A STUDY OF FLOW IN ALLUVIAL CHANNELS
THE EFFECT OF LARGE CONCENTRATIONS OF FINE SEDIMENT ON THE MECHANICS OF FLOW IN A SMALL FLUME

by

W. L. Haushild,

D. B. Simons

and

E. V. Richardson

A small flume study of the variance in resistance to flow, form of bed roughness, and total bed material transport caused by introducing large fine sediment concentrations into the flow over a sand bed.

United States Geological Survey
Colorado State University,
Fort Collins, Colorado

CER60DBS44

CONTENTS

ILLUSTRATIONS

TABLES

SYMBOLS

Symbols	Description	Dimensions	Units
A	Area of flow section	L^2	ft^2
B	Width of channel	L	ft
$C/\sqrt{g}$	Chezy coefficient of discharge in dimensionless form which is equivalent to V/V_*	-----	-----
C_d	Drag coefficient for the particle	-----	-----
C_f	Concentration of fine sediment	-----	ppm
C_t	Concentration of total bed-material load	-----	ppm
d	Median fall diameter of bed material	L	ft
d_t	Median fall diameter of total bed-material load	L	ft
D	Average depth of flow	L	ft
Fr	Froude number which is $V/\sqrt{gD}$	-----	-----
g	Acceleration due to gravity	L/t^2	ft/sec^2
h	Average height of bed roughness	L	ft
L	Average spacing of bed roughness	L	ft
Q	Discharge of water-sediment mixture	L^3/t	ft^3/sec
R_e	Reynolds number, which is VD/ν	-----	-----
S	Slope of energy gradient equal to water surface slope in steady, uniform flow	-----	-----
t	Time	t	sec
T	Temperature	-----	^0C
V	Average velocity based on continuity principle	L/t	ft/sec

SYMBOLS (contin'd)

Symbols	Description	Dimensions	Units
V_s	Average velocity of sand waves	L/t	ft/min
V_*	Shear velocity which is $\sqrt{gDS}$ or $\sqrt{\tau_o/\rho}$ in steady uniform flow	L/t	ft/sec
ω	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
$\Delta\gamma_s$	Difference between specific weights of sediment and water	F/L^3	lbs/ft^3
ν	Kinematic viscosity	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	-----	-----
τ_o	Tractive or shear force developed on the bed, γDS	F/L^2	lbs/ft^2

Fine Material Runs

d'	Effective size of bed material	L	ft
ω'	Fall velocity of sediment particles	L/t	ft/sec
γ'	Specific weight of water-bentonite	F/L^3	lbs/ft^3
$\Delta\gamma_s'$	Difference between specific weights of sediment (bed material) and water-bentonite	F/L^3	lbs/ft^3
ν'	Kinematic viscosity of water-sediment suspension	L^2/t	ft^2/sec

SYMBOLS (contin'd)

Symbols	Description	Dimensions	Units
μ'	Dynamic viscosity of water-sediment suspension	Ft/L^2	lb-sec/ft²
ρ'	Mass density of water-sediment suspension	Ft^2/L^4	Slugs/ft³
τ_o'	Tractive force developed on the bed, $\gamma'DS$	F/L^2	lbs/ft²

STUDIES OF ROUGHNESS IN ALLUVIAL CHANNELS

EFFECTS OF FINE SEDIMENT ON FLUID PROPERTIES, FALL VELOCITY AND FLOW PHENOMENA

by

W. L. Haushild,

D. B. Simons,

and

E. V. Richardson

ABSTRACT

A flume study was made using a natural river sand as the bed material, median diameter = 0.54 millimeters. Clear-water flow was compared with flow containing from 6,000 to 65,000 parts per million of fine sediment (bentonite).

The study shows that the form of bed roughness could be changed by adding sufficient fine sediment (bentonite) to the clear-water flow. The total bed material transport was decreased by 50 percent with increasing fine sediment concentration with the dune bed form and was increased by as much as 550 percent for the transition, standing wave, and antidune forms of bed roughness. Resistance to flow was less ($C/\sqrt{g}$ increased by 45 percent) with fine sediment-laden flow than with clear-water flow for the dune, and transition bed forms; and was greater ($C/\sqrt{g}$ reduced by 25 percent) for the standing waves and the antidunes. A narrow range of bentonite concentration for each form of bed roughness was established as a limit below which only minor changes in bed form, bed material transport, and resistance to flow occurred.

The variation of the liquid properties, specific weight and viscosity, for water-bentonite dispersions were studied and their effect on the properties of the bed material particles measured. The fall velocity of the particles in a dispersion of 100,000 parts per million fine sediment in water was reduced to about one-half their fall velocity in clear water.

INTRODUCTION

Many controversial statements regarding the influence and effect of very fine sediment on the mechanics of flow in alluvial channels prevail. This 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 wash load does not appear to be a function of the flow, that the rate of transport of this fine sediment is usually related to supply and that the streams' capacity to transport this fine material 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 was 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 effected by the concentration and the characteristics of 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[1/] an investigation of the effect of fine sediment was made by Simons, Richardson and Haushild[2/] in a large flume to specifically evaluate the significance of fine sediment load as a variable. This investigation conclusively verified that where fine sediment is transported in appreciable quantities, it is a significant variable. This study also emphasized the need for further research to determine the effect of larger concentrations of fine sediment. To accomplish this a second study was conducted in a small flume, where large fine sediment concentrations could be economically obtained. The investigation covers the effect of fine sediment concentrations exceeding 6,000 parts per million on:

1. The resistance to flow
2. The forms of bed roughness
3. The total bed material transport
4. The properties of the liquid and the properties of the bed material.

1/ Simons, D. B., Richardson, E. V., and Albertson, M. L., 1960, A study of flow in alluvial channels. Flume studies using medium sand (0.45 millimeters) United States Geological Survey Report.

2/ Simons, D. B., Richardson, E. V., and Haushild, W. L. A study of flow in alluvial channels. The effect of fine sediment on the mechanics of flow. United States Geological Survey Report.

EQUIPMENT AND PROCEDURE

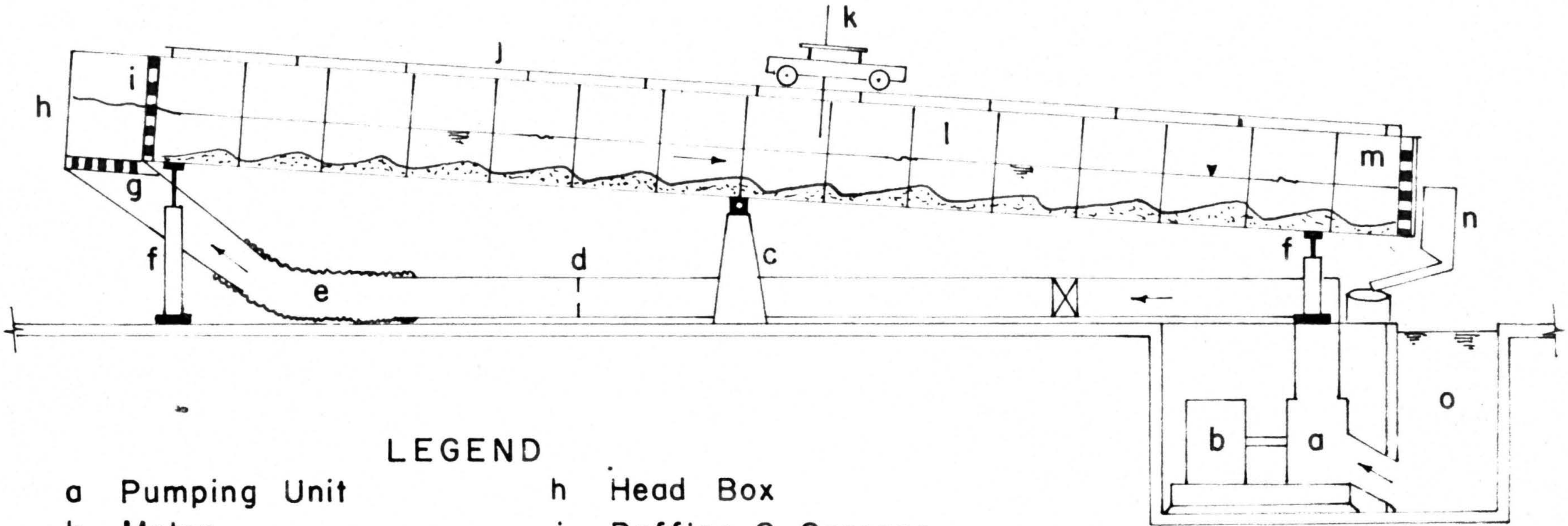
The velocity of flow with a rough movable boundary changes both in magnitude and direction with time and distance and uniform steady flow exists only in a statistical sense. Therefore, the runs were first established in equilibrium and the data were then collected over a period of time necessary to obtain accurate averages. A run was assumed in equilibrium when:

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

Twenty clear-water 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 0.00016 to 0.0144 foot/foot, discharge 1.1 to 7.9 cubic feet per second, and depth 0.59 to 0.91 feet. Nineteen runs with bentonite concentrations ranging from 6,000 to 64,000 parts per million by weight were made. These runs included the range in the forms of bed roughness from dunes to violent antidunes. Slope varied from 0.00198 to 0.0193 foot/foot, discharge from 3.7 to 7.9 cubic feet per second, and the depth range was 0.65 to 0.89 feet.

The Flume

The flume was 60-feet long, 2-feet wide, and 2-1/2 feet deep. A schematic drawing of the flume is shown in Figure 1. The side walls were 1/2 inch clear plastic and the floor was 1/4 inch stainless steel plate. The flume was adjustable to any slope from horizontal to approximately 0.1 foot/foot, and the water-sediment dispersion was recirculated.



LEGEND

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

Fig. 1. Schematic Diagram of the Flume

Alluvial Bed Material

The flume was filled to a depth of 0.7 foot with the sand. The median fall diameter of the bed material was 0.54 millimeters.

Fine Material

The fine material used in the experiments was a bentonite which is mined in Wyoming for commercial purposes. The distribution of particle size is shown in Figure 2. Bentonite was selected as the fine sediment for the studies as it is commercially available and is a typical fine material in the semiarid West.

