Summary of Alluvial Channel Data From Flume Experiments, 1956-61

By H. P. GUY, D. B. SIMONS, *and* E. V. RICHARDSON

SEDIMENT TRANSPORT IN ALLUVIAL CHANNELS

GEOLOGICAL SURVEY PROFESSIONAL PAPER 462-I

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON:1966

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

Library of Congress catalog-care No. GS 66-219

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price 70 cents (paper cover)

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GLOSSARY OF TERMS

Alluvial channel. A channel whose bed is composed of non-cohesive material that has been or can be transported by the flow.

Antidunes. Bed features that usually form in upstream-moving trains and are inphase with and strongly interact with gravity water-surface waves. The flow is in the upper flow regime; therefore, the water-surface waves have larger amplitudes than the antidunes. At higher Froude numbers, the surface waves usually grow until they become unstable and break in the upstream direction. The agitation accompanying breaking obliterates the antidunes, and the process of antidune initiation and growth is then repeated. At lower Froude numbers, the antidunes usually diminish in amplitude without the surface waves ever breaking.

Bar. A depositional feature whose length is of the same order as the channel width or greater, and whose maximum height is comparable to the mean depth of the generating flow. In longitudinal section, bars are approximately triangular, having very long gentle upstream slopes and short downstream slopes that are approximately the same as the angle of repose of the bed material. Alternate bars and point bars have transverse profiles that are triangular and taper from the bank to a point in the channel.

Bed material. The material of which a streambed is composed.

Clay. Sediment finer than 0.004 mm (millimeter), regardless of mineralogical composition.

Chute-and-pool flow. A flow condition that occurs where slopes are relatively steep and water-sediment discharges are relatively great, the channel consists of a series of pools, in which the flow is subcritical, connected by steep chutes, in which the flow is supercritical. A hydraulic jump forms at the downstream end of each chute, where the chute enters a pool. The chutes and pools may move slowly upstream.

Dunes. Bed features smaller than bars but larger than ripples that are out of phase with any water-surface gravity waves that accompany them. Dunes generally form at larger flow and sediment-transport rates than do ripples, but at smaller flow and transport rates than do antidunes; however, ripples often form on the upstream slopes of dunes at smaller rates of flow. In longitudinal profile, dunes are approximately triangular, having fairly gentle upstream slopes and downstream slopes that are approximately equal to the angle of repose of the bed material.

Fall diameter or standard 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.

Fine sediment. That part of the sediment discharge that consists of sediment so fine that it is about uniformly distributed in the vertical and is only an inappreciable fraction of the sediment on the streambed (referred to by some writers as wash load). Its upper size limit at a particular time and cross section is a function of the characteristics of the flow as well as of the characteristics of the sediment particles.

Flow regime. A range of flow conditions having somewhat similar resistance and sediment transport characteristics that produce similar bed forms.

Lower flow regime. Flow in sand channels which result in bed forms of ripples, ripples on dunes, and dunes.

Median diameter. Midpoint in the size distribution of a sediment, at which half the particles by weight are larger and half are smaller.

Plane bed. A bed form that has no irregularities larger in amplitude than a few grain diameters of the bed material. The plane bed in a sand channel that has movement of bed material occurs in the upper flow regime.

Ripples. Small triangular-shaped bed forms that have wave lengths of less than about 2 feet and heights of less than about 0.2 foot.

Sand. Sediment particles between 0.062 and 2.0 mm in diameter.

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

Sediment. Fragmental material that originates from the disintegration of rocks and is transported by, suspended in, or deposited by water or air, or is accumulated in beds by other natural agencies.

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

Sediment discharge. The amount of sediment that is moved by water past a section in a given length of time.

Silt. Sediment particles between 0.004 and 0.062 mm in diameter.

Suspended sediment. Sediment suspended in the flow by turbulent currents and (or) by colloidal suspension.

Standing waves. Virtually stationary waves that generally develop as a train. They are sometimes called nonbreaking antidunes.

Transition. A category for flows that mold bed forms ranging from those typical of the lower flow regime to those typical of the upper flow regime.

Upper flow regime. Flow in sand channels which results in bed forms of plane bed (with sediment movement), standing waves, and antidunes.

Velocity profile. Horizontal components of flow velocity in relation to depth at a vertical section over a point on the bed.

SYMBOLS

A	Area of flow cross section.	sq ft
B	Slope of semilogarithmic plot of velocity versus depth, above the bed.	fps per log unit
C	Velocity at a depth of 1.0 foot above bed.	fps
$C/\sqrt{g}$	Chezy coefficient of discharge; equal to V/V_*.	
C_f	Concentration of fine-sediment discharge.	ppm
C_s	Concentration of suspended-sediment discharge.	ppm
C_t	Concentration of bed material discharge.	ppm
D	Average depth of flow.	ft
d	Particle size in terms of fall diameter.	mm or ft
d_{16}	Particle size for which 16 percent of the sediment by weight is finer.	mm or ft
d_{50}	Median particle size of the sediment.	mm or ft
d_{84}	Particle size for which 84 percent of the sediment by weight is finer.	mm or ft
f	Darcy-Weisbach resistance coefficient; equal to $\frac{8gDS}{V^2}$.	
$\boldsymbol{F}$	Froude number; equal to $\frac{V}{\sqrt{gD}}$.	
g	Acceleration of gravity (32.2 ft per sec per sec).	ft per sec per sec
n	Manning's resistance coefficient.	$ft^{1/6}$
Q	Discharge of water-sediment mixture.	Cu ft per sec
q_s	Discharge of suspended sediment.	lb per sec per ft
q_t	Discharge of bed material.	lb per sec per ft
R	Hydraulic radius.	ft
$\boldsymbol{R}$	Reynolds number; equal to $\frac{VD}{\nu}$.	
S	Water-surface slope.	
T	Temperature.	°C
V	Average velocity based on continuity principal.	fps
V_*	Shear velocity; equal to $\sqrt{gDS}$ or $\sqrt{\tau_0/\rho}$.	fps
W	Width of flume.	ft
γ	Specific weight of water or water-sediment mixture.	lb per cu ft
μ	Dynamic viscosity.	lb-sec per sq ft
ν	Kinematic viscosity.	sq ft per sec
ρ	Mass density of water.	slug per cu ft
σ	A measure of sediment particle size gradation; equal to $\frac{1}{2}\left[\frac{d_{50}}{d_{16}}+\frac{d_{84}}{d_{50}}\right]$.	
τ	Shear stress or tractive force on bed; equal to γDS.	lb per sq ft
ω	Fall velocity of a particle.	ft per sec

ENGLISH-METRIC CONVERSION TABLE

Principal items	*English unit*	*Factor*	*Metric unit*
Depth of flow Length and width of flume Particle size Hydraulic radius	ft	0.3048 30.48 304.8	m cm mm
Area of cross section	sq ft	929.0 .09290	sq cm sq m
Velocity of flow Fall velocity of particles	ft per sec	0.3048 30.48	m per sec cm per sec
Velocity of bed configuration	ft per min	0.005080 .5080 .01829	m per sec cm per sec km per hr
Water discharge	cu ft per sec (cfs)	0.02832 2.832×10^4	cu m per sec cu cm per sec
Sediment discharge	lb per sec per ft	1.488	kg per sec per m
Acceleration of gravity	ft per sec per sec	0.3048 30.48	m per sec per sec cm per sec per sec
Shear stress	lb per sq ft	478.8 0.4882 4.882	dynes per sq cm g per sq cm kgm per sq m
Kinematic viscosity	sq ft per sec	929.0	sq cm per sec (Stokes)
Dynamic viscosity	lb sec per sq ft	0.04788 .4482	g per cm-sec (Poise) g-sec per sq cm
Specific weight	lb.per cu ft	0.01602	g per cu cm
Mass density	slug per cu ft	0.5154	g per cu cm

SEDIMENT TRANSPORT IN ALLUVIAL CHANNELS

SUMMARY OF ALLUVIAL CHANNEL DATA FROM FLUME EXPERIMENTS, 1956–61

By H. P. Guy, D. B. Simons and E. V. Richardson

ABSTRACT

The primary purpose of this report is to summarize and make available to other investigators the results of the hydraulic and sediment data collected by D. B. Simons and E. V. Richardson in a unique series of experiments at Colorado State University between 1956 and 1961. The 339 equilibrium runs were made in 2- and 8-foot-wide recirculating flumes for 10 sets of conditions to determine the effects of size of the bed material, temperature of the flow, and fine sediment in the flow on the hydraulic and transport variables. The investigations for each set cover flow phenomena ranging from a plane bed and no sediment movement to violent antidunes.

INTRODUCTION

As a part of the research program of the Water Resources Division of the U.S. Geological Survey, a project was organized in September 1956 to study the mechanics of water and sediment movement in alluvial channels. Answers to questions on resistance to flow and sediment transport rates were sought at this time. The solutions to resistance and transport problems are complicated by the multitude of variables and parameters involved and by the complex interdependence of the variables.

The objective of the experiments was to obtain mean values of the resistance and transport variables and parameters for a large range of conditions most commonly found in natural streams and artificial channels. The large quantity of data required for a general solution to the problem was considered best obtained by use of recirculating flumes which *tend to simulate* conditions of uniform flow and sediment transport in an infinitely long channel. The recirculating-flume data are indirectly comparable to those for most streams where the water discharge, the imposed sediment discharge, and water temperature change considerably during the period of storm runoff. Such recirculating flume data are very comparable to data for regulated streams and canals fed by ground water or man-made storage facilities and to data for streams in which the water discharge changes slowly.

This report is a compilation of the data for 10 sets of conditions, or for a total of 339 equilibrium runs in recirculating flumes. The investigations for each set covered flow phenomena ranging from a plane bed and no movement of sediment to the antidunes first described by Gilbert (1914). The general procedure of recirculating the water-sediment mixture aided in obtaining the equilibrium conditions, because the roughness elements which resisted the flow were formed by the flow and the respective sediment-movement characteristics. In the experiments used for this compilation, the form of the bed was changed from plane without sediment movement, to ripples, to dunes, to transitional, to plane with sediment movement, and to antidunes by altering flow conditions. For a set of runs with a specific sand and flume, discharge and slope were the principal controllable variants for altering flow conditions. Depth, velocity, fluid resistance, sediment discharge, and, to some extent, slope changed with time until equilibrium was reached.

The scheme of presentation in the report is to:

1. Describe the equipment and sands.
2. Describe the procedure of operation.
3. Describe the data obtained.
4. Describe the characteristics of the individual runs.
5. Tabulate the mean values of the basic data for each run.
6. Tabulate the velocity-profile data for the runs having such data.

The project was under the general supervision of L. B. Leopold, Chief Hydrologist, Water Resources Division, with technical guidance from P. C. Benedict, R. W. Carter, and others from the Geological Survey.

The principal investigators were D. B. Simons, project chief, and E. V. Richardson. Technical guidance was also received from faculty members, especially from M. L. Albertson, at Colorado State University, where the project was located. The principal investigators were assisted in various phases of the work by W. L. Haushild, D. W. Hubbell, and R. K. Fahnestock, of the Geological Survey, and by H. J. Morel-Seytoux, R. J. Garde, A. A. Bishop, K. Al-Shaikh Ali, Niwat Daranandana, and H. C. Hilbrand, graduate students in Civil Engineering. The report was compiled after careful review of the original notes assembled during the laboratory work.

The data contained in this report have been used in several U.S. Geological Survey reports, professional societies' publications, and graduate student theses. A partial list of these papers, exclusive of those given as references, follows:

Bishop, A. A., 1961, Sediment transport in alluvial channels, a critical examination of Einstein's theory: Fort Collins, Colo., Colorado State Univ., Dept. Civil Eng., Ph.D. dissertation.

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Haushild, W. L., Simons, D. B., and Richardson, E. V., 1961, The significance of the fall velocity and effective fall diameter of bed materials: U.S. Geol. Survey Prof. Paper 424–D, p. 17–20.

Hubbell, D. W., and Ali, Al-Shaikh, K., 1961, Qualitative effects of temperature on flow phenomena in alluvial channels: U.S. Geol. Survey Prof. Paper 424–D, p. 21–23.

Richardson, E. V., 1960, Sediment transport in alluvial channels (examination of Bagnold's 1956 hypothesis): Fort Collins, Colo., Colorado State Univ., Dept. Civil Eng., M. S. thesis.

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——— 1962, Depth-discharge relations in alluvial channels: Am. Soc. Civil Engineers Proc., v. 88, no. HY5, 16 p.

Simons, D. B., Richardson, E. V., and Nordin, C. F., Jr., 1965, Sedimentary structures generated by flow in alluvial channels—a symposium: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 12, p. 34–52.

——— 1965, Bed load equation for ripples and dunes: U.S. Geol. Survey Prof. Paper 462–H, 9 p.

EQUIPMENT AND SANDS

The flumes and related equipment used are in the hydraulic laboratory adjacent to the Engineering building on the main campus at Colorado State University. The bed materials were selected from natural river sands found within a few hundred miles of Fort Collins.

EQUIPMENT

Most of the data were collected in a recirculating flume 8 feet wide, 2 feet deep, and 150 feet long. The flow could be varied from 0 to 22 cfs (cubic feet per second) by use of two pumps and a valve control on the discharge lines. The slope of the plywood channel could be adjusted from 0 to 1.5 percent by screw jacks. A schematic diagram of this flume is shown in figure 1.

Many data relative to the effect of temperature and fine sediment on resistance to flow and sediment transport were collected in a recirculating flume 2 feet wide, 2½ feet deep, and 60 feet long that has ½-inch clear-plastic sidewalls and a ¼-inch stainless-steel plate floor. The flow could be adjusted from 0 to 8 cfs, and the slope, from horizontal to 10 percent. A schematic diagram of this flume is shown in figure 2.

Each flume has specific entrance conditions, wall roughness, and flow characteristics which may affect the flow and transport variables. A given run, therefore, cannot be reproduced exactly in another flume. These recirculating flumes with constant-head tailboxes most nearly duplicate flow conditions in alluvial channels, except for highly variable flow of sediment from tributaries.

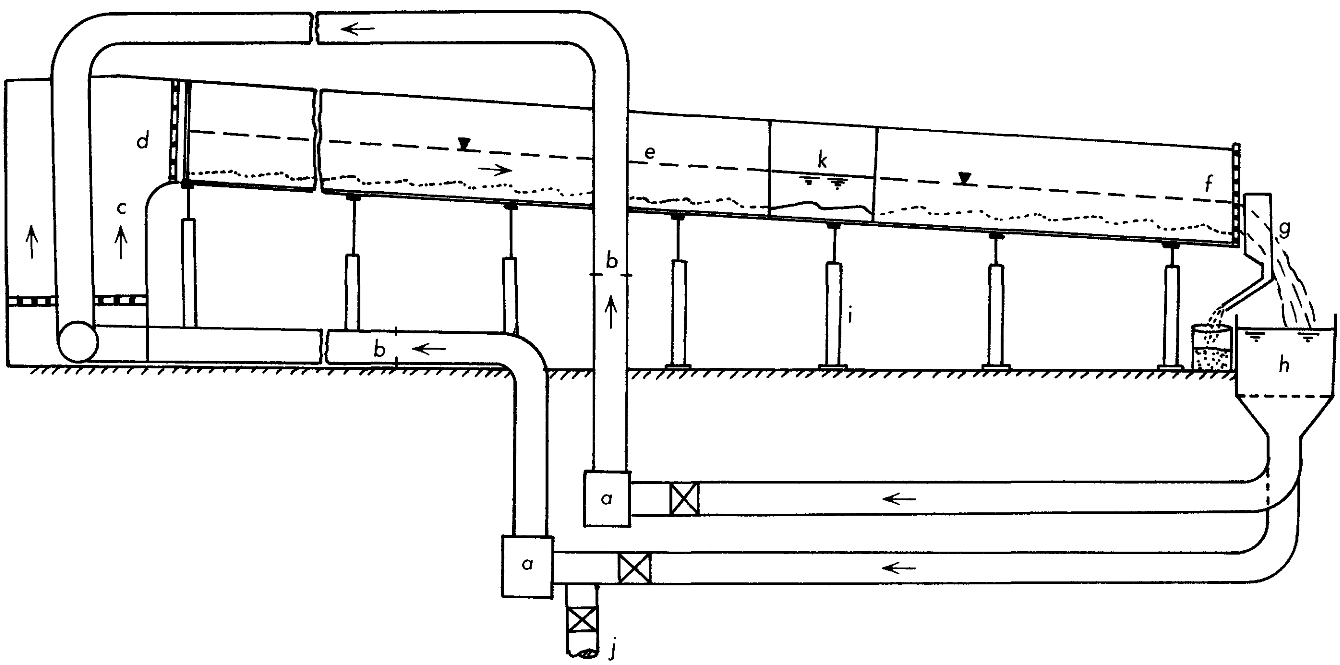

FIGURE 1.—The 8-foot-wide flume. After Simons, Richardson, and Albertson (1961, p. 21). *a*, pumping units; *b*, orifices; *c*, headbox and diffuser; *d*, baffles and screens *e*, flume (8×2×150 ft); *f*, tailgate; *g*, total-load sampler; *h*, tailbox; *i*, jacks supporting flume; *j*, connection to storage sump; *k*, transparent viewing window.

SANDS

The sands used for the 10 sets of experiments were obtained from 5 sources: a deposit of decomposed sandstone near Denver, Colo.; the Elkhorn River near Waterloo, Nebr.; the Cache la Poudre River at Fort Collins, Colo.; the North Platte River near Scottsbluff, Nebr.; and the Black Hills Silica Sand Corp., Hill City, S. Dak. These national sands were modified by sieving or washing away components of different sizes for some of the experimental sets.

The sands used as bed material in the experiments are identified by their median fall diameter. Table 1 lists each sand, where it was obtained, the kind of processing used, and the general character of the experiments. A particle-size distribution curve (size in millimeter versus percent finer than indicated size) is given in figures 3 and 4 for each sand. Figure 5 is a composite of photographs of each sand to show roundness, gradation, and relative size.

OPERATION PROCEDURE

The general operation procedure was the same for both flumes and for the various sand sizes. In a natural stream, depth is dependent on discharge, slope, bed roughness, and shape of channel. In a flume, only discharge and shape of channel can be controlled precisely, and slope only approximately. Slope and

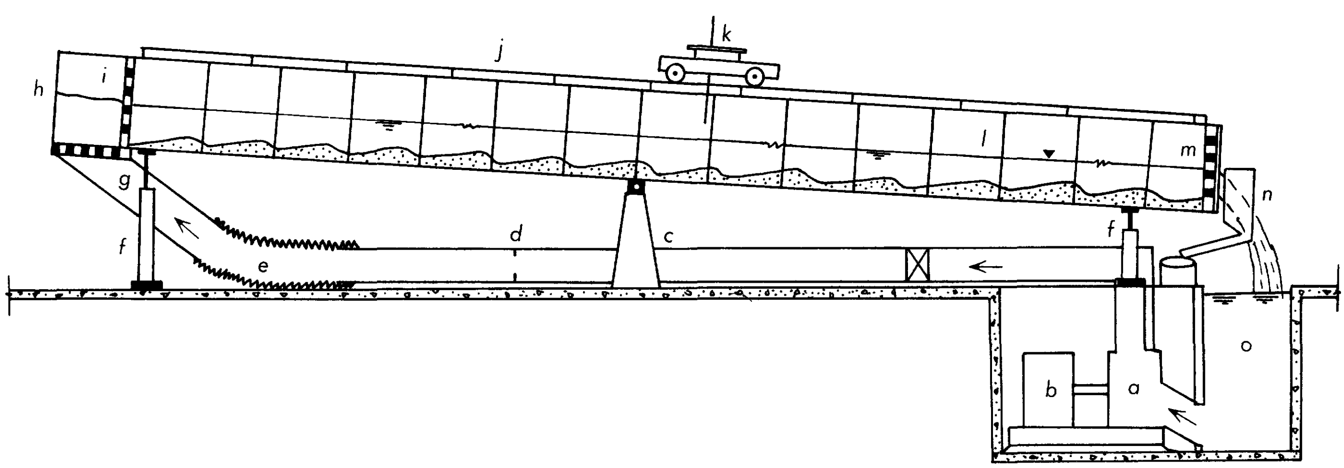

FIGURE 2.—The 2-foot-wide flume. After Simons, Richardson, and Haushild (1963, p. 3). *a*. pumping unit; *b*, motor; *c*, center support; *d*, orifice; *e*, flexible connection *f*, jacks; *g*, manifold diffuser; *h*, headbox; *i*, baffles and screens; *j*, rails; *k*, instrument carriage; *l*, flume (2×2.5×60 ft); *m*, tailgate; *n*, total-load sampler; *o*, tailbox.

TABLE 1.—*General information about the sands used in the experiments*

Median size (mm)	Gradation σ	Source of sample	Method of obtaining and processing sand	Type of study	Width of flume used (ft)
0.19	1.30	Decomposed sandstone near Denver, Colo.	The sandstone was run through a hammermill to break up the large chunks and then washed to remove the clay binder.	General	8
.27	1.56	Elkhorn River near Waterlou, Nebr.	0.28-mm sand wet screened to remove material coarser than 2.0-mm	do	8
.28	1.67	do	Sand scooped from middle of flowing river by dragline. No processing	do	8
.45	1.60	Cache la Poudre River at Fort Collins, Colo.	Washed, passed a No. 8 sieve and retained on a No. 200 sieve	do	8
.93	1.54	North Platte River near Scottsbluff, Nebr.	Washed, passed a No. 4 sieve and retained on a No. 16 sieve	do	8
.32	1.57	Elkhorn River near Waterloo, Nebr.	From 0.27-mm sand. Coarser sand retained as fines were washed away in overflow.	Effect of viscosity by varying temp.	2
.33U	1.25	Black Hills Silica Sand Corporation, S. Dak.	Passed a No. 40 sieve and retained on a No. 60 sieve	Effect of gradation	2
.33G	2.07	do	6 sand sizes mixed to obtain a wide size-gradation range	do	2
.47	1.54	Cache la Poudre River at Fort Collins, Colo.	From 0.45-mm sand. Coarser sand retained as fines were washed away in overflow.	Effect of viscosity by varying concentration of fine sediment.	8
.54	1.52	do	From 0.45-mm sand. Coarser retained as fines were washed away in overflow.	do	2

depth reach equilibrium in accordance with the bed roughness for specific flow conditions.

