Eq. 1 requires the following initial and boundary conditions:

a) There is no net rate of transport in the y direction across the surface. The mathematical formulation of this condition is:

$$\left(\frac{\partial C}{\partial y}\right)_{y=y_o} = - \left(\frac{w}{D_y} C\right)_{y=y_o} \quad (2)$$

where y_o = the total depth of flow.

b) At the bed, the material eroded and re-suspended must be entrained into the main flow by turbulence. Dobbins and McLaughlin (8) used the following mathematical expression:

$$E = - \left(D_y \frac{\partial C}{\partial y}\right) \text{ at } y = 0 \quad (3)$$

where E = rate of erosion. Partheniades (10) has a more detailed discussion of this boundary condition.

c) At time t = 0 the concentration distribution is known, i.e. $C = C_o(x,y)$ is known.

In addition to the initial and boundary conditions, the settling velocity, w, must be known. This is essentially the greatest difficulty in the problem since w, as stated in the introduction, depends on both the flow conditions and the physico-chemical properties of the sediment. McLaughlin studied theoretically and experimentally the settling velocity distribution and the factors affecting it. However, his work was limited to settling in quiescent water.

The first systematic large scale studies on fine sediment deposition in turbulent flows were conducted by Krone (5,6,7) in an open flume. He used a silty-clay type of sediment from the San Francisco Bay commonly known as Bay Mud and composed of about equal proportions of silt and clay. For low concentrations (less than 300 ppm) the following experimental deposition law was derived:

$$\frac{C}{C_o} = \exp \left[- \frac{w_a t}{y_o} \left(1 - \frac{\tau_b}{\tau_c}\right) \right] \quad (4)$$

where w_a = apparent settling velocity, τ_b = the average bed shear stress, τ_c = the critical bed shear stress above which no particle can stick to the bed and C_o = the initial concentration.

For high concentration, the following logarithmic law is obtained:

$$\log C = - K \log t + \text{Constant} \quad (5)$$

where K is a function of the depth of flow, y_o, and the ratio $\frac{\tau_b}{\tau_c}$.

It should be noted that in Eqs. 4 and 5, the concentration, C, tends to zero with increasing time; which means that both equations are valid for velocities low enough for the entire initial sediment to deposit. Krone also conducted interesting studies on the effect of shear stress on the maximum floc size in a laminar flow between two rotating concentric cylinders. He derived the following relationship:

$$r_{max} = \frac{1}{\tau} \left[\frac{16}{3\pi} (\Delta r)\ c_f \right] \quad (6)$$

when r_{max} = the radius of the largest floc assumed to be spherical, τ = the shear stress at the boundary of a laminar shear field, Δr = the roughness of the surface of the floc and c_f = the shear strength of the floc.

Eq. 6 verified by Krone's experiments, permits an estimate of the shear strength of the flocs, if their size and the shear stress are known.

Partheniades (11) investigated both the erosional and depositional behavior of fine sediments. His studies were conducted in an open flume with the same sediment type as used by Krone (6). The deposition experiments indicated that the suspended sediment concentration approaches a constant value, which may be referred to as "equilibrium concentration". Limited evidence at that time suggested that this equilibrium concentration C_{eq} is, for given flow conditions, a constant percentage of the initial concentration, C_0, at the start of the run. Moreover, a critical velocity limit was found above which an appreciable amount of sediment remains in suspension, whereas, at velocities slightly below that critical limit, all the suspended sediment deposits quite rapidly.

The importance of the findings by Partheniades led to further studies on the depositional phenomena at M.I.T. The experiments were conducted in a special apparatus. Its main components were an annular channel with outer and inner diameters of 36 in. and 28-3/8 in. respectively, containing the water-sediment suspension, and an annular ring, positioned within the channel and in contact with the water surface. A simultaneous rotation of the channel and ring in opposite directions generated a turbulent flow field. The advantages of the channel-ring system in comparison with the conventional flume are the following: the flow is uniform at every section; there are no floc disrupting elements in the water, such as pump blades and, moreover, the flocs are not affected in zones of high shear stresses, such as in return pipes and diffusers. The apparatus can be instrumented so that the average shear stresses on the channel and ring can be readily evaluated. Also, the equipment permits a quick and precise variation of the flow parameters over a range much wider than in a flume. Finally, due to the relatively small water volume, a large number of tests with various fluids, sediment types and sediment concentrations can be performed inexpensively and in a relatively short period of time. The effect of the rotation-induced secondary currents on the uniformity of deposition was practically eliminated by properly adjusting the speeds of the channel and ring for uniform sediment deposition across the width of the channel. For these operation speeds, the bed shear stress distribution across the channel width was found to be almost uniform. The details of the instrument and its operation are described in references (2,17). A commercial kaolinite clay was used as the sediment with a grain size distribution ranging from a fraction of one micron to 50 microns. Inasmuch as the experiments at M.I.T. and also at University of Florida have been concentrated on the role of the flow variables on deposition, the type of sediment and the water quality were kept constant. The results of the research are summarized in the sequel.

1. For given geometry, sediment, and flow conditions, the suspended sediment concentration reaches, after a period of relatively

rapid deposition, a constant value, C_{eq}, referred to as equilibrium concentration. This equilibrium concentration is a constant fraction of the initial concentration, C_o; i.e. the ratio C_{eq}/C_o is independent of C_o and is a function of the flow conditions only; therefore, each flow can maintain in suspension a constant percentage of a given initial amount of the sediment.

2. The ratio C_{eq}/C_o for various depths seems to be strongly related to the bed shear stress, τ_b, according to a logarithmic-normal relation (15). For the particular sediment and geometry of the channel of the experiments, this relationship is found to be

$$\frac{C_{eq}}{C_o} = \frac{}{0.49\sqrt{2\pi}} \int_{-\infty}^{\log\Delta P_\omega} \exp\left\{ - \frac{1}{0.48} [\log\Delta P_\omega - 1.764]^2\right\} d(\log\Delta P_\omega) \quad (7a)$$

and

$$\Delta P_\omega = \log(2.38 \times 10^4 \times \tau_b^{0.834} - 65) \quad (7b)$$

where τ_b is expressed in lbs. per square foot.

3. The initiation and rates of erosion of cohesive sediments have also been found to depend strongly on the bed shear stress (11). Moreover, the basic research studies have shown that the stresses at which erosion begins for a given sediment are considerably higher than the stresses at which the same sediment in suspension deposits entirely. This last experimental conclusion is in complete agreement with field observations in irrigation channels (18,19).

4. The conclusions cited so far point out the mode of transport of cohesive sediments and the nature of the equilibrium concentration to be different from that for a coarse sediment. It has been well established that in flows over a movable cohesionless bed there is a simultaneous deposition and erosion of particles. A constant concentration of sediment in such flows is attained when the number of particles eroded is equal to the number of particles deposited per unit area and per unit time. If the suspended load is suddenly increased by an additional amount of sediment of similar mechanical composition to the one already in suspension, the concentration will drop soon to its original equilibrium value, since, for some time, more particles will be deposited than scoured. The constant value of C_{eq}/C_o in the case of fine sediments suggests that interchange of bed and suspended material does not take place. Such an interchange is also excluded by virtue of conclusion (3). Moreover, experiments in the rotating channel at M.I.T. in which the suspended sediment at equilibrium concentration was

gradually flushed out, has directly confirmed this conclusion. The constant equilibrium concentration of sediments in suspension does not, therefore, represent the point of saturation of the sediment transport carrying capacity of the flow. It simply represents the proportion of sediment with weak enough interparticle bonds, such that the settling flocs of that part of the sediment cannot resist the high disruptive shear stresses near the bed. The part of sediment which can form flocs large enough to settle to the bed and with sufficiently strong bonds to resist breaking and re-suspension, deposits permanently without being resuspended.

