Some Effects of Fine Sediment on Flow Phenomena

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1498-G

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By D. B. SIMONS, E. V. RICHARDSON, *and* W. L. HAUSHILD

STUDIES OF FLOW IN ALLUVIAL CHANNELS

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CONTENTS

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_*.	------	-------------
C_f	Concentration of fine sediment discharge.	ppm--	-------------
C_{f-t}	Concentration of fine sediment and bed material discharge.	ppm--	-------------
C_t	Concentration of total bed material discharge.	ppm--	-------------
d	Median fall diameter of bed material.	L-----	ft
d_n	Nominal diameter. The diameter of a sphere that has the same volume as the particle.	L-----	ft
d_t	Median fall diameter of bed material discharge.	L-----	ft
D	Average depth of flow	L-----	ft
F	Force	F-----	lb
$\mathbb{F}$	Froude number	------	-------------
h	Average height of bed roughness	L-----	ft
l	Average spacing of bed roughness	L-----	ft
L	Length	L-----	ft
Q	Discharge of water-sediment mixture.	L^3/T--	cu ft per sec
q_b	Rate of bed-load transport	F/tL--	lb per ft-sec
q_t	Rate of total sediment transport	F/tL--	lb per ft-sec
$\mathbb{R}$	Reynolds number; for a sediment particle, $\mathbb{R}$ is wd_n/ν.	------	-------------
S	Surface slope in steady uniform flow.	------	-------------
t	Time	t-----	sec
T	Temperature	------	° C
V	Average velocity based on continuity principal.	L/T---	ft per sec
V_s	Average velocity of sand waves in the lower flow regime.	L/T---	ft per min
V_*	Shear velocity which is $\sqrt{gDS}$, or $\sqrt{\tau_0/\rho}$.	L/T---	ft per sec

Symbol	*Description*	*Dimensions*	*Units*
w	Fall velocity of sediment particles	L/T	ft per sec
w'	Fall velocity of sediment in an aqueous dispersion of fine sediment.	L/T	ft per sec
γ	Specific weight of an aqueous dispersion of sediment.	F/L^3	lb per cu ft
γ_w	Specific weight of water	F/L^3	lb per cu ft
γ_s	Specific weight of sediment	F/L^3	lb per cu ft
$\Delta\gamma$	Difference between specific weights of air and water.	F/L^3	lb per cu ft
$\Delta\gamma_s$	Difference between specific weights of sediment and water.	F/L^3	lb per cu ft
δ'	Thickness of laminar sublayer	L	ft
ν	Kinematic viscosity	L^2/T	sq ft per sec
ν'	Apparent kinematic viscosity of the aqueous dispersion of fine sediment.	L^2/T	sq ft per sec
μ	Dynamic viscosity	Ft/L^2	lb-sec per sq ft
ρ	Mass density of water	Ft^2/L^4	Slug per cu ft
ρ_s	Mass density of sediment	Ft^2/L^4	Slug per cu ft
σ_r	A measure of the gradation of the sediment.	------	-------------
τ_0	Tractive or shear force developed on the bed, γDS.	F/L^2	lb per sq ft
τ_c	Critical tractive force associated with beginning of bed movement.	F/L^2	lb per sq ft

GLOSSARY OF TERMS

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

Antidunes. Symmetrical sand and water surface waves which are in phase and which move upstream. The surface waves build up with time and become gradually steeper on their upstream sides until they break like surf and disappear. These waves generally form, 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.

Fine sediment. The part of the total load that is composed of particles of smaller sizes than those found in appreciable quantities in the bed material (referred to by some writers as wash load).

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

Lower flow regime. Flow with bed forms of ripples, ripples on dunes, and dunes.

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

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

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

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

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

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

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

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

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

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

Upper flow regime. Flow with bed forms of plane bed with movement, standing waves, and antidunes.

STUDIES OF FLOW IN ALLUVIAL CHANNELS

SOME EFFECTS OF FINE SEDIMENT ON FLOW PHENOMENA

By D. B. Simons, E. V. Richardson, and W. L. Haushild

ABSTRACT

Fine material (bentonite and kaolin clays) dispersed in water has a very definite effect on the viscosity and specific weight of the fluid. Tests at 24° C. with a Stormer viscosimeter showed that the apparent kinematic viscosity of an aqueous dispersion consisting of 10 percent by weight bentonite was 8.75 times greater than that of pure water, and a dispersion consisting of kaolin was 1.40 times greater. The change is viscosity and density of the fluid changes the fall velocity of the bed material. The effect of fine material on the fall velocity of the bed material can be determined, as a first approximation, with the visual accumulation tube by using aqueous dispersions of clay as the sedimentation liquid. The results from visual accumulation analyses are comparable to those obtained by computation using the Reynolds number, drag relation, and the viscosity of the aqueous dispersion of clay as obtained from the Stormer viscosimeter.

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

INTRODUCTION

Many controversial statements regarding the influence and effect of very fine sediment (clay and silt) on the mechanics of flow in alluvial channels are prevalent. Fine material is most commonly referred to as wash load; wash load 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 term "wash load" is controversial and for the most part is referred to as fine-material load in this report. Einstein (1950) pointed out that the fine-material load does not appear to be a function of the flow, but that it is usually related to supply and that the stream's capacity to transport it is always vastly in excess of the available supply. He did not indicate that its presence is apt to influence the mechanics of flow in any way.

Similarly, Brown, in "Engineering Hydraulics" (Rouse, 1950), stated that the fine-sediment load plays a negligible role in normal stream behavior.

In contrast, Langbein (1942) reported changes in bed form and increased antidune activity as the concentration of fine sediment increased. Blench (1957) also implied that fine-sediment load exerts a measurable effect on flow in alluvial channels. He stated that the velocity distribution and the resistance to flow are affected by the concentration and the characteristics of the suspended-sediment load. In addition Bingham (1922) showed that fluidity, the reciprocal of viscosity, of aqueous suspensions of clay varied markedly with the volume percentage of clay.

As a part of the U.S. Geological Survey's study of fluvial mechanics at Colorado State University an investigation was made of the effects of fine-sediment load on flow phenomena in a large 8-foot flume and a small 2-foot flume. Also, the properties of aqueous dispersions were studied in the sediment laboratory. This investigation, the results of which are reported here, covered the effect of concentrations of fine sediment on (1) the physical properties of the liquid and the hydraulic properties of the bed material, (2) the forms of bed roughness, (3) the resistance to flow, and (4) the bed-material transport.

EQUIPMENT, PROCEDURE, AND DATA

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

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

FLUMES

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

A schematic drawing of the smaller flume is shown in Figure 1. The flume was 60 feet long, 2 feet wide, and 2½ feet deep with ½-inch clear-plastic sidewalls and a floor of ¼-inch stainless-steel plate. The flume was adjustable to any slope from horizontal to 0.1 foot per foot, and it recirculated the mixture of water and sediment.

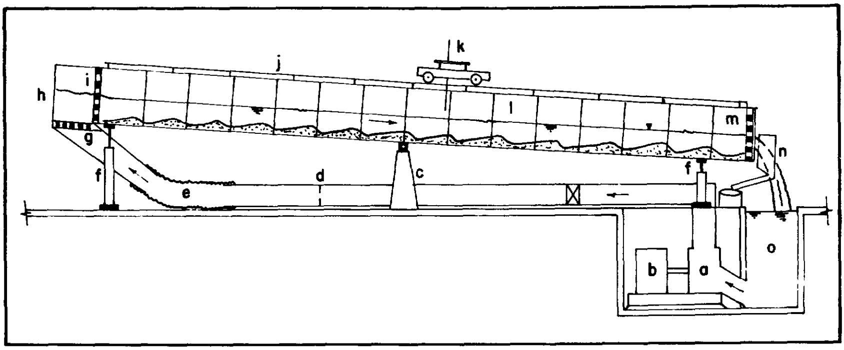

FIGURE 1.—Schematic diagram of the flume. Explanation: *a*, pumping unit; *b*, motor; *c*, center support; *d*, orifice; *e*, flexible connection; *f*, jacks; *g*, manifold diffuser; *h*, head box; *i*, baffles and screens; *j*, rails; *k*, instrument carriage; *l*, flume (2×2.5×60 ft); *m*, tailgate; *n*, total-load sampler; *o*, tailbox.

BED MATERIALS

The sand used as bed material for the flume runs was the same as that used in the study by Simons and others (1961). However, the characteristics of the sand had changed slightly. (See figure 2.) In the study using the 8-foot flume, the median fall diameter d increased slightly, 0.47 versus 0.45 mm, and the measure of gradation σ_r de-

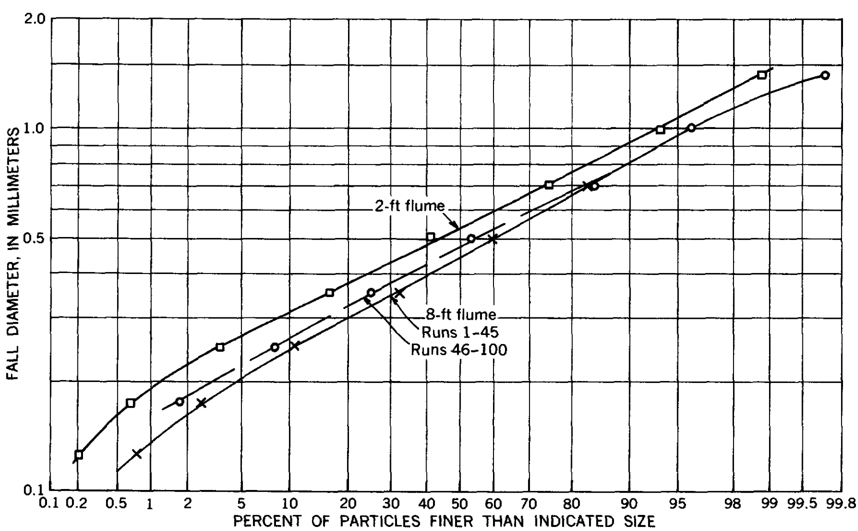

FIGURE 2.—Particle-size distributions of the bed materials.

creased slightly, 1.54 versus 1.60. Also, in the study using the 2-foot flume the median fall diameter was 0.54 mm, and the measure of gradation was 1.50. These changes are attributed to the continued wastage of a small quantity of water introduced through the bearings of the pumps to protect them from sediment; this water carried away some of the fine sand during preceding periods of flume operation.

FINE MATERIALS

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

The size distributions of the bentonite and the kaolin are given in figure 3. The size distributions of the bentonite and the kaolin were determined by standard U.S. Geological Survey sieve-pipette analyses with the samples chemically and mechanically dispersed in water.

GENERAL PROCEDURE

In conducting the experiments to determine the effect of fine sediment on resistance to flow and on bed material transport, specific discharges and slopes were selected, and runs were made with varying concentration of fine material. The mixture of water and sediment 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; and (2) the average water-surface slope remained essentially constant with respect to time.

In the 8-foot flume the first run of a series was started using clear water, and after equilibrium was established, the data that described the run were collected. Then, without stopping the pumps, altering the bed configuration, or changing the external controls (such as tail gate and valves), a measured portion of fine material was added at a time. After the addition of each portion of fine material, the run was continued long enough, at least 24 hours in the lower flow regime, to insure equilibrium, and then the data for the run were collected. When the maximum concentration of fine sediment was reached for a particular series of runs, the process was usually reversed. The slope or discharge or both were changed before starting another maximum-concentration run. Other new runs were then made with the concentration of fine sediment reduced in measured portions between runs

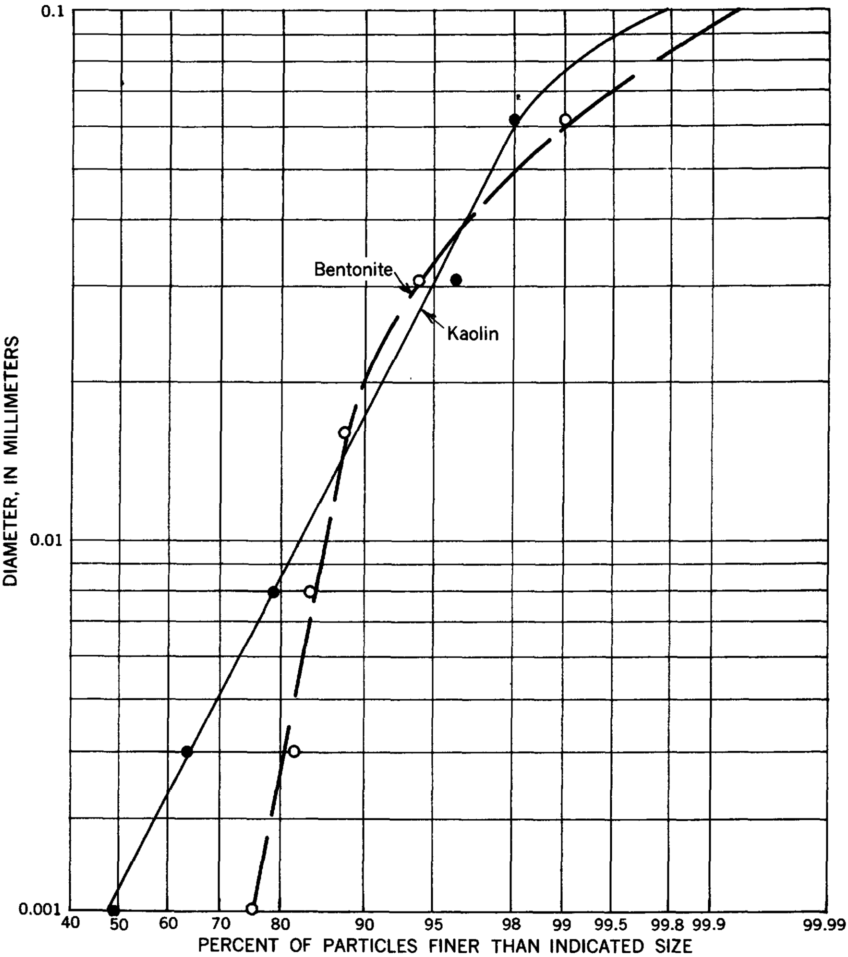

FIGURE 3.—Particle-size distribution of the fine sediments.

by adding water and washing fine material and water through the tail-box overflow.