General Procedure

Fifteen clear-water runs were made prior to the bentonite runs to define the regimes of flow and forms of bed roughness for the 2-foot flume from tranquil flow with no sediment movement to antidunes in the rapid flow regime. Flow depths confined between 0.59 to 0.82 foot minimized the development of abnormal flow phenomena with very shallow or very deep flows. Equilibrium was established for each run and then data were collected during a time interval of 4 to 8 hours.

After the 15 clear-water 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. From three to five runs were made in each series. A fine-sediment run series consisted of a clear-water run plus separate runs at the different fine sediment concentrations. When the series were completed, excluding series 15, the water-bentonite complex was wasted. The system and the bed material was then washed free of bentonite in preparation for the next series of runs.

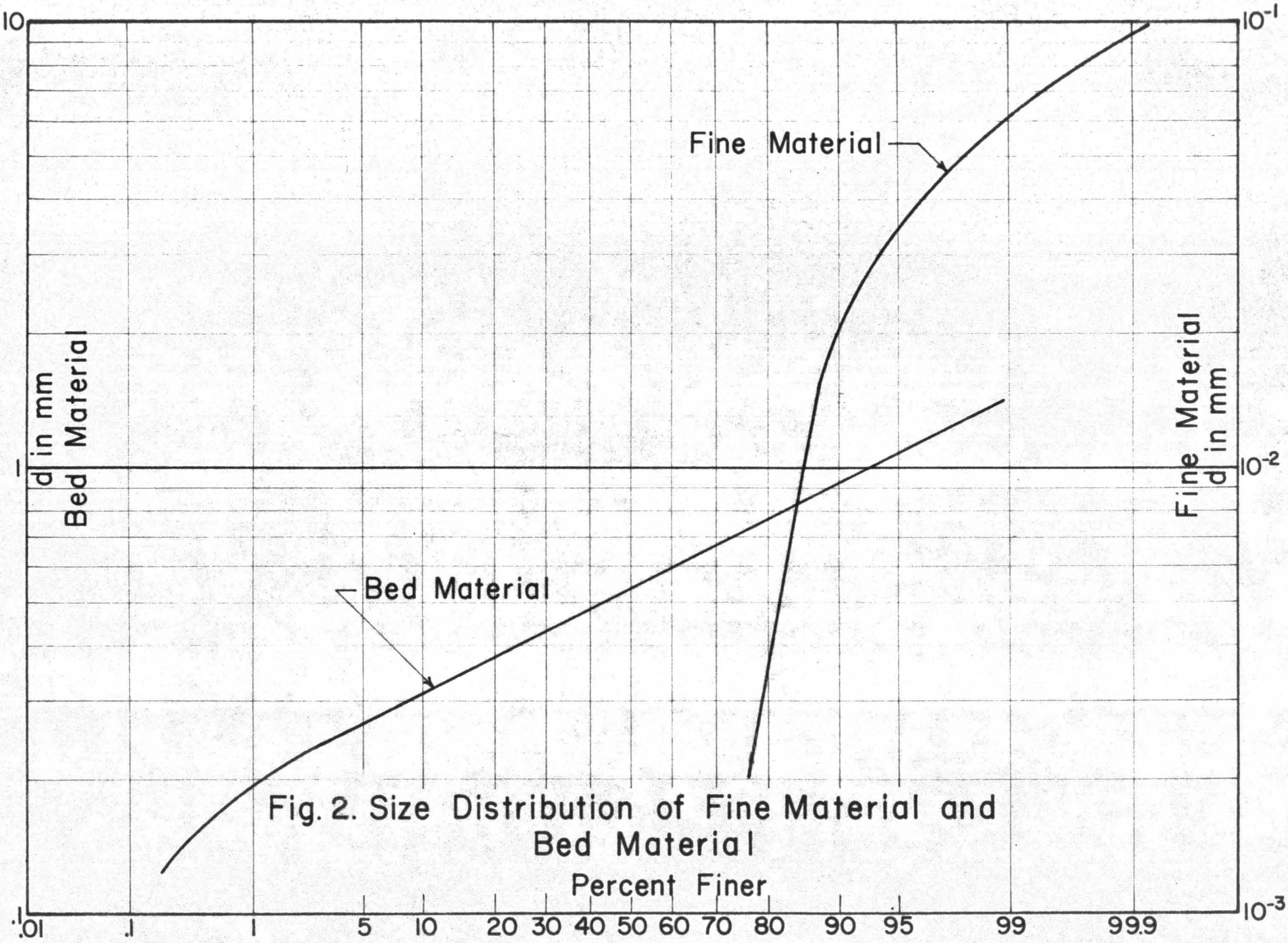


Fig. 2. Size Distribution of Fine Material and Bed Material

For a series, data were first obtained for the clear-water run and the run was continued at the same discharge without changing the flume slope or controls. Bentonite was then injected at the tailbox until the desired fine sediment concentration was attained or the flow and bed pattern were significantly changed. This concentration 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 clear-water runs. This procedure was necessary if a constant fine material concentration was to be sustained as the concentration of bentonite began to decrease as soon as bentonite injection was stopped. 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 wasting of some of the water-bentonite dispersion from the tail box.

After completion of the run series 15, 15A, B, and C, Run 16A was established by altering Run 15C, See Table 1. Though some bentonite was conserved by this method, an undesirable bed condition developed. Run 15C was continued overnight and the sand and bentonite in the system became partly cemented together 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 been followed.

TABLE 1. Basic Variables: d = 0.54 millimeters = 1.76×10^{-3} feet

Run	$S \times 10^2$ ft/ft	Q cfs	D ft	V fps	$\nu \times 10^5$ ft²/sec	$\nu' \times 10^5$ ft²/sec	T_c 0	Concentrations: F.M[a] ppm	B.M[b] ppm	Total[c] ppm	$d^d \times 10^3$ ft	σ^d --
1	.016	1.06	.606	.89	1.203	-----	15.9	-----	-----	-----	-----	-----
2	.019	1.12	.599	.96	1.158	-----	17.4	-----	-----	-----	-----	-----
3	.026	1.21	.617	1.00	1.173	-----	16.9	-----	0.6	0.6	-----	-----
4	.038	1.59	.592	1.37	1.140	-----	18.0	-----	14	14	1.647	1.34
6	.170	2.45	.719	1.74	1.122	-----	18.6	-----	333	333	1.539	1.66
5	.201	3.12	.814	1.95	1.104	-----	19.2	-----	346	346	1.499	1.60
0	.336	4.28	.911	2.39	1.242	-----	14.7	-----	-----	-----	-----	-----
20	.338	4.74	.719	3.36	1.076	-----	20.2	-----	2450	2450	1.621	1.52
8	.351	3.82	.778	2.51	1.113	-----	18.9	-----	1020	1020	1.585	1.55
8A	.331	3.82	.836	2.33	-----	1.31	18.7	5740	1050	6790	1.417	1.58
8E	.248	3.69	.878	2.15	-----	1.46	23.3	14500	660	15200	1.673	1.47
8B	.293	3.84	.850	2.30	-----	1.70	21.5	20600	842	21400	1.483	1.67
8C	.294	3.83	.857	2.28	-----	1.79	22.4	24300	1040	25300	1.594	1.75
8D	.198	3.77	.722	2.65	-----	3.20	25.0	63700	521	64200	0.787	2.92
7	.388	3.42	.715	2.44	1.064	-----	20.6	-----	1090	1090	2.224	1.55
14	.399	4.77	.887	2.74	1.101	-----	19.3	-----	1700	1700	1.667	1.45

a Fine material concentration.
b Total bed material concentration.
c Total bed material concentration plus fine material concentration.
d d and σ of the total bed material concentration.

TABLE 1. - Continued. Basic Variables: d = 0.54 millimeters = 1.76×10^{-3} feet

Run	$S \times 10^2$ ft/ft	Q cfs	D ft	V fps	$\nu \times 10^5$ ft²/sec	$\nu' \times 10^5$ ft²/sec	T_c °	Concentrations F.M[a] ppm	B M[b] ppm	Total[c] ppm	$d^d \times 10^3$ ft	σ^d --
14A	.366	4.78	.824	2.95	-----	1.27	24.3	9580	1760	11300	1.532	1.64
14C	.377	4.80	.868	2.82	-----	1.74	22.2	22400	1840	24200	1.739	1.64
14B	.339	4.84	.704	3.51	-----	2.41	22.3	44100	2960	47100	1.296	2.91
19	.408	3.82	.755	2.58	1.041	----	21.5	-----	1300	1300	1.463	1.56
9	.433	4.16	.722	2.93	1.149	----	17.7	-----	1520	1520	1.421	1.58
10	.486	5.33	.635	4.30	1.073	----	20.3	-----	2690	2690	1.706	1.47
18	.520	7.62	.713	5.44	1.017	----	22.6	-----	3330	3330	1.870	1.61
18A	.508	7.57	.757	5.11	-----	1.44	22.5	13200	3400	16600	1.804	1.62
18B	.790	7.59	.690	5.62	-----	1.70	23.3	37900	9730	47600	1.558	1.61
18C	.900	7.59	.698	5.54	-----	3.00	23.7	58700	22300	81000	1.421	1.40
15	.551	6.94	.744	4.75	1.037	----	21.7	-----	3330	3330	1.821	1.53
15A	.550	6.99	.751	4.76	-----	1.47	22.5	14200	4350	18600	1.519	1.88
15B	.537	6.96	.750	4.73	-----	2.27	23.7	40900	4710	45600	1.476	3.17
15C	.628	6.99	.733	4.85	-----	2.98	24.0	58600	7640	66200	1.247	2.69
13	.565	6.37	.720	4.52	1.137	----	18.1	-----	3350	3350	1.847	1.60
11	.768	7.48	.656	5.80	1.085	----	19.9	-----	5690	5690	2.067	1.46
16A	.980	7.82	.674	5.92	-----	1.35	23.5	11200	5600	16800	2.198	1.33
16B	1.075	7.84	.665	6.03	-----	1.93	25.0	31500	10300	41800	1.496	1.73
16C	1.305	7.86	.653	6.14	-----	2.32	25.1	44500	15800	60300	1.132	2.22
17	1.175	7.89	.648	6.21	1.019	----	22.5	-----	9180	9180	1.460	1.74
17A	1.365	7.83	.650	6.17	-----	2.27	22.3	39600	23800	63400	1.214	1.63
17B	1.928	7.86	.682	5.87	-----	2.60	24.0	51900	50000	102000	1.460	1.30
12	1.438	7.84	.636	6.27	1.173	----	16.9	-----	26000	26000	1.486	1.74