5. The ratio C_{eq}/C_o ceases to be a unique function of the average bed shear stress for any speed combination other than the one resulting in uniform deposition. This suggests that the rotation-induced unbalanced secondary currents also control the equilibrium concentration.

6. Mechanical analysis has revealed that at equilibrium concentration, the suspended sediment contains the entire grain size range of the original sediment. From this observation, it was concluded that the degree of flocculation and the strength of the inter-particle bonds play a dominant role in the deposition process rather than the particle size, and that there is little correlation between absolute size and intensity of inter-particle forces.

7. Limited data from the M.I.T. experiments showed that the deposition rates are also strongly controlled by the bed shear stress. The following two tentative expressions were developed for the instantaneous concentration, C(t) by two different approaches (15):

$$C(t) = C_o f(\tau_b)\ t^{-2.14}\ 10^{-6}\ \tau_b^{-1.84} \qquad (8)$$

and

$$C' = \frac{C_o - C(t)}{C_o - C_{eq}} = -\ 0.592 + 0.135 \log C_o + 0.455 \log t \qquad (9)$$

where t is in minutes and τ_b is in lbs. per square foot. Differentiating Eq. 9 with respect to time, the following equation for the rate of deposition is obtained:

$$\frac{dC(t)}{dt} = -\ \frac{0.198}{t}\ C_o\ (1 - \frac{C_{eq}}{C_o}) \qquad (10)$$

In Eq. 10 the shear stress, τ_b, enters implicity through C_{eq}/C_o.

It should be noted that in all experiments, the suspended sediment concentration was directly and accurately determined by filtering a sample through a membrane. For this purpose. Millipore filtering equipment was used.

SECTION V

EXPERIMENTAL APPARATUS

The experimental apparatus and accessory equipment are as described below.

a. Basic Experimental Apparatus

The basic equipment, consisting of a system of a rotating channel and a ring similar in principle and in operation to that designed at M.I.T. (17), consists of the following basic components:

1. An annular channel 8 inches wide, 18 inches deep and 60 inches average diameter, to contain the water-sediment suspension, shown in Fig. 1. It is made of fiberglass 1/8 inch thick with four plexiglass windows 3 inches by 2 inches at the lower part of its outside wall to permit visual observation. Laterial rigidity is provided by top and bottom flanges and vertical stiffeners.

2. An annular, 1/4 inch thick, plexiglass ring of the same average diameter as that of the channel and slightly less than 8 inches wide, shown in Fig. 2. This ring is positioned within the channel and in contact with the water surface. A plexiglass reinforcing stem has been glued at the center of the ring, forming a T-shaped cross-section, to minimize deflection between supports. Simultaneous rotation of both components in opposite directions by means of two concentric shafts, each driven by a separate variable-speed motor, generates a uniform turbulent flow field. The operational speeds of the channel and ring were evaluated for the sediment deposition to be uniform across the channel (see Section VI).

3. An annular plexiglass, 1/8 inch thick, false bottom pictured in Fig. 3. It has the approximate horizontal dimensions of the ring and is to be placed inside the annular channel supported by four removable cylinders, which in turn will be supported on knife edges on four special removable supports, also shown in Fig. 3. Thus the frictional resistance to the rotation of the false bottom will be minimized, and its tangential movement due to flow-induced shear stresses will be resisted and sensed by an instrumented thin blade. Calibration of the blade using static loads will permit a direct estimate of the total shear force exerted on the bottom.

4. The supporting frame including the two concentric shafts and ring support shown in Fig. 4. It is made of 3 inch by 3 inch by 5/16 inch tubing. The 3 inch outside diameter hollow shaft is supported on the two indicated plates through ball bearings. The one-inch diameter inner shaft is supported also by two ball bearings inside the outer shaft. A turn-table attached to the outer shaft