In the 2-foot flume 15 water-sand runs were made prior to the bentonite runs to define the regimes of flow and the forms of bed roughness for the flume. After the 15 water-sand runs were completed, six series of runs were made to determine the effect of fine sediment. These series of runs covered the range of bed forms from dunes to antidunes, and each series consisted of a water-sand run without bentonite plus three to five runs at different concentrations of fine sediment. When a series of runs were completed, excluding series 15, the aqueous dispersion of bentonite was discarded, and the system and the bed material were washed free of bentonite in preparation for the next series of runs.

TABLE 1.—*Summary of data for runs in flumes*

Run	$s \times 10^2$	Q (cfs)	D (ft)	V (ft/sec)	$\nu \times 10^5$	$\nu \times 10^5$	T (° C)	Sediment discharge				
					Sq ft per sec			C_f (ppm)	C_t (ppm)	C_{f-t} (ppm)	$d_t \times 10^3$ (ft)	σ_r
0.47 mm sand in the 8-foot flume												
46	0.084	14.54	1.11	1.64	1.30	------	13.1	------	181	181	------	------
47	.042	9.59	.75	1.60	1.36	------	11.5	------	23	23	1.141	1.85
48	.052	15.26	1.23	1.55	1.36	------	11.5	------	60	60	1.148	1.85
49	.173	21.32	1.33	2.00	1.38	------	11.0	------	588	588	.823	1.96
85	.047	7.11	.78	1.13	1.31	------	12.7	------	12	12	1.364	1.66
86	.046	6.92	.76	1.14	1.77	1.32	17.0	4,800	1.6	4,800	.249	3.19
87	.046	6.96	.75	1.16	1.11	1.37	19.1	8,400	2.3	8,400	.210	4.37
88	.049	7.10	.74	1.20	1.13	1.50	18.3	11,400	2.5	11,400	.417	3.04
90	.053	6.97	.60	1.45	1.17	1.39	17.1	6,950	37	6,990	1.345	1.70
89	.065	7.08	.60	1.47	1.12	1.42	18.5	9,000	31	9,030	1.361	2.50
93	.072	7.20	.62	1.45	1.24	------	14.7	1	99	100	1.482	1.55
92	.090	7.14	.63	1.43	1.12	1.33	18.5	6,070	106	6,180	1.509	1.93
91	.117	7.12	.58	1.53	1.14	1.42	18.0	8,400	195	8,600	1.443	1.90
82	.248	8.16	.64	1.60	1.00	------	23.2	133	429	562	1.463	1.64
51	.236	8.11	.62	1.62	1.28	------	13.1	584	545	1,130	1.351	1.66
52	.222	8.01	.55	1.81	1.20	1.26	16.0	1,620	578	2,200	1.456	1.63
73	.222	8.20	.61	1.67	1.06	1.24	20.7	5,670	662	6,330	1.509	1.83
74	.215	8.18	.65	1.58	1.05	1.31	21.0	7,970	534	8,500	1.420	2.08
76	.203	8.49	.63	1.69	1.08	1.38	20.0	9,330	463	9,790	1.387	2.00
75	.204	8.24	.64	1.60	1.05	1.36	21.2	9,460	625	10,100	1.574	1.84
53	.235	8.01	.57	1.77	1.16	1.52	17.2	10,700	571	11,200	1.361	1.65
77	.199	8.76	.65	1.68	1.11	1.52	19.1	12,500	639	13,100	1.246	2.91
96	.201	8.31	.53	1.94	1.12	1.93	18.6	25,000	761	25,800	1.066	2.66
94	.237	11.30	.81	1.74	1.28	------	13.5	7	480	487	1.404	1.77
83	.200	15.58	.91	2.14	1.19	------	16.2	------	588	588	1.151	1.74
54	.240	15.36	.92	2.08	1.18	1.25	16.6	1,940	657	2,600	1.253	1.74
56	.242	15.36	.90	2.14	1.03	1.11	22.1	2,860	1,100	3,960	1.148	1.70
55	.237	15.36	.74	2.04	1.12	1.26	18.5	4,060	765	4,820	1.164	1.88
57	.259	15.39	.87	2.20	1.05	1.19	21.3	4,320	761	5,080	1,325	1.91
58	.233	15.28	.90	2.11	1.08	1.25	20.1	5,270	807	6,080	1.210	1.94
95	.180	15.38	.80	2.39	1.12	2.03	18.7	28,300	1,640	29,900	1.099	2.42
78	.320	11.52	.72	2.00	1.07	1.41	20.3	12,000	1,510	13,500	1.089	2.88
59	.326	15.36	.65	2.96	1.04	1.20	21.7	4,570	2,920	7,490	1.312	1.73

60	.342	21.35	.62	4.28	1.06	1.18	21.1	3,600	3,290	6,890	1.427	1.64
61	.355	21.32	.61	4.36	1.00	1.20	23.2	6,170	3,390	9,560	1.440	1.68
71	.531	8.22	.32	3.21	1.04	1.18	21.4	3,600	5,250	8,850	1.525	1.68
72	.550	8.26	.32	3.26	1.08	1.31	20.2	7,100	5,680	12,800	1.505	1.55
70	.640	8.14	.30	3.41	1.08	1.20	20.2	3,910	6,310	10,200	1,476	1.60
63	.570	15.50	.43	4.48	1.05	1.16	21.2	3,020	5,360	8,380	1.633	1.60
64	.578	15.61	.41	4.76	1.05	1.26	21.2	6,440	5,480	12,000	1.630	1.60
65	.571	15.60	.42	4.63	1.04	1.34	21.6	9,090	5,160	14,200	1.584	1.64
66	.575	15.52	.45	4.34	1.01	1.38	23.0	12,300	5,130	17,400	1.647	1.76
80	.643	15.27	.39	4.91	1.04	1.43	21.8	12,100	7,140	19,100	1.624	1.76
81	.634	21.35	.55	4.85	1.38	----------	10.7	7	4,480	4,490	2.076	1.61
62	.622	21.23	.54	4.89	.98	1.12	24.5	4,790	4,490	9,280	2.030	1.54
67	.646	20.87	.53	4.91	1.02	1.36	22.7	11,200	4,390	15,600	1.994	1.57
79	.651	21.31	.55	4.82	1.05	1.46	21.0	12,400	5,760	18,200	2.204	1.82
84	.740	15.36	.41	4.67	1.23	----------	15.0	7	7,100	7,110	1.410	1.39
69	.734	15.54	.43	4.48	1.02	1.24	22.4	7,020	8,280	15,300	1.601	1.71
68	.740	20.94	.53	4.95	1.00	1.23	23.5	7,620	6,760	14,400	2,181	1.55
98	.821	15.80	.44	4.51	1.11	2.46	19.0	42,000	17,700	59,700	1.237	1.90
100	.790	21.42	.51	5.28	1.29	----------	13.3	106	8,440	8,550	2.322	1.40
99	.806	21.27	.50	5.32	1.09	1.96	19.6	26,900	16,100	43,000	1.361	1.93
97	.960	12.01	.37	4.07	1.10	1.29	19.5	5,800	8,960	14,800	2.165	1.50

0.54 mm sand in the 2-foot flume

1	0.016	1.06	0.61	0.89	1.20	----------	15.9	----------	----------	----------	----------	----------
2	.019	1.12	.60	.96	1.16	----------	17.4	----------	----------	----------	----------	----------
3	.026	1.21	.62	1.00	1.17	----------	16.9	----------	0.6	0.6	----------	----------
4	.038	1.59	.59	1.37	1.14	----------	18.0	----------	14	14	1.647	1.34
6	.170	2.45	.72	1.74	1.12	----------	18.6	----------	333	333	1.539	1.66
5	.201	3.12	.81	1.95	1.10	----------	19.2	----------	346	346	1.499	1.60
0	.336	4.28	.91	2.39	1.24	----------	14.7	----------	----------	----------	----------	----------
20	.338	4.74	.72	3.36	1.08	----------	20.2	----------	2,450	2,450	1.621	1.52
8	.351	3.82	.78	2.51	1.11	----------	18.9	----------	1,020	1,020	1.585	1.55
8A	.331	3.82	.84	2.33	1.12	1.31	18.7	5,740	1,050	6,790	1.417	1.58
8E	.248	3.69	.88	2.15	1.00	1.46	23.3	14,500	660	15,200	1.673	1.47
8B	.293	3.84	.85	2.30	1.04	1.70	21.5	20,600	842	21,400	1.483	1.67
8C	.294	3.83	.86	2.28	1.02	1.79	22.4	24,300	1,040	25,300	1.594	1.75
8D	.198	3.77	.72	2.65	.96	3.20	25.0	63,700	521	64,200	.787	2.92
7	.388	3.42	.72	2.44	1.06	----------	20.6	----------	1,090	1,090	2.224	1.55
14	.399	4.77	.89	2.74	1.10	----------	19.3	----------	1,700	1,700	1.667	1.45
14A	.366	4.78	.82	2.95	.98	1.27	24.3	9,580	1,760	11,300	1.532	1.64
14C	.377	4.80	.87	2.82	1.03	1.74	22.2	22,400	1,840	24,200	1.739	1.64
14B	.339	4.84	.70	3.51	1.02	2.41	22.3	44,100	2,960	47,100	1.296	2.91
19	.408	3.82	.76	2.58	1.04	----------	21.5	----------	1,300	1,300	1.463	1.56

TABLE 1.—*Summary of data for runs in flumes*—Continued

Run	$s \times 10^2$	Q (cfs)	D (ft)	V (ft/sec)	$\nu \times 10^5$	$\nu' \times 10^5$	T (° C)	Sediment discharge				
					Sq ft per sec			C_f (ppm)	C_t (ppm)	C_{f-t} (ppm)	$d_t \times 10^3$ (ft)	σ_r
0.54 mm sand in the 2-foot flume—Continued												
9	0.433	4.16	0.72	2.93	1.15	----------	17.7	----------	1,520	1,520	1.421	1.58
10	.486	5.33	.64	4.30	1.07	----------	20.3	----------	2,690	2,690	1.706	1.47
18	.520	7.62	.71	5.44	1.02	----------	22.6	----------	3,330	3,330	1.870	1.61
18A	.508	7.57	.76	5.11	1.02	1.44	22.5	13,200	3,400	16,600	1.804	1.62
18B	.790	7.59	.69	5.62	1.00	1.70	23.3	37,900	9,730	47,609	1.558	1.61
18C	.900	7.59	.70	5.54	.99	3.00	23.7	58,700	22,300	81,000	1.421	1.40
15	.551	6.94	.74	4.75	1.04	----------	21.7	----------	3,330	3,330	1.821	1.53
15A	.550	6.99	.75	4.76	1.02	1.47	22.5	14,200	4,350	18,600	1.519	1.88
15B	.537	6.96	.75	4.73	.99	2.27	23.7	40,900	4,710	45,600	1.476	3.17
15C	.628	6.99	.73	4.85	.99	2.98	24.0	58,600	7,640	66,200	1.247	2.69
13	.565	6.37	.72	4.52	1.14	----------	18.1	----------	3,350	3,350	1.847	1.60
11	.768	7.48	.66	5.80	1.08	----------	19.9	----------	5,690	5,690	2.067	1.46
16A	.980	7.82	.67	5.92	1.00	1.35	23.5	11,200	5,600	16,800	2.198	1.33
16B	1.075	7.84	.66	6.03	.96	1.93	25.0	31,500	10,300	41,800	1.496	1.73
16C	1.305	7.86	.65	6.14	.96	2.32	25.1	44,500	15,800	60,300	1.132	2.22
17	1.175	7.89	.65	6.21	1.02	----------	22.5	----------	9,180	9,180	1.460	1.74
17A	1.365	7.83	.65	6.17	1.02	2.27	22.3	39,600	23,800	63,400	1.214	1.63
17B	1.928	7.86	.68	5.87	.99	2.60	24.0	51,900	50,000	102,000	1.460	1.30
12	1.438	7.84	.64	6.27	1.17	----------	16.9	----------	26,000	26,000	1.486	1.74

