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ABSTRACT

Fine sediments dispersed in water affect the apparent viscosity and specific weight of the resulting dispersion. Tests at 24 degrees centigrade with a Stormer viscosimeter showed that the apparent kinematic viscosity for a 10 percent by weight water-clay dispersion of an impure bentonite was 8.75 times greater than that of distilled water. A 10 percent water-kaolin dispersion was 1.40 times more viscous than distilled water. The change in viscosity and density of the water-fine sediment dispersion changes the fall velocity of the bed material. The fall velocity distribution of the bed material can be determined, as a first approximation, with the visual accumulation tube apparatus when water-clay dispersions are the sedimentation media. The results are comparable to the fall velocities computed by using the Reynolds number-drag relation, the measured viscosity of the water-clay dispersion and the density of the dispersion.

Experiments conducted in water-sand flows with and without bentonite in the flumes at Colorado State University demonstrated that with bentonite in the flow the changes in fall velocity of the bed material particles, resulting

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from the changes in fluid properties, altered the bed configuration. Because the resistance to flow and bed-material transport are dependent on the form of the bed, they were appreciably affected. Generally, as concentration of fine sediment increases with a constant rate of stream flow, flow resistance and transport of bed material always increase in the upper flow regime and sometimes decrease in the lower flow regime.

INTRODUCTION

In the literature, there are many controversial statements regarding the influence and effect of fine sediments on the mechanics of flow in alluvial channels. Fine sediment load has been referred to as wash load and has been defined by Einstein[2] as "that part of the sediment load which consists of grain sizes finer than those in the bed." The use of the term, wash load, is controversial and for the most part is referred to as fine sediment load or simply, fine sediments in this report.

In a broad sense, fine sediments are particles of the sediment load of finer size than those generally found in the bed and therefore would be transported mostly as suspended load. When considering sand channel streams and from a practical viewpoint, fine sediments include all particles finer than about 0.062 millimeter. The fine sediments, commercial kaolin and bentonite, used in these studies are impure in that they contain small percentages of particles coarser than 0.062 mm and minerals other than pure kaolin or bentonite minerals. Einstein[2] pointed out that the fine sediment load does not appear to be a function of the flow, but that it is usually related to supply and that the streams' ability to transport it is always vastly in excess of the available supply. He does not indicate that its presence is apt to influence the

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[2] Einstein, H. A., 1950, The bed load function for sediment transportation in open channel flows: U. S. Dept. of Agriculture Tech. Bull. 1026, 70 p.

mechanics of flow in any way. Similarly, Brown in Engineering Hydraulics by Rouse[3], states that the fine sediment load plays a negligible role in the prediction of normal stream behavior.

In contrast, Langbein[4] reported changes in bed form and increased antidune activity as the concentration of fine sediment increased. Leopold and Maddock[5] recognized that changes in concentration of suspended-sediment in natural rivers were causes of changes in the stream velocity, depth, transport capacity, and channel roughness. In summary, they state "The changes in velocity-depth relations required for quasi equilibrium with load are brought about primarily by changes in bed roughness associated with changes in suspended-sediment concentration." They, as well as many other investigators, did not distinguish between the possible different effects of different size and (or) type of sediments. However, the suspended-sediment in the "western" streams in Leopold and Maddock's treatise would normally be composed of many sizes and types of sediments. Blench[6] has also implied that fine sediment load exerts a measurable effect on flow in alluvial channels. He stated that the velocity distribution and resistance to flow are affected by the concentration and the characteristics of the suspended sediment load.

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[3] Rouse, Hunter, 1950, Engineering hydraulics: New York, John Wiley and Sons.

[4] Langbein, W. B., 1942, Hydraulic criteria for sand waves: Am. Geophys. Union Trans., v. 23, p. 615-618.

[5] Leopold, L. B., and Maddock, T., Jr., 1953, The hydraulic geometry of stream channels and some physiographic implications: U. S. Geol. Survey Prof. Paper 252, 57 p.

[6] Blench, T., 1957, Regime behavior of canals and rivers: London, Butterworths Scientific Publications.

Bingham[7], an early investigator of properties of water-clay dispersions, showed that fluidity, the reciprocal of viscosity, varied markedly with type and volume percentage of clay.

As a part of the United States Geological Survey's study of fluvial mechanics at Colorado State University, Simons and others[8], the effects of the presence of fine sediment in the flow were investigated in a large 8-foot flume, a small 2-foot flume and in the sediment laboratory. This investigation, the results of which are reported herein, covered the physical properties of water-fine sediment dispersions, and the settling characteristics of the bed material in water-fine sediment dispersions; also, the bed configuration, the resistance to flow and the concentration of the bed-material transport in many different stream flows that contained various amounts of bentonite.

As discharge is changed in flume studies, the slope of energy grade line can be varied greatly but depth variations are limited by the size of the pumps and flumes, while in the field, the slope of energy grade line through a given reach of channel varies within narrow limits and depth varies greatly as discharge changes. This distinction should be kept in mind when reading this paper, as it is not at all certain that changes in flow and transport phenomena caused by a change in the product of depth and slope are independent of whether depth or slope is changed. Although discharge was kept constant, tailgate setting, slope of flume and other flume controls were not changed and fluid temperatures did not vary greatly. However, depth and water-surface changes in other slopes varied with changes in concentration factors such as depth of flow and water-surface slope of fine sediment. These variations

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[7] Bingham, E. C., 1922, Fluidity and plasticity: New York, McGraw Hill Book Company.

[8] Simons, D. B., Richardson, E. V., and Albertson, M. L., 1961, Studies of flow in alluvial channels, flume studies using medium sand (0.45 mm): U. S. Geol. Survey Water-Supply Paper 1498-A, 76 p.

might have masked the effects of small concentrations and small changes in concentrations of fine sediment.

The equipment, procedure, materials used, some explanation and definition of terms, and the basic data are given in Appendix 1.

PROPERTIES OF WATER-FINE SEDIMENT DISPERSIONS

Aqueous dispersions of kaolin or bentonite are non-Newtonian, that is, the shearing stress is not directly proportional to the rate of shear. Therefore, the coefficient relating the shearing stress to the rate of shear represents an apparent viscosity and is a function of the rate of shear. The viscosities presented in Fig. 1 were obtained by using the recommended procedure for determination of viscosity for a Newtonian liquid in a Stormer viscosimeter. The modifier "apparent" is intended to indicate that water-kaolin or water-bentonite dispersions are non-Newtonian. The dispersions tested at settling times, after mixing, of 0, 10, and 60 minutes showed no changes in viscosity due to settling out of the coarser particles or the formation of a gel.

These relations of apparent viscosity to concentration of clay are very similar to several Bingham[7] developed by relating temperature and volume concentration of earth, china clay, and graphite to fluidity, the reciprocal of viscosity. Based on his studies, he concluded that for each temperature the fluidity decreases rapidly and linearly with concentration of solids.

Street[9] related the viscosity of aqueous dispersions of clay to their behavior at different stages of neutralization of charge on the particles. He experimentally showed that the viscosity increased with an increase of neutralizing agent up to a maximum which occurs at the isoelectric point (approximately a pH of 7.5 for kaolin and about a pH of 4.5 for montmorillonite).

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[9] Street, Norman, 1958, Viscosity of clay suspension: World Oil, No. 147, p. 151-156.

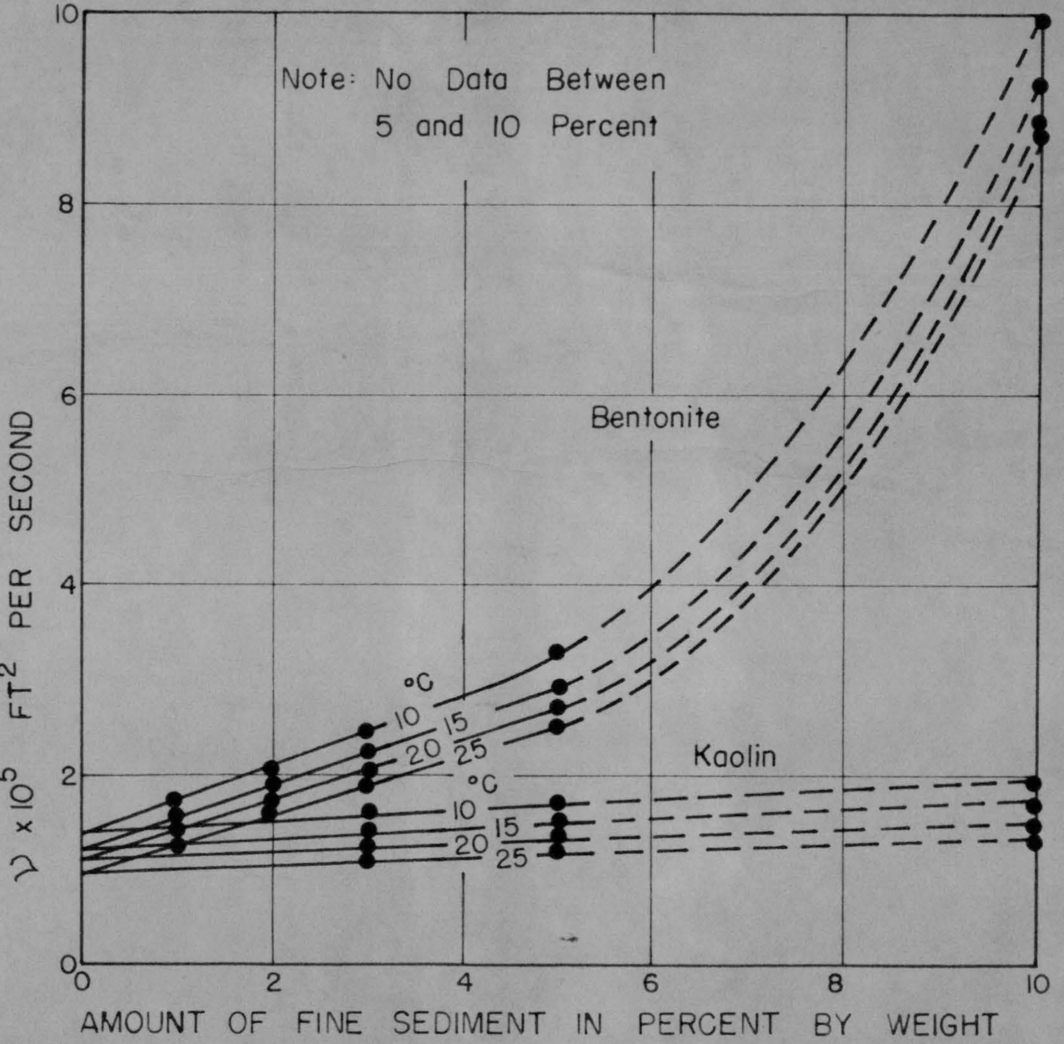

FIG. I APPARENT KINEMATIC VISCOSITY OF WATER-FINE SEDIMENT DISPERSIONS (STORMER VISCOSIMETER DATA)

After this maximum for the deflocculated state, the viscosity decreases rapidly with further addition of the neutralizing agent. He reasoned that the apparent viscosity at any stage of neutralization depended greatly on the type of flocculation present at that stage. He studied the effect of the zeta potential and hydration potential of the cation used for neutralization on the viscosity for the Ba, Ca, K, Na, and Li cations.

A study of the viscosity of dilute clay mineral suspensions by Wood, and others[10] showed that dispersions of Wyoming bentonite, hectorite, and attapulgite exhibited non-Newtonian behavior at 0.5, 1, 2, 3, 4, and 5 percent concentrations. Their results show that the ratio of apparent viscosity of the clay to the viscosity of water at the same temperature becomes independent of the temperature (range 20-50° C). From this, they reasoned that the viscosity of dilute clay suspensions ($\leq$ 5 percent concentration) is governed by the geometry of the particles rather than by specific interactions between particle and solvent or between particle and particle.