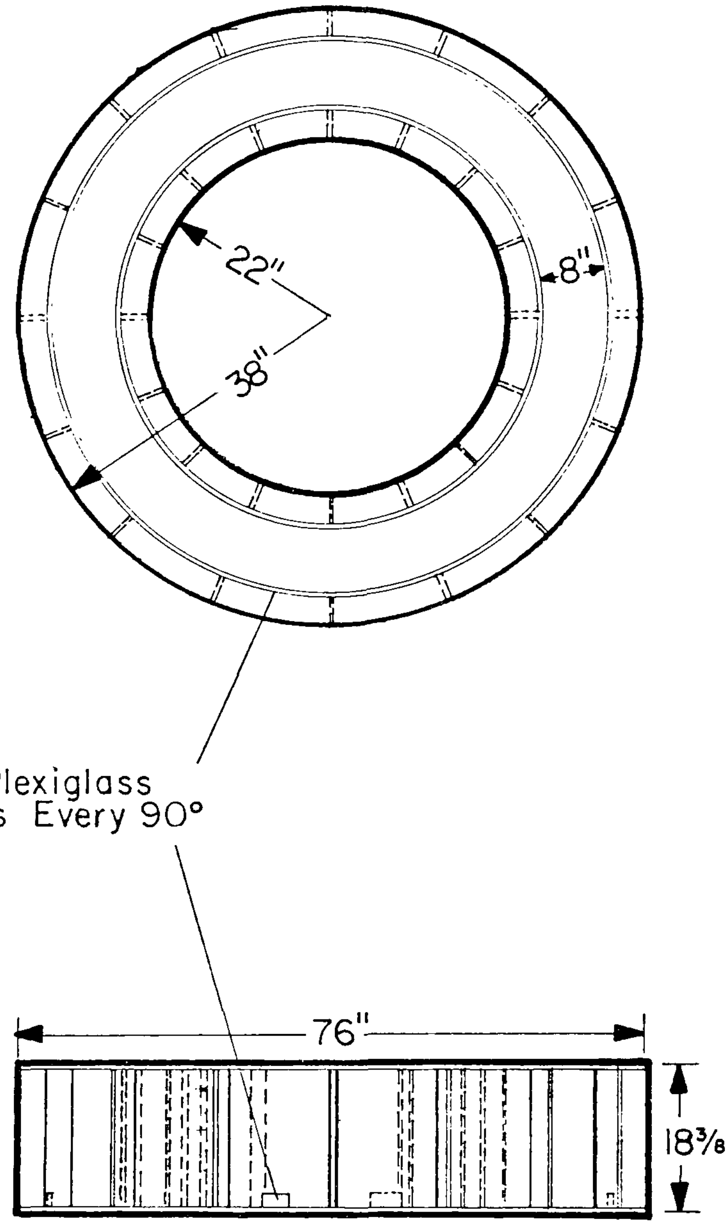


Fig. 1 Annular Channel

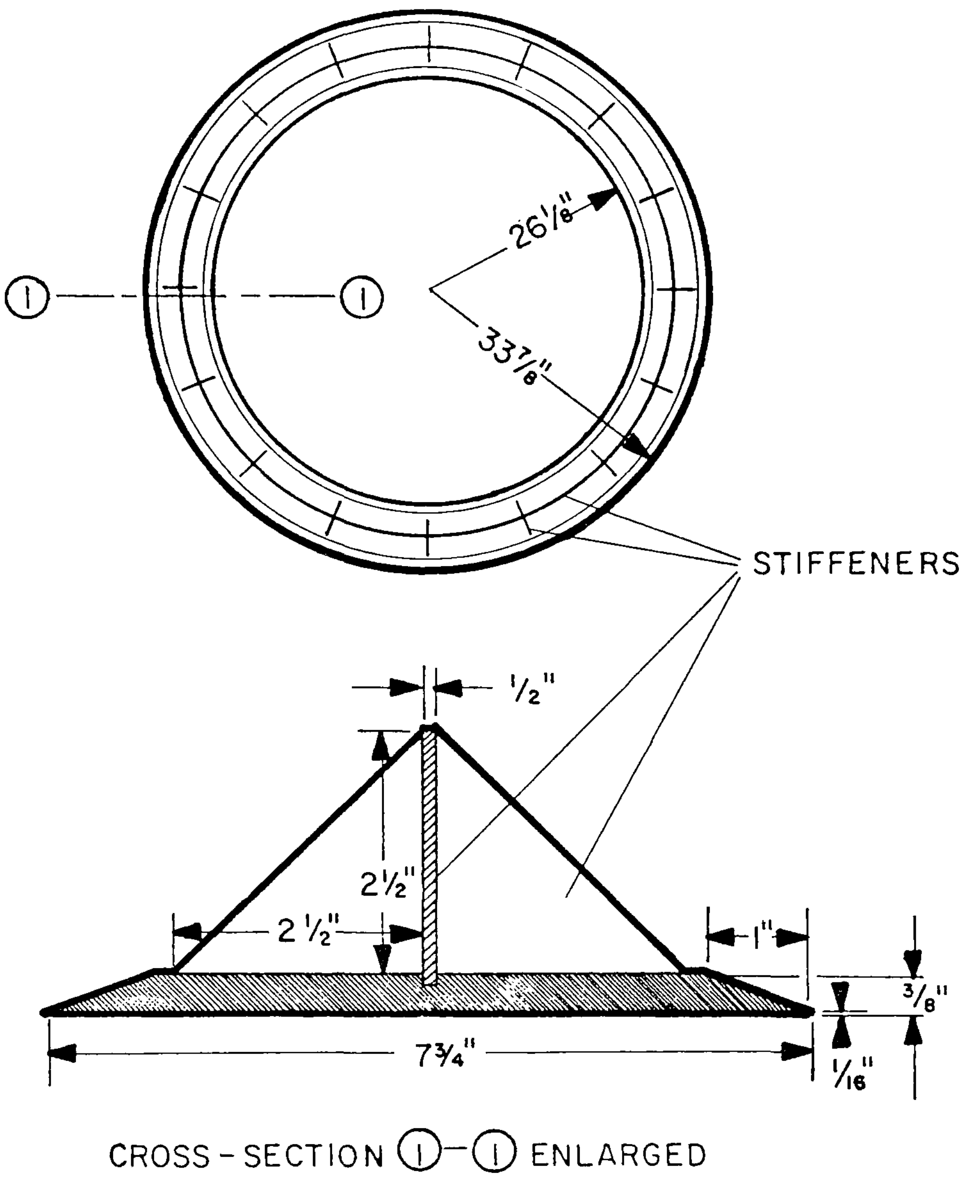


Fig. 2 Annular Ring with Stiffeners

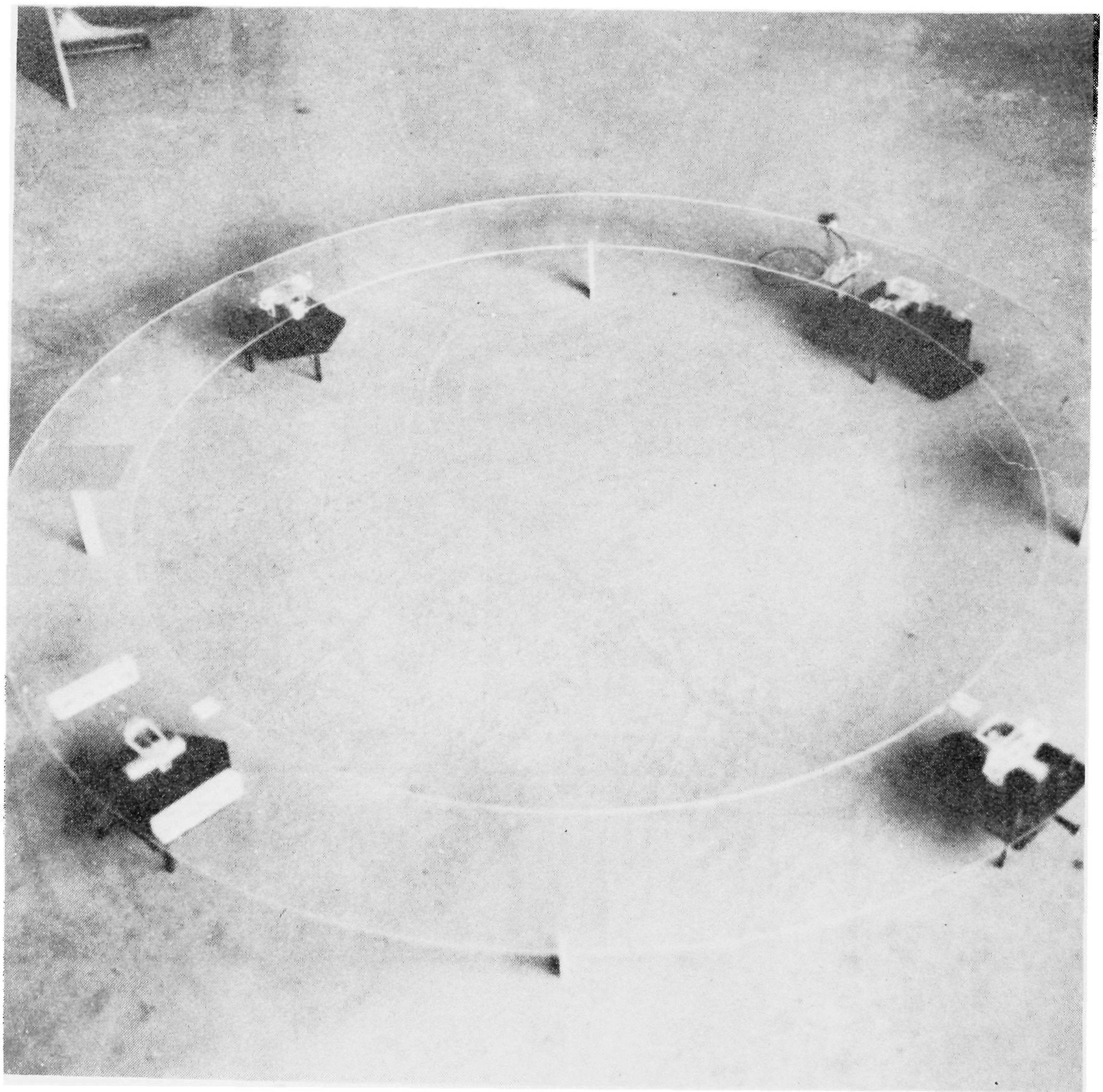


Fig. 3 False Bottom and Supports

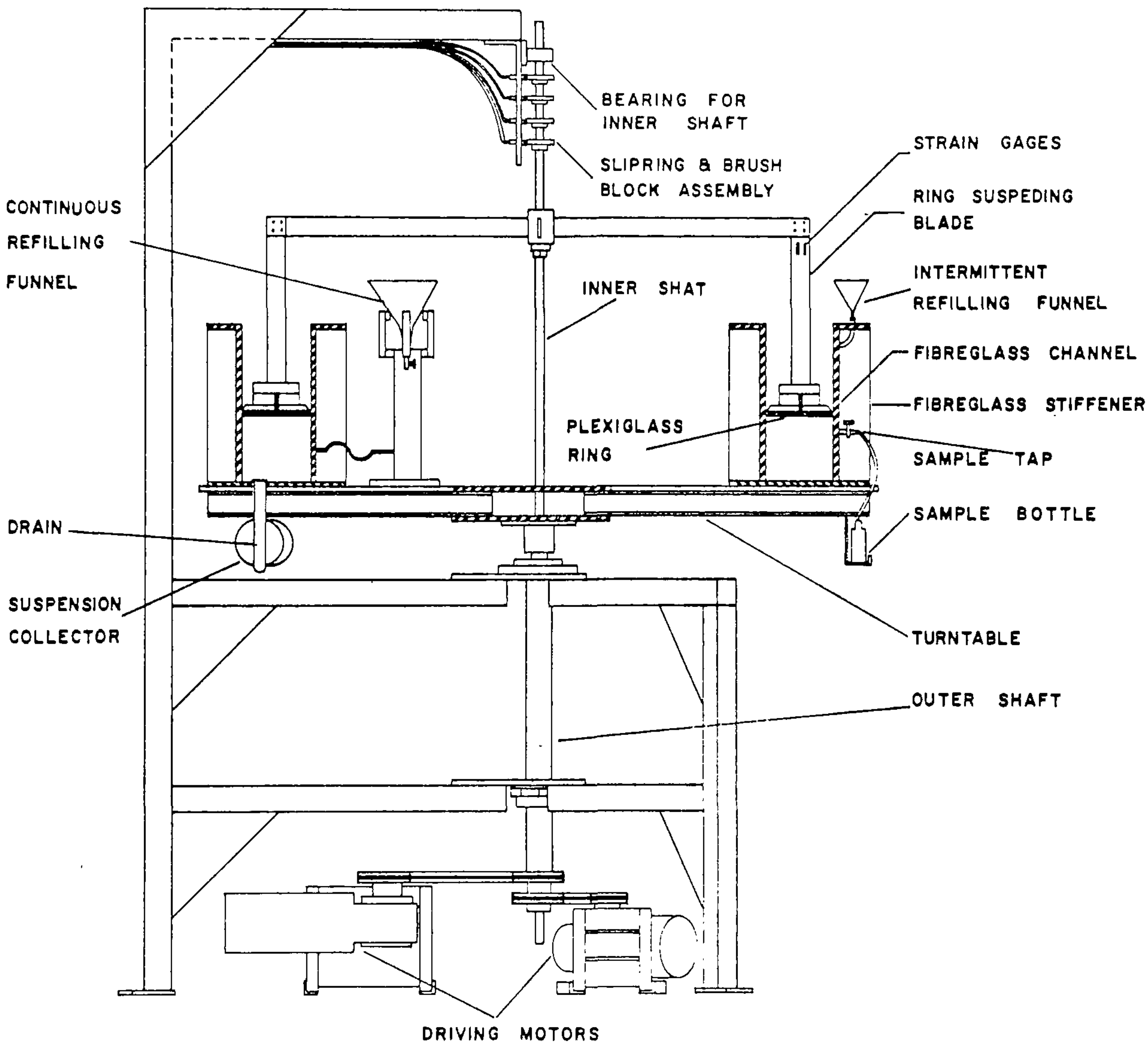


Fig. 4 Turntable Assembly

supports the annular channel, and a mechanism shown in detail in Fig. 5 is used to support the annular ring, suspended from four flexible stainless steel blades. These blades are rigidly secured at the top by clamping fixtures attached to four stiff radial stainless steel arms, which are in turn attached to the 1-inch diameter inner shaft through the device shown in Fig. 5. The blades are instrumented with strain gages whose signal is transmitted to a strain indicator through a set of slip rings. To adjust the ring to touch the water surface for a given depth of water in the channel, a fine and coarse height-adjustment mechanism is provided by the clamping fixture, which attaches the entire ring assembly to the inner driving shaft. The fixture is made of two components which consist of a steel collar fitting closely to the inner shaft. The collar slides on the shaft to the desired height and is locked there by a set-screw which seats into