The procedure followed for some runs involved recirculating a given discharge of water-sediment mixture in the flume at a preselected slope until equilibrium conditions were established. Equilibrium here should be defined as a condition of statistically uniform velocity, concentration, and slope with respect to both time and space in the flume where the variables are observed. Even though discharge can be held relatively constant, depth, slope, and sediment discharge in the final equilibrium condition (several hours or days after the start of the run) could be consider-

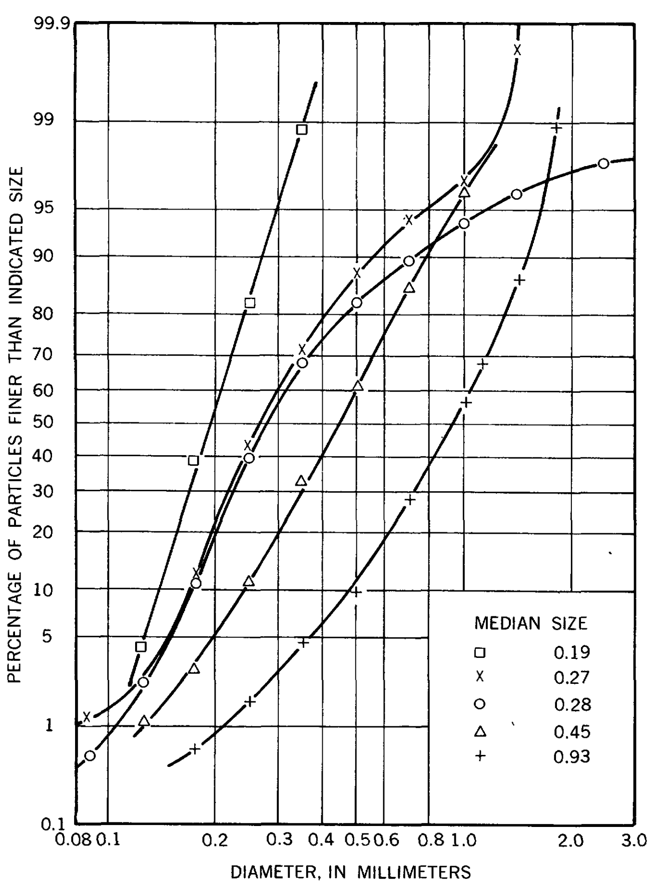

FIGURE 3.—Particle-size distribution curves for bed materials having median sizes of 0.19, 0.27, 0.28, 0.45, and 0.93 mm.

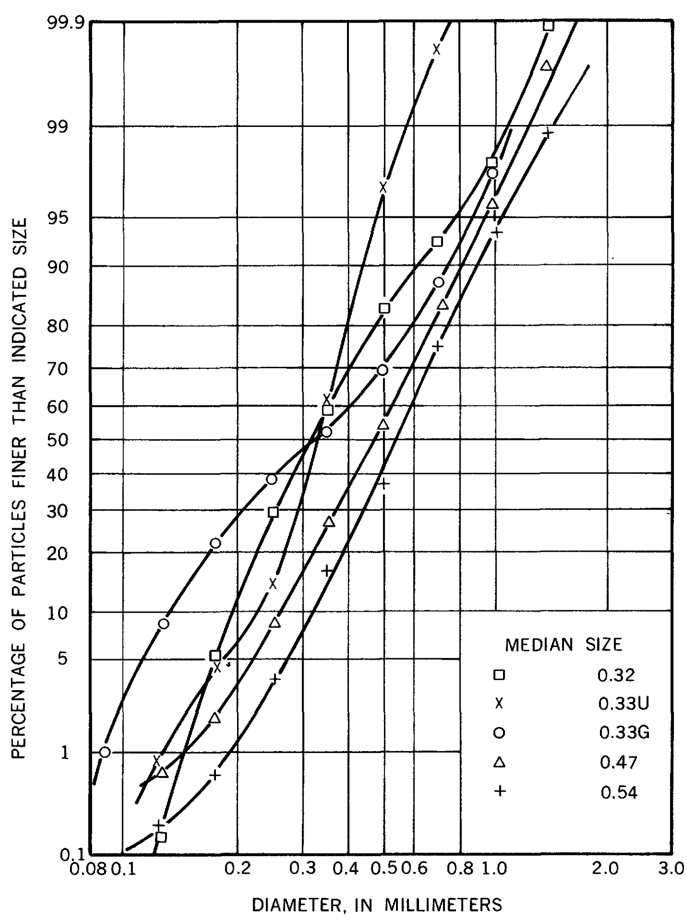

FIGURE 4.—Particle-size distribution curves for bed materials having median sizes of 0.32, 0.33U, 0.33G, 0.47 and 0.54 mm.

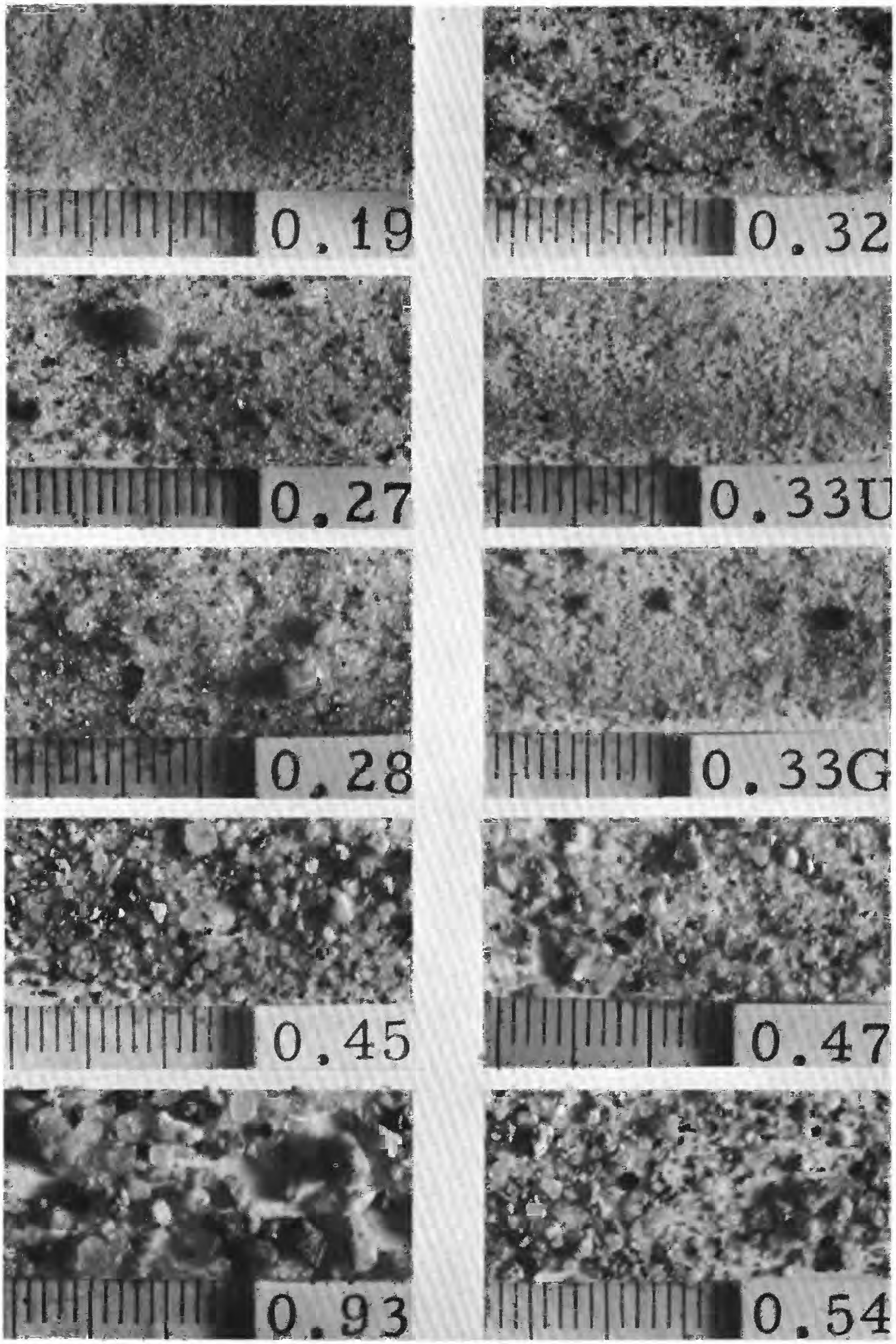

FIGURE 5.—Representative sand particles of bed materials used for the 10 sets of experiments. The number in the lower right corner of each photograph is the median diameter of the sand, in millimeters. The scale also is in millimeters. See table 1 for further description of each sand.

ably different from those in the initial condition. For some runs depth was kept constant either by adjusting the tailgate slope or discharge. For some other runs slope was kept constant either by adjusting the tailgate or the discharge, or both.

For runs having a relatively high rate of sediment discharge and requiring a short time to reach equilibrium (slopes greater than 0.006 ft per ft), the slope was preset by adjusting the tailgate and allowing the bed to adjust itself by scour and fill. For runs with Froude numbers greater than 1, the tailgate was often completely removed. For runs having a low rate of transport (slopes less than 0.006 foot per foot), the desired preset slope was established by planing or screeding the bed and then adjusting the tailgate to make the slope of the water surface parallel to the bed.

The nonequilibrium flow caused by change of bed roughness was eliminated by continuing the run until the average bed slope and the average slope of the water surface became parallel by natural adjustment of the sand bed. Equilibrium flow was considered as established, and collection of the data started, when (1) the bed configuration was consistent in the full length of the flume, excluding the sections influenced by entrance or exit conditions, and (2) the average water- and bed-surface slopes remained constant and parallel with respect to time. The time required to establish equilibrium conditions varied with the slope and the discharge. Some runs on flat slopes required 3 or 4 days to achieve equilibrium, whereas runs on steeper slopes established equilibrium within 2 or 3 hours. In each run, the flume was operated continuously until equilibrium had been reached and the necessary data collected. To insure the achievement of equilibrium conditions, most runs were continued longer than the required time as indicated by observations of variables likely to change prior to equilibrium.

The general procedure was different for the 0.47-, 0.54- and 0.32-mm sands. After equilibrium had been established and the data collected for a given run, the run was continued and, for the 0.47- and 0.54-mm sands, bentonite was either added or extracted from the flow, or, for the 0.32-mm sand, the temperature was changed. The new run was then continued until equilibrium was again established, and the necessary data collected. This procedure of adding or extracting bentonite or changing the temperature without stopping the flow was continued for a series of runs.

DESCRIPTION OF EXPERIMENTAL VARIABLES AND PARAMETERS

Following the operating procedure discussed led to the establishment of equilibrium conditions for a given run. Two or more measurements of slope made some time apart were required prior to the data-collection phase to insure that equilibrium had been established. In this investigation, slope observations were not started until visual inspection showed that a relatively systematic bed configuration and, consequently, a uniform resistance to flow had been established the full length of the test section.

When the rough movable boundary occurred in the flume, flow and transport values varied considerably during a given run. As a result, representative average values for all the basic variables had to be obtained by making successive observations during a relatively long period of time. The frequency and the time period over which the observations were made depended mainly on the bed form. For example, a few slope observations over a short time were sufficient to give a reliable average for the rippled condition; but many observations over a long time were required for the dune condition.

The following kinds of data were collected and are reported in tables 2–11 ("Basic Data" section):

1. Water surface slope.
2. Depth of flow.
3. Water discharge.
4. Water temperature.
5. Suspended-sediment concentration.
6. Concentration of total bed-material discharge.
7. Size graduation of sediment.
8. Bed configuration.

Several of these measured variables can be used to compute other variables and parameters useful for evaluating flow and transport characteristics in the flume channel. These variables include:

1. Mean velocity.
2. Velocity profile.
3. Shear velocity.
4. Sediment discharge.
5. Kinematic viscosity.
6. Shear at bed.
7. Reynolds number.
8. Froude number.
9. Resistance factors.

The inherent errors of each computation are proportional to the errors in the observation data. More specifically, the composite error (ΔX) of the computed variable or parameter will be

$$\Delta X = \frac{m_1X_1 \pm m_2X_2 \pm \ldots + m_nX_n}{\sqrt{n}},$$

where X_1 to X_n is the error of specific observation data, m_1 to m_n is the exponent of the respective X's, and n is the number of X's.

WATER-SURFACE SLOPE

The water-surface slope (col. 2, tables 2–11) was determined by observing the water-surface elevation with a level and a mechanical point gage, and also with a differential bubbler gage (Barron, 1963). The slopes computed using data from both methods were in close agreement.

The mechanical point-gage method consisted of reading the level of the water surface every 5 feet along the centerline of the flume. The point gage was mounted on a four-wheeled carriage that traveled on rails mounted on the walls of the flume. Levels were run on the gage at all locations for which water-surface readings were required. Three to eight sets of water-surface readings were made for each run after equilibrium was reached and during the period of data collection. The elevations for each point along the centerline may be plotted separately or averaged to obtain a mean slope. The average for each of the points was used to compute a least-squares regression for the runs with the 0.45-mm sand. The slope was determined graphically for the runs using the other sands. A study of the two methods indicated that both were sufficiently precise to yield slope values with no more error than is inherent in other variables.

Slope measurements taken after attainment of equilibrium conditions were used to determine the average slope. Also, water-surface elevations reflecting nonuniform flow at the entrance and exit of the flume were discarded.

The bubbler gage continuously recorded the difference in elevation of the water surface to within 0.001 foot between two points, and from this difference the water-surface slope was computed. The bubbler-gage connections to the 8-foot-wide flume were 100 feet apart. The continuous record of slope, as computed from the bubbler-gage headings, was used to determine when equilibrium conditions were established. The bubbler gage was not used in the 2-foot-wide flume or in the 8-foot-wide flume for the 0.45-mm sand.

Any error in the mean-slope value reported for each run can be attributed to two major sources: (1) the plus or minus 0.001 foot accuracy for the bubbler gage or the individual point-gage readings, and (2) the variation about the mean for a series of readings for the bubbler gage or the point gage. If the error for the bubbler gage is 0.001 foot in 100 feet, the absolute error for the gage is $\frac{10^{-5}}{S}$. For the finer sands, this alone would be 5–10 percent for slopes where sediment particles move occasionally. A 0.001-foot error in the point-gage reading is much less significant when plotted with several other readings. The variation about the mean for bubbler-gage readings is caused mostly by the effect of the bed forms moving near the orifices to the bubbler gage in the flume. Variation in the point-gage readings at a specific location is also due to the movement or shape of bed forms near the point-gage readings. This variation may cause errors of as much as 15–20 percent, depending on the size of the bed forms, the relative slope, and the number of observations.

DEPTH OF FLOW

The average depth of flow (col. 3, tables 2–11) was determined by observing the difference in elevation between the water surface and the sand bed with a point gage. Observations were made at preselected intervals down the length of the flumes. The selection of the interval depended upon the bed configuration that existed for the run, the intervals being closer spaced for a dune-bed configuration than for an antidune or a ripple-bed configuration. Only those depths observed in the part of the flume having uniform slope were used to establish the average depth. Because of the rapid changes in water-surface elevation at a point and the softness of the bed, especially for runs in the lower flow regime, many depth observations were required to obtain a reasonably accurate average value.

This method of observing depth was used for all the sands except the 0.45-mm size. Observations of depth for the 0.45-mm sand were made by determining the elevation of a screeded 30-to-40-foot central section of the sand bed and determining the average elevation of the water surface at times when the surface was relatively smooth. The two methods of observing depths yielded virtually the same results. The observations of average depth are considered accurate to plus or minus 0.03 foot. At a depth of 0.60 foot, the observation is therefore accurate to plus or minus 5 percent.

WATER DISCHARGE

Water discharge (col. 4, tables 2–11) was determined in the return-flow lines with calibrated orifice meters connected to water-air manometers. The orifice meters were located in the lines to avoid the possible effect of sand deposits on the calibration. They were checked periodically to determine if any change had occurred in the calibration from abrasion by the sand. The individual observations are considered accurate to plus or minus 2 percent. The mean discharge for each run is determined from the average of 5–15 readings made during the period of data collection.

"Water discharge" actually means the discharge of the water-sediment mixture. For example, a concentration of 50,000 ppm (parts per million) of sediment means that 5 percent of the water-sediment mixture is sediment by weight, or nearly 2 percent of the mixture is sediment by volume. The orifice meters were calibrated in clear water. However, a study by Nobuhiro Yotsukura (written commun., 1961) proved that the use of clear water to calibrate the meters would not produce any appreciable error in the sediment concentrations used in the course of this study.

WATER TEMPERATURE

The water temperature (col. 5, tables 2–11) was measured to the nearest half of a degree centigrade with a mercury thermometer. The temperature reported for each run was based on an average of 5–10 readings obtained during the data-collection phase of each run. The average temperature recorded for each run should be correct to plus or minus 3 percent.

SUSPENDED-SEDIMENT CONCENTRATION

Suspended-sediment concentration is defined as the ratio of the weight of solids to the weight of the water-sediment mixture. Suspended sediment (Col. 6, tables 2–9, and col. 7, tables 10, 11) was sampled 95–100 feet downstream from the headbox of the 8-foot-wide flume and 35 feet downstream from the headbox of the 2-foot-wide flume with a specially designed depth-integrating sampler. The sampler consisted of a brass nozzle 3 inches long and ¼ inch in diameter attached to a "wading rod." The nozzle was connected to a flexible tube. A water-sediment sample was drawn through the tube to a container by means of a vacuum pump which was adjusted to draw in the fluid at a velocity approximately equal to the velocity of the flow. With this equipment, 5- to 8-pound samples of water-sediment mixture were collected from two to four times during each run by a mechanical integration of the flow in the cross section. The integration was attained by traversing the sampler through equally spaced verticals at an equal transit rate for each vertical.

Some suspended-sediment concentrations were found to be larger than corresponding concentrations of bed-material discharge. This difference was due, in part, to the inadequate number of suspended-sediment samples, and to the possibility that samples were taken in a region of flow where local shear stress and turbulence were much greater than average. The standard deviation given in column 7, tables 2–9, is based on the variation among the individual samples and has considerable range depending on the number of samples, the flow, and the bed conditions.

CONCENTRATION OF TOTAL-SEDIMENT DISCHARGE

The concentration of total sediment discharge (col. 9, tables 2–11) was obtained with a width-depth integrating sampler located at the nappe where the flow dropped from the flume into the tailbox. For all sands except the 0.45-mm size, on a dune-bed configuration, eight or more samples were collected during a 2-hour period. For the 0.45-mm sand size, on a dune-bed configuration, and for all sands at all other bed configurations, four to six samples were taken in a 1-hour period. Each sample consisted of 70–110 pounds of the water-sediment mixture. For all sets of data except those for the 0.45-mm sand, the mean concentration obtained for each run is considered accurate to plus or minus 5–10 percent for concentrations in excess of 100 ppm, and to plus or minus 10–50 percent for concentrations between 1 and 100 ppm. The standard deviation given in column 10 of tables 2–11 is based on the variation among the individual samples.

For the experiments using the 0.47- and 0.54-mm sand where fine sediment was added to the flow, the concentration of fine sediment was determined from a sample (about one liter) taken from the large 70- to 110-pound sample of the water-sediment mixture after the large sample settled for 1 minute. The bed-material fraction (col. 9, tables 2–11) of the total-sediment discharge was that material retained after washing on a No. 200 sieve. To obtain the total-sediment discharge, the fine-sediment concentration (col. 6, tables 2–11) must be added to the bed-material discharge (col. 9, tables 2–11). Of course, for those experiments where fine sediment was not added to the flow, the bed-material discharge was the total-sediment discharge.

SIZE GRADATION OF SEDIMENT

The median particle size and (or) the gradation distribution in terms of fall diameter of each suspended- and bed-material-discharge sample and each bed-material sample (cols. 8, 11, 12, and 13, tables 2–11) was determined by drying the total sample, splitting it into a workable size, and then analyzing it in the visual-accumulation tube (Inter-Agency Report No. 11, 1957). Each bed-material sample consisted of several 0.1-foot-diameter cores, about 0.6 foot in length, taken at random from the bed of the flume. In the sets of runs where fine sediment was added to the flow, the fine sediment was washed out of the sample before the sample was dried, split, and analyzed.

The particle-size distribution curves given in figures 3 and 4, the average median diameter of the sand, and the gradation coefficient of the bed material were determined by averaging the results of the size analysis of the bed material for all runs of a given set and sand. The gradation (σ) is determined by the equation

$$\sigma=\frac{1}{2}\left(\frac{d_{50}}{d_{16}}+\frac{d_{84}}{d_{50}}\right),$$

in which d_{50} is the median size and d_{16} and d_{84} are the respective sizes for which 16 and 84 percent of the sample is finer than the indicated size.

BED CONFIGURATION

The general bed configuration (col. 30, tables 2–11) was noted visually and recorded photographically through the observation window in the side of the flume, at the water surface through the central measuring section of the flume, and at the bed surface in the flume. The bed-surface observations were made either through the water, if the water was sufficiently clear, or from the flume at the end of the run after the water had been carefully drained out.

A sonic depth sounder was being developed during the collection of most of these data (Richardson and others, 1961). After development of the sounder, sonic data were obtained over ripple-and-dune runs by (1) setting the sounder at a stationary point and allowing the sand wave to move past the sounder, and (2) traversing the sounder over the length of the flume at a predetermined uniform velocity.

The length, height, and velocity of the sand waves (cols. 14–16, tables 2–11) were evaluated by:

1. Observations through the wall of the flumes marked by a grid.
2. Observations in the center of the flume by point gage and foot attachment.
3. Observations by a sonic sounder.

The sonic-sounder method was only applicable when the bed configuration was ripples, dunes, or transition-dunes. The number of observations made for each run was generally considered adequate to define within plus or minus 10 percent, the mean values reported.

MEAN VELOCITY OF FLOW

The velocity of flow of a stream is usually determined from a series of velocity readings in the stream section. In the flume, however, the mean velocity (col. 17, tables 2–11) was determined from the observed values of discharge (Q), depth (D), and width (W) by use of the continuity equation,

$$V=\frac{Q}{A}=\frac{Q}{D\times W}.$$

The expected error of V from the above equation would be about 6 percent if, for example, Q and D had errors of 3–5 percent, respectively. A small error in W would be constant for all runs and thereby be canceled with respect to evaluation of other variables.

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VELOCITY PROFILE

Velocity-profile data, obtained from the horizontal movements of flow at specific verticals in the flow, are reported in tables 12–21. The observations were made with a standard Prandtl pitot tube which had been calibrated in a towing tank. Tables 12–21 show the velocity at various distances above the sand bed for most runs.