TABLE 1 . - Continued. Basic Variables: d = 0.54 mm = 1.76×10^{-3} ft

Run	Bed Material					Sand Waves			Bed Form
	$d \times 10^3$ ft	σ ---	ω fps	ω' fps	$d' \times 10^3$ ft	L ft	H ft	V_s fpm	
1	-----	-----	.258	-----	-----	-----	-----	-----	Plane
2	-----	-----	.262	-----	-----	-----	-----	-----	Plane
3	1.585	1.53	.261	-----	-----	0.47	.03	.0001	Ripples
4	1.526	1.55	.264	-----	-----	-----	-----	-----	Plane
6	1.640	1.67	.266	-----	-----	4.6	.35	.0047	Dunes
5	1.575	1.57	.268	-----	-----	5.0	.26	.0080	Dunes
[illegible]	1.565	1.56	.254	-----	-----	4.0	.30	.0054	Dunes
20	1.716	1.51	.271	-----	-----	4.3	.17	.0359	Trans.
8	1.903	1.48	.267	-----	-----	3.6	.23	.0115	Dunes
8A	1.699	1.45	.265	.258	1.730	3.8	.20	.0116	Dunes
8E	1.968	1.45	.278	.262	1.688	3.6	.19	.0073	Dunes
8B	1.949	1.49	.274	.252	1.654	3.6	.20	.0100	Dunes
8C	1.772	1.47	.276	.248	1.632	4.4	.24	.0114	Dunes
8D	1.706	1.51	.282	.208	1.343	0.7	.08	.0062	Modified Dunes
7	1.804	1.53	.272	-----	-----	3.3	.17	.0124	Dunes
14	1.903	1.50	.268	-----	-----	4.0	.20	.0208	Trans.
14A	1.837	1.50	.280	.270	1.711	5.8	.20	.0298	Trans.
14C	1.837	1.53	.275	.250	1.643	5.8	.19	.0338	Trans.
14B	1.837	1.48	.276	.228	1.500	-----	-----	-----	Plane
19	1.788	1.54	.274	-----	-----	4.2	.16	.0181	Trans.

TABLE 1. Continued. Basic Variables: $d = 0.54$ mm $= 1.76 \times 10^{-3}$ ft

Run	Bed Material					Sand Waves			Bed Forms
	$d \times 10^3$ ft	σ ---	ω fps	ω' fps	$d' \times 10^3$ ft	L ft	H ft	V_s fpm	
9	1.549	1.50	.263	----	-----	4.2	.18	.0220	Trans.
10	1.824	1.64	.271	----	-----	---	---	-----	Plane
18	1.870	1.49	.276	----	-----	---	---	-----	S. Waves
18A	1.837	1.48	.276	.262	1.695	---	---	-----	S. Waves
18B	1.837	1.45	.278	.237	1.544	---	---	-----	S. Waves
18C	1.919	1.44	.279	.208	1.388	---	---	-----	Antidunes
15	1.732	1.48	.274	----	-----	---	---	-----	S. Waves
15A	1.854	1.52	.276	.261	1.689	---	---	-----	S. Waves
15B	1.837	1.49	.279	.232	1.522	---	---	-----	S. Waves
15C	1.722	1.44	.280	.213	1.388	---	---	-----	S. Waves
13	1.713	1.60	.265	----	-----	---	---	-----	S. Waves
11	1.509	1.62	.270	----	-----	---	---	-----	S. Waves
16A	-----	----	.278	.266	1.703	---	---	-----	S. Waves
16B	1.713	1.45	.282	.248	1.587	---	---	-----	Antidunes
16C	1.837	1.38	.282	.232	1.497	---	---	-----	Antidunes
17	1.690	1.46	.276	----	-----	---	---	-----	Antidunes
17A	1.837	1.42	.276	.233	1.532	---	---	-----	Antidunes
17B	2.100	1.40	.280	.221	1.441	---	---	-----	Antidunes
12	1.847	1.58	.261	----	-----	---	---	-----	Antidunes

DATA COLLECTION

The collected data is summarized in Table 1. The methods and equipment used to collect the data are listed in the following tabulation and paragraphs.

Variable	Method or equipment
Water-surface slope	Level, cart, point gage
Depth	Cart, point gage
Discharge	Calibrated orifice, water-air manometer
Mean velocity	Q/A
Point velocities	Pitot tube
Temperature	Centigrade thermometer

Bed Configuration

The length and height of the dunes given in Table 1 were measured in that part of the flume unaffected by exit or entrance conditions. The average lengths are from crest to crest of the dunes.

The change with time in bed configuration for clear-water runs was measured ($\pm$ .01 foot) at one vertical with a sonic depth sounder and recorded. The number of dunes per unit of time was determined from this record and converted to feet per minute by using the average length of the dunes. The velocity, length and height of the dunes for the bentonite runs was based on the average of several measurements made by observation through the plastic side walls of the flume.

Concentrations

The total load was sampled with a width-depth integrating sampler which sampled the free overfall into the tailbox. Concentration of fine sediment was determined from a sample of the top portion of the total load sample. Sufficient time was allowed, before sampling, for the bed material particles to fall out of the sampling zone. Concentrations obtained by this method were identical to the fine sediment concentrations of depth-integrated samples of the flow collected with a DH-48 sampler.

The total bed-material load samples containing bentonite were washed on a No. 200 sieve to remove the bentonite.

Concentrations shown in Table 1 were computed from the dry weight of the sediments in the sample compared to the total weight of water and sediment.

Particle Size Distribution

Bed material. -- A sample of the bed material consisted of eight to ten full depth cores obtained at equal lengthwise distances in the flume. Samples containing bentonite were wet sieved on a No. 200 mesh sieve to remove the bentonite. Particle size distribution for each run was determined from a representative portion of each sample which was analyzed in the visual accumulation tube, United States Inter-Agency report No. 11 (1957).

The median fall diameter, d, of the bed material is given in Table 1 for each run. The average median fall diameter and the average standard deviation for the bed material was determined from the size distribution graph in Figure 2. This size distribution is the average of all the bed material size analyses.

Total load. -- Total bed-material load samples for each run were composited after the individual sample concentrations were determined. Particle size distribution was determined using the same procedure as for the bed material. The median diameter is listed for each run in Table 1.

Bentonite. -- A sample of the bentonite was analyzed for particle size distribution at the United States Geological Survey Sedimentation Laboratory in Lincoln, Nebraska. The analysis was by the pipette method in distilled water, and the sample was chemically and mechanically dispersed.

Fall Velocities

The fall velocity, ω , given in Table 1 was based on the average d (0.54 millmeter) for the clear-water runs, the mean water temperature for the run, and Tables 2 and 3 of Inter-Agency Report No. 12 (1957). The fall velocity for the runs with fine material added was determined using the procedure outlined in the section on the effect of fine material on fall velocity and fall diameter.

Standard Deviation

The standard deviation for the total bed material load and the bed material was determined from the formula

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

in which d_{16} was the size of the material for which 16 percent was finer and d_{84} was the size of the material for which 84 percent was finer.

Viscosity

The kinematic viscosity of the clear-water runs was determined from the average water temperature for each run. The viscosity of distilled water was used.

For the fine-sediment runs an apparent viscosity of the water sediment dispersion was used. A Stormer Viscosimeter was used to measure the apparent dynamic viscosity, μ , of the water bentonite complex. Viscosity of concentrations of bentonite in distilled water of 0.5, 2, 3, 5, and 10 percent was measured by tests made at temperatures ranging from 5 to 45^{0}C. To determine if the small amount of grit present in the bentonite or the tendency of bentonite solutions to gel affected the viscosity tests, the samples of the mixture were tested at settling times after mixing of 0, 10, and 60 minutes. No measurable difference was observed.

The apparent kinematic viscosities of the water-bentonite dispersions are given in Figure 3.

This relation is very similar to several developed by Bingham (1922) based on experiments from which he related temperature and volume concentration of earth, china clay, and graphite to fluidity, the reciprocal of viscosity. Based on Bingham's studies he concluded that for each temperature the fluidity falls off rapidly and linearly with concentration of solids.

Bentonite Entering the Bed

The method of sampling and preparing total depth core samples of the bed material for particle size determination has been previously explained. The top one inch of the bed was also sampled. The excess water-sediment dispersion was poured off the cores immediately after sampling and the percent of fine material contained in the bed was determined. The percent of bentonite in the bed material for each fine material run is given in Table 2.