counter sunk holes, vertically spaced 1 inch apart on the inner shaft. The outer component is attached to the ring assembly and through threads over the inner collar and provides a fine vertical adjustment.

Fig. 6a shows a general picture of the entire assembled basic experimental apparatus, which, has worked perfectly. Fig. 6b shows a more detailed picture of the annular channel with the ring inside it.

b. Accessory Equipment

In addition to the described basic experimental apparatus, the following accessory equipment and material is provided.

1. Kent 265 Miniflow Velocity Kit with high and low speed velocity probes of 10 mm diameter. It is supplemented with a 4 mm diameter miniature current meter. These meters are to be used for measurement of local flow velocities inside the channel.

2. Two variable-speed motors with speed regulators.

3. Millipore filtering equipment with the necessary filtering membranes, for measurements of concentration of suspended sediment.

4. Kaolinite clay, a commercial variety, tradenamed Peerless No. 2, mined and processed by Dixie Clay Company, in Bath, South Carolina.

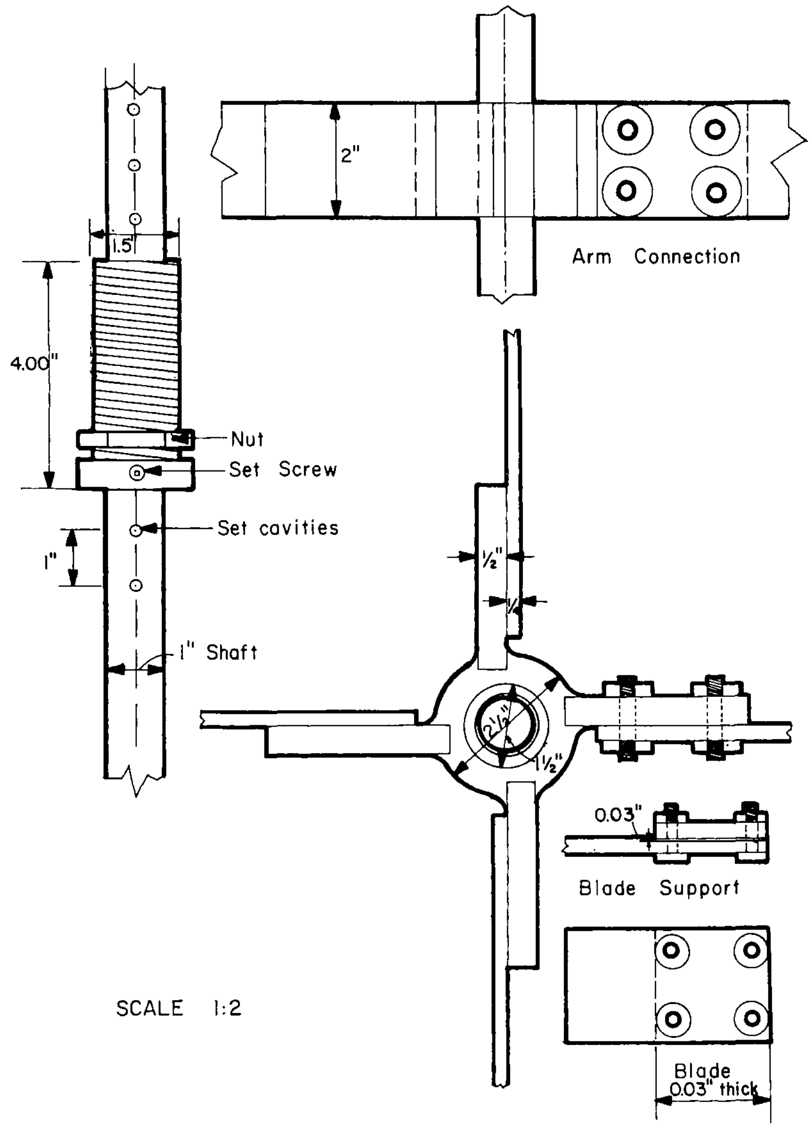
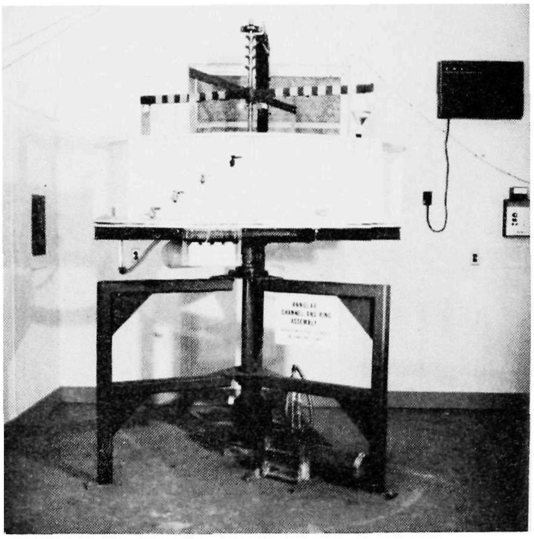
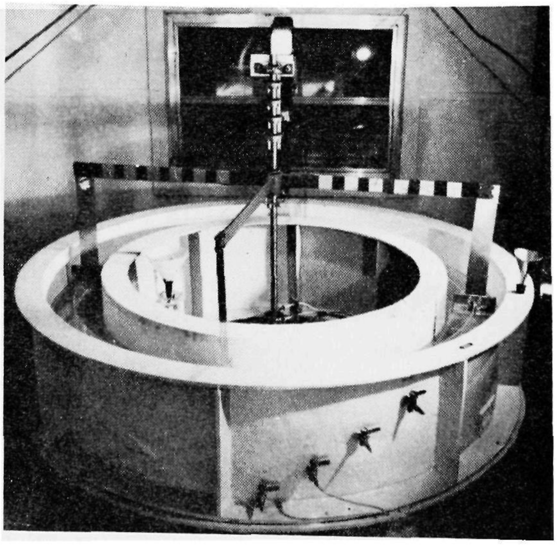