The ratio of the weight of dispersing agent (sodium hexametaphosphate) to weight of fine sediment was 1/100 for the viscosity determinations, the fall velocity studies, and the flume experiments. This ratio resulted in an approximately deflocculated bentonite-water system but was probably too great to yield a maximum deflocculated kaolin-water dispersion. A constant ratio was sufficient to study the effect of the change in fluid properties caused by water-fine sediment dispersions on the settling characteristics of the bed material and on flow phenomena; but a full study would necessarily include the effect of amount and nature of adsorbed cations on the properties of the clay-water dispersions. The numerous investigators of viscosity of clay-water dispersions

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[10] Wood, W. H., Granquist, W. T., and Krieger, I. M., 1955, Viscosity studies on dilute clay mineral suspensions; clays and minerals: National Research Council Publ., 456, p. 240-250.

attribute the variation of viscosity with added base to the electric charge, the degree of ionization, the hydration of the ions, and the degree of flocculation. Apparently, the relation is more properly a function of all the foregoing physiochemical properties. In a stream, fine sediment effects on fluid and flow properties and fall velocity of the bed materials would depend upon the concentration, size and type of fine sediment, the amount and nature of the adsorbed ions, and the relatively uninvestigated role of turbulence in sustaining a dispersed-fine-sediment system.

The specific weight of a water-fine-sediment dispersion depends upon the concentration of sediment and the specific gravity of the sediment. The specific weight, γ , of the sediment-water dispersion, in pounds per cubic foot, is given by

$$\gamma = \frac{\gamma_w \gamma_s}{\gamma_s - \frac{(\gamma_s - \gamma_w) C}{10^6}}$$

where

C is the sediment concentration in parts per million by weight

γ_w is the specific weight of water in pounds per cubic foot

γ_s is the specific weight of the sediment in pounds per cubic foot.

The importance of the increased specific weight of the fluid with increasing concentration of fine sediment is shown when it is related to the specific weight of the bed material particles. The unit submerged weight of these particles is $\gamma_s - \gamma$ and represents the driving force causing downward motion. In fall velocity studies, the significance of this force is obvious.

FALL VELOCITY

In a study of flow in alluvial channels, the properties of the bed material are significantly involved. The mineral identification, density, shape, short, long and intermediate diameters, volume of individual particles, and the size distribution of all the particles are sometimes used to describe the bed material. The fall velocity of the individual particles and particle-size distributions based on fall velocity integrate the properties of the bed material into one fundamental hydraulic characteristic. Also, because fall velocity varies with changes in the fluid characteristics, it is a means of relating the bed material properties to the liquid characteristics. The effect of changes in the viscosity and specific weight of the stream fluid on the fall velocity of sand particles has been generally ignored in alluvial channel research, Langbein[4].

Definitions of sedimentation terms, used in this and other sections, might not have universal acceptance and are therefore presented after Inter-Agency Report No. 12[11].

The nominal diameter of a particle is the diameter of a sphere that has the same volume as the particle.

The fall diameter of a particle is the diameter of a sphere that has a specific gravity of 2.65 and has the same standard fall velocity as the particle.

The standard fall velocity of a particle is the average rate of fall that the particle would finally attain if falling alone in quiescent distilled water of infinite extent and at a temperature of 24° C.

Fall velocity and settling velocity are general terms which may apply to any rate of fall or settling as distinguished from standard fall velocity.

The particle size distributions of the sand samples in water and in aqueous dispersions of fine sediments were determined by the visual accumulation tube method. The visual accumulation tube method (Inter-Agency Report No. 11[12]) was developed to give fall-diameter distributions of sand

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[11] U. S. Inter-Agency Report No. 12, 1957, Some fundamentals of particle size analysis: U. S. Dept. Army, St. Paul, Minnesota.

[12] U. S. Inter-Agency Report No. 11, 1957, The development and calibration of the visual accumulation tube: U. S. Dept. Army, St. Paul, Minnesota.

samples in terms of the standard fall velocity of the individual particles. Naturally worn sand particles having specific gravities of about 2.65 were used in the calibration of the visual accumulation tube. Provided that the calibration of the visual accumulation tube was valid for a sedimentation media of water-fine-sediment dispersions, the change in particle-size distribution of a sand sample owing to the change in fall velocity of the individual sediment particles in the water-fine-sediment dispersion could be determined by analyzing the sample in distilled water and in different concentrations of fine sediment dispersed in distilled water.

The settling velocities of particles of a sediment sample depend on the characteristics of the particles, the sample volume, the properties of the sedimentation media, and the measuring apparatus. Because of this, test conditions were established so that the only variable in the particle-size analyses was the sedimentation media.

Samples of sands were analyzed in the visual accumulation tube for particle size distribution in distilled water, in 3, 5, and 10 percent kaolin-water dispersions, and 1, 5, and 10 percent bentonite-water dispersions. The particle size distributions of one of the samples of sand (Poudre River, Colorado sand) as determined from the visual accumulation tube analyses and based on the fall velocity of individual particles in distilled water and in various concentrations of bentonite are shown in Fig. 2. Similar analyses were made of several different samples of sand in water-kaolin and water-bentonite dispersions. The size for which 50 percent of the sample was finer than (the median diameter) progressively decreased with increasing concentration of fine sediment and the fall velocities shown in Fig. 3 and Fig. 4 are the results of converting the median diameters to fall velocities by using information given in Table 2, Inter-Agency Report 12[11].

Another method of determining the terminal fall velocity of a single-size of particle in different sedimentation media is by using the empirically established relation between the drag coefficient, C_D , and the Reynolds

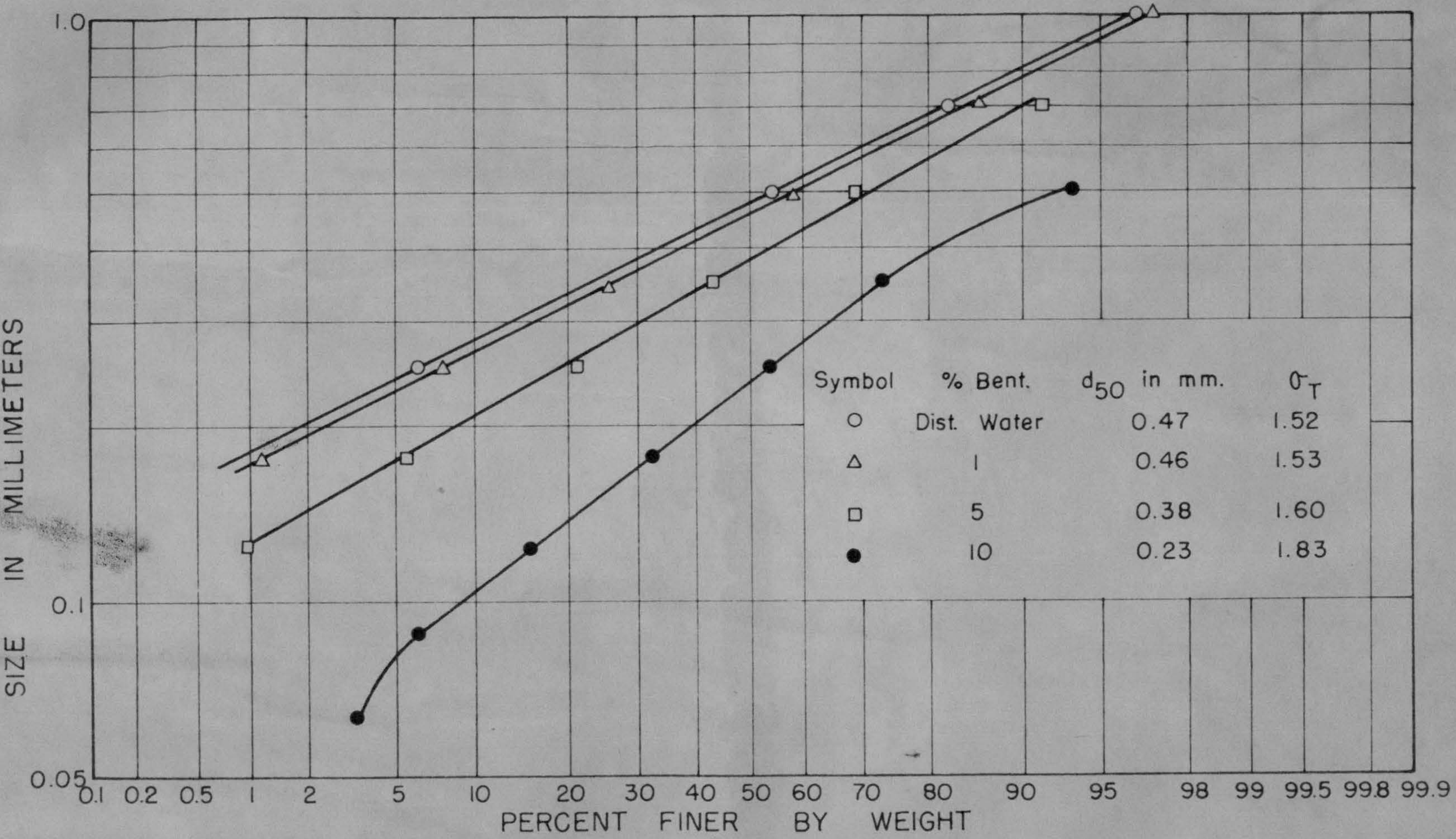

FIG. 2 PARTICLE SIZE DISTRIBUTIONS OF A POUDRE RIVER, COLO. SAND SAMPLE BASED ON PARTICLE FALL VELOCITY IN VARIOUS WATER-BENTONITE DISPERSIONS.