The magnitude and shape of the velocity profile in open-channel flow depend on the bed roughness and on the sediment-transport characteristics. The bed roughness and transport, in turn, depend on several waves. Figure 28 shows a breaking wave. The bed material, and viscosity of the water-sediment mixture.

Except for the plane-bed run, the velocity profiles were not constant with either time or space. As the bed configuration changed with time, so did the velocity profiles. In consideration of the time required to obtain a single velocity profile (5–15 min.), there was some change in the profile during the measurement. Also, the velocity profiles did not plot as a straight line on semilogarithmic paper (V_y = B log y + C) except for those for the plane-bed runs and some made on the back of the ripples or dunes near their crest.

The profile data were plotted on semilogarithmic paper with depth (log) as the ordinate and velocity as the abscissa. A "best fit" straight line was then used to define the relation between V_y and log y (that is, $V_y=B\log y+C$), where B defines the slope of the line in terms of velocity per log unit, and C defines the intercept of the line at a depth of 1.0 foot above the bed in terms of velocity. The values of B and C, although of limited utility for the dune runs, are listed in columns 18 and 19 in tables 2–11.

SHEAR VELOCITY, V_*

Shear velocity (col. 20, tables 2–11) is defined as $\sqrt{gDS}$, or $\sqrt{\tau/\rho}$. The error in V_* would be about 7 percent if D and S both have errors of 10 percent, or about 5 percent if D and S have errors of 10 and 4 percent, respectively.

BED-MATERIAL DISCHARGE, q_s AND q_t

Bed-material discharge (cols. 21–22, tables 2–11) was computed from Q, C_s or C_t, and a constant. Since q_s and q_t are expressed in pounds per second per foot of width, $q_s=\frac{Q}{W}\times C_s\times 0.0000624$, and $q_t=\frac{Q}{W}\times C_t\times 0.0000624$. If Q, W, and C_s or C_t have average errors of 5, 2, and 10 percent, respectively, then the mean error for q_s or q_t is about 10 percent.

KINEMATIC VISCOSITY, ν

The kinematic viscosity (ν) of the water-sediment mixture (col. 23, tables 2–11) was determined from the temperature of the water and appropriate standard tables. For runs in which fine material (bentonite) was added to the flow, the "apparent" kinematic viscosity was determined from figure 6. Dynamic viscosity values were determined by testing water-bentonite mixtures in a Stormer Viscometer (Simons and others, 1963, p. 17) for 0.5-, 1-, 2-, 3-, 5-, and 10-percent concentrations and for a temperature range from 5° to 45° C. The "apparent" kinematic viscosities plotted in figure 6 were computed from the dynamic viscosity values (μ) and the density of the water-bentonite mixture (ρ); $\nu=\frac{\mu}{\rho}$.

SHEAR STRESS AT BED, τ

The shear stress (τ) or tractive force at the bed (col. 24, tables 2–11) is a parameter commonly used as a measure of the intensity of forces related to resistance to flow and transport of sediment particles. It is computed by the formula

$$\tau=\gamma DS,$$

where D and S are from columns 3 and 2, tables 2–11, respectively, and γ is the specific weight of water (62.42 lbs per cu ft at 0° C).

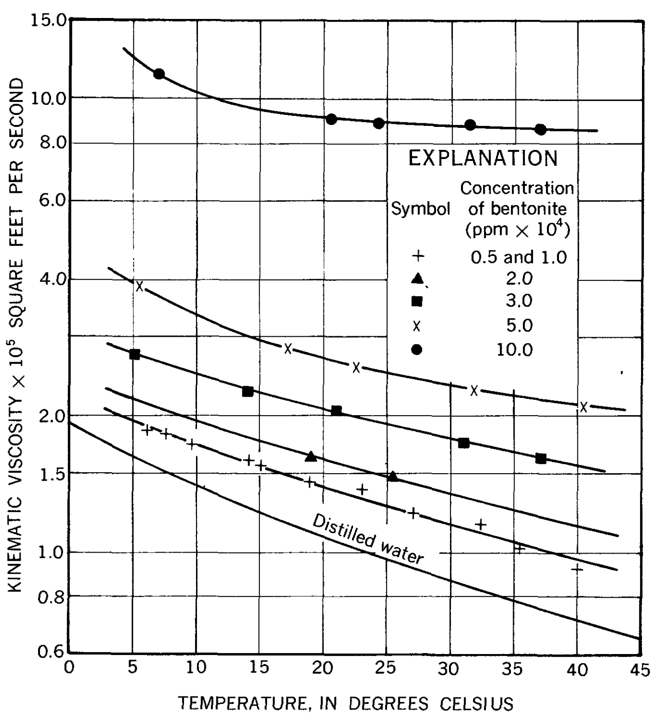


FIGURE 6.—Relationship of "apparent" kinematic viscosity of aqueous dispersions of bentonite to temperature.

REYNOLDS NUMBER, R

The Reynolds number, $\boldsymbol{R}$ (col. 25, tables 2–11) is a ratio of the viscous force to the total inertial force in the channel:

$$\boldsymbol{R}=\frac{VD\rho}{\mu} \text{ or } \frac{VD}{\nu}.$$

It is commonly used as a measure of the effect of viscosity on the flow pattern.

The Reynolds number is also often used with respect to a sediment particle:

$$\boldsymbol{R}=\frac{\omega d\rho}{\mu}, \text{ or } \frac{\omega d}{\nu},$$

where ω is fall velocity of the particle and d is fall diameter of the particle.

FROUDE NUMBER, F

The effect of gravity on the flow pattern is commonly related to the Froude number, $\boldsymbol{F}$ (col. 26, tables 2–11), which is the ratio of the gravity force to the total inertial force. As commonly used and reported herein,

$$\boldsymbol{F}=\frac{V}{\sqrt{gD}}.$$

RESISTANCE FACTORS, f, $C/\sqrt{g}$, n

Parameters related to average resistance to flow in channels are based on the variables S, D, and V. They are:

1. Darcy-Weisbach resistance coefficient, $f=\frac{8gDS}{V^2}$.
2. The dimensionless Chezy discharge coefficient, $C/\sqrt{g}=\frac{V}{V_*}$ or $\frac{V}{\sqrt{gDS}}$. Note that the discharge coefficient is the inverse of resistance.
3. The Manning n, $n=\frac{1.49D^{2/3}S^{1/2}}{V}$, where D is nearly equal to $\boldsymbol{R}$ the hydraulic radius. These resistance factors are listed in columns 27–29, tables 2–11.

DESCRIPTION OF INDIVIDUAL RUNS

This section of the report documents pertinent laboratory notes from general and unusual observations of the flow and transport phenomena during the period in which the run was approaching equilibrium and during the collection of the routine basic data. Most notes refer to methods used to set up the runs, the bed forms, the flow characteristics, and to unusual conditions relative to data collection. Many photographs were taken to show the flow and roughness characteristics. The photographs were generally taken either through the glass wall at the side of the flume, from above the water surface, or from above the bed surface after careful draining of the flume at the end of the run.

Notes and corresponding photographs, if any, for each run are headed by the respective run number. These make up the set of runs for a specific sand and flume size. The run numbers and the order of presentation (usually by increasing slope) correspond to the run numbers and order given in tables 2–11.

RUNS USING 0.19-MM SAND IN 8-FOOT-WIDE FLUME

The sand used in this set of runs was the finest used during the investigation. The runs were made between November 3, 1959, and January 21, 1960. The experimental variables and parameters are given in table 2, and the velocity-profile data in table 12.

Run 24.—The data are an average from two runs during which slope, discharge, depth, and temperature remained nearly the same. Beginning of motion or transport occurred at a low slope ($S = 0.00006$) because of the fine sand and the 0.94-foot depth of flow. The error in the mean slope measurement was in the order of 10–20 percent. The problem of determining when beginning of motion occurred (Rubey, 1937) was further complicated by the effect of small local irregularities on the bed. Particle movement on the bed nearly ceased as very small ripples became established. The ripples, in turn, increased roughness and depth, and decreased velocity. Equilibrium was thus established.

Run 22A.—The bed material was carefully screened to a plane, and then flow was established to a depth of 0.6 foot. Slope was increased and depth decreased by opening the tailgate in small increments until beginning of sand particle motion was observed. With $Q = 2.99$, $T = 17.5$, $S = 0.00010$, and $D = 0.48$, there was some movement of lightweight particles. The coarse light-weight particles (0.5–1 mm) which moved on the bed surface were sand grains cemented with a clay material. This coarser material collected along with the fine material into isolated ridges about 0.005 foot high.

Run 2.—The conditions for this ripple run were similar to those for run 1 (page I 12) except that depth and discharge were doubled and slope was reduced. Movement of the bed material in the form of very slowly moving ripples occurred throughout the flume. No armor plating developed, as it did in runs using coarser sands. The ripple waves seemed very fluid and soft in comparison to the troughs. Depth measurements may have been too great, owing to the ease with which the probe penetrated the surface of the sand waves. The average concentration from eight samples was used to determine bed-material discharge. Longitudinal and transverse views of the ripples are shown in figures 7 and 8. The photographs were taken after the water was slowly drained from the flume, without disturbing the ripples. The troughs between many ripples appeared flat owing to water standing in the depressions.

Run 22B.—This run was established from 22A by increasing the slope to 0.00016 and, thereby, decreasing the depth to 0.43 foot. All the particles moved occasionally, and then, very slowly as the slope was increased. Careful observation was required to detect such small amounts of movement. Slight indentations,

FIGURE 7.—Longitudinal upstream view of the flume bed, showing ripple formation at end of run 2 after slowly draining the water from the flume.

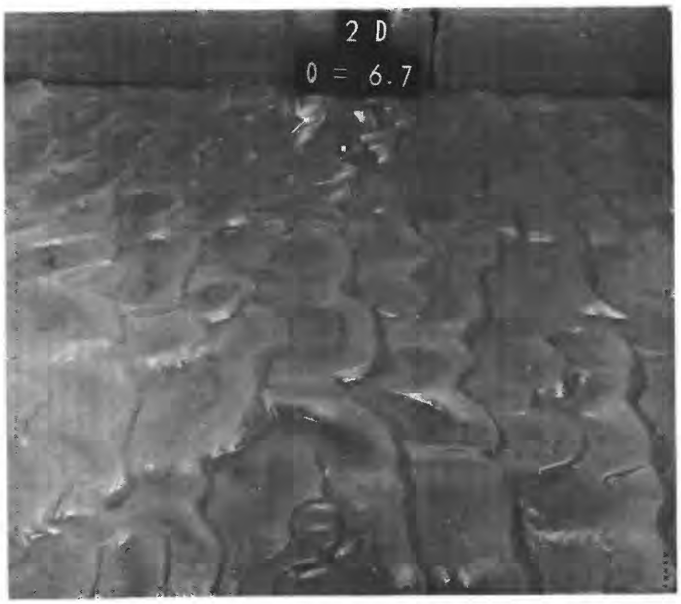


FIGURE 8.—Transverse view of ripple formation at end of run 2. The direction of flow was from left to right.

similar to those described by Bagnold (1956), formed on the bed as primary features (the beginning of ripple forms). Ripples that formed upstream from station 15 were caused by entrance effects and should not affect data relative to beginning of particle motion.

Run 26.—Some particle movement occurred over the entire flume bed. Large particles moved farther than smaller particles. These larger particles (0.2–0.3 mm) collected together and formed very small ridges spaced about the same as those ordinarily formed by ripples. It may be concluded that this segregation was responsible for the formation of ripples, except that other investigators (Brooks, 1958; Liu, 1957) reported such ridges and ripples when using a more uniform sand.

Run 25.—The conditions for this run were the same as for run 24 except that the slope was steeper. The bed was completely covered with very small ripples while the water surface was very tranquil. Ripples began to form wherever there was a slight bed irregularity, such as a large particle, and, motion having begun, continued to form progressively downstream and laterally from this point. A few coarse clay particles rolled freely on the sand surface until stopped by a depression or another large stationary particle. The ripple waves were fluidlike or soft to the probe. Figure 9 shows the smaller size of ripples formed in this run, in contrast with those formed in run 2. Note the absence of a plane with respect to the troughs of the ripples.

Run 22C.—This run was a continuation of runs 22A and 22B, but at a slightly increased slope and decreased depth. Movement of sediment was general over the entire bed, and thus ripples formed over most of the bed within about four hours after starting the run. Beginning of motion was best represented in run 22B. The rate of transport was very low; therefore, sediment samples were not taken.

FIGURE 9.—Upstream view of ripples formed during run 25. Ripples are smaller and more completely developed than those formed in run 2 (figs. 7, 8).

Run 30.—The bed was screeded prior to starting the run, and the slope of the bed was set parallel to an assumed water surface slope which would insure uniform flow over ripples at the desired depth of about 1 foot. The ripples formed a more irregular pattern than did those of runs with less shear. The water surface was tranquil or mirrorlike. The individual ripples changed shape with time and moved very slowly. The bed-material discharge, determined from nine samples, ranged from 3.1 to 4.3 ppm (parts per million), and the suspended-sediment concentration of four samples was composited and equals 7.0 ppm.

Run 1.—This run was started with the bed screeded level. Small ripples 0.3–0.4 foot long and 0.02 foot high covered the entire bed immediately after the run began. The ripples gradually increased in length and height to about 0.6 foot and 0.05 foot, respectively. Ripple crests were very soft and fluidlike in comparison with the intervening troughs. The transport rate was very low; so that the velocity of the ripples was extremely slow. The run had been in progress for about 40 hours before data were taken. The bed-material discharge, determined from eight samples, ranged from near 0 to 3 ppm. Suspended-sediment concentration was not measured.

Run 31.—Ripples formed under the flow conditions of this run were larger and had more irregular patterns than those formed at lower slope and depth. The velocity was such that sand was eroded at the headbox and moved downstream as a wave. This wave affected the water-surface slope downstream to station 45. The ripple waves in the test section seemed to be much softer than the underlying, nonmoving material. A transverse view through the flowing water (fig. 10) shows the more triangular shape of the ripples, in contrast with those shown in figure 8. The seven bed-material discharge samples ranged from 25.0 to 34.9 ppm, and the four suspended-sediment samples was composited and equals 42 ppm.

Run 27.—The shifting part of the bed was very fluid, but the underlying part was firm because of screeding. The seven bed-material discharge samples ranged from 3.1 to 5.1 ppm. Suspended-sediment movement was negligible; therefore, samples were not taken. The measured bed-material discharge was less than was expected for the given hydraulic conditions.

The pattern of ripple development for all runs suggested that flow conditions can easily be set up which

FIGURE 10.—Transverse view, through the flowing water, of ripples formed during run 31. The direction of flow is from left to right.

will form very uniform ripples of small amplitude that are nearly continuous across the flume. Then, slightly increasing shear stress by increasing depth or slope will cause larger more irregular ripples to form which are distinctly discontinuous across the flume.

Run 5.—Run 4 was not completed because of a sand wave in the flume. The bed form of run 5 was large ripples. The bed was very soft, particularly on the crest of the ripples. The large ripples and consequent transverse currents caused very small boils, which could be seen by careful observation of the water surface. Flow tended to meander through the flume and cause somewhat uneven depth of flow across the flume at a particular across section. The seven bed-material discharge samples ranged from 110 to 144 ppm, and the four suspended sediment samples ranged from 95 to 119 ppm.

Run 23.—After runs 22A–C, the bed was raked crosswise to create artificial roughness. Ripples formed overnight on the entire bed. Seemingly, the run was not in perfect equilibrium; that is, minor slope, roughness, and depth adjustments were occurring which caused nonuniform flow. The water surface was very placid, although not as smooth as before beginning of motion. The seven bed-material discharge samples ranged from 1.8 to 2.8 ppm. As indicated for run 27, the measured sediment transport rate was much less than expected when the hydraulic factors were compared with those for runs of similar hydraulic conditions. Figure 11 shows the ripple pattern which formed during run 23.

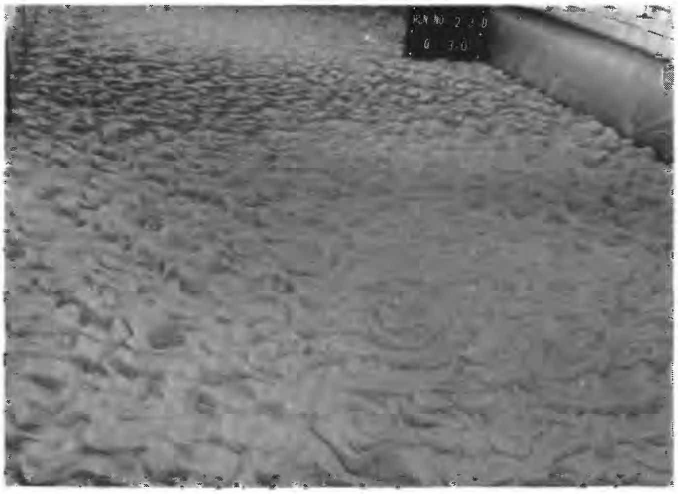


FIGURE 11.—Upstream view of ripple pattern on flume bed at end of run 23.

Run 32.—Bed roughness appeared to be small dunes with superposed ripples. The bed material to a depth of 0.1–0.2 foot was moved. Depth observations were very difficult to make because the rapidly moving material was very soft. Ripples changed shape rapidly: old ones vanished and new ones formed. Data on the length and height of ripples, from observations through the side windows, may be misleading because of the wall effect. The sonic recorder was used to determine the dimensions and velocity of the sand waves. The character of the bed configurations is indicated in figure 12.

Run 8.—Bed roughness consisted of ripples superposed on dunes. The bed was soft as with dunes,

FIGURE 12.—Upstream view of bed configurations at the end of run 32. Light spots are reflection of lights on water left from incomplete drainage in ripple troughs.

particularly on the shifting parts. Boils associated with the dunes appeared on the water surface, but they were not very violent. Figure 13 is an upstream view of the bed form for this run. The upstream side of the dunes had no ripples where the depth was shallowest and the shear was greatest.

Run 28.—Conditions for this run were similar to those for run 27 except that the slope was greater. The suspended-sediment discharge was still very small. The water surface was relatively smooth, but a brickworklike pattern of ripples formed on the bed. The bed was very soft in the zone of movement. Seven samples of bed-material discharge ranged from 28.4 to 42.4 ppm.

Run 33.—The bed configuration for this run was very large widely spaced dunes. Large strong eddies carried sand from the bed to the water surface just downstream of the dune crests. These eddies resulted in boils or local crowns at the water surface, from which moved small horizontal components of flow. The backs of most dunes, according to feel with a foot plate, were covered with ripples. The velocity of flow over the crest of a few very high dunes was sufficient to plane away all roughness on the crest. Slope and depth observations were difficult to make because of the rapid change in position and shape of the dunes. Small dunes were continually forming and moving onto the crest of the large dunes, thus changing the amplitude and rate of travel of the large dunes. Bed-material discharge, determined from nine samples of flow, ranged from 606 to 1,152 ppm; four suspended-sediment concentration samples ranged from 652 to 1,460 ppm.

Run 29.—The discharge was less than one-third, the depth was less than one-half, and the slope was nearly the same as that of run 33. The result was an increase in roughness, a decrease in velocity, and about one twenty-fourth as much sediment discharge. This effect of depth on the flow and bed-material discharge was found to be comparable to that shown by Colby (1961). The ripples moved faster and there was more sediment in suspension than in other ripple runs. The ripples, which were soft and fluid in their moving parts, formed a brickworklike pattern. The water surface was rather smooth, as in the preceding ripple runs. The eight samples of bed-material discharge ranged from 45.2 to 68.6 ppm. The four samples of suspended-sediment concentration were composited for a mean concentration of 30.6 ppm.

Run 3.—The ripples were somewhat larger in amplitude and more widely spaced than those in runs 1 and 2. The considerably increased sediment discharge caused the ripples to move faster and with greater irregularity of pattern. The irregular ripple pattern is shown in a photograph of the bed taken through the flow (fig. 14). The seven samples of bed-material discharge ranged from 61 to 120 ppm.

Run 11.—At the beginning of the run, the bed was nearly plane; during the run large regular dunes formed, which in turn caused the slope to increase. This was the first run using the fine sand for which the form, the individual element, and bed roughness as a whole, was similar to that observed in runs using coarser sands. The amplitude of the dunes was about 0.5 foot. Some ripples formed in the dune troughs

FIGURE 13.—Upstream view of ripple-dune pattern at end of run 8.

FIGURE 14.—Downstream view through flow showing rippled-bed configuration during run 3.

FIGURE 15.—Upstream view of bed configuration at end of run 11. The small surface ripples formed during shutdown of the run. Note the scour hole to the floor of the flume in the foreground.

adjacent to the walls. The bed was very firm on the back of the dunes, where the surface was planelike; and it was very soft in the trough area, where the velocity was less and the sand was being deposited. When the flow was stopped and the flume drained, more ripples were seen on the dunes than were apparent when the run was in progress. (See fig. 15). Four observations of dune velocity were made through the window to show the range of velocity of the more prominent dunes. The results were 0.085, 0.181, 0.182, and 0.480 fpm (feet per minute). The eight bed-material discharge samples ranged from 1,140 to 1,560 ppm, and the four suspended sediment samples ranged from 766 to 856 ppm.

Run 13.—Discharge was about the same as in run 12, but the tailgate was slightly opened. The resultant increased slope and decreased depth caused the downstream dunes to be partly planed out and, thus, caused decreased resistance to flow. The upstream dunes near the flume entrance were fully developed, but decreased in amplitude downstream until, at station 100, plane-bed conditions prevailed. (See fig. 16.) A few small dunes, however, remained below station 100. The water surface was very smooth over the plane-bed area. Considerable sediment was carried into suspension by eddies in the dune area. Low, more streamlined, dunes offered less resistance to flow and, hence, caused less suspension of sediment than did the regularly shaped dunes at the upper end of the flume. Eight observations of bed-material discharge ranged from 1,180 to 1,385 ppm, and four observations of suspended-sediment concentration ranged from 695 to 852 ppm.

FIGURE 16.—Typical bed conditions at end of run 13. The small surface waves were caused by slow flow at the time of shutdown.

Run 14.—The shear stress was increased from that in run 13 by increasing slope. More of the bed was plane for this run than for run 13, and the dunes at the upper end of the flume were reduced to long flat sand waves about 0.1 foot high. (See fig. 17.) The resulting decreased resistance caused a decrease in depth from that observed for run 13. When core samples of the bed were taken, a crusty surface was noted. This indicated that the sand particles were more densely packed at the surface than at the lower levels. On the whole, the bed was much firmer than that for the ripple-and-dune runs. The variation in concentration of bed-material discharge was nearly the same as for run 13. The differential-bubbler-gage record of slope showed considerable variation. However, this varying of slope was not as great as that for a dune-bed configuration because it was caused by changes in water-surface elevation as dunes moved downstream.

