CHAPTER 41

DEPOSITIONAL BEHAVIOR OF FINE SEDIMENT IN A TURBULENT FLUID MOTION

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ABSTRACT

An experimental investigation, utilizing an apparatus consisting of a counterrotating annular channel and ring, of the depositional characteristics of fine, cohesive sediment revealed that after an initial period of rapid deposition, the sediment concentration approaches asymptotically an equilibrium value. The ratio of this equilibrium concentration to the initial concentration is nearly independent of initial concentration and for a given sediment and environment depends only on the flow conditions. For the three water depths investigated, the ratio of equilibrium to initial concentration was found to be a single function of an average shear stress around the channel-section perimeter. A comparison of the size distributions of the parent material with the material retained in suspension when equilibrium was achieved indicated that the greatest losses occur in the clay-size fractions, suggesting that the deposition is controlled predominantly by flocculation, and that the strength and size of the flocs exert a stronger influence on the deposition than does the particle weight. A silty-clay sediment with a mean particle diameter of 0.0009 mm was used in all experiments.

INTRODUCTION

The depositional behavior of fine cohesive sediments is one of the primary factors controlling shoaling in estuarial channels, the formation of deltas, and the persistence of turbidity currents. These sediments range in size from a small fraction of one micron up to a few microns, and normally contain a large proportion of colloids, i.e., particles small enough and with specific area (area per unit volume) large enough that the effects of the surface, inter-particle, physico-chemical forces are as important as the effects of gravity forces. Completely dispersed individual fine particles may stay in suspension, even in quiescent water, for periods of several days. In fact, particles smaller than one micron may never settle under gravity because of Brownian motion. Moreover, even very slight agitation can be adequate to prevent settling of the heavier fine particles.

Some of the interparticle physico-chemical forces are attractive (for example, the van der Waals atomic forces) while others are repulsive (for example, surface ionic forces due to charge deficiency of either surface molecules or absorbed ions [11]). The magnitudes of some of the forces vary with time, temperature, and water quality. The net effect of all the inter-particle forces may be a net inter-particle repulsion or attraction, depending on the character of the water environ and the absorbed ions. Under certain conditions, as in the presence of slight salinity (although this is not the only necessary condition), the net inter-particle forces become attractive.

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As a result, particles tend to cling to each other and form agglomerations called flocs, whose size and settling velocity may become several orders of magnitude higher than those of the individual particles. This phenomenon is known as flocculation and it is the main cause of deposition of fine suspended sediment. Moreover the flocs may combine into larger systems, known as floc aggregates and aggregate networks, with still larger settling velocities.

The floc size-distribution and the maximum floc size in a given flow field are functions of the sediment properties, water chemistry, and the flow conditions themselves. It is this multi-dependence which makes the problem of erosion, transport, and deposition of cohesive sediments extremely complex. However, a rational approach to the control of shoaling in estuarial waters, which is very frequently due predominantly to fine sediment [7], requires a good understanding of the behavior of this type of sediment in a flow field. More specifically, the important flow parameters and soil properties which control the initiation and the rates of erosion and deposition need to be investigated in order to determine quantitative functional relationships between these variables. The investigation described here was concerned with the role of flow parameters. The rather unconventional experimental apparatus used consists of an annular rotating channel and an annular rotating ring positioned within the channel. This equipment, its operation, and the results obtained to date are herein reported.

PREVIOUS INVESTIGATIONS

Previous investigations have been extensively summarized and discussed elsewhere [7, 8]. R. T. McLaughlin [6] studied the settling properties of fine sediment suspensions and on the basis of the sediment continuity principle derived the fundamental differential equation for the deposition of these suspensions. R. B. Krone [4, 5] conducted systematic experimental studies on the deposition of San Francisco silty clay (commonly known as "bay mud") in an open flume. He found that for low clay concentrations, the concentration decreases exponentially with time, whereas for high concentration the decrease is logarithmic. Both the exponential and logarithmic equations contain factors which are functions of the apparent settling velocity, the depth of flow, the bed shear stress, and the "critical" shear stress below which no sediment remains in suspension. He also studied experimentally the strength of the flocs and derived a relationship between maximum floc size, floc shear strength, and boundary shear in a laminar shear field between two concentric rotating cylinders.

Partheniades [7] studied the erosion and deposition characteristics of the same silty clay used by Krone. The deposition studies showed that after an initial period of rapid decrease, the concentration of suspended sediment reaches a more or less constant value, called the "equilibrium concentration". Limited results at that time suggested that for given flow, this concentration is a constant proportion of the total sediment in suspension at the beginning of a run. Moreover, Partheniades found that for given geometry, roughness, and depth, there exists a threshold velocity above which a substantial part of the initial suspended sediment may be retained in suspension and below which rapid deposition of all suspended sediment occurs. This threshold velocity is smaller than the minimum velocity required to erode the deposited sediment.

APPARATUS AND PROCEDURE

The major item of apparatus, shown in Figures 1 and 2, consists of a rotating annular channel, in which the water-sediment mixture is placed, and an annular ring which rotates in a direction opposite to that of the channel. The ring is positioned in the channel so that it just touches the water surface. The speeds of the ring and channel are controlled independently through the two variable-speed driving motors. The ring is suspended from three flexible stainless steel blades instrumented with strain gages, whose output was calibrated statically and used to measure the shear applied to the fluid by the ring.

The annular channel consists of two concentric cylinders, with diameters of 28-3/8 and 36 inches and a depth of 12 inches. The cylinders are made of 3/16-inch Plexiglas, mounted at the bottom to a 3/8-inch Plexiglas plate and stiffened at the top by two annular 3-inch wide flanges. The entire annular channel assembly is attached to a steel turntable through a wooden base. A drain is provided through the channel bottom and wooden base. Water and sediment are introduced into the channel through the open top of the channel when the ring is raised.

The width of the shear ring is 1/4 inch less than that of the channel, so that there is 1/8 inch gap between its edges and the walls of the channel. The three supporting blades are 0.3 inch thick, 2 inches wide, and 15 inches long; they were found to be quite rigid in the radial direction. The shear ring can easily be moved up and down and positioned at any desired vertical location. The strain gage signals are transmitted to the galvanometer through a set of slip rings attached to the drive shaft of the ring. To achieve simultaneous rotation of the channel and the ring, a concentric shaft assembly was provided. The inner shaft drives the shear ring and the outer, connected to the turntable, drives the annular channel. More constructional and circuit details are given elsewhere [3, 9]. The main advantages of this apparatus are the absence from the flow field of floc disrupting elements, such as pumps, elbows, return pipes, etc., and uniform flow conditions at every section of the system.

The rotational motion of the channel and ring generally induces a secondary motion in the radial direction in addition to the main tangential flow. When both channel and ring rotate at the same angular velocity a rigid-body rotation (forced vortex) will eventually be established, and no secondary flow will then occur since at any cylindrical surface (r = constant) the velocity is constant at every elevation and therefore the centrifugal force on any fluid element is exactly counterbalanced by the net pressure force acting on it. This static balance no longer prevails if only the ring or only the channel is rotating, or if they are rotating at different velocities. The radial pressure gradients are then different at different elevations, and the resulting pattern of secondary currents induced is as illustrated qualitatively in Figures 3. The secondary currents illustrated tend to move the deposited sediment towards the inside or outside of the channel. It is obviously desirable to minimize this effect in order to achieve approximately uniform sediment deposition across the channel. This was accomplished by rotating the channel and ring in opposite directions and at different speeds. This counter-rotation caused the fluid to move outward both near the bottom of the channel and near the ring, thus setting up two circulatory motions in opposite directions, as shown in Figure 3c. Now if the velocity of the ring is sufficiently greater than that of the channel, the vertical momentum of the downward moving fluid near the outer wall can be great enough to balance the radial pressure gradient near the channel bottom and thus eliminate the secondary motion there. Then a nearly uniform deposition of suspended particles across the width of the channel can be expected.