Run	Bed material				Sand waves			Bed form	Remarks
	$d \times 10^3$ (ft)	σ_r	w	w'	l (ft)	h (ft)	V_s (fpm)		
0.47 mm sand in the 8-foot flume									
[w computed on the basis of average median fall diameter (0.47 mm) and water temperature for runs. w' computed on the basis of average median fall diameter (0.47 mm) taking into account the effect of fine sediment and temperature on fluid properties]									
46	-----	-----	0.217	-----	5.98	0.41	-----	Dunes	
47	-----	-----	.214	-----	8.20	.22	0.035	do	
48	-----	-----	.214	-----	6.24	.32	.030	do	
49	-----	-----	.212	-----	7.28	.35	.080	do	
85	1.502	1.52	.216	-----	1.20	.07	.0074	Ripples	
86	1.437	1.56	.227	0.223	.96	.06	.0033	do	
87	1.521	1.56	.232	.224	.91	.06	.0055	do	
88	1.640	1.54	.230	.220	1.00	.07	.0015	do	
90	1.355	1.54	.227	.221	1.63	.06	.027	do	
89	1.509	1.48	.230	.223	1.62	.06	.030	do	
93	1.742	1.50	.221	-----	5.98	.17	.039	Dunes	
92	1.619	1.55	.230	.225	4.56	.25	.050	do	
91	1.610	1.58	.229	.222	4.33	.25	.084	do	
82	1.679	1.55	.240	-----	4.12	.28	.17	do	
51	-----	-----	.217	-----	5.55	.20	.19	do	
52	1.417	1.47	.224	.223	5.33	.26	.18	do	
73	1.565	1.52	.235	.231	5.45	.29	.26	do	
74	1.627	1.55	.236	.229	5.50	.34	.17	do	
76	1.456	1.51	.234	.226	5.71	.30	.16	do	
75	1.443	1.47	.236	.228	4.37	.28	.15	do	
53	1.564	1.59	.227	.217	5.81	.34	.11	do	
77	1.581	1.53	.232	.220	5.12	.29	.091	do	
96	1.588	1.52	.231	.205	4.31	.24	.20	do	
94	1.624	1.54	.218	-----	5.21	.32	.28	do	
83	1.633	1.54	.225	-----	5.78	.43	.16	do	
54	1.469	1.51	.226	.224	6.54	.41	.33	do	
56	-----	-----	.238	.236	5.30	.29	.20	do	
55	1.692	1.53	.230	.227	5.87	.27	.23	do	
57	1.518	1.39	.237	.232	5.12	.29	.29	do	
58	1.535	1.48	.234	.230	5.36	.26	.21	do	
95	1.771	1.60	.231	.203	-----	.33	.31	do	
78	1.453	1.49	.235	.223	7.36	.39	.34	do	

TABLE 1.—*Summary of data for runs in flumes*—Continued

Run	Bed material				Sand waves			Bed form	Remarks
	$d \times 10^3$ (ft)	σ_r	w	w'	l (ft)	h (ft)	V_s (fpm)		
0.47 mm sand in the 8-foot flume—Continued									
59	1.535	1.50	0.237	0.234	7.50	.07	0.72	Dunes	
60	1.699	1.48	.236	.233				Plane	
61	1.722	1.55	.240	.234				do	
71	1.673	1.61	.237	.233				do	
72	1.588	1.56	.234	.228				do	
70	1.515	1.63	.234	.231	2.43	.12		do	
63	1.535	1.54	.236	.233	3.43	.23		Antidunes	
64	1.601	1.56	.236	.230	3.43	.20		do	
65	1.506	1.49	.237	.230	3.44	.20		do	
66	1.526	1.56	.240	.228	3.34	.20		do	
80	1.594	1.46	.238	.227	3.36	.26		do	
81	1.584	1.66	.211		4.40	.04		Standing wave	
62	1.647	1.48	.243	.239				do	
67	1.620	1.55	.239	.229	4.00	.10		do	
79	1.355	1.48	.236	.224	3.90	.08		do	
84	1.640	1.53	.222		3.60	.21		Antidune	
69	1.430	1.58	.239	.232	3.73	.26		do	
68	1.738	1.58	.241	.234	4.00	.05		Standing wave	
98	1.440	1.57	.232	.188	3.10	.24		Antidunes	
100	1.561	1.51	.218					Plane	
99	1.492	1.60	.233	.207	4.04	.31		Antidunes	
97	1.597	1.66	.233	.228	3.38	.16		do	

0.54 mm sand in the 2-foot flume

[w computed on the basis of average median fall diameter (0.54 mm) and water temperature for runs. w' computed on the basis of average median fall diameter (0.54 mm) taking into account the effect of fine sediment and temperature on fluid properties]

Run	$d \times 10^3$ (ft)	σ_r	w	w'	l (ft)	h (ft)	V_s (fpm)	Bed form	Remarks
1									
2			0.258					Plane	Some movement
3			.262					do	Do.
4	1.585	1.53	.261		0.47	0.03	0.0001	Ripples	Artificially induced.
5	1.526	1.55	.264			.10	.0004	Plane	One dune front.
6	1.640	1.67	.266		4.6	.35	.0047	Dunes	

5	1.575	1.57	.268		5.0	.26	.0080	do	
0	1.565	1.56	.254		4.0	.30	.0054	do	
20	1.716	1.51	.271		4.3	.17	.036	do	Transition.
8	1.903	1.48	.267		3.6	.23	.012	do	
8A	1.699	1.45	.265	.258	3.8	.20	.012	do	
8E	1,968	1.45	.278	.262	3.6	.19	.0073	do	
8B	1.949	1.49	.274	.252	3.6	.20	.010	do	
8C	1.772	1.47	.276	.248	4.4	.24	.011	do	
8D	1.706	1.51	.282	.208	.7	.08	.0062	Sand waves	
7	1.804	1.53	.272		3.3	.17	.012	Dunes	
14	1.903	1.50	.268		4.0	.20	.021	do	Transition.
14A	1.837	1.50	.280	.270	5.8	.20	.030	do	Do.
14C	1.837	1.53	.275	.250	5.8	.19	.034	do	Do.
14B	1.837	1.48	.276	.228				Plane	Do.
19	1.788	1.54	.274		4.2	.16	.018	Dunes	Do.
9	1.549	1.50	.263		4.2	.18	.022	do	Do.
10	1.824	1.64	.271					Plane	Do.
18	1.870	1.49	.276					Standing waves	
18A	1.837	1.48	.276	.262				do	
18B	1.837	1.45	.278	.237				do	
18C	1.919	1.44	.279	.208				Antidunes	
15	1.732	1.48	.274					Standing waves	
15A	1.854	1.52	.276	.261				do	
15B	1,837	1.49	.279	.232				do	
15C	1.722	1.44	.280	.213				do	
13	1.713	1.60	.265					do	
11	1.509	1.62	.270					do	
16A			.278	.266				do	
16B	1.713	1.45	.282	.248				Antidunes	
16C	1.837	1.38	.282	.232				do	
17	1.690	1.46	.276					do	
17A	1.837	1.42	.276	.233				do	
17B	2.100	1.40	.280	.221				do	
12	1.847	1.58	.261					do	

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

After completion of run series 15, run 16A was made by reversing run 15C. (See table 1.) Although some bentonite was conserved by this method, an undesirable bed condition resulted. The sand bed became partly stabilized with bentonite and difficult to move. Runs 16A, B, and C were completed with this anomalous bed condition and probably would have been similar to run series 17, 17A, and 17B had the normal procedure of starting with clear water been followed.

BASIC DATA

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

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

Typical records of the slope measured by the bubble gage for various forms of bed roughness are illustrated in figure 4. A study of figure 4 shows that the pattern of variation of slope with time is directly related to the form of bed roughness.

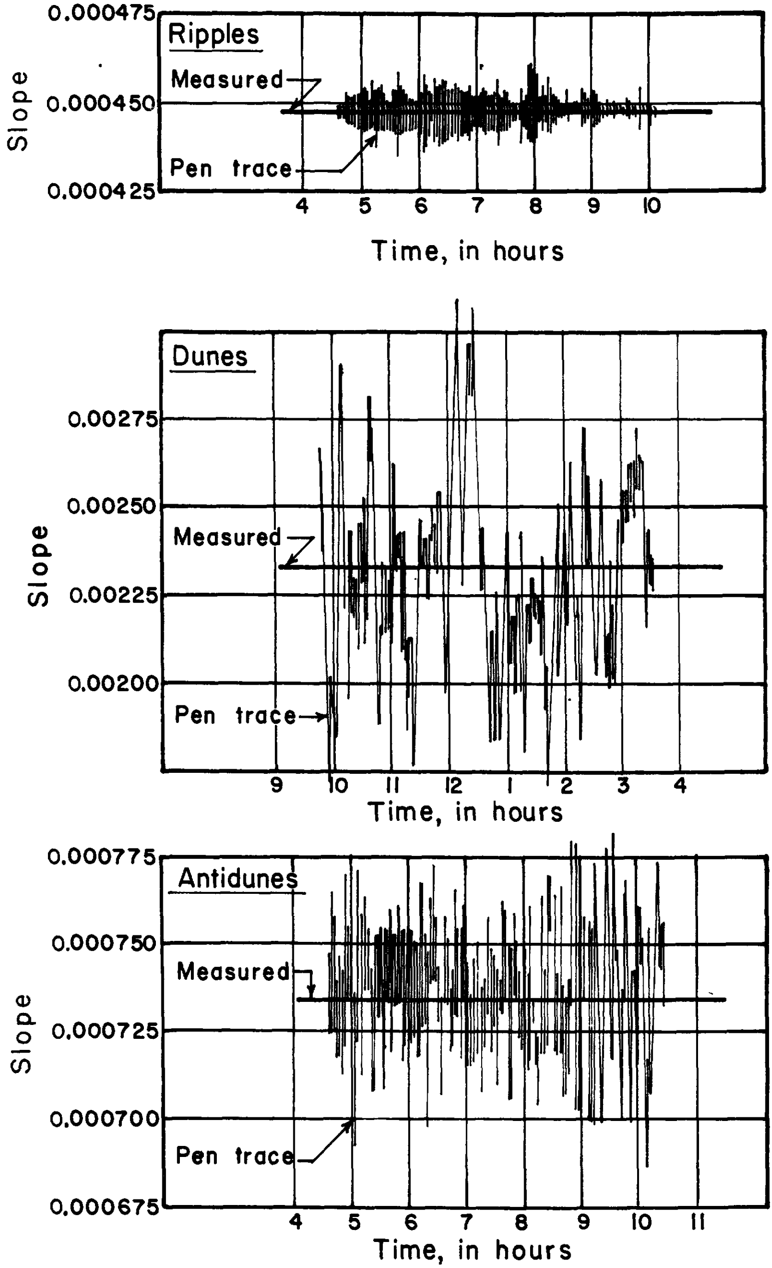

FIGURE 4.—Measured and recorded water-surface slopes.

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

The water temperature was measured in degrees centigrade to the nearest 0.1° wth a mercury thermometer. Water temperature was virtually constant for a particular run but ranged from 10.7°C to 25.1°C during the study.

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

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

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

The total sediment load was sampled with a width-depth integrating total-load sampler where the water discharged from the flume into the tail box. In the lower flow regime eight samples were collected over a 2-hour period, and in the upper flow regime four to six samples were collected over a 1-hour period. Each sample consisted of 70 to 110 pounds of the mixture of water and sediment.

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

Part of the bed-material discharge for the bentonite runs could have been bentonite because 0.5 percent of the bentonite was coarser than the number 200 sieve (0.074 mm opening) and 2.0 percent was coarser than the number 270 sieve (0.053 mm opening). (See figure 3.) For example, in run 8D the concentration of the bed-material discharge contributed by the bentonite could be 318 ppm (0.5 percent of 63,700 ppm, which is 61 percent of the concentration of bed material C_t). In run 17B the possible 230 ppm contributed by the bentonite is only 0.46 percent of the concentration of the bed material.