FIGURE 17.—Upstream view of bed conditions at the end of run 14. The small surface ripples formed during shutdown.

Run 15.—Slope was greater and depth was less than in runs 13 and 14. The bed was plane throughout the flume except for very minor long flat sand waves. The bed was very firm and had a crustlike surface. The water surface was very plane and showed neither boil activity nor standing waves. Thus, data were easy to collect for this kind of flow condition. Through the side window, small chunks of sandstone were visible only 0.1–0.2 foot below the sand surface. This was the maximum depth at which the sand moved in this bed.

Run 34.—The bed configuration for this run comprised small dunes with large ripples superposed, which caused considerable roughness of the water surface. A smoother surface would probably have resulted if depth had been greater under these conditions of roughness. Figure 18 is an upstream view of the water surface. Bed-material discharge ranged from 464 to 543 ppm for eight samples and the suspended-sediment ranged from 342 to 467 ppm for four samples.

Run 12.—The conditions for this run were very similar to those for run 11 except that both the slope and velocity were increased. Large dunes, spaced 15–30 feet apart, formed on the bed. The back of the dunes was very firm, the intervening troughs, soft. Some dunes had a rather flat avalanche face; consequently, upstream circulation over the bed in the trough was weak. This condition resulted in a lower roughness value for this run than for run 11, and a firmer bed in the trough area. Figures 19 and 20 show the water surface and the bed, respectively. Nine concentration measurements of bed-material discharge ranged from 1,180 to 1,540 ppm, and six concentration measurements of suspended sediment ranged from 887 to 1,040 ppm.

FIGURE 18.—Upstream view of water surface during run 34.

FIGURE 19.—Upstream view of water surface during run 12.

FIGURE 20.—Bed configuration at the end of run 12, viewed upstream. Note large rather streamlined dunes.

FIGURE 21.—Upstream view of ripples on low dunes characteristic of run 6. The pools of water remained after incomplete drainage at the end of the run.

Run 6.—As is shown in figure 21, the bed roughness elements for this run consisted of ripples and irregularly spaced dunes about 6 feet long. The ripples had an irregular shape which changed rapidly. Some ripples had the usual triangular shape; others were rounded and symmetrical. The water-surface slope also varied considerably between the measurement points. Several slope measurements were averaged to get a value for the representative slope of this run. An upstream view of the water surface is shown in figure 22.

Run 7.—The principal bed configuration was dunes, although ripples formed in the deeper and lower velocity parts, as is indicated in figure 23. Turbulence at the water surface seemed to be less than in run 6, although many boils were seen which carried sand to the surface. Once during the run, a dune crest was seen. Downstream from the dune crest, at the zone of separation, ripples were orientated in the upstream direction.

Run 35.—The conditions for this run were similar to those for run 34 except that slope and mean velocity were increased. The bed roughness elements were dunes with ripples superposed, but the dunes were larger than those in run 34. The water surface was not as rippled as in run 34, but much stronger eddies carried clouds of sand from the bed to the water surface. Transverse flow apparently formed long sand ridges parallel to the direction of flow. Sediment streaming off these ridges indicated greater than average sediment transport. The bed was very soft near the dune crests. A plane-bed condition with very intense sediment movement near the bed, existed on the upper part of the dunes, where the water was shallowest. Sediment transport differed widely, both from point to point on the bed and in suspension. The shapes of the dunes and ripples were very irregular and changed

FIGURE 22.—Upstream view of water surface during run 6.

FIGURE 23.—Upstream view of bed configuration at the end of run 7.

quickly. Thus, tracking dunes either visually through the window or with the sonic sounder was difficult. This sand was much more fluidlike and more sensitive to probing forces than were the coarser sands.

Run 16.—The slope was steeper, the velocity greater, and the depth less than in runs 13, 14, and 15. Upstream from station 110 the bed and water surface were essentially plane; downstream from this point, standing waves were inphase with bed waves. Figure 24 shows these water-surface characteristics. The waves in the lower end of the flume had an amplitude of less than 0.1 foot and were about 3–4 feet apart.

Run 10.—This was essentially a plane-bed run. Very long and low sand waves moved down the flume. A few ripples persisted at the walls of the flume downstream from the crests of these waves. The presence

FIGURE 24.—Upstream view during run 16, taken from station 140. Standing waves can be seen in the part of the flume downstream from station 110, and plane con ditions, upstream from station 110.

of the sand waves was also shown by the cycling of the bubbler gage. The bed was firm and plane except near the ends of flume.

Run 9.—The dunes formed in this run were very long and rather low but not as rounded as a sand wave. On the basis of observations though the window, some ripples apparently formed in the troughs. The back of the dunes (upstream from the crest) was very firm and plane; over which, the velocity was greater than in the deeper trough areas where the bed was irregular and very soft. Such variation in velocity caused considerable variation in elevation of the water surface at a point where the dunes passed. The water surface showed strong boils over the trough area. Nine sample measurements of bed-material discharge made in an 8-hour period ranged from 967 to 1,640 ppm. Suspended-sediment concentration in six samples ranged from 497 to 1,070 ppm—three samples taken from the back of the dune (plane area) averaged 600 ppm, and three from the trough area averaged 948 ppm.

Run 17.—The slope was increased by opening the tailgate after run 16 without stopping the flow. Velocity increased from 3.84 to 4.14 fps (feet per second), and depth decreased from 0.72 to 0.67 foot. In the first 60–70 feet the flume had a plane bed. Downstream the bed condition became one of small standing waves and then, with an increase in wave size, antidunes in the vicinity of stations 90–100. The most consistent and greatest antidune activity was downstream from station 110. The bed was very firm in the plane-bed areas and got softer with increasing wave activity in the downstream direction. See description of runs 18 and 19 for photographs showing these flow conditions.

Run 18.—Slope was increased from that for run 17 by further opening the tailgate. This resulted in a velocity increase from 4.14 to 4.33 fps and caused waves and antidunes to form from station 30 downstream to the end of the flume. Very symmetrical waves formed upstream from station 80 and extended all the way across the flume but did not break. Below station 80, waves were accented on one side of the flume or the other or extended the full width of the flume. The condition downstream from station 100 (fig. 25) was the same as that below station 80 except that interfering waves caused a choppy water surface. In the lower part of the flume, the water surface at a specific location went through the cycle of choppy, smooth, increasing wave, and breaking wave. When the waves broke, the flow in the area nearly stopped. The antidunes formed at a much lower slope than they did in runs using the coarser sands.

FIGURE 25.—Upstream view of the water surface in the area of antidune activity during run 18.

Run 19.—The slope was increased from 0.00300 (for run 18) to 0.00350, but the mean velocity remained unchanged. The antidunes traveled upstream faster than did those in runs using the 0.45-mm sand. Not more than three or four waves broke, and then, very gently. Sometimes waves built up and then subsided without breaking. Occasionally, at a section, wave interference from breaking waves upstream caused the water surface to be very choppy. As in the previous run, this choppy water surface smoothed and then waves developed again. Figure 26 shows the flow and bed characteristics during this run. View *A* shows a condition at near minimum depth (about 0.45 ft) and maximum velocity, and view *B* shows an area of deceleration where depth increases to about 0.75 foot. Both views *A* and *B* show that the stream bed remained relatively plane and uniform from scour despite the very large amount of sand being swept along near the bed. View *C* shows a breaking wave carrying a large amount of sand in suspension. The sand obscures the bed in the right part of the picture. The depth of the breaking wave is slightly less than twice the depth of the trough.

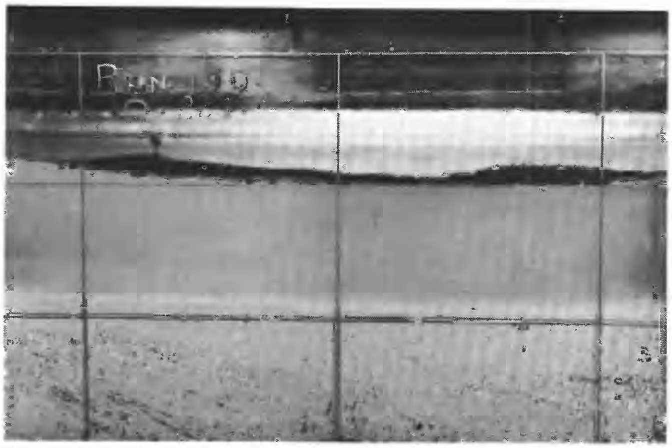
Run 39.—Conditions for this run were similar to those for run 19 except that slope and velocity were increased. Antidunes formed throughout the entire width and length of the flume. The average length of waves from crest to crest was 4.8 feet for 12 observations. The average depth was 0.50 foot in the trough (21 observations) and 0.88 foot at the crest (27 observations).

Run 20.—The intensity of turbulence due to antidune activity was nearly uniform through the flume. Most waves built up and broke, but a few waves built up and died down without breaking. Almost all waves moved gradually upstream. The amount of sediment being moved, including both that in contact with the bed and that in suspension increased considerably. The amount of sediment in suspension was sometimes so great that the position of the bed was practically impossible to distinguish through the window. In the trough the bed was firm; but where the water surface was choppy in the areas of breaking waves, the bed was soft.

Run 21.—For this run, the tailgate setting was left the same as for run 20, but the discharge was reduced from about 22 cfs to 16 cfs. Decreasing discharge caused the slope of the energy grade line and the alluvial bed to increase considerably. The antidune waves, shown in figure 27, formed both single trains occupying the full width of the flume and some double trains. A choppy water surface occasionally resulted from interference of upstream antidune waves or, when the waves were not quite at right angles to the flow and reflected off the sides of the flume, from criss-cross waves. Figure 28 shows a breaking wave. The bed surface is more irregular than it was in run 19 (fig. 26*C*). In comparison to run 19, the depth of flow in the breaking waves was more than twice the depth of flow in the trough.

Run 38.—The flow conditions for this run were nearly the same as for run 21 even though discharge, depth, velocity, and slope were increased. Antidune activity was apparent throughout the flume, and a pool and small chute formed. (See description for runs 36 and 37.) The pool, possibly the result of antidunes breaking, was only about 5 feet long, and the chute was indistinct.

Run 36.—Chute-and-pool activity was very pronounced in this run. (See fig. 29.) As many as four



A

B

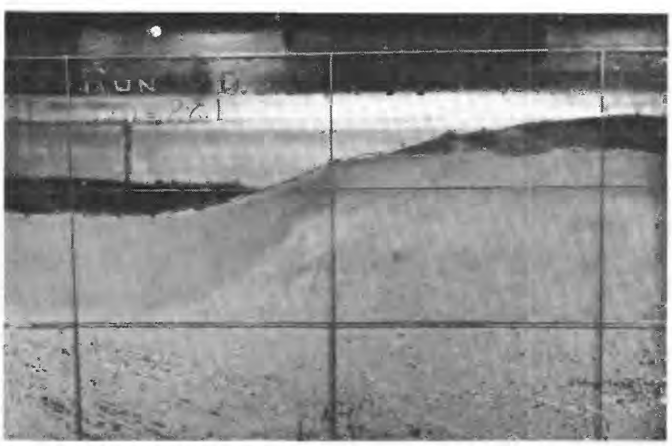


FIGURE 26.—Flow and bed characteristics of antidune conditions during run 19, photographed through window in side of the flume. *A*, The trough of a water wave. *B*, The upstream side, or deceleration area, of a wave. *C*, A breaking wave, showing heavy concentration of suspended sand.

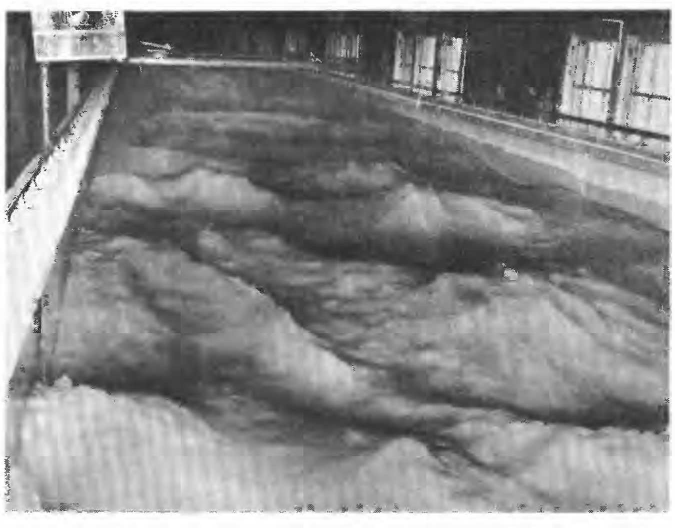


FIGURE 27.—Upstream view of antidune wave pattern during run 21.

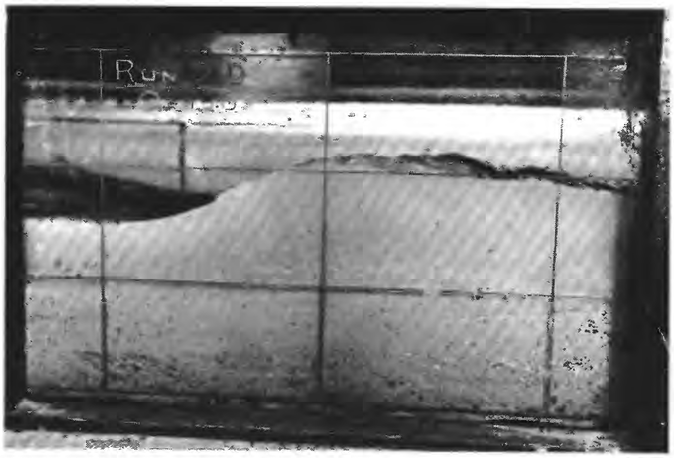


FIGURE 28.—Side view of breaking antidune during run 21.

FIGURE 29.—Upstream view of chute-and-pool flow conditions during run 36. Note the air bubbles on the water surface downstream from the hydraulic jump in the foreground of the picture.

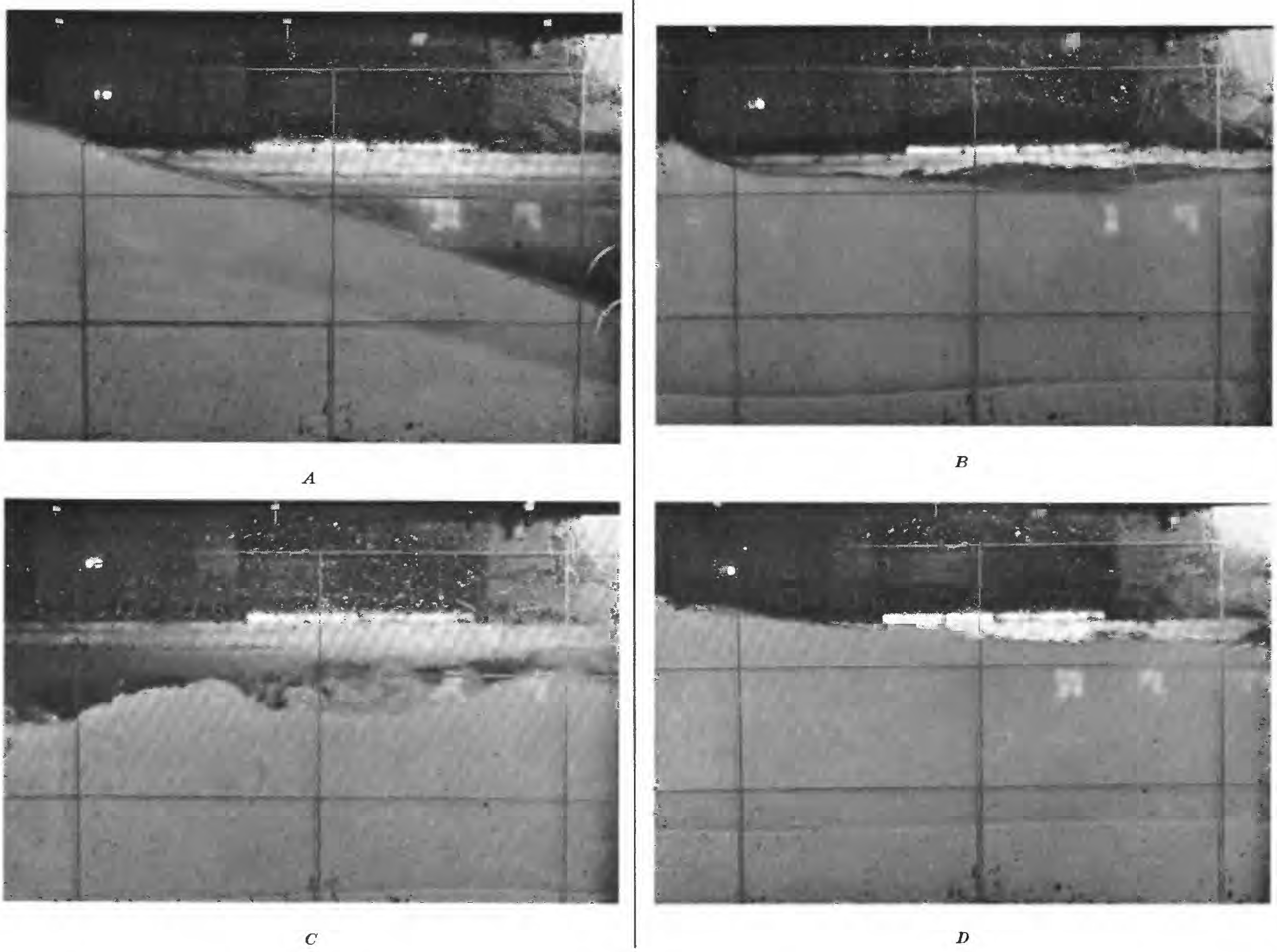


FIGURE 30.—Side views of chute-and-pool flow conditions during run 37. *A*, The chute. *B*, The hydraulic jump. *C*, The pool. *D*, The acceleration of flow toward the next chute. Photographs were taken through the window in the side of the flume.

chutes and four pools formed in the flume at one time. The gradient into the pools was very steep. The storage of water in and the release of water from the pools caused the discharge of the pump to vary. The flow in the pool sections, which were as much as 30 feet long, was 0.5–0.8 foot deep and was tranquil (Froude No. less than 1); whereas, the flow in the shorter, chute sections was 0.2–0.3 foot deep and was rapid (Froude No. more than 1). The bed elevation changed about 0.4 foot with time, but at no time was the floor of the flume exposed.

Run 37.—A chute began to form at station 50, near the lower end of the flume, and moved upstream. When it reached station 100, another chute began to form at station 50; thus, the chutes were about 50 feet apart. The chutes and pools moved upstream at a rate of about 8 feet per minute. Figure 30 shows the flow conditions during run 37. The slope of the water surface was nearly 40 percent on the steepest part of the chute.

RUNS USING 0.27-MM SAND IN 8-FOOT-WIDE FLUME

The 0.27-mm sand was obtained by wet screening the 0.28-mm sand and removing the fraction coarser than 2.0 mm (table 1). These experiments were conducted during the period March–April 1959. The experimental variables and parameters are given in table 3, and the velocity-profile data, in table 13.

Run 50A.—During this run the bed material was very close to beginning of motion. The bed was planed prior to starting flow and then once again after the water was flowing by moving the planer from upstream to downstream. Ripples formed on 3–4 percent of the bed. The formation of ripples may have been due to vibration of the flume. Vibrations of the flume caused by very small water-surface waves to form, which made precise measurement of slope difficult.

Run 50D.—The slope was increased to 0.00018, compared with 0.00007 for run 50A, and ripples formed. The mean velocity increased only a small amount (0.79 to 0.84 fps) in consideration of the large increase in slope because of the increase in bed roughness from the plane bed in run 50A to the ripples formed in this run. The rippled bed was very soft. The sand in the trough between ripples felt and looked coarser than the sand in the back and the crest of the ripples. Apparently, only the finer sand moved up the incline to form the ripple. The coarse fraction tended to armorplate the trough and inhibit further growth of the ripples. This sorting, shown in figure 31, is opposite that indicated by Bagnold (1941) for blown sand, in which the coarsest material collects at the crest and the finest in the trough.

Run 51.—The amplitude and spacing of ripples were greater than in run 50D. The coarser particles moved, and the sand felt as if it were about the same diameter in both the trough and the crest of the ripples. Figure 32 shows that the ripples were more fully developed than those in run 50D (fig. 31) and that the coarse material was deposited at the base of the ripple face rather than being a residual in the trough of the ripple. The concentration of bed-material discharge ranged from 10 to 15 ppm for seven samples, and the suspended-sediment concentration averaged 9.0 ppm for four samples.

Run 52.—The ripples formed were slightly larger than those formed in run 51, more sand was moving, the slope was steeper, and the velocity was greater. The bed seemed very fluidlike, and all sizes of particles

FIGURE 31.—Upstream view of ripples on the bed of the flume at the end of run 50D.

FIGURE 32.—Upstream view of ripples on the bed at end of run 51. Note that the ripples are better developed than those shown in figure 31.

were in motion sometime during the run. The rate of ripple movement was difficult to determine because of the rapid change of ripple shape. Some lateral shifting occurred as the ripples moved downstream. Figure 33 shows the shape of the ripples formed under the flow conditions for run 52.

These ripples were more irregular in size and shape than those formed during run 51 (fig. 32). The sand movement over the bed was typical of ripples. It moved by sliding and bounding up the back side of the ripple and then sliding or leaping until it came to rest on the foreplane of the ripple. Some fine sand went into suspension at the ripple crest. The bed-material discharge ranged from 72 to 121 ppm for eight samples, and the suspended-sediment concentration ranged from 46 to 62 ppm for four samples.

Run 54.—The bed form was one of dunes with ripples superposed. The ripples and dunes were irregular in form and changed shape rapidly as they moved past the observation window. The bed was soft, and particles of different size were well mixed, even in the troughs. The bed was firmest on the back of the larger dunes. Bed-material discharge ranged from 163 to 287 ppm for eight samples and suspended-sediment concentrations ranged from 102 to 197 ppm for four samples.

Run 53.—The back of some of the large dunes was plane where the depth was shallow and the shear was great. Most dunes were covered with small ripples or with sand waves nearly equivalent to ripples. The flow conditions were such that a slight increase in shear would cause the bed form to change to the non-rippled dune. The bed was much softer than in runs where only ripples formed. The dunes constantly changed shape and speed as small ones caught up with the larger ones. Some lateral shifting of dunes and formation on longitudinal ridges or fins parallel to the flow also occurred. Large amounts of sediment from those fins went into suspension. The characteristic shape of the dunes, ripples, and fins is shown in figure 34.