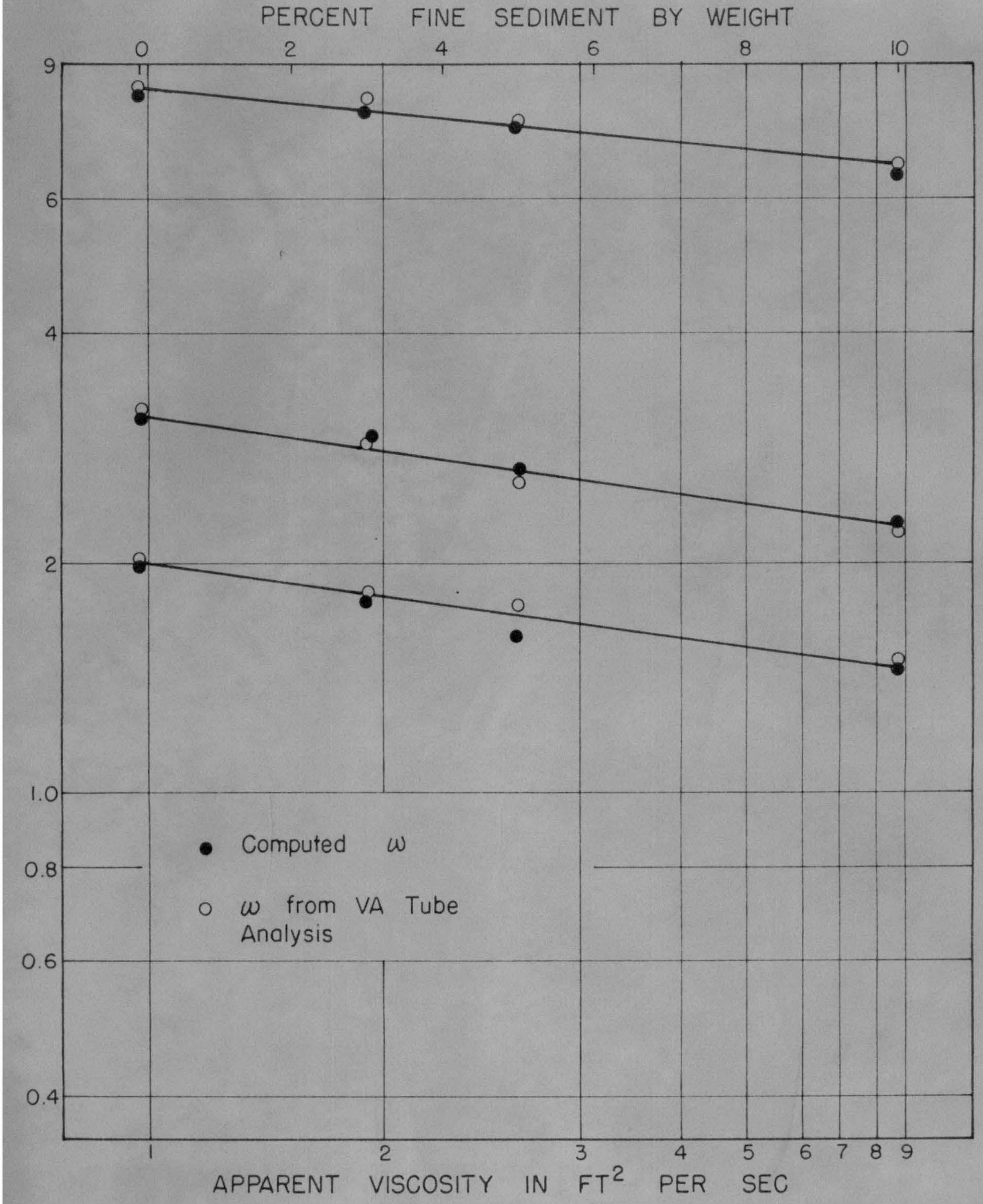

FIG. 3 VARIATION OF FALL VELOCITY OF SAND PARTICLE REPRESENTING THE MEDIAN FALL DIAMETER OF NATURALLY-WORN SAND SAMPLE WITH APPARENT VISCOSITY OF WATER-KAOLIN DISPERSIONS.

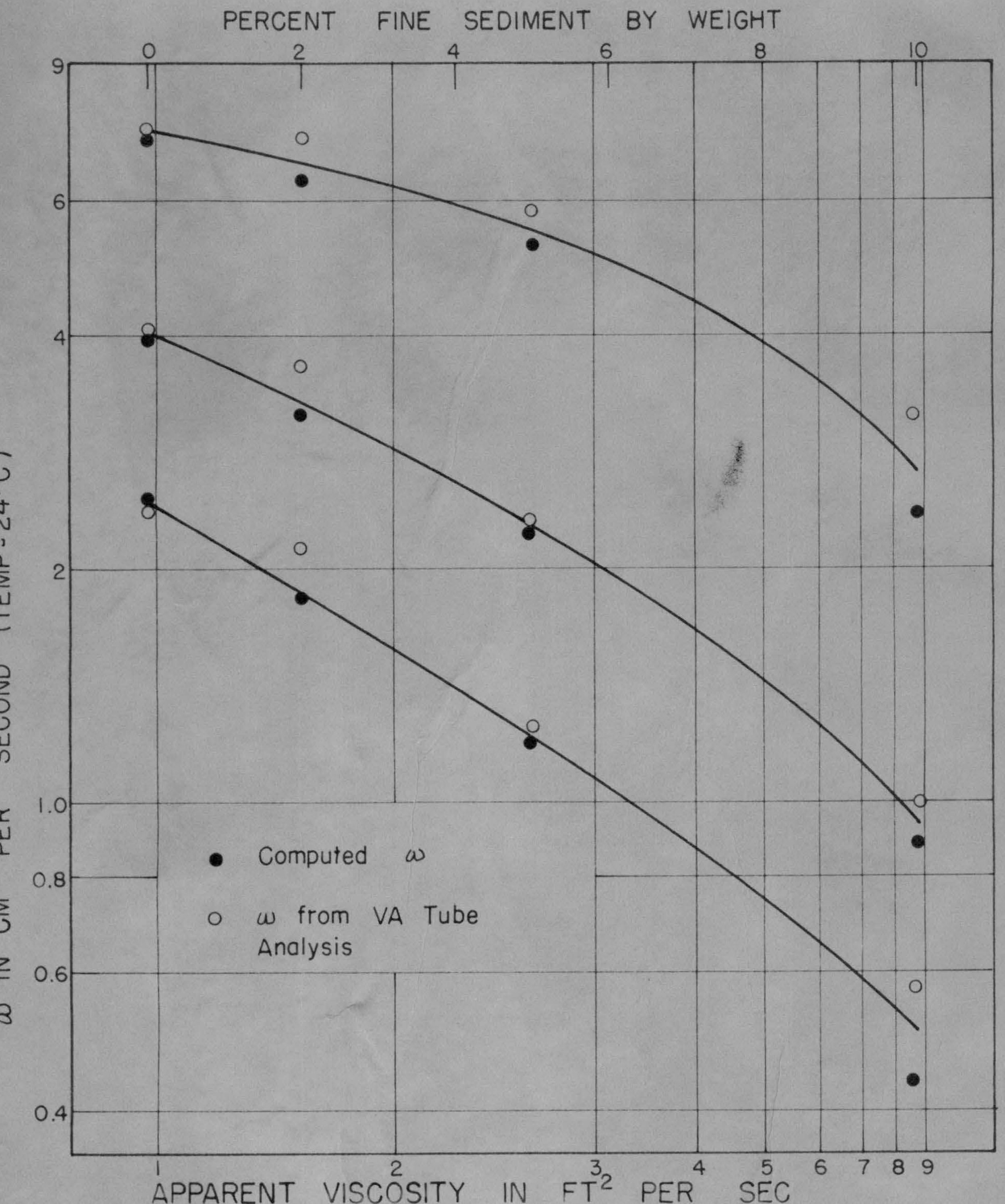

FIG. 4 VARIATION OF FALL VELOCITY OF SAND PARTICLE REPRESENTING THE MEDIAN FALL DIAMETER OF NATURALLY-WORN SAND SAMPLES WITH APPARENT VISCOSITY OF WATER-BENTONITE DISPERSIONS.

number of the particle, Re . This relation, with shape factor of the particle as the third variable, for naturally worn sediment particles is shown in Fig. 5, which is a reproduction of Fig. 1, Inter-Agency Report No. 12[11]. The fall velocities of particles representing the median fall diameters of the sand samples was computed for water-fine-sediment dispersions having the same ratio of fine sediment to water as that used in the visual accumulation tube analyses. In the computations, the median fall diameter was converted to a nominal diameter from the relation given in Fig. 3, Inter-Agency Report No. 12[11], and the apparent viscosity of the dispersions, the mass densities of the dispersion and the particle, and a particle shape factor of 0.7 were used. With these factors known, the computation of the fall velocity consists of a trial and error procedure until the C_D vs Re values are on the curve for a shape factor of 0.7.

The computed fall velocities agreed closely with those determined from the visual accumulation tube analyses, see Figs. 3 and 4. Several of the many factors that might contribute to disagreement are: the lack of a good definition of the C_D versus Re relation for sediment particles; errors in the apparent viscosity of the water-fine-sediment dispersions; the shape factor of the sand particles may differ appreciably from 0.7; and the fine sediment particles probably affect the fall velocity of the sand particles through interference, the currents and eddies generated by the falling fine sediment particles, and the possibility that the fine sediment was not uniformly, or quickly became non-uniformly, distributed in the sedimentation column.

The actual fall velocity of bed materials in streams that contain fine sediments apparently may be determined by two procedures.

1. Direct computation by using the C_D versus Re relation. This entails determining or knowing the variation of the properties of the particles and the characteristics of the stream liquid with time and temperature. However, a more exact definition of the C_D versus Re relation for irregular shaped sediment particles is also needed.

2. The size distribution can be determined by dropping a representative sample of the bed material in the visual accumulation tube when the stream liquid is used as the sedimentation medium and size can be converted to a fall velocity. However, the visual accumulation tube was calibrated for the range of temperatures from 20 to 30 degrees centigrade, therefore outside this range, the procedure reverts back to the direct computation method. Extending the calibration of the visual accumulation tube to include temperatures normally encountered in streams appears to be desirable and the reliability of particle size distributions obtained from the visual accumulation tube analyses needs to be checked for sedimentation media other than distilled water.

The C_D versus Re relations given in Fig. 5 were regarded as preliminary attempts at definition and as additional data become available, they would be revised as necessary. Two suggested possibilities for future research were listed in Inter-Agency Report No. 12[11] and are repeated here because of the added emphasis placed on them by this study.

1. Effect of concentration on fall velocity for a variety of sedimentation systems.
2. The C_D versus Re relation for natural sediment particles, perhaps emphasizing study of the same particle for a wide range of Reynolds numbers.

SEDIMENT TRANSPORTATION

The observed regimes of flow, bed configurations, and the flow phenomena associated with them for sand channels were described in detail by Simons and Richardson[13] and the classification resulted from combining laboratory

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[13] Simons, D. B., and E. V. Richardson, 1961, Form of bed roughness in alluvial channels: Am. Soc. Civil Engineers Jour. v. 87, no. HY3.

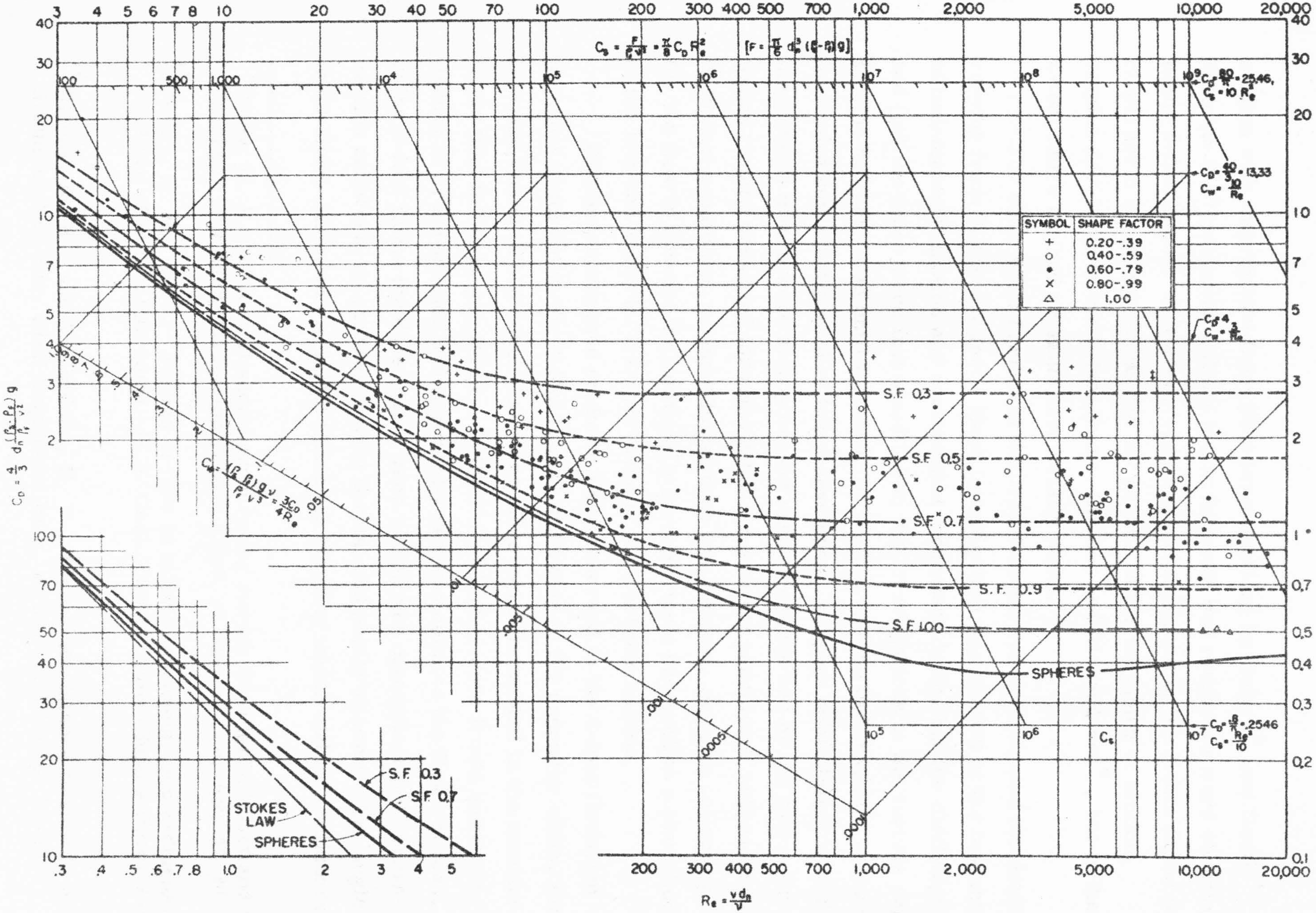

FIG. 8 RELATION BETWEEN COEFFICIENT OF DRAG AND REYNOLDS NUMBER FOR NATURALLY WORN SEDIMENT PARTICLES. (TAKEN FROM REPORT 12, INTER-AGENCY COMMITTEE ON WATER RESOURCES, SUBCOMMITTEE ON SEDIMENTATION, 1957.)

studies with information from field investigations by Colby[14] and Dawdy[15]. With the 0.47 mm sand, all the major forms of bed roughness were observed in the 8-foot flume. However, with the 0.54 mm sand in the 2-foot flume the ripple form of bed roughness did not occur. After beginning of motion, ripples developed in the 8-foot flume, Simons and Richardson[16], but in the 2-foot flume the bed remained essentially plane.