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

Suspended sediment was sampled near the midpoint of the 8-foot flume with a specially designed depth-integrating sampler. The sampler consisted of a brass nozzle, 3 by ¼ inches, 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. To determine the suspended-sediment concentration, one 5–8 pound sample was collected from the flow along equally spaced verticals in the cross section. The transit rate for the sampler was approximately uniform throughout the collection period (no variation in transit rate between upward and downward trips at a vertical or between verticals). Suspended sediment was not sampled in the 2-foot-flume study.

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

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

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

in which

d = the median fall diameter,
d_{16} = the size, by weight, for which 16 percent is finer, and
d_{84} = the size for which 84 percent is finer.

In addition to the median fall diameter and the gradation coefficient, the fall velocity w of the median fall diameter at the temperature of the run is given in table 1. Also when fine material was in the flow the fall velocity w' is given that takes into account the effect of the concentration of fine sediment for that run.

The amplitude h, length l, and velocity V_s of the various bed configurations were evaluated by (1) direct measurement at the observation window, (2) direct measurement with a point gage and foot attachment, and (3) utilization of a sonic depth sounder (Richardson and others, 1961), a method which was only applicable when the form of bed roughnesss was ripples, dunes, or transition.

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

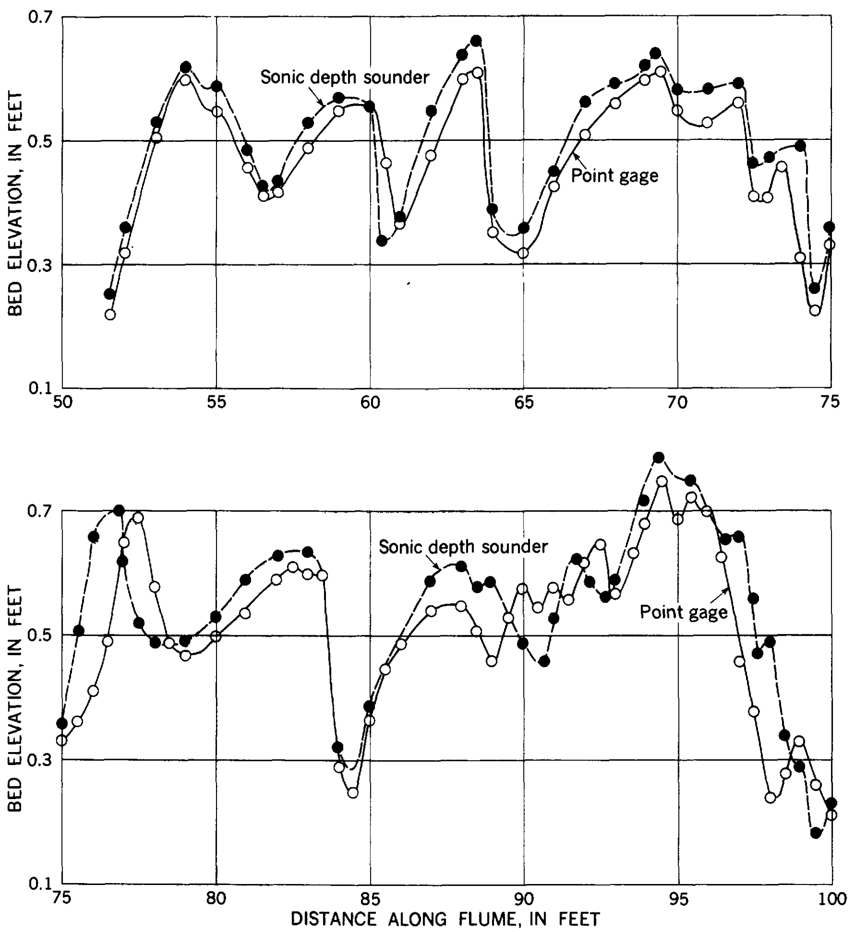

Figure 5.—Comparison of bed-configuration measurements.

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

EFFECT OF FINE SEDIMENT ON FLUID PROPERTIES

VISCOSITY

Aqueous dispersions of kaolin or bentonite are non-Newtonian; that is, the shearing stress is not directly proportional to the rate of shear. Therefore, the coefficient relating the shearing stress to the rate of shear represents an apparent viscosity and is a function of the rate of shear. The modifier "apparent" is used to indicate that aqueous dispersions of bentonite or kaolin are non-Newtonian liquids. The apparent viscosities of aqueous dispersions of kaolin and bentonite were experimentally determined by using a Stormer viscosimeter and sodium hexametaphosphate as a dispersing agent. Viscosities of dispersions having 0.5, 1, 2, 3, 5, and 10 percent bentonite and 3, 5, and 10 percent kaolin by weight in distilled water were measured at temperatures ranging from 5 to 45° C. The dispersions tested after mixing at settling times of 0, 10, and 60 minutes showed no changes in viscosity due to settling out of the coarser particles or to the formation of a gel. The apparent kinematic viscosity of the aqueous dispersions of bentonite is shown in figure 6, and the viscosity of the aqueous disper-

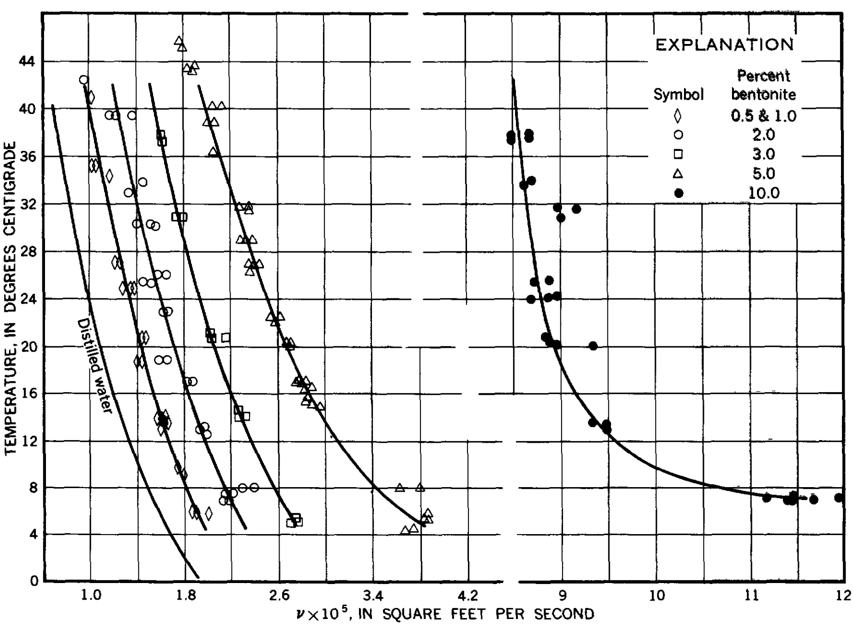

FIGURE 6.—Apparent kinematic viscosity of aqueous dispersons of bentonite.

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

These relations of apparent viscosity to concentration of clay are very similar to several that Bingham (1922) investigated by relating temperature and volume concentration of earth, china clay, and graphite to fluidity, the reciprocal of viscosity. On the basis of his studies, he concluded that at each temperature fluidity decreases rapidly and linearly with increasing concentration of solids.

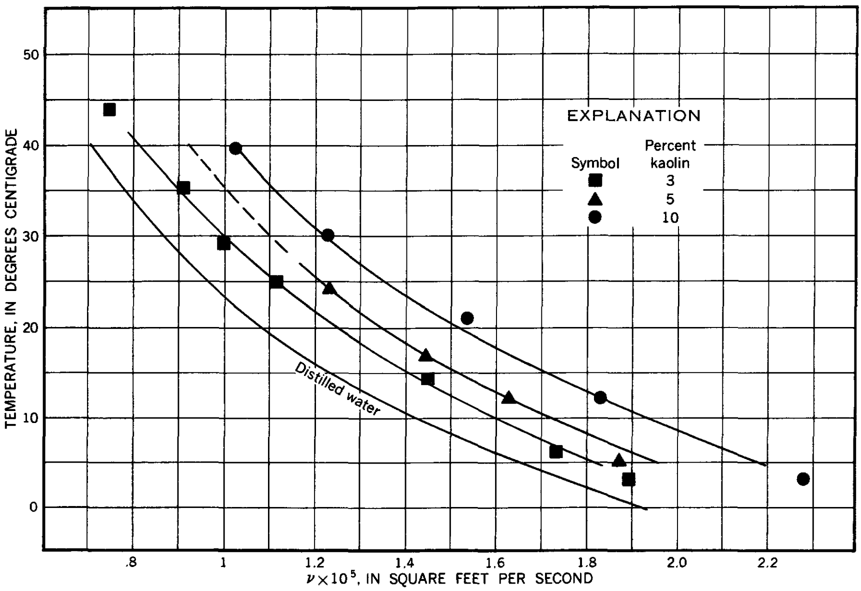

FIGURE 7.—Apparent kinematic viscosity of aqueous dispersons of kaolin.

Street (1958) related the viscosity of aqueous dispersions of clay to their behavior at different stages of neutralization. He showed experimentally that the viscosity increases with an increase of neutralizing agent to a maximum that occurs at the isoelectric point (approximately a pH of 7.5 for kaolin and about a pH of 4.5 for montmorillonite). After this maximum for the deflocculated state, the viscosity decreases rapidly with further addition of the neutralizing agent. He reasoned that the apparent viscosity at any stage of neutralization depends greatly on the type of flocculation present at that stage. He studied the effect of the zeta potential and hydration potential of the Ba, Ca, K, Na, and Li cations used for neutralization on the viscosity.

A study of the viscosity of dilute clay-mineral suspensions by Wood and others (1955) indicated that aqueous dispersions of bentonite from Wyoming, hectorite, and attapulgite exhibited non-Newtonian behavior at 0.5, 1, 2, 3, 4, and 5 percent concentrations. Their results show that the ratio of apparent viscosity of the liquids to the viscosity of water at the same temperature is independent of the temperature. From this, they reasoned that the viscosity of dilute aqueous clay suspensions ($\leqq$ 5 percent concentration) is governed by the geometry of the particles rather than by the specific interactions between particle and suspending media or between particle and particle. Inspection of figures 6 and 7 indicates that at a specific temperature the ratio of the viscosity of the aqueous dispersions of kaolin and bentonite, for concentrations $\leqq$ 5 percent, to the viscosity of water is relatively independent of temperature, which conforms with the findings of Wood and others (1955).

The ratio of the weight of dispersing agent (sodium hexametaphosphate) to weight of fine sediment was kept constant at 1/100 for the flume experiments, the viscosity determinations, and the fall velocity studies. This ratio resulted in a dispersion of approximately deflocculated bentonite in water but was probably too great to yield a dispersion of maximally deflocculated kaolin in water. The constant ratio was sufficient to allow study of the effect of change in fluid properties caused by addition of clays to water on flow phenomena and hydraulic properties of the bed material; however, a full study would necessarily include the effect of the amount and nature of adsorbed cations on the properties of the aqueous dispersions of clay. Figure 8 was prepared from the literature and indicates in a general way that the viscosity of clay-water systems varies with amount and nature of adsorbed cations. Figure 8 is only the general shape of the relation

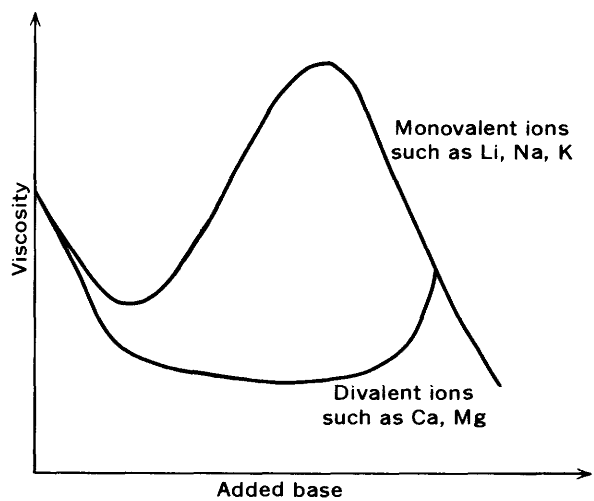

FIGURE 8.—General shape of the viscosity curves for clay-water systems with various amounts of added base.

of viscosity to added base, and the relation varies with the type of clay and the amount of added base (Baver, 1959; Street, 1958). The many investigators of viscosity of aqueous clay dispersions attribute the variation in viscosity with the amount of added base to the electric charge, the degree of ionization, the hydration of the ions, and the degree of flocculation. Apparently, the relation is more properly a function of all the foregoing physiochemical properties. The effect of fine sediments in a stream would depend upon the concentration, the size and type of the fine sediment, the amount and nature of the adsorbed ions, and the relatively uninvestigated role of turbulence in sustaining a dispersion of fine sediment.