Fig. 5 Mechanism Supporting Annular Ring



a. General View



b. Annular Channel with Ring in Operational Position

Fig. 6 Basic Experimental Apparatus

SECTION VI

OPERATIONAL PROCEDURE

The special annular channel and ring apparatus was designed to obtain a uniform turbulent flow field at each section of the annular channel as was mentioned perviously. This was done (also see Section IV) by rotating the channel and ring in opposite directions, so that the generated cells of secondary currents were neutralized (17). For this purpose, the ring and channel speeds were calibrated, as described below. The method of taking concentration samples is also outlined.

Operating Curves

Since the idea was to obtain a uniform flow field in the channel so as to have no secondary radial flow, and consequently a uniform sediment deposition across the width of the channel, small plastic beads of 1.06 specific gravity were placed at the bottom of the channel, which was filled to different depths with water, and the ring was positioned on its surface. A simultaneous rotation of the ring and the channel in opposite directions caused the beads to move toward the inside or the outside wall of the channel, depending on the strength of the secondary current. If the channel rotated too fast, the beads moved toward the outside wall. On the other hand, if the ring rotated too fast, the beads moved toward the inside wall. At the proper speed combination therefore, the beads stayed uniformly across the width of the bed. It was later verified by the actual measurement of the depth of deposited sediment bed across the width of the channel that the beads did in fact represent the sediment, for the purpose of its uniform deposition, adequately.

In Fig. 7, the speed combinations obtained by the foregoing procedure for various depths are shown. These are the operating curves for the ring-channel system and they were adhered to throughout the present experimental phase. A deviation from these curves would of course result in non-uniform sediment deposition due to secondary currents. This aspect of secondary current has been covered in some detail in (17).

Sample Extraction

Four stop-cocks were provided in the channel as observed in Fig. 6a, for extracting concentration samples from the channel. The tubes and bottles provided below were used to collect the sample while the channel was in operation.

Initially, to begin a given test run, the ring and channel were rotated at high speeds to ensure complete suspension of the material inside. Then the speeds were suddenly lowered to those corresponding

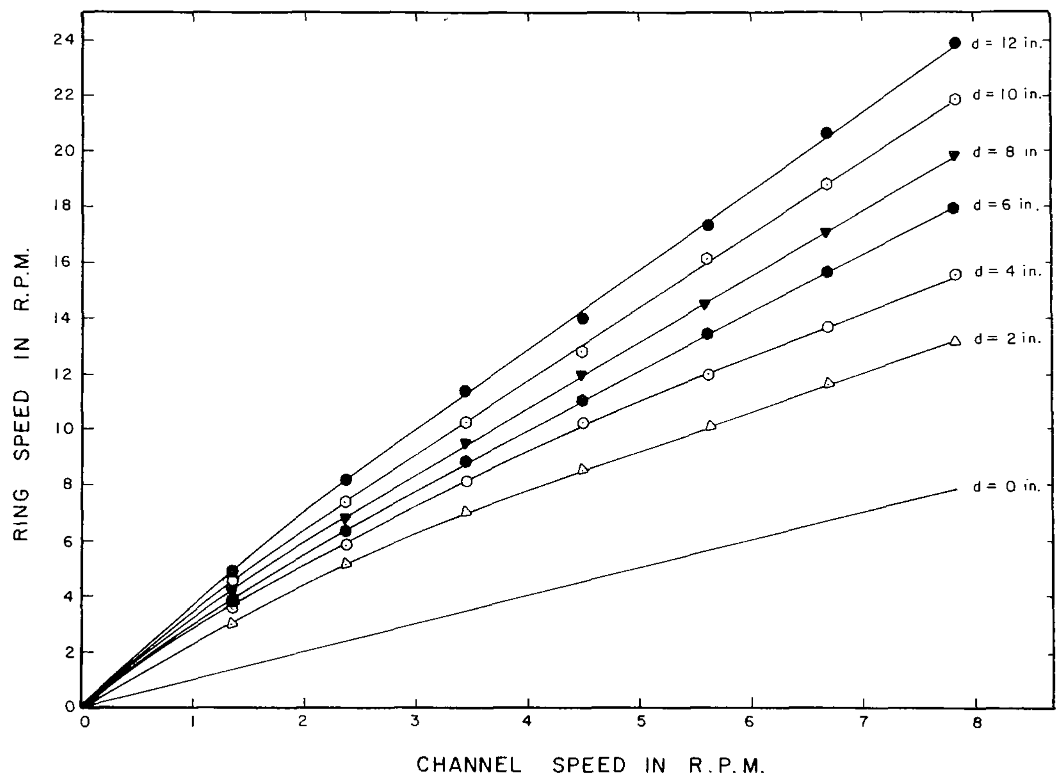


Fig. 7 Operating Curves

to a point on the operating curve of Fig. 7. This was accomplished in less than 10 seconds and at this point a stop-watch was used to commence the time of deposition.

SECTION VII

RESULTS OF INVESTIGATION

The experimental investigation was concerned with a detailed study of the time-deposition rates (20). Three different channel depths of 6, 9, and 12 inches were conveniently selected and used with initial sediment concentrations ranging from about 1000 ppm to about 25,000 ppm. The bed shear stress was varied over a wide range, but was kept above the minimum value, τ_{bmin} at which C_{eq} becomes zero.

The independence of the relative equilibrium concentartion, C_{eq}/C_o from C_o, and its dependence solely on the bed shear stress, was once more verified. The data obtained for all depths and concentrations are summarized in Fig. 8 on a logarithmic-normal paper, indicated by a straight line with random scattering. The bed shear stresses have been computed from the experimental equation derived previously (15):

$$\tau_b = [4.20 \times 10^{-5} \frac{(\Delta\omega)^2}{1 + 2\frac{d}{b}}]^{1.20} \qquad (11)$$

where τ_b is the bed shear stress at the center of the channel in psf, $\Delta\omega$ is the sum of the absolute velocities of the channel and ring in rpm, d is the depth and b is the width of the channel.