FIGURE 33.—Upstream view of ripples on the bed at the end of run 52.

FIGURE 34.—Upstream view of the bed configuration at the end of run 53.

Run 57.—The shallow depth of flow caused the bed to revert to a rippled condition even though the slope had been increased from the previous run. The ripples were fully developed and soft, particularly near the crest. The bed was firmest just downstream from the ripple troughs. The bed looked very similar to that of run 51 (fig. 32). Bed-material discharge ranged from 69 to 110 ppm for eight samples.

Run 56.—The slope was the same for this run as for run 57, but discharge, depth, and velocity were greater. The bed form changed to dunes with superposed ripples. Again, no ripples formed on the back of the larger dunes, where depth of flow was shallow, the velocity high, and the bed very firm. The "plane" flow condition on the back of the dunes caused a rather compact crust, possibly as much as one-half inch thick, to form on the dune. At places where sand was being carried into suspension, the bed was very fluidlike or soft. Figure 35 shows the irregularity of the dune and ripple pattern of run 56. The variation of concentration among sediment samples was very high. Bed-material discharge ranged from 355 to 829 ppm, and suspended-sediment discharge ranged from 252 to 852 ppm.

Run 55.—The slope of the flume for this run was not changed from that for runs 56 and 57; but as the discharge, depth, and velocity were increased, the slope increased from 0.00126 to 0.00130 as equilibrium was

FIGURE 35.—Upstream view of bed configuration at the end of run 56.

established. The dunes formed were rather large, and caused some troughs to extend to the floor of the flume. (See fig. 36.) The top layer of sand on the back of large dunes was firm, but it was very easily broken to expose the softer body of the dune. The bed was soft both at the crest and in the trough of the dunes. The condition of the water surface varied greatly with distance and time. It was very smooth and sloped downward where the velocity increased up the back side of the dune. A series of eddies and the reverse flow in the trough downstream from the dune caused a rapid increase in elevation of the water surface at the crest of the dune. Water-surface elevation varied 0.035 foot within a 5-feet distance along the flume. The reverse flow in the troughs of the dunes was further substantiated by reverse-orientated ripples in these troughs.

FIGURE 36.—Upstream view of bed configuration at the end of run 55. Note the large dual fins in the left foreground.

Run 45.—The bed was firm and felt plane except near scattered very low dunes or depressions. No eddies reached the surface from these depressions. Small symmetrical surface waves were seen near the headbox and occasionally near the tailbox.

Run 43.—The dunes formed in this run were very large. The bed was firm and very smooth on the back of dunes, and soft at the crest and through the trough of dunes. The reverse circulation in the trough of the large regularly-shaped dunes was very strong. The largest dune observed through the window, was 0.75 foot high (fig. 37). This dune probably would have been even larger if the depth of the sand bed had been greater. Some segregation of coarse and fine sand was noted, but it was not as noticeable as in runs using the 0.28-mm sand, which contained more coarse material. Again, reverse-orientated ripples frequently formed in the dune trough. Bed-material discharge ranged from 583 to 1,310 ppm for eight samples, and suspended-sediment discharge ranged from 505 to 684 ppm for three samples. Ten observations of the slope of the avalanche faces of dunes ranged from 24° to 32° and averaged 30°.

Run 44.—The dunes were longer, lower, and more irregularly shaped than those of run 43. The irregular shapes made measurement of dune velocity at the window more difficult. The back of the typical dune was firm and smooth, and the trough was soft and rather rippled. The concentration of nine bed-material discharge samples ranged from 550 to 1,060 ppm, and of four suspended-sediment samples, from 501 to 843 ppm. Concentrations of bed-material discharge were

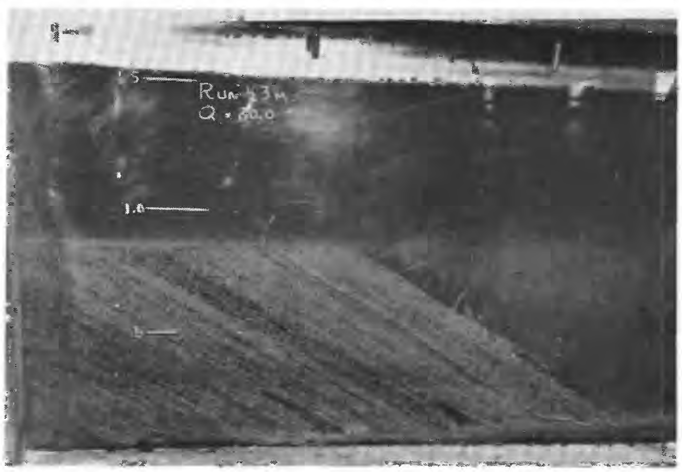


FIGURE 37.—Sliding face of the largest dune (0.75 ft) observed during run 43, viewed from window. Direction of flow is from left to right. Foreslope of the dune is 30°.

considerably lower than normal for the given flow conditions.

Run 42.—This was a dune run that was very similar to run 43. The bed-material discharge of eight samples ranged from 629 to 809 ppm, and the suspended-sediment concentration of three samples ranged from 378 to 481 ppm.

Run 46.—The slope was the same as for run 42, but a substantial increase in discharge planed the bed. Low resistance to flow resulted in a 0.2-foot reduction in depth and an increase in velocity from 2.09 to 3.68 fps. The increased tractive force caused the average bed-material discharge to increase from 704 to 1,670 ppm. The sand bed was firm and smooth, similar to the back of dunes mentioned in descriptions of previous runs. Low (about 0.05 ft) standing waves formed on the water surface throughout the flume and then dissipated. The bed level at any point varied only about 0.03 foot. The concentration of eight bed-material discharge samples ranged from 1,400 to 1,880 ppm, and the concentration of four suspended-sediment samples ranged from 771 to 1,000 ppm.

Run 58.—The depth of flow was shallow and probably inhibited dune growth. Strong vortices in the flow affected the water surface, as is shown in figure 38. The bed was firm except at the crest of the dunes. The troughs were much firmer than those in previous dune runs. The firmness in the troughs was probably caused by the shape of the trough and the height of the dune. Several minor roughness elements about the size of large ripples, but with greater length between crests were seen. After the water had been carefully drained from the flume at the end of the run, some longitudinal formations were noted. (See fig. 39.) The

FIGURE 38.—Upstream view of water surface during run 58.

FIGURE 39.—Upstream view of the bed configuration at the end of run 58.

bed-material discharge ranged from 567 to 880 ppm for eight samples, and the suspended-sediment discharge ranged from 240 to 484 ppm for three samples.

Run 47.—This was an antidune run. Wave activity was slow and weak, but waves broke throughout the flume. Some waves moved upstream while others rose and fell without much migration. The concentration of seven bed-material discharge samples ranged from 4,080 to 5,900 ppm, and the concentration of four suspended-sediment samples ranged from 3,230 to 4,360 ppm.

Run 48.—Increasing the slope from 0.00280 (for run 47) to 0.00493 caused more antidune activity to occur than was noted in run 47. Considerable water was stored in the flume when waves broke, thus the level in the tailbox dropped and discharge decreased slightly. Bed level was difficult to locate in the areas where the waves were breaking, because of the large amount of suspended load. Between the breaking waves, in the rapid-flow areas, the suspended-sediment discharge was small but the bed-material discharge was very large. The surface flow conditions are shown in figure 40.

Run 39.—The antidune activity in this run was considerably more violent than that in run 48. Some chute-and-pool activity was noted. (See description of runs 36 and 37, for the 0.19-mm sand.) The discharge was nearly the same as that in run 48, but the slope was increased considerably, the depth was decreased from 0.59 to 0.55 foot, the mean velocity was increased from 4.60 to 4.93 fps, and the mean concentration of bed-material discharge was increased from 9,080 to 28,700 ppm.

Run 41.—Discharge and depth were decreased and slope was increased after run 39. The result was a typical chute-and-pool type of flow. The velocity of flow in the pools just downstream from the breaking waves was essentially zero. Suspended sediment moved in all directions in the pools, but it mainly settled to the bed. The unstable conditions caused very large variations in instantaneous values of velocity, slope, depth, suspended load, and bed load at any point in the flume. Velocity profiles could not be obtained with the available equipment. The concentration of six samples of bed-material discharge ranged from 23,200 to 46,500 ppm, and that of four samples of suspended sediment ranged from 37,400 to 51,800 ppm.

Run 40.—Increased flow and depth caused the flow conditions to be even more unstable than those of run 41. During most of the run, three pools and three chutes could be seen. The rapid flow running into a large wave or pool looked exactly like a hydraulic jump. Air was entrained in the water as the waves broke, just as air is entrained in a hydraulic jump. Many waves were nearly 1 foot high just before they broke. Sediment movement in the area of the waves was so great that the boundary between the flow and the bed could not be located—in fact, it appeared that part of the bed was moving. Figure 41 is a photograph showing a breaking wave or hydraulic jump in the foreground and a variety of flow conditions farther downstream.

RUNS USING 0.28-MM SAND IN 8-FOOT-WIDE FLUME

These experiments were conducted during the period November 1958–February 1959. The experimental variables and parameters are given in table 4, and the velocity-profile data, in table 14.

FIGURE 40.—Downstream view of water-surface conditions during run 48. Note the breaking antidune near the center of the flume.

FIGURE 41.—Downstream view of flow conditions (chute-and-pool flow) during run 40.

Run 7.—The bed was screeded in the direction of the water flow prior to the beginning of the run, so that the particles were arranged in a relatively stable pattern on the bed. A few small grains and an occasional large grain moved when the flow began. After 36 hours, a few ripples had developed near the headbox because of the irregular flow conditions, but no sediment movement was observed in the data-observation area of the flume.

Run 8.—The run was very close to beginning of motion, because small ripples formed downstream to station 40, a few formed at station 90, and a few formed near the end of the flume. In all, ripples covered about 15–20 percent of the flume bed. Ripples would probably have covered the entire bed if the run had been continued for several days.

Run 9.—The bed was raked at the end of run 8. The discharge was unchanged from run 8. Ripples soon formed over the entire bed, and these caused resistance and slope to become greater than those of run 8. The ripples generally extended transversely across the flume, but not in a perfectly straight line. (See fig. 42.) The coarse material armored the troughs and gave the sand waves a starved appearance. The armored troughs were very firm, whereas the ripple waves were soft and thus were different from dunes, which have firm backs.

Run 10.—Ripples formed which looked very much like those formed in run 9. The transverse pattern of the ripples, however, was more irregular, and the movement was more erratic. The stress on the bed seemingly was somewhat greater than that in run 9;

FIGURE 42.—Transverse view of rippled bed pattern at the end of run 9. Note the armor plate of coarse material in the ripple troughs and the rather regular transverse pattern of the ripples.

yet the armor of coarse material on the bed did not move. The resulting starved ripples did not yield as much sediment to transport as would normally be expected for this sediment, flow, depth, and slope. The run began about 44 hours prior to the beginning of data collection.

Run 5.—The ripples formed in this run were more fully developed than those of the previous runs, but a thick layer of coarse particles was again noted in the troughs of the ripples. The sand was scoured out around the nonmoving coarse particles, and, as a result, the particles were lowered to the zone of lowest sand movement. No suspended sediment was present, and the water surface was very smooth; consequently, the bed was clearly visible through the flow. Eight measurements of bed-material discharge ranged from 5 to 16 ppm.

Run 13.—An extensive study of the effect of time on equilibrium was done during this run. Data collected December 11, about 24 hours after the start of the run, was not significantly different from data collected on December 15. The bed roughness was made up of fully developed ripples, few of which had characteristics almost like those of dunes. These few large forms caused some disturbance of the water surface. Many ripples not only moved downstream, but also, moved laterally several tenths of a foot. The rapidly changing form of the ripples made measurement of their velocity difficult. Also, observations of the velocity of specific ripples were ruined when the observed ripple either was overtaken by a faster moving ripple from upstream, was invaded by a ripple from the side, or overtook another ripple. The ripple velocity is affected by the size of the ripple and the flow and transport conditions in the vicinity of the ripple. Bed-material discharge ranged from 58 to 88 ppm for 10 observations. The sediment from four suspended-sediment samples was composited in the laboratory, so that a range cannot be given.

Run 4.—This was a ripple run. Figure 43 is an upstream view of the ripples after the water had been carefully drained from the flume. The water surface had only a few minor surface disturbances. Little or no suspended sediment was present. Coarse particles moved slowly and intermittently, while the finer sand moved from around the larger particles.

Run 11.—The ripples were more irregular than those formed in previous runs, at flatter slopes. They were deeper and the distance was greater from crest to crest. The coarse material did not influence the shape of the ripples, and movement occurred in the same manner as in previous runs of this set. Again, the finer sand was eroded away from the coarse particles, so that the rate of transport of the coarse particles was reduced. The bed-material discharge ranged from 18 to 22 ppm for eight observations. There was no suspended sediment in the flow.

Run 33.—This run was designed to provide data to fill a gap in those for the dune range of bed roughness. Ripples formed on the dunes except on the back of the very largest dunes. The top of most dunes rose and fell as ripples caught up with the dune crest. The counter-circulation in the dune troughs was very weak. The angle of the avalanche face of the dunes ranged from 23° to 30°, depending on the form of the dune

FIGURE 43.—Upstream view of the rippled bed form at the end of run 4.

and the amount of counter-circulation in the trough. The bed was very soft at all locations. Bed-material discharge ranged from 238 to 400 ppm for nine observations, and suspended-sediment concentration ranged from 195 to 558 ppm for four observations.

Run 1.—The bed form consisted of relatively large dunes with a profuse pattern of ripples superposed. The ripple pattern was very hetrogeneous as a result of the irregular flow patterns around the dunes. Suspended-sediment concentration seemed very uniform vertically, and the eddies (boils) of the water surface downstream from the dune crests were not particularly strong. The slope for this run was poorly defined.

Run 12.—The run began about 16 hours prior to data collection. The general bed roughness was classed as ripples, but it contained a few elements which looked like poorly developed dunes. The coarse particles did not influence the roughness elements. These coarse particles either settled in the sand as the finer material was eroded away from them, rolled downstream to the next trough, or, occasionally, rolled upstream into a deeper part of the ripple trough. The upstream movement occurred only in the zone of reverse flow in the trough of a dunelike form. The bed was very soft. The water surface was rougher than that of most ripple runs, and some suspended sediment was present, indicating that the flow was approaching the dune condition. The ripples rapidly changed form, size, and shape; thus, measurement of ripple velocity was very difficult.

Run 14.—The run began December 15 and continued to December 17, when the final data were recorded. The mean slope at 0800 December 16, 1500 December 16, 0800 December 17, and 1045 December 17 was 0.00122, 0.00109, 0.00122, and 0.00118, respectively. The roughness on the bed was mainly ripples and a few larger elements resembling dunes. (See fig. 44.) Some sediment moved in suspension. The water surface was more turbulent than in the preceding ripple runs; but, despite the small quantity of suspended sediment, the streambed could still be seen through the flow. The bed was very soft. Accumulation of coarse material on the bed was not excessive. Small ripples moved over larger ones and seemed to consist of sand finer than the average in the bed.

FIGURE 44.—Upstream view of the dune-bed configuration at the end of run 14.


FIGURE 45.—Upstream view of the dune-bed configuration at the end of run 20.

Run 20.—The bed condition for this run consisted of dunes, as is shown in figure 45. The bed was very soft in the troughs but firm on the back of the dune upstream from the crest, where the depth was at a minimum and the velocity was at a maximum. The area in the trough and immediately downstream from the trough contained ripples. Some dune faces were very round, and the counter-circulation in such places was weak and intermittent. The dune face generally was of the normal type shown in figure 46. The angle of the dune face was generally between 25° and 27°, but occasionally as low as 20° or as much as 30°, depending upon the strength of the counter-circulation in the dune trough. The coarse particles rolled readily from the downstream part of the trough area up the back of the dune and then slid down the face of the dune until they came to rest. After coming to rest they were buried and were not exposed again after passage of the dune. Such large particles were never seen in suspension. Twelve measurements of bed-material discharge ranged from 365 to 754 ppm, and 3 measurements of suspended-sediment concentration ranged from 323 to 373 ppm.

Run 2.—This run was very similar to run 20 except that the dunes formed were lower and longer. The

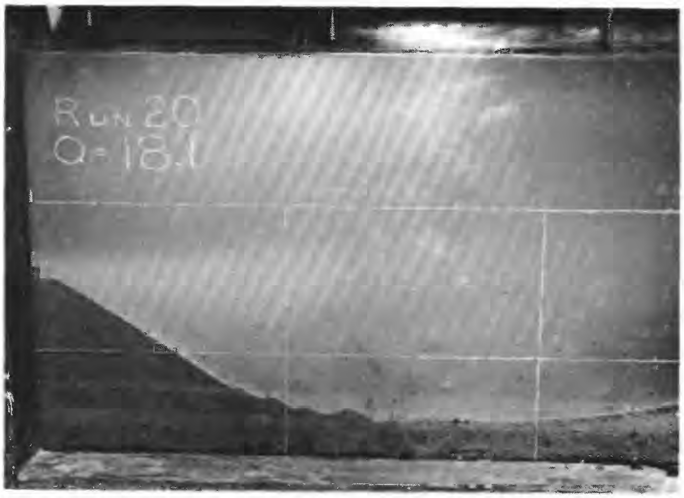


FIGURE 46.—Avalanche face of a large dune formed during run 20. Direction of flow is from left to right.

flatness of the dunes, compared with those formed in run 20, was probably due to the shallower depth and somewhat greater slope during run 20. Again, the bed was firm and crusted on the back of the dunes and soft on the dune crest and in the trough. Boils on the water surface marked the separation zone, and large-scale eddies occurred downstream from the dune crest. The slope was poorly defined.

Run 21.—Very few ripples were associated with the dune pattern for this run. As in runs 20 and 2, the distance between dunes was great, but the dune height was somewhat less than in runs 20 and 2. The water surface was relatively smooth over the back of the dunes; but it was very turbulent, because of large boils over the troughs and slightly downstream from the troughs. The water surface stood high over the trough, relative to that over the back of the dunes, because of the change of velocity head as the flow moved from one area to another.

Run 19.—Except for flow depth, which was shallower, the flow conditions and bed forms were very similar to those of runs 2 and 21. The shallower mean depth caused the eddies and turbulence to be stronger and the dunes smaller.

Run 16.—The large dunes moved faster than in preceding runs. The rate of transport of sediment by the sand waves was very high, but the limited sand depth on the bed of the flume seemingly was not adequate to allow full-scale roughness to develop—some troughs extended to the floor of the flume. The dunes traveled through the flume at all elevations. Occasionally, a dune crest formed just upstream from a short trough that extended below the average downstream bed elevation. The jet from the crest of such a low dune, in its effort to "normalize" the dune and the trough, impinged on the downstream edge of the trough and caused very rapid erosion of the trough. Rate of dune movement for a given height of dune was not constant, because the main current was sometimes directed around an area by upstream forms, and because part of the sediment in transport was sometimes captured by a dune immediately upstream from the one being observed. The slope was poorly defined.

Run 23.—This was a transitional run in which the bed forms oscillated between dunes and washed-out dunes. Dunes generally existed when resistance was relatively great and slope was steep. Then the dunes seemed to vanish, and resistance and slope decreased to the point where dunes again developed. The cycling between dunes and washed-out dunes probably resulted from the change in depth and slope that occurred when the resistance changed with a change in bed form. Some cycling may have resulted, however, from segregation of the bed material into different sizes for different dunes because it was observed that dunes of fine, coarse, and intermediate sized material passed by the observation window. Large boils resulting from eddies near the dune trough and the rapid flow over the irregular bed configuration caused the water surface to be very turbulent.

Run 17.—The slope was nearly the same as that of run 16, but the depth of flow had been reduced considerably. Dunes formed which rapidly changed shape and direction of motion. The water surface had an appearance typical to that over a dune bed. More surface turbulence, in the form of small waves, occurred than in runs with greater depth of flow.

Run 3.—With depth increased (at the same slope) over that for run 17, dune height and length increased. As in run 17, most dunes moved. Small dunes moved faster than large ones, and small dunes in shallow fast water moved faster than small dunes in deep slow water. When a small dune approached a large dune and began taking sediment from it, the large dune stopped (or nearly stopped) until the small dune caught up. The result was a new dune. The bed was firm on the back of the dunes upstream from the crest and was very soft on the crest, on the avalanche face, and in the trough. The slope for this run was poorly defined.

Run 18.—The bed condition for this run was a typical dune bed. Ripples formed in some of the deeper troughs. Large eddies formed downstream from the dune crests, or over the troughs, and carried much sand to the water surface; the suspended load was large in these areas. On the back of the dunes, upstream from the crest, particles moved mostly in contact with the bed. Suspended-sediment concentration was small enough in this zone that both the bed and the "sheet" of moving sand could be seen.

Run 30.—The flow was tranquil, and the bed was nearly plane. An occasional dune or bar less than 0.1 foot high was seen moving through the flume. The bed was not soft, but neither was it as firm as during a plane-bed run with greater velocity. The run was classed as transitional between dunes and plane bed.

Run 34.—The depth of flow was shallow, and the bed configuration was reduced almost to ripples. Figure 47, a photograph taken after the water had been drained from the flume, shows ripples on the left and small dunes with ripples on the right. The slope was steeper than for previous runs having fully developed dunes. The suspended load was negligible, and the total load was small for this slope.

Run 22.—A plane bed and little resistance to flow were the significant characteristics of this run. The elevation of the bed varied no more than 0.01 foot about the mean. Most sediment transport was near the bed, and the coarse material rolled along at a rather uniform rate. Run 22 has nearly the same slope as run 34, but the rate of flow has been increased from 5.5 to 14.9 cfs. The increased flow caused the depth to increase from 0.44 to 0.60 foot even though the resistance decreased from 0.021 to 0.013 (Manning n). The rate of energy input, or in this case depth of flow, strongly affects other variables.

Run 15.—Reducing discharge from that of run 22 (14.92 to 12.87 cfs) caused the bed form to change to fully developed dunes. With this increased roughness, the mean depth increased from 0.60 to 0.75 foot and the mean velocity decreased from 3.11 to 2.14 fps. The

FIGURE 47.—Upstream view of bed configuration at the end of run 34.

dunes ranged from 0.3 to 0.5 foot in height and were as much as 30 feet apart. The wide spacing of the dunes resulted in a large variation in the amount of bed-material discharge at the tailbox. Twelve samples, collected there over a long period of time (0820–1155), had concentrations ranging from 674 to 998 ppm. Suspended sediment in four samples ranged from 358 to 419 ppm.