SPECIFIC WEIGHT

The specific weight of an aqueous dispersion of fine sediment depends on the concentration and specific gravity of the sediment. The specific weight of the aqueous dispersion of sediment is given by

$$\gamma=\frac{\gamma_w\gamma_s}{\gamma_s-C_f(\gamma_s-\gamma_w)}. \tag{1}$$

Assume that

γ_w=62.4 lb per cu ft, and
γ_s=165.4 lb per cu ft,

then the equation becomes

$$\gamma=\frac{10{,}021.8}{160.6-\frac{C_f}{104}}.$$

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

EFFECT OF FINE SEDIMENT ON FALL VELOCITY

In a study of flow in alluvial channels, the properties of the bed material are significant. The mineral identification, density, shape, surface area, and volume of individual particles, and the size distribution of all the particles are usually used to describe the bed material. The fall velocity of the individual particles and the particle-size distribution based on fall velocity combine the properties of the bed material into one fundamental hydraulic principle. Because fall velocity varies with changes in the fluid characteristics, it is also a means of directly relating the bed-material properties to the fluid characteristics. The effect of changes in the viscosity and specific weight of the fluid on the fall velocity of sand particles has been generally ignored in alluvial-channel research (Langbein, 1942). On pages G1 and G2 the appreciable effect of bentonite and kaolin on fluid properties was discussed. In this section the effect of the two fine sediments on fall velocity are discussed.

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

The settling velocities of particles in a sample of a mixture of water and sediment depend on the characteristics of the particles, the volume of the sample, the characteristics of the liquid, and the measuring apparatus. Test conditions were arranged so that the only variable in the particle-size analyses was the sedimentation media. A basic assumption was that the calibration of the visual accumulation tube was valid for the sedimentation media of fine sediments in water.

Samples of the three sands were analyzed in the visual accumulation tube for particle-size distribution in distilled water, in aqueous dispersions of 3, 5, and 10 percent kaolin and of 1, 5, and 10 percent bentonite. A graph of typical size distribution is shown in figure 9. The change in the fall velocities of the median fall diameters with the percentage of bentonite in water is shown in figure 10 and with the percentage of kaolin in water in figure 11. The fall velocities were computed from the relation of the fall diameter of naturally worn quartz particles to fall velocity given in Inter-Agency Report 12.

The variation of the gradation coefficient σ_r, with concentration of bentonite is summarized in table 2. The gradation coefficient varies because the coefficient of drag for any specific sand particle changes with viscosity, but the change is less for a large particle than a small particle.

A check was made on the accuracy of particle-size analyses in the visual accumulation tube when aqueous dispersions of fine sediment were used. The change in the fall velocity of a particle representing a single size, the median fall diameter of the sand sample, was computed for each of the fine-sediment media used in the visual accumulation tube. In the computations, the median fall diameter (converted to a nominal diameter), the apparent viscosity of the medium, the mass density of the medium and of the particle, and a particle shape

TABLE 2.—*Variation of the measure of gradation with percentage of bentonite in water*

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

factor of 0.7 were used. The empirically established relation between the drag coefficient C_D for a particle falling at terminal velocity and the Reynolds number $\mathbb{R}$ was then determinable and from these the fall velocity was computed. The C_D versus $\mathbb{R}$ relation for naturally worn sediment particles is given in figure 1 of Inter-Agency Report 12.

The agreement between the computed fall velocities and those determined from the visual accumulation tube analyses is surprisingly good. (See figures 10 and 11.) Several of the many factors that might contribute to disagreement are: (1) the lack of a good definition

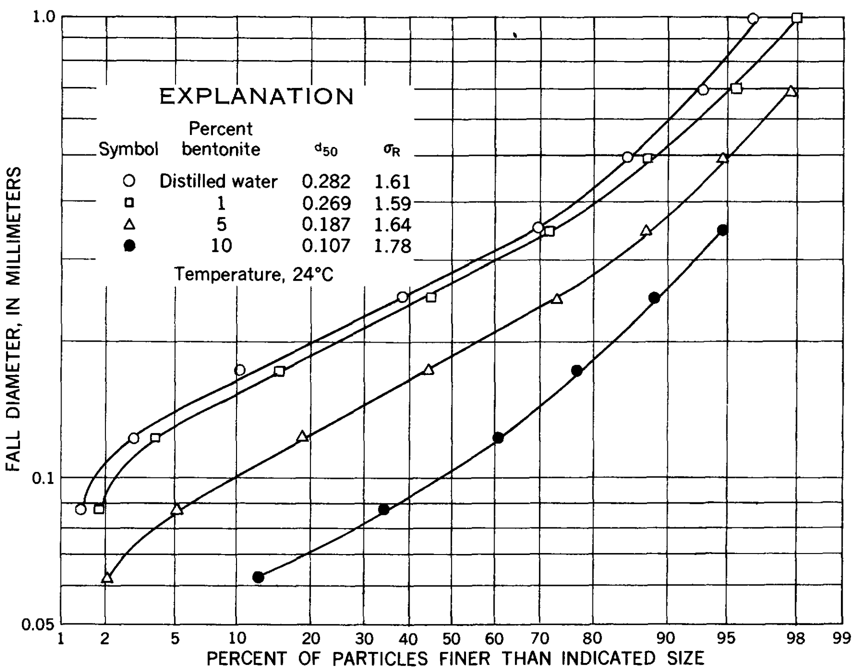

FIGURE 9.—The particle-size distribution of a sand sample from the Elkhorn River, Nebr., based on its fall velocity in various concentrations of bentonite dispersed in distilled water (analyzed in the visual accumulation tube).

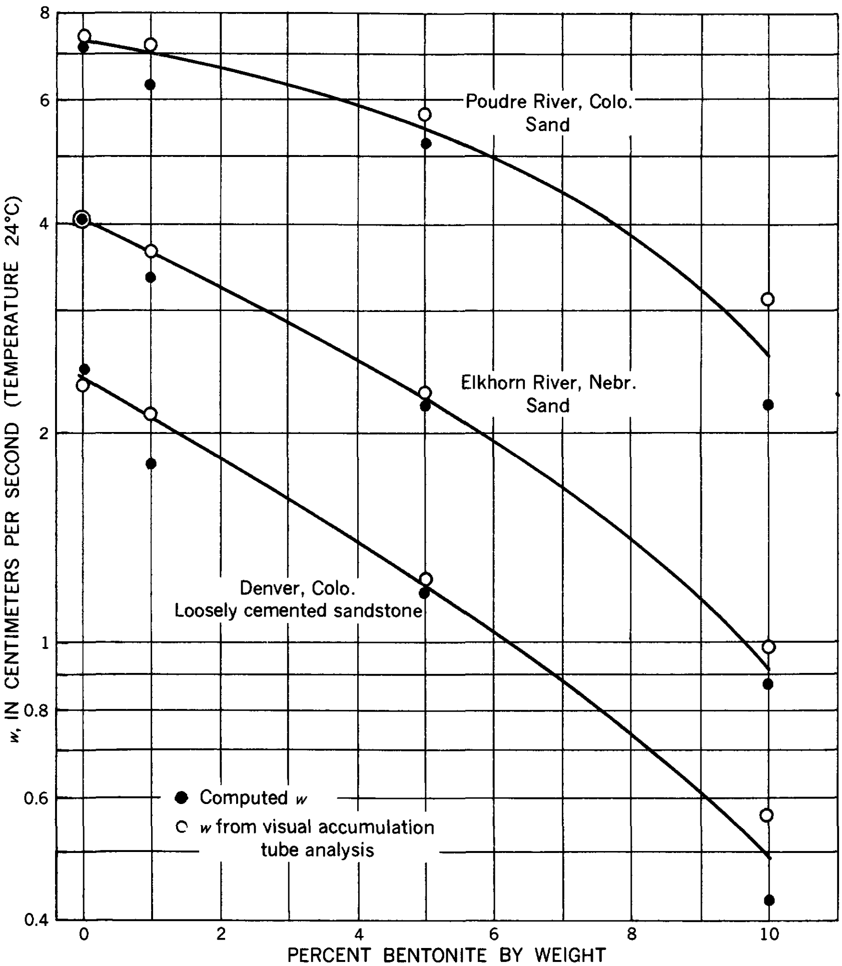

FIGURE 10.—Variation of fall velocity with varying percentage of bentonite in water.

of the C_D versus R relation for sediment particles; (2) errors in measuring the apparent viscosity of the fine sediment in water dispersions; (3) the shape factor of the sand particles that may differ appreciably from 0.7; and (4) the presence of the fine sediment particles in the visual accumulation tube that probably affects the fall velocity of the sand particles through interference, the currents and eddies generated by the falling fine sediment particles, and the possibility that the fine sediment was not uniformly distributed in the sedimentation column.

The variation of fall velocity of the three sands with water temperature is given in figure 12. As the change in the specific weight of distilled water with temperature is relatively slight when compared with the change in the viscosity, the variation shown in figure 11 em-

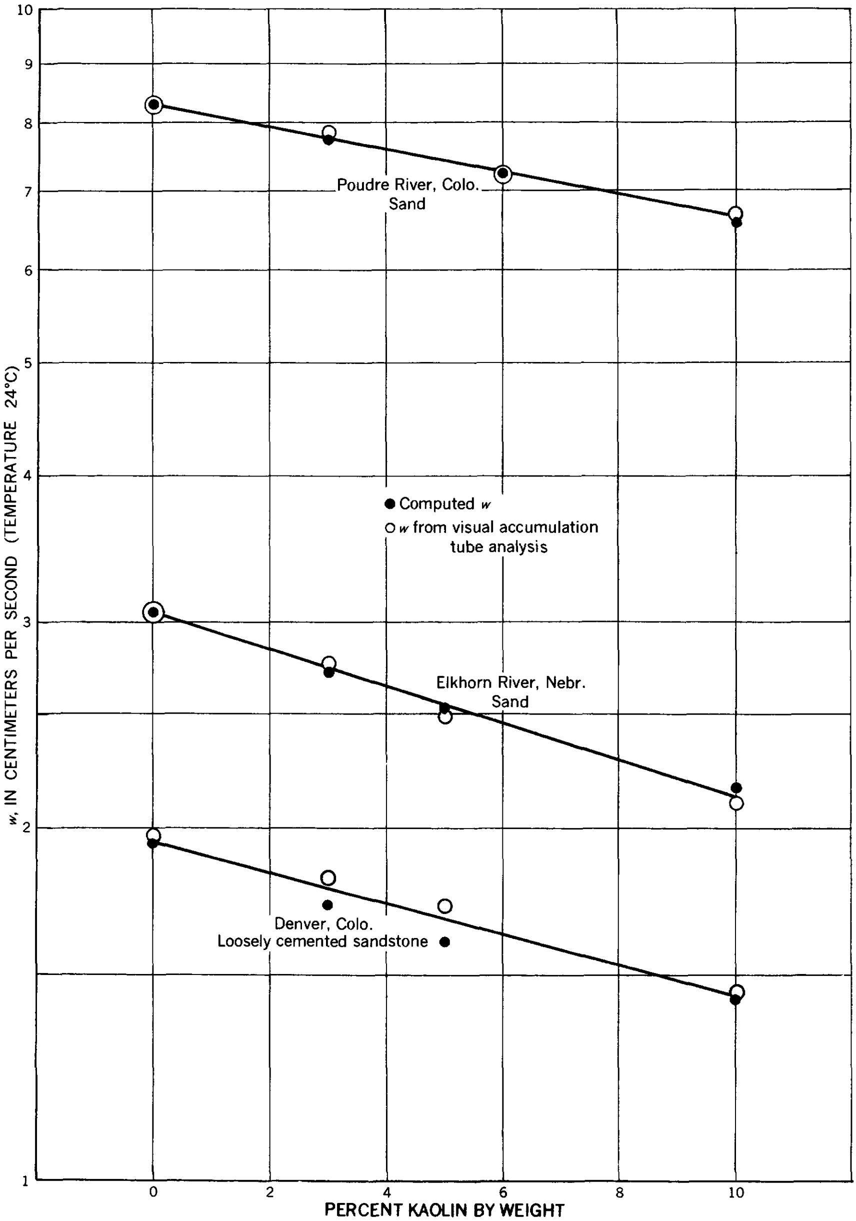

FIGURE 11.—Variation of fall velocity with varying percentage of kaolin in water.

phasizes the part that viscosity of the liquid has on the fall velocity without the complications introduced when considering a fine sediment dispersed in water.

