MLA

STUDIES OF ROUGHNESS IN ALLUVIAL CHANNELS
WSP 1948, CHAPTER B.

THE EFFECT OF FINE SEDIMENT ON THE MECHANICS OF FLOW IN ALLUVIAL CHANNELS

by

D. B. Simons,
E. V. RICHARDSON,
and
W. L. HAUSHILD

U. S. Geological Survey
Colorado State University
Fort Collins, Colorado

CER60DBS10

TABLE OF CONTENTS

PAGE

ILLUSTRATIONS

TABLES

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_T	Concentration of total bed material load (silt-sand)	ppm	O
C_f	Concentration of fine sediment	ppm	O
d	Median standard fall diameter of bed material	L	ft
d_t	Median standard fall diameter of total sediment load	L	ft
D	Average depth of flow	L	ft
Fr	Froude number	O	--
h	Average height of bed roughness	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
	surface slope in steady uniform flow	O	--
T	Temperature	O	^0C
V	Average velocity based on continuity principal	L/T	ft/sec
V_s	Average velocity of tranquil flow sand waves	L/T	ft/min

Symbol	Description	Dimensions	Units
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
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-sediment complex	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	Relative standard deviation of the size distribution of the sediment	O	--
τ_o	Tractive or shear force developed on the bed, γDS	F/L^2	lbs/ft^2
λ	Porosity of the bed material	O	--
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 transported 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 becoming 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.

Effective Fall Diameter: The fall diameter of a quartz sphere with a specific gravity of 2.65 in water with a temperature of 24°C which has the same fall velocity as the particle in question falling in the stream liquid at stream temperature.

Equal Transite Rate (ETR): A method of sampling suspended sediment to obtain the 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).

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 ridges and/or crests and troughs, similar to dunes in shape but smaller in magnitude, which have rather small width normal to the direction of flow.

Sand Wave: A ridge (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 and is usually expressed in parts per million (ppm).

Standard Fall Diameter: The diameter of a sphere that has a specific gravity of 2.65 and also has 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°C.

Standing Waves: Symmetrical sand and water waves which are in phase and which gradually build up and just as gradually die down. Waves of this type are stationary, or essentially so, 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 in a given length of time.

ACKNOWLEDGEMENTS

The writers wish to acknowledge the constructive participation of P. C. Benedict and R. W. Carter. Their suggestions and review have materially improved this report.

STUDIES OF ROUGHNESS IN ALLUVIAL CHANNELS
WSP 1948, CHAPTER B.

THE EFFECT OF FINE SEDIMENT ON THE MECHANICS OF FLOW IN ALLUVIAL CHANNELS

ABSTRACT

The effect of a fine sediment (bentonite clay) on resistance to flow, bed material transport, and the mechanics of flow was studied in a large recirculating laboratory flume at Colorado State University.

Concentrations of fine sediment investigated ranged from 0 to 42,000 ppm. The presence of the fine sediment increases the density and viscosity of the water, reduces the effective fall diameter of bed material, alters and under certain conditions changes the form of bed roughness completely, decreases the resistance to flow in the tranquil flow regime, increases the resistance to flow when antidunes exist; and in general, increases bed material transport particularly with antidune flow.

Based upon the results of the study, it is possible to qualitatively predict the effect of various concentrations of fine sediment on flow phenomenon in the field. However, additional studies should be conducted to determine the effect of larger concentrations of fine sediment and other types of fine sediment.

INTRODUCTION

The theory of flow in alluvial channels is being studied by the U. S. Geological Survey at Colorado State University. The investigation is being conducted in a large recirculating, adjustable slope-flume using different sizes and gradations of bed material. The first phase of this investigation was a study of resistance to flow in alluvial channels using a bed material which had a median standard fall diameter of 0.45 mm. The equipment utilized and the results of the first phase of study were presented by Simons, Richardson, and Albertson (1960).

In the current phase of the study the objectives were to:

1. Investigate the influence of fine sediment (a clay) on observed flow phenomenon.
2. Investigate the effect of fine sediment on resistance to flow.
3. Investigate the effect of various concentrations of fine sediment on total bed material transportation.

EQUIPMENT, PROCEDURE, AND DATA

A series of 54 equilibrium runs were completed in which slope was varied from 0.00046 to 0.0096, the discharge ranged from 6.9 to 21.4 cfs, and fine sediment was added in concentrations varying from 0 to 42,000 ppm. Flow conditions ranged from tranquil flow with the ripple form of bed roughness to antidunes in the rapid flow regime.

The basic data are presented in table 1, Appendix A.

Flume

The runs were made in a tilting recirculating flume 150 ft long, 8 ft wide and 2 ft deep. The only change made in the flume prior to this sequence of runs was 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.

Alluvial Bed Material

The sand used as bed material for these runs was the same as that used in the study published as WSP1498A. However, the sand characteristics had changed slightly, see fig. 1. The average median standard fall diameter, d , was slightly larger, 0.47 mm vs 0.45 mm, and the standard deviation decreased slightly, 1.54 vs 1.60. These changes are attributed to the continuous wasting of water which carried away some of the fine sand during the preceeding period of flume operation.

Fine Material

A bentonite clay was used as the fine sediment to determine its effect on resistance to flow, total transport of bed material, and flow phenomenon.