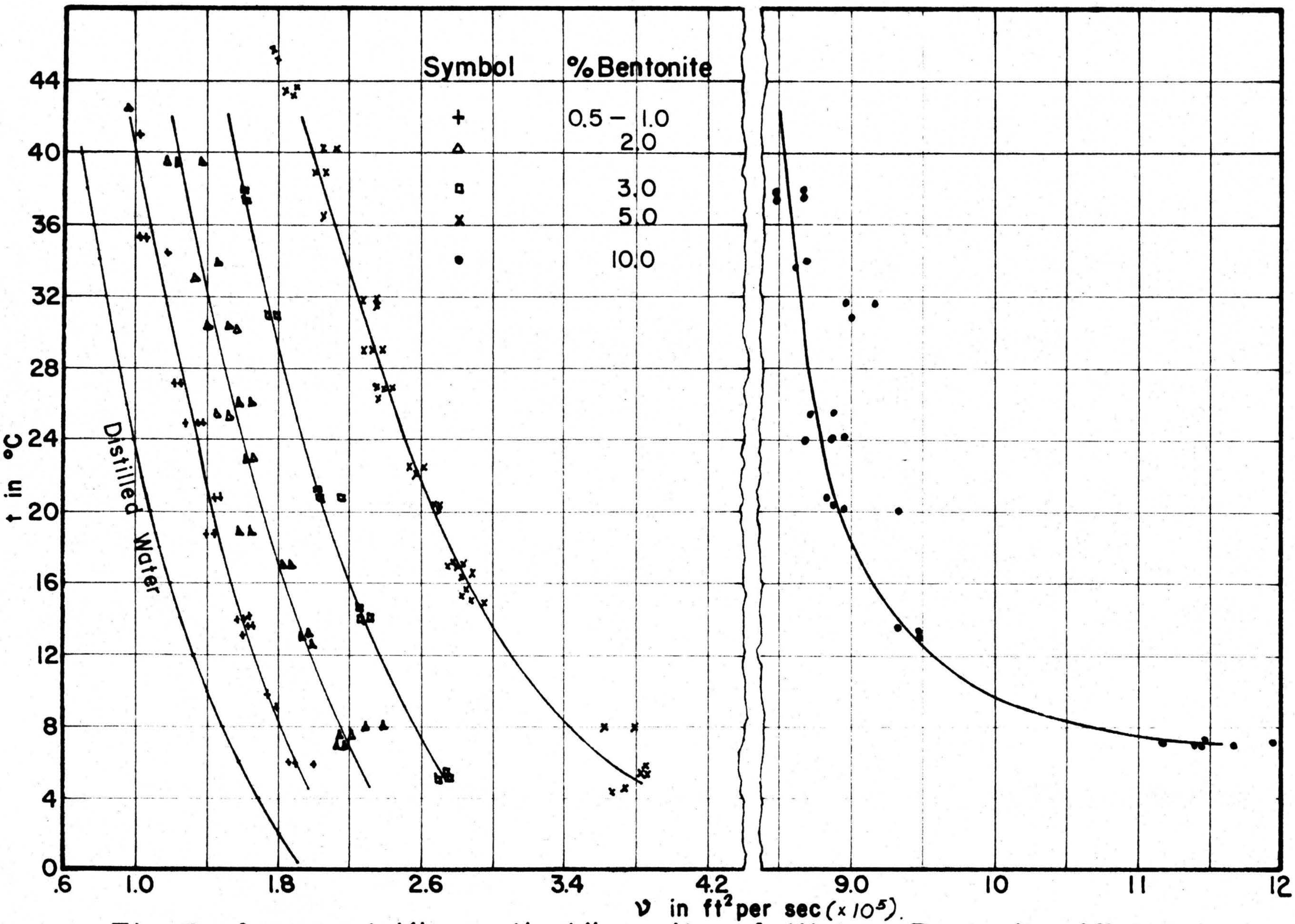


Fig. 3. Apparent Kinematic Viscosity of Water–Bentonite Mixtures

TABLE 2. Amount of fine material in the sand bed

Run	Flow conc. (bentonite) percent	1 inch deep cores percent bentonite	Full depth cores percent bentonite	Bed forms
8	----	----	----	Dunes
8A	5.7	0.08	0.10	Dunes
8E	14.5	0.35	0.41	Dunes
8B	20.6	0.19	0.22	Dunes
8C	24.3	0.38	0.46	Dunes
8D	63.7	0.46	1.11	Rounded sand waves
14	----	----	0.21	Trans.
14A	9.6	0.29	0.55	Trans.
14C	22.4	0.64	0.60	Trans.
14B	44.1	1.40	1.10	Plane
18	----	----	0.37	S. waves
18A	13.2	0.65	0.55	S. waves
18B	37.9	0.94	0.90	S. waves
18C	58.7	1.29	1.34	Antidunes
15	----	----	0.70	S. waves
15A	14.2	1.51	0.82	S. waves
15B	40.9	1.61	0.97	S. waves
15C	58.6	1.57	1.10	S. waves
16A	11.2	2.04	1.73	S. waves
16B	31.5	1.86	1.20	Antidunes
16C	44.5	1.63	1.35	Antidunes
17	----	----	0.54	Antidunes
17A	39.6	1.16	0.99	Antidunes
17B	51.9	1.43	0.46	Antidunes

EFFECT OF FINE SEDIMENT ON FALL VELOCITY AND FALL DIAMETER

Particle size distribution of sands in distilled water and 1, 5, and 10 percent by weight of bentonite in water dispersions were determined using the visual accumulation tube. The sands analyzed were natural river sands with median diameters of 0.46, 0.28, and 0.18 millimeters.

The settling velocity for any particle of a sediment sample varies depending on the characteristics of the sample, the sample volume, (concentration), the fluid, and the apparatus used. The same sample was analyzed in each sedimentation median which eliminated the variables of the characteristics of the sample and the sample concentration. The apparatus used was the same for all analyses. The effect of temperature was controlled as analyses temperatures were $24 \pm 1^{0}C$.

The variation in the settling velocity of a sand particle with concentrations of bentonite was then dependent on the properties of the liquid. Apparent kinematic viscosity increased proportionately to the increase in bentonite for concentrations less than about 60,000 parts per million. Apparent viscosity increased rapidly for bentonite concentrations greater than 60,000 parts per million and was almost 9 times that for distilled water at a bentonite concentration of 100,000 parts per million ($T = 20^{0}C$), see Figure 3.

The specific weight of water-bentonite dispersions was directly proportional to the percentage of bentonite in the dispersion and for 10 percent by weight bentonite in distilled water was about 7 percent greater than that of distilled water.

The settling velocity of the sand particles in a water-bentonite complex might be affected by the interference or the intergranular stresses between the sand particles and the bentonite particles. Density currents may form owing to the nonuniform distribution of particles throughout the cross section of the sedimentation column. However, bentonite in water tended to be uniformly dispersed in a sedimentation column when reasonable precautions were exercised. Each analysis was started as soon as the water-bentonite complex was placed in the tube to avoid uneven distribution because of the settling of the coarser clay and the silt size particles of the bentonite. Currents and eddies generated by the falling bentonite particles may also affect the settling velocity of the sand grains.

The variation in median diameter and standard deviation with fine material concentration are shown in Figure 4 and the variation in fall velocity is shown in Figure 5. For a fine material concentration of 100,000 parts per million, the median fall diameter of the 0.54 millimeter (Cache La Poudre River) sand sample was decreased by 50 percent and the fall velocity was 60 percent less than the distilled water analysis indicated. Standard deviation increased from 1.54 with distilled water to 1.84 when the complex contained 10 percent bentonite.

In Figure 5 the fall velocities computed from the empirically established relation between the drag coefficient, C_d , for a particle falling at terminal velocity and the Reynolds number, R_e , are also shown. The relation between C_d and R_e for spheres and naturally worn sediment particles is given in United States Inter-Agency Report No. 12 (1957). The definition of C_d and R_e is repeated here for clarity.

$$C_d = \frac{4}{3} \frac{d_n (\rho_s - \rho) g}{\rho \omega^2} \text{ (spheres)}$$

$$R_e = \frac{\omega d_n}{\nu}$$

in which

d_n = diameter of a sphere that has the same volume as the particle (nominal diameter),

and the other symbols are defined in the list of symbols.

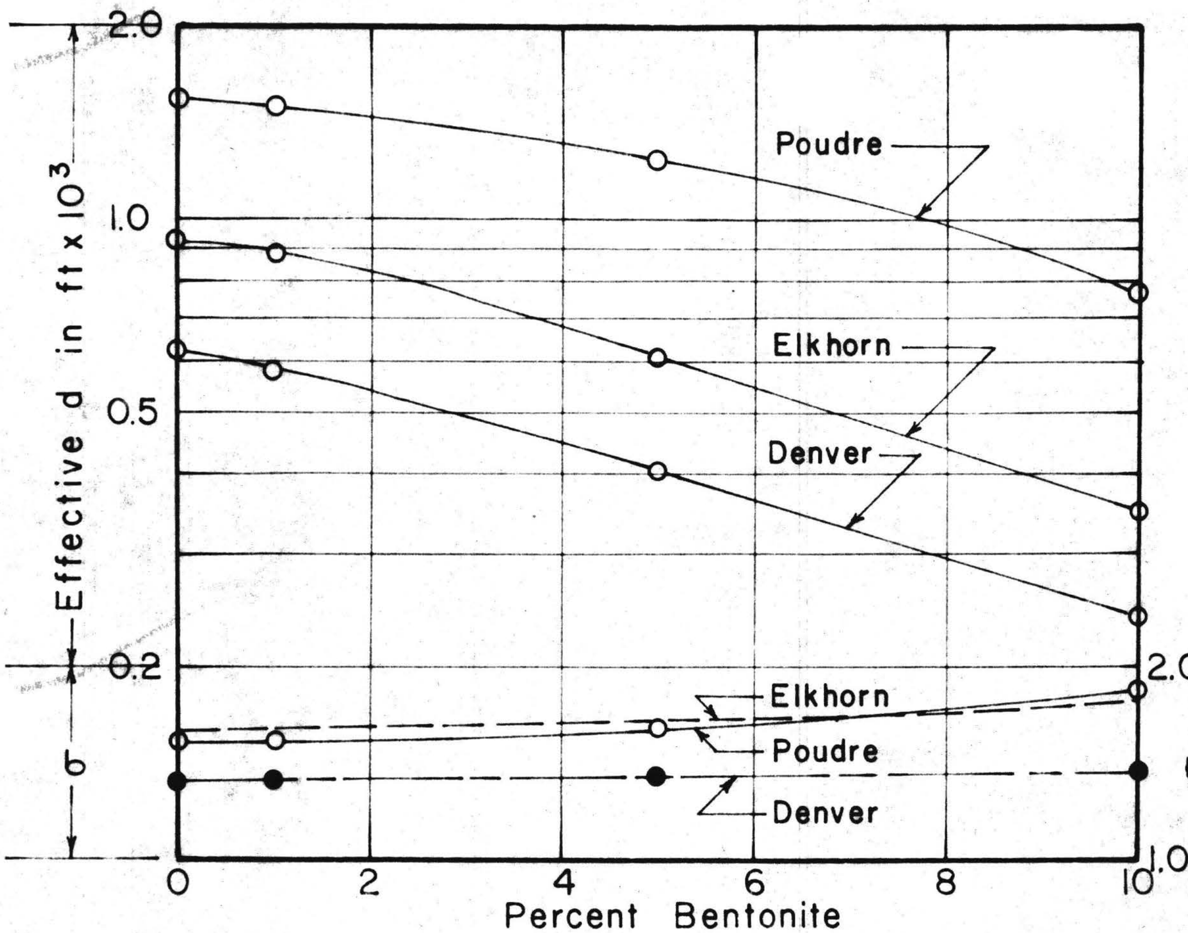


Fig. 4. Effect of Fine Material on Median Diameter and Standard Deviation of Bed Material