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

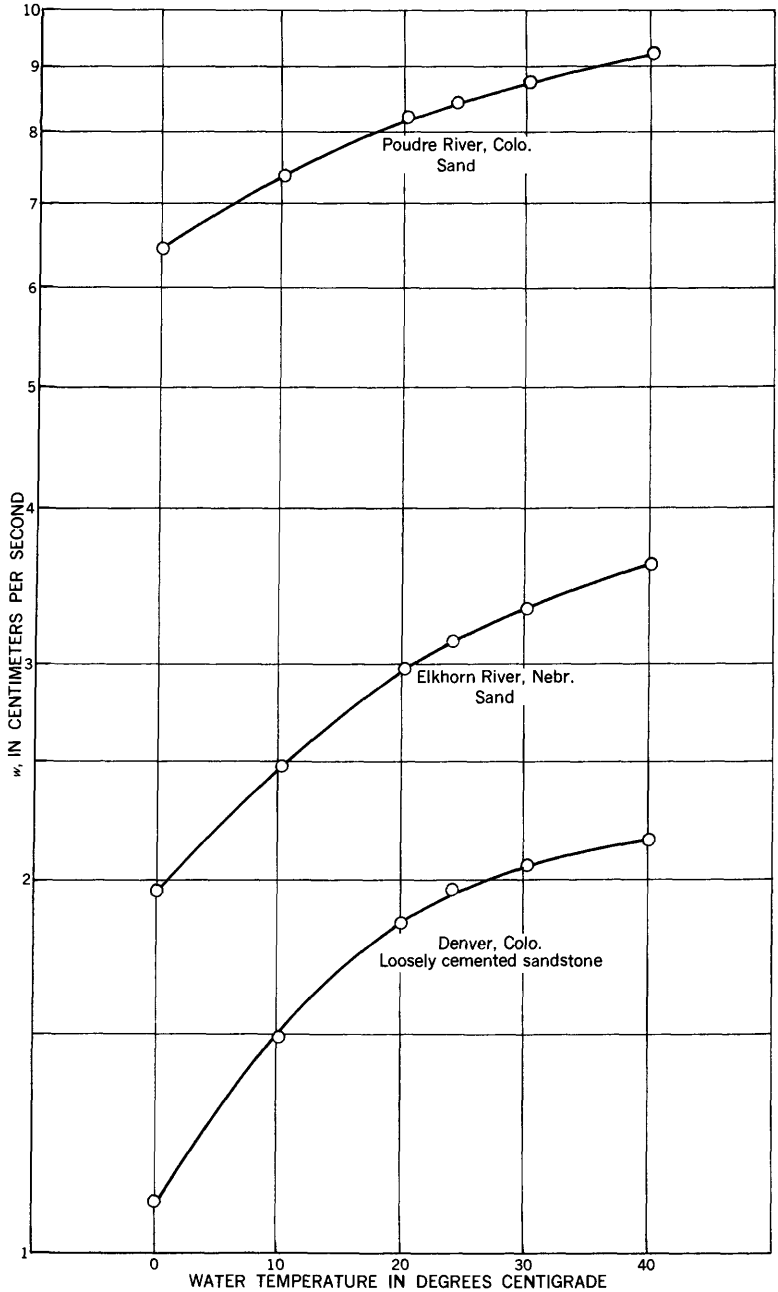

FIGURE 12.—Variation of fall velocity with water temperature.

1. Direct computation of using the C_D versus R relation. This entails determining or knowing the variation of the properties of the particles and of the characteristics of the stream liquid with

time and temperature. However, a more exact definition of the C_D versus ℝ relation for irregular shaped sediment particles is needed.

2. Determine the size distribution of the bad material in the stream liquid by dropping a representative sample in the visual accumulation tube using the stream liquid as the sedimentation medium. The size distribution can then be converted to a fall velocity. However, the visual accumulation tube was calibrated for the range of temperatures from 20° centigrade to 30° C.; therefore, outside this range, the procudure reverts back to the method of direct computation. Extending the calibration of the visual accumulation tube to include temperatures normally found in streams appears to be desirable, and the reliability of particle-size distributions obtained from the visual accumulation tube analyses needs to be checked for sedimentation media other than distilled water.

OBSERVED FLOW PHENOMENA

REGIMES OF FLOW AND FORMS OF BED ROUGHNESS

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

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

Lower flow regime: (1) plane bed without movement, (2) ripples, (3) dunes with ripples superposed, and (4) Dunes;

Transition: transition from dunes to upper flow regime;

Upper flow regime: (1) Plane bed and water surface, (2) Standing sand and water waves which are in phase, and (3) Antidunes.

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

The absence of ripples was investigated at depths varying from 0.2 to 2.0 feet and at various water-surface slopes. Each investigation was started at the beginning of sediment motion. For each investigation, the depth was held constant, and the discharge and (or) the slope was increased until the shear on the bed and the bed material in transport increased sufficiently so that dunes developed. Artificially induced ripples were slowly erased back to a plane bed by the flow. Run 3, where ripples were artificially produced that persisted throughout the run, was not considered representative of normal conditions. During run 3, insufficient time was allowed prior to collecting data for the flow to convert the artificially formed ripple bed back to a plane bed at the low transport rate of bed material, which was 0.6 ppm.

Ripples superposed on dunes were observed in the 8-foot flume but were not observed in the 2-foot flume. Owing to the narrower width, the flow and forms of bed roughness were more two dimensional in the smaller flume than in the larger flume. The dune fronts across the 2-foot flume were continuous and virtually perpendicular to the flow, whereas in the 8-foot flume they were not. (See figures 13 and 14.) Also, in the 2-foot flume the standing waves and antidunes formed across the entire flume width. (See figures 15 and 16.)

With large concentrations of fine sediment, the spacing and shape of the ripples and dunes and the antidune activity were modified. For example, in run series 14, where flow conditions were not changed, the

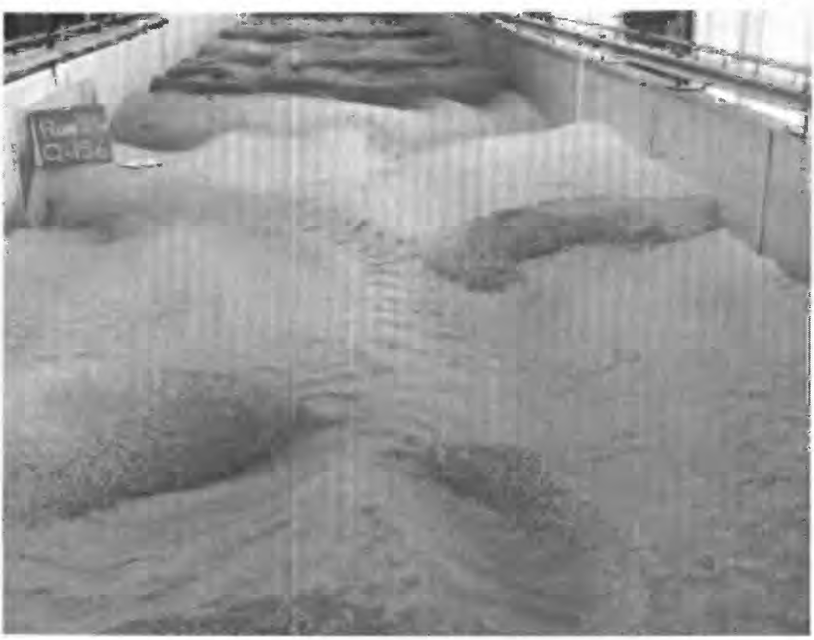

FIGURE 13.—Dune bed configuration in the 8-foot flume.

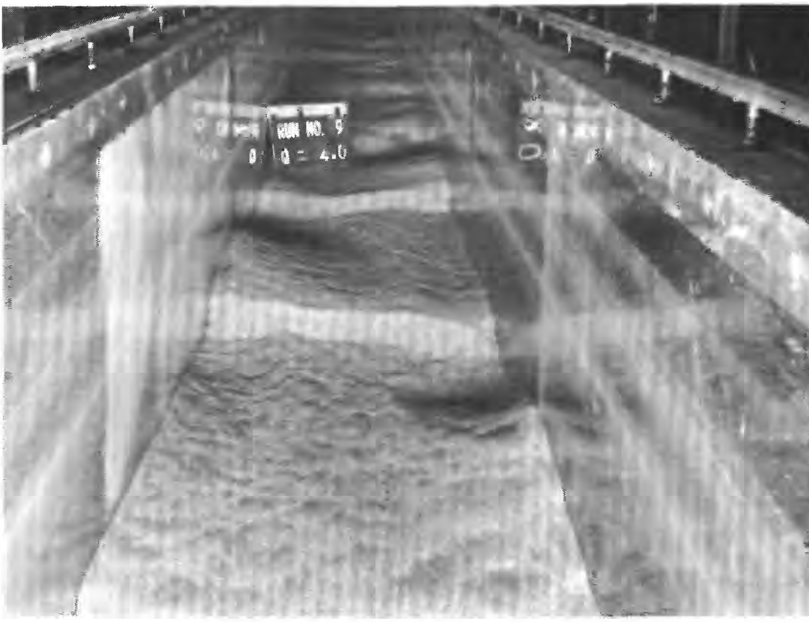

FIGURE 14.—Dune bed configuration in the 2-foot flume.

FIGURE 15.—Antidunes in the 8-foot flume. Note the three-dimensional aspect of the two lines of waves.

dunes increased in length from 4 feet to 5.8 feet, and eventually the bed became plane with increasing concentration of fine sediment. The changes that occurred in the bed form, the resistance to flow, and the sediment transport are elaborated on in subsequent paragraphs.

FIGURE 16.—Antidunes in the 2-foot flume. Note the two-dimensional aspect of the waves.

LOWER FLOW REGIME

RIPPLES

Runs 85–90, in the 8-foot flume, were made with ripple-bed configuration, holding Q and S constant and varying the concentration of fine material. (See table 1.) This sequence of runs was made without stopping the flow. The fine material load was increased from 0 to 11,400 ppm by portions added between runs. The addition of fine material that was in as 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 bed. The fine material partly filled the voids in the bed and adhered to the sand particles causing a cohesive stable boundary to form. With the smaller concentrations of the fine material in runs 86 and 87, the stabilized patches of the bed were not as extensive in area as with the higher concentrations in runs 88 and 89, and the flow was able to break up the cohesive patches. However, new patches formed elsewhere on the sand bed. With the largest concentration (11,400 ppm), a major percentage of the surface of the ripple bed was stabilized, as a result of the presence of the clay binder, and the turbulence of the mixture of water and sediment was much greater than with the normal ripple bed. Run 90 had a larger percentage of the bed stabilized with the fine sediment than run 87, even though the concentration of fine material was less. This resulted from the residual effects of run 88.

Where the bed was not bound by the fine material and the ripples were advancing, fine material was deposited in the ripple troughs. When the ripples moved over former troughs, lenses of fine material were trapped in the bed. (See figure 17.)

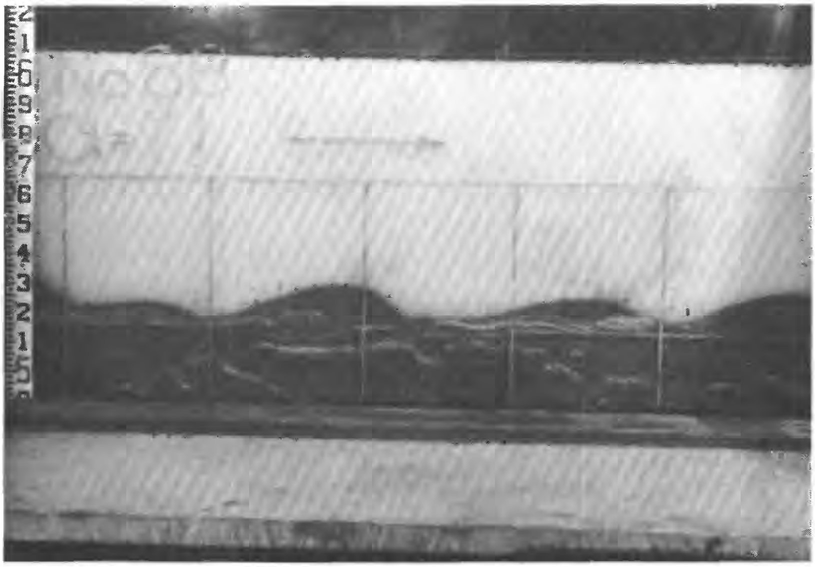

FIGURE 17.—Lenses of fine material trapped in the bed. Note rounded crests.

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

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

Although there was enough fine material deposited on the bed to stabilize large areas for a given condition of flow, the bed material sampled never contained more than 2 percent of material finer than 53 microns.