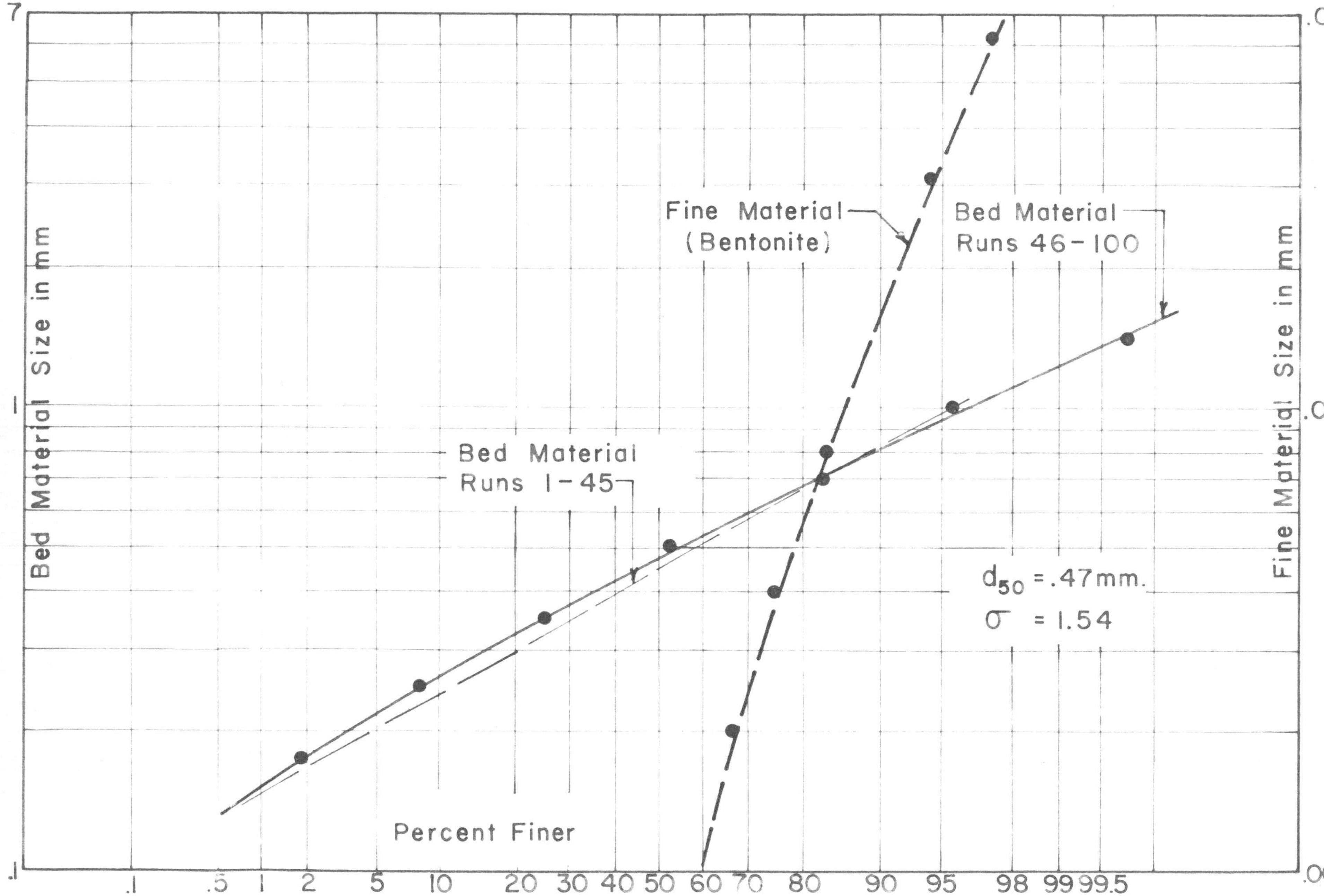

Fig. 1 Size Distribution of the Bed Material and the Fine Material

Bentonite was selected because it is commercially available in large quantities and is typical of much of the fine material found in streams in the semi-arid West.

The size distribution of the bentonite is also given in fig. 1. The size distribution of the bentonite was determined by standard U. S. Geological Survey sieve-pipette analysis with the samples chemically and mechanically dispersed.

General Procedure

In conducting the experiments to determine effect of fine sediment on resistance to flow and total load 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 water-surface slope remained essentially constant with respect to time.

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 tranquil flow regime, to insure equilibrium conditions and then the data for the new 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.

BASIC DATA

The data obtained for each equilibrium run includes: water-surface slope, S; discharge, Q; water temperature, T; depth, D; average velocity, V; velocity profiles, total bed material transport, C_T; concentration of fine sediment, C_f (clay); suspended bed material load, characteristics of the bed material, bed configuration, the apparent kinematic viscosity of the water-sediment complex, ν'; and photos of the water surface and corresponding bed configuration.

The water-surface slope was determined by measuring the water-surface elevation with a mechanical point gage and also by a differential bubble gage--both methods are in close agreement. The bubble gage continuously records the difference in elevation of the water surface, to within 0.001 ft, between two points from which water-surface slope can be computed. The continuous record of the bubble-gage slope can be used to determine when equilibrium conditions are established. Equilibrium exists when the average slope is not changing with time.

Typical records of the slope measured by the bubble gage for various forms of bed roughness are illustrated in fig. 2. A study of fig. 2 shows that the pattern of variation of slope with time is directly related to the form of bed roughness.

The discharges which were obtained by using two centrifugal pumps were measured with calibrated orifice meters and water-air manometers.

The water temperature was measured to the nearest 0.5 degree centrigrade with a mercury thermometer. Water temperature was essentially constant for a particular run, but varied from 10.7°C to 24.5°C considering all of the runs, see table 1.

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 flume. The range

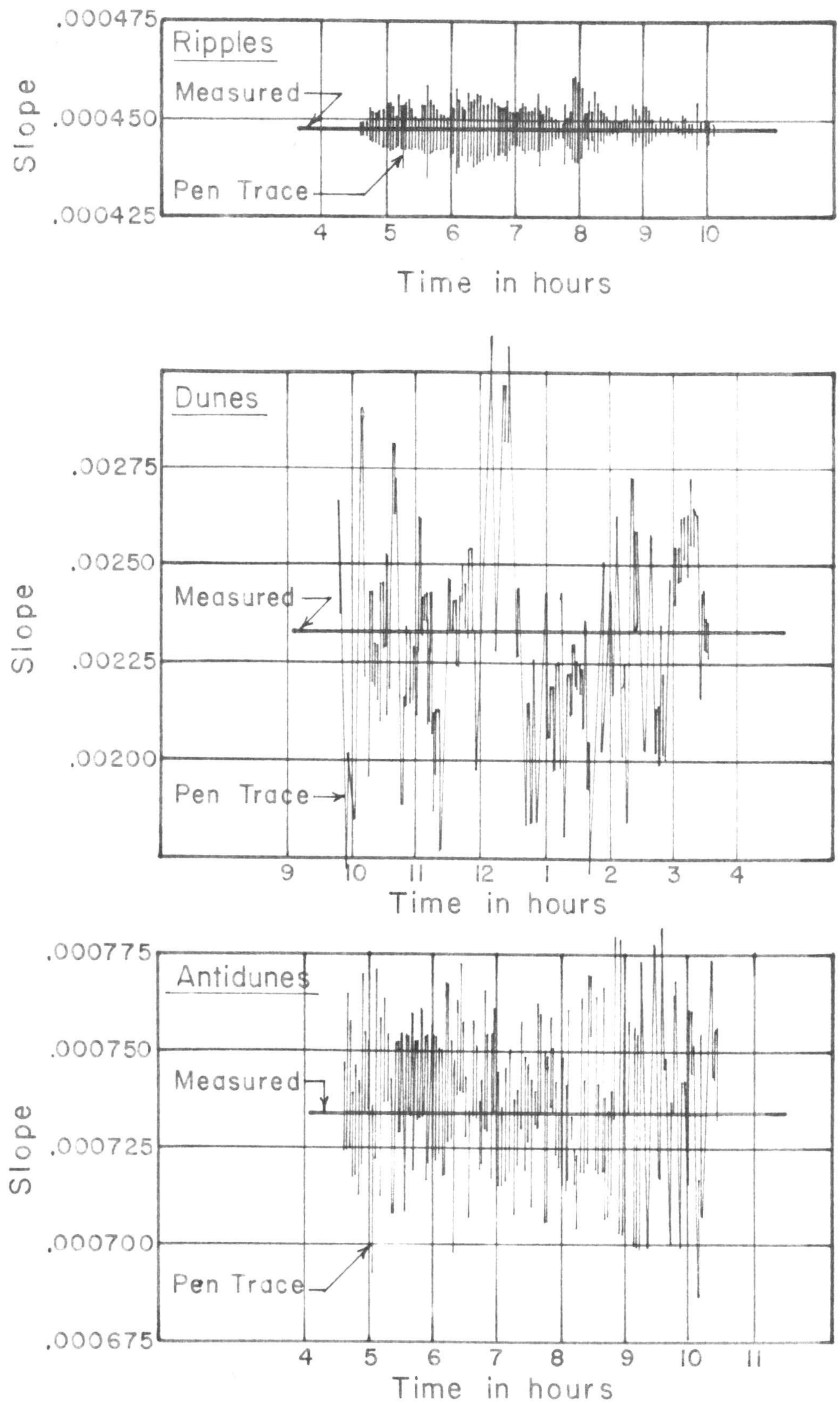

Fig 2. Measured and Recorded Water Surface Slopes

of average depth was 0.53 to 1.33 ft in the tranquil flow regime and 0.30 to 0.62 ft in the rapid flow regime. The measurements of average depth are accurate to within 0.02 ft.

