STUDIES OF FLOW IN ALLUVIAL CHANNELS

WSP ~~1948~~, CHAPTER
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SOME PROPERTIES OF WATER-CLAY DISPERSIONS AND THEIR EFFECTS ON FLOW

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PARTIAL LIST OF SYMBOLS

Symbol	Description	Dimensions	Units
$\frac{C}{\sqrt{g}}$	Chezy coefficient of discharge in dimensionless form which is equivalent to V/V_*	O	--
C_f	Concentration of fine sediment discharge	ppm	O
C_{f+t}	Concentration of fine sediment and bed material discharge	ppm	O
C_t	Concentration of total bed material discharge	ppm	O
d	Median fall diameter of bed material	L	ft
d_n	Nominal diameter. The diameter of a sphere that has the same volume as the particle	L	ft
d_t	Median fall diameter of bed material discharge	L	ft
D	Average depth of flow	L	ft
F	Force	F	lb
Fr	Froude number	O	--
h	Average height of bed roughness	L	ft
l	Average spacing of bed roughness	L	ft
L	Length	L	ft
Q	Discharge of water-sediment mixture	L^3/T	ft^3/sec
q_b	Rate of bed load transport	F/tL	lbs/ft sec
q_t	Rate of total sediment transport	F/tL	lbs/ft sec
Re	Reynolds number; for a sediment particle, Re is wd_n/ν	O	--
S	Surface slope in steady uniform flow	O	--

Partial List of Symbols - continued

Symbol	Description	Dimensions	Units
t	Time	t	sec
T	Temperature	O	^{0}C
V	Average velocity based on continuity principal	L/T	ft/sec
V_s	Average velocity of sand waves in the lower flow regime	L/T	ft/min
V_*	Shear velocity which is $\sqrt{gDS}$, or $\sqrt{\tau_o/\rho}$	L/T	ft/sec
w	Fall velocity of sediment particles	L/T	ft/sec
w'	Fall velocity of sediment in a water-fine sediment dispersion	L/T	ft/sec
γ	Specific weight of water	F/L^3	lbs/ft^3
γ_s	Specific weight of sediment	F/L^3	lbs/ft^3
Δ_γ	Difference between specific weights of air and water	F/L^3	lbs/ft^3
$\Delta_{\gamma s}$	Difference between specific weights of sediment and water	F/L^3	lbs/ft^3
δ'	Thickness of laminar sublayer	L	ft
ν	Kinematic viscosity	L^2/T	ft^2/sec
ν'	Apparent kinematic viscosity of the water-fine sediment dispersion	L^2/T	ft^2/sec
μ	Dynamic viscosity	Ft/L^2	$lb\text{-}sec/ft^2$
ρ	Mass density of water	Ft^2/L^4	$Slug/ft^3$
ρ_s	Mass density of sediment	Ft^2/L^4	$Slug/ft^3$
σ_r	A measure of the gradation of the sediment	O	--

Partial List of Symbols - continued

Symbol	Description	Dimensions	Units
τ_o	Tractive or shear force developed on the bed, γDS	F/L^2	lbs/ft^2
τ_c	Critical tractive force associated with beginning of bed movement	F/L^2	lbs/ft^2

GLOSSARY OF TERMS

Alluvial Channel: A channel whose bed is composed of appreciable quantities of the sediments transport ed by the flow at a given discharge or greater.

Antidunes: Symmetrical sand and water surface waves which are in phase and which move upstream. The surface waves build up with time and become gradually steeper on their upstream sides until they break like surf and disappear. These waves usually develop, break, and reform in groups of two or more.

Bed Material: The material of which a stream bed is composed.

Dune: A sand wave of approximately triangular cross-section in a vertical plane in the direction of flow with gentle upstream slope and steep downstream slope. It travels downstream as a result of the movement of the sediment up the upstream slope and the deposition of part of this material on the downstream slope.

Equal Transite Rate (ETR): A method of sampling suspended sediment to obtain the velocity weighted mean concentration of the water-sediment mixture in the flume. By this method a depth integrating sediment sampler is traversed through equally-spaced verticals at an equal transite rate for each vertical.

Fine Sediment: That part of the total load composed of particle sizes not found in appreciable quantities in the bed material (referred to by some writers as wash load).

Flow Regime: A range of flows with similar bed forms, resistance to flow and mode of sediment transport.

Lower Flow Regime: Flow with bed forms of ripples, ripples on dunes and dunes.

Median Diameter: The mid-point in the size distribution of a sediment such that one-half of the weight of the material is composed of particles larger than the median diameter and the other one-half is composed of particles smaller than the median diameter.

Plane Bed: A bed without elevations or depressions larger than the maximum size of the bed material.

Ripple: Small triangular shaped sand waves, similar to dunes in shape but smaller in magnitude, which have rather small width normal to the direction of flow.

Sand Waves: Crests and troughs (such as ripples, dunes, or symmetrical undulations) on the bed of an alluvial channel formed by the movement of the bed material.

Sediment: Fragmental material that originates from weathering of rocks and is transported by, suspended in, or deposited by water.

Sediment Concentration: The ratio of dry weight of sediment to total weight of the water-sediment mixture, expressed in parts per million.

Standard Fall Diameter or Fall Diameter: The diameter of a sphere that has a specific gravity of 2.65 and the same terminal uniform settling velocity as the particle (any specific gravity) when each is allowed to settle alone in quiescent distilled water of infinite extent and at a temperature of 24 degrees centigrade.

Standing Waves: Symmetrical sand and water waves which are in phase and which gradually build up and die down. Waves of this type are essentially stationary and usually develop in series and often reform, somewhat periodically, after disappearing.

Suspended Load: The sediment moving in suspension in a fluid as a result of turbulent currents and (or) by colloidal suspension.

Total Load: The total amount of sediment that is transported by water past a section in a given length of time.

Upper Flow Regime: Flow with bed forms of plane bed with movement, standing waves and antidunes.

STUDIES OF FLOW IN ALLUVIAL CHANNELS

WSP 1948, CHAPTER

FLUME STUDIES USING MEDIUM SAND AND BENTONITE

ABSTRACT

Fine material (bentonite and kaolin clays) dispersed in water have a very definite affect on the viscosity and specific weight of the fluid. Tests at 24 degrees centigrade, with a Stormer viscosimeter showed that the apparent kinematic viscosity for a ten percent by weight water-clay dispersion of bentonite was 8.75 times greater than that of clear water and kaolin was 1.40 times greater. The change in viscosity and density of the fluid changes the fall velocity of the bed material. The affect of fine material on the fall velocity of the bed material can be determined, as a first approximation, with the visual accumulation tube apparatus by using water-clay dispersions as the sedimentation liquid. The results from visual accumulation analyses are comparable to those obtained by computation using the Reynolds number, drag relation and the viscosity of the water-clay dispersion as obtained from the Stormer viscosimeter.

Experiments conducted in flumes at Colorado State University demonstrated that when changes in fall velocity, caused by the changes in fluid properties, occurred the form of bed roughness was altered. Resistance to flow and sediment transport, because they are dependent on the form of bed roughness, were appreciably affected.

INTRODUCTION

Many controversial statements regarding the influence and effect of very fine sediment (clay and silt) on the mechanics of flow in alluvial channels prevail. Fine material is most commonly referred to as wash load and it has been defined by Einstein (1950) as "that part of the sediment load which consists of grain sizes finer than those in the bed." Even the name wash load is controversial and for the most part is referred to as fine material load in this report. Einstein (1950) pointed out that the fine material load does not appear to be a function of the flow, but that it is usually related to supply and that the streams' capacity to transport it is always vastly in excess of the available supply. He does not indicate that its presence is apt to influence the mechanics of flow in any way. Similarly, Brown in Engineering Hydraulics (Rouse, 1950) states that the fine sediment load plays a negligible role in the prediction of normal stream behavior.

In contrast, Langbein (1942) reported changes in bed form and increased antidune activity as the concentration of fine sediment increased. Blench (1957) 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.

In support of those indicating a fine sediment effect, Bingham (1922) showed that fluidity, the reciprocal of viscosity, of aqueous suspensions of clay in water varied markedly with the 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 (1961), investigated significance of fine sedimend load in a large 8-foot flume, a small 2-foot flume and in the soils laboratory. This investigation, the results of which are reported herein, covered the effect of concentrations of fine sediment on:

The physical properties of the liquid and the hydraulic properties of the bed material

The forms of bed roughness

The resistance to flow

The bed-material transport.

EQUIPMENT, PROCEDURE, AND DATA

In the 8-foot flume a series of 54 equilibrium runs were completed in which slope was varied from 0.00046 to 0.0096 foot per foot, the discharge was varied from 6.9 to 21.4 cubic feet per second, and the concentration of fine sediment was varied from 0 to 42,000 parts per million. Flow conditions ranged from the lower flow regime with ripples to antidunes in the upper flow regime.

In the 2-foot flume 39 equilibrium runs were completed which covered the forms of bed roughness from plane bed prior to movement of sediment to antidunes. The range in the basic variables was: slope from 0.00016 to 0.0144 foot per foot, discharge from 1.1 to 7.9 cubic feet per second, depth from 0.59 to 0.91 feet, and concentrations of fine sediment from 0 to 64,000 parts per million. The basic data are presented in table 1 and table 2.

Flumes

The larger flume is a tilting recirculating flume 150 feet long, 8 feet wide and 2 feet deep. The flume is the same as described by Simons and others (1961) except that a plastic window was installed in the flume wall between stations 90 and 96 so that bed configuration, dune velocity, sediment transport, and flow conditions could be directly observed.

A schematic drawing of the smaller flume is shown in Figure 1.

Figure 1. Schematic diagram of the flume

The flume is 60 feet long, 2 feet wide, and 2-1/2 feet deep with 1/2-inch clear plastic side walls and a floor of 1/4-inch stainless steel plate. The flume is adjustable to any slope from horizontal to 0.1 foot per foot, and recirculates the water-sediment mixture.

Bed Materials

The sand used as bed material for the flume runs was the same as that used in the study by Simons and others, 1961. However, the sand characteristics had changed slightly, see figure 2. In the 8-foot flume study

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Figure 2. Particle size distributions of the bed materials

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the average median fall diameter, d , was slightly larger, 0.47 millimeters versus 0.45 millimeters, and the measure of gradation, σ_r , decreased slightly, 1.54 versus 1.60. Whereas, in the 2-foot flume study the median fall diameter was 0.54 millimeters and the measure of gradation was 1.50. These changes are attributed to the continuous wasting of a small quantity of water introduced through the pumps bearings to protect them from sediment, which carried away some of the fine sand during preceeding periods of flume operation.

Fine Materials

A bentonite clay was used in the flume studies to determine the effect of fine sediment on resistance to flow, transport of bed material, and flow phenomena. Bentonite was selected because it was commercially available in large quantities and typical of much of the fine material found in streams in the semi-arid West. In addition, the effect of the bentonite and a kaolin clay on the properties of the fluid and the hydraulic properties of the bed material were studied in the sediment laboratory.

The size distributions of the bentonite and kaolin are given in figure 3.

Figure 3. Particle size distribution of the fine sediments

The size distributions of the bentonite and the kaolin were determined by standard U. S. Geological Survey sieve-pipette analyses with the samples chemically and mechanically dispersed.

General Procedure

In conducting the experiments to determine effect of fine sediment on resistance to flow and bed material transport, specific discharges and slopes were selected and runs made varying the concentration of fine material. The water-sediment mixture was recirculated at a given slope and discharge 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.

In the 8-foot flume the first run of a series was started using clear water and after equilibrium was established the data which described the run were collected. Then without stopping the pumps, altering the bed configuration, or changing the external controls (tail gate, valves, etc.), fine material was added an increment at a time. After the addition of each increment of fine material, 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. The slope or discharge or both were changed to establish another maximum concentration run. Other new runs were then made by reducing the concentration of fine sediment in increments, between runs, by adding water and washing fine material and water through the tail box overflow.

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. After the 15 water-sand runs were completed, six series of runs were made to determine the effect of fine sediment. These series of runs covered bed forms from dunes to antidunes and each series consisted of a water-sand run without bentonite plus three to five runs at different concentrations of fine sediment. When a series of runs were completed, excluding series 15, the water-bentonite dispersion was wasted to an outside drain and the system and the bed material were washed free of bentonite in preparation for the next series of runs.

For a series, data were first obtained for the water-sand run and the run was continued with no changes made to the flow or system controls except that bentonite was injected at the tail box until the desired concentration of fine sediment was attained. The concentration of fine sediment was maintained during the collection of data by adding more bentonite when necessary. Data were collected in a relatively short time interval compared to the runs without bentonite so that a constant concentration of fine material was sustained, because the fine sediment concentration decreased with time owing to deposition of bentonite at the contact plane of the sand bed and the flume floor and loss of some of the bentonite with the overflow from the tail box.

After completion of the run series 15, run 16A was established by altering run 15C, see table 2. Although some bentonite was conserved by this method, an undesirable bed condition developed. The sand bed became partly cemented with bentonite and difficult to move; runs 16A, B, and C, were completed with this anomalous bed condition and probably would have been similar to run series 17, 17A, and 17B had the normal procedure of starting with clear water been followed.

Basic Data

The data obtained for each equilibrium run includes: water-surface slope, S; discharge, Q; water tenperature, T ; depth, D ; average velocity, V ; velocity profiles; concentration of bed material transport, C_T ; concentration of the fine sediment (bentonite) transport, C_f ; concentration of suspended sediment; characteristics of the bed material; bed configuration; and photos of the water surface and corresponding bed configuration. The basic data are given in tables 1 and 2 .

The water-surface slope was determined by measuring the water-surface elevation with a mechanical point gage and also, in the 8-foot flume, by a differential bubble gage--both methods were in close agreement. The bubble gage continuously records the difference in elevation of the water surface, to within 0.001 foot, between two points located at different cross sections on the flume. From the difference in water surface elevation and the distance between the two cross sections, water-surface slope can be computed. The continuous bubble-gage record of the slope can be used to determine when equilibrium conditions are established as equilibrium exists when the time average of the slope does not change with time.

Typical records of the slope measured by the bubble gage for various forms of bed roughness are illustrated in figure 4. A study of figure 4 shows

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Figure 4. Measured and recorded water-surface slopes

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that the pattern of variation of slope with time is directly related to the form of bed roughness.

The discharges of the water-sediment mixture were measured with calibrated orifice meters and water-air manometers.

The water temperature was measured to the nearest 0.1 degree centigrade with a mercury thermometer. Water temperature was essentially constant for a particular run, but varied from 10.7 degrees centigrade to 25.1 degrees centigrade during the study.

The average depth of flow was determined by measuring the difference in elevation between the water surface and the sand bed. Measurements were made every foot over a 100 foot length of the 8-foot flume and over a 35-foot length of the 2-foot flume. In the 8-foot flume the average depth ranged from 0.53 to 1.33 feet in the lower flow regime and from 0.30 to 0.89 feet in the upper flow regime. In the 2-foot flume the depths ranged from 0.59 to 0.82 feet. The measurements of average depth were accurate to within 0.02 feet.

The mean velocity was calculated by dividing the measured discharge by the area of water cross section. Therefore, it accumulates the errors inherent in the depth and discharge measurements. In the study mean velocity ranged from 0.89 to 2.96 feet per second in the lower flow regime and from 2.58 to 6.21 feet per second in the upper flow regime.

Velocity profiles for each run were obtained with a calibrated pitot tube and a tilting water-air manometer. They were obtained in three verticals in the cross section in the 8-foot flume and in one vertical in the 2-foot flume.

The total sediment load was sampled with a width-depth integrating total-load sampler where the water discharged from the flume into the tail box. In the lower flow regime eight samples were collected over a two-hour period and in the upper flow regime four to six samples were collected over a one-hour period. Each sample consisted of from 70 to 110 pounds of the water-sediment mixture.

The total load samples were separated into a fine-material fraction and a bed-material fraction. The fine-material fraction was determined by taking a sample of the water-sediment mixture after it had been allowed to settle one minute. The bed-material fraction was that material retained after washing on a 270 sieve for the 8-foot flume study and on a 200 sieve for the 2-foot flume study. The concentration of both fractions, which make up the total load, are given in tables 1 and 2.

Part of the bed-material discharge for the bentonite runs could have been bentonite because 0.5 percent of the bentonite was coarser than the number 200 sieve (0.74 millimeter opening) and 2.0 percent was coarser than the number 270 sieve (0.53 millimeter opening) see figure 3. 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 bed material, 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.

For a run series, the median fall diameter of the bed material discharge generally decreased with increasing concentration of bentonite, see tables 1 and 2 . The decrease in median fall diameter was attributed to the finer particles contributed by the coarser portion of the bentonite which was retained upon the sieves used for separating the bentonite from the bed material load before analyzing for particle size distribution. The small median fall diameter of the total bed-material discharge for run 8D is certainly due to the relatively finer sediments contributed by the bentonite.