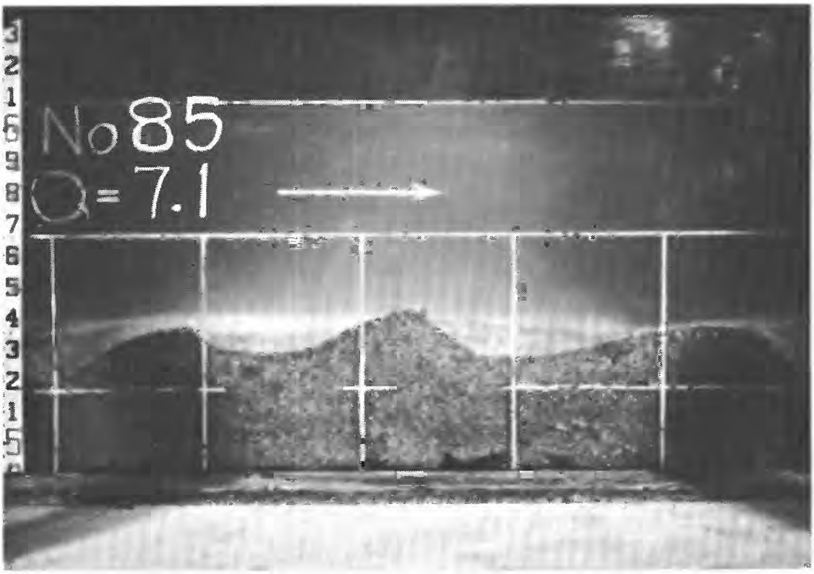

FIGURE 18.—Ripples during clear-water run. Note angular crests.

DUNES, 8-FOOT FLUME

As stated on pages G29 and G30, the change from the ripples to dunes was resisted by the somewhat cohesive nature of the bed resulting from the presence 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 stabilized areas and form a typical dune bed (run 91). There was a noticeable difference in the appearance of the water surfaced before the flow was able to break up the stabilized areas and form dunes. The water surface over the stabilized areas was choppy, as if the flow were 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 would predict that fine material would be in the bed, and direct measurement proved that some fine material was in the bed.

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

The maximum amount of fine material in the bed was about 2 percent, as determined from the size analysis of bed material samples.

This fine material was fairly well distributed throughout the bed material. The presence of the fine material in the bed did not appear to reduce the mobility of the bed material, and the bed was as soft and mobile as when the fine material was not present. The flow of clear water removed the fine material from the bed in a few hours.

The presence of fine material in the flow in concentrations greater than 5,000 ppm (0.5 percent) decreased resistance to flow. The increase in $C/\sqrt{g}$ was as large as 40 percent (run 96) when the concentration was 25,000 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 distinguish from the natural fluctuations in resistance. The decrease in resistance to flow as the fine sediment concentration was increased resulted from the reduction in the fall velocity of the bed material and the change in the shape of the dunes.

The data indicate that transport of bed material increased slightly with the addition of fine material. However, part of the increase in bed-material load transported may have resulted from bentonite retained on the 270 sieve (0.053 mm), on which the fine-material discharge was separated from the bed-material discharge. About 2 percent of the bentonite was retained on the sieve (fig. 3); this bentonite, which became added to the flow as fine material, could account for some of the increase in bed-material transport.

DUNES, 2-FOOT FLUME

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

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

The form of bed roughness, and therefore the resistance to flow and the bed-material transport, was considerably modified when the concentration of fine sediment was increased over 25,000 ppm. As additional bentonite was added to the flow, the dunes increased in length and decreased in height until the bed configuration became rounded sand waves of small amplitude at a concentration of 63,700 ppm of fine sediment (run 8B). 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 and trapped it in the bed in lenses and layers, which were visible through the plastic flume walls; however, no stabilizing of the bed was discernible, and it remained soft and mobile. The resistance to flow decreased, and the bed-material transport was reduced.

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

TRANSITION

SHEARED-OUT DUNES, 2-FOOT FLUME

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

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

UPPER FLOW REGIME

STANDING WAVES, 2-FOOT FLUME

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

The form of bed roughness did not change for the sequence of runs 15, 15A, 15B, and 15C. The length of the standing sand waves, measured from crest to crest, changed very little, but their height decreased as the concentration of fine sediment was increased. The resistance to flow was unchanged for concentrations of fine sediment less than 41,000 ppm, but increased slightly at the largest concentrations of fine material. The data in table 1 show that for each fine sediment run the amount of bed material in transport increased over the amount of bed material transported by the water-sand flow without bentonite.

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

ANTIDUNES, 8-FOOT FLUME

The most obvious effects of the fine-material load on flow phenomena in the upper flow regime was the increase in antidune activity with the increase in concentration of fine material. With the increase in antidune activity, the transport of bed material and the resistance to flow increased. With fine material present, antidunes occurred, at smaller Froude numbers than without the presence of fine material. In one set of runs, the concentration of fine sediment was reduced from 26,900 (run 99) to 106 ppm (run 100) by adding clear water and discarding the excess mixture of water and sediment. When concentration of fine material was large, antidune activity was intense, and the concentration of bed material in transport was 16,100 ppm. Antidune activity decreased with the decrease in concentration of fine material until, during run 100, the water surface and bed were plane, and the bed-material concentration was 8,440 ppm. The only other changes in flow condition during runs 99 and 100 were a slight decrease in water temperature and possibly a slight coarsening of the bed material, which resulted from the wastage of the mixture of water and fine sediment. The increase in antidune activity with increasing concentration of fine sediment was the result of the reduction of the fall velocity of the bed material and, hence, the increase in the mobility of the bed material.

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

In runs in the 8-foot flume, the antidune water-surface patterns generally formed in two parallel lines of waves (fig. 15). This pattern is different from the antidune water-surface patterns observed during the first 45 runs (Simons and others, 1961), when only a single train of antidune waves generally formed.

ANTIDUNES, 2-FOOT FLUME

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

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

EFFECT OF FINE SEDIMENT ON RESISTANCE TO FLOW

The influence of fine sediment on resistance to flow is illustrated in figures 19 and 20. The magnitude of the change in $C/\sqrt{g}$ depends on the concentration of fine sediment, the form of bed roughness, and whether the addition of the fine sediment causes only a modification of the existing roughness or causes a complete change in form of bed roughness, as from dunes to plane bed.

With a dune-bed form, an increase in the concentration of fine sediment decreased resistance to flow. The decrease resulted from the increase in length of the dunes. In the extreme, the bed changed from dunes in the low flow regime to plane bed in the upper flow regime. With standing waves and antidunes, an increase in fine sediment concentration increased resistance to flow. The increase resulted from the increase in size of the standing waves and from the violence of the antidune activity. In some runs the addition of fine sediment changed standing waves to antidunes.

EFFECT OF FINE SEDIMENT ON BED-MATERIAL TRANSPORT

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

With relatively low concentrations of fine material and with a ripple-bed form, the bed was partly stabilized, and bed-material transport was reduced. With larger concentrations of fine material, larger areas of the bed were stabilized.

The effect of concentrations of less than 10,000 ppm of fine material was relatively small on bed-material transport in flows with a dune bed configuration. With concentrations greater than 10,000 ppm of fine sediment bed-material transport in the 2-foot flume decreased (fig. 21). The decrease may have been greater because the concentration of bed material in transport may have contained some fine-material load. Data for the 8-foot flume show either no change or an increase in bed-material transport with an increase in fine material load. However, the increase could have resulted from fine sediment in the bed-material transport. The decrease in the transport of bed material when the concentration of fine sediment was increased probably resulted from the decrease in resistance to flow that occurred and

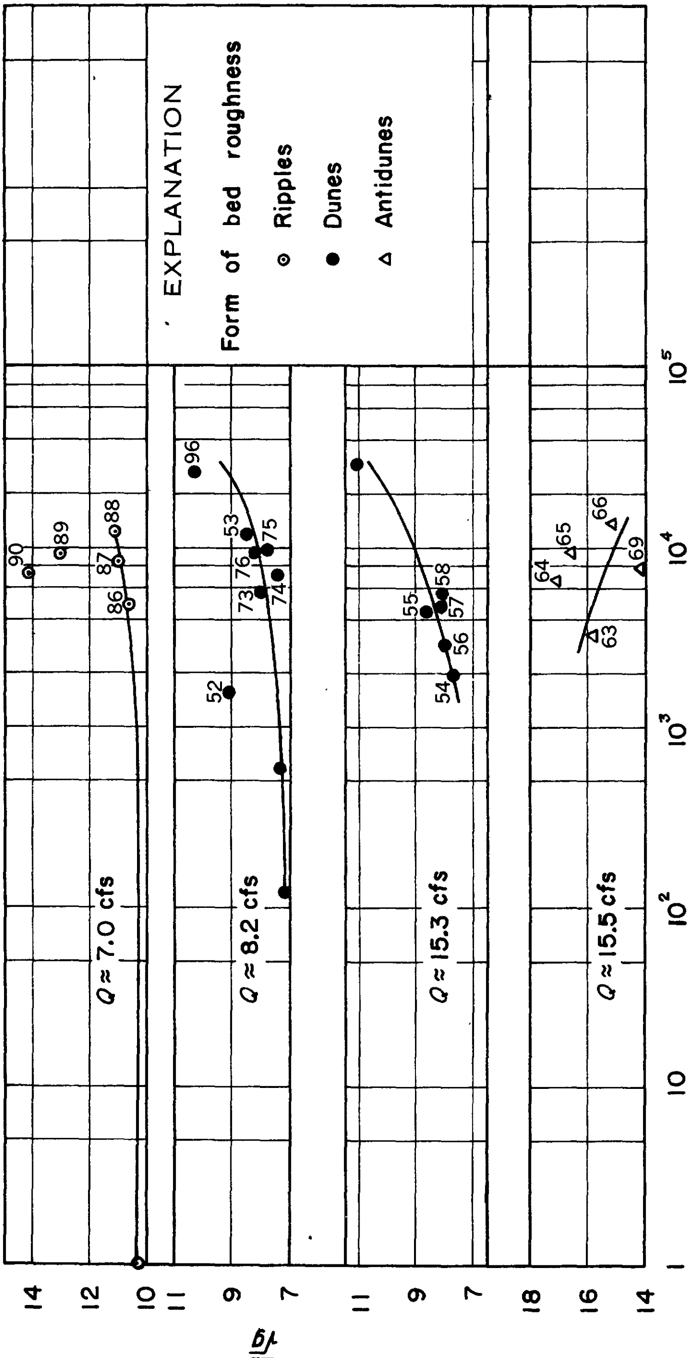

FIGURE 19.—Variation of resistance coefficient, $C/\sqrt{g}$, with concentration of fine sediment; 8-foot flume data

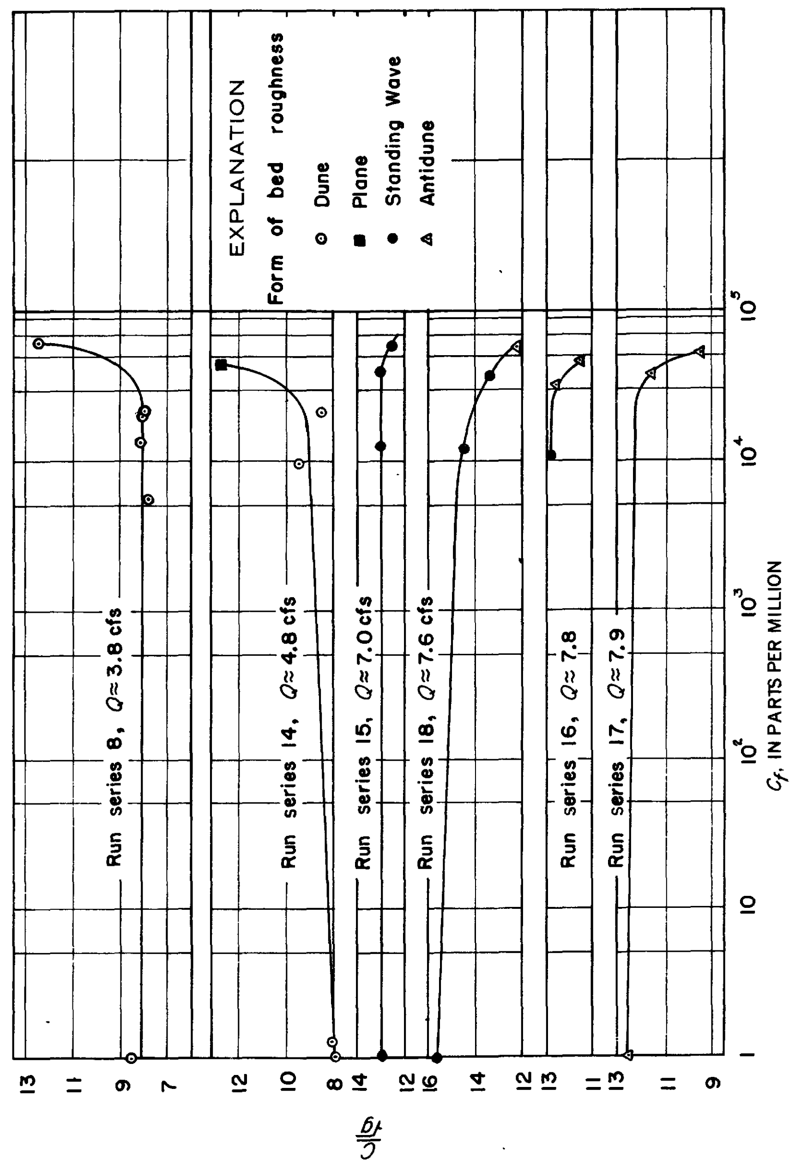

FIGURE 20.—Variation of resistance coefficient, $C/\sqrt{g}$, with concentration of fine sediment; 2-foot flume data