For each channel speed, the corresponding ring speed yielding uniform deposition was determined by placing small plastic beads of specific gravity 1.05 in the water-filled channel with no sediment present and then seeking the ring speed that resulted in a uniform distribution of the beads across the bed. The curves shown in Figure 4 were thereby obtained for the four different channel depths indicated. These curves, which are practically straight lines, were used as "operating curves" for the deposition experiments and always yielded a nearly uniform thickness of deposited sediment over the whole channel bottom. The relative magnitude of the secondary currents was roughly and qualitatively investigated by attaching small threads to the channel bed as shown in Figure 5. The threads were fixed at one end and free to deflect at the other, and their alignment thus indicated the general direction of the resultant of the tangential and the superimposed secondary flow, since the tangent of the deflection angle is proportional to their ratio. These visual observations indicated that the secondary current velocities are of the order of 10 to 20 percent of the corresponding tangential velocities when the operating curves were adhered to. The higher values occurred at lower speeds of rotation.

The rate of deposition was determined by measuring the instantaneous sediment concentration at frequent time intervals. This was done by extracting small samples through stop-cocks placed on the outside wall of the annular channel at various levels and subsequently determining the sediment concentration either by filtering and weighing or by an optical method [1, 3, 9]. The water level in the channel was maintained by the constant-level reservoir placed near the center of the turntable. The volume of the samples withdrawn was less than one percent of the volume of water in the channel.

The size distributions of sediment samples were obtained from hydrometer analyses.

PRESENTATION AND DISCUSSION OF RESULTS

The experimental work reported here may be divided into two parts. The first had as its main purpose the determination of some general fundamental aspects of the depositional behavior of fine sediments. The second phase, still in progress at the time this paper was prepared, is a more detailed continuation of the first phase, aiming at the determination of the flow variables which control certain important depositional characteristics.

Since the present study was confined to the role of the flow variables, only one sediment was used. This was a commercial kolinite clay known as Peerless No. 2, which originates in South Carolina [12], and whose grain size distribution is shown in Figure 6. Sixty-five percent of the material lies in the clay range, twenty percent in the fine silt range, and fifteen percent in the medium and coarse silt range. This sediment is among the least active electrochemically. Flocculation occurs predominantly by attraction of positively charged edges to negatively charged faces (edge-to-face or card-house type flocculation). Such flocculation occurs more readily in salt-free water. Tap water was used in the experiments of the first phase (Series I, II, III, and IV) of this study. It was discovered later, however, that some depositional and flocculation characteristics varied slightly over a period of several months, although the same clay was being used. These variations were attributed to slight changes in the dissolved chemical content of the tap water and for that reason distilled water was used in the later experiments. The experiments of Series I constituted a preliminary investigation of some depositional characteristics of the sediment, studied in more detail in Series III and IV. Series II consisted of some erosion experiments. Only the results of Series III and IV will be presented here.

Prior to the deposition experiments, measurements were made to determine the relationship between the average shear stress on the ring and differential speed of rotation between the ring and the channel, using clear water. This empirical relationship is shown in Figure 7 for depths of 8 and 16 cm and for three rotational configurations ring only rotating; channel only rotating, and both the ring and the channel rotating at speeds determined by the operating curves of Figure 4. It is seen that all points for both depths plot as a single parabolic curve which may be represented by the equation

$$\tau_r = K\,(\Delta V)^2 \qquad (1)$$

where τ_r is the shear stress on the ring in dynes per cm^2, ΔV is the differential velocity (at the center of the annulus) between the ring and the channel in cm/sec, and K, the constant of proportionality, equals 1.7×10^{-3}. Further experiments with sediment concentrations up to 6,600 ppm showed no measurable effect of sediment on shear stress.

Figure 8 shows the results of the deposition experiments for the 8-cm depth. The initial concentrations varied from about 900 ppm to 15,000 ppm. The velocity (sum of the ring and channel speeds) for all runs was 64.4 cm/sec. It is seen that after an initial period of rapid deposition, the suspended sediment concentration reaches a constant value. It is also seen that the ratio of the equilibrium concentration, C_{eq} to the initial concentration, C_o, does not vary more than 10 percent for a 16-fold variation of C_o.

The results of the deposition experiments at the 16-cm depth at a velocity of 81 cm/sec are shown in Figure 9. The velocity was selected so that the average rate of energy dissipation per unit volume of fluid was the same as for the experiments at the smaller depth [9]. The ratio of equilibrium concentration to the initial concentration appears to be practically constant and equal to about 0.54. The dashed line shows that the time for the apparent equilibrium concentration to be reached decreases with increasing initial concentration. A similar phenomenon was also reported by Krone [5, p.36], and is a direct consequence of the mechanism of flocculation; the frequency of particle collision and therefore the rate of flocculation (which is reflected in the rate of settling) is higher at higher concentrations of suspended sediment.

The ratio C_{eq}/C_o is portrayed as a function of C_o in Figure 10 for the experiments summarized in Figures 8 and 9. It is seen that for Series IV (larger depth) this ratio is practically independent of C_o, whereas in Series III it increases slightly with increasing C_o. There is as yet no completely satisfactory explanation for this increase, which at first glance is the opposite of what one might expect. Since, however, the maximum variation of C_{eq}/C_o is of the order of only 10 percent for a 16-fold variation of C_o, it appears that for given flow conditions and sediment properties the equilibrium concentration is practically a constant fraction of the initial concentration. The value of this ratio is determined by the maximum grain size or floc size that the turbulence configuration associated with a given flow can carry in suspension. Moreover, this observation suggests the nature of the mechanism controlling the equilibrium concentration. In the case of coarse, non-cohesive sediment, the equilibrium concentration is that for which the number of particles deposited per unit area and unit time is equal to the number of particles eroded [2]. If an additional sediment load of the same grain size range as the original load is added to the flow, it will eventually deposit since the number of particles eroded per unit area and unit time is a function of the flow conditions and sediment size only, and not of the number of particles present (provided the bed is covered). In the case of fine sediment, the equilibrium concentration does not appear to be controlled by the interchange mechanism between bed and suspended particles; if it were, it would be constant and independent of the initial concentration. Rather, it appears to be regulated by the rate of floc formation and disruption, which is in turn dependent on the amount of sediment present. In any event, Figure 10 demonstrates that the rate of energy dissipation per unit volume, which is the same for both curves, is not the primary factor governing C_{eq}/C_o.

The next question to consider is what readily determined flow variable or variables govern the value of C_{eq}/C_o for given sediment characteristics. The answer to this question was the first objective of the second experimental phase of the program. In these experiments the initial concentration was kept constant at 8,020 ppm. Each experiment was run for 24 hours. Three experimental series were performed for three different depths. 8 cm, 16 cm, and 12 cm. Figure 11 shows a plot of the equilibrium concentration versus the differential angular speed for these three depths. The curves have two distinct parts: a flat segment indicating low deposition with decreasing speed, and a steep part over which rapid deposition accompanies decreasing speed. The transition for all depths occurs at approximately $C_{eq}/C_o = 0.65$.

Next, C_{eq}/C_o was plotted as a function of $(\Delta\omega)^2/(1 + 2d/b)$, which is proportional to the average shear stress around the boundary since the ring shear stress τ_r is proportional to $(\Delta\omega)^2$ and the moment balance about the center of rotation gives

$$\tau_{av}(b + 2d) = b\tau_r \tag{2}$$

It is seen that all points for the three depths fall on the same curve, indicating that the average shear stress on the channel boundary has a strong influence on the equilibrium concentration (provided the secondary flow pattern is such that an approximately uniform deposition occurs across the channel; i.e., when the speeds of the ring and channel are in accordance with the operating curves of Figure 4). For speed combinations off the operating curves, the points do not plot on the same curve. Two such points are shown in Figure 12, one for only the ring rotating and the other for the channel alone rotating. It appears therefore that as long as the pattern of secondary currents is such that their effect is minimized at the bed and uniform deposition occurs across the channel, the equilibrium concentration depends primarily on the average channel shear stress. However, in general the equilibrium concentration must be strongly influenced by the secondary currents.

The strong dependence of the equilibrium concentration on bed shear stress is quite understandable, since it is near the bottom that the turbulence is most intense and the settling flocs will be subjected to the highest disrupting stresses [10]. Although the distribution of shear stress around the channel perimeter is no doubt far from uniform, the experimental results suggest that τ_{av} may still be an adequate measure of the bottom shear stress. The dependence of the ring shear stress on only the relative speed and its independence of the depth indicates that most of the shear resistance has its origin at the narrow gaps between the ring and the channel walls. If this is the case, the shear force on the ring is not a good direct measure of the shear stress on the bed. However, if there is a similar distribution of shear stress, as appears reasonable, values of τ_{av} calculated from Eqn. (2) would give a direct indication of variation of the bed shear stress.