Suspended sediment was sampled near the mid-point of the 8-foot flume with a specially designed depth-integrating sampler. The sampler consisted of a 3 x 1/4-inch brass nozzle attached to a wading rod. The nozzle was connected to a flexible tube. The sample was drawn through the tube to a container by a vacuum pump which was adjusted to draw water at a velocity approximately equal to the velocity of the flow. With this equipment, one 5-8 pound sample was collected by the equal-transit-rate method for each run. Suspended sediment was not sampled in the 2-foot flume study.

Concentration of suspended material, which included the clay fraction, ranged from 0 to 43,500 parts per million in the lower flow regime and from 3,046 to 57,700 parts per million in the upper flow regime. Some supended bed-material concentrations were larger than corresponding total-bed material concentrations. This was due, in part, to the inadequate number of suspended-sediment samples and the possibility of sampling in a region of flow where local bed shear stress and turbulence were much larger than average so that local-suspended loads were abnormally large.

The samples of the bed material were washed to remove all bentonite, dried, split and analyzed in the visual accumulation tube (Colby and Christensen, 1956) to determine median fall diameter and gradation. The gradation of the material is indicated by σ_r which can be 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

d_{16} is the size, by weight, for which 16 percent is finer

d_{84} is the size for which 84 percent is finer.

In addition to the median fall diameter and gradation coefficient in table 2 the fall velocity, w, of the median fall diameter at the temperature of the run is given. Also when fine material was in the run the fall velocity, w', is given that takes into account the effect of the concentration 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, 1961. This method was only applicable when the form of bed roughness was ripples, dunes, or transition.

A comparison of the bed configurations as determined by the sonic depth sounder and the point gage is given in figure 5. The sonic depth sounder was in

Figure 5. Comparison of bed configuration measurements.

the developmental stage while collecting most of these data and was not available to measure the bed configuration of all the ripple and dune runs.

The kinematic viscosity, ν, for the water-sand runs was determined by using 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-sediment dispersion was used.

EFFECT OF FINE SEDIMENT ON FLUID PROPERTIES

Viscosity

The apparent viscosities of aqueous dispersions of kaolin and bentonite were experimentally determined by using a Stormer viscosimeter and sodium hexametaphosphate as a dispersing agent. Viscosities of dispersions having 0.5, 1, 2, 3, 5, and 10 percent bentonite and 3, 5, and 10 percent kaolin by weight in distilled water were measured at temperatures ranging from 5 to 45 degrees centigrade. 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. The apparent kinematic viscosity of the aqueous dispersions of bentonite is shown in figure 6 and the

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Figure 6. Apparent kinematic viscosity of water-bentonite dispersions

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viscosity of the aqueous dispersions of kaolin is shown in figure 7. For comparison, the kinematic viscosity of distilled water is also given in each figure.

Figure 7. Apparent kinematic viscosity of kaolin-water dispersions

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These relations of apparent viscosity to concentration of clay are very similar to several Bingham (1922) 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 (1958) related the viscosity of aqueous dispersions of clay to their behavior at different stages of neutralization. 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). 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 (1955) 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 dispersions to the viscosity of water at the same temperature is independent of the temperature. 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. Inspection of figures 6 and 7 indicates that at a specific temperature the ratio of the viscosity of the kaolin and bentonite dispersions for concentrations $\leq$ 5 percent to the viscosity of water is independent of temperature, which conforms with the findings of Wood, Granquist, and Kreiger.

The ratio of the weight of dispersing agent (sodium hexametaphosphate) to weight of fine sediment was kept constant at 1 / 100 for the flume experiments, the viscosity determinations and the fall velocity studies. 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 change in fluid properties caused by addition of clays to water on flow phenomena and hydraulic properties of the bed material; but a full study would necessarily include the effect of amount and nature of adsorbed cations on the properties of the clay-water dispersions. From the literature, figure 8 was developed that indicates

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Figure 8. General shape of the viscosity curves for clay-water systems with various amounts of added base

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the generalized variation of viscosity of clay-water systems with amount and nature of adsorbed cations. Figure 8 is only the general shape of the relation of viscosity to added base and the relation varies with the type of clay and the added base (Baver, 1959)(Street, 1958). The numerous investigators of viscosity of clay-water dispersions 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. The effect of fine sediments in a stream 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.

Specific Weight

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

$$\gamma = \frac{\gamma_w \gamma_s}{\gamma_s - 1.03 \frac{C}{10^4}}$$

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 their specific weight, γ_s, minus the specific weight of the fluid, γ. The $\gamma_s - \gamma$ represents the driving force causing downward motion and in fall velocity studies the significance of this force is obvious.

EFFECT OF FINE SEDIMENT ON FALL VELOCITY

In a study of flow in alluvial channels, the properties of the bed material are significantly involved. The mineral identification, density, shape, area and volume of individual particles, and the size distribution of all the particles are usually used to describe the bed material. The fall velocity of the individual particles and particle-size distributions based on fall velocity integrates 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 directly relating the bed material properties to the liquid characteristics. The effect of changes in the viscosity and specific weight of the flow on the fall velocity of sand particles has been generally ignored in alluvial channel research (Langbein, 1942). In the previous section an appreciable effect of bentonite and kaolin on fluid properties was found. In this section the effect of the two fine sediments on fall velocity are explored.

The particle size distributions of three different natural sand samples in aqueous dispersions of fine sediments were determined by the visual accumulation method. This method is described in detail in Inter-Agency Report Number 11, but briefly, it is a calibrated system for determining the fall diameter distribution of sand samples in distilled water. Naturally worn sand particles having specific gravities of about 2.65 were used in the calibration of the visual accumulation tube.

The settling velocities of particles of a sediment sample depend on the characteristics of the particles, the sample volume, the liquid characteristics, 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. A basic assumption was that the calibration of the visual accumulation tube was valid for sedimentation media of fine sediments in water.

Samples of the three 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. A typical graph of size distribution is shown in figure 9. The change

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Figure 9. The particle size distribution of an Elkhorn River, Nebraska, sand sample based on its fall velocity in various concentrations of bentonite dispersed in distilled water (analyzed in the visual accumulation tube).

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in the fall velocities of the median fall diameters with percent bentonite in water is shown in figure 10 and for percent kaolin in water in figure 11.

Figure 10. Variation of fall velocity with percent bentonite in water

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Figure 11. Variation of fall velocity with percent kaolin in water

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The fall velocities were computed from the relation of the fall diameter of naturally worn quartz particles to fall velocity given in Inter-Agency Report Number 12.

The variation of the gradation coefficient σ_r, with concentration of bentonite is summarized in table 3. The gradation coefficient varies because, as will be discussed in the next section, the coefficient of drag for any specific sand particle changes with viscosity but the change is less for a large particle than a small particle.

TABLE 3

Variation of The Measure of Gradation, σ_r,
With Percent Bentonite in Water

Percent Bentonite.	Measure of Gradation, σ_r,		
	Poudre River, Colo. Sand	Elkhorn River, Nebr. Sand	Loosely cemented ss Denver, Colo.
0	1.52	1.61	1.32
1	1.53	1.59	1.32
5	1.60	1.64	1.37
10	1.83	1.78	1.39

A check was made on the accuracy of the visual accumulation tube particle size analyses when aqueous dispersions of fine sediment were the sedimentation media. The change in the fall velocity of a particle representing a single size and the median fall diameter of the sand sample was computed for each of the fine sediment media used in the visual accumulation tube. In the computations, the median fall diameter (converted to a nominal diameter), the apparent viscosity of the dispersion, the mass density of the dispersion and the particle, and a particle shape factor of 0.7 were used. The empirically established relation between the drag coefficient, C_D , for a particle falling at terminal velocity and the Reynolds number, Re , was then determinable and from these the fall velocity was computed. The C_D versus Re relation for naturally worn sediment particles is given in figure 1, Inter-Agency Report Number 12.

The agreement between the computed fall velocities and those determined from the visual accumulation tube analyses is surprisingly good, see figures 10 and 11. Several of the many factors that might contribute to disagreement are:

1. The lack of a good definition of the C_D versus Re relation for sediment particles.

2. Errors in measuring the apparent viscosity of the fine sediment in water dispersions.

3. The shape factor of the sand particles may differ appreciably from 0.7.

4. The presence of the fine sediment particles in the visual accumulation tube probably affects 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 distributed in the sedimentation column.

The variation of fall velocity of the three sands with water temperature is given in figure 12. As the change in the specific weight of distilled

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Figure 12. Variation of fall velocity with water temperature

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water with temperature is relatively slight when compared with the change in the viscosity, the variation shown in figure 11 emphasizes the part that viscosity of the liquid has on the fall velocity without the complications introduced when considering a fine sediment in water dispersion.

Considering the determination of the actual fall velocity of bed materials in streams, apparently, two procedures can be used.

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 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 degrees centigrade 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.

OBSERVED FLOW PHENOMENA

Regimes of Flow and Forms of Bed Roughness

The form of the bed roughness in alluvial channels is a function of the bed material characteristics, the fluid characteristics, and the characteristics of the channel. The bed configuration can be changed by changing any one or more of discharge, slope, the median fall diameter of the bed material, the size distribution of the bed material, and the fall velocity of the bed material particles.

The observed regimes of flow, bed configurations, and the flow phenomena associated with them were described in detail by Simons and Richardson (1961). The classification resulting from combining laboratory results with information from field investigations by Colby (1960), Dawdy (1961). The regimes of flow and forms of bed roughness are:

Lower flow regime

1. Plane bed without movement
2. Ripples
3. Dunes with ripples superposed
4. Dunes.

Transition

1. Transition from dunes to upper flow regime.

Upper flow regime

1. Plane bed and water surface
2. Standing sand and water waves which are in phase
3. Antidunes.

In this study these same major forms of bed roughness were observed in the 8-foot flume. However, in the 2-foot flume there were some differences. The major difference was that the ripple form of bed roughness did not occur in the smaller flume. After beginning of motion, ripples developed in the 8-foot flume (Simons and Richardson, 1960), but in the 2-foot flume the bed remained plane except for a few oblong shaped bed irregularities which occasionally developed and were randomly spaced in the flume.

The absence of ripples was investigated at depths varying from 0.2 to 2.0 feet and at various water-surface slopes. Each investigation was started at the beginning of sediment motion and for each investigation holding the depth constant and increasing the discharge and (or) the slope a plane bed persisted until the shear on the bed and the bed material in transport ripples were slowly erased back to a plane bed by the flow. Run 3 where ripples were artificially produced that persisted throughout the run was not considered representative of factual conditions. Considering run 3, 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 parts 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. The dune fronts were continuous clear across the 2-foot flume and essentially perpendicular to the flow whereas, in the 8-foot flume the dune fronts were not, see figures 13 and 14. Also, in the 2-foot flume

Figure 13. Dune bed configuration in the 8-foot flume

Figure 14. Dune bed configuration in the 2-foot flume

the standing waves and antidunes formed over the entire flume width, see figures 15 and 16.

Figure 15. Antidunes in the 8-foot flume. Note the three dimensional aspects of the two runs of waves.

Figure 16. Antidunes in the 2-foot flume. Note the two dimensional aspects of the waves.

With large concentrations of fine sediment the spacing and shape of the ripples and dunes and the antidune activity were modified. For example, in run series 14 where flow conditions were not changed the dunes increased in length from 4 feet to 5.8 feet and eventually the bed became plane with increasing concentration of fine sediment. The changes that occurred in the bed form, resistance to flow and sediment transport are elaborated on in subsequent paragraphs.

Lower Flow Regime

Ripples: -- In the 8-foot flume, runs 85 - 90, were a sequence of runs made with ripple bed configuration holding Q and S constant and varying the concentration of fine material, see table 1. This sequence of runs was made without stopping the flow. Fine material load was increased by increments between runs from 0 to 11,400 parts per million. The addition of fine material in as small a concentration as 4,800 parts per million affected sediment transport and resistance to flow. This amount of fine material was more than the turbulence of the flow could effectively keep in suspension. Consequently, the fine material was deposited on, and in, the surface of the bed and formed a firm semi-cemented boundary. With the smaller concentrations of the fine material for runs 86 and 87, the cemented patches of the bed were not as extensive in area as with the higher concentrations for runs 88 and 89 and the flow was able to disperse them. However, new patches reformed elsewhere on the stream bed. With the largest concentration (11,400 parts per million), a major percentage of the ripple bed was quite rigidly cemented and the turbulence of the water-sediment mixture was much greater with the semi-rigid bed than with the normal rippled bed. The bed for run 90 had a larger percent of cemented area than run 87, even though the concentration of fine material was less. This resulted from residual effects of run 88.

Where the bed was not cemented by the fine material and the ripples were moving, fine material was deposited in the ripple troughs. When the ripples moved over former troughs lenses of fine material were trapped in the bed, see figure 17.

Figure 17. Lenses of fine material trapped in the bed. Note rounded crests.

The fine material decreased bed material transport from 12 parts per million to 2 parts per million and increased $C/\sqrt{g}$ from 10.4 to 14.4 . The decreased transport resulted from the cementing of the bed which reduced the amount of bed material available. The deposit of fine material and the cementing of the bed changed the form of the ripples so that they were no longer angular but had rounded crests. The resultant change in form drag reduced resistance to flow. The change in the shape of ripples is illustrated by comparing the ripples which are affected by the fine sediment, figure 17, with moving ripples (no fine sediment) in figure 18.

Figure 18. Ripples, clear-water run. Note angular crests.

In the last two runs of the sequence, 89 and 90, slope was increased so as to change the bed form to dunes but the cohesive deposit of fine material on , and in, the bed resisted the change. However, the increase in slope did break up some of the cemented areas and increased total bed material transport from 2 to 37 parts per million.

With bentonite in the flow, it was possible to observe small vortices at the water surface which were not observed with the water-sand runs without bentonite. These vortices had centers of clear water. Presumably, the centrifugal force removed the fine material. The force must be large to accomplish this as it is difficult to separate the fine material from the water under laboratory conditions.

Although there was enough fine material deposited on the bed to cement large areas, the sampled bed material never contained more than 2 percent of material finer than 53 microns.

Dunes, 8-foot flume: -- The change from ripples to dunes, as stated in the previous section, was resisted by the cementing action of the fine material deposited during the ripple runs. With discharge constant, the slope was double that measured for ripples before the flow was able to break up the cemented areas and form a typical dune bed, run 91. There was a noticeable difference in the appearance of the water surface before the flow was able to break up the cemented areas and form dunes. The water surface over the cemented areas was choppy as if the flow was over cobbles. A water surface typical of sand bed streams with dunes was restored after the dune bed configuration had formed.

With the dune bed configuration, the turbulence of the flow was large enough to suspend the fine material even at the maximum concentration introduced into the flow, 28,300 parts per million. This does not mean that fine material was not in the bed material. The turbulence exchange theory for sediment transport would predict that fine material would be in the bed and direct measurement proved that some fine material was in the bed.

However, the fine material did not settle and coat the bed, never to go into suspension again, as with the ripples; instead, there was a constant exchange between the fine material in suspension and in the bed.

The maximum amount of fine material in the bed was about 2 percent as determined from the size analysis of bed material samples. This fine material was fairly well distributed throughout the bed material. The presence of the fine material in the bed did not appear to reduce the mobility of the bed material and the bed was just as soft and fluid as when the fine material was not present. The flow of clear water removed the fine material from the bed in a few hours.

The presence of fine material in the flow in concentrations greater than 5,000 parts per million (0.5 percent) decreased resistance to flow. The increase in $C/\sqrt{g}$ was as large as 40 percent, run 96, when the concentration was 25,000 parts per million. There may have been a decrease in resistance at concentrations lower than 5,000 parts per million, but if so it was not large enough to detect with the natural variations which exist. The decrease in resistance to flow as the fine sediment concentration was increased results from the fact that the fall velocity of the bed material was reduced and the shape of the dunes changed.

The data indicate that transport of bed material increased slightly with the addition of fine material. However, the increase in bed-material load may have resulted from separating the fine-material load from the bed-material load on the 270 sieve (0.053 millimeter). About 2 percent of the bentonite was retained on the 270 sieve, see figure 3, and this 2 percent of the bentonite which was added to the flow as fine material could account for some of the increase in bed material transport.

Dunes, 2-foot flume: -- When bentonite was being added to the flow it entered the bed with the pore water and the accumulations in the bed were visible through the plastic sides. While the bentonite was being added, the dunes increased in length and decreased in amplitude until in the extreme case, a plane bed developed throughout most of the flume. The initial bed configuration was quickly broken up by the flow after the desired concentration of fine sediment was reached and the addition of bentonite was stopped. Except for the build up of a bentonite layer near the flume floor, the accumulations of bentonite in the bed when exposed by a dune front moving through the flume were added to the material in suspension. Only the normal exchange between bentonite in suspension and bentonite in the bed occurred after equilibrium was established.

Concentrations of fine sediment less than 25,000 parts per million had little or no effect on the resistance to flow or bed material transport.