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. Mean velocity ranged from 1.13 to 2.96 fps in the tranquil-flow regime and from 3.21 to 5.32 fps in the rapid-flow regime.

Velocity profiles for each run were obtained in three verticals in the cross-section with a calibrated pitot tube and a tilting water-air manometer.

The total-sediment load was measured where the water discharged from the flume into the tail box with a width-depth integrating total-load sampler. In the tranquil-flow regime 8 samples were collected over a two-hour period. In the rapid-flow regime four to six samples were collected over a one-hour period. Each sample consisted of from 70 to 110 lb. of the water-sediment mixture. Concentration of sediment in ppm was computed on a dry weight basis.

The concentration of fine sediment was determined by separating the total load samples 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.

The total bed-material load varied from 0 to 3000 ppm in the tranquil regime and from 3000 to 17,700 ppm in the rapid-flow regime. The median-standard fall diameter of the total bed material load varied from 0.064 to 0.71 mm.

Suspended sediment was sampled near the mid-point of the 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. Using this equipment, one 5 - 8 lb sample was collected by the equal-transit rate method for each run.

Concentration of suspended material which included the clay fraction ranged from 0 to 43,500 ppm in the tranquil-flow regime and from 3,046 to 57,700 ppm in the rapid-flow regime. Some suspended 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 values. This resulted in larger than average local-suspended loads.

The median standard fall diameter of the bed material, based on the analysis of samples collected each run, was 0.47 mm or 1.54×10^{-3} ft. The samples were washed to remove all bentonite, dried, split and analyzed in the visual accumulation tube (Colby, 1956) to determine median size and gradation. The gradation is indicated by the standard deviation, σ, of the material which can be computed from the equation

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

in which

d is the median size

d_{16} is the size for which 16 per cent is finer

d_{84} is the size for which 84 per cent is finer

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

1. Direct measurement at the observation window.
2. Direct measurement using a point gage and foot attachment.
3. Utilizing a sonic depth sounder. 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 fig. 3. The sonic depth sounder was in 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 apparent dynamic viscosity μ' of the water-bentonite mixture was measured with a Stormer Viscometer. These measurements were made for concentrations of 0.5, 2, 3, 5, and 10 per cent bentonite on a dry weight basis. Temperature was varied from 5 to 45°C for each concentration. The apparent kinematic viscosity, fig. 4, was computed using the dynamic viscosity values and the specific gravity of the fine sediment.

A water-clay mixture with a temperature of 24°C, in which the concentration of clay is 100,000 ppm, has an apparent kinematic viscosity which is about 900 per cent larger than that of water at the same temperature. This change in kinematic viscosity, fig. 4, is the basic reason the effective fall diameter, which is defined in the following paragraph, of sand is reduced as the concentration of fine sediment is increased.

Effective Fall Diameter and its Variation with Concentration of Fine Sediment and Temperature

Effective fall diameter is defined as the diameter of a sphere with a specific gravity of 2.65 and a fall velocity in water at 24°C which corresponds to the fall velocity of the particle in question in the stream fluid at stream temperature. Thus, if a given particle has a fall velocity in water