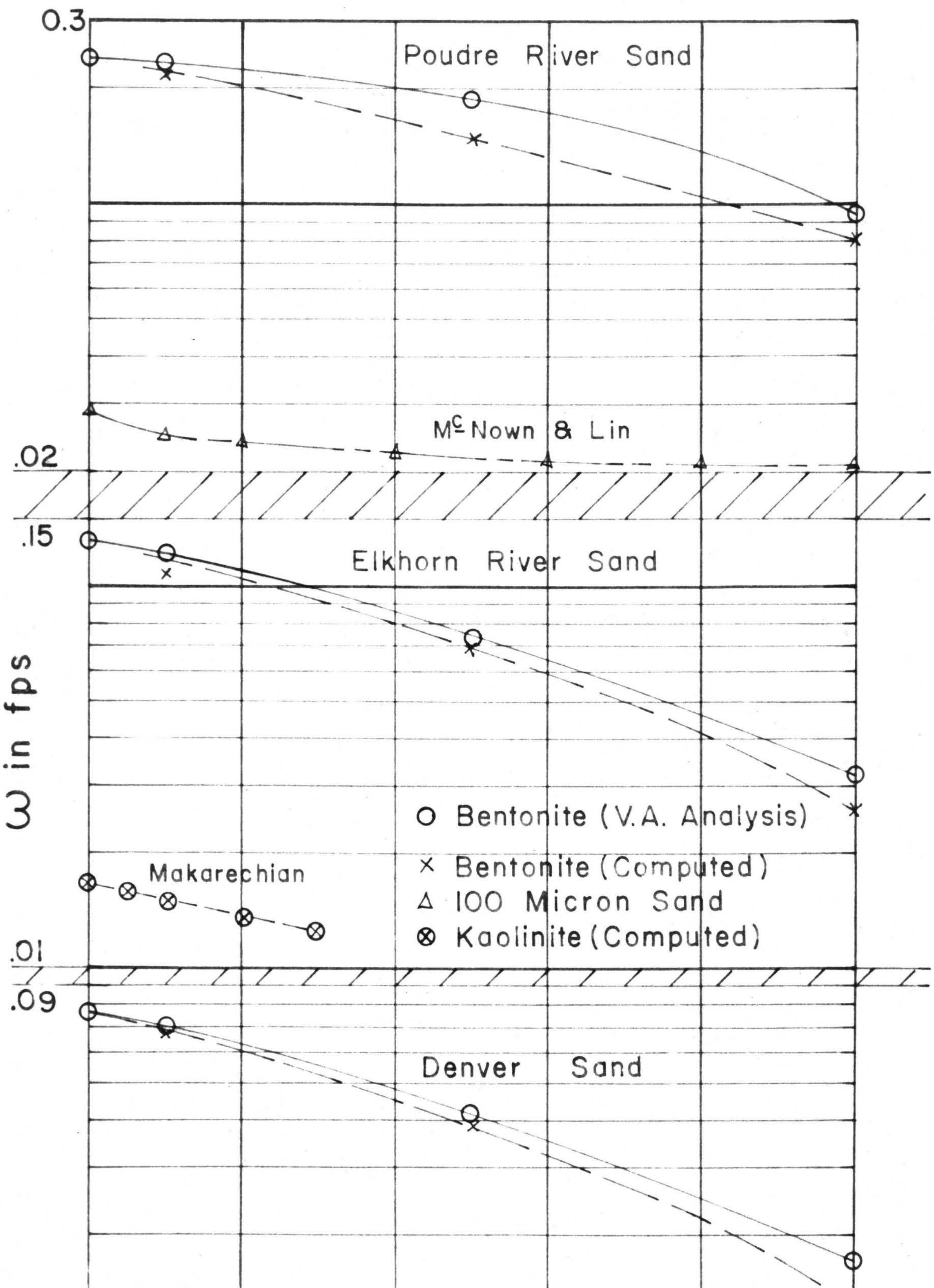


Fig.5. Effect of Concentration on Fall Velocity

For values of R_e less than 1, the terminal velocity was computed from Stokes' equation

$$\omega = \frac{d_n^2 \Delta\gamma}{18\mu}$$

The differences between the computed values of the fall velocity and those from the visual accumulation tube analyses shown in Figure 5 can be attributed to several factors:

1. The inexactness of computing ω from the C_d versus R_e relation.
2. Errors in viscosity, μ, of water-bentonite dispersions determined by the Stormer Viscosimeter.
3. The presence of the bentonite particles in the water-bentonite complex may cause the sand particles to fall at a faster rate than the theoretical computations show.
4. The assumption that the specific gravity of the sand particles is 2.65.
5. The assumption that the shape factor of the sand particles was 0.7.

Fall velocities for the median fall diameter of the glass beads which Makarechian [3/] used for concentration of kaolin up to 3 percent were computed and are shown in Figure 5. Viscosities of the kaolin mixtures were given in his thesis. McNown and Lin (1952) reported on the effect of concentration on settling velocity for increasing concentration of particles of a uniform hydraulic size (d_n = 0.1 millimeter). They found that the settling velocity progressively decreased with increasing concentration.

[3/] Makarechian, A. H., 1956, Effect of wash load on suspension of bed material load: M. S. Thesis, Colorado State University, Ft. Collins, Colorado.

The results of the study on the effect of fine sediments on fall velocity and fall diameter of sands analyzed in the visual accumulation tube are:

1. There is a change in the liquid properties of the water-bentonite mixture. That is, an increase in viscosity and specific weight of the mixture.
2. Fall velocity progressively decreases with increasing fine sediment concentration.
3. Most of the change in fall velocity is directly attributed to the increase in apparent viscosity and specific weight of the dispersion.
4. Analysis made in the visual accumulation tube provides a method of closely approximating the change in fall velocity and hence, a change in median fall diameter of bed material with fine sediment present in the flow. Conversely, an approximation of the viscosity of water and fine sediment mixtures can be made from the visual accumulation tube analysis.

The median fall diameter of sand samples when water-bentonite dispersions were used as the sedimentation media are designated effective median fall diameter (d'). The effective fall-diameter distribution of a sample is the distribution which would result if each particle in the sample was a quartz sphere, which in an infinite extent of quiescent distilled water ($T = 24^{0}C$), would have a fall velocity equal to that of the particle falling alone in an infinite extent of a particular water-fine sediment dispersion at a specified temperature. The effective median fall diameter of the bed material in this paper was determined from the approximation to the effective fall-diameter distribution from analyses made in the visual accumulation tube with the 1, 5, and 10 percent bentonite in distilled water mixtures. The amount that the effective median fall diameter was affected by temperature was not considered.

The effective fall velocity, ω', is the average rate of fall that the effective median fall diameter would finally attain if falling alone in the particular water-fine material complex of infinite extent and at a temperature of 24°C. The effective ω' was determined by converting d' into a fall velocity by use of Table 2, United States Inter-Agency Report No. 12 (1957), but it may also be computed from the C_d, R_e, relation.

The ω' for each run was determined from a curve similar to the curves in Figure 5 relating ω' and C_f and was also corrected to the average temperature of each run.

Since the primary effect of fine sediment is apparently a viscous effect, the addition of fine sediment is analogous to a decrease in stream temperature. By changing temperature it is also possible to change the form of bed roughness and resistance to flow. However, the increase in effective viscosity which can be achieved by adding fine sediment to the liquid is relatively much larger than the normal change in viscosity which occurs as a result of decreasing the stream temperature.

OBSERVED FLOW PHENOMENA

Resistance to flow and sediment transport are directly related to the form of bed roughness which occurs in an alluvial channel. This is illustrated in Table 3, where the resistance to flow and sediment transport for the various bed forms are tabulated. This tabulation was obtained from investigations in a large flume by Simons and Richardson, 1960. Their investigations determined that the form of bed roughness which form on the bed of an alluvial channel are intimately related to S, D, d, ω, and less significantly to ν, seepage forces caused by inflow and outflow through the alluvial bed, and concentration of fine sediment, C_f.

The major forms of bed roughness as observed in alluvial channels in their normal order of occurrence with increasing shear, τ_o, on the bed are shown in Figure 6 and listed below:

Lower flow regime, $Fr < 1$ (Fr is based upon local V and D values).

- Plane bed without bed movement
- Ripples
- Dunes with ripples superposed
- Dunes

Transition, $Fr < 1$

- Region in which dunes are sheared out

Upper flow regime

Plane bed	$0.5 < Fr \leqq 1$
Standing waves	$Fr \geqq 1$
Antidunes	$Fr \geqq 1$

This classification results from combining the results of Simons and Richardson (1960) investigation in a large flume and Dawdy's (1960)[3/] and Colby's (1960) investigations in the field.

3/ Dawdy, D. W., 1960, A study of flow in alluvial channels, depth-discharge relationship in alluvial material: United States Geological Survey report.