The absence of ripples in the 2-foot flume was investigated for depths varying from 0.2 to 2.0 feet. Each investigation was started at the beginning of bed-material motion and continued at a constant depth, but the discharge and (or) the slope were increased. For the investigations at the various depths, a plane bed persisted until the shear on the bed and the bed material in transport increased sufficiently so that dunes developed. Ripples artificially formed by mechanical means were slowly erased back to a plane bed by the flow. Run 3, where ripples persisted throughout the run was not considered representative of factual conditions, as insufficient time was allowed, prior to collecting data, for the flow to convert the artificially formed ripple bed back to a plane bed at the low-bed-material transport rate of 0.6 part per million.

Ripples superposed on dunes were observed in the 8-foot flume but were not observed in the 2-foot flume, and owing to the narrower width, the flow and forms of bed roughness were more two dimensional in the smaller flume than in the larger flume. In the 2-foot flume, dune fronts were continuous in cross-section and essentially perpendicular to the flow whereas, in the 8-foot flume the dune fronts were sometimes discontinuous in cross-section and were, in general, partly normal and partly at some other angle to the flow. Also, in the 8-foot flume the standing waves and (or) antidunes

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[14] Colby, B. R., 1960, Discontinuous rating curves for Pigeon Roost and Cuffawa Creeks in Northern Mississippi: U. S. Dept. of Agriculture, ARS 41-36.

[15] Dawdy, D. R., 1961, Studies of flow in alluvial channels, depth-discharge relations of alluvial streams: U. S. Geol. Survey Water-Supply Paper 1498-C, 16 p.

[16] Simons, D. B., and Richardson, E. V., 1960, Resistance to flow in alluvial channels: Am. Soc. Civil Engineers Jour. v. 86, no. HY5, p. 73-99.

occasionally formed over the entire flume width, but generally formed in single or double rows which, singly or together, were of lesser width than that of the flume. The standing waves and antidunes formed over the entire width of the smaller flume.

The effect of the presence of fine sediment in the flow on bed material transport is difficult to determine exactly because of the possibility that the coarser fraction of the fine-sediment load was included in the bed-material load owing to the method of separation of the two loads. However, if it is remembered that the concentration of bed material discharge given in Tables 1 and 2 may be greater than the true value by some percentage of the concentration of fine sediment (maximums of 2 percent for the 8-foot flume data and 0.5 percent for the 2-foot flume data, approximately), some generalizations can be made.

Deposition of fine sediment in and on the sand bed was sufficient at a fine sediment concentration of 4800 ppm with ripples and a concentration of 63,700 ppm with dunes to cause partial stabilization of the bed. With the partly stabilized beds, bed material continued to move but formed ripples or sand waves with rounded crests rather than the angular ripples or dunes formed in flow without fine sediment. The water surface for the flow over the ripples with rounded crests was very choppy and resembled the water surface for shallow flow over cobblestones. Fine sediment which was deposited in the trough areas of the ripples or dunes was trapped by the advancing ripples or dunes and formed lense and layer deposits in the bed. When the slope and (or) discharge were increased with the stabilized beds, the change of the bed to a form that conformed to the imposed slope or discharge was resisted by the cohesive deposits of fine material on and in the bed. However, the stabilized bed was eventually broken up and a bed form that was in conformity with the new slope and discharge conditions was formed.

With ripples and a fine sediment concentration of 4800 ppm, some areas of the bed became partly stabilized and bed material transport decreased from 12 ppm to about 2 ppm. Even though more bed area became stabilized at greater concentrations of fine sediment, the bed material transport remained practically constant at about 2 ppm.

With dunes in the 2-foot flume, the bed material transport was either unchanged or decreased when the ratio of fall velocities ω'/ω_s was greater than about 0.87, that is, concentration of fine sediment was less than about 26,000 ppm, see Fig. 6.

The fall velocity, ω', is given in Table 2, Appendix 1, and equals ω for runs without bentonite and ω_s, a reference fall velocity, is the standard fall velocity. Both velocities are based upon the bed material particle that represents the median fall diameter. As concentration of fine sediment increases, the ratio ω'/ω_s decreases. At greater concentrations of fine sediment and a consequent further decrease in the fall velocity, ω', there was a decrease in bed material transport. The decrease may have been larger because the measured bed material transport might have contained some fine material load. The 8-foot flume data for dunes show either no change or an increase in bed material transport with an increase in fine sediment load; however, the increase could have resulted from including some of the fine sediment in the bed material transport. The decrease in transport of bed material load with an increase in concentration of fine sediment probably is caused by the accompanying decreased resistance to flow that causes a decrease in shear when depth and slope adjust to the smaller resistance to flow. Also, in some dune runs in the 2-foot flume the bed was partly stabilized and bed material transport was further decreased. However, some decrease in bed material transport also occurred when the bed was not stabilized.

In the transition zone, the bed-material transport was considerably increased when the bed form changed from long dunes having low amplitudes to a plane bed as the fall velocity, ω', was reduced with increasing concentration of fine sediment.

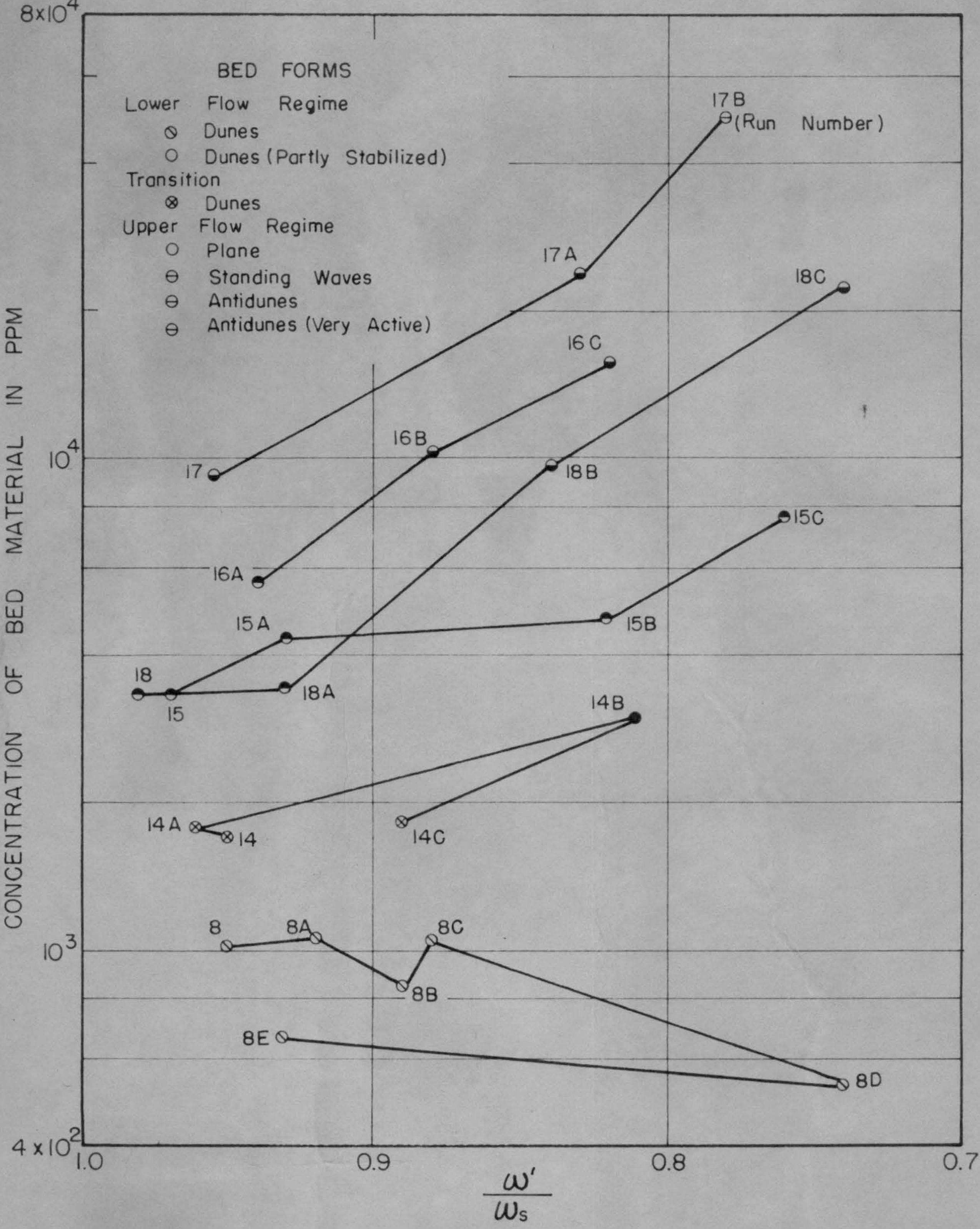

FIG. 6 CHANGE IN TRANSPORT OF BED MATERIAL WITH THE RATIO $\frac{\omega'}{\omega_s}$ FOR SEQUENCE OF RUNS, 2FT. FLUME DATA.

With the bed forms of the upper flow regime a large concentration of fine sediment increased bed material transport, see Fig. 6. This increase exists even if the bed material load is adjusted for the possible presence of some fine sediment. The bed material load is greater because the fine sediment increases the viscosity and specific weight of the water-sediment mixture, decreases fall velocity of the bed material and increases the resistance to flow and the shear on the bed. With shear constant there is an increase in bed material transport with a decrease in sand size or decrease in fall velocity and when fine sediment is added to a constant rate of flow, depth and (or) slope changes occur such that the shear on the bed is also increased in the upper flow regime.

When fine sediment is in the flow, knowledge of fluid, bed sediment, and channel characteristics are insufficient to estimate the total sediment discharge of a stream, unless the concentration of fine sediment is measured and its effects on the fluid properties of the stream and in turn their effect on the fall velocity of the bed material particles are considered. That is, total transport when fine sediment is present in the flow cannot be computed from equations such as Einstein's[2] and Bagnold's[17]. Although total load cannot be obtained from a knowledge of hydraulic and bed material characteristics unless the concentration of fine sediment and its effects are known, an approximate method has been developed that estimates total load, including fine sediment, Colby and Hembree[18]. However, the effects of the presence of high concentrations of fine sediment on the fall velocity of the bed material and the apparent viscosity of the water-sediment mixture and the consequent effects on total sediment transport were not considered.