The form of bed roughness and therefore the resistance to flow and bed material transport was considerably modified when the concentration of fine sediment was increased over 25,000 parts per million. The dunes increased in length and decreased in height as additional bentonite was added to the flow until the bed configuration was rounded sand waves of small amplitude at a concentration of fine sediment of 63,700 parts per million, run 8D. This amount of fine sediment was more than the turbulence of the flow was able to keep in suspension, and fine sediment was deposited on the bed in the dune troughs. The dunes moved over the deposited sediment trapping it in the bed in lenses and layers which were visible through the plastic flume walls, but no cementing or greater firmness of the bed was discernible and it remained soft and fluid. The resistance to flow decreased and the bed material transport was reduced.

After the completion of data collection for run 8D, the concentration of fine sediment in the flow was decreased with time by losses due to some bentonite entering the bed and some being wasted away with the overflow water. Five hours after the end of run 8D the bed configuration was partly long dunes of very small amplitudes and partly plane bed. Sixteen hours after run 8D the concentration of fine sediment had decreased from 63,700 to 14,500 parts per million and data for run 8E were collected. The bed configuration was dunes of the same length but of smaller height and slower velocity than the dunes for the water-sand run 8. Resistance to flow was the same as that of runs 8, 8A, 8B, and 8C, but the concentration of bed material discharge was less. The decrease in bed material transport may have resulted from either a cementing of the bed by the bentonite or a change in the shear-transport relationship by the addition of the bentonite.

Transition

Sheared-out-dunes, 2-foot flume: -- Fine sediment was added in amounts from 9,580 parts per million to 44,100 parts per million in the sequence of runs numbered 14 through 14C, and these runs represented the effect of adding fine sediments to the sheared-out-dune form of bed roughness. Bentonite entered the bed and a layer of sand adjacent to the flume floor became saturated with bentonite. Fine sediment did not coat the bed and accumulate in the troughs of the transition type dunes but remained in suspension once the dune action removed the bentonite which entered the bed during the initial bentonite addition.

The bed material transport increased and resistance to flow decreased for concentrations of fine sediment as small as 9,580 parts per million. The amplitude of the sand waves remained nearly constant but their length and velocity increased. As the concentration of fine sediment was increased to amounts greater than 22,000 parts per million the transition dune lengths increased to 10 to 20 feet compared to transition dunes 4 to 6 feet long at concentrations less than 22,000 parts per million. The form of bed roughness changed from the long sheared-out-dunes to a plane bed at about 30,000 parts per million bentonite when the concentration of fine sediment was being increased and changed from a plane back to transition dunes at approximately the same concentration of fine sediment, 30,000 parts per million, when the concentration of bentonite was being decreased.

Upper Flow Regime

Standing waves, 2-foot flume: -- Sand beds are quite firm and consolidated for the standing wave form of bed roughness. When bentonite was added to the flow the bed surface became very firm and felt slightly crusty, however, when the bed was thoroughly disturbed by raking several times during the sequence of runs, no differences in flow phenomena were observed or were detected in the measurements.

Bed roughness form did not change for the sequence of runs 15, 15A, 15B, and 15C. The length of the standing sand waves measured from crest to crest changed very little, but their height decreased as the concentration of fine sediment was increased. The resistance to flow was unchanged for concentrations of fine sediment less than 41,000 parts per million, but increased slightly at the largest concentrations of fine material. The data in table 2 show that the bed material in transport was increased for each fine sediment run over the bed material transported by the water-sand flow without bentonite.

There was a more noticeable effect as fine sediment was added to the standing wave runs in the series 16, 16A, 16B, and 18, 18A, 18B, and 18C. When the fine material concentration was increased, antidunes developed. The larger the concentration of fine material the greater the antidune activity. This action was reversible. With the increase in concentration of fine material there was an increase in resistance to flow and transport of bed material. The increase in resistance to flow and the bed material transport was due primarily to the change of the standing waves to antidunes resulting from the increase in concentration of fine sediment. The resistance to flow and the bed material in transport is greater with antidunes than with standing waves.

Antidunes, 8-foot flume: -- The most obvious effects of the fine-material load on flow phenomena in the upper flow regime was the increase in antidune activity with the increase in concentration of fine material. With the increase in antidune activity, bed material transport and resistance to flow increased. Antidunes occurred, with fine material present, at smaller Froude numbers than otherwise. In one set of runs, the concentration of fine sediment was reduced from 26,900 parts per million for run 99 to 106 parts per million for run 100 by adding clear water and wasting the excess water-sediment mixture. With the large fine material concentration, antidune activity was intense and the concentration of bed material in transport was 16,100 parts per million. With the decrease in concentration of fine material, there was a decrease in antidune activity until with run 100 the water surface and bed were plane and the bed material concentration was 8,440 parts per million. The only other change in flow conditions during runs 99 and 100 was a slight decrease in water temperature and possibly a slight coarsening of the bed material resulting from wasting the water-fine-sediment mixture. The increase in antidune activity with increasing concentration of fine sediment is the result of reducing the fall velocity of the bed material and hence increasing the mobility of the bed material.

In the upper flow regime fine sediment was not deposited on the bed. However, the fine material built up with time on the rigid floor of the flume under the sand bed as with the dunes. The rate of increase or decrease of concentration of fine material in the bed is smaller than for dunes due to the increased compaction and reduced porosity of the bed. Also, only about 0.05 feet of the top surface of the bed material was moving, whereas large dunes turn over the full depth of the alluvial bed.

In the sequence of runs in the 8-foot flume the antidunes usually formed in two parallel lines of waves, see figure 15. This is different than the antidune water-surface patterns observed during the first forty-five runs (Simons and others, 1961) when only a single train of antidune waves usually formed.

Antidunes, 2-foot flume: -- Antidune activity increased with increasing concentration of fine sediment. The antidunes occupied more of the flume length, the sand and water waves broke more frequently, and the breaking lasted longer and was more violent with the larger concentration of fine sediment. Consequently, the resistance to flow and concentration of total bed-material discharge increased with increasing concentration of fine sediment.

The decrease in fall velocity of the bed material was evident by observing the sand suspended during the antidune runs with bentonite. The suspended bed-material load was composed of dark colored particles which contrasted sharply with the creamy white water-bentonite dispersion. The bed material particles suspended in the water and bentonite dispersion stayed in suspension much longer and were carried a greater distance by the flow than in the water-sand flow. This could account for a substantial amount of the increase in the total bed material in transport.

EFFECT OF FINE SEDIMENT ON RESISTANCE TO FLOW

The influence of fine sediment on resistance to flow is illustrated in figures 19 and 20. The magnitude of the change in $C/\sqrt{g}$ depends upon the

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Figure 19. Variation of resistance coefficient, $C/\sqrt{g}$, with concentration of fine sediment, 8-foot flume data

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Figure 20. Variation of resistance coefficient, $C/\sqrt{g}$, with concentration of fine sediment, 2-foot flume data

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concentration of fine sediment, the form of bed roughness, and whether or not the addition of the fine sediment causes only a modification of the existing roughness or a complete change in form of bed roughness such as from dunes to plane bed.

With a dune bed form there was a decrease in resistance to flow with an increase in fine sediment concentration. The decrease resulted from the increase in length of the dunes. In the extreme case the bed changed from dunes to the lower flow regime to plane bed of the upper flow regime. With standing waves and antidunes an increase in fine sediment concentration increased resistance to flow. The increase resulted from the increase in size of the standing waves and violence of the antidune activity. In some cases the addition of fine sediment changed a standing wave run to antidunes.

EFFECT OF FINE SEDIMENT ON BED MATERIAL TRANSPORT

Analyzing the flume data the effect of fine sediment on bed material transport is difficult to determine because of the possibility that the coarser fraction of the fine-material load was included in the bed-material load due 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 material (2 percent for the 8-foot flume data and 0.5 percent for the 2-foot flume data approximately). Some generalizations can be made.

With relatively low concentrations of fine material and a ripple bed form the bed was partly cemented and bed material transport was reduced. The larger the concentration of fine material the larger the area of the bed that was cemented.

With dunes there was relatively little effect on bed material transport at concentrations of fine material less than 10,000 parts per million. With concentrations of fine sediment greater than 10,000 parts per million there was a decrease in bed material transport in the 2-foot flume, see figure 21.

Figure 21. Variation of bed material transport with concentration of fine material

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The decrease may have been larger because the bed material transport concentration may contain some fine material load. The 8-foot flume data show either no change or an increase in bed material transport with an increase in fine material load. However, the increase could have resulted from including fine sediment in the bed material transport. The decrease in transport of bed material load with an increase in concentration of fine sediment probably results from the decrease in resistance to flow that also occurs and the decrease in the shear that results when depth and slope adjust to the smaller resistance to flow. In some dune runs in the 2-foot flume the bed was partly cemented and bed material transport decreased. However, the decrease in bed material transport also occurred when the bed was known not to be cemented.

With the bed forms of the upper flow regime a large concentration of fine sediment increased bed material transport, see figure 21. This increase exists even if the bed material load is adjusted for the possibility that some of it is fine sediment. The increase in bed material load occurs because the fine sediment increases the viscosity and specific weight of the fluid, decreases fall velocity of the bed material and increases resistance to flow and fluid shear. With shear constant there is an increase in bed material transport with a decrease in sand size or decrease in fall velocity. With fine sediment added to the flow there is even an increase in shear in the upper flow regime.

The total sediment discharge of a stream when fine sediment is in the flow cannot be predicted from knowledge of fluid, sediment, and channel characteristics, 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, equations such as Einstein's (1950), and Bagnold's (1956), cannot predict total transport when fine sediment is included in the load. To illustrate this Bagnold's equations are used. His dimensionless transport and shear parameters are defined respectively as:

$$\phi = \frac{\phi'}{B} = \frac{M}{B\rho_s d \sqrt{\frac{\Delta\rho_s g d \cos\beta}{\rho}}} \tag{2}$$

and

$$\theta_* = \left[(\theta_o - \theta_t) \; \theta_o^{1/2} \right]^{2/3} \tag{3}$$

in which

M = the mass of sediment transport passing a fixed plane per unit width of channel per unit time.

β is the angle the channel bed makes with the horizontal.

B is a constant for a given bed material which can be related to the grain diameter of the bed material.

d is the median diameter of the bed material.

θ_o is the dimensionless shear stress, $\tau_o / \Delta\gamma d$.

θ_t is the critical shear stress, $\tau_c / \Delta\gamma d$, at beginning of motion.

ρ is the mass density of the water.

$\Delta\rho_s$ is the difference in mass density of the water and the sediment.

Using equations 2 and 3, the two curves of figure 22 were developed.

Figure 22. Variation of sediment transport parameter ϕ' with shear parameter θ_*, 8-foot flume data

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In the curve on the right only bed material transport has been considered in computing ϕ. In the curve on the left total load (including fine sediment) was used to evaluate the respective values of ϕ for each run. In the total load relationship the scatter is so great when fine sediment transport is included that the relation has no significance. In fact, an infinite number of possibilities exist for the 0.47 millimeter bed material when fine sediment is included in the computation of ϕ. This illustrates that the transport parameter should not include the concentration of fine sediment. Although, total load cannot be predicted from a knowledge of hydraulic and bed material characteristics unless the concentration of fine sediment and its effects are known. Approximate methods have been developed that estimate total load including fine sediment (Colby and Hembree, 1955) but these methods do not consider the effects of fine sediment on the flow phenomena.

A discontinuity exists in Bagnold's sediment transport relation at the point where form of bed roughness changes from dunes through transition to standing waves. This discontinuity, which also exists when Einstein's (1950) equations are used, is caused by the large reduction in resistance to flow which takes place as the form of bed roughness changes. Because of this discontinuity it ultimately may be desirable to break the theory of flow in alluvial channels into two parts; one which treats the ripple, dune, and transition forms of bed roughness; the other which treats the plane bed, standing waves, and antidune forms of bed roughness.

FINE SEDIMENT TRANSPORT

Fine material as defined in this report is "that part of the total load composed of sediment sizes not found in appreciable quantities in the bed material." From a practicle viewpoint fine sediment includes all material finer than 0.062 millimeter (when considering sand channel streams).

The definition has been used by others although fine material load may have been termed wash load by them. This definition has the connotation that the fine material is not present in the bed. However, logic indicates and experimental evidence proves that the fine material is present in the bed. In this series of runs, 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 this change had very little effect on the median fall diameter. 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-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 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 figure 23.

Figure 23. Layer of bed material adjacent to the flume floor impregnated with fine sediment

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In a natural stream what may happen to the fine material in transport will depend to some extent on the position of the water table. A high water table which contributes water to the flow in the stream would probably help keep the bed material free of the fine material. With a low water table, the concentration of fine material in the interstitial water and the bed would vary with time depending upon the concentration of fine sediment in the stream and the concentration gradient. The concentration in the bed will increase if it is smaller than the stream concentration or decrease if it is larger. This fact may account for a small part of the lag of the sediment hydrograph behind the water hydrograph as a flood peak travels downstream (Heidel, 1956). It is anticipated that a layer of fine material such as observed on the floor of the flume, figure 21, may build up in a natural stream bed if:

1. The ground water is not flowing into the stream.
2. The ground water is considerably lower than the stream bed and a filter layer or hard pan exists within a foot or so of the channel bed.
3. The ground water is slightly lower than the stream bed. In this case the layer of fine material may form at the contact between the static ground water and the water flowing in the stream bed or at some higher elevation where a layer of material has a smaller coefficient of permeability. This zone of deposition would probably be slightly lower than the deepest pothole which developed with the dune form of bed roughness.

CONCLUSIONS AND RECOMMENDATIONS

The specific weight and apparent viscosity of dispersions of water and fine sediment are different than those of clear water. 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 amount and type of any base added as a dispersing agent; and, with some fine sediments at certain concentrations, the temperature of the fluid.

The apparent viscosity of water-bentonite dispersions with a 1 percent concentration of sodium hexametaphosphate as a dispersing agent, as measured with a Stormer viscosimeter, was independent of the temperature at concentrations of less than about 3 percent by weight, but dependent at concentrations greater than about 3 percent. Whereas, the apparent viscosity of water with kaolin dispersions was independent of temperature at concentrations less than 10 percent. The apparent viscosities of water-bentonite dispersions were much greater than those for water-kaolin dispersions. At 40 degrees centigrade, the difference between the viscosity of water and the apparent viscosity of a 10 percent, by weight, water-bentonite dispersion was 1,100 percent and the difference with a kaolin dispersion under the same conditions was 45 percent.

The specific weight of the water-fine-sediment dispersions increased in accordance with the amount and density of fine material that was added.

The change in fluid properties that results from the addition of fine sediment has a definite effect on the fall velocity of the bed material. For instance, at 24 degrees centigrade, the fall velocity of a 0.47 millimeter median fall diameter sand in 10 percent, by weight, dispersions of bentonite and kaolin is decreased 65 and 20 percent, respectively. This 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 a 0.24 millimeter sand particle.

The resistance to flow and bed-material transport is decreased in the lower flow regime and 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 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. With very large concentrations of fine material the dune bed may become plane. The reduction in transport of bed material results from a decrease in shear that occurs when the resistance to flow decreases.

In the upper flow regime, the reduction in fall velocity that results from the addition of fine sediment may change a plane bed flow to a standing wave or antidune flow, or change a standing wave flow to an antidune flow, or increase the activity and turbulence of an antidune flow. These changes increase resistance to flow and bed material transport.

Total sediment transport can be predicted if, where fine sediment is involved, the concentration of fine sediment is determined by sampling and the effects of the fine sediment on the properties of the stream liquid are taken into account.

Since 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 of fine sediment.