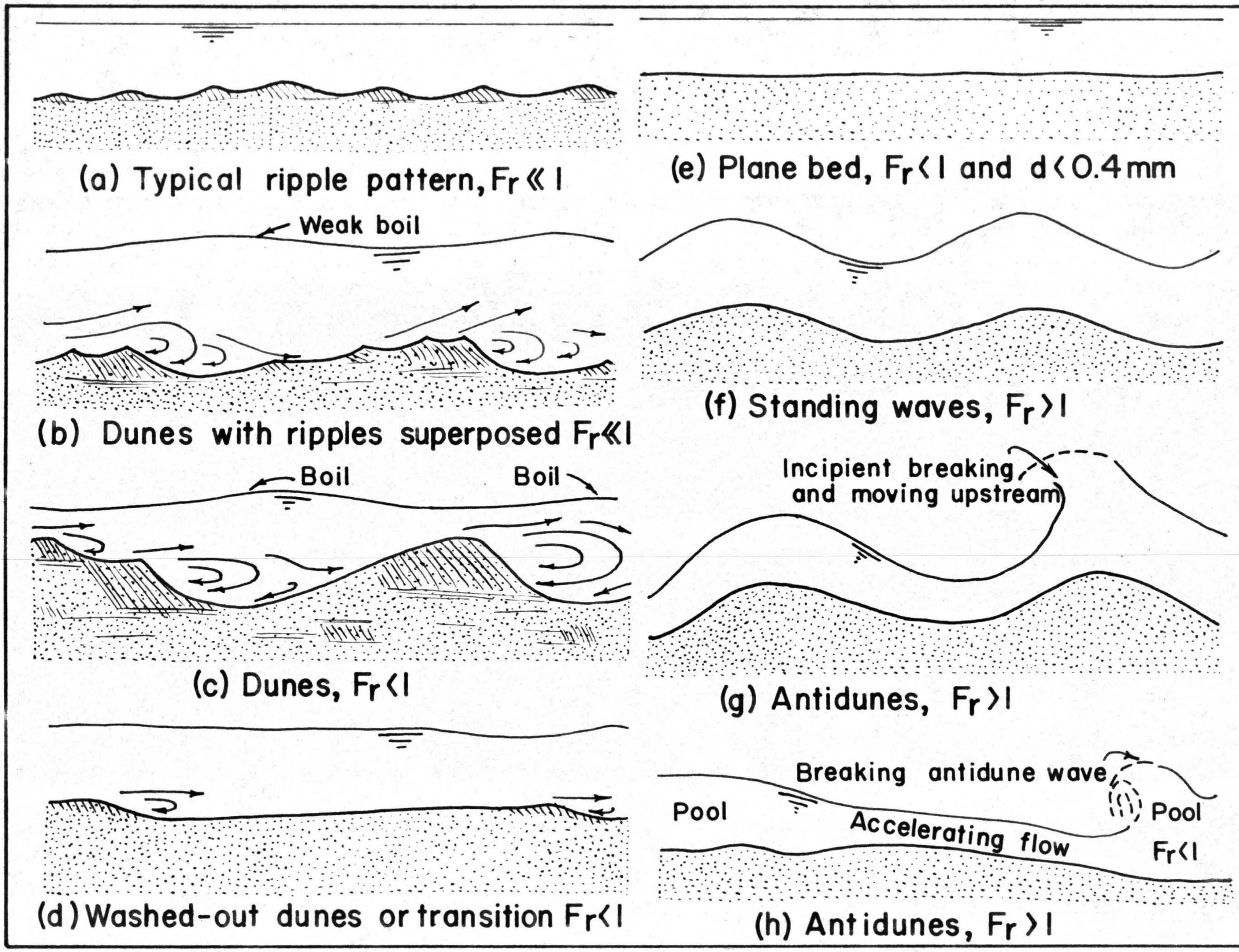


Fig. 6. Forms of Bed Roughness in Alluvial Channels

TABLE 3. Variation of $C/\sqrt{g}$ and concentration of total load, C_T with forms of bed roughness.

	Forms of bed roughness	0.45 millimeter		0.28 millimeter	
		C_t ppm	$C/\sqrt{g}$	C_t ppm	$C/\sqrt{g}$
Lower flow regime	Plane	0	14.4	0	14.0-16.3
	Ripples	1-100	7.8-12.3	1 to 150	8.8-11.9
	Dunes	100-1,000	7.0-12.8	150 to 1,200	10.1-11.4
Transition	Sheared out dunes	1,000-4,000	10.0-26.9	1,200-2,500	14.7-17.9
Upper flow regime	Plane or standing waves	4,000-7,000	13.8-20.0	1,500-3,000	17.5-18.1
	Antidunes	6,000-15,000	12.0-18.0	3,000-42,000	10.9-16.9

Clear Water Runs

In the following paragraphs, the forms of bed roughness which occurred in the 2-foot flume are briefly compared with those observed by Simons and Richardson in the 8-foot flume.

The major difference noted between clear-water runs using sand of approximately the same size (median diameter 0.5 millimeters) in the 2-foot and 8-foot flume was that the ripple form of bed roughness did not occur in the 2-foot flume. Ripples developed in the 8-foot flume as soon as movement of the sand grains commenced, Simons and Richardson (1960). A plane bed persisted with the sediment moving in contact with the bed for this condition in the 2-foot flume except for a few oblong shaped bed irregularities which occasionally developed and were randomly spaced in the flume.

Many runs were made at depths varying from 0.2 to 2.0 feet and at various water-surface slopes to investigate the non-forming of the ripples. Each run was started at the beginning of sediment motion and continued holding the depth constant and increasing the discharge and (or) the slope. A plane bed persisted for the runs until the shear on the bed and the sediment transport increased sufficiently so that the dune form of bed roughness developed. Ripples artifically induced were slowly erased back to a plane bed by the flow. Run 3 where ripples were artifically produced which persisted throughout the run was not considered representative of factual conditions. Considering Run 3, the sediment transport rate was only 0.6 parts per million and insufficient time was allowed prior to collecting data for the flow to convert the artificially formed ripple bed back to a plane bed.

Ripples superposed on dunes were also never observed in the 2-foot flume. The flow and forms of bed roughness were more two dimensional in the 2-foot flume owing to the narrower width. Very little or no meandering of the dune front occurred in the small flume and the standing waves and antidunes formed over the entire flume width.

Fine Sediment Runs (Lower flow regime)

Dunes. -- Bentonite was injected into the tailbox using mixing water pumped from the tailbox. The turbulence in the tailbox, pipe, and the manifold diffuser insured thorough mixing of the water and the bentonite. The bentonite entered the bed with the pore water and accumulated in the bed while bentonite was being added to the flow. These accumulations were visible at the side windows. A layer deposit formed at the interface between the flume flow and the bed material.

An initial change in bed configuration was noted while the bentonite was being added. The dunes increased in length and decreased in amplitude until a plane bed developed throughout most of the flume in the extreme case. This initial bed configuration change was quickly broken up by the dune action after the desired concentration of fine sediment was reached and the addition of the bentonite was stopped. Except for the 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. The maximum amount of bentonite contained in the bed for this series of runs was 1.1 percent for the full depth cores and 0.5 percent for the 1-inch depth cores.

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 total bed material transport was about 1000 parts per million and $C/\sqrt{g}$ remained essentially constant. The explanation for the smaller bed material transport for Run 8B (842 parts per million) was not readily apparent. The decreased length, height, and velocity of the dunes of this run confirmed the decreased transportation of the bed material.

The form of bed roughness and therefore the resistance to flow and bed material transport was considerably modified when the fine sediment concentration 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 fine sediment concentration of 63,700 parts per million. 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. No cementing or greater firmness of the bed was discernible and it remained soft and fluid. The resistance to flow decreased as shown by an increase in $C/\sqrt{g}$ of 46 percent. Bed material transport was reduced to 521 parts per million which was 1/2 the clear-water transport.

After the completion of data collection for Run 8D, the flume was continued in operation with no change in the controls. The concentration of fine sediment in the flow decreased with time 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 fine sediment concentration had decreased from 63,700 to 14,500 parts per million and data for Run 8E were collected. The bed configuration was restored to dunes of the same length but of smaller height and slower velocity than the clear-water dunes for Run 8. Resistance to flow was the same as that of Runs 8, 8A, 8B, and 8C, but the total bed material concentration was only 660 parts per million. The return to a total bed material concentration that the flow was capable of transporting was apparently quite slow after a large concentration of fine sediment had been introduced into the flow.

Similar conditions for the ripple form of bed roughness were found in the 8-foot flume study as was noted with the dunes in the 2-foot flume study. Fine sediment cemented and coated the bed and some was trapped in the bed. The ripples were rounded and the total bed material transport decreased from 12 parts per million to 2 parts per million while $C/\sqrt{g}$ increased from 10.4 to 14.4 with fine sediment concentration as low as 4,800 parts per million. The bed form resisted a change from ripples to dunes although the slope was increased so that the shear on the bed was sufficient to produce dunes.

Fine Sediment Runs (Transition)

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. 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 total bed material transport increased and resistance to flow decreased for fine sediment concentrations as small as 9,580 parts per million. The Chezy coefficient of discharge, $C/\sqrt{g}$, increased by 16 percent and 8 percent at the respective concentrations of 9,580 and 22,400 parts per million of bentonite. The amplitude of the sand waves remained nearly constant but their length and velocity increased.

As the fine sediment concentration was increased to about 30,000 parts per million the dune lengths increased to 10 to 20 feet compared to dunes 4 to 6 feet long at concentrations less than 22,000 parts per million. The form of bed roughness changed from the long washed out dunes to a plane bed at about 30,000 parts per million bentonite when the fine sediment concentration was being increased. The reverse of the form of bed roughness change (plane bed to dunes) occurred at approximately the same fine sediment concentration, 30,000 parts per million, when the concentration of bentonite was being decreased.

The bed material concentration for the plane bed Run 14B was 2,960 parts per million and $C/\sqrt{g}$ was 13 compared with 1700 parts per million and $C/\sqrt{g}$ of 8 for the clear-water Run 14.

Fine Material Runs (Upper flow regimes)

Standing waves. -- Sand beds are quite firm and consolidated for the standing wave form of bed roughness. The maximum fine sediment found in the bed was 1.6 percent by weight for the series of runs 15, 15A, 15B, and 15C where the Froude number was slightly less than 1.0. The bed surface became very firm and felt slightly crusty, but when the bed was thoroughly distrubed 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 this sequence of runs. The resistance to flow was unchanged for fine sediment concentrations less than 41,000 parts per million but increased at greater concentrations.

The data in Table 1 indicate that the total bed material transport was increased for each fine sediment run over the transport with clear water.

The length of the standing sand waves measured from crest to crest changed very little, but their height decreased as the fine sediment concentration was increased.

There was a more noticeable effect as fine sediment was added to standing waves when the average Froude number was greater than 1.0, Runs 18, 18A, B and C. When the fine material concentration was increased, antidunes developed. This action was reversible.

For fine sediment concentrations greater than 30,000 parts per million, the bed material transport was 3 to 7 times greater than that transported in the clear water standing wave run. The increase in total bed material concentration was less for smaller concentrations of fine sediment.

The values of $C/\sqrt{g}$ was reduced by 9 to 20 percent with fine sediment concentrations greater than about 15,000 parts per million. The increase in resistance to flow and the bed material transport was due greatly to the change in form of bed roughness caused by the increase in fine sediment concentrations. The resistance to flow and the total bed material transport is greater with antidunes than with standing waves.