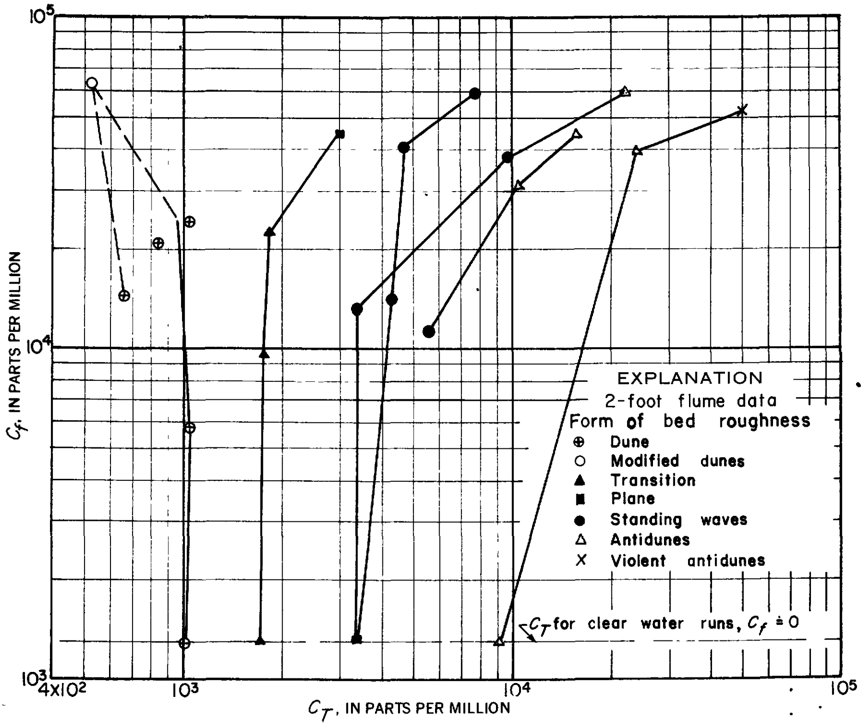

FIGURE 21.—Variation of bed-material transport with varying concentration of fine material.

from the decrease in the shear that resulted when depth and slope adjusted to the smaller resistance to flow. In some dune runs in the 2-foot flume the bed was partly stabilized, and bed material transport decreased; however, the decrease in bed-material transport also occurred when the bed was known to be not stabilized.

With the bed forms of the upper flow regime, a large concentration of fine sediment increased bed-material transport (fig. 21). This increase existed even if the values for the amount of bed-material load were adjusted for the possibility that some of the load was fine sediment. The increase in bed-material load occurred because the fine sediment increased the viscosity and the specific weight of the fluid, decreased the fall velocity of the bed material, and increased the resistance to flow and fluid shear. With shear constant, bed-material transport increased with a decrease in sand size or a decrease in fall velocity. When fine sediment was added to the flow, shear increased in the upper flow regime.

The total discharge of sediment by a stream when fine sediment is in the flow cannot be predicted from knowledge of fluid, sediment, and channel characteristics, unless the concentration of fine sediment is measured and the effects of the concentration on the fluid properties of the stream and, in turn, the effect of the fluid properties on the fall velocity of the bed-material particles are considered—that is, equations, such as Einstein's (1950) and Bagnold's (1956), cannot predict total transport when fine sediment is included in the load. It has long been known that total load cannot be predicted when fine sediment is in the flow (Einstein and Chien, 1953a, b). To illustrate this, Bagnold's equations are used. His dimensionless transport and shear parameters are defined respectively as:

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

and

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

in which

M=the mass of sediment transport passing a fixed plane per unit width of channel per unit time.
β=the angle the channel bed makes with the horizontal.
B=a constant for a given bed material which can be related to the grain diameter of the bed material.
d=the median diameter of the bed material.
θ_o=the dimensionless shear stress, $\tau_o/\Delta\gamma d$.
θ_t=the critical shear stress, $\tau_c/\Delta\gamma d$, at beginning of motion.
ρ=the mass density of the water.
$\Delta\rho_s$=the difference in mass density of the water and the sediment.

The two groups of values shown on figure 22 were computed using equations 2 and 3. In the group of values on the right, only bed-material transport has been considered in computing ϕ. In the group of values on the left, total load (including fine sediment) was used to compute the respective values of ϕ for each run. In the group of values using total load, the scatter is so great when fine sediment transport is included that the relation between ϕ and θ_* has no significance. In fact, an infinite number of possible values for ϕ exist for the 0.47 millimeter bed material when fine sediment is included in the computation. This illustrates that the transport parameter should not include the concentration of fine sediment. Although total load cannot be predicted from a knowledge of hydraulic and bed-material characteristics unless the concentration of fine sediment and its effects are known, approximate methods have been formulated that estimate total load including fine sediment (Colby and Hembree, 1955), but these methods do not account for the effects of fine sediment on the flow phenomena.

A change exists in the sediment-transport relation of Bagnold at the point where the form of bed roughness changes from dunes through

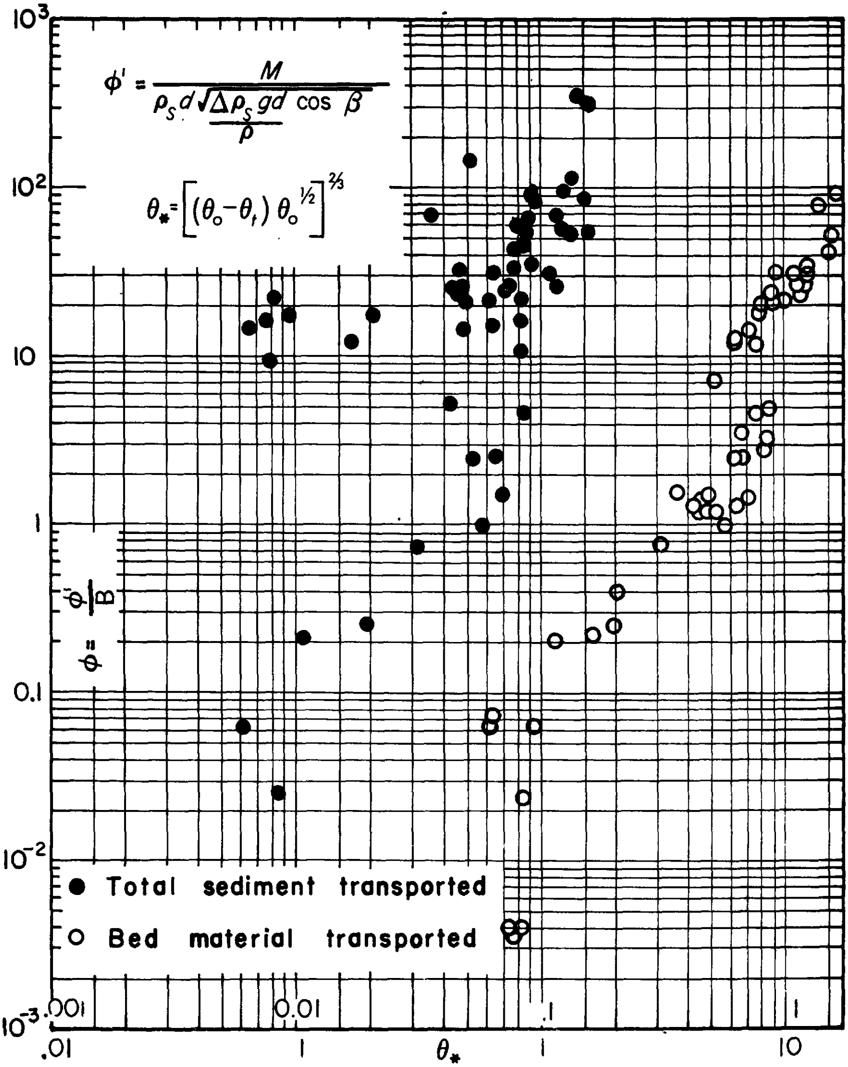

FIGURE 22.—Variation of sediment transport parameter ϕ with shear parameter θ_*; 8-foot flume data.

transition to standing waves. This change in relation, which can be a discontinuity that also exists when the equations of Einstein (1950) are used, is caused by the large reduction in resistance to flow that takes place as the form of bed roughness changes. Because of this change in the relation, it ultimately may be desirable to break the theory of flow in alluvial channels into two parts: one which treats the ripple, dune, and transition forms of bed roughness and another which treats the plane bed, standing wave, and antidune forms of bed roughness.

FINE SEDIMENT TRANSPORT

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

Another comparable definition of fine-material load used by others is wash load. This definition has the connotation that the fine material is not present in the bed, but logic indicates and experimental evidence proves that the fine material is present in the bed. Einstein and Chien (1953a,b) also concluded that fine sediment (wash load) would be present in the bed; however, they found that the fine material always managed to stay at the top of the bed whereas the fine material in our experiments was distributed throughout the bed material. The different observations probably resulted from the fact that the fine material used by Einstein and Chien was much coarser than the fine material used in our experiments.

In our 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 finer bed material, but this change had very little effect on the median fall diameter. Whether or not this small amount of fine material in the bed affects the relation between sand properties, fluid properties, resistance to flow, or total load depends largely on the form of bed roughness. Surprisingly enough, when clear water was added to the flow and the excess mixture of water and sediment was discarded, the fine material in the bed was removed along with that in the water in a relatively short time.

In both flume studies, the concentration of fine material in the flow for each run decreased with time logarithmically from its peak value. The rate of decrease was determined by periodic measurements of concentration with a hydrometer. The decrease in concentration of fine material in the flow resulted from the increase in concentration of fine material in the bed and from the deposition of some of the fine material at the contact plane between the sand bed and flume floor. This deposition, over a period of several runs, built up a layer of clay-impregnated sand about 0.1 foot thick (fig. 23).

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 in the bed would vary with time depending on the

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

concentration of fine sediment in the stream and on the concentration gradient. The concentration in the bed will increase if it is smaller than the stream concentration or will decrease if it is larger. This fact may account for a small part of the lag of the sediment hydrograph behind the water hydrograph as a flood peak travels downstream (Heidel, 1956). A layer of fine material such as observed on the floor of the flume (fig. 21), may build up in a natural streambed if:

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

CONCLUSIONS AND RECOMMENDATIONS

The specific weight and apparent viscosity of aqueous dispersions of fine sediment are different than those of pure water. The apparent viscosity of an aqueous dispersion of fine sediment depends on the concentration of the fine sediment, the chemical and physical properties of the fine sediment, the amount and type of any base added as a dispersing agent, and, with some fine sediments at certain concentrations, the temperature of the fluid.

The ratio of the apparent viscosity of aqueous dispersions of bentonite, as measured with a Stormer viscosimeter, to the viscosity of water was independent of the temperature at concentrations of less than about 5 percent by weight but was dependent on the temperature at concentrations greater than about 5 percent. The ratio of the apparent viscosity of aqueous dispersions of kaolin to the viscosity of water, however, was independent of the temperature at concentrations less than 10 percent. The apparent viscosities of aqueous dispersions of bentonite were much greater than those of aqueous dispersions of kaolin. At 40°C the difference between the viscosity of water and the apparent viscosity of an aqueous dispersion of bentonite, 10 percent by weight, was 1,100 percent, and the difference with an aqueous dispersion of kaolin under the same conditions was 45 percent.

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

The change in fluid properties that results from the presence of fine sediment has a definite effect on the fall velocity of the bed material. For example, at 24°C the fall velocity of a 0.47-mm median fall-diameter sand in aqueous dispersions of bentonite and of kaolin, 10 percent by weight, is decreased by 65 and 20 percent, respectively. This decrease of fall velocity in aqueous dispersions of bentonite is equivalent to the difference between the fall velocities of a 0.47-mm and of a 0.24-mm sand particle in water of 24°C.

The resistance to flow and bed-material transport are decreased in the lower flow regime and increased in the upper flow regime when fine sediment is added to the flow. When there are ripples, fine sediment, even in moderate concentrations, stabilizes the bed, streamlines bed forms, reduces resistance to flow, and reduces bed-material transport. When there are dunes, fine sediment, in relatively large concentrations, may stabilize the bed, reduce resistance to flow, and reduce bed-material transport; however, resistance to flow and bed-material transport are reduced even when the bed is not stabilized. The reduction in resistance to flow when the bed is not stabilized results from increases in dune length and from the changes in dune shape that occur when the fall velocity of the bed material decreases.

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

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

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

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

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INDEX