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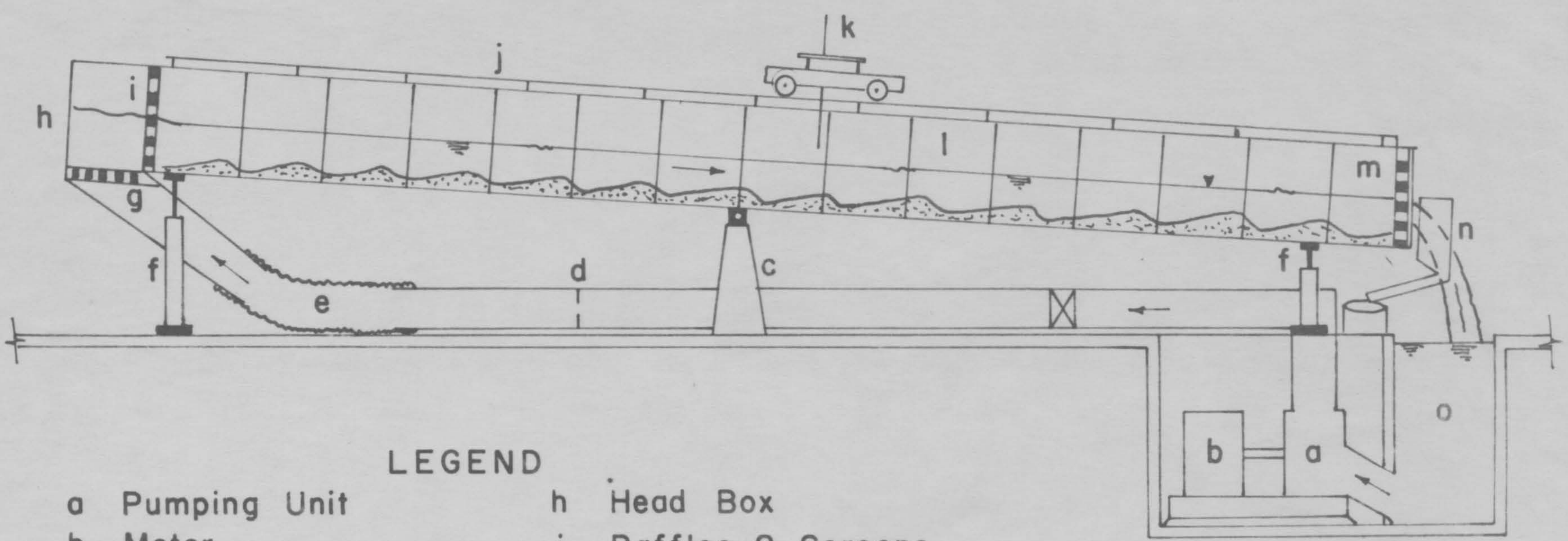

LEGEND

a	Pumping Unit	h	Head Box
b	Motor	i	Baffles & Screens
c	Center Support	j	Rails
d	Orifice	k	Instrument Carriage
e	Flexible Connection	l	Flume 2x2.5x60 ft.
f	Jacks	m	Tailgate
g	Manifold Diffuser	n	Total Load Sampler
		o	Tailbox