Fig. 8 leads to following equation relating the relative equilibrium concentration to the bed shear stress:

$$\frac{C_{eq}}{C_o} = \int_{-\infty}^{\log(\tau_b - \tau_{bmin})} \frac{1}{\sigma\sqrt{2\pi}} \exp\{-\frac{1}{2}\left[\frac{\log(\tau_b-\tau_{bmin})-M'}{\sigma}\right]^2\}d\{\log(\tau_b-\tau_{bmin})\} \qquad (12)$$

where M' is the geometric mean, i.e. the logarithm of $\tau_b-\tau_{bmin}$ at $C_{eq}/C_o = 0.50$, and σ is the standard deviation. For the type of sediment and the water quality used $M' = 0$, $\tau_{bmin} = 1.60$ dynes/cm^2 and $\sigma = 0.49$.

The dotted line in Fig. 8 represents the average C_{eq}/C_o versus $\tau_b-\tau_{bmin}$ relationship of the earlier limited results of M.I.T. (16,17). The two lines are very nearly parallel with almost identical σ values and thus confirm the validity of the functional form of the Eq. 12. At the present time, it is not known whether the difference in the values of the means in the two cases is due to a variation of the constant factor in Eq. 11 or to slight

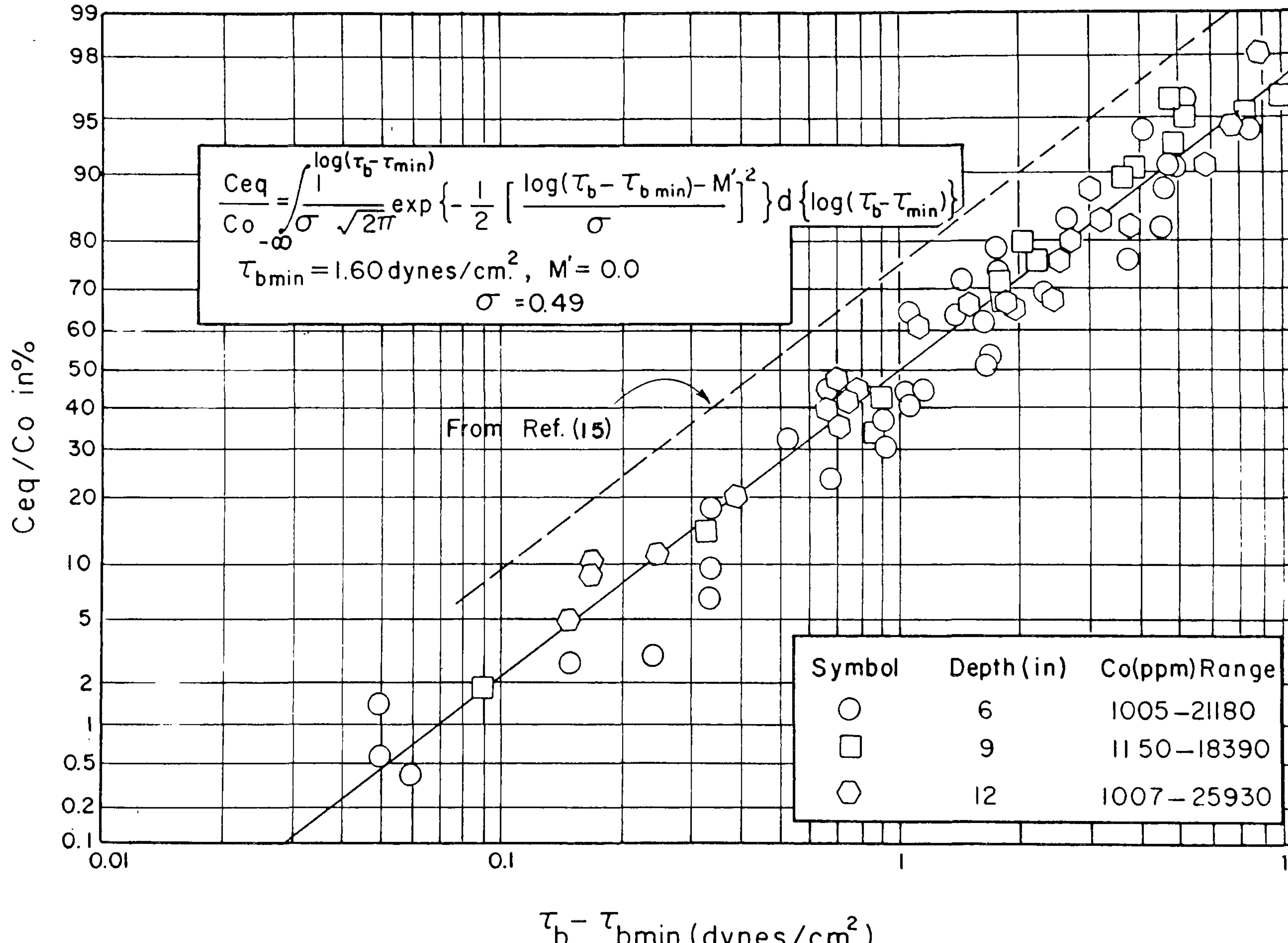


Fig. 8 Variation of Relative Equilibrium Concentration C_{eq}/C_o with Bed Shear Stress

differences in the chemistry of the water or of the admixtures of the sediment used. It should be noted at this point that the depositional behavior of cohesive sediments is extremely sensitive even to slight changes in water temperature, to differences in the chemical constituents of the sediment, and to the dissolved ions.

Fig. 9 shows an example of the time-concentration relationship for the 6 inch depth and for an initial concentration of 9570 ppm. C(t) is the average instantaneous suspended sediment concentration at time t. It can be observed that the time-concentration lines are nearly parallel for all bed shear stress values and initial sediment concentration C_o. The general empirical relationship thus has the form:

$$C' = \frac{1 - C(t)/C_o}{1 - C_{eq}/C_o} = \alpha \log t + \beta \qquad (13)$$

It should be noted that $1-C_{eq}/C_o$ represents the proportion of the total depositable sediment, or the degree of deposition, whereas $1-C(t)/C_o$ indicates the fraction of the original sediment deposited at time t. Therefore C' is the fraction of the depositable sediment deposited at time t. Obviously the left hand member is expected to vary from zero to unity. The coefficient α is the slope of the lines and the coefficient β is the value of C' at any arbitrary time, selected equal to 1 minute, since this was the minimum time after the beginning of each run at which dependable measurements were obtained. For a given depth, α is independent of the bed shear stress, τ_b. Eq. 13 is valid for a time interval from 0.5 minute up to the time at which equilibrium concentration is attained, i.e. when C' is equal to unity.

Fig. 10 shows a plot of α versus C_o for all three depths. It is seen that α remains independent of concentration up to about C_o = 10,000 ppm. From then on it decreases gradually and linearly with C_o. For the 6 inch depth α decreases from 0.32 to 0.27, corresponding to an increase of C_o from 10,000 to 20,000 ppm, i.e. α decreases by 17% for an increase of C_o by 100%. Since a smaller α implies a lower deposition rate, it seems that a concentration of 10,000 ppm marks the beginning of hindered settling, without the same hinderance affecting the relative equilibrium concentration C_{eq}/C_o. It should be noted, however, that even the highest observed concentrations of a suspended fine sediment in natural waters are well below that limit, so that for practical purposes α can be considered as being independent of C_o. A small but systematic variation of α with depth is observed. A doubling of depth causes an increase of α by 20% without any effect on the relative equilibrium concentration. The reason for this increase is currently under study.