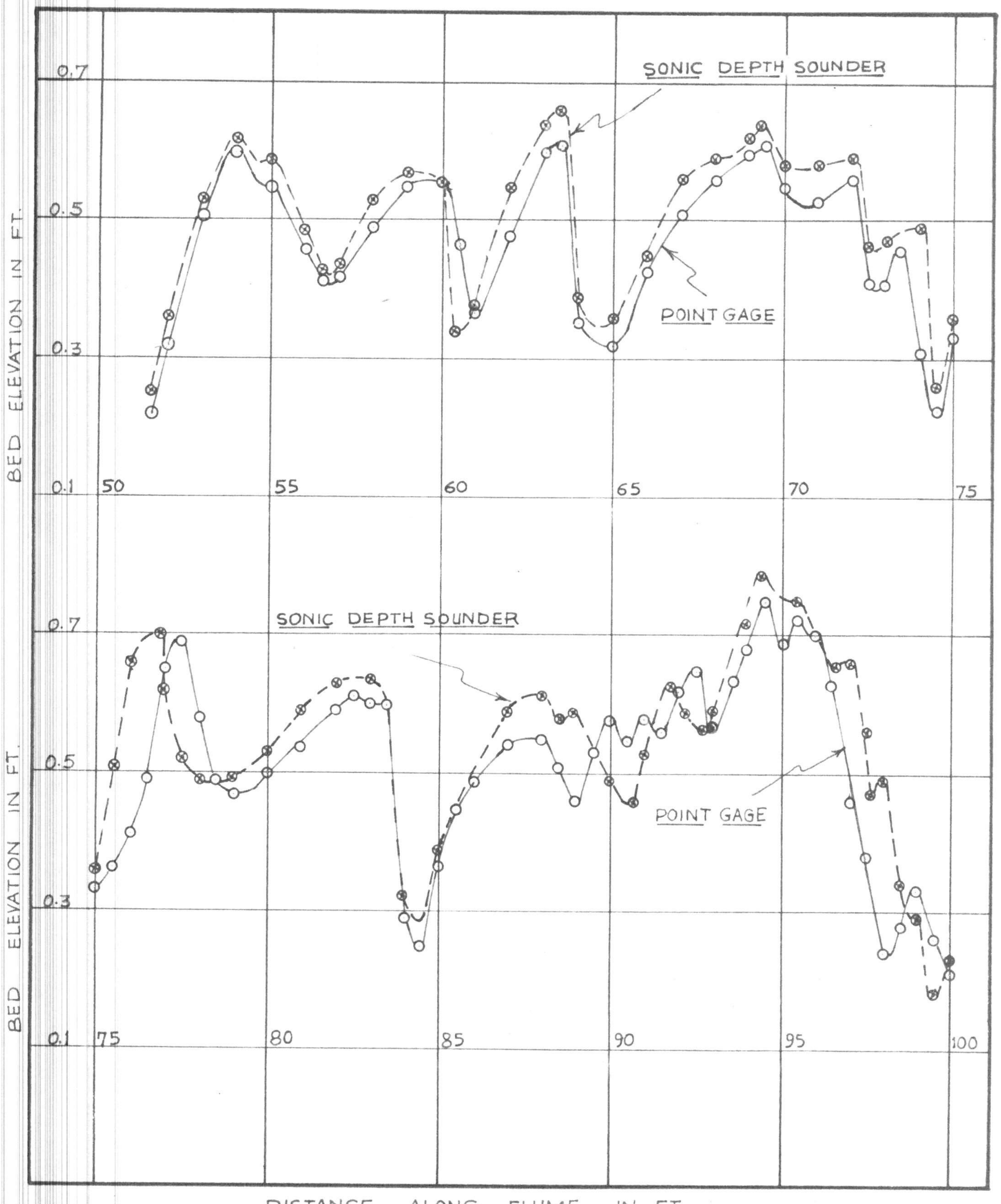

FIG. 3 COMPARISON OF BED CONFIGURATION MEASUREMENTS

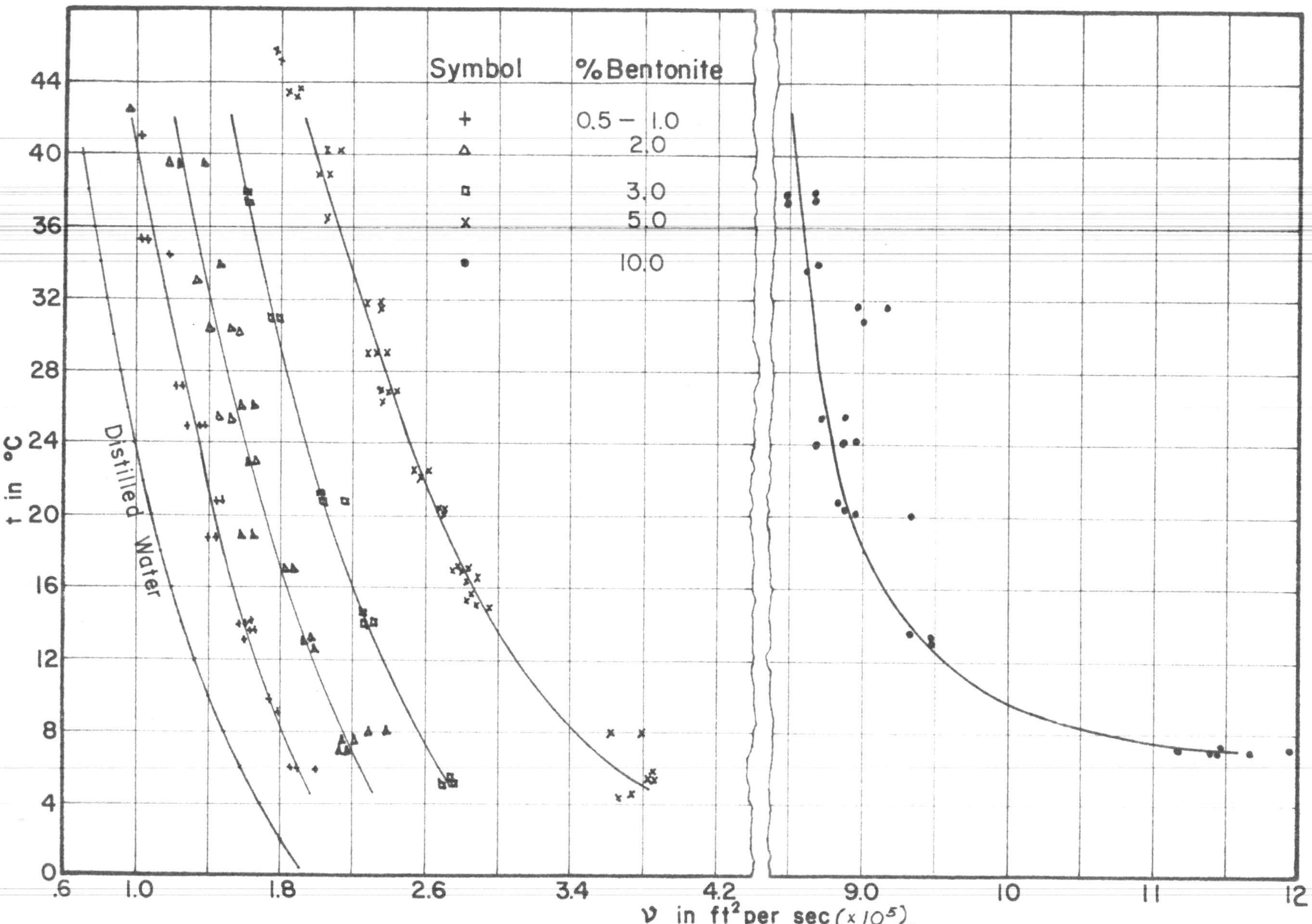

Fig. 4 Apparent Kinematic Viscosity of Water–Bentonite Mixtures

at 24°C equivalent to that of a quartz sphere with a diameter of 0.47 mm, under the conditions imposed 0.47 mm is the effective fall diameter and also the standard fall diameter of the particle.

If this same particle is dropped in a water-bentonite dispersion and the measured fall velocity is the same as that of a quartz sphere with a diameter of 0.25 mm in water at 24°C, the effective fall diameter of the particle is 0.25 mm.

To observe the influence of various concentrations of fine sediment on effective fall diameter see fig. 5. This curve was developed by dropping the same sample of bed material through various water-bentonite mixtures in the VA tube at constant temperature. The curve of fig. 5 illustrates that the effective fall diameter is reduced from 0.47 mm in clear water to 0.24 mm in a mixture of water and 10 percent bentonite.

A lesser but similar effect is caused by a change in water temperature. As with the addition of fine sediment, a decrease in temperature increases the viscosity and specific weight of the water. These changes in the fluid properties decrease the fall velocity and hence the effective fall diameter of the sediment in question; and thus, it also changes the mobility of the particle.

The effect of other types of fine material, such as a koalin clay, should be investigated. It is anticipated that a pure high-swell bentonite of the type studied as the fine material will have the maximum effect on fall velocity and effective fall diameter.

Research conducted to date indicates that the fall velocity or effective fall diameter, depending on whether or not a geometric size or kinematic size is desired, is one of the primary variables in sedimentation studies. However, there are several problems associated with the determination of effective fall diameter. Considering the effect of temperature