Fig. 1. Schematic Diagram of the 2ft Flume

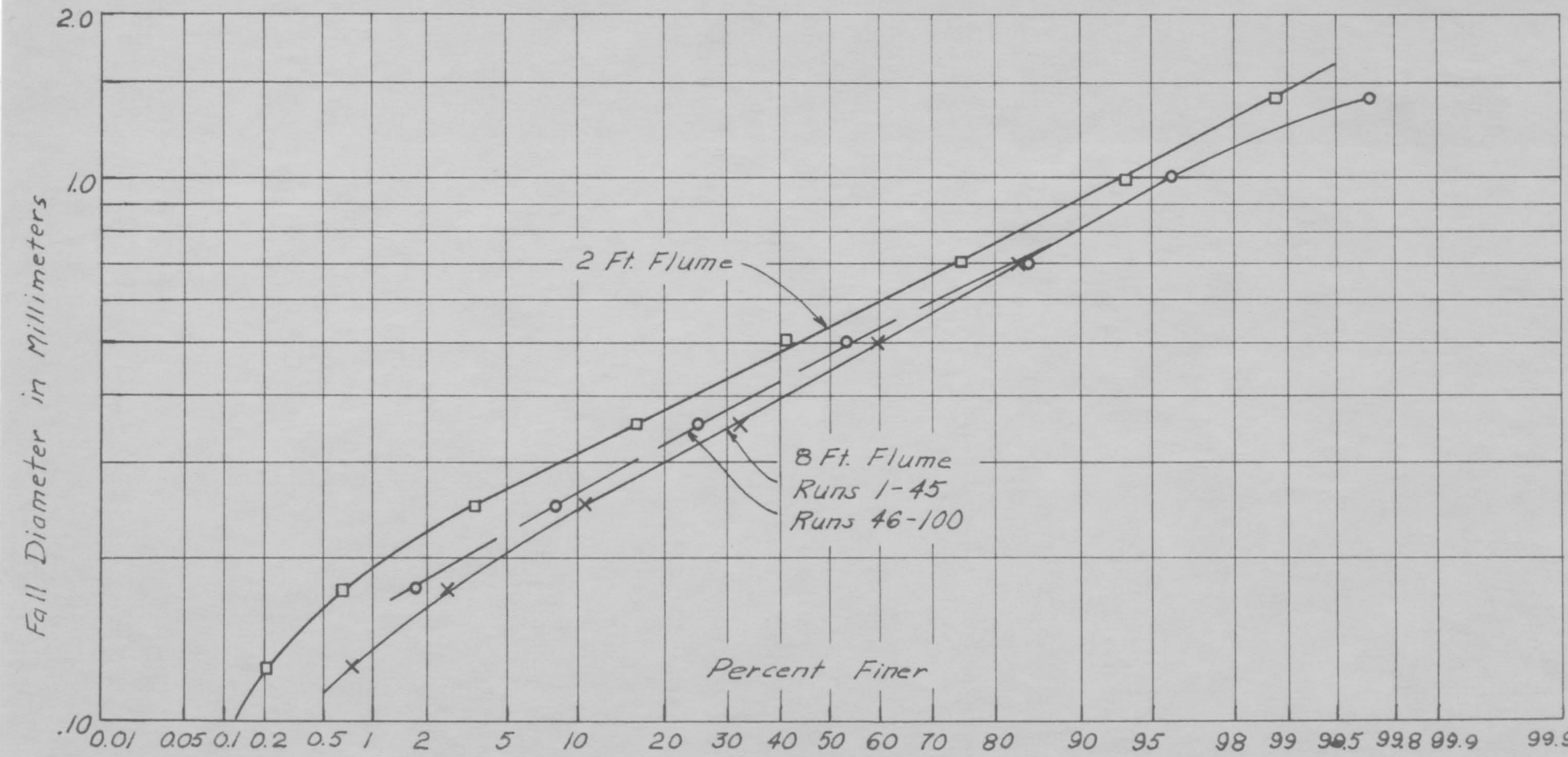

Fig. Particle Size Distribution of the Bed Materials

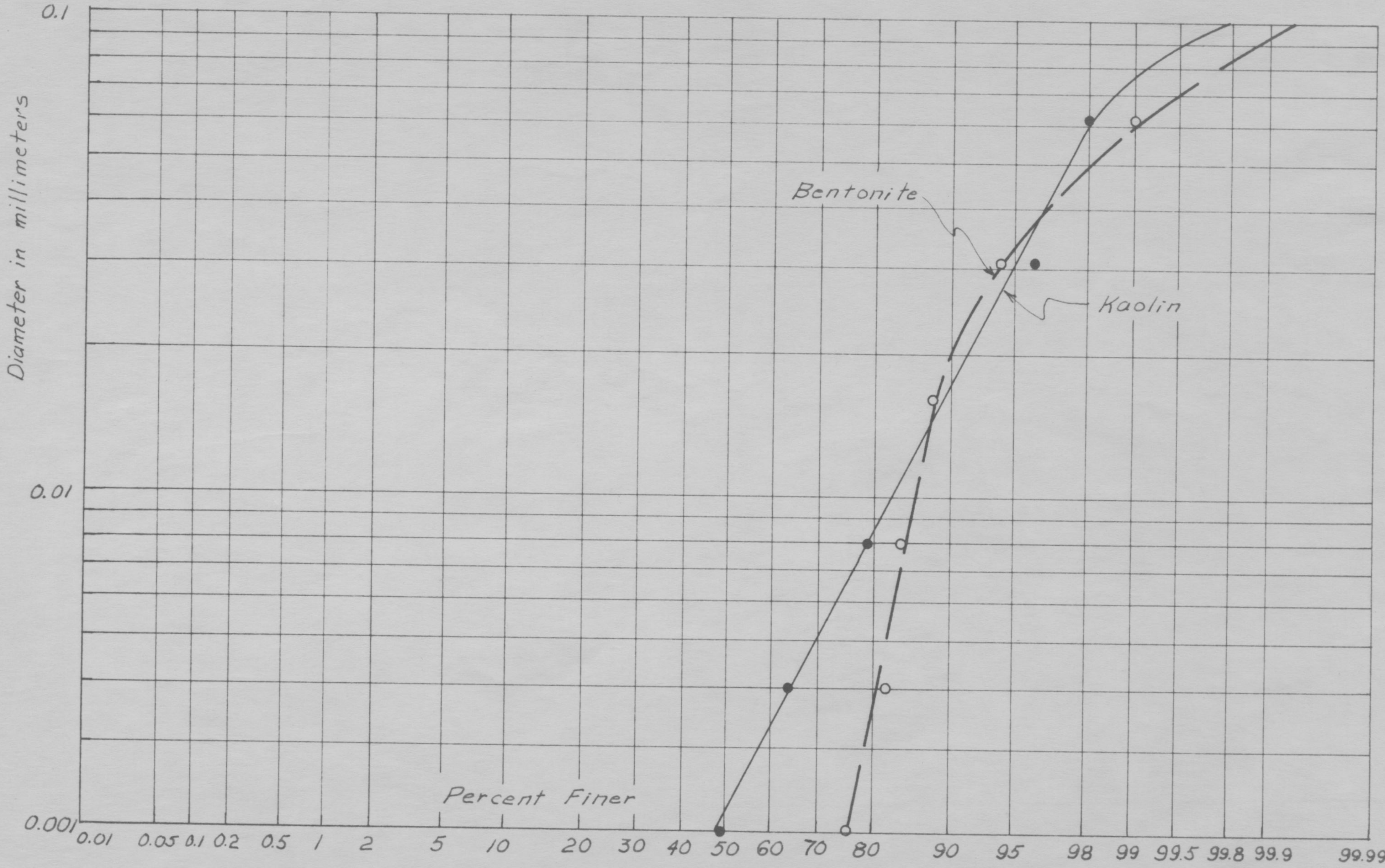

Fig. Particle Size Distribution of the Fine Sediments

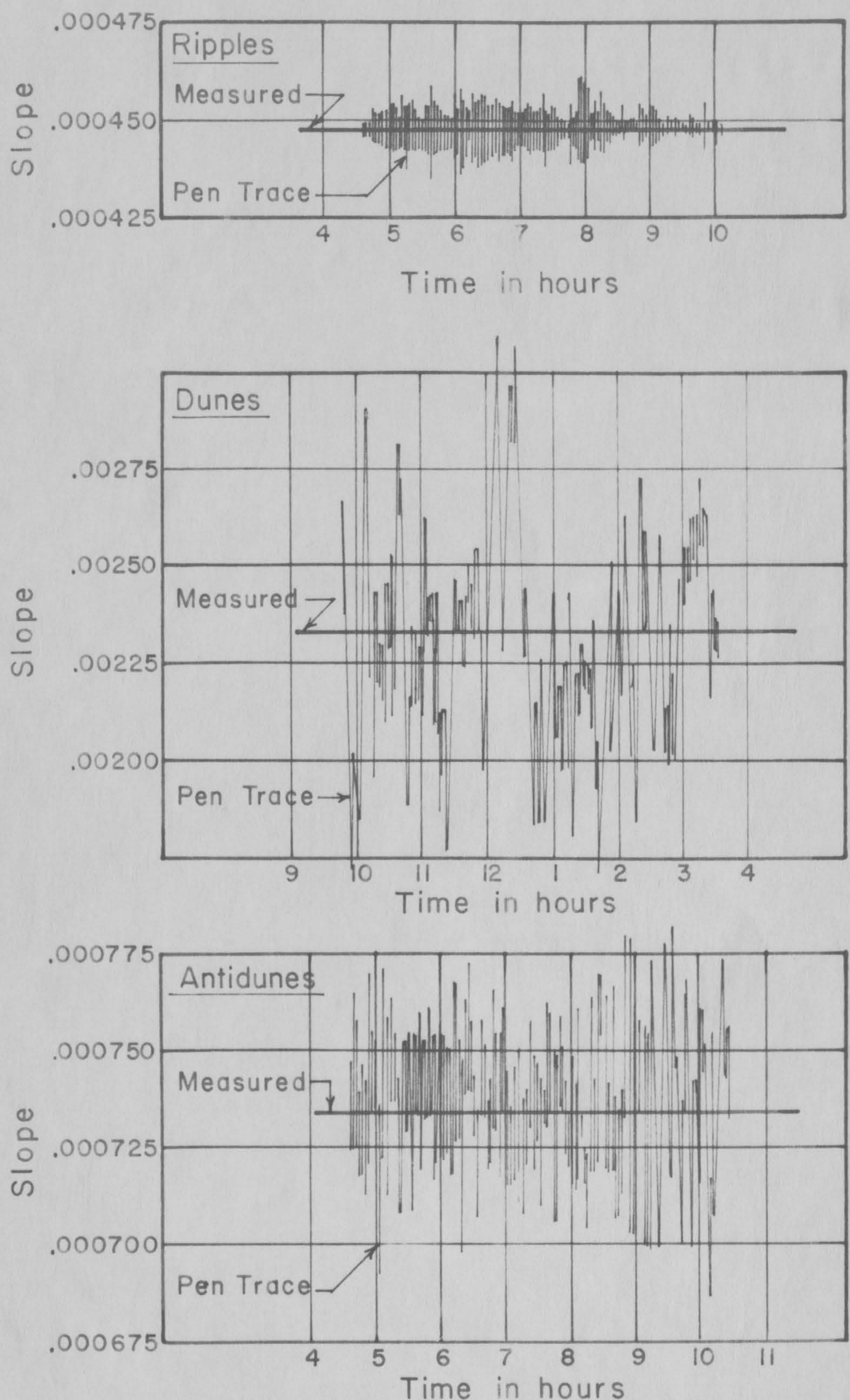

Fig 4 Measured and Recorded Water Surface Slopes

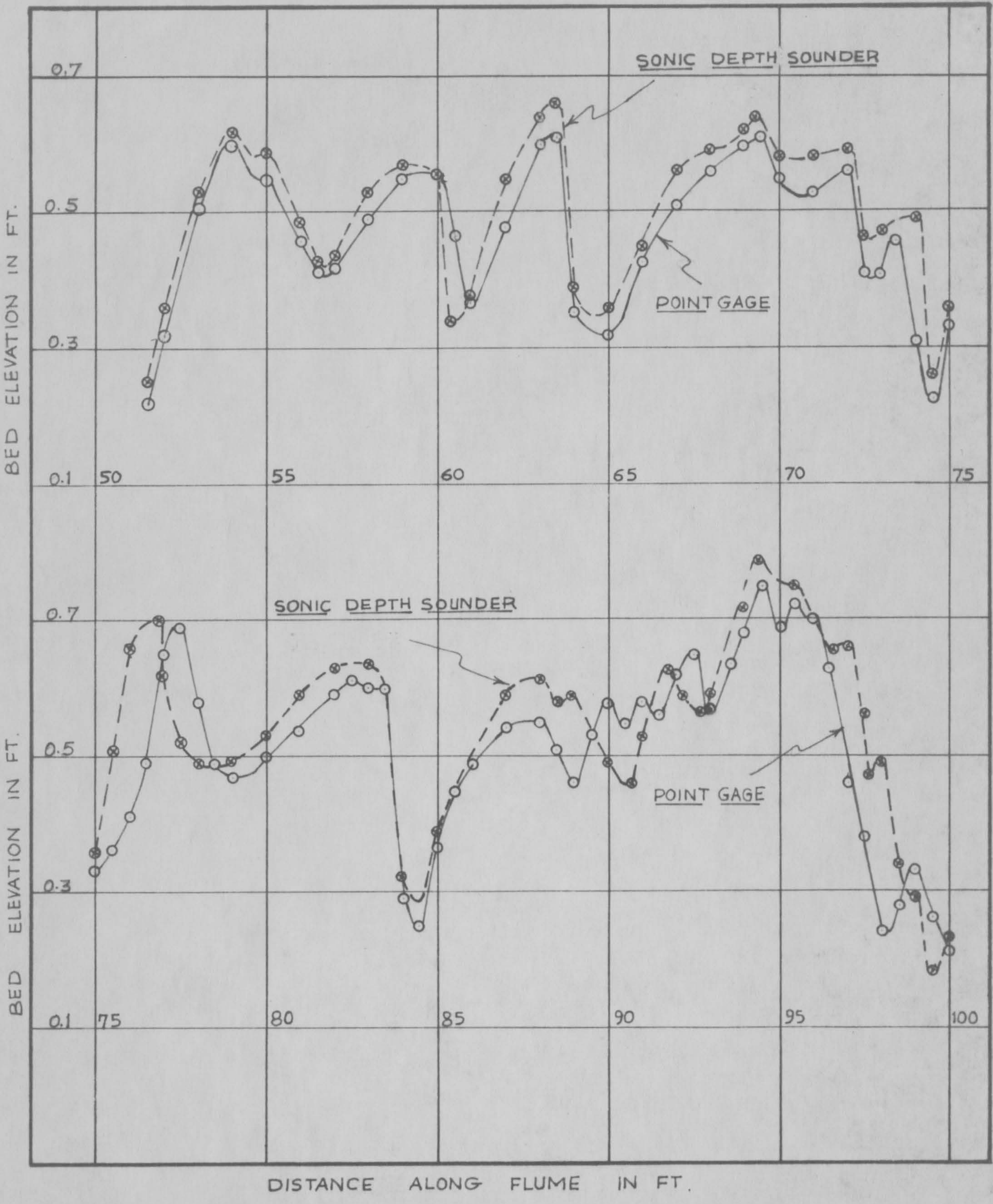

FIG. 5 COMPARISON OF BED CONFIGURATION MEASUREMENTS

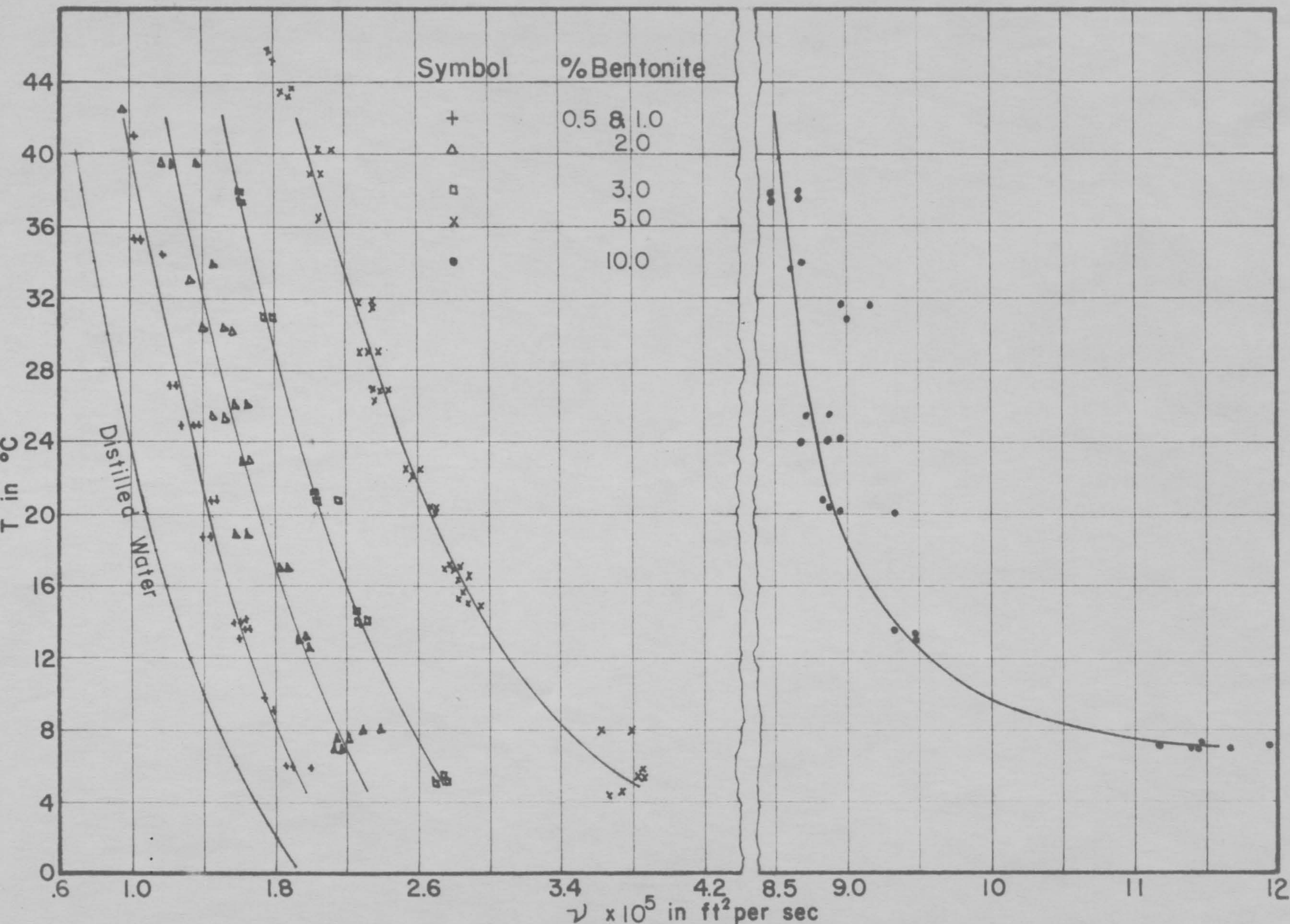

Fig. 6 Apparent Kinematic Viscosity of Water–Bentonite Dispersions

6

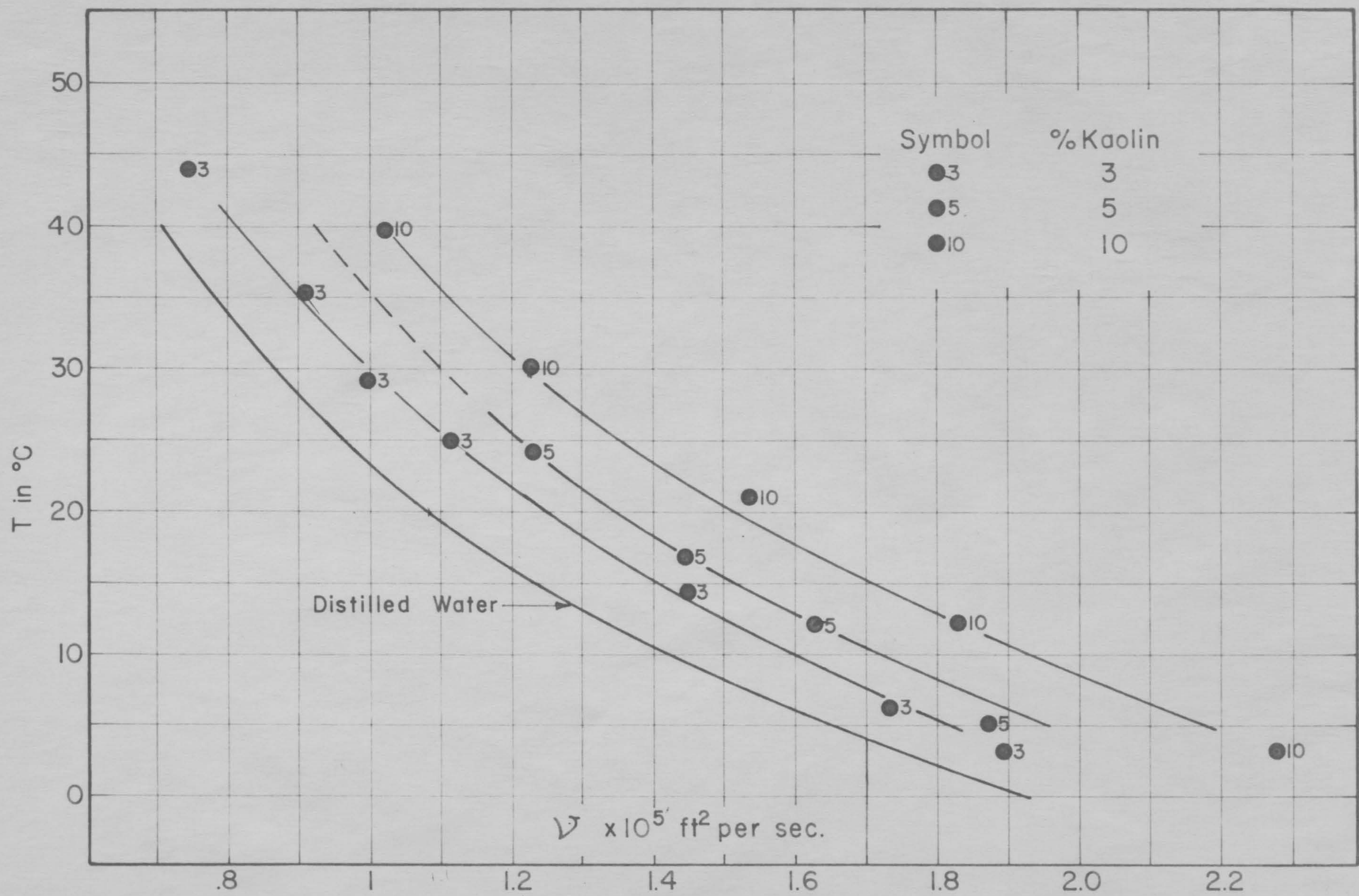

Fig. 7 Apparent Kinematic Viscosity of Kaolin-Water Dispersions

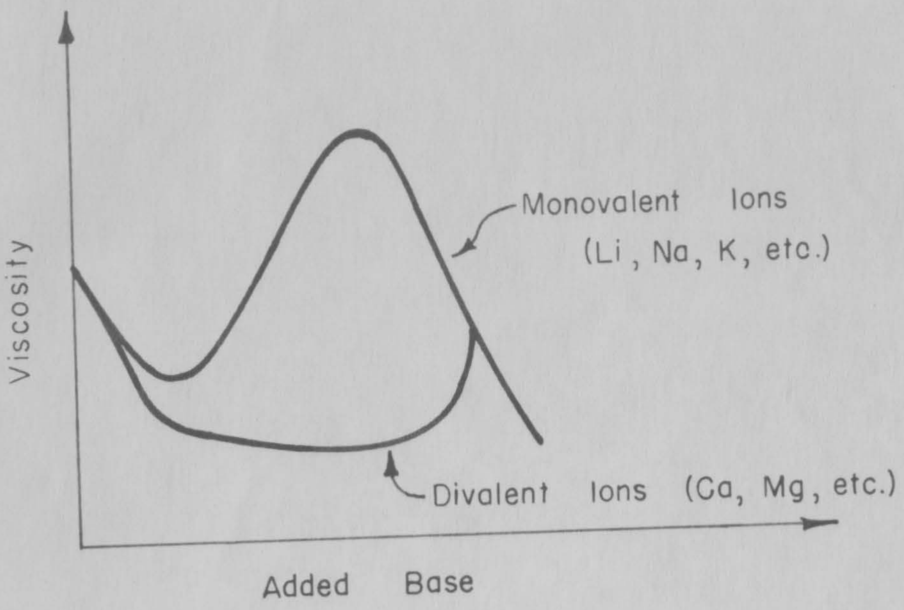

Fig. General shape of the viscosity curves for clay-water systems with various amounts of added base.

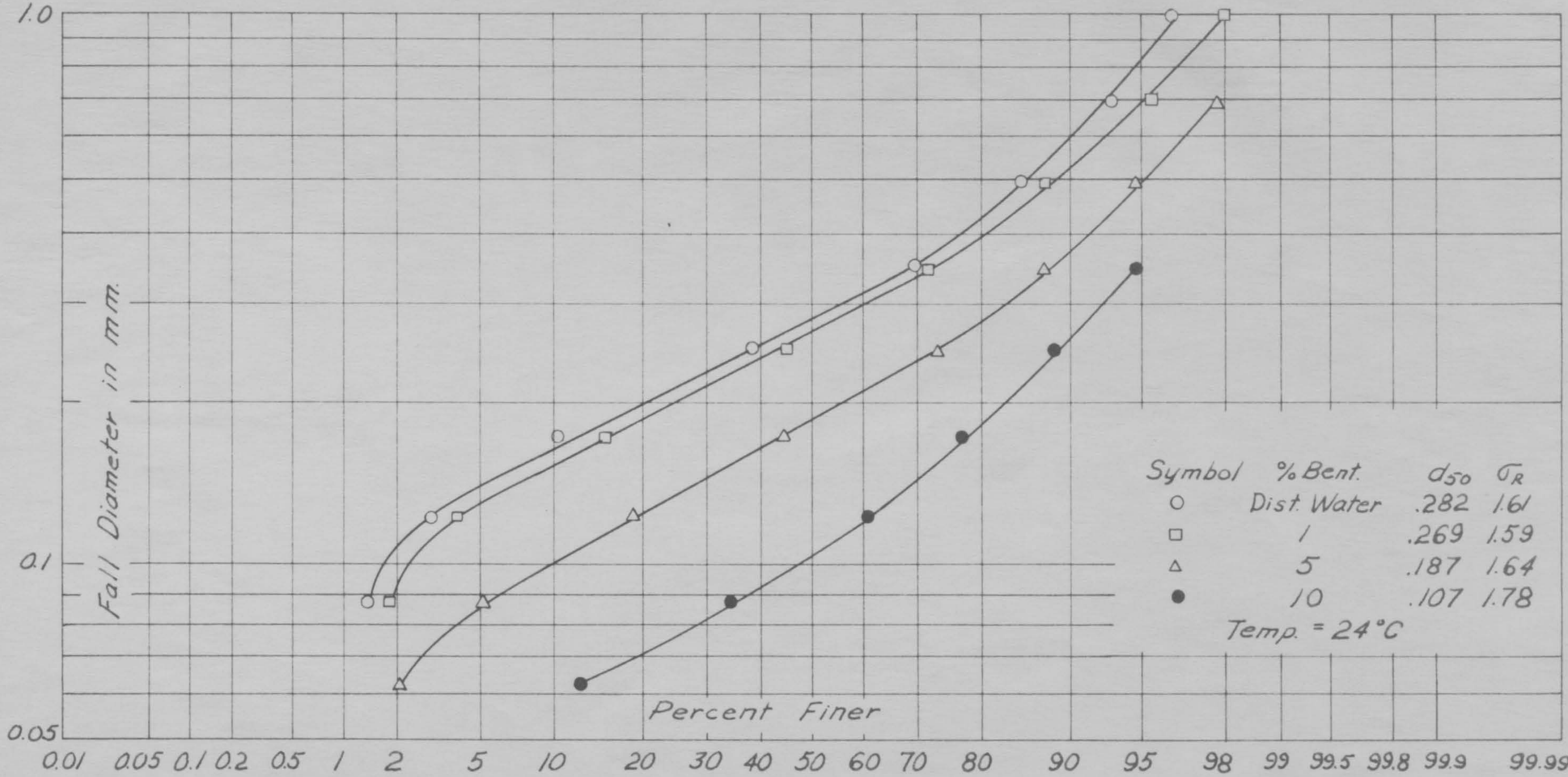

Fig. The Particle Size Distribution of an Elkhorn River, Nebr. Sand Sample Based on its Fall Velocity in Various Concentrations of Bentonite Dispersed in Distilled Water. (Analyzed in the Visual Accumulation Tube)