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[17] Bagnold, R. A., 1956, The flow of cohesionless grains in fluids: Royal Soc. (London) Philos. Trans., v. 249, no. 964, p. 235-297.

[18] Colby, B. R., and Hembree, C. H., 1955, Computations of total sediment discharge, Niobrara River near Cody, Nebraska: U. S. Geol. Survey Water-Supply Paper 1357.

Fine sediment load has the connotation that the fine sediment is generally not present in the bed and moves mostly as suspended load. However, logic indicates and experimental evidence proves that the fine material is present in the bed.

In a study of transport of sediment mixtures with large ranges of grain sizes, Einstein and Chien[19] found that fine sediment would be found in the bed, but stated "While material of all sizes was continuously settling out and building up the bed, this fine layer always managed to stay at the top of the bed." The fines used by Einstein and Chien[19] were natural sand or ground quartz and were generally coarser than the fine sediments used in this investigation. In this study, results somewhat contradictory to the findings fo Einstein and Chien[19] were noted. The concentration of fine material in the interstitial water in the bed increased rapidly with time until it was equal to the concentration of fine material in the stream. This amount of fine material changed the size distribution curve of the bed material for the finer sizes, but the median fall diameter remained nearly constant. Whether or not this small amount of fine material in the bed affects the relationship between sand properties, fluid properties, and resistance to flow or total load depends largely on the form of bed roughness. Surprisingly enough, when clear water was added to the flow and the excess water-fine-sediment mixture was wasted, the fine material was removed from the bed along with that from the water in a relatively short time.

In both flume studies the concentration of fine material in the flow for each run decreased logarithmically from its peak value with time. This was determined by periodic measurements of concentration with a hydrometer. The decrease in fine material concentration resulted from the increase in

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[19] Einstein, H. A., and Chien, N., 1953, Can the rate of wash load be predicted from the bed-load function: Trans. American Geophysical Union, vol. 34, no. 6, p. 876-882.

concentration of fine material in the bed and the fact that some of the fine material was deposited at the contact plane between the sand bed and flume bed. This deposition, over a period of several runs, built up a layer of clay impregnated sand about 0.1 foot thick, see Fig. 7. Under favorable conditions, a layer of fine sediments will also build up in a natural stream.

RESISTANCE TO FLOW

The effect of the presence of fine sediment in the flow on total resistance to flow depends on the concentration and physical properties of the fine sediment, the size and gradation of the bed material, and the form of bed roughness that existed in the channel, preceding the introduction of fine sediment. Fine sediment in the flow, by changing the apparent viscosity and specific weight of the fluid, changes the fall velocity of the bed material particles and the bed form adjusts to conform with the new fall velocity of the bed material. The degree of modification of the bed form depends upon the size and gradation of the bed material, the initial bed form, the change in fall velocity caused by the change in fluid properties, and the adjustments that occur in the depth and slope. That is, there is an interdependence between all the variables affecting bed form and resistance to flow. Whenever one variable is changed the other variables must adjust until a new equilibrium has been reached. Changes in fall velocity can change a dune bed to a plane bed or a standing wave run to violent antidunes. The changes in resistance to flow resulting from the addition of fine sediment, are similar to those that would occur if the fall velocity was changed by changing the bed material[13]. Although the primary way that fine sediment affects flow resistance is by a change in bed configuration, other factors which might be important are cohesion between grains, modification of the turbulence and coating of the bed.

The influence of fine sediment on resistance to flow is illustrated in Figs. 8 and 9. The Darcy-Weisbach f was used as the resistance coefficient

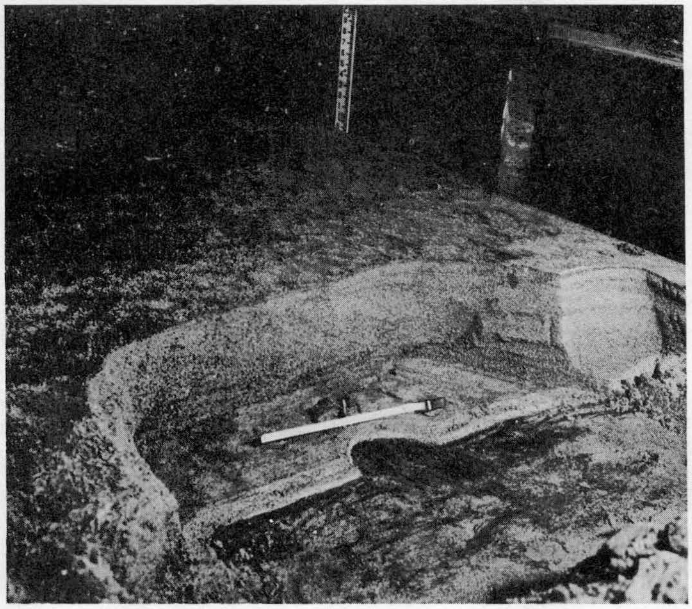

Fig. 7. Layer of Bed Material Adjacent to the Flume Floor. Impregnated with Fine Sediment.

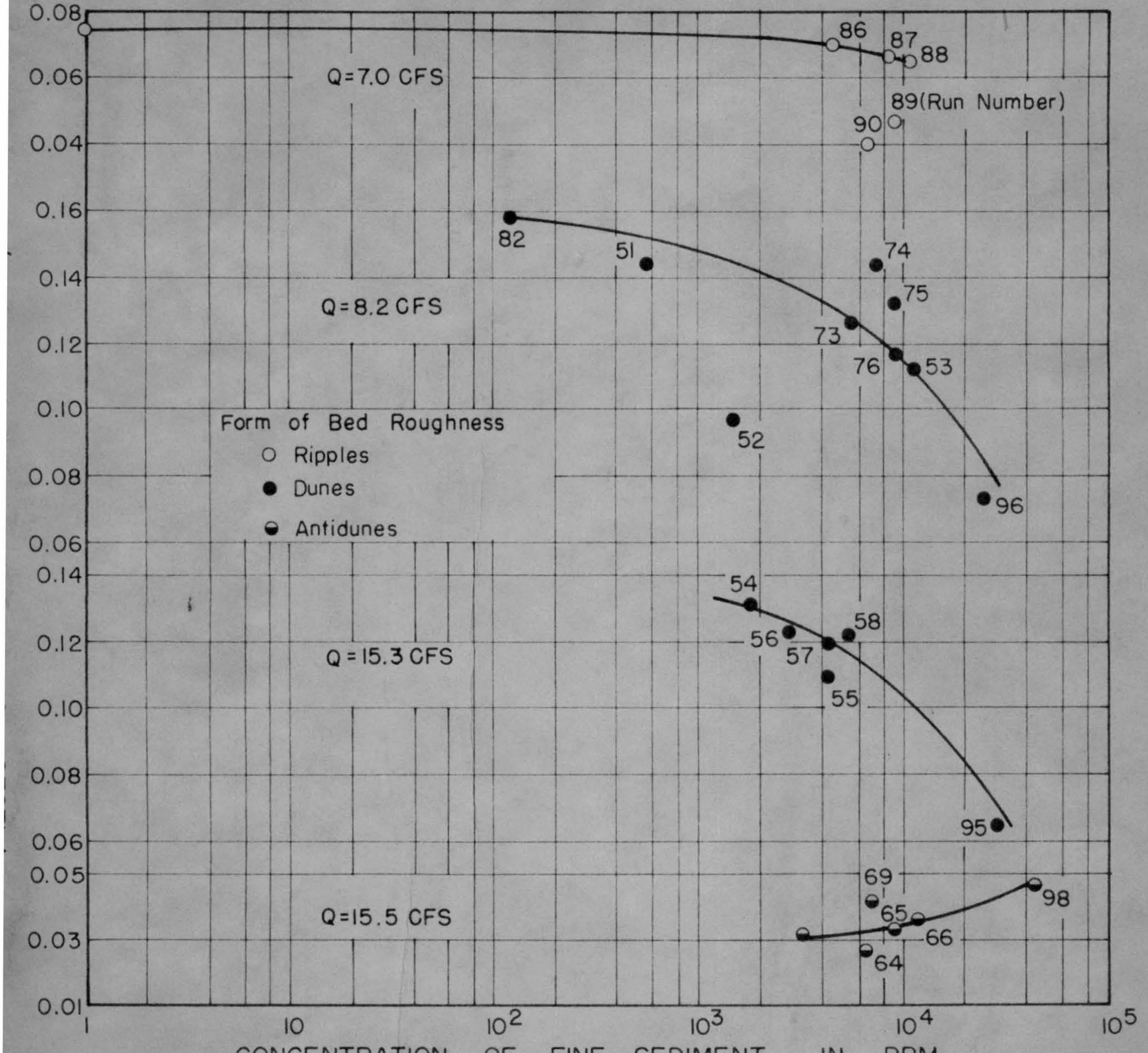

FIG. 8 VARIATION OF THE RESISTANCE COEFFICIENT, f, WITH CONCENTRATION OF FINE SEDIMENT, 8 FT. FLUME DATA.

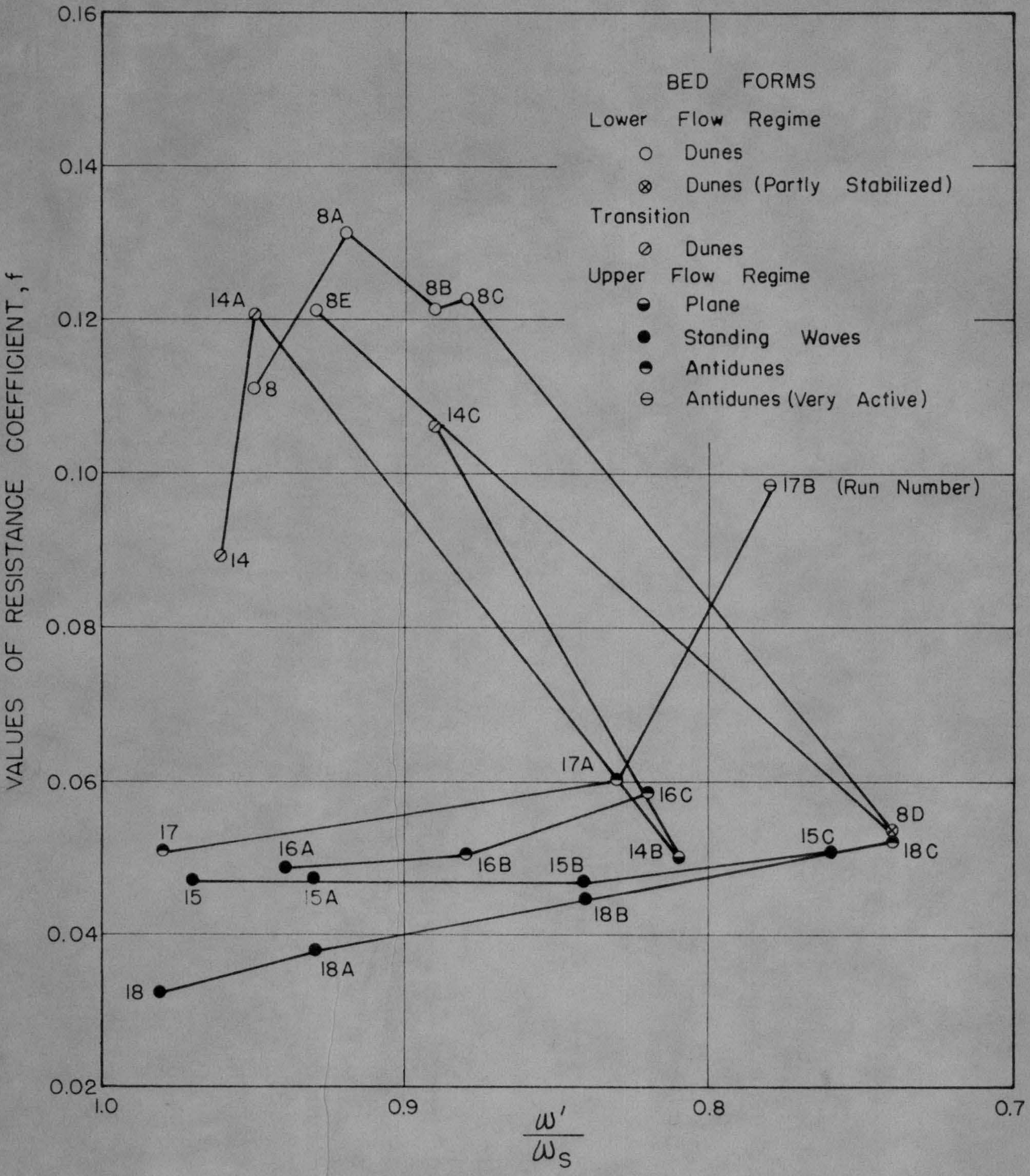

FIG. 9 CHANGES IN THE RESISTANCE COEFFICIENT, f, WITH THE RATIO, $\frac{\omega'}{\omega_s}$, FOR SEQUENCES OF RUNS, 2 FT. FLUME DATA.