Finally, Fig. 11 shows the variation of β with bed shear stress for all three depths and for the entire range of initial concentrations

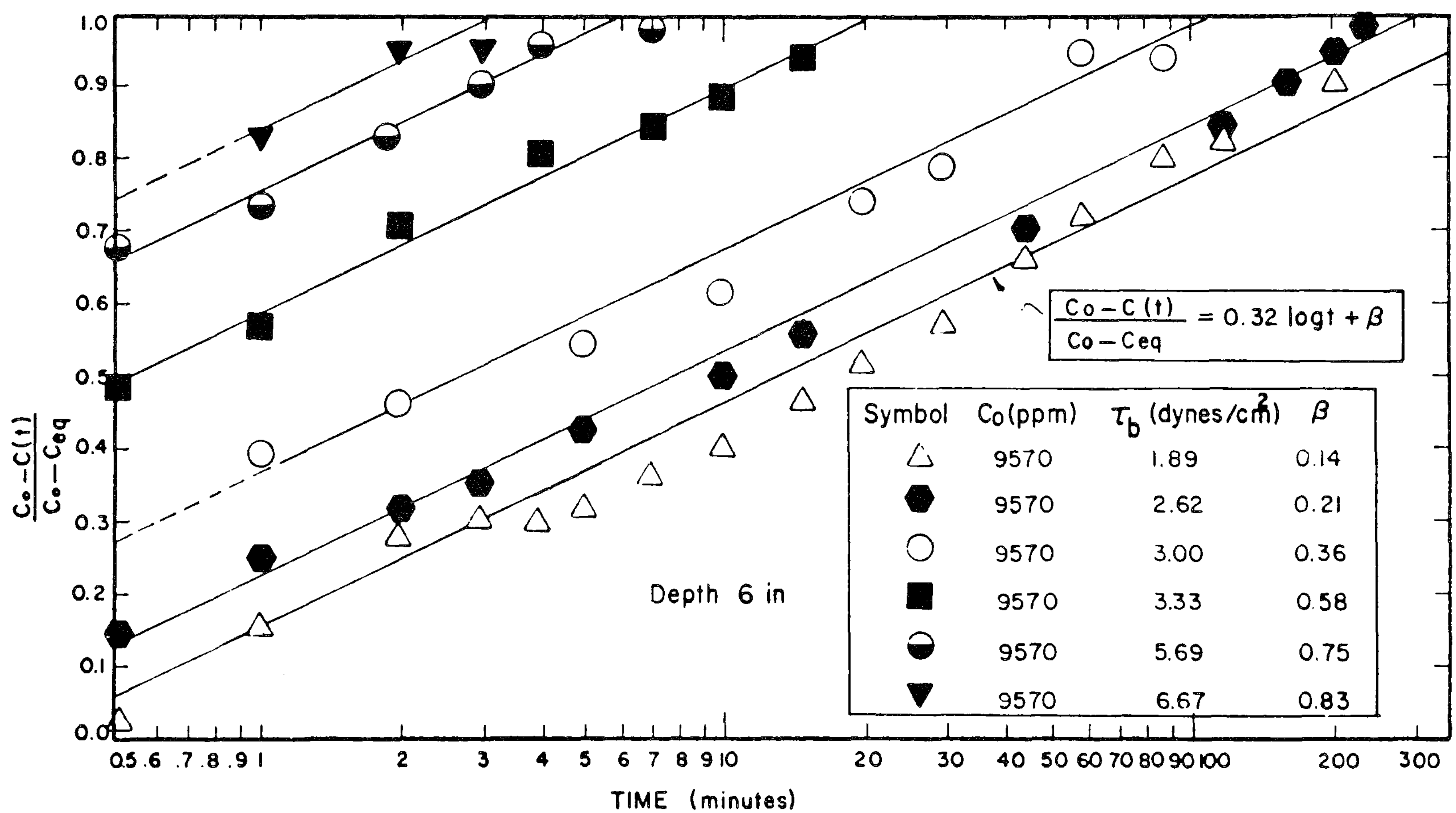


Fig. 9 Variation of Relative Depositable Concentration $(C_o-C)/(C_o-C_{eq})$ with Time