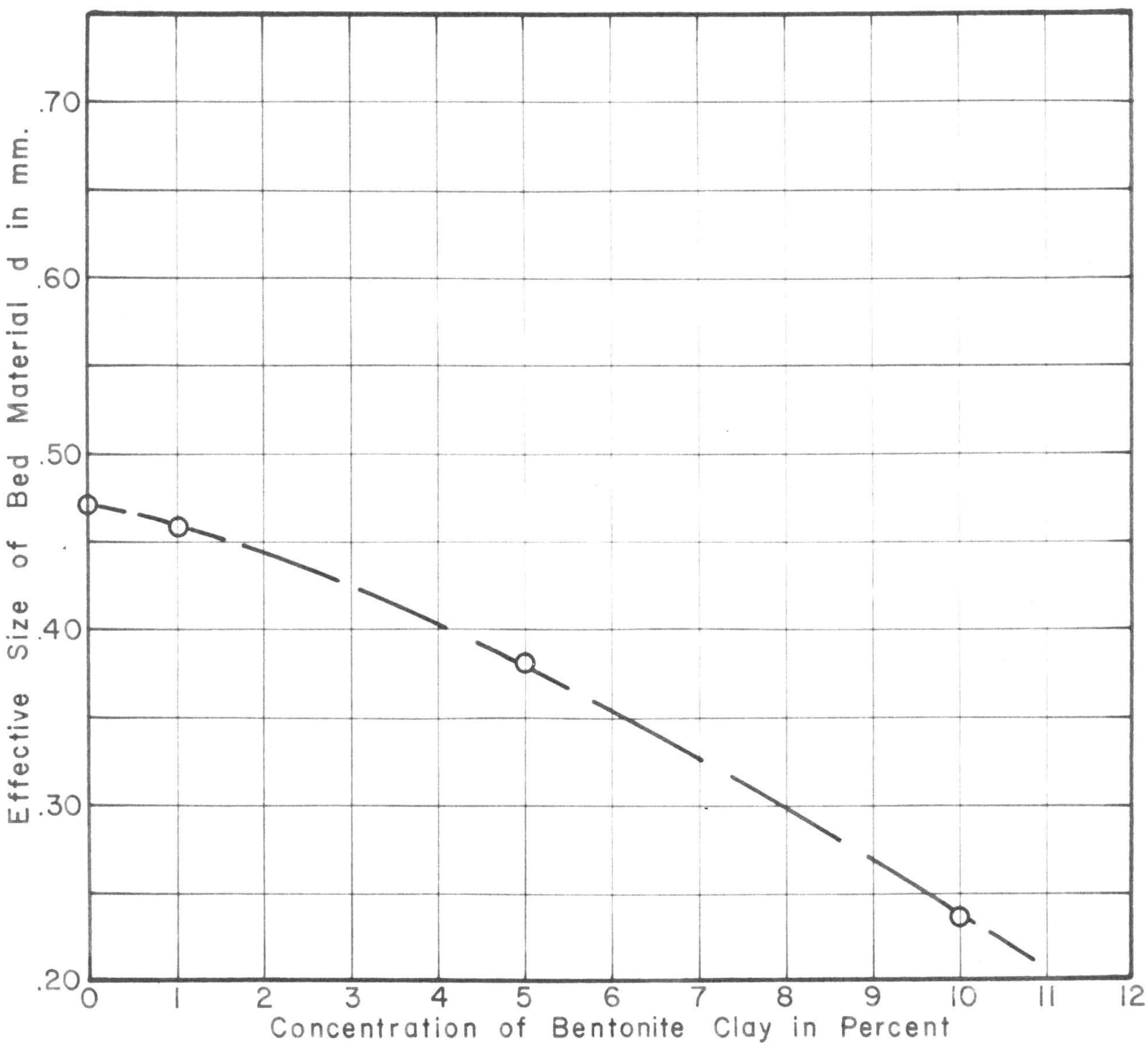

Fig. 5 Variation of Effective Size of Bed Material with Concentration of Fine Sediment

the fall velocity of the standard fall diameter, determined by VA tube analysis, can be estimated for the stream temperature from table 2, presented in Report No. 12 (1957). Then a corresponding effective size which has the same fall velocity at 24°C can also be estimated from table 2, which is the effective fall diameter.

With both fine sediment and temperature effect, it is suggested that effective fall diameter may be estimated by dropping a representative sample of bed material through the stream liquid in the VA tube to determine a fall diameter. Then to include temperature effect, use table 2 to approximate the effective fall diameter. This procedure assumes that temperature variation influences the viscosity of the water-sediment complex the same way it effects the viscosity of the water. Since the viscosity curves for water and water sediment mixtures (see fig. 4) are essentially parallel except at low temperatures and large concentrations of fine sediment, large errors are not introduced using this procedure.

The effective fall diameter could be determined more accurately by developing charts for the VA tube which would give the fall velocity of the particles in the stream liquid at stream temperature. Then effective diameter could be determined from table 2.

OBSERVED FLOW PHENOMENA AND ANALYSIS OF DATA

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 sediment characteristics, and the characteristics of the flow. The bed configuration can be changed by changing any one or more of discharge, slope, temperature, the median standard fall diameter of bed material, the size distribution of the bed material, and the concentration of fine sediment. The mechanics involved in changing form of bed roughness by changing concentration of fine sediment or temperature of the water is considered in subsequent paragraphs.

The observed regimes of flow, bed configurations, and the flow phenomena associated with them were described in detail by Simons, Richardson, and Albertson (1960). These regimes of flow and forms of bed roughness are:

Tranquil flow regime, $Fr \leqslant 1$

1. Plane bed without movement
2. Ripples
3. Dunes
4. Transition from dunes to rapid flow
5. Plane bed and water surface (This form of bed roughness only develops when $d \leqq \pm$ 0.4 mm).

Rapid flow regime, $Fr > 1$

1. Standing sand and water waves which are in phase.
2. Antidunes.

In this study essentially these same major forms of bed roughness were observed. However, at large concentrations of fine sediment the spacing and shape of the ripples and dunes and the antidune activity were slightly modified. For example, with given flow conditions, the shape of the dunes changed with increasing concentration of fine sediment.

Fine Material Load

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."

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. Hence, it may be concluded that the fine material was never present in the bed in appreciable quantities. 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 the 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.

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 using 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 ft thick.

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 on 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 accounts 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, fig. 6, 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.

Fig. 6 - Layer of Bed Material Adjacent to the Flume Floor Impregnated with Fine Sediment (Clay).

Tranquil Flow Regime

Ripples. -- A sequence of runs were made with a ripple bed configuration holding Q and S constant and varying the concentration of fine material. They were runs 85 to 90, see table 1. This sequence of runs were made without stopping the flow. Fine material load was increased by increments between runs from 0 to 11,400 ppm. The addition of fine material in a small a concentration as 4,800 ppm 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 hard semi-cemented boundary. With the smaller concentrations of the fine material, the cemented patches of the bed were not as extensive in area and the flow was able to disperse them. However, new patches reformed elsewhere on the stream bed. With the largest concentration, a major percentage of the ripple bed was quite rigidly cemented. The turbulence of the water-sediment mixture was much greater with the semi-rigid bed than when it flowed over a normal rippled bed.

Where the bed was not cemented by the fine material and the ripples were moving, fine material was deposited in the ripple troughs. The ripple moving over this trough, trapped lenses of fine material in the bed which can be observed in fig. 7.

The fine material decreased total bed material transport from 12 ppm to 2 ppm 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, fig. 7, with moving ripples (no fine sediment) in fig. 8.

Fig. 7 - Lenses of Fine Material Trapped in the Sand Ripples (Note rounded crests).

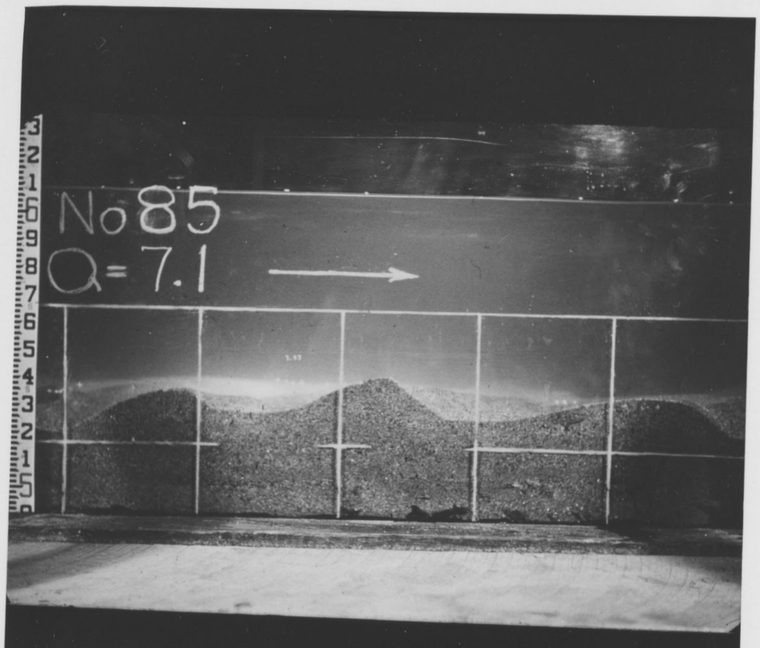

Fig. 8 - Ripples-Clear Water Run (Note angular crests).

In the last two runs of the sequence, 89 and 90, slope was increased slightly so as to change the bed form to dunes but the deposit of fine material on 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 ppm.