Figure 13 shows a plot of the equilibrium concentration versus channel speed only. The points conforming to the operating curves of Figure 4 again fall on one curve, although the correlation is not as good as that in Figure 12. The former correlation is believed to be a direct result of the latter, since it can easily be shown that if the two speeds conform to the operating curves, the rotational speed of the channel is very nearly proportional to $\Delta\omega/\sqrt{1 + 2d/b}$. The points with the channel only rotating are seen to fall far to the right of the points complying with the operating curves.

A size analysis of a sample of suspended sediment obtained at equilibrium concentration was performed only once. A representative sample was withdrawn through the wall of channel in the manner described by Partheniades *et al.* [9]. The size distribution of the sample, shown in Figure 14 and unfortunately somewhat deficient in the finer size-fractions, reveals that the 50-percent size suspended material is somewhat smaller than that of the parent material. A detailed comparison of the size distributions shown in Figures 6 and 14 shows that most of the change in the distribution occurs in the clay-size range, where a disproportionately large attrition of the larger clay sizes has occurred, due presumably to a high flocculation and settling rate in this size fraction. Hence it appears that floc growth and the consequent higher settling velocity outweigh the higher settling velocities of the individual silt particles as an agent of deposition. However, any conclusions based on one, somewhat incomplete, size analysis is at best speculative.

SUMMARY AND CONCLUSIONS

Experiments with kolinite clay-silt suspensions in the rotating annular apparatus revealed the following important depositional characteristics of fine sediments.

1. For given geometry, sediment, and flow conditions, the suspended sediment concentration reaches, after a period of relatively rapid deposition, a constant value, herein called "equilibrium concentration", which is very nearly a constant fraction of the initial concentration.

2. The ratio of the equilibrium concentration to the initial concentration appears to correlate very well with the average shear stress around the channel boundary, provided that the speeds of the channel and the ring are adjusted so that the sediment deposits uniformly across the channel. These speed combinations presumably also yield a similar pattern of shear stress around the channel.

3. The secondary currents generated by the rotational motion also have a significant effect on the equilibrium concentration and the rate of deposition.

4. A size analysis of a sample of material obtained at equilibrium concentration showed that most of the deposited material comes from the size fractions corresponding to the larger clay particles, and suggests that flocculation is more important as a settling agent than the initially higher particle weight and settling velocity of the silt particles.

ACKNOWLEDGMENTS

The study presented in this paper is part of the basic research program of a major research project on the interaction of tides, salinity, fresh water and sediment transport in estuaries, specifically in the Lake Maracaibo navigation channel in Venezuela. The project has been carried out jointly by the Instituto Nacional de Canalizaciones, Caracas, Venezuela; the Hydraulic Laboratory of the University of Zulia, Maracaibo, Venezuela, and the Hydrodynamics Laboratory, Department of Civil Engineering, M.I.T. It has been sponsored under the M.I.T. Inter-American Program in Civil Engineering by the Agency for International Development, U. S. Department of State. The basic research aspects of the project were pursued at the M.I.T. Hydordynamics Laboratory.

The contributions of the following individuals to this study are gratefully acknowledged· Dr. Arthur T. Ippen, Director of the Hydrodynamics Laboratory of M.I.T. acted as general supervisor of the project and offered valuable assistance and suggestions throughout the investigation, Mr. Robert J. Etter and Richard P. Hoyer, Graduate Students and Research Assistants at M.I.T. during the academic years 1963-65 designed the details of the experimental apparatus, and performed the initial preliminary experiments, Mr. Alfredo Ayora and Mr. David S. Graber, Graduate Students and Research Assistants at M.I.T. have continued the experimental work since September, 1965, and have made further significant contributions.

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Fig. 1. Experimental apparatus.

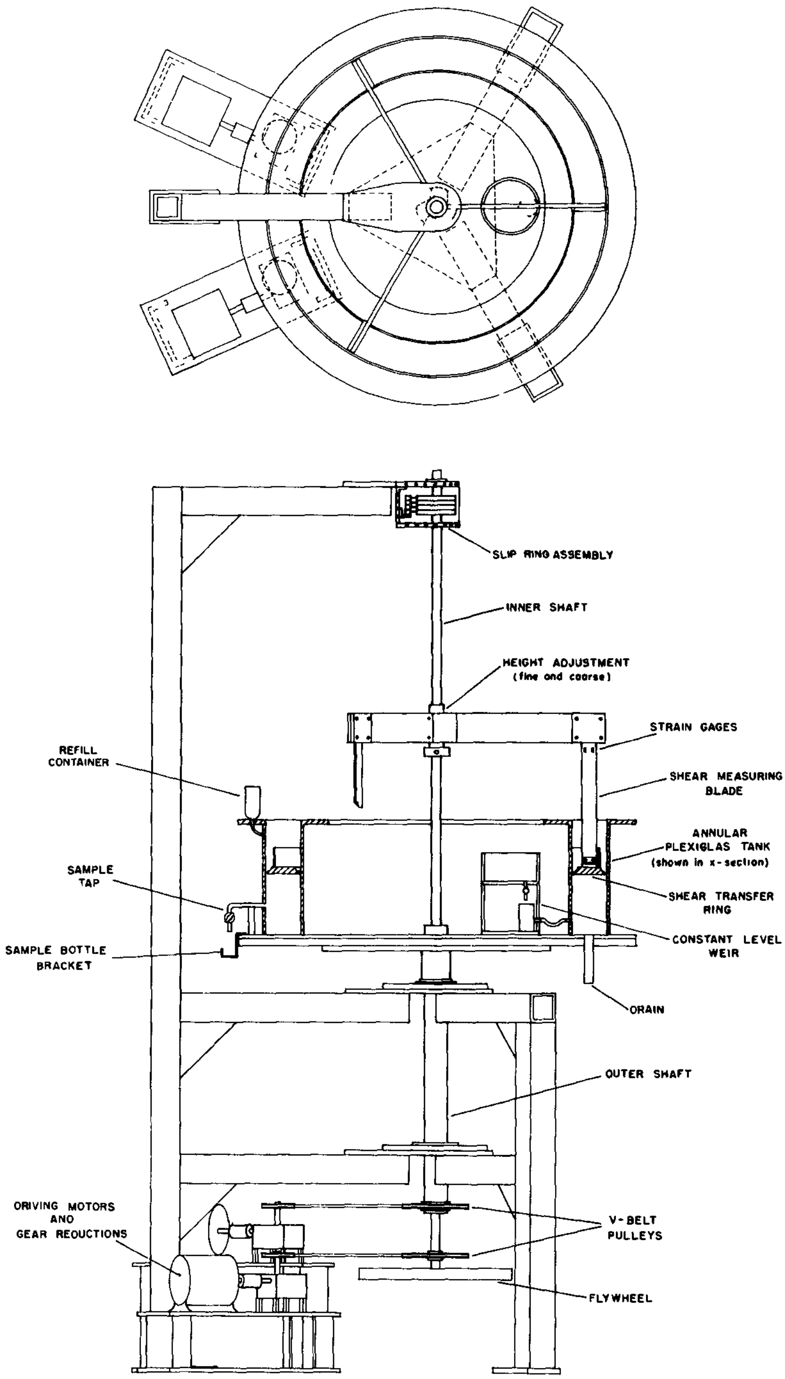

Fig. 2. Schematic drawing of rotating apparatus.