where

$$f = \frac{8gDS}{V^2}$$

Selected 8-foot flume data was used to show the variation of f with concentration of fine sediment. The 2-foot flume data was used to show the variation in f with the ratio ω'/ω_s , where ω' is the fall velocity given in Table 2 and equals ω for runs without bentonite and ω_s is the standard fall velocity with both velocities based upon the particle representing the median fall diameter. As concentration of fine sediment increases, the ratio ω'/ω_s decreases. The lines connecting points in Fig. 9 are intended only to aid in following the sequence in which the runs in a series were made.

With increasing concentration of fine sediment the reduced resistance to flow with ripples was caused by the lesser form drag of the rounded crests. With a dune bed form there was a decrease in resistance to flow with an increase in concentration of fine sediment. The decrease was a result of the increase in length of dunes. In the extreme case the bed changed from dunes of the lower flow regime to the plane bed of the upper flow regime. In the upper flow regime, the addition of fine sediment increased the size of standing waves and activity of the antidunes, and in some cases, changed a standing wave run to antidunes. The increased energy dissipation by the larger standing waves or more active antidunes increased resistance to flow.

SUMMARY AND CONCLUSIONS

The specific weight and apparent viscosity of dispersions of water and fine sediment are different than those for clear water. At 40 degrees centigrade the apparent viscosity of a 10 percent, by weight, water-bentonite dispersion was 1,100 percent greater than the viscosity of distilled water and the apparent viscosity of a 10 percent water-kaolin dispersion for the same conditions was 45 percent greater. The specific weight of the water-fine-sediment dispersions increased in accordance with the amount and density of fine material that was added. The apparent viscosity of a dispersion of fine sediment in water depends on the concentration of the fine sediment, the chemical and physical properties of the fine sediment, the amounts and types of impurities in the water, and temperature.

The changed fluid properties of the sediment-water dispersions significantly affect the fall velocity of the bed material particles. For instance, at 24 degrees centigrade, the fall velocity of a 0.47 millimeter (fall diameter) sand particle in 10 percent, by weight, dispersions of bentonite and kaolin in water is decreased 65 percent and 20 percent, respectively. The decrease in fall velocity in bentonite is equivalent to the difference between the fall velocities in water at 24 degrees centigrade, of a 0.47 millimeter and 0.24 millimeter sand particle.

The resistance to flow and bed-material transport is sometimes decreased in the lower flow regime and nearly always increased in the upper flow regime when fine sediment is added to the flow. With ripples, fine sediment, even in moderate concentrations, stabilizes the bed, streamlines bed forms and reduces resistance to flow and bed-material transport. With dunes, fine sediment in relatively large concentrations, may stabilize the bed and reduce resistance to flow and bed-material transport; however, resistance to flow and bed-material transport are sometimes reduced even when the bed is not stabilized. The reduction in resistance to flow when the bed is not stabilized results from increases in dune length and changes in dune shape that occur when the fall velocity of the bed material decreases. When fine sediments are in the flow, the reduction in transport of bed materials with dunes results from a complicated interaction between many variables; the properties of the stream fluid change, the fall velocity of the bed material is reduced, configuration of the dune bed may be altered and velocity may increase with the lesser resistance to flow at the same time that shear on the bed is decreasing because of changes in depth and (or) slope. With very large concentrations of fine material a dune bed may become plane and resistance to flow would decrease but the bed material transport would increase.

In the upper flow regime, the reduction in fall velocity that results from the addition of fine sediment may cause a flow with plane bed to change to a flow with standing waves or antidunes; or a flow with standing waves may change to flow with antidunes, or the activity and turbulence of flow with antidunes may increase. These changes in flow phenomena are characterized by increased resistance to flow and bed material transport.

Total sediment transport may be obtained only if, where fine sediment is involved, the concentration of fine sediment is determined by sampling, and when determining the transport of bed material, the effects of the presence of fine sediment in the flow on the properties of the stream fluid, the hydraulic properties of the bed material particles, and the hydraulic properties of the flow are taken into account.

Because fluid properties are affected differently by fine sediment having different physical and chemical properties, there is a definite need for further study of the rheology of dispersions of fine sediment in water. Also, there is a need to study the effects that different kinds of fine sediment have on the fall velocity of sand particles. Furthermore, additional flume studies should be made with coarse bed materials and various concentrations and types of fine sediment.

APPENDIX 1 -- EQUIPMENT, PROCEDURE, AND DATA

The basic data are presented in Tables 1 and 2. In the flumes, flow and bed conditions ranged from ripples in the lower flow regime to antidunes in the upper flow regime. Runs were conducted in two variable slope flumes; the larger flume is 150 feet long, 8 feet wide and 2 feet deep and the smaller flume is 60 feet long, 2 feet wide, and 2-1/2 feet deep. In both flumes the water-sediment dispersions were recirculated.

The fall-diameter distributions of the sand used as bed material are shown in Fig. 10. In the 8-foot flume study, the average median fall diameter, d , was 0.47 millimeters, and the measure of gradation was 1.54, whereas, in the 2-foot flume study the median fall diameter was 0.54 millimeters and the measure of gradation was 1.50.

A bentonite clay was used in the flume studies. In addition, the properties of water-bentonite and water-kaolin dispersions and the sedimentation of the bed material in these dispersions were studied in the sediment laboratory. When used alone or modifying clay, bentonite or kaolin signify that the fine sediment is composed predominantly of secondary mineral particles, bentonite or kaolin, of smaller dimensions than 0.002 mm but are not intended to imply that all the particles of fine sediment are either pure bentonite or kaolin minerals or finer than 0.002 mm. The size distributions of the bentonite and kaolin are given in Fig. 11.

The total sediment load was sampled with a width-depth, integrating, total-load sampler where the water-sediment mixture discharged from the flume into the tail box. The total load samples were separated into a fine-sediment fraction and a bed-material fraction. The concentration of fine sediment, C_f , was determined from a sample of the top portion of the total water-sediment sample; the sample was taken immediately after the coarser bed-material and bentonite particles had settled out of the upper portion of the total water-sediment sample. The bed-material fraction was that

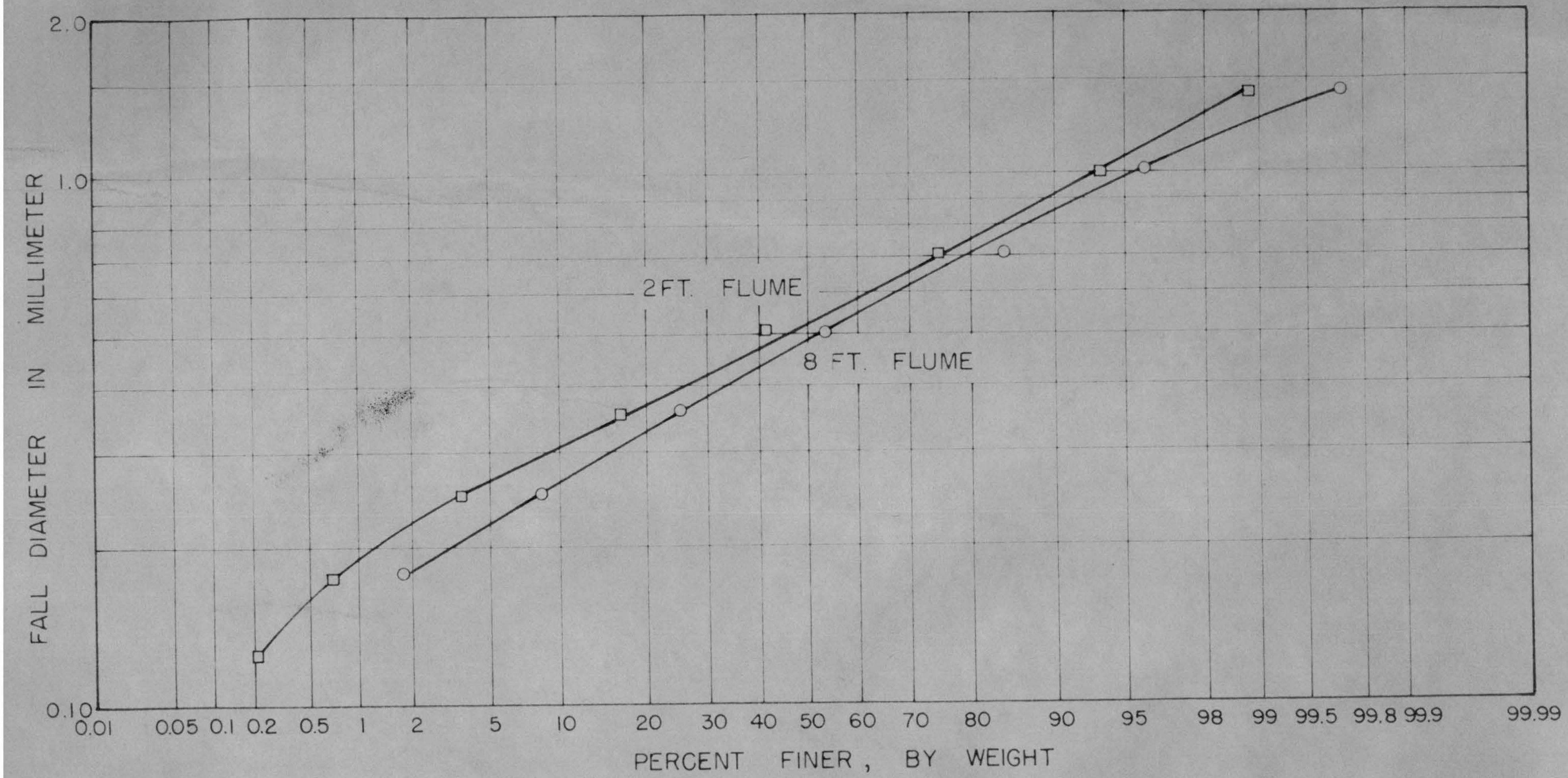

FIG. 10 PARTICLE SIZE DISTRIBUTION OF THE BED MATERIALS.