With fine sediment in the flow, it was possible to observe small vortices at the surface which were not observed with the clear-water runs. 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:-- 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 ppm. This does not mean that fine material was not in the bed material. The turbulence exchange theory for sediment transport as well as direct measurement proves 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. 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. Thus, if a flood occurred in a natural stream with a large concentration of fine materials it is doubtful that the fine material would be present in bed material samples obtained after the flood.

In observing dune movement it became readily apparent that dune velocities were directly proportional to the rate of sediment transport and inversely proportional to the height of the dunes. A small dune travels at a greater velocity than a large dune; consequently, small dunes overtake larger dunes immediately downstream from them forming a larger dune with a height equal to the combined height of the two. This new dune travels downstream at a slower velocity. Often an upstream dune, by trapping the sediment, would practically stop the movement of a downstream dune. This way a large dune can capture a small dune. These observations of ripple and dune movement provide a new method of estimating total bed load transport as follows:

$$q_b = (1 - \lambda) \frac{V_s h}{2} \tag{1}$$

in which

q_b is the rate of bed material transport

λ is the porosity of the bed material

V_s is the average velocity of the ripples or dunes

h is the average amplitude of the dunes.

The presence of fine material in the flow in concentrations greater than 5,000 ppm (0.5 percent) decreased resistance to flow. The increase in $C/\sqrt{g}$ was as large as 40 percent when the concentration was 20,000 ppm. There may have been a decrease in resistance at concentrations lower than 5,000 ppm, but if so it was not large enough to detect with the natural variations which exist. The decrease in resistance to flow was largely due to the fact that the effective fall diameter of the bed material was reduced and the shape of the dunes changed as the fine sediment concentration was increased.

Total transport of bed material also was increased with the addition of fine material. Total transport rate doubled when the concentration of fine material was 25,000 ppm. However, the increase in total load may have resulted from separating fine material load from the bed material load on the 270 sieve (0.053 mm). The bentonite which was added to the flow passed a 200 sieve and about 4 percent of this material was retained on the 270 sieve, see fig. 1. This 4 percent of the bentonite which was added to the flow as fine material could account for the increase in bed material transport.

Rapid Flow

Antidunes:-- The most obvious effects of the fine-material load on flow phenomena in the rapid flow regime was the increase in antidune activity and bed material transport with increase in concentration of fine material. 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 ppm for run 99 to 106 ppm 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 bed material concentration was 16,100 ppm. With the decrease in fine material concentration, 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 ppm.

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 again the result of reducing the effective fall diameter of the bed material and hence increasing the mobility of the bed material.

In the rapid flow regime the presence of fine sediment had little measurable effect on resistance to flow. $C/\sqrt{g}$ was small ranging from 12 to 17. The breaking antidunes resembled the hydraulic jump and considerable energy was dissipated. However, the antidunes only occupied a fraction of the flume during small increments of time, and resistance to flow when antidunes were not breaking was very small which resulted in small total resistance to flow. The smaller $C/\sqrt{g}$ values in table 1 are associated with runs of greater energy dissipation and more antidune activity. The resistance to flow increased when fine sediment was added to antidune flow because of the increased antidune activity.

The fine sediment in the rapid flow regime was not desposited 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 ft of the top surface of the bed material was moving whereas large dunes turn over the full depth of the alluvial bed.

In this sequence of runs the antidunes usually formed in two parallel lines of waves, fig. 9. This is different than the antidune water surface patterns observed during the first forty-five runs when only a single train of antidune wave usually formed.

Fig. 9 - Antidunes

Influence of Concentration of Fine Sediment on Resistance to Flow

The influence of fine sediment on resistante to flow, using $C/\sqrt{g}$ as the resistance parameter, is illustrated in fig. 10. The magnitude of the change in $C/\sqrt{g}$ depends upon the 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.

Fig. 10 does not show any marked change in $C/\sqrt{g}$ with increase in concentration of fine sediment when dealing with antidunes, but the increase in antidune activity with increasing concentration of fine material indicates that $C/\sqrt{g}$ should decrease.

Effect of Concentration of Fine Sediment on Forms of Bed Roughness

It was illustrated in fig. 5 that the effective fall diameter of the bed material is dependent on the concentration of fine sediment and to a lesser degree on the temperature of the water. The fact that the form of bed roughness which develops is a function of size of bed material has been verified by Simons, Richardson, and Albertson (1960) as illustrated in fig. 11. The relationship qualitatively shows that the forms of bed roughness which can exist when using a 0.47 mm sand in clear water with a temperature of 24°C are: ripples, dunes, transition, standing waves, and antidunes. It also illustrates that a 0.28 mm sand in clear water at a temperature of 24°C develops ripples, dunes, transition, plane bed, and antidunes. Thus if a 0.47 mm sand has its effective fall diameter reduced to about 0,24 mm by introducing a concentration of fine sediment of approximately 100,000 ppm, it should develop the forms of bed roughness mentioned for the 0.28 mm sand.