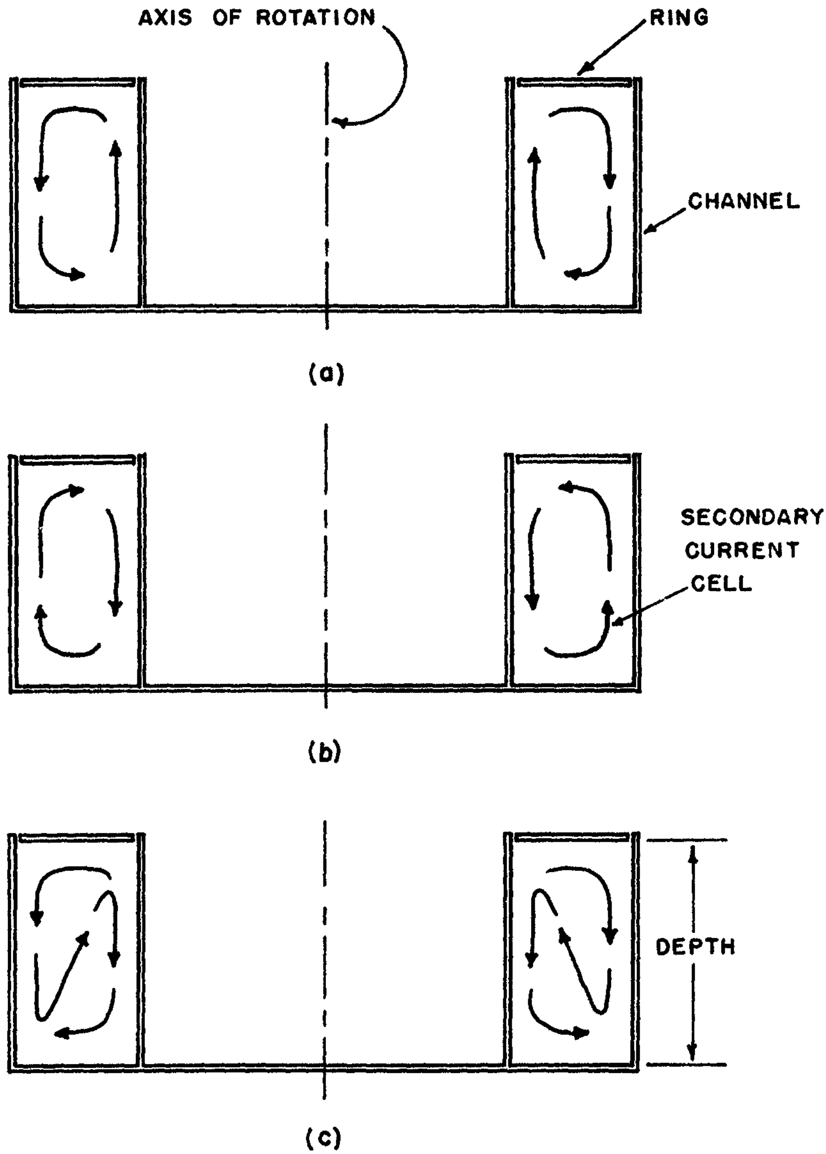

Fig. 3. Secondary currents in the rotating apparatus (a) ring only rotating. (b) Tank only rotating. (c) Both rotating.

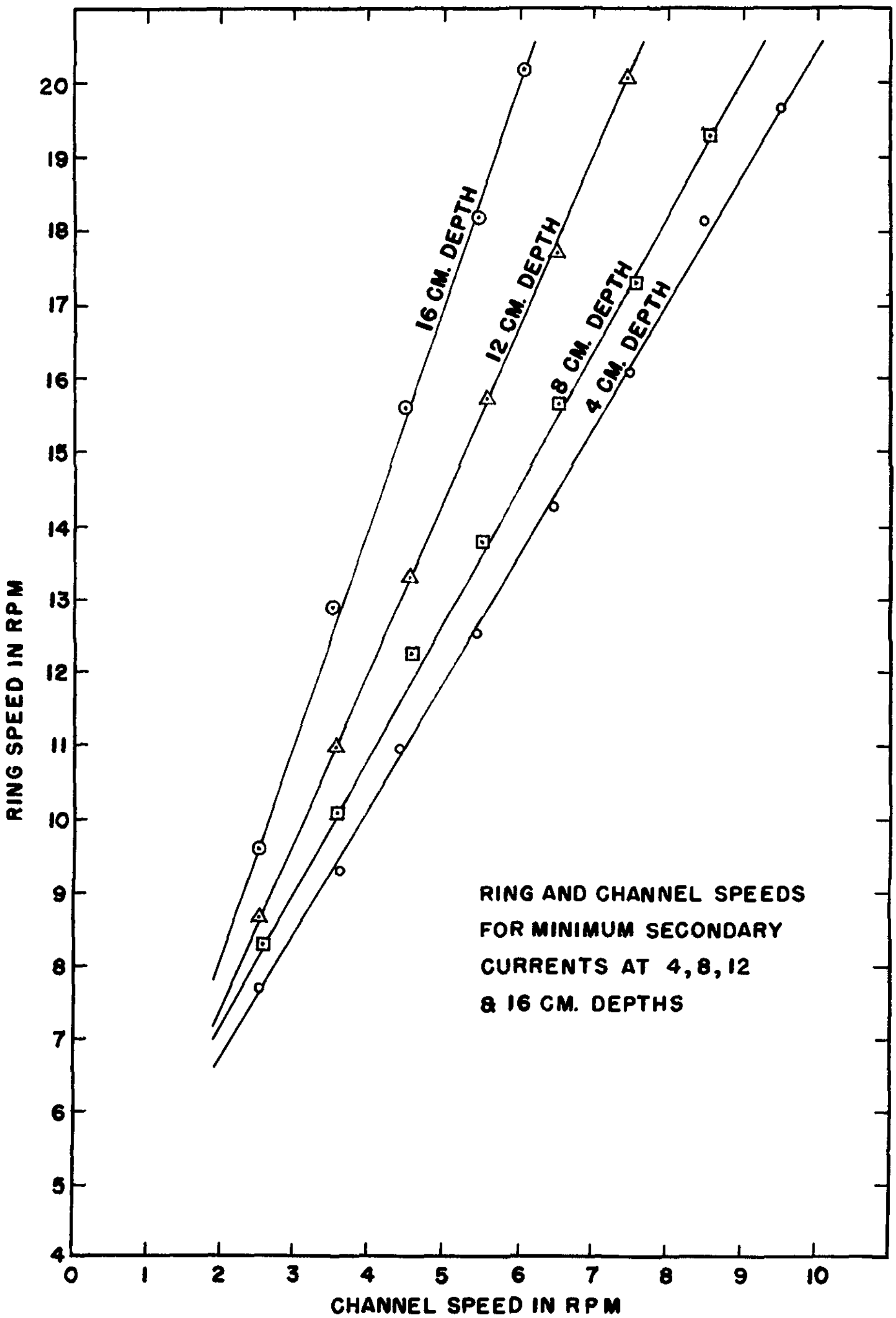

Fig. 4. Operating curves.

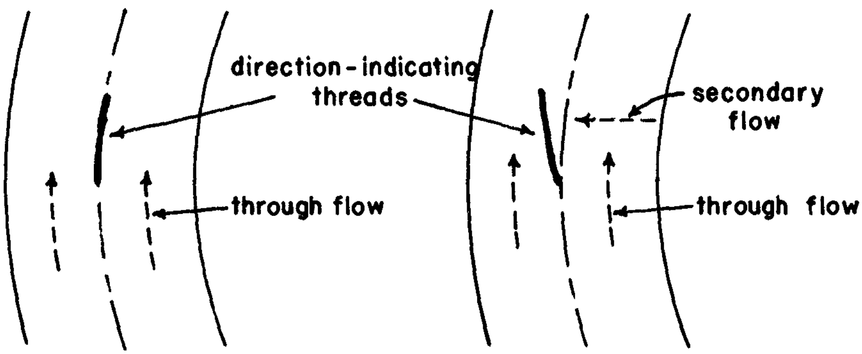

Fig. 5. Illustration of the effect of secondary flow on the direction-indicating threads.