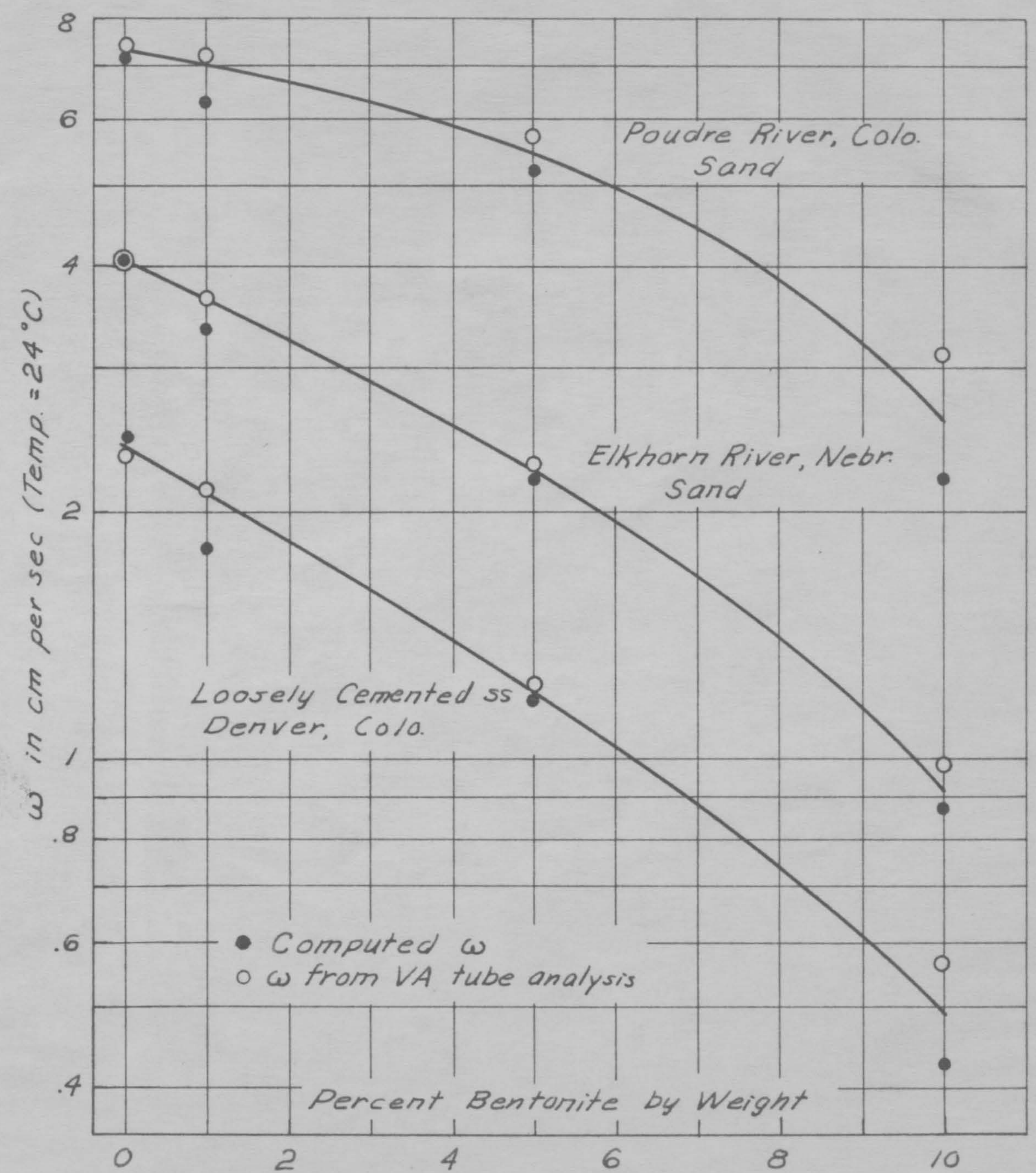

Fig. 10 Variation of Fall Velocity with Percent Bentonite in Water

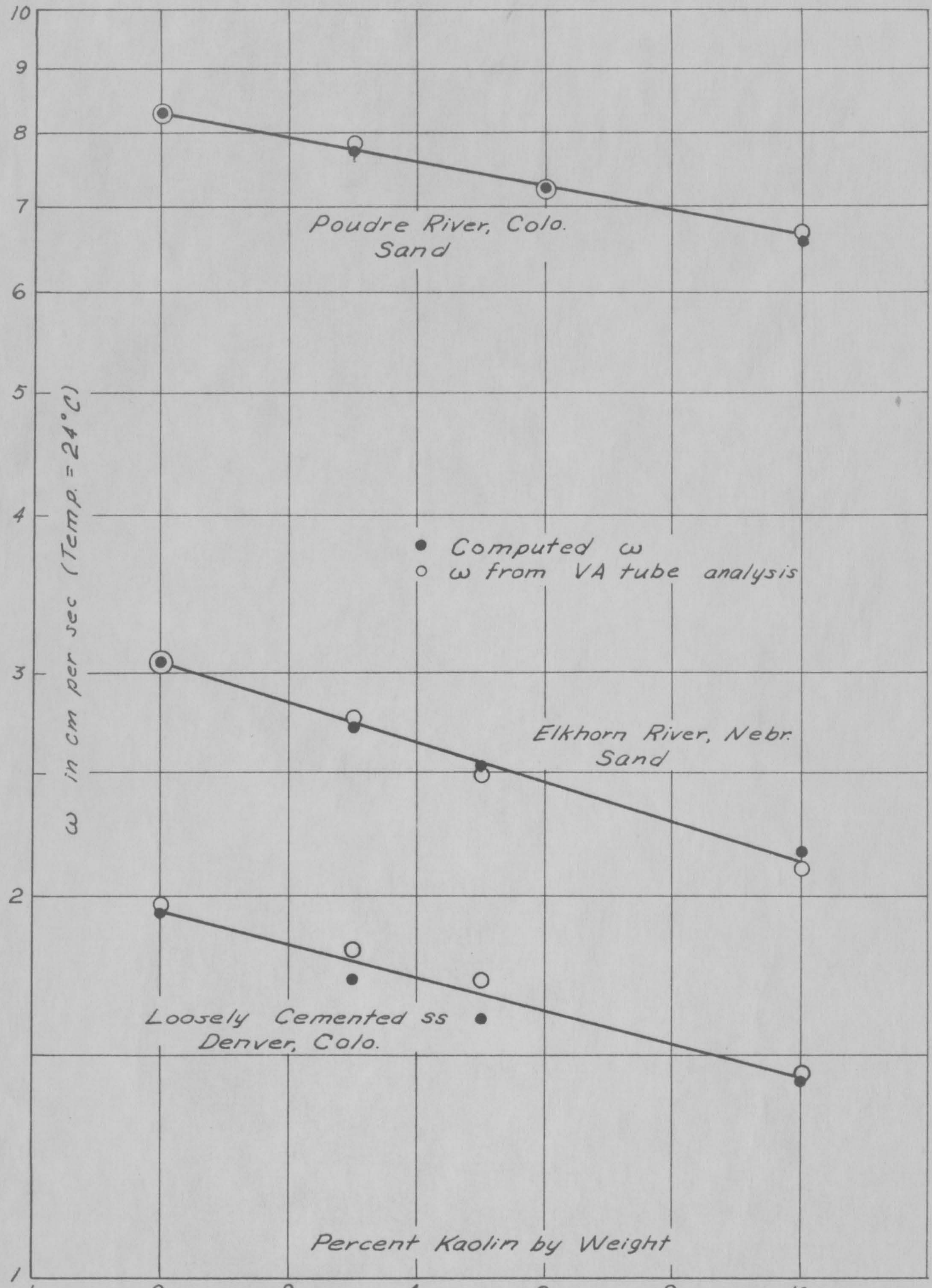

Fig. 11 Variation of Fall Velocity with Percent Kaolin in Water

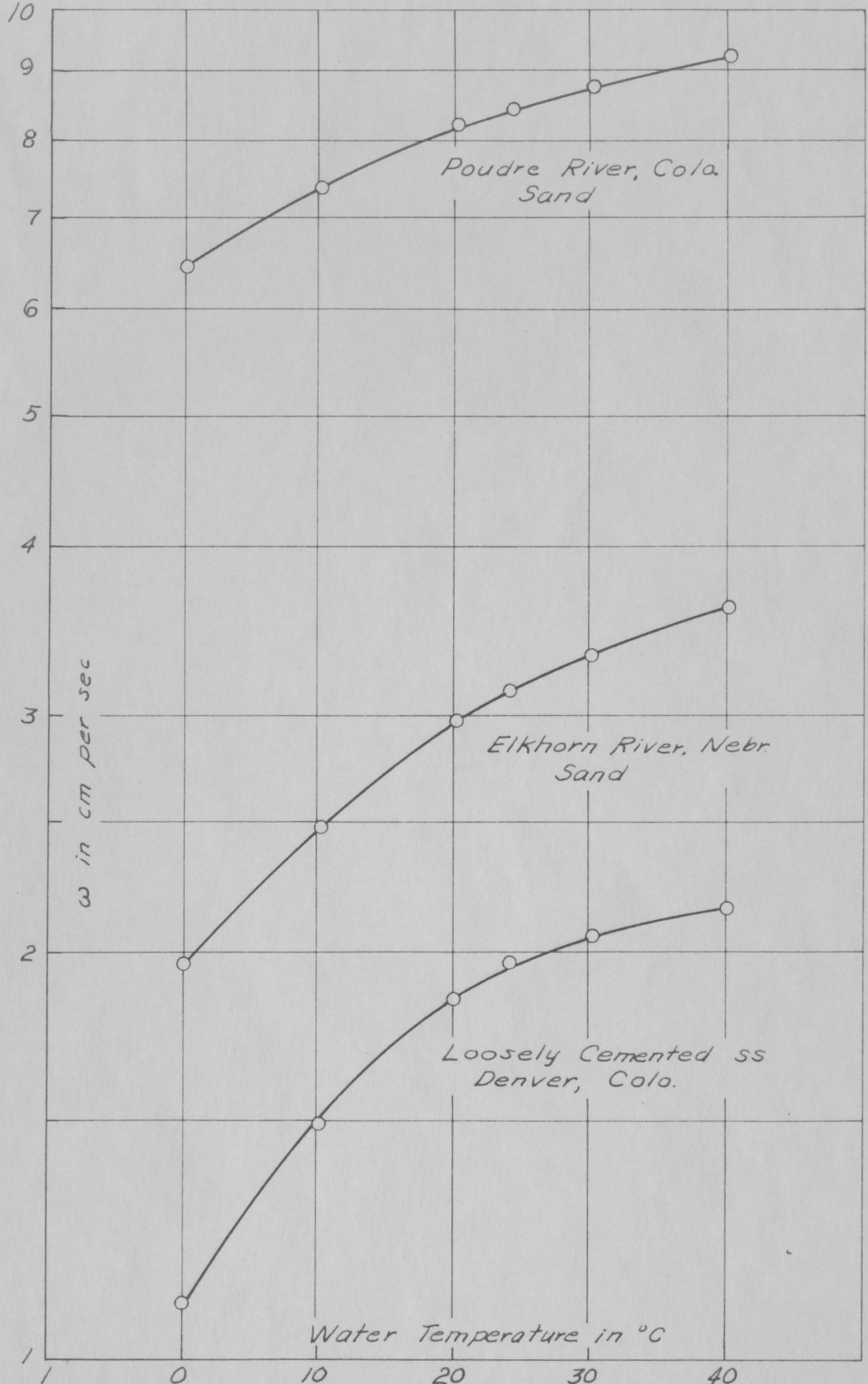

Fig. 12 Variation of Fall Velocity with Water Temp.

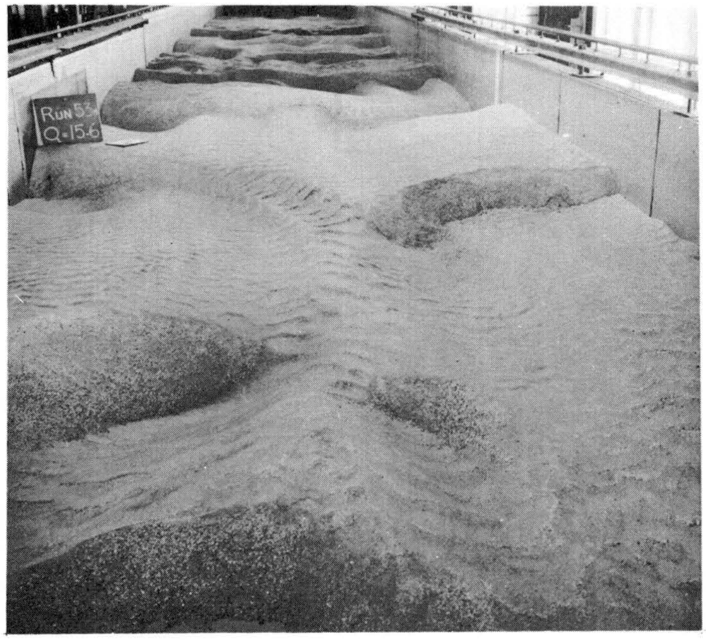

Fig. 13. Dune Bed Configuration in 8-foot Flume

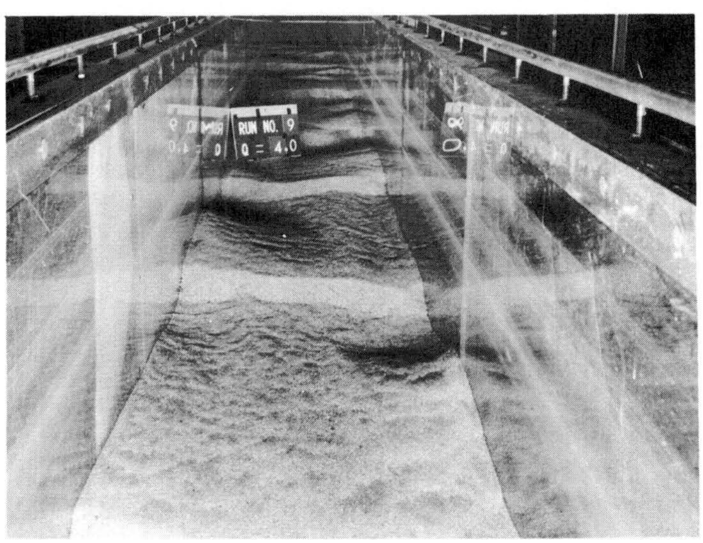

Fig. 14. Dune Bed Configuration in 2-foot Flume

Fig. 15. Antidunes in 8-foot Flume. Note the three dimensional aspects of the waves.

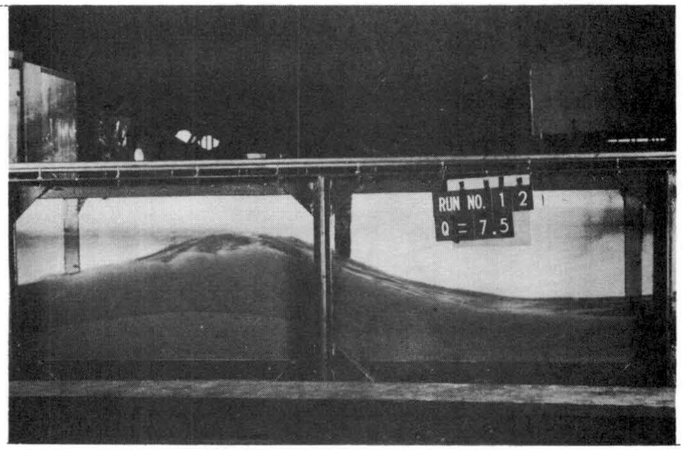

Fig. 16. Antidune in 2-foot Flume. Note the two dimensional aspects of the waves.

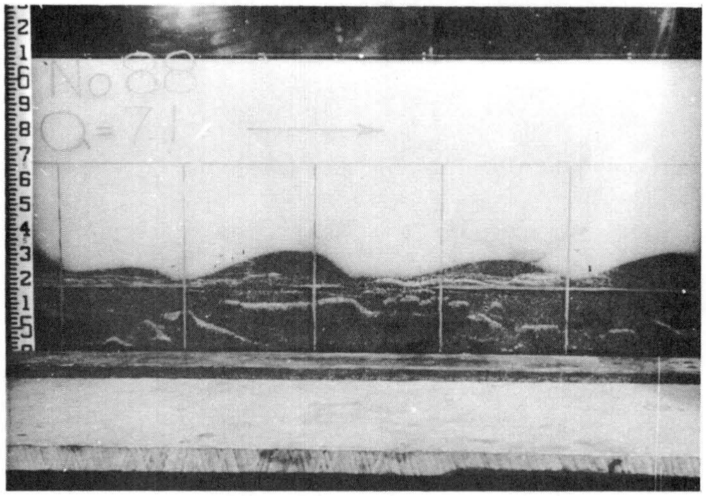

Fig. 17. Lenses of Fine Material Trapped in The Bed. Note rounded crests.

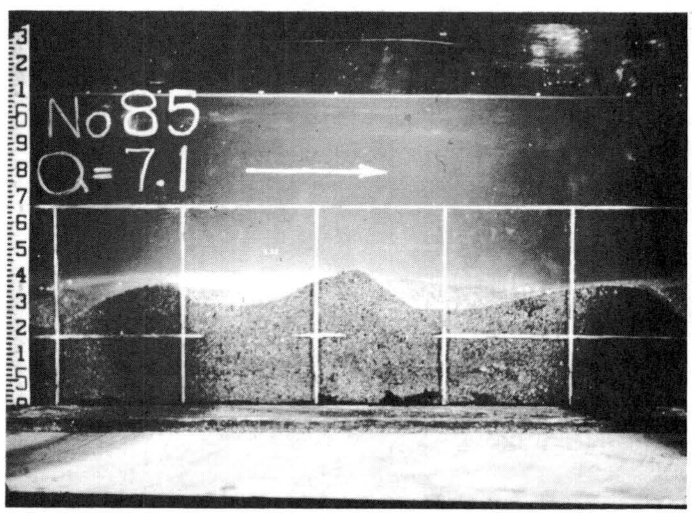

Fig. 18. Ripples, Clear-Water Run. Note angular crests.