Run 24.—The bed configuration was transitional between dunes and plane bed. The dunes were very irregularly spaced and had an amplitude of 0.2 to 0.4 foot. The avalanche angle of a typical dune in this run was small, and the flat trough inhibited counter-circulation. Occasionally a dune formed that had a more normal avalanche angle and a trough with some counter-circulation. The water surface was very choppy. The flow expanded, or decelerated, over the dune troughs and contracted, or accelerated, over the crests; hence, surface waves formed. Eddies in the dune troughs did not reach the water surface.

Run 25.—The bed of sand in the flume was firm and plane. It fluctuated vertically no more than 0.05 foot at the window. The water surface was smooth compared with that in the dune runs and transitional runs. A minor disturbance on the water surface was generated downstream from station 50 by a wall roughness. Figure 48 shows the flow and bed conditions of this run. Much of the material that rolled along the bed was coarser than the average bed-material size. The windrow effect, or lines of coarse particles, may have been caused by secondary circulation.

Run 28.—The flow variables and resulting plane-bed configuration were nearly the same as for run 25. Most sediment transport occurred close to the bed.

Run 29.—For this plane-bed run, slope was increased from that for run 28. As a result, velocity increased from 3.57 to 3.77 fps and sediment transport increased from 2,760 to 3,120 ppm. The bed and water surfaces, as seen through the window, slowly varied about 0.1 foot, approximating a standing-wave condition.

Run 26.—The increased slope over that of run 29 (from 0.00278 to 0.00328) resulted in a flow pattern of standing waves and an occasional breaking wave. The standing waves built up near stations 35–40 and traveled down the remainder of the flume to the tailbox. The largest waves formed near the tailbox. Waves extended the full width of the flume except when they were first forming. Some of the waves moved upstream; and, of these, some broke and some did not.

Run 32.—The flow conditions (antidunes) were similar to those described for run 31, except that wave

A

B

C

FIGURE 48.—Flow and bed conditions for run 25. *A*, Water surface during flow. *B*, View through the side window. *C*, Flume bed after draining the flume at the end of the run.

activity was not as great and the total-sediment transport was much less.

Run 27.—This was an antidune run. Much breaking-wave activity occurred, but seldom did more than three waves break at one time. Some waves moved upstream and subsided without breaking. The waves extended most of the way across the flume except when they first began to form. The coarse fraction of the bed material may be an important factor in causing the sand waves to move upstream, because much of the coarse material that eroded from the downstream part of the sand wave moved only to the upstream slope of the next sand wave.

Run 31.—Violent antidune action occurred throughout the flume. The waves were large, and as many as six or none at all may have been breaking at a given instant. Figure 49 shows the flow conditions downstream from near the middle of the flume. Near breaking waves the mean velocity of the water was reduced to nearly zero, and sediment moving into this region was lifted into suspension. As the flow accelerated and smoothed out to a plane-bed condition, the zone of maximum transport shifted toward the bed. The plane-bed condition gradually evolved into a low-standing wave, and then into a higher wave that moved upstream prior to breaking. Small rollers turned from the flow toward the bed on the upstream side of the sand waves as they broke. The bed was firm in the trough, firm on the downstream side of the waves, softer on the upstream side of the sand wave, and much softer on the crest or peak of the sand wave.

Run 35.—Conditions for this run were similar to those for run 31 except that slope was increased from

FIGURE 49.—Downstream view of antidune flow conditions during run 31.

0.00593 to 0.00815. This caused a greater number of violent antidune waves of larger amplitude to form and caused the transport rate to be more than double that in run 31. The mean velocity and depth did not change appreciably from run 31, but resistance to flow increased.

Run 37.—Discharge and depth were much less than in runs 35 and 31, and the size of the waves formed and the violence of the antidune activity were accordingly less. Breaking waves were farther apart. Many waves built up to near the breaking elevation, and then the sand appeared to be pushed out from under the water wave and the wave subsided without breaking.

Run 38.—The discharge for this chute-and-pool run was intermediate between that of runs 37 and 36. Although the slope and the tailgate setting were not changed for the three runs, the slope and the flow conditions changed considerably as a result of the change of shear stress on the bed with the change in rate of discharge. The flow conditions were very violent. A series of three or four chutes and pools formed in the length of the flume, each with rapids, large standing waves, breaking waves, and a pool, in downstream order. Figure 50 is a sketch of this phenomenon as seen through the window. The pool was like a small hydraulic jump or stilling basin, where sediment was brought into full suspension and then settled onto the bed at the lower end of the pool, at the head of the next sand wave and chute. The sediment-transport rate was higher for specific slope, depth, and bed material than was expected for the antidune roughness.

Run 36.—This run was similar to run 38 except that the discharge was increased and the chute-and-pool activity was, therefore, more intense.

RUNS USING 0.45-MM SAND IN 8-FOOT-WIDE FLUME

This was the first set of runs completed for the project. The notes were not as complete as for other sets, and the data-collection system lacked some refinements which were developed later. The significant differences in data-collection methods between this set and other sets are:

1. For runs having antidune flow, depth was measured only in areas where the water surface was relatively smooth; thus, the measured depth is too shallow.
2. Fewer bed-material discharge samples were taken over a shorter period of time, causing a greater error in the mean.
3. Slope was determined by averaging the several readings taken at different times every 5 feet along the flume and then computing a least-squares regression from these averages. The slope for other sets of runs was determined by plotting each and (or) the average of several slope measurements on graph paper and then visually drawing the mean slope line through these points. The water-surface elevation from which the slope was computed for antidune runs was only obtained when the water surface was relatively smooth. The water-surface elevation and depth for the other sets of runs were taken at random times at a given flume station. A system for taking good pictures was lacking for several runs in this set.

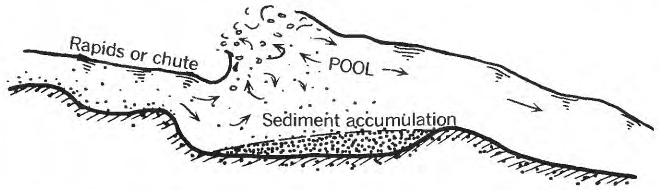


FIGURE 50.—Sketch of chute-and-pool phenomenon as viewed through the window in the wall of the flume. The vertical scale is exaggerated 3–5 times. Each chute-and-pool series is 20–30 feet long.

These experiments were conducted during the period January–July 1957. The experimental variables and parameters are given in table 5, and the velocity-profile data, in table 15.

Run 14.—The flow for this run was increased from 1.84 cfs (run 13) to 3.94 cfs. The velocity increased from 0.65 to 0.81 fps, and the shear stress was below beginning of motion.

Run 13.—The bed was planed to a slope of 0.00010 prior to the beginnning of the run. The bed material did not move under the given flow conditions.

Run 17.—The flow for this run had sufficient shear stress to move particles into a configuration of ripples, which averaged 0.77 foot long and 0.04 foot high. All transport was on or very close to the bed. No sediment was in suspension.

Run 16.—The transport rate of 1.2 ppm for this run was in equilibrium with the low-ripple bed configuration. The ripple waves transported sand much finer than the sand remaining in the troughs. This made the ripples appear "starved," as in ripple runs with the 0.27- and 0.28-sands.

Run 15.—The run began March 4, 1957. Several adjustments of the tailgate were made prior to 1700 March 6, by which time ripples had formed over the full length of the flume. At 0800 March 7 the slope, transport, and bed configuration were stabilized throughout the flume. The bed slope was 0.00021, and the water-surface slope was 0.00023; thus, flow conditions were nearly uniform. The concentration of five bed-material-discharge samples taken March 8 ranged from 0.26 to 1.38 ppm. This large range reflected the uneven transport at the end of the flume caused by the transverse pattern of waves moving in the flume.

Run 18.—The bed was not planed after run 17. The discharge was reduced from 6.22 to 3.62 cfs, and the slope was increased from 0.00020 to 0.00031. These changes did not alter the ripple-bed configuration appreciably from that of run 17. (See fig. 51.) The mean bed-material discharge was reduced from 0.7 to 0.4 ppm.

Run 2.—The bed was screeded to a slope of 0.00050 before the run began. The mean bed-material discharge was 9.4 ppm, about 10 times greater than that for the previous runs. Ripples on the flume bed had greater spacing and amplitude than those for the runs already described. The ripples were more random with respect to size, shape, and location on the bed. They no longer had a well-arranged transverse pattern, and sorting of the sand was no longer noticeable.

Run 3.—The flow conditions and ripples of this run were similar to those in run 2. The slope was increased and the velocity decreased because of increased resistance. The bed-material discharge was increased by less than 10 percent.

Run 9.—The discharge of this run was reduced from 7.90 cfs (run 3) to 3.84 cfs. The result was a ripple run with little bed-material discharge. The concentration of five bed-material discharge samples ranged from 0.8 to 1.8 ppm.

FIGURE 51.—Transverse view of the ripples formed during run 18. The flow was from right to left, and the scale is 1.3 feet long. The crests of the ripples contain finer sand than is found in the troughs.

Run 1.—This run was nearly the same as runs 2 and 3, except that the slope was increased, and this caused a reduction in the resistance to flow. The reduced resistance to flow may have been the result of the longer, relatively lower and more rounded ripples. Either the measured bed-material discharge was too high or the slope was too low compared with other runs of similar bed-material characteristics and energy of flow.

Run 5.—The bed was screeded to a slope of 0.00050 before the run began. The mean slope of the water surface was 0.00047 at the time of data collection. The flow and bed-material-discharge conditions were nearly the same as those of run 1, but the ripples were smaller.

Run 11.—The slope was set at 0.00070 until ripples formed, and then it was reduced to 0.00050. The final slope was 0.00049. Discharge was reduced from 7.93 cfs (run 5) to 1.95 cfs. The shear stress was sufficiently low that the bed-material discharge was less than 20 percent of that of run 5. The ripple pattern was very uniform, and the pattern of ripple waves was mostly perpendicular to the direction of flow.

Run 4.—The bed configuration was low dunes and ripples. The resistance to flow was less than for regular ripple conditions and resulted in greater velocity and shallower depth than in previous runs of this set. Seventeen observations of bed-material discharge ranged from 67 to 140 ppm and had an 18-ppm standard deviation from the 92-ppm mean. Either the sediment concentration was too high, or the slope measurement was too flat in comparison with "normal" conditions found from similar runs.

Run 8.—Reducing the rate of flow from that of run 4 resulted in reduced velocity, depth, and bed-material discharge. The bed configuration was ripples.

Run 7.—Bed features formed were dunes 4–8 feet long. Many of the dune troughs were 0.4 foot deep. Small ripples were seen on the crest of the dunes. Ripple waves were spaced about 0.3 foot from crest to crest and ranged from 0.02 to 0.06 foot in height. The reported concentration of bed-material discharge was about double the normal value for these flow conditions.

Run 10.—The shallow depth and low rate of flow reduced the shear stress on the bed so that apparently, only ripples formed on the flume bed. The configuration was nearly that of a staggered pattern of individual ripples.

Run 6.—The bed configuration was a transverse pattern of ripples across the flume. A diagonal pattern (about 45°) of slightly larger forms was also evident. The transverse bed waves were about 0.08 foot high and 0.7 foot apart. The diagonal waves were about

0.15 foot high and 2.5 foot from crest to crest. No sediment was in suspension.

Run 12.—The shallow depth of this run caused a low bed-material discharge and a rippled bed configuration. The shallow depth also accentuated the effect of a backwater curve from the tailgate. This backwater curve reduced the bed-material discharge near the tailgate compared with the discharge near the central part of the flume. The total measured transport may be too low by a factor of 10–20. The other measurements of basic data probably were satisfactory.

Run 19.—Dunes formed which were 3–8 feet long and almost completely covered with ripples. The dunes had a maximum height about equal to the mean flow depth. Many dune crests moving down the flume were normal to the flume walls, but some were 20–30° from the normal. The resistance to flow seemed to be less than in runs in which fully developed dunes formed.

Run 21.—Flow was increased from 4.24 cfs (run 19) to 12.12 cfs. This increase in flow caused the depth of flow to more than double and caused the velocity to increase from 1.30 to 1.58 fps. The bed-material discharge also was nearly doubled. Figure 52 is a view of the dune-bed configuration in the flume after carefully draining the flume at the end of the run. The fin or longitudinal dune in the foreground is evidence of transverse-flow components resulting from either secondary circulation or flow diversion around the upstream dunes, or both. The spacing of the ripples on the dunes varied from close in the deep troughs to wide, and even obliteration, on the crest.

Run 22.—The bed configuration and resistance to flow were nearly the same as for run 21. A small increase in flow rate caused the bed-material discharge to increase.

FIGURE 52.—Upstream view of the dune-bed configuration at the end of run 21.

FIGURE 53.—Upstream view of the dune-bed configuration at the end of run 25.

Run 25.—Low discharge and shallow depth caused the dune height to be less than in runs 21 and 22. Figure 53 shows that the dune pattern was more regular than in the previous runs. The avalanche faces were normal to the flow and averaged about 6 feet in width. The orientation of the ripples, although not continuous on the dunes, indicated the direction of flow over the dunes.

Run 20.—The flow and transport conditions resulted in a dune-bed configuration and an overall resistance to flow transitional between those of runs 25 and 21. The bed-material discharge was nearly the same as that of run 21, which had the deeper flow, because of the much higher slope.

Run 23.—The flow rate for this run was about the same as that for runs 21 and 22, but the slope was about double. The dunes had a more natural appearance than those of run 25. Compare figures 53 and 54. The dunes appeared to consist of slightly coarser material than that seen on the surface of the trough. The finer material in the trough settled out of suspension as a result of the lower velocity of flow over the trough area.

Run 24.—The dunes that formed on the bed were similar to those formed in run 23, but somewhat smaller. The resistance to flow and the bed-material discharge were greater than for the previous run.

Run 40.—The water surface was extremely turbulent, and the waves were neither symmetrical nor smooth-surfaced. Some disturbances on the surface could be correlated with points of maximum roughness on the bed. Slope measurement was difficult because of the rough water surface. The water surface in the area

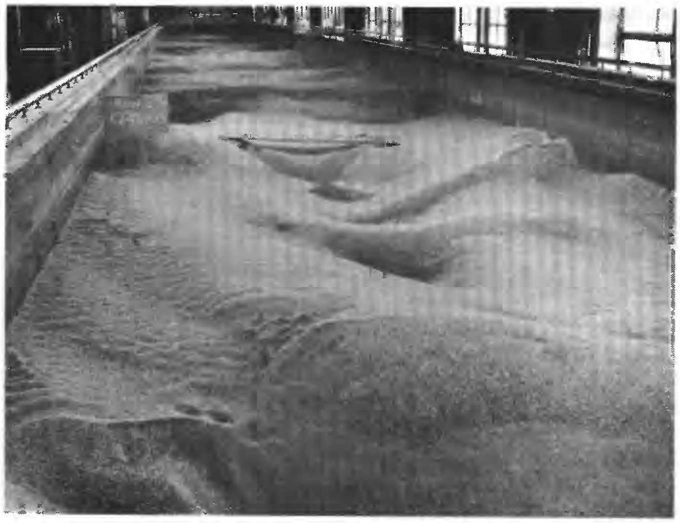


FIGURE 54.—Upstream view of the dune-bed configuration formed during run 23. Note that the dune wave and avalanche face consist of coarser material than is in the trough.

of a boil stood several hundredths of a foot higher than in the surrounding area. Both horizontal and inclined bedding planes were observed through the window as the dunes moved by at different levels. The inclined bedding planes were on the avalanche face of the dunes and appeared to be formed of material somewhat coarser than the median diameter of the bed material. The horizontal layers were composed of suspended sediment deposited in the trough of some dunes and appeared to be somewhat finer than the median diameter of the bed material.

Run 39.—Slope was 0.00364 and discharge was 2.58 cfs per foot of width. All dune roughness was planed out. A train of well-rounded standing waves traveled from near the entrance of the flume to the exit. The water surface was much smoother and the bed was firmer than in the dune runs. A train of inphase sand waves formed under the water waves, the reverse of the phenomenon observed for the dune forms. The relative variation of bed-material-discharge concentration was much less than for the dune runs.

Run 26.—This was a plane-bed run. The flow was essentially the same as described for run 39 except that no standing waves or undulations in the bed elevation occurred.

Run 28.—The flow of this run was in a transition phase. One side of the flume had low washed-out dunes, where the water surface was out of phase with the sand waves; and the other side had low standing waves, where the surface was inphase with the bed waves. The amplitude of both kinds of sand waves was much smaller than that of the water waves. The proportion of the two kinds of flow changed considerably with time.

Run 29.—Long flat dunes formed during this run, each with an avalanche face as much as 0.15 foot high. A typical observation showed smooth flow 0.25 foot deep on the back of the dune and, after the flow passed a 0.10 foot high avalanche face, turbulent flow 0.42 foot deep in the trough area. The water surface was actually 0.07 foot higher over the dune trough than over the smooth back of the adjacent dune.

Run 31.—The flow lines were relatively straight, and the water surface was relatively smooth, except for rounded standing waves which generally developed slowly into trains. Small ripples formed near the wall of the flume. They were probably due to the wall effect and did not extend into the flow more than 1 foot. Some water waves near the tailbox became steep and broke.

Run 27.—The moving bed forms were low alternate bars, which caused the flow to meander. Some standing waves formed in the flume, and occasionally a wave would break gently. The standing-wave condition seemed to alternate with the plane-bed condition. (See fig. 55.)

Run 36.—The low discharge (3.15 cfs) and shallow depth (0.19 ft) for this run accentuated formation of the alternate-bar type of flow mentioned for run 27. The bars were 0.1–0.2 foot high and generally occupied about half the flume width. Shallow flow over the bars moved sediment and deposited it at the downstream edge of the bar; thus, the bars slowly migrated downstream. In the deeper flow, which moved from side to side in the flume, around the bars, antidunes formed. Generally the antidunes were standing waves, but occasionally a wave broke. Figure 56 shows the water surface during this run and the bed condition at the end of the run, after the flume was drained.

Run 41.—A train of standing waves formed in the middle half of the flume. The standing waves were a train of sand waves under inphase water waves. The waves generally increased somewhat in height as they traveled along the flume. The waves occasionally migrated slowly upstream or downstream, but they generally were nearly stationary. The height of the water waves varied 0.20–0.25 foot from trough to crest, whereas the height of the sand waves varied 0.12–0.16 foot from trough to crest. The bed was very firm where the water surface was smooth, but it was either soft or firm under waves.

Run 30.—The flow in this run was similar to that described for run 36. The thalweg wandered from side to side along the flume and contained an occasional small antidune. The water surface was more wavy over the entire flume than it was for run 36. These waves averaged about 0.2 foot high and 1.2 feet from

A

B

FIGURE 55.—Flume conditions for run 27. *A*, Water surface downstream from station 100. *B*, Diagonal bars formed by flow upstream from station 100.

A

B

FIGURE 56.—Upstream views during and after run 36. *A*, The water surface. *B*, The bed after the flume was drained. Note that the main thread of streamflow is on the left side of the flume in the area of the sign and then moves downstream toward the right side of the flume toward the lower right corner of the photographs.

crest to crest. The alternate bars were 0.2–0.3 foot high on the downstream or avalanche edge. Waves on the bed under water-surface waves had a pattern similar to that of the surface waves, but they were less than half as high.

Run 35.—This run was similar to run 30 except that the alternate bars which formed were not as prominent and the standing waves were more evenly spaced in the flume. Some standing waves occasionally moved upstream, but they generally remained in one position, growing in amplitude and then gently receding.

Run 34.—The slope, depth, and velocity were greater than those of run 35. A series of standing waves formed.

Run 33.—The mean velocity was 4.60 fps compared with 2.80 fps for run 35. The standing-wave flow pattern occurred at varying rates of mean velocity for several runs. Occasionally a train of small antidunes formed and moved upstream without breaking (standing waves). These waves grew in amplitude and then gently receded to a plane bed. The resistance to flow was very low.

Run 38.—The flow was deeper than for run 33, and standing waves formed from wall to wall across the flume at approximately right angles to the flow. More waves moved upstream than moved downstream. No waves broke.

Run 37.—The flow conditions were very similar to those of run 38. The train of standing waves extended from wall to wall in the flume. The waves varied greatly in size, but never disappeared nor broke. The channel bed was very firm and, as seen through the window, appeared to be horizontally bedded. Clouds of suspended sediment extended up through about two-thirds of the flow depth.

Run 32.—The size of the water-surface waves increased with distance downstream in the flume. During most of the run, a train of antidunes existed between stations 40 and 95. These dunes continuously built up, broke, and then reformed. (See fig. 57*A*.) From station 105 to the end of the flume, the dunes and resulting water waves extended the full width of the flume (See fig. 57*B*.) The antidunes did not move upstream very much during their buildup. The waves on the bed surface under the main train of water waves were inphase with the water waves and had an amplitude about one-fourth that of the water waves. Most sediment moved near the bed, but some suspended sand was seen in the top part of the larger waves. Wave activity at the side window was mild compared with that in midstream; small inphase waves migrated downstream, and the amplitude of the bed undulations under them was about one-fourth that of the water waves. The bed undulations were still apparent after the flume had been drained at the end of the run. They extended all the way across the flume, were generally less than 0.1 foot high, and appeared to be parallel to each other and perpendicular to the flow direction.

Run 45.—The water-surface condition varied widely, from plane, to antidune waves (either breaking or standing), to trains of waves extending nearly the full length of the flume. The sand bed was firm except where the antidunes broke (see fig. 58). Very heavy concentrations of sediment moved, mostly near the bed. Analysis of data showed that the concentration was about double that ordinarily expected for the imposed hydraulic conditions.

Run 44.—Antidune waves formed just to the left of the center line of the flume, generally in a single train, but occasionally in a double train. The waves moved slowly upstream until they broke. New waves that formed downstream from the breaking position continued the process, so that net upstream movement was minor. The bed was firm except under the crest of a breaking wave. Mean flow depth for this run was shallow (0.28 ft), so a given antidune sand wave was generally higher than the adjacent trough of the water wave.

Run 42.—The flow condition and the bed configuration for this run are similar to run 44 even though the slope was steeper, the discharge, depth, and velocity were greater, and the bed-material discharge was less.