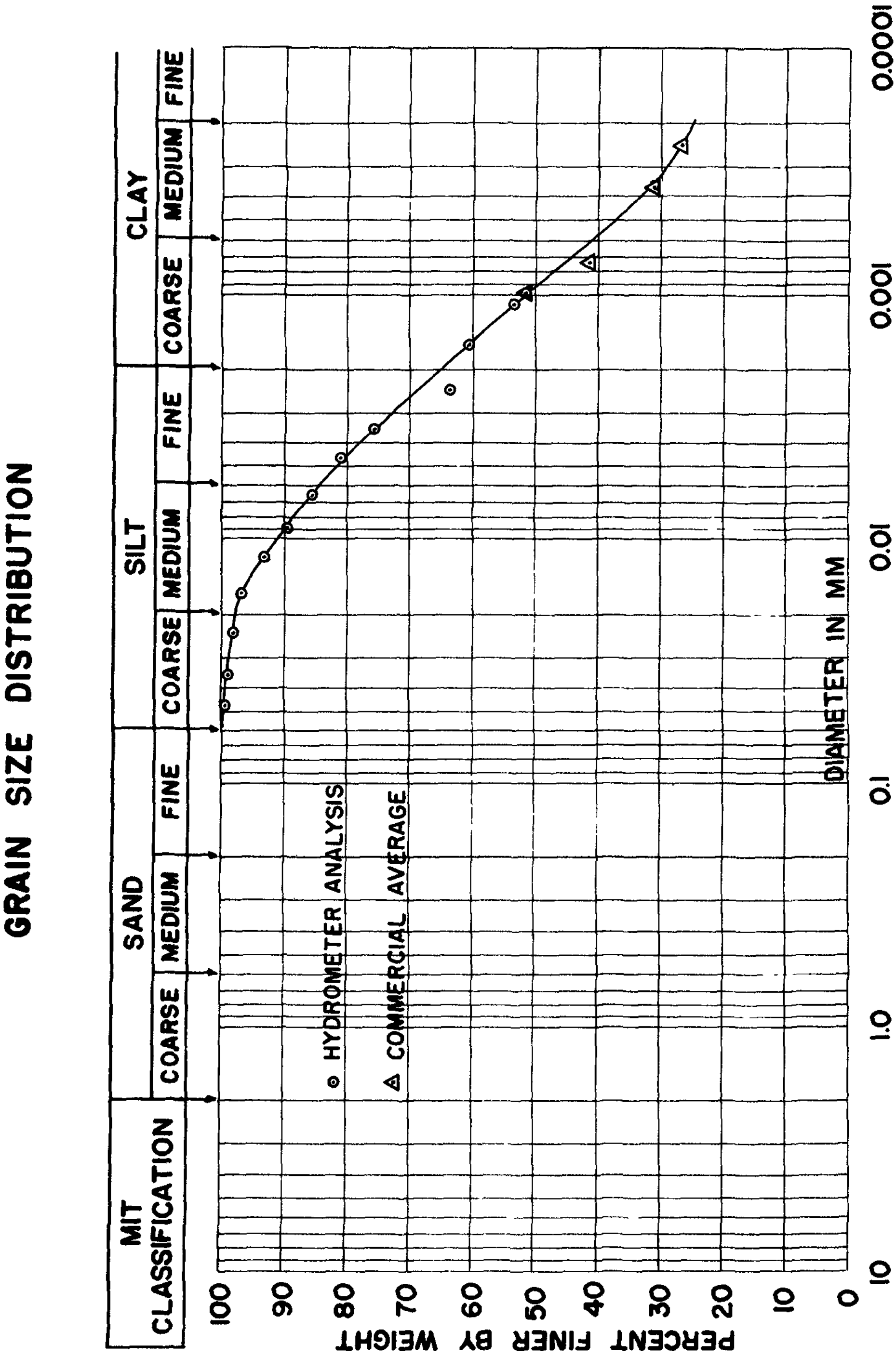

Fig. 6. Particle size analysis of peerless no. 2 kaolinite.

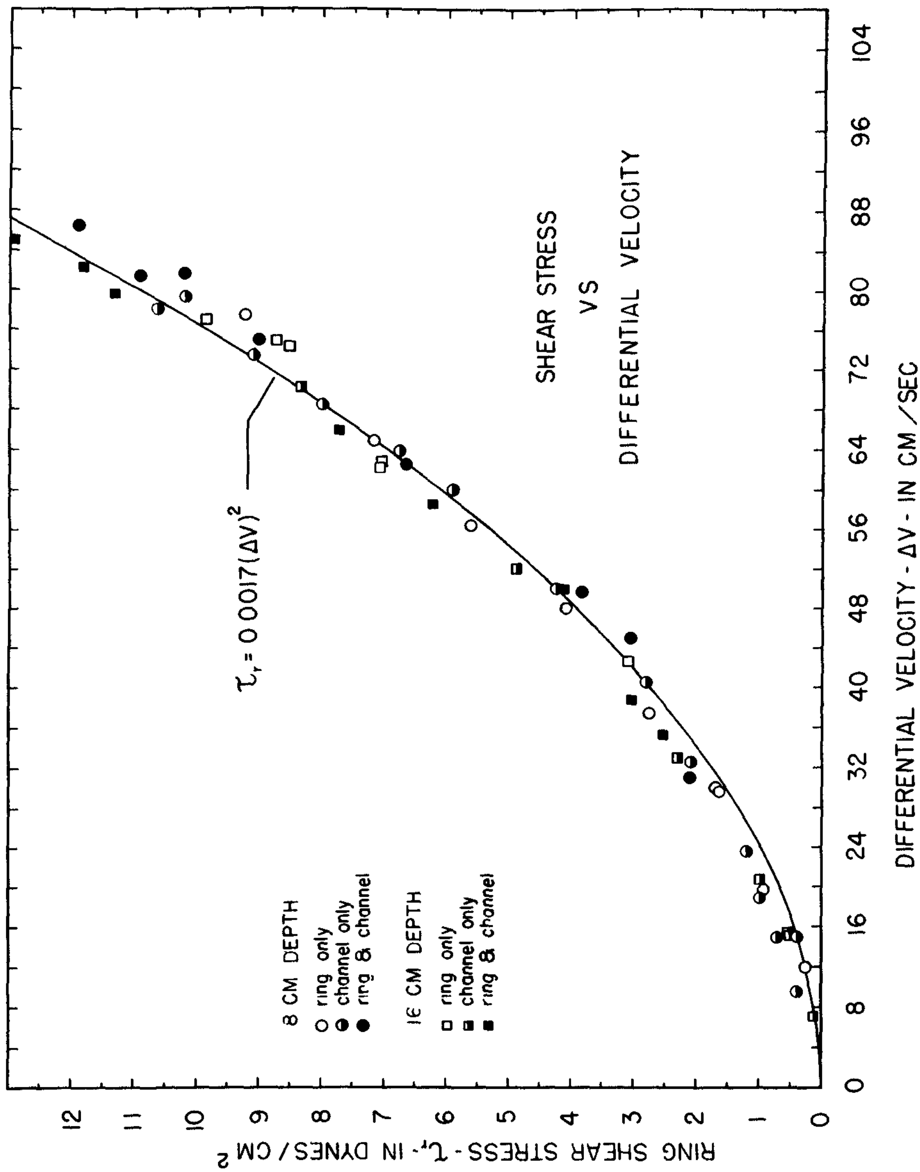

Fig. 7. Ring shear stress vs. differential velocity.