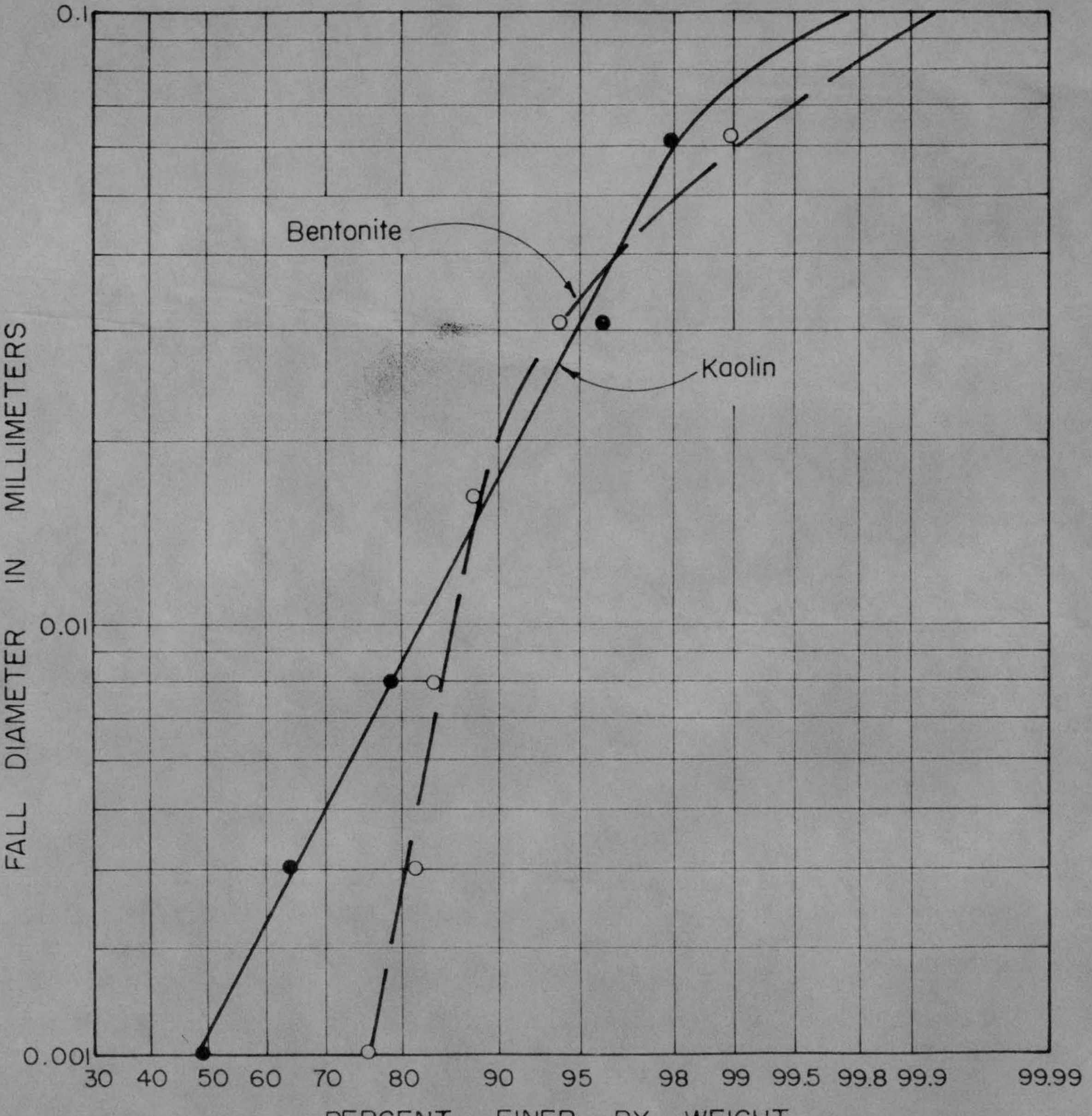

FIG. 11 PARTICLE SIZE DISTRIBUTION OF THE FINE SEDIMENTS.

material retained after wet-sieving the sample on a 270 sieve for the 8-foot flume study and on a 200 sieve for the 2-foot flume study. The bed-material fraction for the bentonite runs probably contained some particles contributed by the bentonite because 0.5 percent of the bentonite was coarser than the number 200 sieve (0.074 millimeter opening) and 2.0 percent was coarser than the number 270 sieve (0.053 millimeter opening), see Fig. 11. For example, in Run 8D the concentration of the bed-material discharge contributed by the bentonite could be 318 parts per million (0.5 percent of 63,700 parts per million) which is 61 percent of the concentration of the bed material discharge, C_t. In run 17B the possible 230 parts per million contributed by the bentonite is only 0.46 percent of the concentration of the bed-material discharge. Similarly, the median fall diameter of the bed material discharge, d_t, generally decreased as the concentration of bentonite increased, because of the addition of the coarsest particles in the impure bentonite to the bed material.

The samples of the bed material were wet-sieved and washed to remove all bentonite, dried, split and analyzed for particle size distribution in the visual accumulation tube, Colby and Christensen[20]. The median fall diameter, d, and gradation was determined from Fig. 1. The gradation of the material, indicated by σ_r, was computed from the equation

$$\sigma_r = 1/2 \left(\frac{d}{d_{16}} + \frac{d_{84}}{d} \right)$$

in which

d is the median fall diameter, fifty percent is finer or coarser than this diameter;

d_{16} is the fall diameter for which 16 percent is finer;

d_{84} is the fall diameter for which 84 percent is finer.

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[20] Colby, B. D., and Christensen, R. P., 1956, Visual accumulation tube for size analysis of sand: Am. Soc. Civil Engineers Jour., v. 82, no. HY3, p. 1004-1-17.

The fall velocity, ω, of the particle representing the median fall diameter at the temperature of the run is given in Table 2. For the fine sediment runs, the fall velocity, ω', is also given and takes into account the presence of fine sediment for that run on the fall velocity.

The amplitude, h, length, l, and velocity, V_s, of the various bed configurations were evaluated by:

1. Direct measurement at the observation window;
2. Direct measurement with a point gage and foot attachment;
3. Utilizing a sonic depth sounder, Richardson and others[21]. This method was only used when the form of bed roughness was ripples, dunes, or transition.

The kinematic viscosity, ν, used for the water-sand runs was the viscosity of distilled water at the average water temperature for each run. For the water-sand runs with bentonite the apparent viscosity, ν', of the water-fine-sediment dispersion was used.

In conducting the flume experiments, a specific discharge was selected at which a series of runs were made and the concentration of fine sediment was varied for each run in the series. The water-sediment mixture was recirculated until equilibrium was achieved. Equilibrium was considered established when:

1. The bed configuration was completely developed for the full length of the flume, excluding the sections influenced by entrance and exit conditions.
2. The average water-surface slope remained essentially constant with respect to time.

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[21] Richardson, E. V., Simons, D. B., and Posakony, G. J., 1961, Sonic depth sounder for laboratory and field use: U. S. Geological Survey Cir. 450.

In the 8-foot flume water from the city mains was used in the first run of a series and then bentonite was added an increment at a time. After the addition of each increment of fine sediment, the run was continued long enough, at least 24 hours in the lower flow regime, to insure equilibrium conditions and then the data for the run were collected. When the maximum concentration of fine sediment was reached for a particular series of runs the process was usually reversed for the next series. The slope or discharge or both were changed to establish a maximum concentration run and other runs were also made at lesser concentrations of fine sediment. The concentration of fine sediment was reduced between runs by adding water which, consequently, caused some fine sediment to be carried away in the overflow from the tail box.

In the 2-foot flume 15 water-sand runs were made prior to the bentonite runs to define the regimes of flow and forms of bed roughness for the flume. Six series of runs were then made which covered bed forms from dunes to antidunes and each series consisted of a water-sand run without bentonite plus three to five runs with different concentrations of bentonite.

The data obtained for each equilibrium run includes: water-surface slope, S ; discharge, Q ; water temperature, T ; depth, D ; average velocity, V ; velocity profiles; concentration of bed material transport, C_t ; concentration of fine sediment (bentonite) transport, C_f ; characteristics of the bed material; bed configuration; and photos of the water surface and corresponding bed configuration.

Table 1. Summary of data for runs with 0.47 mm (1.54×10^{-3} ft) sand in the 8-foot flume.

Run No.	s $\times 10^2$ (O)	Q (cfs)	D (ft)	V (ft/sec)	ν $\times 10^5$	ν' $\times 10^5$	T (°C)	Concentration of Sediment Discharge			Bed Material		Sand Waves			Bed Form[3]
					(ft^2/sec)			C_f (ppm)	C_t (ppm)	C_{f+t} (ppm)	w[1] (fps)	w'[2] (fps)	l (ft)	h (ft)	V_s (fpm)	
46	0.084	14.54	1.11	1.64	1.30	---	13.1	---	181	181	.217	---	5.98	.41	---	D
47	.042	9.59	.75	1.60	1.36	---	11.5	---	23	23	.214	---	8.20	.22	.035	D
48	.052	15.26	1.23	1.55	1.36	---	11.5	---	60	60	.214	---	6.24	.32	.030	D
49	.173	21.32	1.33	2.00	1.38	---	11.0	---	588	588	.212	---	7.28	.35	.080	D
85	.047	7.11	.78	1.13	1.31	---	12.7	---	12	12	.216	---	1.20	.07	.0074	R
86	.046	6.92	.76	1.14	1.77	1.32	17.0	4,800	1.6	4,800	.227	.223	.96	.06	.0033	R
87	.046	6.96	.75	1.16	1.11	1.37	19.1	8,400	2.3	8,400	.232	.224	.91	.06	.0055	R
88	.049	7.10	.74	1.20	1.13	1.50	18.3	11,400	2.5	11,400	.230	.220	1.00	.07	.0015	R
90	.053	6.97	.60	1.45	1.17	1.39	17.1	6,950	37	6,990	.227	.221	1.63	.06	.027	R
89	.065	7.08	.60	1.47	1.12	1.42	18.5	9,000	31	9,030	.230	.223	1.62	.06	.030	R
93	.072	7.20	.62	1.45	1.24	---	14.7	1	99	100	.221	---	5.98	.17	.039	D
92	.090	7.14	.63	1.43	1.12	1.33	18.5	6,070	106	6,180	.230	.225	4.56	.25	.050	D
91	.117	7.12	.58	1.53	1.14	1.42	18.0	8,400	195	8,600	.229	.222	4.33	.25	.084	D
82	.248	8.16	.64	1.60	1.00	---	23.2	133	429	562	.240	---	4.12	.28	.17	D
51	.236	8.11	.62	1.62	1.28	---	13.1	584	545	1,130	.217	---	5.55	.20	.19	D
52	.222	8.01	.55	1.81	1.20	1.26	16.0	1,620	578	2,200	.224	.223	5.33	.26	.18	D
73	.222	8.20	.61	1.67	1.06	1.24	20.7	5,670	662	6,330	.235	.231	5.45	.29	.26	D
74	.215	8.18	.65	1.58	1.05	1.31	21.0	7,970	534	8,500	.236	.229	5.50	.34	.17	D
76	.203	8.49	.63	1.69	1.08	1.38	20.0	9,330	463	9,790	.234	.226	5.71	.30	.16	D
75	.204	8.24	.64	1.60	1.05	1.36	21.2	9,460	625	10,100	.236	.228	4.37	.28	.15	D
53	.235	8.01	.57	1.77	1.16	1.52	17.2	10,700	571	11,200	.227	.217	5.81	.34	.11	D
77	.199	8.76	.65	1.68	1.11	1.52	19.1	12,500	639	13,100	.232	.220	5.12	.29	.091	D
96	.201	8.31	.53	1.94	1.12	1.93	18.6	25,000	761	25,800	.231	.205	4.31	.24	.20	D
94	.237	11.30	.81	1.74	1.28	---	13.5	7	480	487	.218	---	5.21	.32	.28	D
83	.200	15.58	.91	2.14	1.19	---	16.2	---	588	588	.225	---	5.78	.43	.16	D
54	.240	15.36	.92	2.08	1.18	1.25	16.6	1,940	657	2,600	.226	.224	6.54	.41	.33	D
56	.242	15.36	.90	2.14	1.03	1.11	22.1	2,860	1,100	3,960	.238	.236	5.30	.29	.20	D
55	.237	15.36	.94	2.04	1.12	1.26	18.5	4,060	765	4,820	.230	.227	5.87	.27	.23	D
57	.259	15.39	.87	2.20	1.05	1.19	21.3	4,320	761	5,080	.237	.232	5.12	.29	.29	D
58	.233	15.28	.90	2.11	1.08	1.25	20.1	5,270	807	6,080	.234	.230	5.36	.26	.21	D

[1] Computed on basis of average median fall diameter (0.47 mm) and temperature for the runs.