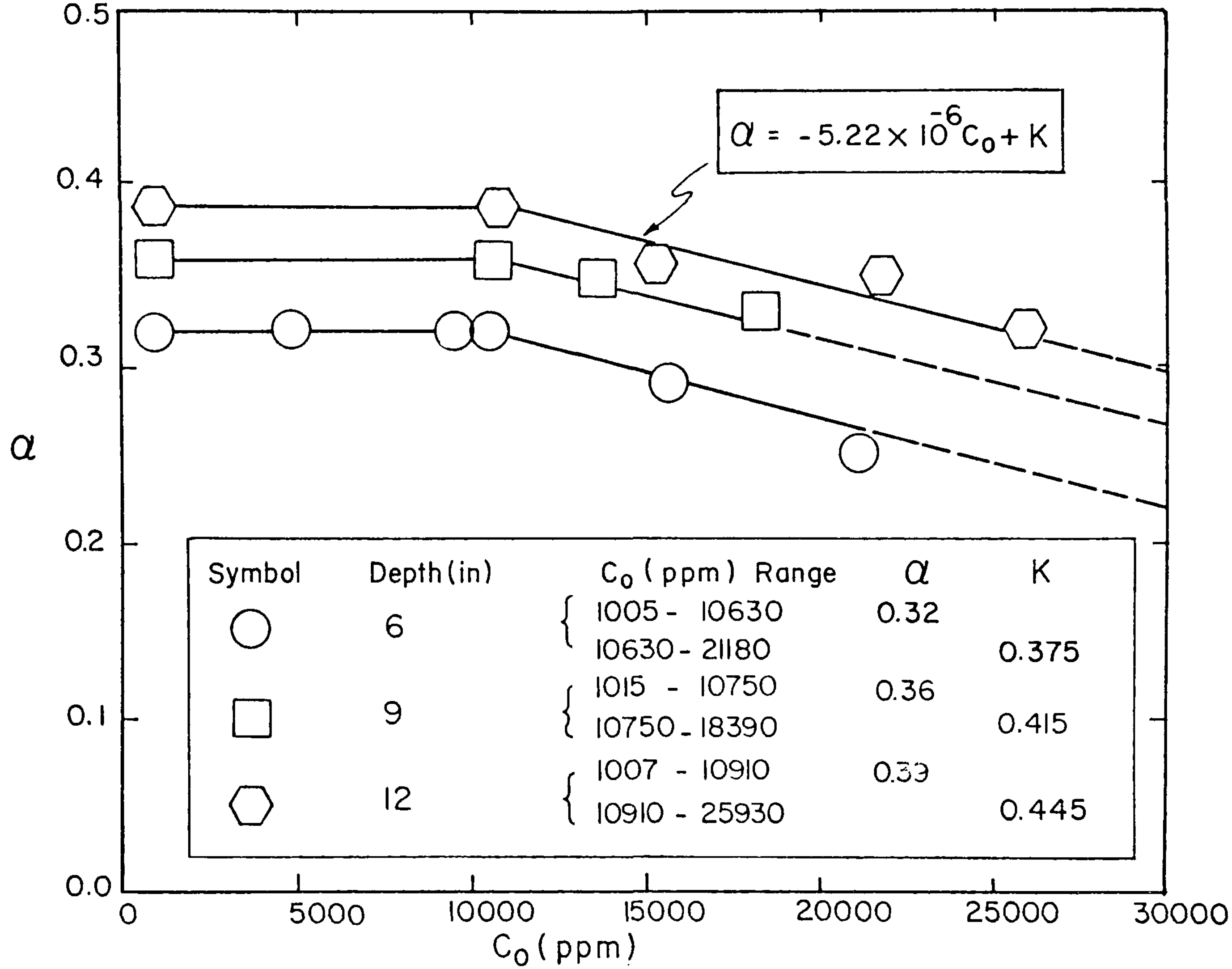


Fig. 10 Variation of Slope α with Channel Depth and Initial Concentration

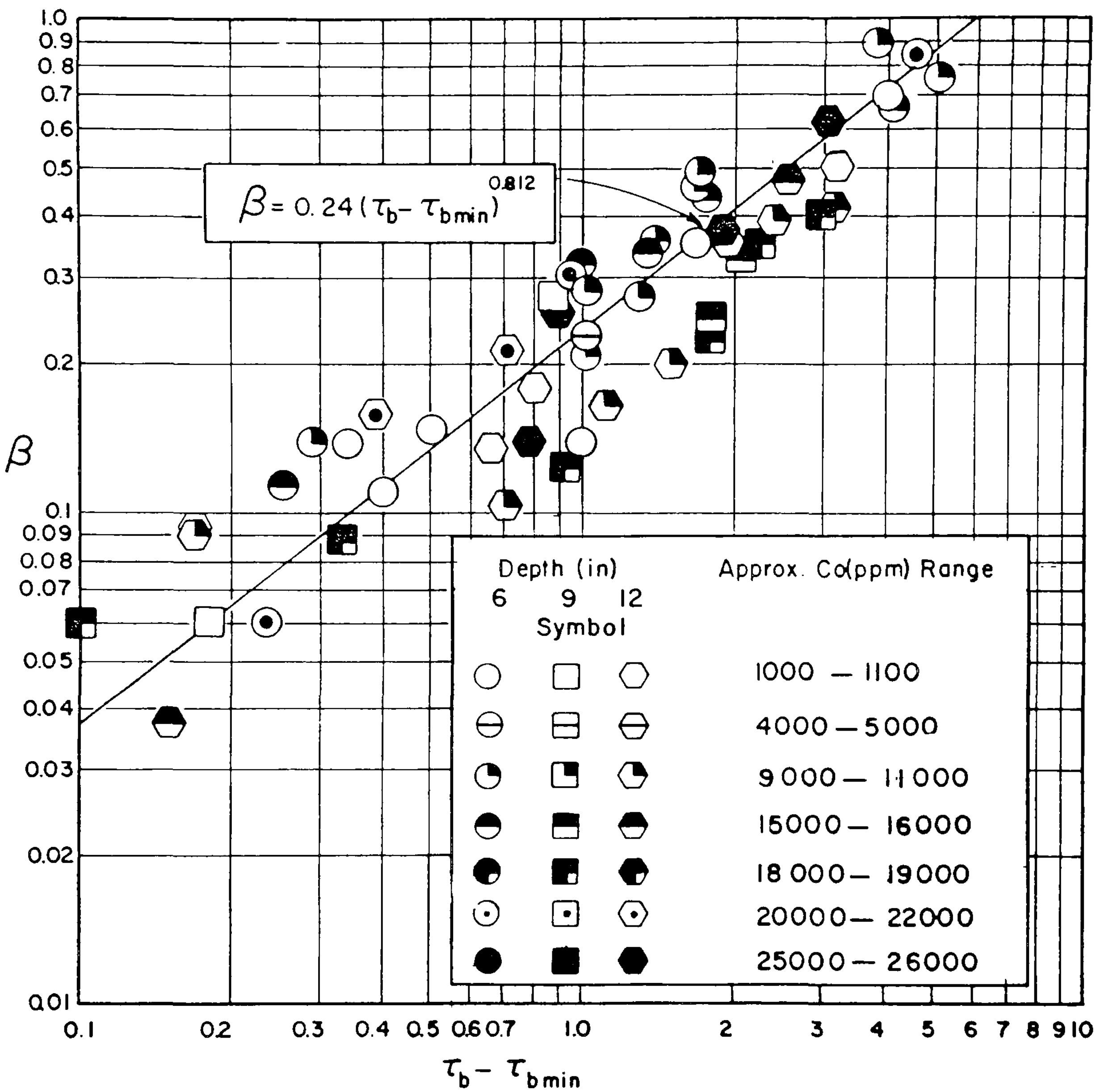


Fig. 11 Variation of Coefficient β with Bed Shear Stress

The random scattering suggests that β is independent of the depth of flow and of the initial sediment concentration, and depends only on the bed shear stress according to the relationship:

$$\beta = 0.24\ (\tau_b - \tau_{bmin})^{0.812} \qquad (14)$$

or

$$\beta = 0.24\ \tau_{bmin}^{0.812}\ \left(\frac{\tau_b}{\tau_{bmin}} - 1\right)^{0.812} \qquad (15)$$

Accordingly, Eq. 13 can be modified as:

$$\frac{1 - C(t)/C_o}{1 - C_{eq}/C_o} = \alpha \log \frac{t}{t_o} + k \left(\frac{\tau_b}{\tau_{bmin}} - 1\right)^{\delta} \qquad (16)$$

where C_{eq}/C_o is given by Eq. 12, $k = k_2\tau_{bmin}^{\delta}$ and t_o is a reference time. The coefficients α and k are, of course, dimensionless. The parameters, α, τ_{bmin}, k, M and σ in Eqs. 12 and 16 are functions of the physico-chemical properties of the sediment only. Thus the degree of deposition and the deposition rates describing the entire deposition process, have been expressed in terms of the flow variables, represented, according to the reported results, by the bed shear stress, and by the sediment physico-chemical properties represented in the above listed coefficients. For the kaolinite clay used in the current experiments α ranges from 0.32 to 0.38, τ_{bmin} = 1.60 dynes/cm^2, k = 0.352, M' = 0 and σ = 0.49 dynes/cm^2.

Differentiating Eq. 13 with respect to time gives rise to the following equation for the time rate of concentration change:

$$\frac{dC(t)}{dt} = - \frac{\alpha(C_o - C_{eq})}{2.3}\ \frac{1}{t} \qquad (17)$$

Eq. 17, which is consistent with the results of earlier preliminary investigations (15), states that at any time the deposition rate is proportional to the total depositable sediment, as represented by C_o-C_{eq}, and, for the concentrations normally encountered in natural water bodies, is independent of the initial concentration itself. The effect of the bed shear stress appears implicitly in C_{eq}.

The dependence of β exclusively on the bed shear stress can be explained if one considers that β represents that portion of the depositable sediment that has been deposited at 1 minute. The value of the concentration of the depositable sediment, $C_o - C_{eq}$, decreases with increasing bed shear stress in accordance with Eq. 12. Moreover, the average strength, size and settling velocity of the flocs which eventually reach the bed and which constitute the depositable sediment concentration are expected to increase with increasing bed shear stress. Therefore, the average settling rate and the percent of deposition at any arbitrary time are expected to be functions of the relative equilibrium concentration, which in turn depends entirely on the bed shear stress. It follows that β should also be a function of τ_b. The initial concentration C_o could affect β by increasing the rate of floc formation, since the probability of particle collision is expected to be proportional to C_o. The observed independence of β from C_o,however, suggests that the time of floc formation is negligibly small in comparison with the average time of deposition of floc.

SECTION VIII

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The assistance of the staff of the Coastal Engineering Laboratory at the University of Florida, where the tests were conducted, is greatly appreciated.

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SECTION X

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1. Partheniades, E., and Mehta, A.J., "Rates of Deposition of Fine Cohesive Sediments in Turbulent Flows", Proc. 14th Conf. Int. Assoc. of Hydr. Res., Paris, France, V. 4, D3-1, pp. 17-26, August, 1971.

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27 *Abstract*

Basic laboratory investigations were carried out to study the role of flow parameters on the deposition of fine cohesive sediments in a turbulent flow field. The study utilized a special apparatus consisting of a system of a rotating annular channel and ring. The results obtained have confirmed earlier conclusions that the percentage of the total sediment that a given flow can maintain in suspension depends only on the bed shear stress and is independent of the initial sediment concentration.

The percentage C', of the depositable sediment deposited at time t has been found to vary with time according to the law $C' = \alpha \log t + \beta$, where the coefficient α appears to be independent of the flow conditions and sediment concentration, while the coefficient β is a function of the bed shear stress only. Both α and β are expected to depend on the physico-chemical properties of the sediment and the water environment. It follows that the deposition rates are proportional to the depositable sediment concentration and inversely proportional to time. (Partheniades-University of Florida)

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