Run 43.—Wave activity was very diverse. The waves generally occupied the full width of the flume and formed and broke rather quickly compared with those formed in runs described previously. When several of these large waves broke at once, the flow velocity was greatly reduced and considerable water was stored in the flume. The result was a lowering of the water level in the tailbox and, consequently, a reduction of the discharge of the pumps. Thus, the rate and magnitude of discharge variation depended on the antidune activity.

RUNS USING 0.93-MM SAND IN 8-FOOT-WIDE FLUME

Data for these runs were collected during the period March–July 1960. The experimental variables and parameters are given in table 6, and the velocity-profile data, in table 16.

Run 19.—The bed was screeded to a plane prior to this run. Then flow was carefully increased until several particles close to incipient motion had settled into a more stable position. No sediment was moving when the hydraulic data were collected. Resistance to flow due to the stationary sand grains was computed (table 6).

Run 25.—The flow depth was the same as for run 19, but the slope was greater and, consequently, the velocity was 1.22 instead of 1.00. No sediment movement occurred.

Run 26.—Discharge was increased about 10 percent over that for run 25, and the resulting shear stress and a mean velocity of 1.32 fps were sufficient to cause some movement of particles finer than 1 mm. The movement of the grains was very random and infrequent. The rate of bed-material discharge was too low for reliable measurement.

Run 27.—Further increase in the shear stress over that in run 26 caused general movement of all particles except those larger than about 2.0 mm. The bed-material discharge, determined from a composite of six samples, was 2.8 ppm.

Run 20.—The slope for this run was the same as for run 27, but the discharge and velocity were less. The measured bed-material discharge was about 0.4 ppm, but data from other runs indicated that it should have been about 2 ppm. The slope was more than double that for run 19, and the velocity was about one-third greater. The bed seemed denser than that in run 19 because of the fact that particles fell to a lower elevation on the bed as they moved in run 20.

A

B

FIGURE 57.—Flow conditions during run 32. *A*, View downstream showing train of antidunes near station 80. *B*, View upstream from station 125 showing large antidunes occupying full width of flume, and narrower antidunes from station 95 to the head of the flume.

Run 21.—The slope and discharge were increased for this run over those for run 20. Some particles moved constantly, but the largest ones moved only occasionally. The bed was very plane, and the largest grains were gradually buried. The water surface was smooth but not as glassy as in runs 19 and 20. The measured bed-material discharge (0.4 ppm) was about one-sixth that normally expected for the given flow conditions.

Run 18.—A series of very low dunes or sand waves formed along the left wall of the flume. They tapered down to the plane bed along the right side of the flume. Some armoring occurred in the areas of greater boundary shear stress as a result of sorting of the fine material from the coarse. At least 99 percent of the bed-material discharge (21 ppm) moved in contact with the bed, so the water remained very clear.

Run 28.—The discharge was about 10 percent greater than that in run 18, but the slope remained the same. Low dunes formed in a pattern similar to that in run 18. The dunes in this run, however, extended farther across the flume than did those in run 18.

Run 29.—The slope was increased over that of run 28, but no sediment moved because of the low shear stress. The low shear stress resulted from a reduction in velocity (from 1.75 to 1.16 fps) and in depth (from 1.04 to 0.50 ft).

Run 22.—This run was nearly identical with run 29.

Run 30.—The velocity was increased to 1.25 fps by increasing both slope and discharge. Only particles less than about 1.0 mm in diameter moved.

Run 31. This was the first of the shallow-depth (about 0.5 ft) runs with the 0.93-mm sand during which there was general transport of the sand on the bed. No sand waves or dunes were seen, but some sorting of the fine and coarse material was noted. Movement of fine material occurred about 0.5 foot from the walls of the flume and was parallel to the direction of the flow. A few small depressions or pockets were eroded in the bed. No sand waves were seen downstream from such erosion pockets.

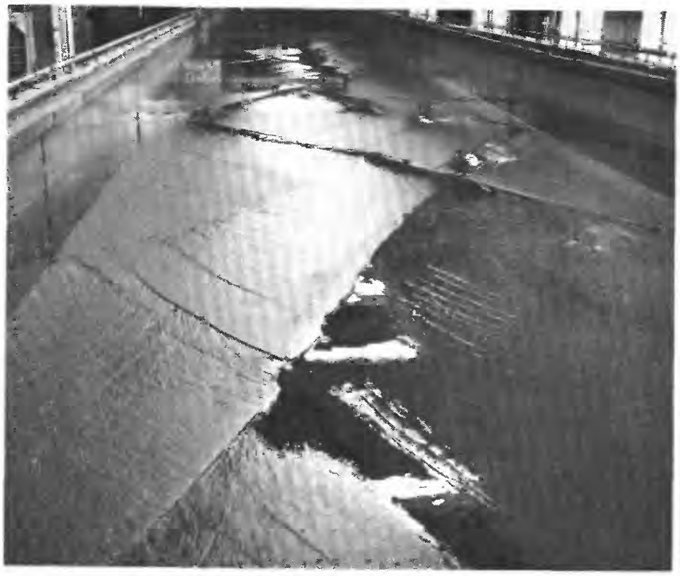
Run 15.—Very small regular dunes about 0.10 foot high formed and moved slowly downstream. These dunes were typical of those obtained with finer sands, except that they were perhaps more regular and more closely spaced. They looked like those of run 14 shown in figure 59. The water surface was calm except downstream from dune crests, where small boils were generated by eddies. The bed was easily seen through the flow, because the amount of sand in suspension was very small.

Run 23.—Conditions were similar to those in run 30 except that the velocity was 1.30 instead of 1.25 fps. No particles larger than about 1.5 mm moved. The bed-material discharge was greater over patches of finer material. Even large particles rolled across these areas and then stopped when they reached the zone of normal gradation and other large particles.

Run 32.—The bed was essentially a plane, and the bed-material discharge was 26 ppm. The bed-material discharge was nearly the same as for runs 18 and 28, but the hydraulic conditions were much different. Eight or nine bands of relatively fine material moved at equally spaced increments across the flume. Figure 60 shows the bed after the flume had been drained at the end of the run.

Run 24.—The discharge was about 10 percent less than that of run 32. The bed was plane, the depth was 0.49 foot instead of 0.52 foot, and the velocity was 1.46 fps instead of 1.50 fps. As in run 32, segregated move-

A



B

FIGURE 58.—Upstream views of flow conditions for run 45. *A*, Train of antidune waves (sometimes called rooster tails). *B*, Bed configuration caused by the antidune flow.

ment occurred: the bed-material discharge was mostly composed of fine particles. Some small depressions or pockets were noted.

Run 14.—The bed roughness for this run consisted of small dunes having an amplitude of less than 0.05 foot and spaced 2.5–3.0 feet apart. This state of equilibrium was reached by washing out the large dunes formed in run 13, in which discharge and slope were much larger. The sand bed was very soft, particularly on the crest of the dunes. There was little or no suspended load, and the bed roughness did not affect the water surface. The bed was plane adjacent to the flume walls. Figure 59 shows the bed after the flume had been drained at the end of the run. Evidence of differential transport can be seen in view *B*, which shows that the finer material is concentrated where the dunes are highest. Differential bed-material discharge was also indicated by the fact that the median diameter of the bed-material discharge was 0.00272 foot, whereas the median diameter of the bed material on or near the surface was 0.00325 foot;

Run 34.—The flow conditions were similar to those described for run 14 (fig. 59) but the dunes that formed were slightly more irregular in shape. The increased shear stress caused the dune velocity and bed-material discharge to increase. The average particle size in the dunes or sand waves was smaller than that in the bed as a whole.

Run 16.—The shear stress was sufficient to cause dunes to form that were more typical of natural dunes that those formed in runs 18, 28, 15, 14, and 34. The pattern of the dune faces was generally perpendicular to the direction of flow, but some advancement of the faces sometimes occurred near the centerline of the flume. Figure 61 shows the degree of dune development at the end of the run. Some sediment was carried in suspension, but not so much that the bed could not be seen through the water surface. Although the bed was very soft during flow, especially near the dune crests, the depth was much easier to measure than in runs using finer sands. As the size of the bed material increased, the avalanche face of the dunes grew steeper, recirculation downstream from the dune crest grew stronger, and the dunes moved in a more definite plane, were closer together, and had a more uniform shape.

Run 35.—The depth of flow was shallow (0.53 foot) and slope, fairly steep (0.00130). Dunes formed that appeared to have characteristics between those of dunes formed in runs 16 and 34. (See fig. 60, 61 and 62.) The steeper slope caused an increase in the bed-material discharge and the dune velocity. The resistance to flow was about midway between those in runs 16 and 34; yet, the water surface was more turbulent than in runs 16 and 34. Small boils were seen on the water surface downstream from the crest of the low dunes. Small fins of sediment that were parallel to the flow formed downstream from some avalanche faces. Many fins consisted of material finer than the average in transport.

Run 17.—This run was similar to run 16 except that the slope and, consequently, the shear stress were increased by opening the tailgate. The dunes were well formed and moved faster because the shear stress was increased. The suspended bed-material discharge con-

A

B

FIGURE 59.—Flume bed at end of run 14. *A*, View upstream. *B*, View downstream. Note in view *B* that the finer material is in the areas of maximum dune height.

sisted mainly of the finer particles, and the water was sufficiently clear that the bed could be seen through the flow. A few ripples moved on the backs of the largest dunes.

Run 33.—The bed was raked and rough-screeded prior to the beginning of this run. Because of the shallower depth of flow, the dunes that formed were not as high as those formed in run 17. The water surface was rough and choppy, and a few boils were seen downstream from the dune crests. The dune height and the resistance to flow were greater than in runs 35 and

FIGURE 60.—Upstream view of the plane bed at the end of run 32.

34. Figure 63 shows the bed at the end of run 33 and may be contrasted with figure 62, which shows the bed at the end of run 35.

Run 5.—The dunes formed were larger and more irregularly shaped than those formed at nearly the same discharge but at lesser slope in runs 16 and 17. The rate of dune movement was nearly equal to that in run 17 (table 6), but the bed-material discharge was greater because the dunes were larger. The water surface was depressed in depth over the dune crests and was expanded over the troughs. Boils due to the strong counterflow in the troughs, could be seen on the water surface downstream from the dune crests. The bed

FIGURE 61.—Upstream view of dunes formed during run 16.

FIGURE 62.—Upstream view of the dune-bed condition at the end of run 35.

with these larger dunes was softer and more fluid than in the previous runs. The suspended-sediment concentration was very small so the bed could be seen through the flow. Small fast-moving dunes moved on top of the large dunes, possibly causing the change in level of the major dune movement.

Run 10.—The slope was steeper, the depth shallower, and the bed-material discharge greater than in run 33. The result was a low dune pattern. The relatively large amount of bed-material discharge near the bed and possibly also the increased strength of secondary circulations accentuated the "fins" downstream from the dune crest. (See fig. 64.) The irregularly shaped dunes and "fins" seemed to indicate that at such shallow depths, meandering might develop if slope and transport rate were increased.

FIGURE 63.—Upstream view of low dunes on the flume bed at the end of run 33.

FIGURE 64.—Upstream view of the dune configuration at the end of run 10.

Run 37.—The flow conditions in this run were similar to those in run 6, which will be described later.

Run 36.—This was another shallow-depth run and was similar to run 10. The water surface was so turbulent that eddies, generated by the dunes, were indistinct. Waves generated in the flow by the dunes were reflected from the side walls, giving the appearance of additional roughness. The dunes were larger than those in other shallow-depth runs. The large dunes at this shallow depth caused much resistance to flow.

Run 6.—This run was similar to run 37. As can be seen in figure 65, the bed consisted of large dunes. The

FIGURE 65.—Upstream view of the dune-bed configuration formed during run 6.

A

B

FIGURE 66.—Upstream views of the flow conditions for run 11. *A*, The water surface. *B*, The bed configuration at the end of the run.

dunes were very regular in form and had small dunes or ripples on their back. The bed was soft on the crest and firmer on the back, but in general it was softer and more porous than in runs having smaller dunes. The high velocity of flow over these large dunes resulted in a very rough water surface. If the depth had been greater, the surface waves would probably have been dampened and eddies and boils would have been more conspicuous. The turbulence was sufficient to cause some larger particles to be carried in suspension, and some of these were seen "jumping" from dune crest to dune crest. Most of the moving sediment was, however, in nearly continuous contact with the bed. The dunes advanced by the processes of (1) sediment avalanching and deposition on the front of the dune crest and (2) erosion of the dune back and at the front of the trough. The amount of bed-material discharge varied greatly, depending on the position of the dune or dunes in relation to the flume exit.

Run 7.—The slope was about the same as that for run 6, but the discharge was reduced to about 10 cfs. Compared with run 6, the velocity and depth were less, the dunes were smaller, and the water surface was smoother. Boils were conspicuous on the water surface downstream from the dune crests. As in other sets of runs, the large dunes moved much slower than the small dunes. The speed was directly proportional to the size or amplitude of the avalanche face, which varied with the volume of sediment in transport. The speed was also proportional to the shear stress, to the bed-material discharge over the back of the dune, which, in turn, was affected by the position of upstream dunes, and to the exposure or elevation at which the dune moved through the flume.

Run 38.—The dunes formed in this run were similar to those formed in runs 6 and 37. Increasing the slope for this run caused the velocity of flow and the bed-material discharge to increase; consequently, the mean dune velocity was considerably greater. Many short dune troughs formed, in which the impinging flow from the crest of the dune at the upstream edge of the trough caused very rapid scour on the downstream part of the trough. The components of flow from this impingement, both forward and reverse, caused considerable suspension of sediment.

Run 11.—The bed configuration consisted of large fast-moving dunes. The water surface was turbulent, and a few random surface waves were generated. Figure 66 shows the water-surface and bed conditions of this run. As can be seen in figure 66*B*, ripples or small dunelike sand waves formed on the back of the dunes. The distance between the major dunes seemed to increase as they moved downstream. When the distance between dunes had increased to about 10 feet, either a new dune formed or the distance gradually decreased, depending on the position and shape of the dune pattern upstream.

Run 8.—This run was similar to run 7 except that the slope was steeper and the velocity was higher. The discharge was increased over that of run 7 to maintain nearly the same depth. The dunes that formed were longer, lower, and traveled faster. The characteristics of the flow on the dunes seemed to represent the beginning stages of the transition between dunes and plane bed, although the energy of the flow was much

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less than the rapid-flow condition in which $F > 1$. The wavy water surface effectively masked the typical dune-type boils on the water surface.

Run 12.—The dunes were medium sized but moved rapidly and caused many surface waves. Some surface waves had white caps, but did not exhibit antidune characteristics. The bed increased in firmness as the velocity increased, especially on the back of the dunes. The dune shapes were sometimes observed to be very regular and consistent or, at other times and locations, change rapidly. Occasionally, a jet of flow moved over a dune that had a steep avalanche face, inpinged on the steep upstream face of the trough, or on the back of the next dune downstream, and caused very rapid erosion and the suspension of large quantities of sediment. Where such flow conditions occurred, very strong reversed flow originating from the eroding area and moving across the bottom of the trough was evident. Figure 67 shows these flow conditions.

Run 13.—The slope for this run was steeper than that for run 12. Faster flow and more bed-material discharge resulted. The water surface was very rough, and short trains of irregularly shaped waves with white caps formed. The dunes were elongated and irregular in shape. Figure 68 shows the flow conditions of the run. The suspended-sediment concentration was greater than that in run 12. The dunes moved fast and changed shape rapidly; thus, useful data on dune velocity and amplitude were difficult to obtain through observation windows.

Run 9.—The water surface was very rough, and the dunes were low and moving downstream very rapidly. This was a true transitional run. Standing waves in-phase with the underlying bed configuration were common, but, more typically, the water waves were out of

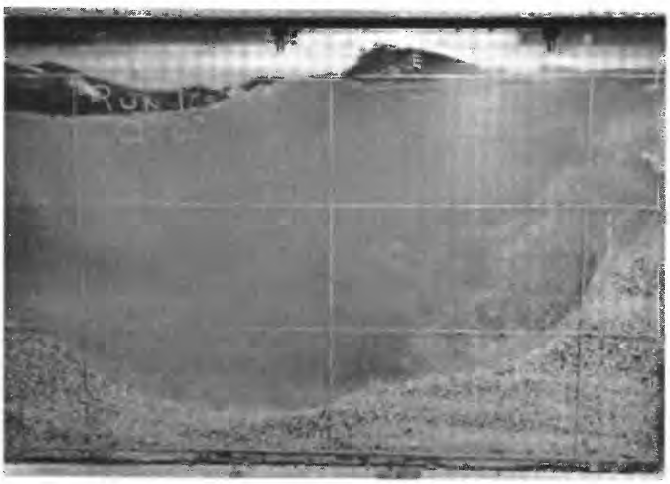


FIGURE 67.—Rapid flow from the dune crest on the left impinging on the downstream wall of the trough and causing rapid erosion and suspension of sediment during run 12.

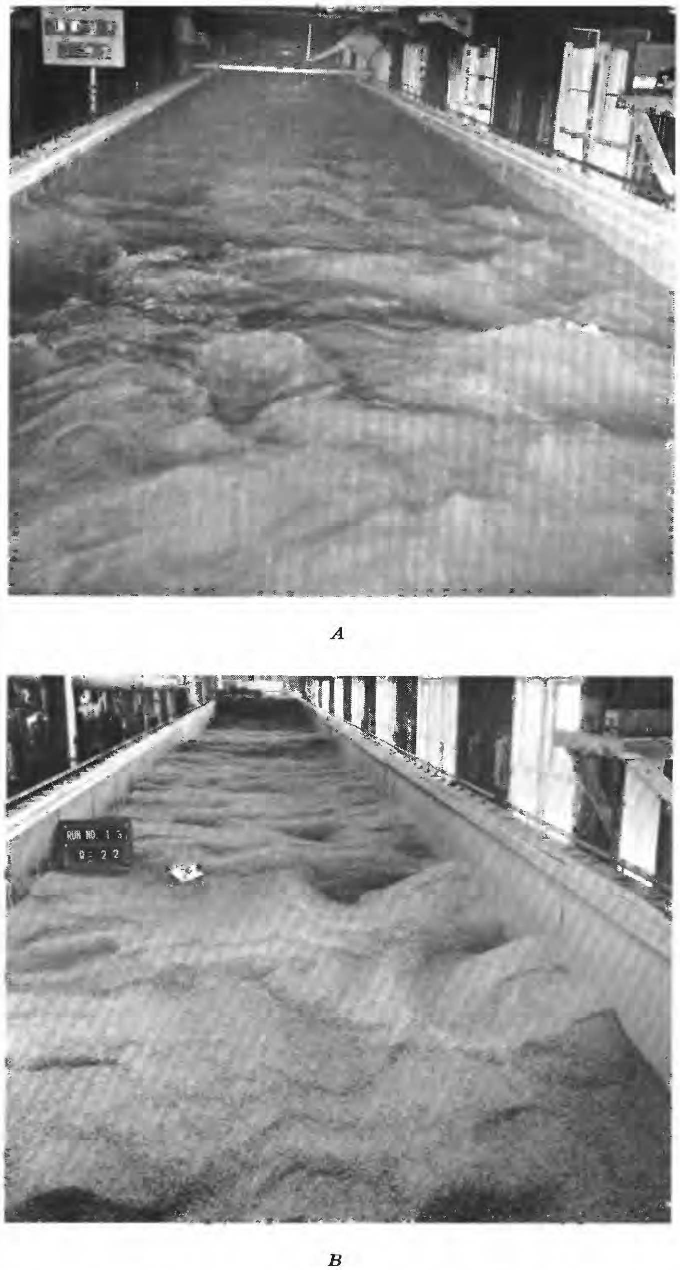


FIGURE 68.—Upstream views of flow and bed conditions for run 13. *A*, Water-surface condition. *B*, Bed configuration at end of run.

phase with the bed configuration. Some trains of standing waves built up and then broke.

Run 3.—The flow and roughness conditions of this run were similar to those described for run 9. Greater depth and velocity, however, caused much more suspension of sediment.

Run 1.—The water surface was very rough, and some standing waves broke. The waves were less symmetrical and wider spaced than those in runs using smaller diameter sands. The water surface indicated

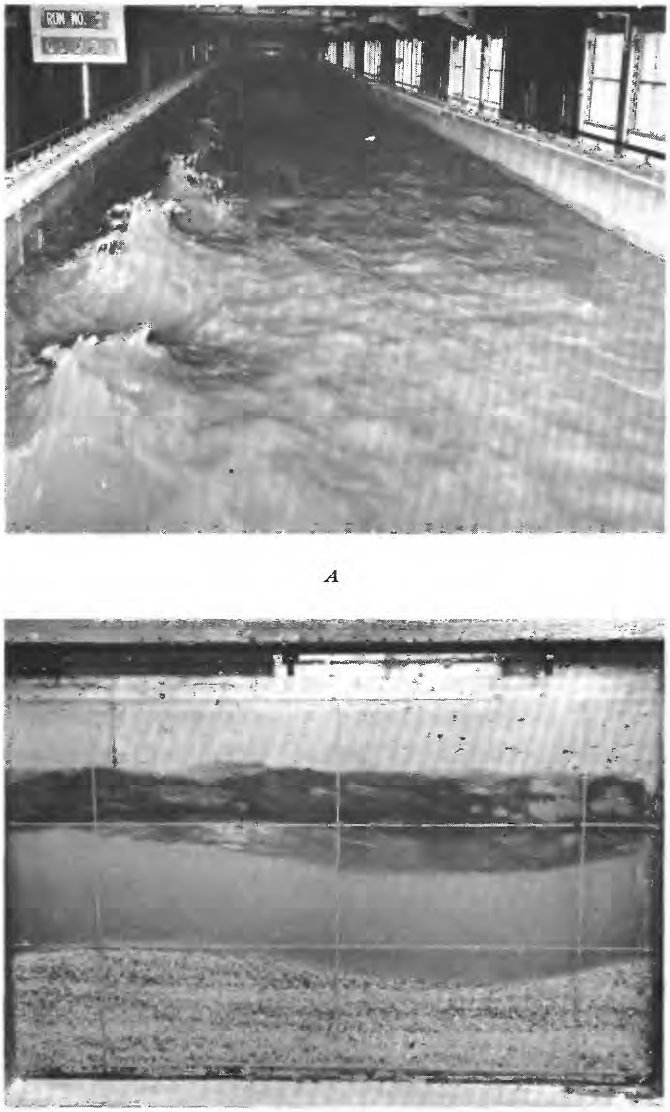


FIGURE 69.—Flow conditions during run 2. *A*, An upstream view of a train of rough standing waves, and the water surface. *B*, A side view of inphase water and bed surfaces typical of standing waves.