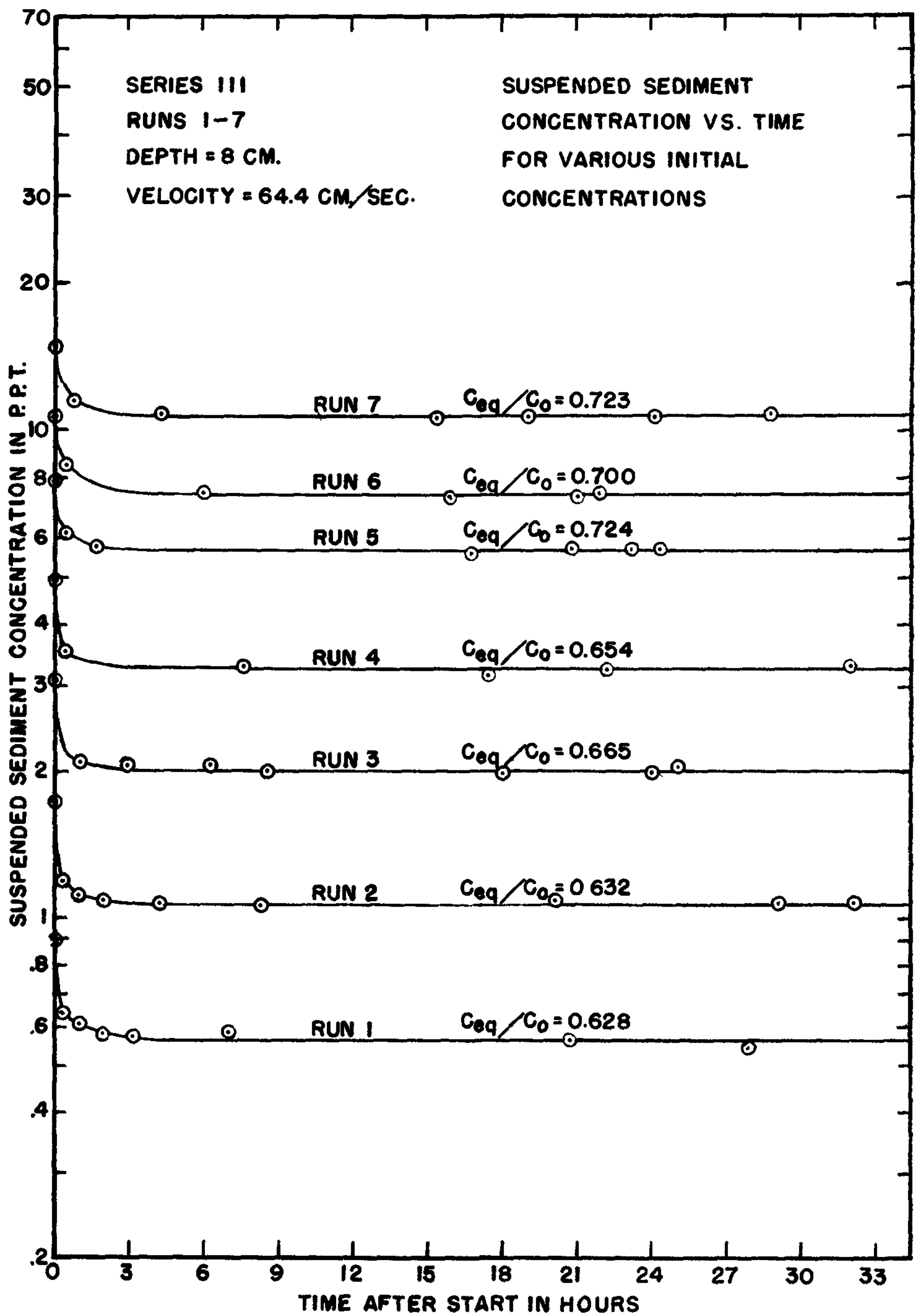

Fig. 8. Log concentration vs. time, series III.

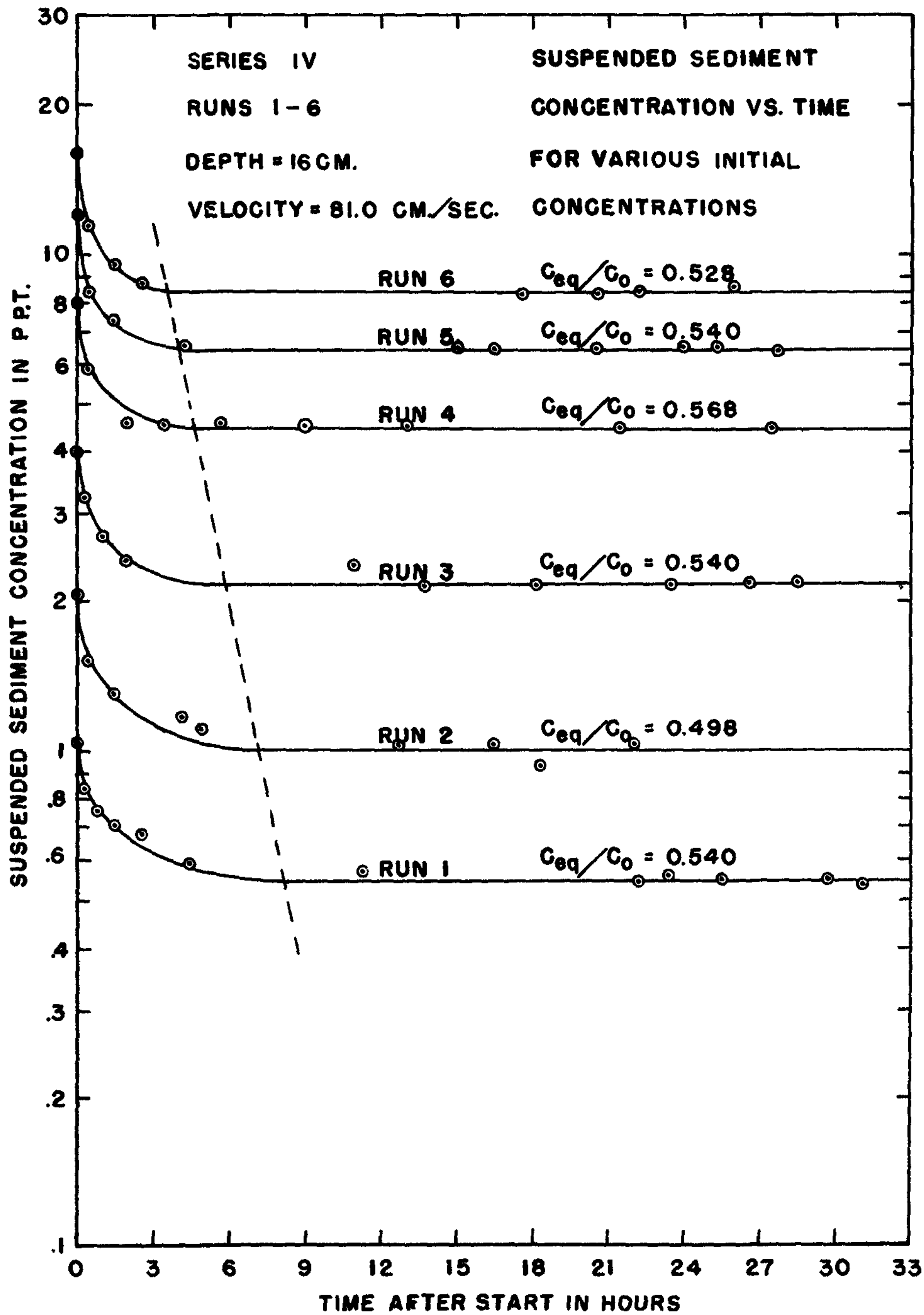

Fig. 9. Log concentration vs. time, series IV.