[2] Computed from average median fall diameter (0.47 mm) considering the effects of fine sediment and temperature.

[3] D - Dunes; R - Ripples; P - Plane; A - Antidunes; SW - Standing Wave.

Table 1, cont'd. Summary of data for runs with 0.47 mm(1.54×10^{-3}ft) sand in the 3-foot flume.

								Concentration of Sediment Discharge			Bed Material		Sand Waves			
Run No.	s $\times 10^2$ (O)	Q (cfs)	D (ft)	V $\left(\frac{ft}{sec.}\right)$	ν $\times 10^5$ (ft^2/sec)	ν' $\times 10^5$	T (^{0}C)	C_f (ppm)	C_t (ppm)	C_{f+t} (ppm)	w^1 (fps)	w'^2 (fps)	l (ft)	h (ft)	V_s (fpm)	Bed^3 Form
95	.180	15.38	.80	2.39	1.12	2.03	18.7	28,300	1,640	29,900	.231	.203	---	.33	.31	D
78	.320	11.52	.72	2.00	1.07	1.41	20.3	12,000	1,510	13,500	.235	.223	7.36	.39	.34	D
59	.326	15.36	.65	2.96	1.04	1.20	21.7	4,570	2,920	7,490	.237	.234	7.50	.07	.72	D
60	.342	21.35	.62	4.28	1.06	1.18	21.1	3,600	3,290	6,890	.236	.233	---	---	---	P
61	.355	21.32	.61	4.36	1.00	1.20	23.2	6,170	3,390	9,560	.240	.234	---	---	---	P
71	.531	8.22	.32	3.21	1.04	1.18	21.4	3,600	5,250	8,850	.237	.233	---	---	---	P
72	.550	8.26	.32	3.26	1.08	1.31	20.2	7,100	5,680	12,800	.234	.228	---	---	---	P
70	.640	8.14	.30	3.41	1.08	1.20	20.2	3,910	6,310	10,200	.234	.231	2.43	.12	---	P
63	.570	15.50	.43	4.48	1.05	1.16	21.2	3,020	5,360	8,380	.236	.233	3.43	.23	---	A
64	.578	15.61	.41	4.76	1.05	1.26	21.2	6,440	5,480	12,000	.236	.230	3.43	.20	---	A
65	.571	15.60	.42	4.63	1.04	1.34	21.6	9,090	5,160	14,200	.237	.230	3.44	.20	---	A
66	.575	15.52	.45	4.34	1.01	1.38	23.0	12,300	5,130	17,400	.240	.228	3.34	.20	---	A
80	.643	15.27	.39	4.91	1.04	1.43	21.8	12,100	7,140	19,100	.238	.227	3.36	.26	---	A
81	.634	21.35	.55	4.85	1.38	---	10.7	7	4,480	4,490	.211	---	4.40	.04	---	SW
62	.622	21.23	.54	4.89	.98	1.12	24.5	4,790	4,490	9,280	.243	.239	---	---	---	SW
67	.646	20.87	.53	4.91	1.02	1.36	22.7	11,200	4,390	15,600	.239	.229	4.00	.10	---	SW
79	.651	21.31	.55	4.82	1.05	1.46	21.0	12,400	5,760	18,200	.236	.224	3.90	.08	---	SW
84	.740	15.36	.41	4.67	1.23	---	15.0	7	7,100	7,110	.222	---	3.60	.21	---	A
69	.734	15.54	.43	4.48	1.02	1.24	22.4	7,020	8,280	15,300	.239	.232	3.73	.26	---	A
68	.740	20.94	.53	4.95	1.00	1.23	23.5	7,620	6,760	14,400	.241	.234	4.00	.05	---	SW
98	.821	15.80	.44	4.51	1.11	2.46	19.0	42,000	17,700	59,700	.232	.188	3.10	.24	---	A
100	.790	21.42	.51	5.28	1.29	---	13.3	106	8,440	8,550	.218	---	---	---	---	P
99	.806	21.27	.50	5.32	1.09	1.96	19.6	26,900	16,100	43,000	.233	.207	4.04	.31	---	A
97	.960	12.01	.37	4.07	1.10	1.29	19.5	5,800	8,960	14,800	.233	.228	3.38	.16	---	A

[1] Computed on basis of average fall diameter (0.47 mm) and temperature for the runs.

[2] Computed from average median fall diameter (0.47 mm) considering the effects of fine sediment and temperature.

[3] D - Dunes; R - Ripples; P - Plane; A - Antidunes; SW - Standing Wave.

Table 2. Summary of data for runs with 0.54 mm (1.74×10^{-3}ft) sand in the 2-foot flume.

Run No.	s $\times 10^2$ (O)	Q (cfs)	D (ft)	V (ft/sec)	ν $\times 10^5$ (ft²/sec)	ν' $\times 10^5$ (ft²/sec)	T (°C)	Concentration of Sediment Discharge			Bed Material		Sand Waves			Bed Form[3]
								C_f (ppm)	C_t (ppm)	C_{f+t} (ppm)	w[1] (fps)	w'[2] (fps)	l (ft)	h (ft)	V_s (fpm)	
1	.016	1.06	.61	0.89	1.20	---	15.9	---	---	---	.258	---	---	---	---	P
2	.019	1.12	.60	.96	1.16	---	17.4	---	---	---	.262	---	---	---	---	P
3	.026	1.21	.62	1.00	1.17	---	16.9	---	0.6	0.6	.261	---	0.47	.03	.0001	R
4	.038	1.59	.59	1.37	1.14	---	18.0	---	14	14	.264	---	---	.10	.0004	P
6	.170	2.45	.72	1.74	1.12	---	18.6	---	333	333	.266	---	4.6	.35	.0047	D
5	.201	3.12	.81	1.95	1.10	---	19.2	---	346	346	.268	---	5.0	.26	.0080	D
0	.336	4.28	.91	2.39	1.24	---	14.7	---	---	---	.254	---	4.0	.30	.0054	D
20	.338	4.74	.72	3.36	1.08	---	20.2	---	2,450	2,450	.271	---	4.3	.17	.036	D
8	.351	3.82	.78	2.51	1.11	---	18.9	---	1,020	1,020	.267	---	3.6	.23	.012	D
8A	.331	3.82	.84	2.33	1.12	1.31	18.7	5,740	1,050	6,790	.265	.258	3.8	.20	.012	D
8E	.248	3.69	.88	2.15	1.00	1.46	23.3	14,500	660	15,200	.278	.262	3.6	.19	.0073	D
8B	.293	3.84	.85	2.30	1.04	1.70	21.5	20,600	842	21,400	.274	.252	3.6	.20	.010	D
8C	.294	3.83	.86	2.28	1.02	1.79	22.4	24,300	1,040	25,300	.276	.248	4.4	.24	.011	D
8D	.198	3.77	.72	2.65	0.96	3.20	25.0	63,700	521	64,200	.282	.208	0.7	.08	.0062	SB
7	.388	3.42	.72	2.44	1.06	---	20.6	---	1,090	1,090	.272	---	3.3	.17	.012	D
14	.399	4.77	.89	2.74	1.10	---	19.3	---	1,700	1,700	.268	---	4.0	.20	.021	D
14A	.366	4.78	.82	2.95	0.98	1.27	24.3	9,580	1,760	11,300	.280	.270	5.8	.20	.030	D
14C	.377	4.80	.87	2.82	1.03	1.74	22.2	22,400	1,840	24,200	.275	.250	5.8	.19	.034	D
14B	.339	4.84	.70	3.51	1.02	2.41	22.3	44,100	2,960	47,100	.276	.228	---	---	---	P
19	.408	3.82	.76	2.58	1.04	---	21.5	---	1,300	1,300	.274	---	4.2	.16	.018	D
9	.433	4.16	.72	2.93	1.15	---	17.7	---	1,520	1,520	.263	---	4.2	.18	.022	D
10	.486	5.33	.64	4.30	1.07	---	20.3	---	2,690	2,690	.271	---	---	---	---	P
18	.520	7.62	.71	5.44	1.02	---	22.6	---	3,330	3,330	.276	---	---	---	---	SW
18A	.508	7.57	.76	5.11	1.02	1.44	22.5	13,200	3,400	16,600	.276	.262	---	---	---	SW
18B	.790	7.59	.69	5.62	1.00	1.70	23.3	37,900	9,730	47,600	.278	.237	---	---	---	SW

[1] Computed on basis of average median fall diameter (0.54 mm) and water temperature for the runs.

[2] Computed from average median fall diameter (0.54 mm) considering the effects of fine sediment and temperature.

[3] D - Dunes; R - Ripples; P - Plane; A - Antidunes; SW - Standing Waves; SB - Stabilized Bed.

Table 2, cont'd. Summary of data for runs with 0.54 mm (1.74 x 10^{-3} ft) sand in the 2-foot flume.

Run No.	s x 10^2 (O)	Q (cfs)	D (ft)	V (ft/sec)	ν x 10^5 (ft²/sec)	ν' x 10^5 (ft²/sec)	T (°C)	Concentration of Sediment Discharge			Bed Material		Sand Waves			Bed Form[3]
								C_f (ppm)	C_t (ppm)	C_{f+t} (ppm)	w[1] (fps)	w'[2] (fps)	l (ft)	h (ft)	V_s (fpm)	
18C	.900	7.59	.70	5.54	0.99	3.00	23.7	58,700	22,300	81,000	.279	.208	---	---	---	A
15	.551	6.94	.74	4.75	1.04	---	21.7	---	3,330	3,330	.274	---	---	---	---	SW
15A	.550	6.99	.75	4.76	1.02	1.47	22.5	14,200	4,350	18,600	.276	.261	---	---	---	SW
15B	.537	6.96	.75	4.73	0.99	2.27	23.7	40,900	4,710	45,600	.279	.232	---	---	---	SW
15C	.628	6.99	.73	4.85	0.99	2.98	24.0	58,600	7,640	66,200	.280	.213	---	---	---	SW
13	.565	6.37	.72	4.52	1.14	---	18.1	---	3,350	3,350	.265	---	---	---	---	SW
11	.768	7.48	.66	5.80	1.08	---	19.9	---	5,690	5,690	.270	---	---	---	---	SW
16A	.980	7.82	.67	5.92	1.00	1.35	23.5	11,200	5,600	16,800	.278	.266	---	---	---	SW
16B	1.075	7.84	.66	6.03	0.96	1.93	25.0	31,500	10,300	41,800	.282	.248	---	---	---	A
16C	1.305	7.86	.65	6.14	0.96	2.32	25.1	44,500	15,800	60,300	.282	.232	---	---	---	A
17	1.175	7.89	.65	6.21	1.02	---	22.5	---	9,180	9,180	.276	---	---	---	---	A
17A	1.365	7.83	.65	6.17	1.02	2.27	22.3	39,600	23,800	63,400	.276	.233	---	---	---	A
17B	1.928	7.86	.68	5.87	0.99	2.60	24.0	51,900	50,000	102,000	.280	.221	---	---	---	A
12	1.438	7.84	.64	6.27	1.17	---	16.9	---	26,000	26,000	.261	---	---	---	---	A

[1] Computed on basis of average median fall diameter (0.54 mm) and water temperature for the runs.

[2] Computed from average median fall diameter (0.54 mm) considering the effects of fine sediment and temperature.

[3] D - Dunes; R - Ripples; P - Plane; A - Antidunes; SW - Standing Waves; SB - Stabilized Bed.