Antidunes.-- Antidune activity increased with increasing concentration of fine sediment. The antidunes occupied the full length of the flume, and the sand and water waves broke more frequently and the breaking lasted longer for the fine material runs. The build up and breaking of the water and sand waves occurred less frequently, and was restricted to the middle and downstream sections of the flume during the clear-water run.

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

Bed material transport and resistance to flow increased with increasing concentration of fine sediment. When the fine sediment concentration was 51,900 parts per million, the bed material concentration was 5-1/2 times greater than the corresponding clear-water transport and $C/\sqrt{g}$ was decreased by 28 percent.

ANALYSIS OF EXPERIMENTAL RESULTS

Bed Material Transport

The relation between total bed material transport and fine sediment concentration is shown in Figure 7. The form of bed roughness is shown as a third variable.

The effect of high concentration of fine sediment with the ripple or dune bed form was to cement the bed, thus reducing the transport of bed material. With the other bed forms the high concentration of fine material did not cement the bed. Therefore, because the fine sediment increased the viscosity of the fluid, decreasing the fall velocity of the bed material there was an increase in transport of bed material. This increase results from the increase in sediment transport for the same shear with decreasing sand size.

This increase in transport with decreasing sand size for the same shear results from the change in bed form and the increase in time. The sediment is in suspension. The change in transport with large concentration of fine sediment was of the same order of magnitude as if, for the same shear, the sand had a diameter equivalent to its fall velocity in the new media. This new diameter is its effective diameter.

Data from this study and the research in the 8-foot flume indicate a lower limit of fine sediment concentration below which the transport of bed material was not appreciably affected for this size and gradation of bed material, see Table 4.

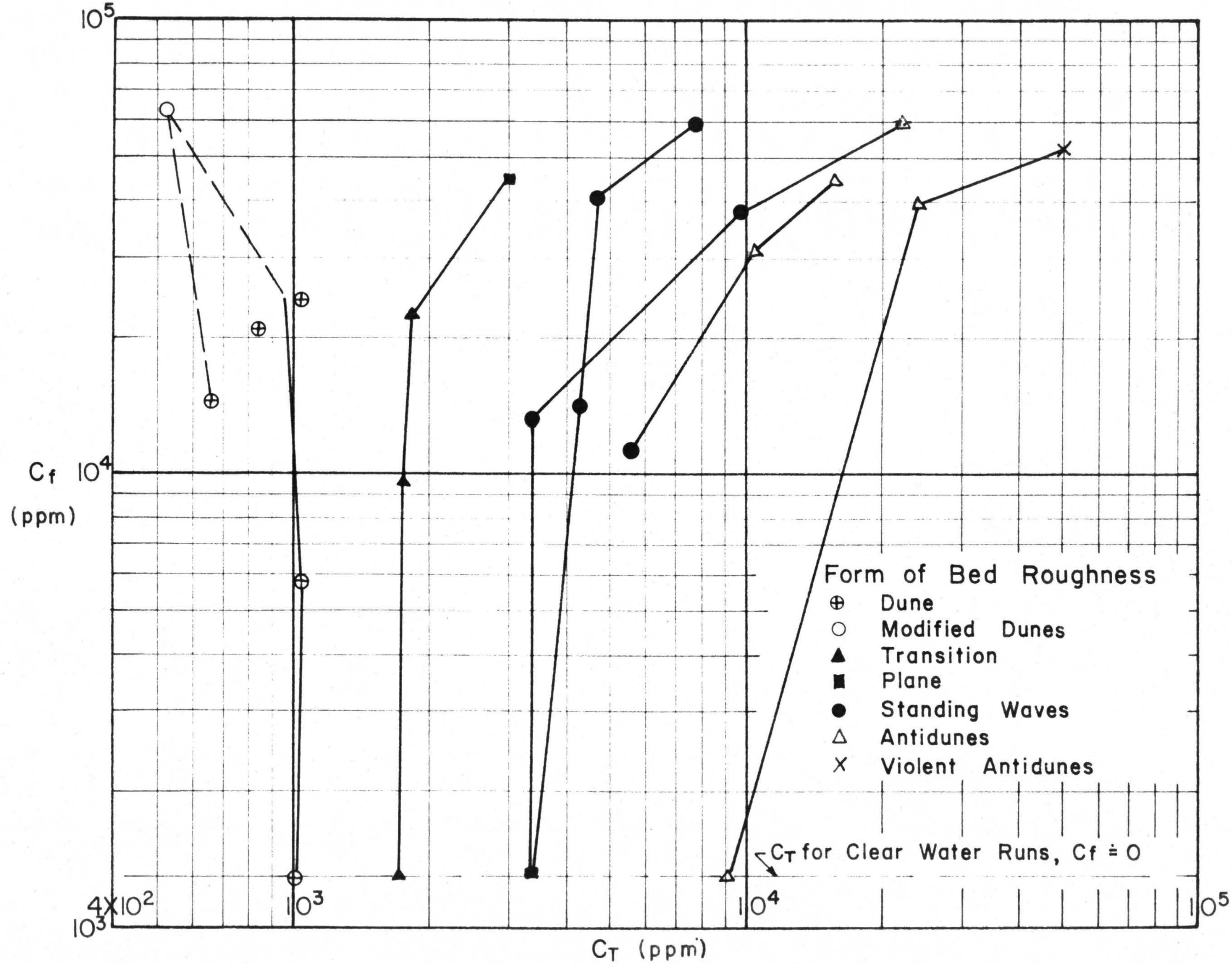


Fig. 7 Variation of Bed Material Transport with Concentration of Fine Material

TABLE 4. Range of C_f below which C_t is not appreciably affected for each form of bed roughness.

Form of bed roughness	Range of C_f ppm
Ripples	2,000 to 4,000 1/
Dunes	20,000 to 30,000 1/
Transition	20,000 to 25,000
Standing waves	10,000 to 15,000
Antidunes	< 5,000

1/ Range where bed becomes partly consolidated with increasing C_f and C_t decreases.

Resistance to Flow

The variation of resistance to flow with concentration of fine sediment is shown in Figure 8. Chezy's coefficient of discharge in dimensionless form, $C/\sqrt{g}$, increases at large fine sediment concentrations for the dune and transition forms of bed roughness and decreases for the standing waves and antidunes.

The sharp increase or decrease in $C/\sqrt{g}$ shown in Figure 8 occurs when the form of bed roughness changes at the greater fine sediment concentrations. The effective median fall diameter of the bed material and its effective fall velocity decreases with increasing C_f ; and for this essentially finer sand, the form of bed roughness is apt to be different than the form of bed roughness with clear water. The resistance to flow changes with bed configuration. As an example, the resistance to flow for antidunes is less than that for the more violent antidunes.

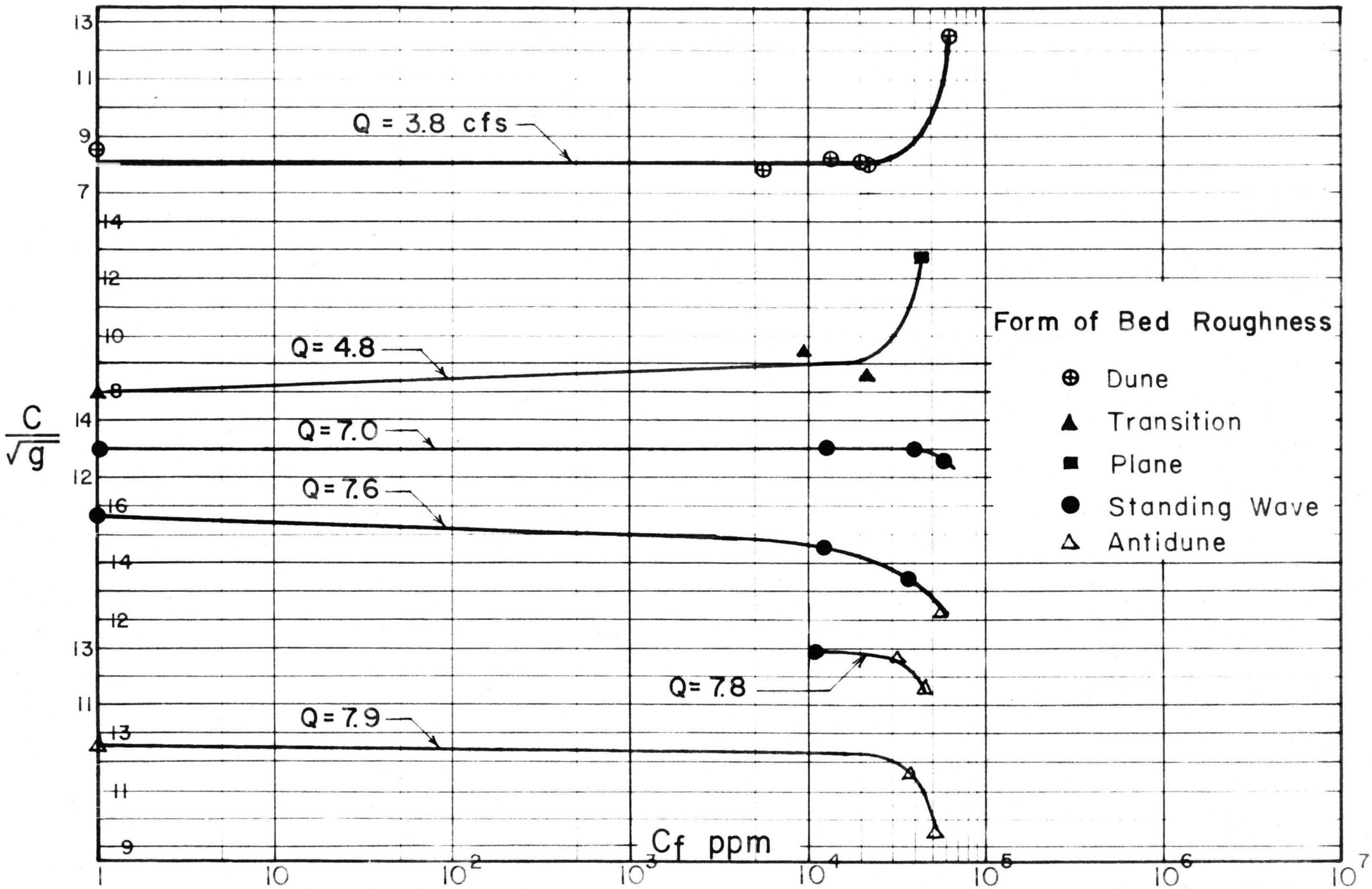


Fig. 8. Variation of the Resistance Coefficient with Concentration of Fine Material

Bed Roughness

Increasing the concentration of bentonite because it changes the effective size of the bed material has the following effect on the bed configuration:

1. Dunes are modified in form to rounded sand waves,
2. Transition dunes change to plane bed,
3. Standing waves change to antidunes, and
4. Antidunes become violent antidunes.