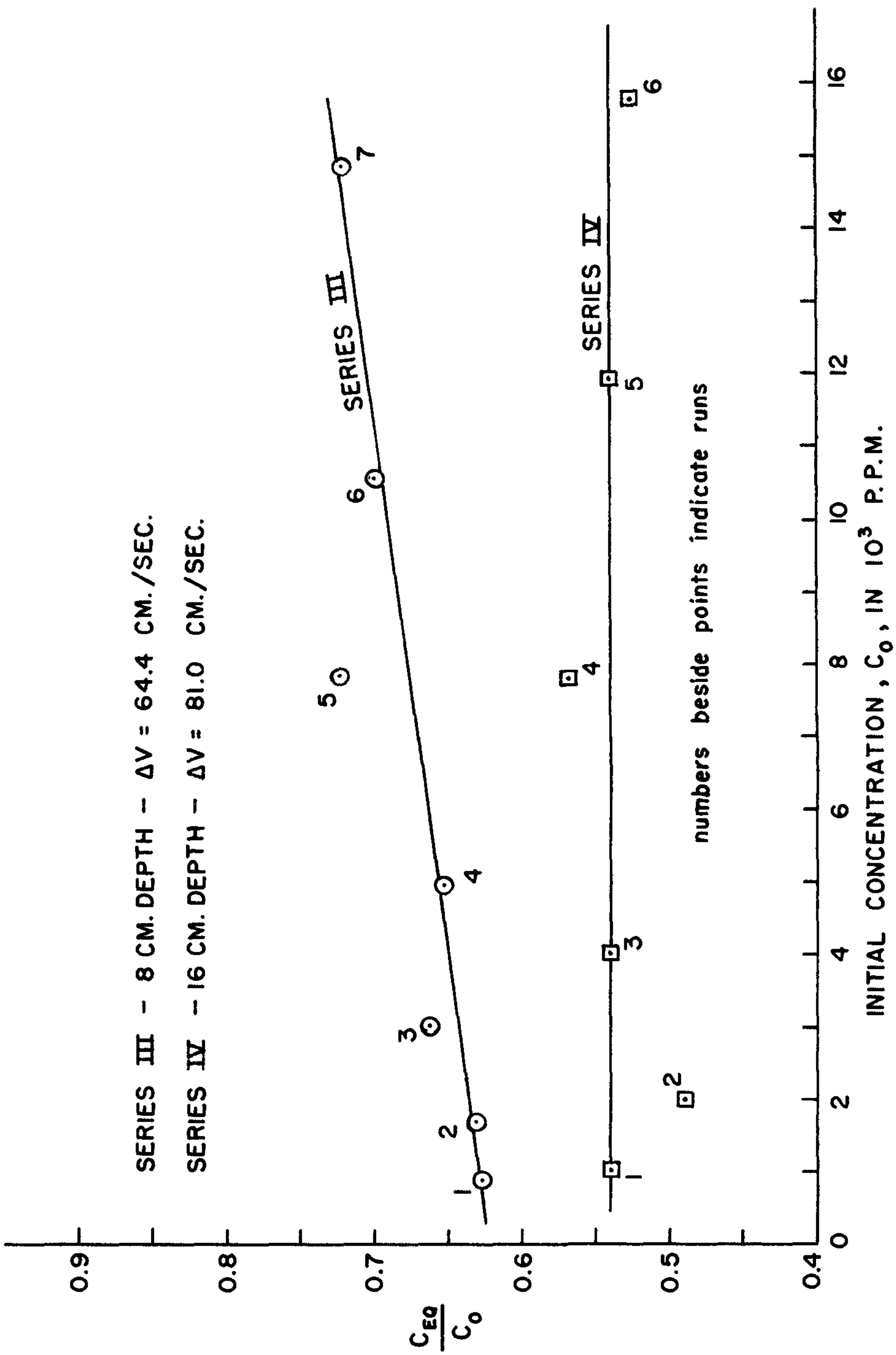

Fig. 10. Ratio of equilibrium concentration to initial concentration vs. initial concentration for series III, 8 cm. depth, and series IV, 16 cm. depth.

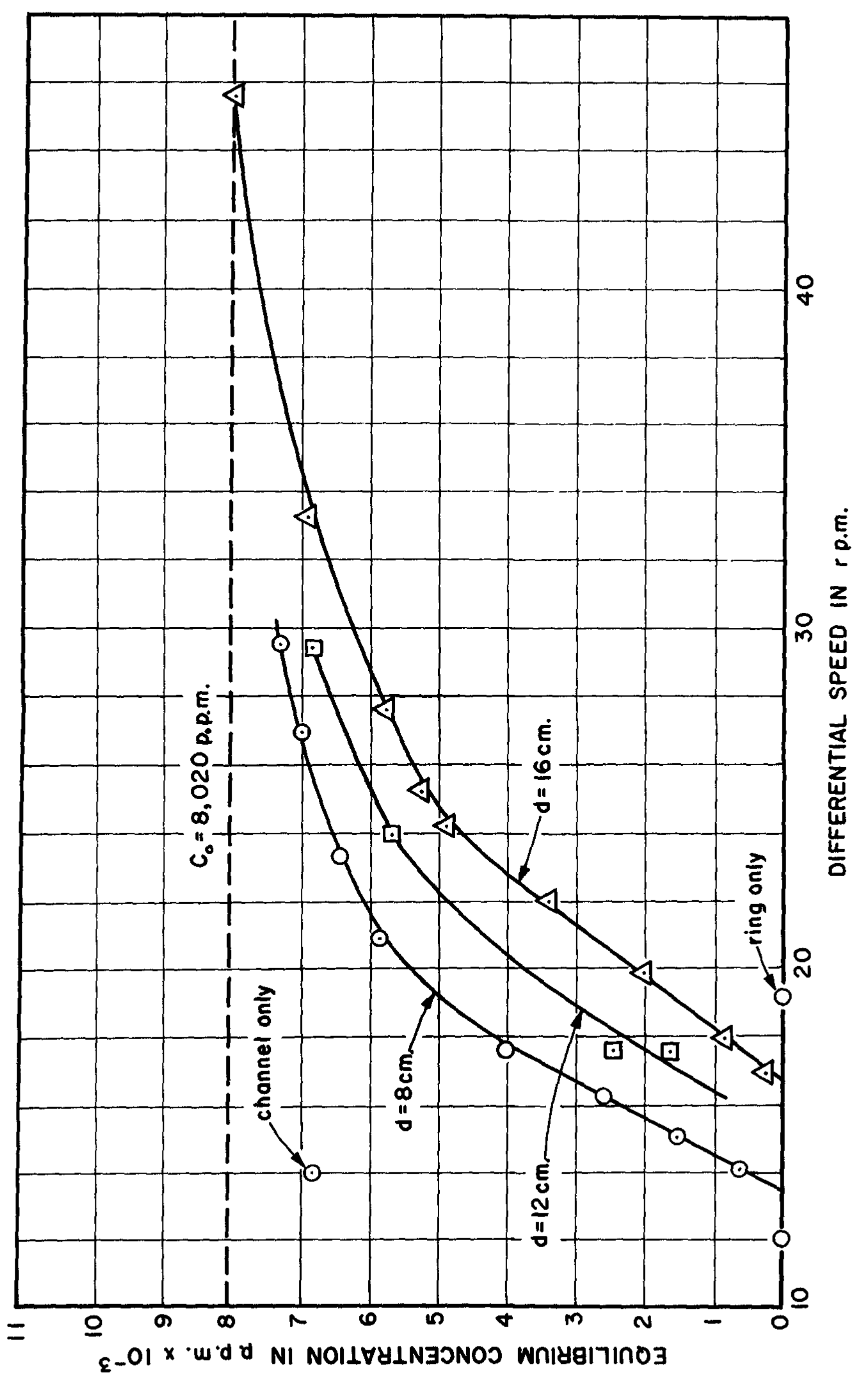

Fig. 11. Variation of equilibrium concentration with total speed $\Delta\omega$ of channel and ring.

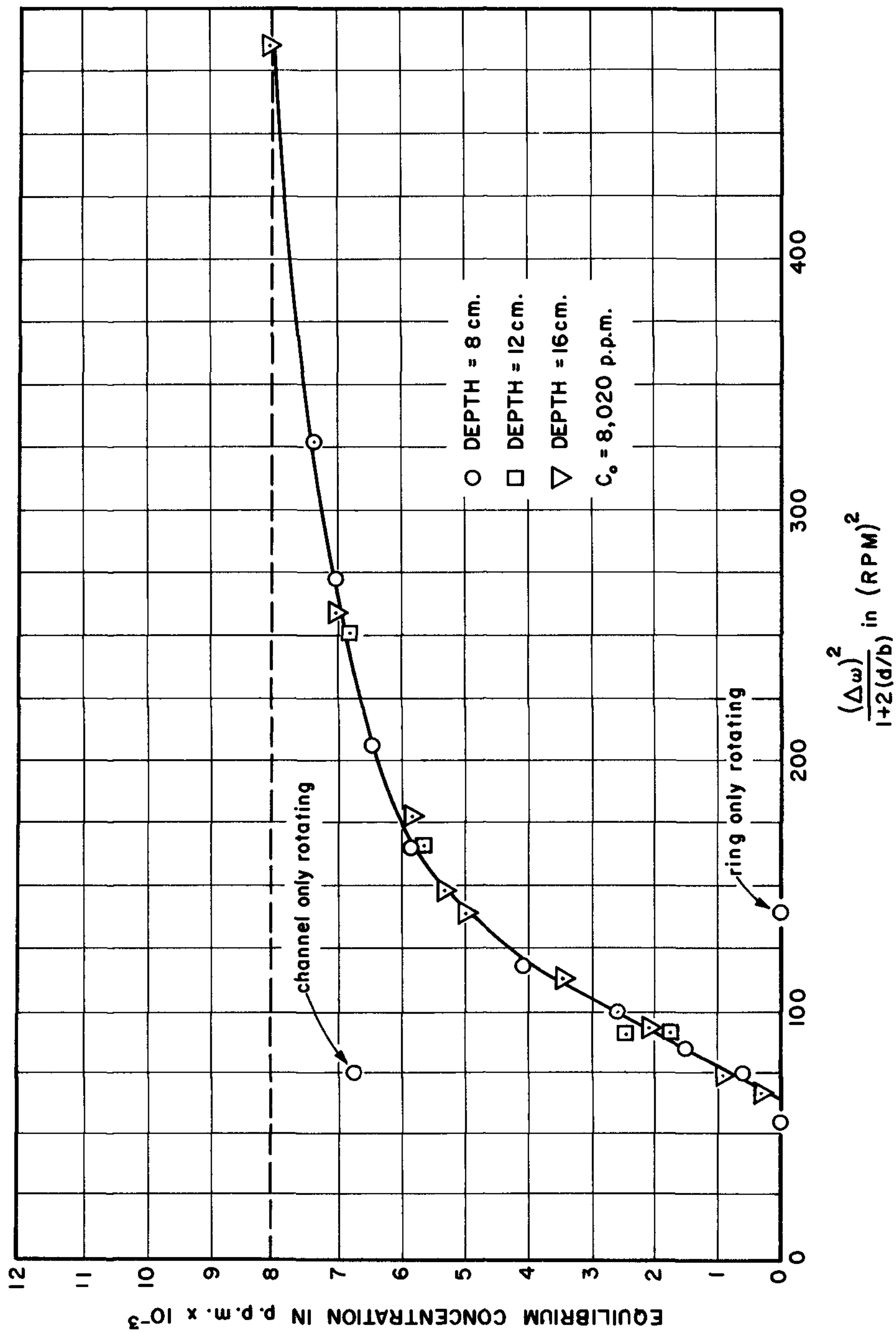

Fig. 12. Variation of equilibrium concentration with average channel shear stress.