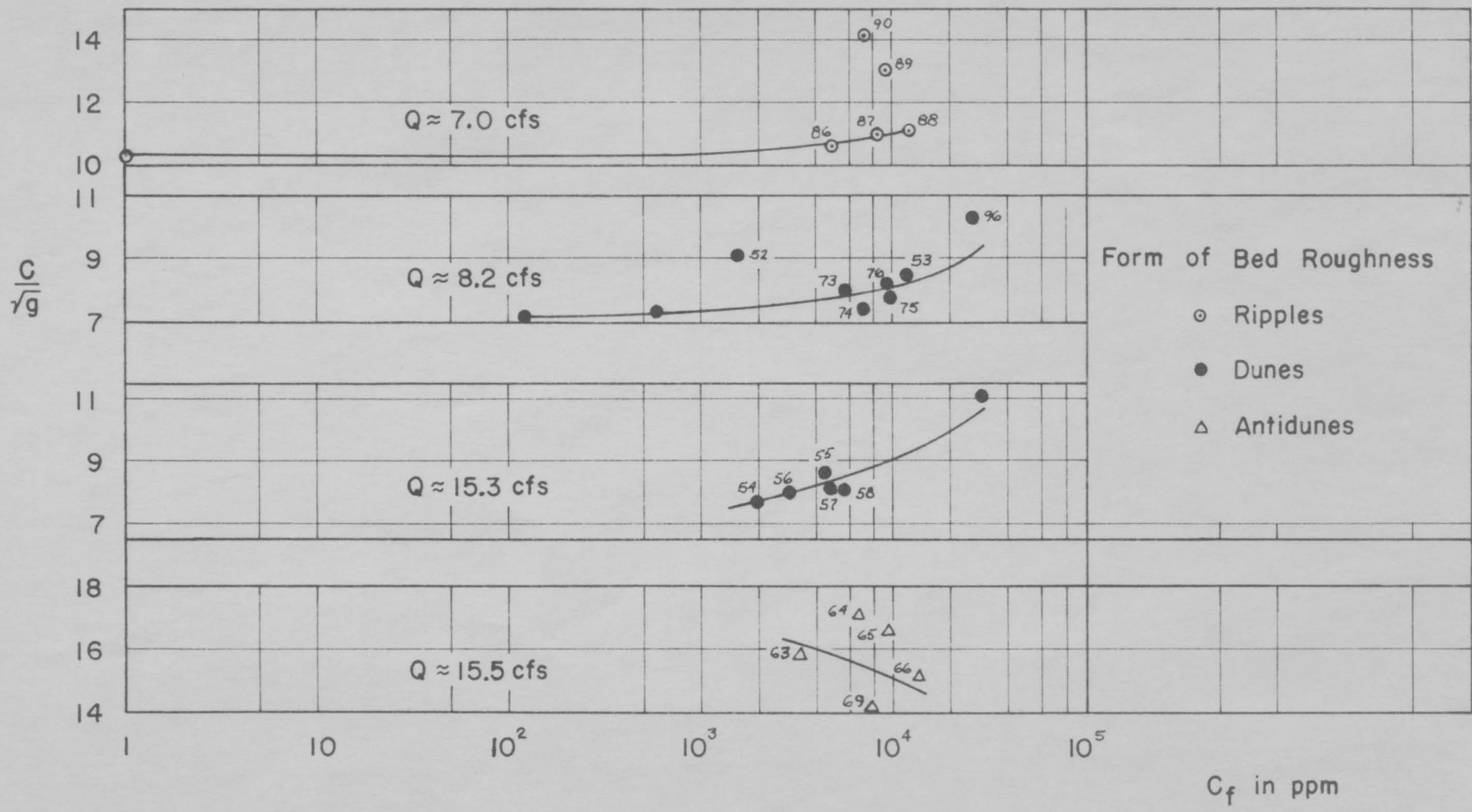

Fig. 19 Variation of the Resistance Coefficient, $C/\sqrt{g}$, with Concentration of Fine Sediment, 8 ft Flume Data

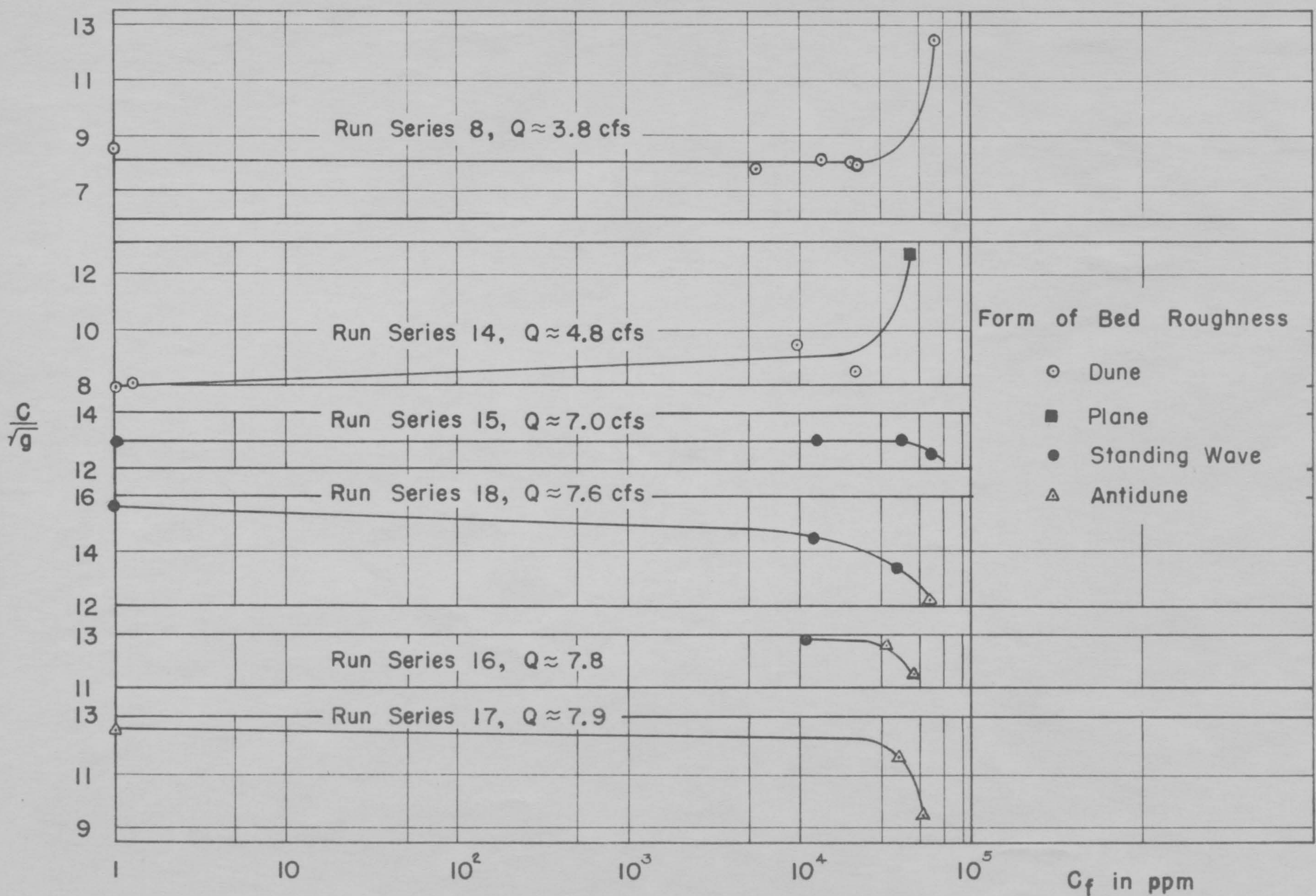

Fig. 20 Variation of the Resistance Coefficient, $C/\sqrt{g}$, with Concentration of Fine Sediment, 2 ft Flume Data

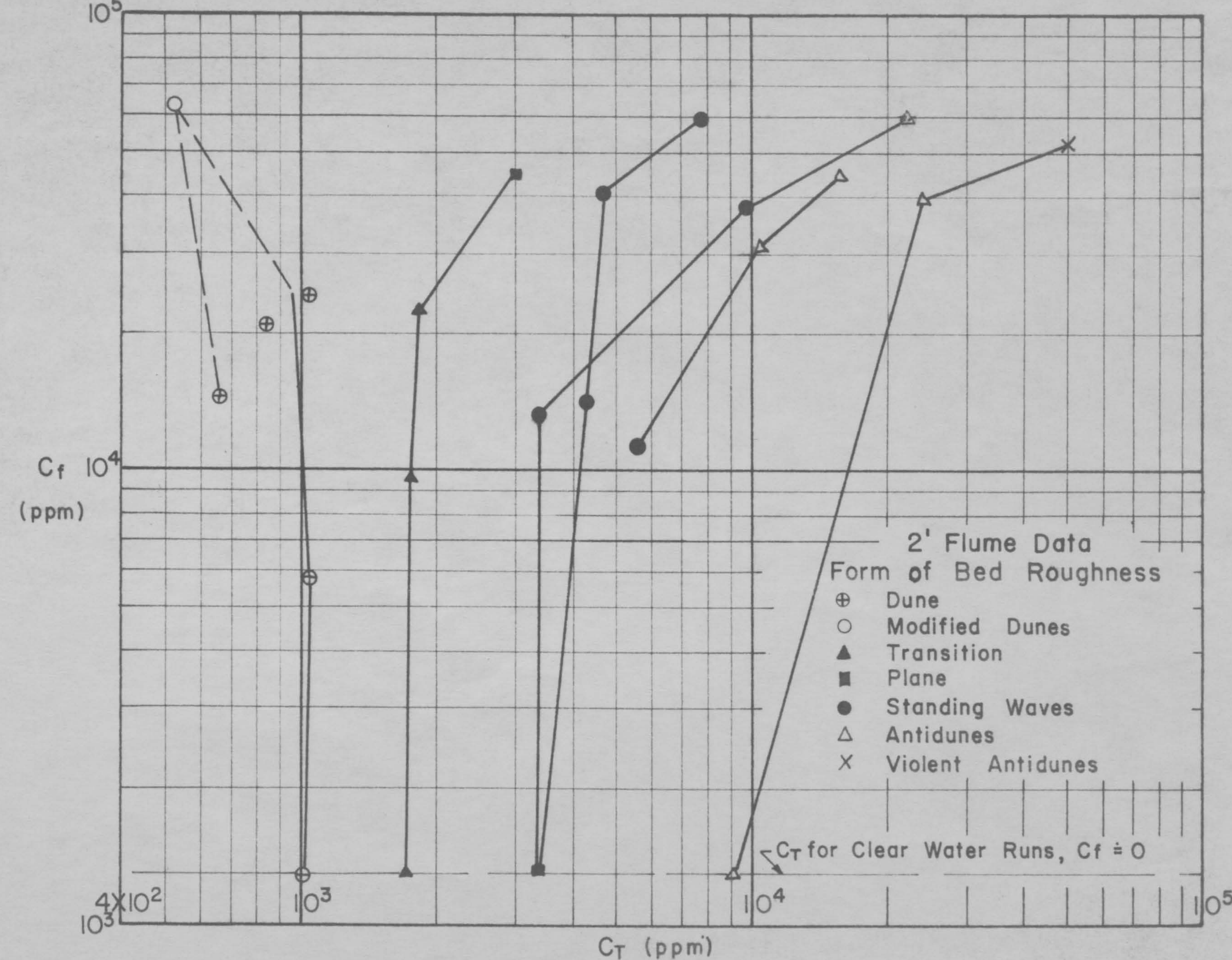

Fig. 21 Variation of Bed Material Transport with Concentration of Fine Material

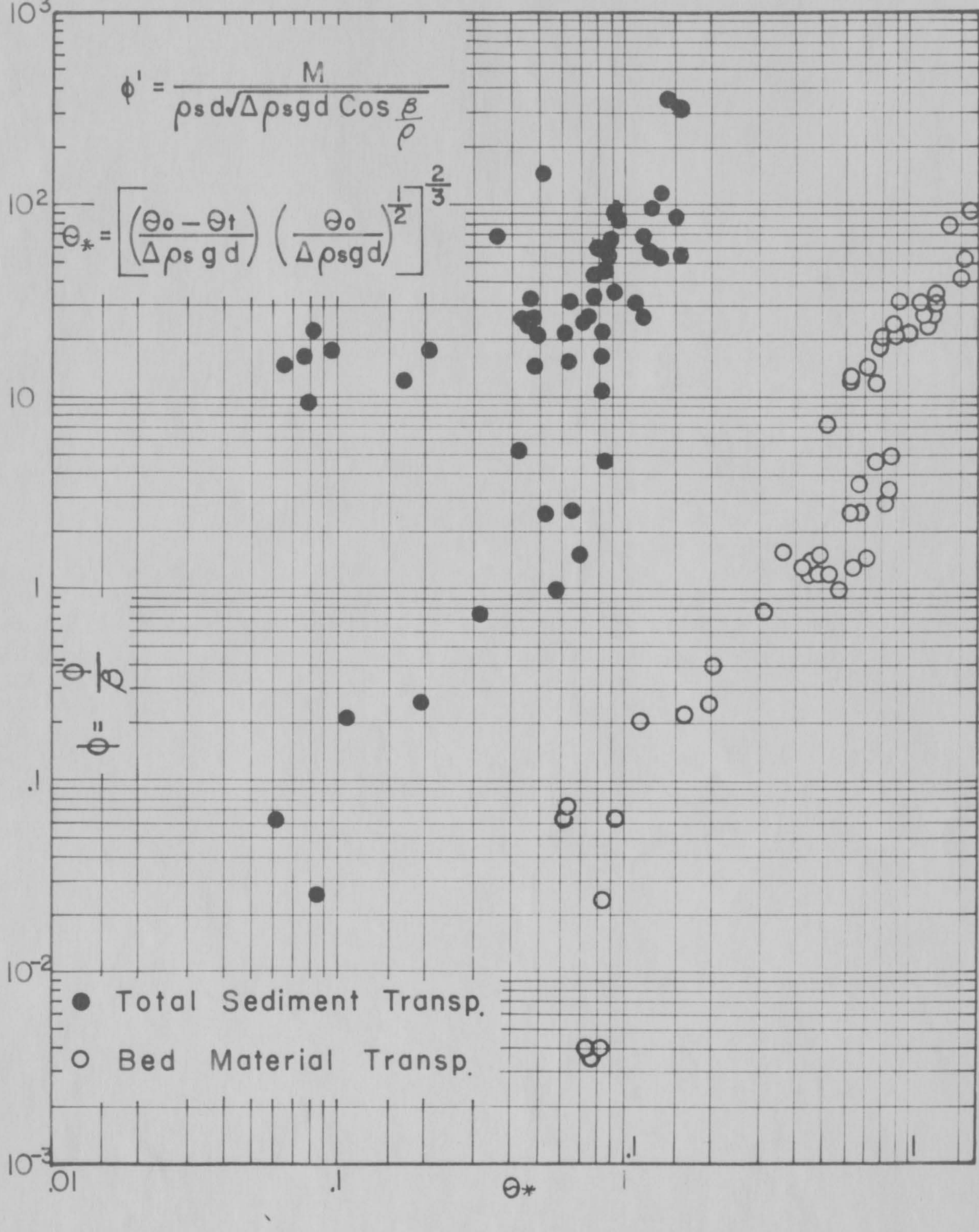

Fig. 22 Variation of Sediment Transportation Parameter ϕ' with Shear Parameter Θ_*, 8 ft Flume Data

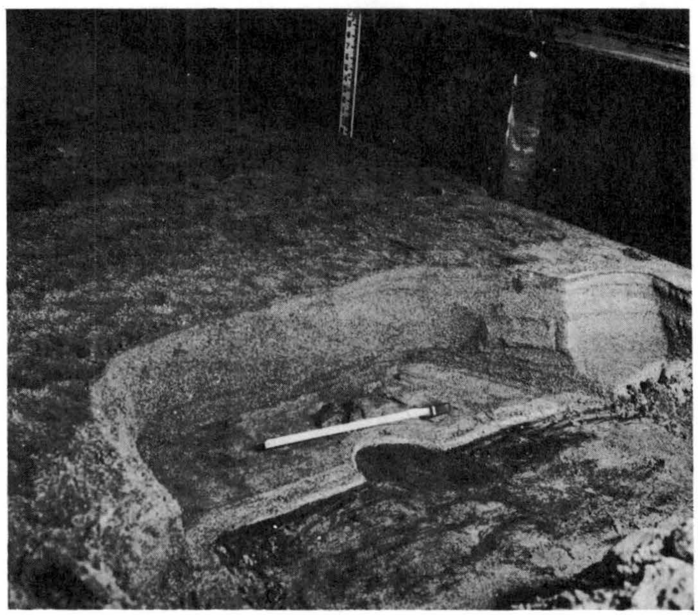

Fig. 23. Layer of Bed Material Adjacent to the Flume Floor. Impregnated with Fine Sediment.