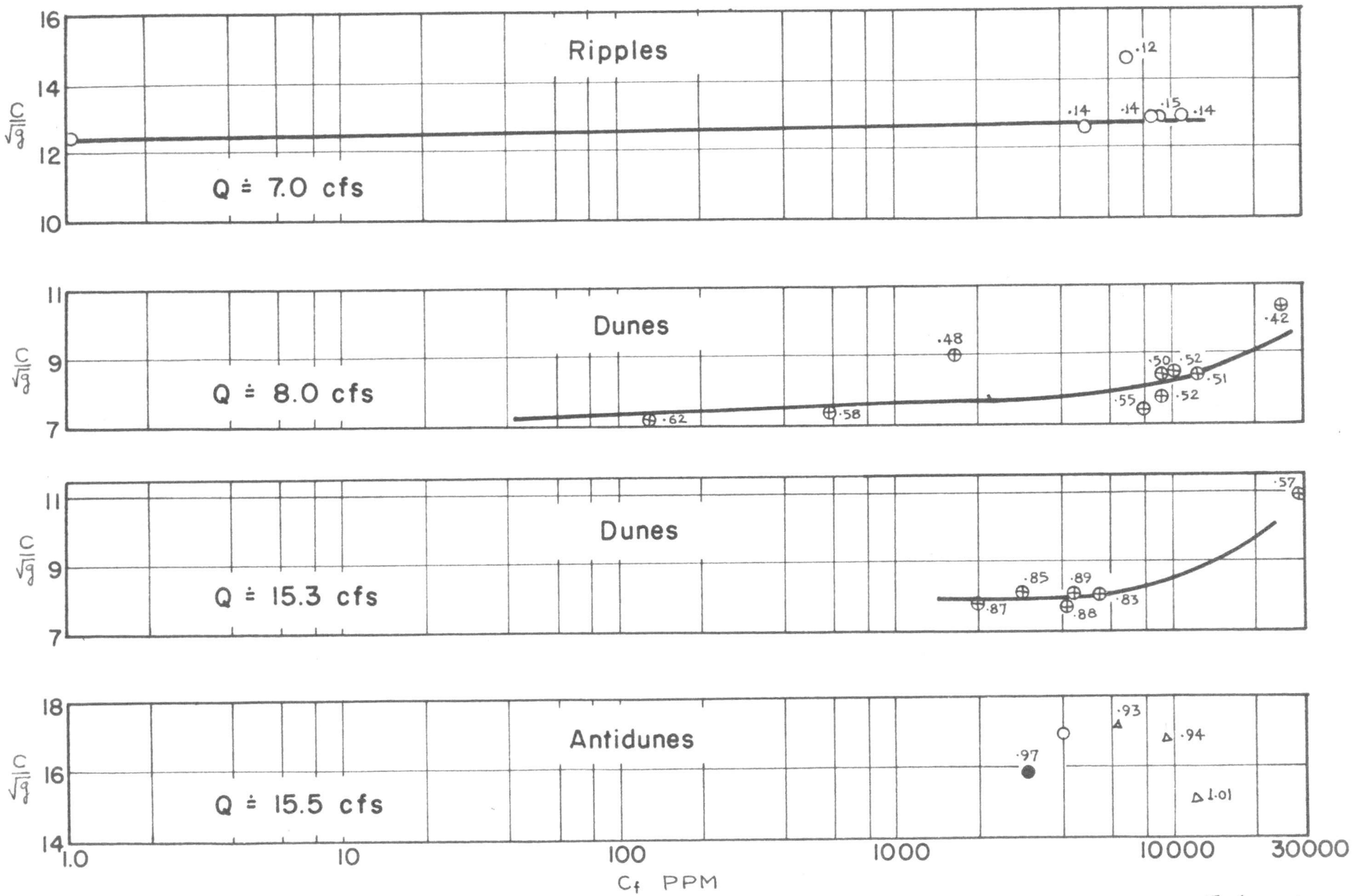

FIG. 10 VARIATION OF $\frac{C}{\sqrt{g}}$ WITH CONCENTRATION OF FINE MATERIAL C_f IN PPM WITH $\tau_o/\Delta\gamma_s d$ AS A THIRD VARIABLE

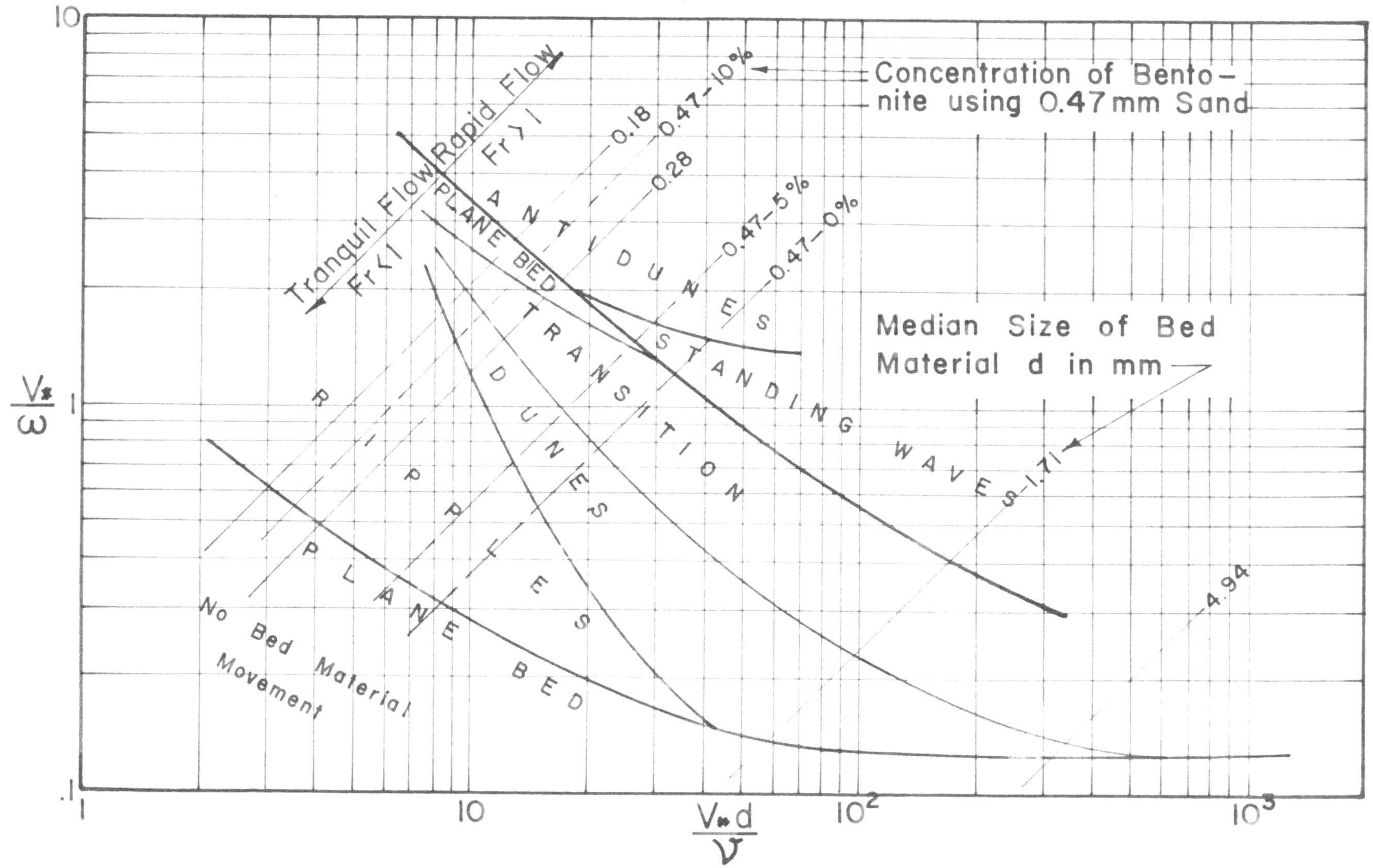

Fig. 11 Qualitative Concept of Effect of Fine Sediment on Forms of Bed Roughness in Alluvial Channels

This is indicated in fig. 11 for its effective fall diameter (0.24 mm) which was determined from fig. 5. The effect of concentration of fine sediment on the effective fall diameter of the 0.47 mm sand is also indicated on fig. 11 for concentrations of 5 and 10 percent bentonite by weight.

The foregoing implications have been verified to a limited extent by tests made in the large flume as discussed under observed flow phenomenon. Additional verification work of a qualitative nature has been done in a smaller flume (Haushild, 1960) where larger concentration of fine material could be introduced with better control and less expense; and the actual effect of large concentrations of bentonite on forms of bed roughness could be observed.

The Effect of Fine Sediment on The Application on Bagnold's Sediment Transport Concept

Bagnold's (1956) dimensionless transport and shear parameters are defined respectively as:

$$\phi = \frac{\phi'}{B} = \frac{M}{B \rho_s d \sqrt{\frac{\Delta\rho_s}{\rho} gd, \cos \beta}} \qquad (2)$$

and

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

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 the 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 Eqs 2 and 3, the two curves of fig 12 were developed. 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. The relation which is based upon bed material transport is a reasonably good relation. In the other relationship the scatter is so great that it has no significance. In fact, an infinite number of possibilities exist for the 0.47 mm bed material when fine sediment is included in the computation of ϕ. This illustrates that the transport parameter should not include C_f and that further consideration and study of the influence of fine sediment should be considered in connection with application of Bagnold's (1956) Concepts.

A definite discontinuity exists in the significant relation at the point where form of bed roughness changes from dunes through transition to standing waves. This discontinuity is caused by a large reduction in resistance to flow which takes place as the form of bed roughness changes. This discontinuity can be eliminated by using a shear parameter of the form

$$\theta_*' = \theta_* + \phi(Fr).$$

The relationship between ϕ and θ_* is superior for the standing wave and antidune runs to the relation for ripples, dunes, and transition forms of bed roughness. Ultimately, it 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 antidunes forms of bed roughness.