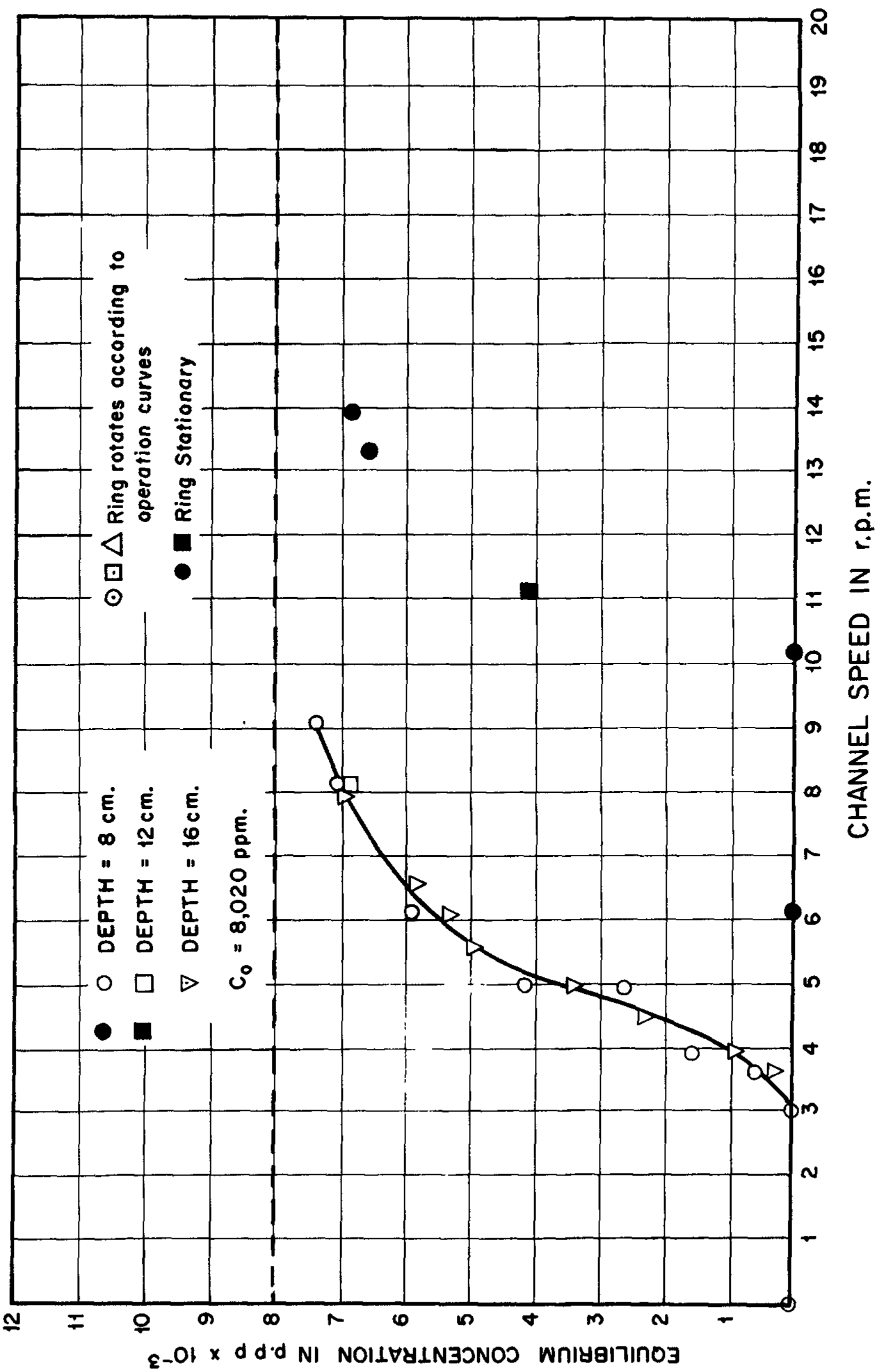

Fig. 13. Variation of equilibrium concentration with channel speed.

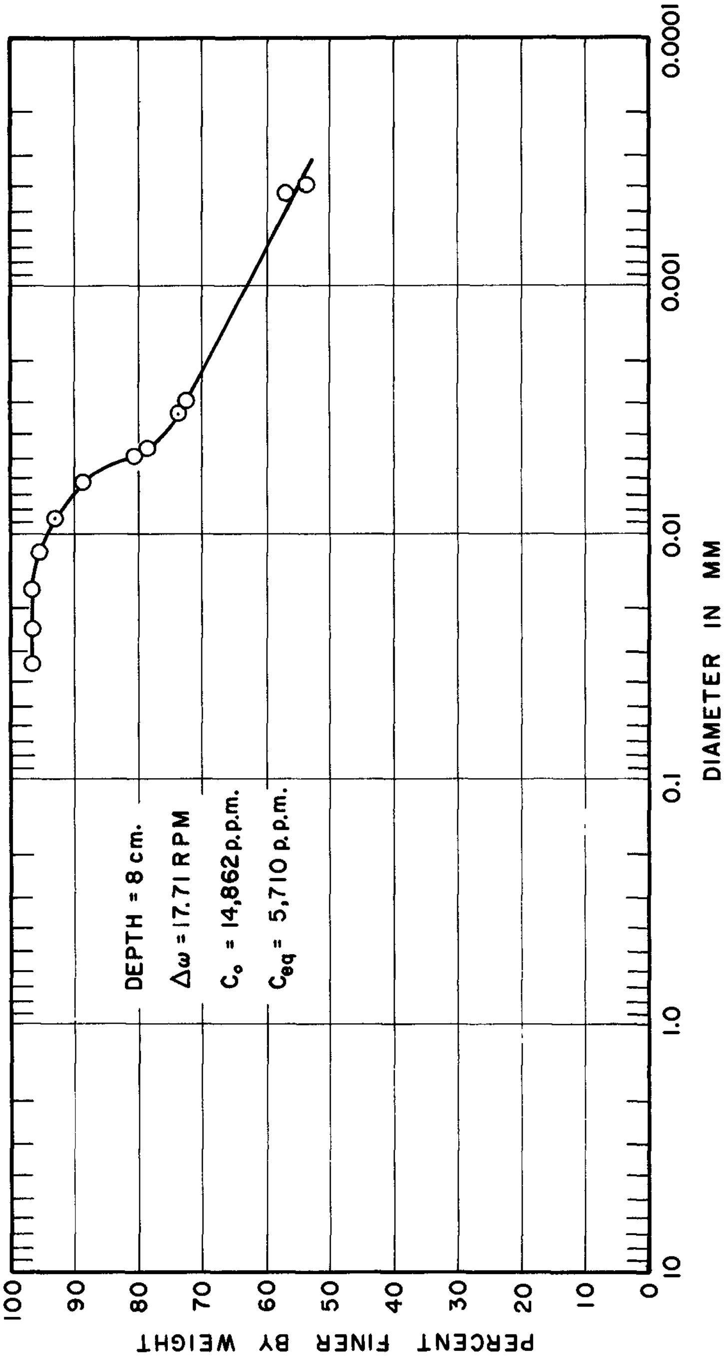

Fig. 14. Grain size distribution of suspended sediment at equilibrium cconcentration.