The writers used the 8-foot flume data for the 0.18, 0.28, and 0.45 millimeter sands, to develop a relationship between forms of bed roughness, size of bed material and the parameters V/ω Fr and Vd/ν Fr which is quite effective for flume and laboratory data. The 2-foot flume data have been added to a reproduction of this relationship in Figure 9. The clear-water data show the same general delineation of bed roughness forms as the 8-foot flume data.

The fine sediment data were analyzed using the effective median fall diameter, and corresponding effective fall velocity of the bed material, and the apparent kinematic viscosity. These depend on the concentration of fine sediment for each run. Referring to Figure 9, the bentonite runs plot as though the median fall diameter of the bed material were decreasing with increasing C_f, and lines of constant fine sediment concentrations were drawn as suggested by the consistency of the data.

Qualitatively, the change in bed form with increasing fine sediment is explainable for the flume studies. The effect of fine sediment on the resistance to flow and the transport of bed material is also explained because of their dependence on the form of bed roughness. Considering clear-water flow and a coarse sand, the forms of bed roughness near the transition regime, with increasing shear on the bed are dunes of relatively short length and large amplitude, transition dunes with a longer length and a smaller amplitude, and standing waves in the upper flow regime. As the bed material size is decreased, the dunes and transition dunes change; their length increases greatly and they are much smaller in amplitude; and a plane bed is the form of bed roughness in the upper flow regime for the finer sands.

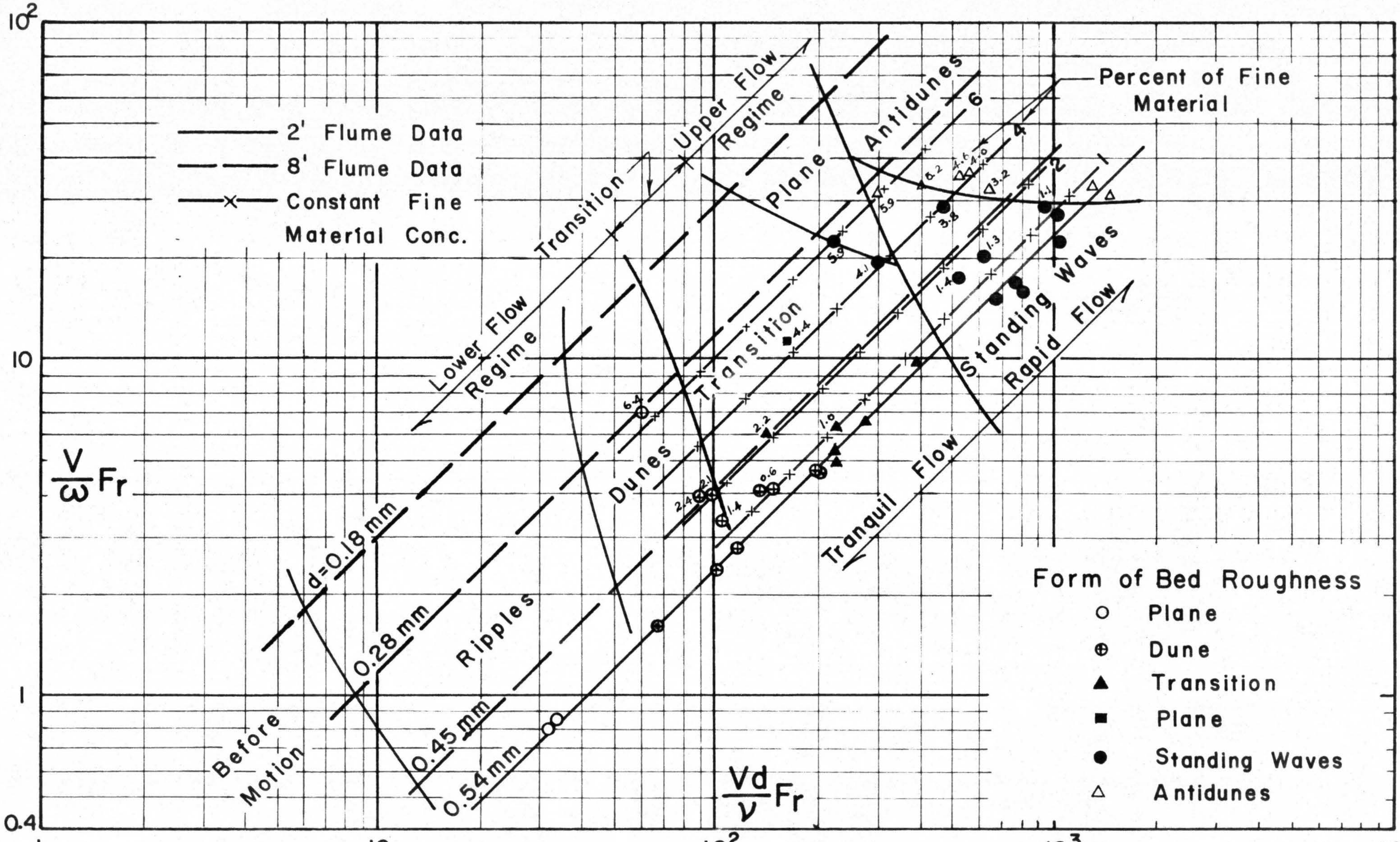


Fig. 9. Forms of Bed Roughness in Alluvial Channels

A similar change to that of decreasing bed material size with clear water occurred with fine sediment flow. The transition type of dune increased in length and decreased in amplitude with increasing fine sediment concentration and at a large fine sediment concentration, the bed became plane. Similar analogies for standing waves to antidunes, antidunes to violent antidunes, and dunes to lesser dunes can be made. However, the form of bed roughness that developed with the ripples and the dunes was affected by the cementing and consolidation of the bed which occurred with relatively large fine sediment concentrations.

Field Application

It has been shown that effective size of bed material is a very significant variable. Consequently, in the analysis of alluvial channel problems, the effective diameter (which is a function of type of fine sediment, concentration of fine sediment, and water-fine sediment dispersion temperature) should be evaluated and utilized.

The effective size can be determined by dropping a representative sample of the bed material in the visual accumulation tube using the water-fine sediment dispersion from the stream as the liquid medium and correcting for temperature effect. Working with the effective diameter, a more realistic insight to form of bed roughness, resistance to flow, and bed material transport is possible; and consequently, a more accurate evaluation of the mechanics of flow.

CONCLUSIONS

1. The apparent viscosity of water-bentonite dispersions are nine to ten times greater than that of clear water when the bentonite concentration is 100,000 parts per million, and the specific weight is about 7 percent greater than that of water.

2. The change in the sediment properties was approximated by analyses in the visual accumulation tube with various bentonite in water dispersions. The standard deviation for the bed material (d = 0.54 millimeters) increased from 1.53 with clear water to 1.83 with 100,000 parts per million of bentonite, the effective fall velocity decreased from 0.28 feet per second to 0.14 feet per second and the effective fall diameter decreased from 0.54 millimeters to 0.32 millimeters.

3. The forms of bed roughness, resistance to flow, and bed material transport for a water-bentonite dispersion flowing over a bed material in a flume study are the same as those occurring with clear water flowing over a finer bed material. The median size of the smaller bed material is closely approximated by the effective median fall diameter of the original sand in the water-bentonite dispersion.

4. The forms of bed roughness, resistance to flow, and bed material transport for flow of clear water and flow containing large fine material concentrations are summarized in the following tabulation.

Form of bed roughness		Resistance to flow $C/\sqrt{g}$		Total bed material transport in ppm	
Clear water	Large fine material conc.	Clear water	Large fine material conc.	Clear water	Large fine material conc.
Ripples	Rounded ripples and rounded sand waves	10.4	14.4	12	2
Dunes		8.5	12.4	1,020	521
Transition dunes	Plane	8.1	12.7	1,700	2,960
Standing waves	Standing waves	13.1	12.6	3,330	7,640
Standing waves	Antidunes	15.7	12.3	3,330	22,300
Antidunes	Violent antidunes	12.5	9.0	9,180	50,000

LITERATURE CITED

Bingham, E. C., 1922, Fluidity and plasticity, McGraw Hill Book Company.

Blench, T., 1957., Regime behavior of canals and rivers, Butterworths Scientific Publications, London.

Colby, Bruce R., 1960, Discontinuous rating curves for Pigeon Roost and Cuffawa Creeks in northern Mississippi: ARS 41-36, Agricultural Research Service, USDA.

Einstien, H. A., 1950, The bed-load function for sediment transportation in open channel flows. Technical bulletin no. 1026, United States Department of Agriculture Soil Conservation Service, Washington, D. C.

Langbein, W. B., 1942, Hydraulic criteria for sand waves, American Geophysical Union Transactions, Part 2, pp 615 - 618.

McNown, J. S., and Lin, P. N., 1952, Sediment concentration and fall velocity: Iowa Institute of Hydraulic Research, State University of Iowa, Reprint in Engineering No. 109.

Rouse, Hunter, 1950, Engineering hydraulics, John Wiley and Sons.

Simons, D. B., and Richardson, E. V., 1960, Resistance to flow in alluvial channels: Am. Soc. Civil Engineers Proc., Vol. 86, p. 73-99.

United States Inter-Agency Committee on Water Resources, 1957, A study of methods used in measurement and analysis of sediment loads in streams; the development and calibration of the visual accumulation tube: Report 11, 109 p.

LITERATURE CITED - Continued

United States Inter-Agency Committee on Water Resources, 1957, A study of methods used in measurement and analysis of sediment loads in streams; some fundamentals of particle size analysis: Report 12, 55 p.