Table 1. Summary of data for runs with 0.47 mm sand in the 8-foot flume

Run No.	S x 10² (O)	Q (cfs)	D (ft)	V (ft/sec)	ν x 10⁵	ν' x 10⁵	T (⁰C)	Sediment Discharge				
					ft²/sec			C_f (ppm)	C_t (ppm)	C_{f-t} (ppm)	d_t x 10³ (ft)	σ_r (O)
46	0.084	14.54	1.11	1.64	1.30	–	13.1	–	181	181	–	–
47	.042	9.59	.75	1.60	1.36	–	11.5	–	23	23	1.141	1.85
48	.052	15.26	1.23	1.55	1.36	–	11.5	–	60	60	1.148	1.85
49	.173	21.32	1.33	2.00	1.38	–	11.0	–	588	588	0.823	1.96
85	.047	7.11	.78	1.13	1.31	–	12.7	–	12	12	1.364	1.66
86	.046	6.92	.76	1.14	1.77	1.32	17.0	4,800	1.6	4,800	0.249	3.19
87	.046	6.96	.75	1.16	1.11	1.37	19.1	8,400	2.3	8,400	0.210	4.37
88	.049	7.10	.74	1.20	1.13	1.50	18.3	11,400	2.5	11,400	0.417	3.04
90	.053	6.97	.60	1.45	1.17	1.39	17.1	6,950	37	6,990	1.345	1.70
89	.065	7.08	.60	1.47	1.12	1.42	18.5	9,000	31	9,030	1.361	2.50
93	.072	7.20	.62	1.45	1.24	–	14.7	1	99	100	1.482	1.55
92	.090	7.14	.63	1.43	1.12	1.33	18.5	6,070	106	6,180	1.509	1.93
91	.117	7.12	.58	1.53	1.14	1.42	18.0	8,400	195	8,600	1.443	1.90
82	.248	8.16	.64	1.60	1.00	–	23.2	133	429	562	1.463	1.64
51	.236	8.11	.62	1.62	1.28	–	13.1	584	545	1,130	1.351	1.66
52	.222	8.01	.55	1.81	1.20	1.26	16.0	1,620	578	2,200	1.456	1.63
73	.222	8.20	.61	1.67	1.06	1.24	20.7	5,670	662	6,330	1.509	1.83
74	.215	8.18	.65	1.58	1.05	1.31	21.0	7,970	534	8,500	1.420	2.08
76	.203	8.49	.63	1.69	1.08	1.38	20.0	9,330	463	9,790	1.387	2.00
75	.204	8.24	.64	1.60	1.05	1.36	21.2	9,460	625	10,100	1.574	1.84
53	.235	8.01	.57	1.77	1.16	1.52	17.2	10,700	571	11,200	1.361	1.65
77	.199	8.76	.65	1.68	1.11	1.52	19.1	12,500	639	13,100	1.246	2.91
96	.201	8.31	.53	1.94	1.12	1.93	18.6	25,000	761	25,800	1.066	2.66
94	.237	11.30	.81	1.74	1.28	–	13.5	7	480	487	1.404	1.77
83	.200	15.58	.91	2.14	1.19	–	16.2	–	588	588	1.151	1.74
54	.240	15.36	.92	2.08	1.18	1.25	16.6	1,940	657	2,600	1.253	1.74
56	.242	15.36	.90	2.14	1.03	1.11	22.1	2,860	1100	3,960	1.148	1.70
55	.237	15.36	.74	2.04	1.12	1.26	18.5	4,060	765	4,820	1.164	1.88
57	.259	15.39	.87	2.20	1.05	1.19	21.3	4,320	761	5,080	1.325	1.91
58	.233	15.28	.90	2.11	1.08	1.25	20.1	5,270	807	6,080	1.210	1.94
95	.180	15.38	.80	2.39	1.12	2.03	18.7	28,300	1,640	29,900	1.099	2.42
78	.320	11.52	.72	2.00	1.07	1.41	20.3	12,000	1,510	13,500	1.089	2.88
59	.326	15.36	.65	2.96	1.04	1.20	21.7	4,570	2,920	7,490	1.312	1.73
60	.342	21.35	.62	4.28	1.06	1.18	21.1	3,600	3,290	6,890	1.427	1.64
61	.355	21.32	.61	4.36	1.00	1.20	23.2	6,170	3,390	9,560	1.440	1.68
71	.531	8.22	.32	3.21	1.04	1.18	21.4	3,600	5,250	8,850	1.525	1.68
72	.550	8.26	.32	3.26	1.08	1.31	20.2	7,100	5,680	12,800	1.505	1.55
70	.640	8.14	.30	3.41	1.08	1.20	20.2	3,910	6,310	10,200	1.476	1.60
63	.570	15.50	.43	4.48	1.05	1.16	21.2	3,020	5,360	8,380	1.633	1.60
64	.578	15.61	.41	4.76	1.05	1.26	21.2	6,440	5,480	12,000	1.630	1.60
65	.571	15.60	.42	4.63	1.04	1.34	21.6	9,090	5,160	14,200	1.584	1.64
66	.575	15.52	.45	4.34	1.01	1.38	23.0	12,300	5,130	17,400	1.647	1.76
80	.643	15.27	.39	4.91	1.04	1.43	21.8	12,100	7,140	19,100	1.624	1.76
81	.634	21.35	.55	4.85	1.38	–	10.7	7	4,480	4,490	2.076	1.61
62	.622	21.23	.54	4.89	.98	1.12	24.5	4,790	4,490	9,280	2.030	1.54
67	.646	20.87	.53	4.91	1.02	1.36	22.7	11,200	4,390	15,600	1.994	1.57
79	.651	21.31	.55	4.82	1.05	1.46	21.0	12,400	5,760	18,200	2.204	1.82
84	.740	15.36	.41	4.67	1.23	–	15.0	7	7,100	7,110	1.410	1.39
69	.734	15.54	.43	4.48	1.02	1.24	22.4	7,020	8,280	15,300	1.601	1.71
68	.740	20.94	.53	4.95	1.00	1.23	23.5	7,620	6,760	14,400	2.181	1.55
98	.821	15.80	.44	4.51	1.11	2.46	19.0	42,000	17,700	59,700	1.237	1.90
100	.790	21.42	.51	5.28	1.29	–	13.3	106	8,440	8,550	2.322	1.40
99	.806	21.27	.50	5.32	1.09	1.96	19.6	26,900	16,100	43,000	1.361	1.93
97	.960	12.01	.37	4.07	1.10	1.29	19.5	5,800	8,960	14,800	2.165	1.50

Table 1 - continued. Summary of data for runs with 0.47 mm sand in the 8-foot flume

Run No.	Bed Material				Sand Waves			Bed Form
	$dx10^3$ (ft)	σ_r (O)	w_1 (fps)	w'_2 (fps)	l (ft)	h (ft)	V_s (fpm)	
46	-	-	0.217	-	5.98	0.41	-	Dunes
47	-	-	.214	-	8.20	0.22	0.035	Dunes
48	-	-	.214	-	6.24	0.32	.030	Dunes
49	-	-	.212	-	7.28	0.35	.080	Dunes
85	1.502	1.52	.216	-	1.20	0.07	.0074	Ripples
86	1.437	1.56	.227	0.223	.96	0.06	.0033	Ripples
87	1.521	1.56	.232	.224	.91	0.06	.0055	Ripples
88	1.640	1.54	.230	.220	1.00	0.07	.0015	Ripples
90	1.355	1.54	.227	.221	1.63	0.06	.027	Ripples
89	1.509	1.48	.230	.223	1.62	0.06	.030	Ripples
93	1.742	1.50	.221	-	5.98	0.17	.039	Dunes
92	1.619	1.55	.230	.225	4.56	0.25	.050	Dunes
91	1.610	1.58	.229	.222	4.33	0.25	.084	Dunes
82	1.679	1.55	.240	-	4.12	0.28	.17	Dunes
51	-	-	.217	-	5.55	0.20	.19	Dunes
52	1.417	1.47	.224	.223	5.33	0.26	.18	Dunes
73	1.565	1.52	.235	.231	5.45	0.29	.26	Dunes
74	1.627	1.55	.236	.229	5.50	0.34	.17	Dunes
76	1.456	1.51	.234	.226	5.71	0.30	.16	Dunes
75	1.443	1.47	.236	.228	4.37	0.28	.15	Dunes
53	1.564	1.59	.227	.217	5.81	0.34	.11	Dunes
77	1.581	1.53	.232	.220	5.12	0.29	.091	Dunes
96	1.588	1.52	.231	.205	4.31	0.24	.20	Dunes
94	1.624	1.54	.218	-	5.21	0.32	.28	Dunes
83	1.633	1.54	.225	-	5.78	0.43	.16	Dunes
54	1.469	1.51	.226	.224	6.54	0.41	.33	Dunes
56	-	-	.238	.236	5.30	0.29	.20	Dunes
55	1.692	1.53	.230	.227	5.87	0.27	.23	Dunes
57	1.518	1.39	.237	.232	5.12	0.29	.29	Dunes
58	1.535	1.48	.234	.230	5.36	.26	.21	Dunes
95	1.771	1.60	.231	.203	-	.33	.31	Dunes
78	1.453	1.49	.235	.223	7.36	.39	.34	Dunes
59	1.535	1.50	.237	.234	7.50	.07	.72	Dunes
60	1.699	1.48	.236	.233	-	-	-	Plane
61	1.722	1.55	.240	.234	-	-	-	Plane
71	1.673	1.61	.237	.233	-	-	-	Plane
72	1.588	1.56	.234	.228	-	-	-	Plane
70	1.515	1.63	.234	.231	2.43	.12	-	Plane
63	1.535	1.54	.236	.233	3.43	.23	-	Antidunes
64	1.601	1.56	.236	.230	3.43	.20	-	Antidunes
65	1.506	1.49	.237	.230	3.44	.20	-	Antidunes
66	1.526	1.56	.240	.228	3.34	.20	-	Antidunes
80	1.594	1.46	.238	.227	3.36	.26	-	Antidunes
81	1.584	1.66	.211	-	4.40	.04	-	Standing Wave
62	1.647	1.48	.243	.239	-	-	-	Standing Wave

Table 1 - continued. Summary of data for runs with 0.47 mm sand in the 8-foot flume

Run No.	Bed Material				Sand Waves			Bed Form
	$d \times 10^3$ (ft)	σ_r (O)	w [1] (fps)	w' [2] (fps)	l (ft)	h (ft)	V_s (fpm)	
67	1.620	1.55	.239	.229	4.00	.10	-	Standing Wave
79	1.355	1.48	.236	.224	3.90	.08	-	Standing Wave
84	1.640	1.53	.222	-	3.60	.21	-	Antidune
69	1.430	1.58	.239	.232	3.73	.26	-	Antidune
68	1.738	1.58	.241	.234	4.00	.05	-	Standing Wave
98	1.440	1.57	.232	.188	3.10	.24	-	Antidunes
100	1.561	1.51	.218	-	-	-	-	Plane
99	1.492	1.60	.233	.207	4.04	.31	-	Antidunes
97	1.597	1.66	.233	.228	3.38	.16	-	Antidunes

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

2 Computed on basis of average median fall diameter (0.47 mm) taking into account the effects of fine sediment and temperature on fluid properties.

Table 2. Summary of data for runs with 0.54 mm sand in the 2-foot flume.

Run No.	s x10² (O)	Q (cfs)	D (ft)	V (ft/sec)	x10⁵ (ft²/sec)	ν' x10⁵ (ft²/sec)	T (°C)	Sediment discharge C_f (ppm)	C_t (ppm)	C_{f-t} (ppm)	d_t x10³ (ft)	σ (O)
1	0.016	1.06	0.61	0.89	1.20	–	15.9	–	–	–	–	–
2	.019	1.12	.60	.96	1.16	–	17.4	–	–	–	–	–
3	.026	1.21	.62	1.00	1.17	–	16.9	–	0.6	0.6	–	–
4	.038	1.59	.59	1.37	1.14	–	18.0	–	14	14	1.647	1.34
6	.170	2.45	.72	1.74	1.12	–	18.6	–	333	333	1.539	1.66
5	.201	3.12	.81	1.95	1.10	–	19.2	–	346	346	1.499	1.60
0	.336	4.28	.91	2.39	1.24	–	14.7	–	–	–	–	–
20	.338	4.74	.72	3.36	1.08	–	20.2	–	2450	2450	1.621	1.52
8	.351	3.82	.78	2.51	1.11	–	18.9	–	1020	1020	1.585	1.55
8A	.331	3.82	.84	2.33	1.12	1.31	18.7	5740	1050	6790	1.417	1.58
8E	.248	3.69	.88	2.15	1.00	1.46	23.3	14500	660	15200	1.673	1.47
8B	.293	3.84	.85	2.30	1.04	1.70	21.5	20600	842	21400	1.483	1.67
8C	.294	3.83	.86	2.28	1.02	1.79	22.4	24300	1040	25300	1.594	1.75
8D	.198	3.77	.72	2.65	0.96	3.20	25.0	63700	521	64200	0.787	2.92
7	.388	3.42	.72	2.44	1.06	–	20.6	–	1090	1090	2.224	1.55
14	.399	4.77	.89	2.74	1.10	–	19.3	–	1700	1700	1.667	1.45
14A	.366	4.78	.82	2.95	0.98	1.27	24.3	9580	1760	11300	1.532	1.64
14C	.377	4.80	.87	2.82	1.03	1.74	22.2	22400	1840	24200	1.739	1.64
14B	.339	4.84	.70	3.51	1.02	2.41	22.3	44100	2960	47100	1.296	2.91
19	.408	3.82	.76	2.58	1.04	–	21.5	–	1300	1300	1.463	1.56
9	.433	4.16	.72	2.93	1.15	–	17.7	–	1520	1520	1.421	1.58
10	.486	5.33	.64	4.30	1.07	–	20.3	–	2690	2690	1.706	1.47
18	.520	7.62	.71	5.44	1.02	–	22.6	–	3330	3330	1.870	1.61
18A	.508	7.57	.76	5.11	1.02	1.44	22.5	13200	3400	16600	1.804	1.62
18B	.790	7.59	.69	5.62	1.00	1.70	23.3	37900	9730	47600	1.558	1.61
18C	.900	7.59	.70	5.54	0.99	3.00	23.7	58700	22300	81000	1.421	1.40
15	.551	6.94	.74	4.75	1.04	–	21.7	–	3330	3330	1.821	1.53
15A	.550	6.99	.75	4.76	1.02	1.47	22.5	14200	4350	18600	1.519	1.88
15B	.537	6.96	.75	4.73	0.99	2.27	23.7	40900	4710	45600	1.476	3.17
15C	.628	6.99	.73	4.85	0.99	2.98	24.0	58600	7640	66200	1.247	2.69
13	.565	6.37	.72	4.52	1.14	–	18.1	–	3350	3350	1.847	1.60
11	.768	7.48	.66	5.80	1.08	–	19.9	–	5690	5690	2.067	1.46
16A	.980	7.82	.67	5.92	1.00	1.35	23.5	11200	5600	16800	2.198	1.33
16B	1.075	7.84	.66	6.03	0.96	1.93	25.0	31500	10300	41800	1.496	1.73
16C	1.305	7.86	.65	6.14	0.96	2.32	25.1	44500	15800	60300	1.132	2.22
17	1.175	7.89	.65	6.21	1.02	–	22.5	–	9180	9180	1.460	1.74
17A	1.365	7.83	.65	6.17	1.02	2.27	22.3	39600	23800	63400	1.214	1.63
17B	1.928	7.86	.68	5.87	0.99	2.60	24.0	51900	50000	102000	1.460	1.30
12	1.438	7.84	.64	6.27	1.17	–	16.9	–	26000	26000	1.486	1.74

Table 2 - continued. Summary of data for runs with 0.54 mm sand in 2-foot flume

Run No.	Bed Material				Sand Waves			Bed Form	Remarks
	$d \times 10^{3}$ (ft)	σ_r (O)	w^1 (fps)	w'^2 (fps)	l (ft)	h (ft)	V_s (fpm)		
1	-	-	0.258	-	-	-	-	Plane	Some Movement
2	-	-	.262	-	-	-	-	Plane	Some Movement
3	1.585	1.53	.261	-	0.47	0.03	0.0001	Ripples	Artificially Induced
4	1.526	1.55	.264	-	-	.10	.0004	Plane	One Dune front
6	1.640	1.67	.266	-	4.6	.35	.0047	Dunes	-
5	1.575	1.57	.268	-	5.0	.26	.0080	Dunes	-
0	1.565	1.56	.254	-	4.0	.30	.0054	Dunes	-
20	1.716	1.51	.271	-	4.3	.17	.036	Dunes	Transition
8	1.903	1.48	.267	-	3.6	.23	.012	Dunes	-
8A	1.699	1.45	.265	.258	3.8	.20	.012	Dunes	-
8E	1.968	1.45	.278	.262	3.6	.19	.0073	Dunes	-
8B	1.949	1.49	.274	.252	3.6	.20	.010	Dunes	-
8C	1.772	1.47	.276	.248	4.4	.24	.011	Dunes	-
8D	1.706	1.51	.282	.208	0.7	.08	.0062	Sand Waves	-
7	1.804	1.53	.272	-	3.3	.17	.012	Dunes	-
14	1.903	1.50	.268	-	4.0	.20	.021	Dunes	Transition
14A	1.837	1.50	.280	.270	5.8	.20	.030	Dunes	Transition
14C	1.837	1.53	.275	.250	5.8	.19	.034	Dunes	Transition
14B	1.837	1.48	.276	.228	-	-	-	Plane	Transition
19	1.788	1.54	.274	-	4.2	.16	.018	Dunes	Transition
9	1.549	1.50	.263	-	4.2	.18	.022	Dunes	Transition
10	1.824	1.64	.271	-	-	-	-	Plane	Transition
18	1.870	1.49	.276	-	-	-	-	Standing Waves	-
18A	1.837	1.48	.276	.262	-	-	-	Standing Waves	-
18B	1.837	1.45	.278	.237	-	-	-	Standing Waves	-
18C	1.919	1.44	.279	.208	-	-	-	Anti-Dunes	-
15	1.732	1.48	.274	-	-	-	-	Standing Waves	
15A	1.854	1.52	.276	.261	-	-	-	Standing Waves	-
15B	1.837	1.49	.279	.232	-	-	-	Standing Waves	-
15C	1.722	1.44	.280	.213	-	-	-	Standing Waves	-
13	1.713	1.60	.265	-	-	-	-	Standing Waves	-
11	1.509	1.62	.270	-	-	-	-	Standing Waves	-
16A	-	-	.278	.266	-	-	-	Standing Waves	-
16B	1.713	1.45	.282	.248	-	-	-	Anti-Dunes	-
16C	1.837	1.38	.282	.232	-	-	-	Anti-Dunes	-
17	1.690	1.46	.276	-	-	-	-	Anti-Dunes	-
17A	1.837	1.42	.276	.233	-	-	-	Anti-Dunes	-
17B	2.100	1.40	.280	.221	-	-	-	Anti-Dunes	-
12	1.847	1.58	.261	-	-	-	-	Anti-Dunes	-

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

[2] Computed on basis of average median fall diameter (0.54 mm) taking into account the effect of fine sediment and temperature on fluid properties.