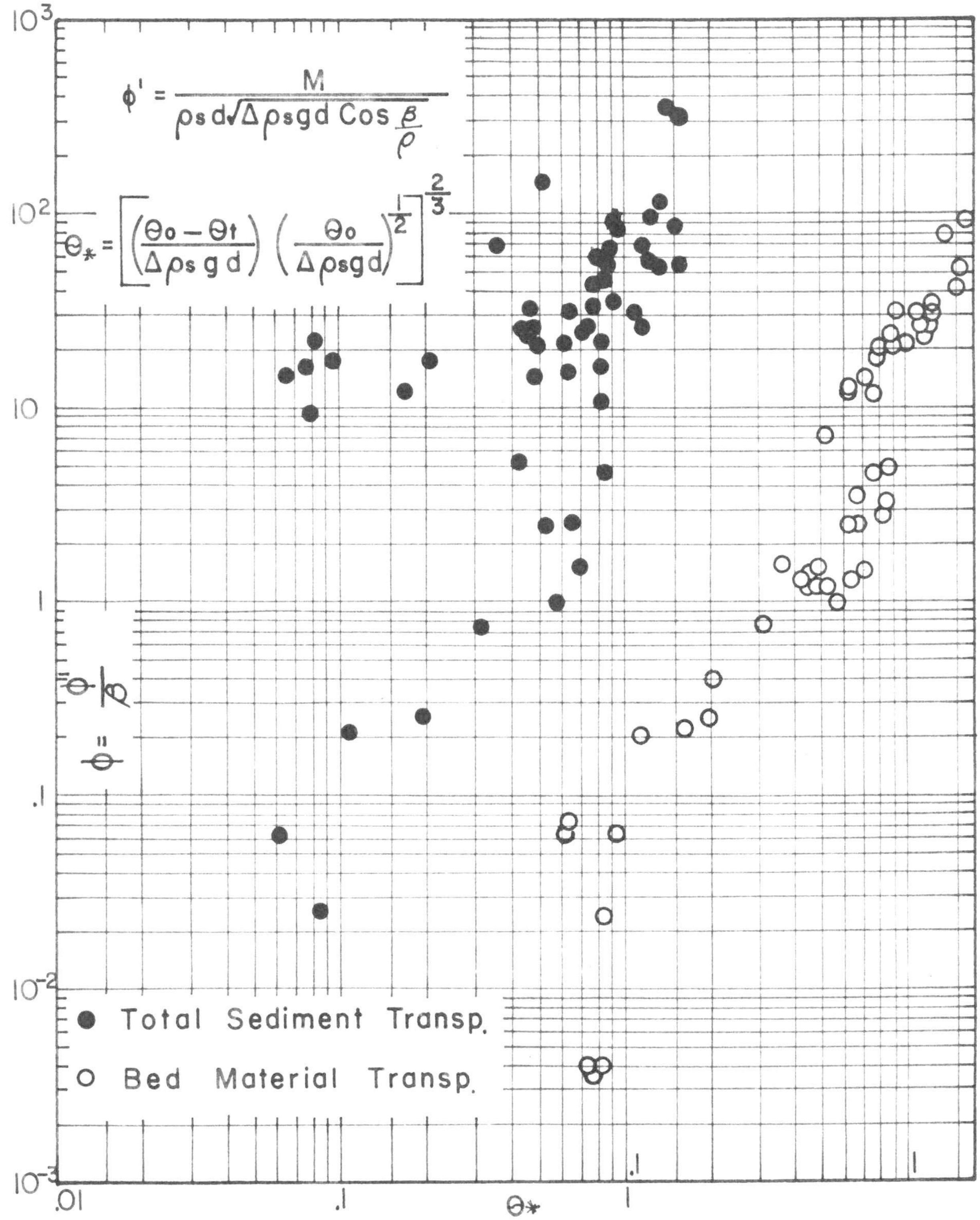

Fig. 12 Variation of Bed Material Transportation Parameter ϕ' with Shear Parameter Θ_*

CONCLUSIONS

This study to evaluate the effect of bentonite clay, used as a fine sediment, on the mechanics of flow in alluvial channels has verified that:

1. The presence of fine sediment in the flow can drastically change the effective viscosity of the water-sediment complex--as much as 900 percent at a concentration of 100,000 ppm.
2. The specific weight of the water-sediment complex increases linearly with concentration--about 7 percent when $C_f = 100,000$ ppm.
3. The increased viscosity and specific weight of the water sediment complex reduces the fall velocity of the bed material and increases its mobility. In effect the fine sediment reduces the effective fall diameter of the bed material. For example, a bed material with a median standard fall diameter of 0.47 mm has a fall velocity in water at 24°C with a concentration of fine sediment of 100,000 ppm equivalent to that of a bed material with a median standard fall diameter of 0.24 mm.
4. Temperature changes influence the viscosity and specific weight (the latter is negligible) and hence, the effective fall diameter of bed material in a manner similar to that of fine sediment but to a much smaller degree. Specifically a bed material in water which has a temperature of 35°C exhibits characteristics of a coarser sand when referred back to a base temperature of 24°C.
5. The resistance to flow in an alluvial channel is related to concentration of fine sediment. With ripples, large concentrations may partly stabilize the bed, make the ripple shapes more streamlined, and reduce resistance to flow. With dunes, the resistance to flow decreased with increasing concentration of fine sediment. In fact, a very large reduction in resistance to flow

is possible if concentration of fine sediment is increased sufficiently to reduce the effective fall diameter of bed material to the point where at the existing shear stress the dunes vanish and and plane bed results. With standing waves, there was very little, if any, noticeable effect of fine sediment on resistance to flow. With antidunes, however, it stands to reason that since the presence of the fine sediment reduces the effective fall diameter of the bed material and increases the antidune activity and turbulence that resistance to flow should increase with increasing concentration of fine sediment.

6. The fine sediment can reduce total bed material load with a rippled bed because the bed is partly stabilized by the large concentrations of fine sediment. A little effect was observed on bed material transport with the dune roughness, and bed material transport increased with increasing concentration of fine sediment with antidune flow. The latter statement is logical, but it is based on very limited data, see runs 99 and 100 in table 1.

7. Application of Bagnold's concepts illustrate that fine sediment can not be included in the dimensionless transport term without destroying the relation between transport and shear. Working with bed material transport only the significance of the results are comparable to the results based upon runs in which fine sediment was not utilized.

The importance of fine sediment in the study of alluvial channels has been clearly demonstrated, but because of the single type of fine sediment used and the limited magnitude of fine sediment concentration the study should be continued to verify the effect of larger concentrations of fine sediment as well as the effects of other types of fine sediment.

LITERATURE CITED

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

Colby, B. C., and Christensen, R. P., 1956, Visual accumulation tube for size analysis of sands: Jour. Hydr. Div. Am. Soc. Civil Eng. v. 82.

Haushild, W. L., 1960, The effect of fine sediment on the mechanics of flow in alluvial channels: M.S. Thesis, Colorado State University, Fort Collins, Colorado.

Heidel, S. G., 1956, The progressive lag of sediment concentration with flood waves: Am. Geophys. Union Trans., v. 37, no. 1, p. 56-66.

Simons, D. B., Richardson, E. V., and Albertson, M. L., 1960. A study of roughness in alluvial channels, flume studies using median sand: U. S. Geological Survey Water Supply Paper 1498A.

APPENDIX A.

Basic Variables