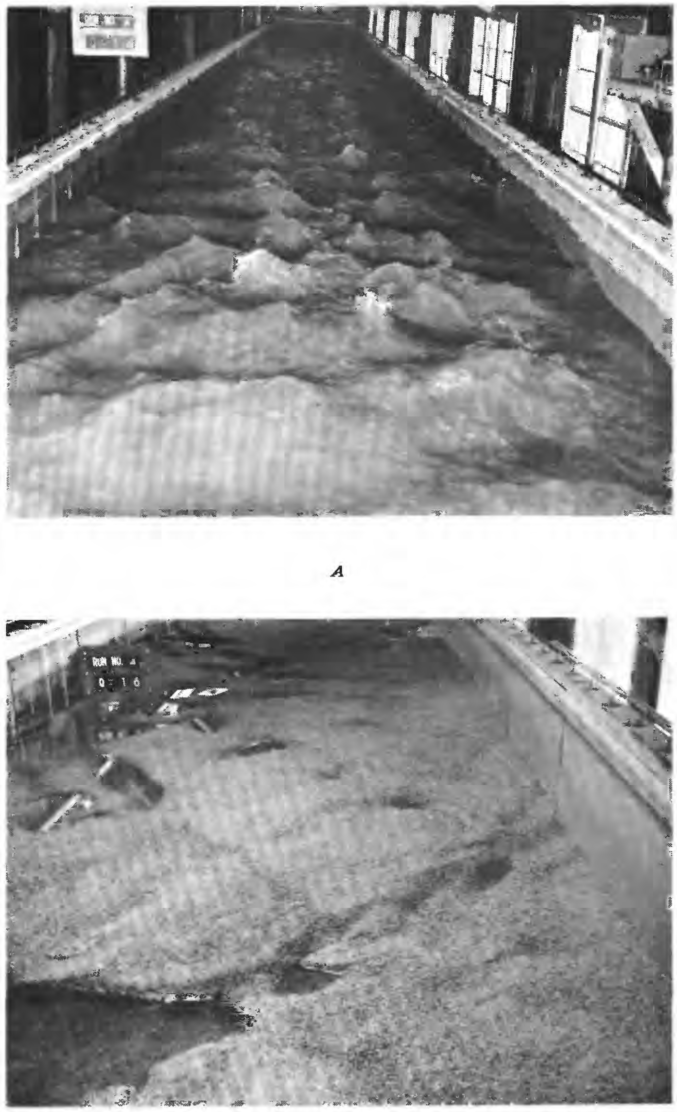


FIGURE 70.—Upstream views of flow conditions for run 4. *A*, The rough water surface. *B*, The bed configuration at end of run.

a condition of an upper regime flow, but the bed consisted of low rapidly moving dunes. Very streamlined dunes indicated a transitional condition.

Run 2.—In this run, the slope was steeper, the resistance was less, the velocity was higher, and the depth was less than in run 1. Trains of standing waves (fig. 69*A*) formed, but the waves generally disintegrated or washed out without breaking. The sand and water waves were inphase (fig. 69*B*) and generally were nearly stationary. Under these flow conditions, most sediment transport was close to the bed. As the sharpest and largest waves broke, "rooster's tails" formed on the water surface.

Run 4.—The conditions at the start of this run were the same as in run 2, except that the discharge was less. The reduced discharge caused the depth and the bed-material discharge to decrease, and the resistance to increase. The water surface was extremely rough, as is shown in figure 70. A variety of conditions, such as small elongated dunes rapidly advancing across a flat area and a few symmetrical or inphase waves, was visible from the side window. The symmetrical sand waves were very unstable and rapidly changed to dunes or planed out.

Run 41.—This was another transitional run. Sometimes the bed and water surfaces were plane, sometimes they were undulating inphase, and sometimes they

A

B

FIGURE 71.—Upstream views of flow conditions for runs 43 and 39. *A*, The water surface. *B*, The sand bed.

were out of phase. The out-of-phase condition was caused by small and rounded dunes having weak zones of flow separation. The resistance to flow was less than that in run 4; therefore, the water surface was smoother, and both the velocity and the bed-material discharge were greater.

Run 42.—The flow conditions over the bed were more plane than those of run 41. Small trains of large amplitude standing waves occasionally formed and then died out; but did not break. The bed was very firm except on the crest of dunes in a wave train.

Run 40.—This run differed from run 42 by having more standing waves, greater resistance to flow, and more bed-material discharge. The wave trains sometimes built up nearly to the breaking point and then moved slightly upstream without breaking.

Runs 43 and 39.—Input variables, resistance to flow, and bed-material discharge for these two runs were nearly identical. The water and bed surfaces are shown in figure 71. Small-amplitude standing waves occasionally formed on the water surface, and these affected the bed. The bed was at least as firm as that in any other run or set of runs. The firmness of the bed may have been a major factor causing the low bed-material discharge noted for these two runs. Turbulence was reduced by the pavementlike bed.

RUNS USING 0.32-MM SAND IN 2-FOOT-WIDE FLUME

The purpose of this set was to determine the effect of viscosity on resistance to flow and bed-material discharge. The viscosity of the flow was varied for each run by changing the temperature of the flow. The temperature of the flow for a given run was maintained at a specific level by immersing a steam hose into the tailbox, thus warming the water before it was pumped back to the head of the flume. The sand used was the 0.27-mm sand used in the 8-foot-wide flume, but made coarser by washing away some of the fine particles. This set of experiments was conducted during the period November 1959–April 1960. The experimental variables and parameters are given in table 7, and the velocity profiles in table 17.

The order of presenting the runs in the following discussion and in table 7 is different from that used for the preceding sets because increasing slope cannot be used if the low- and high-temperature runs for a given discharge are to be compared. The low- and high-temperature paired runs are presented in the order of increasing discharge, the low-temperature run preceding the high-temperature run. For a specific temperature, the order approximated that of increasing slope, velocity, and bed-material discharge. Only water temperature and, hence, fluid viscosity were changed for any pair of runs. Changes in slope, depth, roughness, and bed-material discharge were the direct response to the change in fluid viscosity. In some sets the first run was made with cold water, and the second with heated water; in others the procedure was reversed.

Run 1.—The run was started with the bed planed to a slope of about 0.00015. At a mean velocity of 0.90 fps, small particles moved more steadily than large ones. When large particles moved, they generally became stabilized at a lower elevation, a very short distance, from where they started. The very small ripples formed from this kind of selective movement were most evident at the lower end of the flume, mainly because the depth of the flow there was less and the velocity was higher, but also because most of the fine sediment had been moved, by selective movement, from the upper to the lower end of the flume.

Run 2.—The conditions for this run were similar to those for run 1 except that the temperature of the flow was 23.4°C in contrast to 10.0°C in run 1. The sediment transport rate was slightly greater than in run 1. Small particles moved constantly, medium particles moved intermittently, and large particles moved occasionally. The final bed form, very low ripples, caused somewhat greater resistance to flow and, in turn, lower velocity, than in run 1.

Run 3.—Fully developed ripples as much as 0.2 foot high formed on the bed. Although these ripples moved downstream very rapidly, the water surface remained generally smooth. Clouds of sand occasionally swirled off the crests of the ripples, but no true suspended sediment extended from the bed to the water surface.

Run 4.—The bed configuration of this run was ripples averaging 0.07 foot high and 0.66 foot long. The water surface was relatively smooth. Most sediment rolled or slid over the crest of each ripple. Small clouds of the finer particles were occasionally carried up into the flow. Few if any particles reached the surface, however, and the suspended concentration, for all practical purposes, was zero.

Run 30.—Large and fairly uniform ripples formed throughout the length of the flume. Suspended sediment (24 ppm) was especially noticeable downstream from the ripple crests.

Run 29.—The higher water temperature for this run caused a higher flow velocity and a higher bed-material discharge than run 30 at nearly the same slope. The dunes formed on the bed were smooth and flat and were partly covered with small ripples. Some dunes were almost indistinguishable. Ripples were the dominant bed form. Suspension of sediment was especially noticeable downstream from the ripple or dune crests. Suspended transport was only a small portion of the total transport as was attested by the smooth water surface.

Run 5.—Both dunes and ripples formed on the bed of the flume. The water surface was undulating and was much rougher than in any other run previously described in this set. The bed sloped transversely near the larger dunes. Some bed-material discharge moved as suspended sediment, but most rolled and slid rapidly over the crest of the dunes.

Run 6.—Rate of discharge was the same as in run 5, but the water temperature was 17°C higher than in run 5. Depth of flow was greater than in run 5, but slope, velocity, and bed-material discharge are all significantly less. Again the bed features comprised low dunes with small ripples superposed. (See fig. 72.) Occasionally small vortices were seen carrying sand to the surface of the flow.

Runs 27 and 28.—Fully developed dunes (and a few ripples) formed throughout the flume. In run 27 (cold water) the dunes were longer and more rounded and the water surface was smoother than in run 28 (warm water). The effect on depth, velocity, slope, and bed-material transport caused by changing water temperature seemed to be the inverse of that in the previous three pairs of runs, in which ripples were the dominant forms.

Runs 26 and 25.—The dunes formed on the flume bed in runs 26 and 25 were generally of typical shape and were out of phase with water-surface undulations—that is, the depression in the water surface was over the crest of a sand wave. Occasionally, some irregular dune troughs formed, such as an erosion pocket with both steep upstream and downstream slopes. Ripples formed in some dune troughs where the velocity was lowest. In run 25 the dunes increased in size downstream. As in runs 27 and 28, velocity and slope were higher in runs using warm water, whereas bed-material discharge was less.

Run 21.—The run was typical of the transitional regime. The bed alternately was nearly a plane or comprised long low dunes. During the near-plane condition, the water surface conformed closely to any bed irregularities. Small irregularities slowly developed into low dunes, most of which did not extend uniformly across the flume. Dunes were 0.2–0.3 foot high on the left side of the flume but only 0.1 foot high on the right side. The bed was firm though easily scoured

FIGURE 72.—Downstream view of dune-bed configuration formed during run 6.

under the plane conditions, and very soft in the vicinity of the dune crests.

Run 22.—The higher water temperature in this run resulted in a bed condition closer to that of dunes, although it was actually transitional. Long low very irregular dunes occupied about two-thirds of the flume. Most dunes were about 0.15 foot high, but at least one in each train of dunes that moved through the flume was about 0.3 foot high. The water surface was rough, and the depth of flow varied greatly. The more dune-like configuration caused the velocity and the slope to be lower and the bed-material discharge to be larger, especially the suspended part, than in run 21.

Runs 24 and 23.—These runs were similar to runs 21 and 22 except that the increased discharge resulted in a greater depth and somewhat lower velocity. The dunes formed in the warmer water (run 23) were more fully developed than those in run 22.

Run 7.—The flow conditions for this run resulted in a smooth bed form of very long waves. The water surface was rough and followed the same pattern as the bed. Much of the bed-material discharge was rapidly rolled or slid along the bed, but some went into suspension very easily like dust swept by a broom. The bed-material discharge varied rapidly. Undulation of the bed surface caused stratification in the form of thin alternate layers of fine and coarse sediment in the bed, at least in the areas near the walls of the flume.

Run 8.—The warm water caused the bed configuration to revert back to dunes from the nearly plane condition of run 7. About two-thirds of the length of the flume was covered with dunes, which started at the upper end of the flume and became progressively smaller as they moved downstream. In a few places the bed was intermittently scoured to the floor of the flume. The water surface was very rough, and the crest-to-crest distance between water waves was much less than the distance between dune crests. The downstream face of the dunes was not steep, so that any eddies downstream from the dunes were small. Figure 73 is a side view of the dune configuration and flow of run 8. Sediment streaming from the crest of the dune can be seen in the photograph.

Run 20.—Downstream from station 35, very small antidunes formed. These moved upstream very slowly but did not break. The water and sand waves were inphase because the flow was in the upper regime.

Run 19.—The higher temperature in comparison with run 20 caused the bed form and flow to change from one of mild antidunes to a plane bed. The downstream one-third of the flow surface had a slightly

FIGURE 73.—Side view of dunes and flow conditions during run 8.

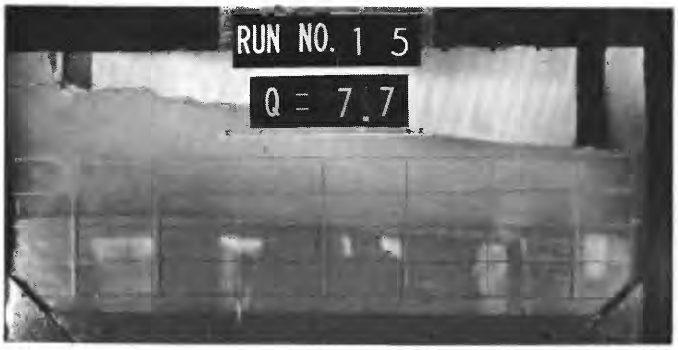
wavy appearance, but the rest was very smooth. The bed was very firm except in a few upstream areas of the flume. Even though the downstream water surface became increasingly wavy, it was very smooth compared with the surface in runs having greater slope.

Runs 10 and 9.—The flow velocity and the amount of bed-material discharge were similar in these runs. The bed configuration was one of standing waves. Slope and resistance to flow were greater in run 10, seemingly because the viscosity of the water was greater (1.55 as opposed to 1.00). The standing waves were more persistent in runs 9 and 10 than in runs 19 and 20. They generally formed and remained for about 15 seconds and then gradually diminished. Figure 74 shows the long low amplitude of the inphase sand and water waves. The amplitude of the water waves was greater than that of the sand waves.

Runs 12 and 11.—The depth of flow was increased from that in runs 10 and 9, and for a given temperature a decrease in bed-material discharge and slope resulted. The bed was nearly plane in both runs, although standing waves formed in run 11. The water surface undulated gently in run 11. The magnitude of the undulations was about 0.1 foot at the downstream end of the flume. The bed-surface undulations were not as large as those of the water surface.

Runs 14 and 13.—Antidunes formed in both runs. Those formed in run 14 (cold water) were better de-

FIGURE 74.—Side view of bed and flow during run 9.



A

B

FIGURE 75.—Side views of antidune flow conditions during run 15. *A*, Dune crest (left) and zone of flow acceleration (center and right). *B*, Trough of sand and water waves (left) and breaking wave and very heavy concentration of sediment near the bed (center and right).

veloped than those formed in run 13 (warm water), and they moved upstream at about 0.2 fps compared with 0.1 fps for those in run 13. The magnitude of the antidunes and their rate of movement decreased upstream in the flume. The bed-material discharge was greater in run 14 than in run 13 because the cold water resulted in greater antidune activity and, thus, more suspension of sediment.

Runs 15 and 16.—The antidunes formed in these two runs were similar to those formed in runs 14 and 13. Bed-material discharge was greater in runs 15 and 16 than in 14 and 13 because mean velocity and depth were greater and possibly because the water temperatures were lower. The suspension of bed material developed upward from a densely transported layer at the bed and was significantly greater than in runs 14 and 13. Figure 75 shows two views of the flow conditions.

Run 17.—A chute-and-pool condition formed during this run that was nearly like that formed during runs using finer sands in the 8-foot-wide flume. Occasionally, an 8- to 10-foot-long chute formed in which flow accelerated downstream to a hydraulic jump or a strong downstream standing wave. Breaking antidunes were seen all along the flume, and often the lower 20 feet of the flume had a continuous series of breaking antidunes. The antidunes seemed to break when the crest of the sand wave was level with the water surface in the upstream trough.

Run 18.—Flow in this run appeared similar to that in run 17 except that it was not as violent and no chutes and pools formed. The water surface was very rough; so reliable measurements of depth and slope were difficult to make. Eight measurements of the velocity of the upstream movement of the antidunes ranged from 0.020 to 0.082 fps and averaged 0.052 fps.

Run 31.—This was a chute-and-pool run. The length of the chutes was possibly limited by the amount of sediment on the flume bed; that is, the lower part of the chute at the hydraulic jump may have been scoured to the floor of the flume. Nonuniform suspended-sediment concentration was indicated by analyses of four samples in which the mean concentration was 41,600 ppm and the standard deviation was 27,800 ppm. Four measurements of bed-material discharge averaged 49,300 ppm and had a standard deviation of 7,700 ppm. A comparable high-temperature run was not made.

RUNS USING 0.33-MM (UNIFORM) SAND IN 2-FOOT-WIDE FLUME

The sand used in this set of runs had a median diameter of 0.33 mm and as little size gradation as was practical to obtain. Table 1 and figures 4 and 5 have more detailed information on the character of the sand. The runs were all made with temperature of the water close to 20°C and the depth of flow close to 0.50 foot. This set of experiments was conducted during the period January–April 1961. The experimental variables and parameters are given in table 8. Velocity-profile data are given in table 18. The runs are discussed on the following pages and are listed in table 8 in chronological order by increasing slope.

Run 7.—The bed was planed smooth under quiet water and set at a slope of 0.00025 immediately prior to this run. When flow had been established, the resulting mean flow velocity was 1.14 fps. The shear stress was great enough to cause movement of sediment throughout the length of the flume but was not great enough to cause ripples to form anywhere but near the headbox.

Run 8.—The slope was increased to 0.00087, and this increase caused much sediment movement; consequently, resistance to flow increased and ripples formed. The increase in resistance made it necessary to decrease the discharge and the velocity so that a depth of 0.50 foot could be maintained. As is shown in figure 76 and in columns 14 and 15 of table 8, the ripples had small amplitude and length. Ripples appeared to be slightly larger near the flume walls than at midstream. The bed-material discharge was only 6.6 ppm, and nearly all of it moved very close to the bed. The bed was very firm except on ripple crests, which were very soft and fluidlike.

Run 5.—A continuous flow for 3 days was required to establish equilibrium in this run. Little or no change in flow conditions occurred during the last 24 hours. The ripples were about twice as high as those formed in run 8, and their size and shape varied more widely. The bed-material discharge was 47 ppm, of which about 15 ppm was carried in suspension.

Run 11.—The bed form consisted of dunelike highs and lows almost completely covered with ripples. The high areas did not have discernible crests, as one would expect for dunes. The entire bed was soft.

Run 10.—The slope was 0.00213, more than double that for run 11. The consequent flow and transport variables achieved equilibrium with a bed form consisting of ripples superposed on dunes. Some shorter dunes, 1.5–2.0 feet long, did not have ripples on their surface. The sand bed felt soft and fluidlike.

Run 6.—The flow characteristics were similar to those expected over a dune-bed configuration. The dunes varied greatly in size and shape, and some had ripples on their surface; some even had a very round crest. Figure 77 illustrates the bed and flow conditions in run 6. The rounded shape of some of the dunes apparently resulted from the specific dune being subjected to a jet of flow from over the next upstream dune.

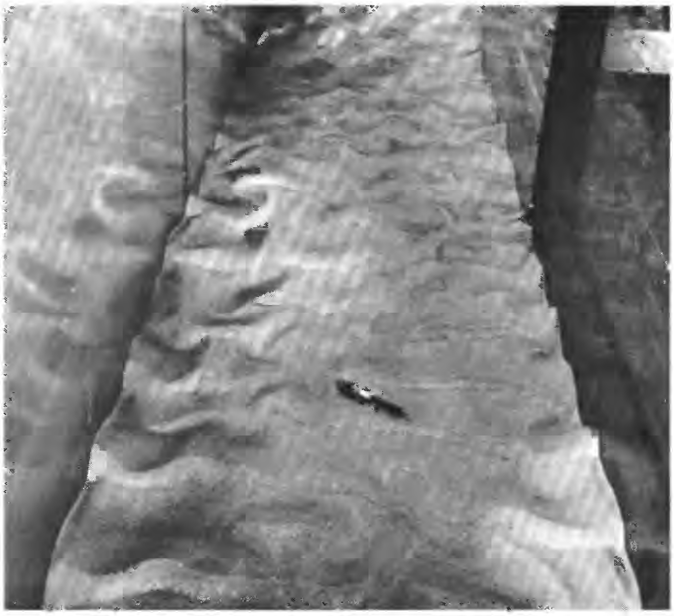
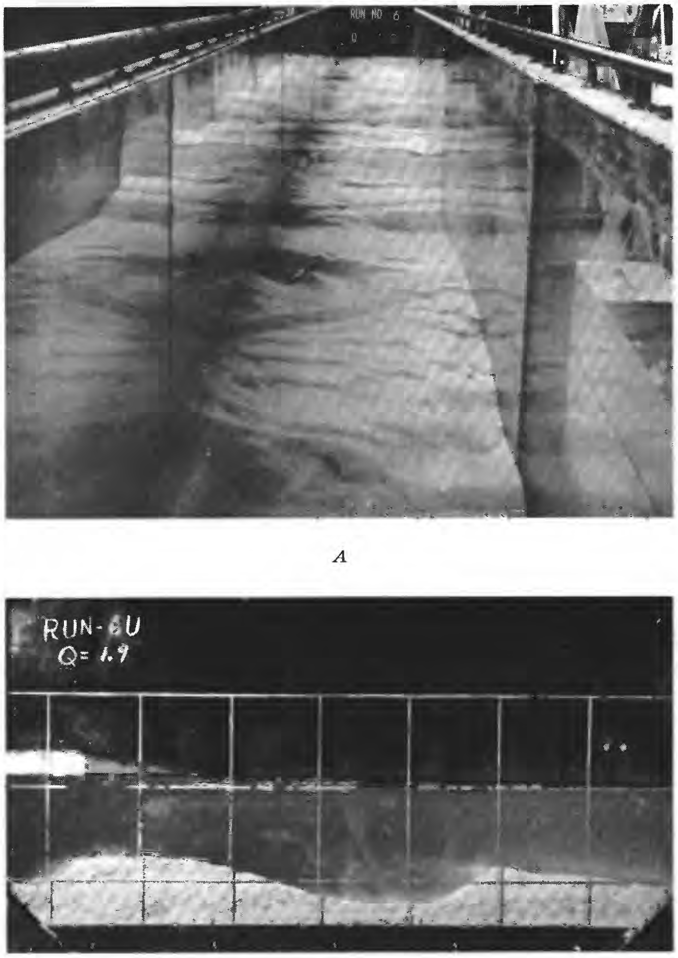


FIGURE 76.—Upstream view of rippled flume bed at the end of run 8.



A

B

FIGURE 77.—Bed and flow conditions for run 6. *A*, Upstream view of the flume after the water had been drained from it at the end of the run. *B*, Side view of two dunes. The flow is from right to left.

Run 4.—The slope and depth seemed to fluctuate considerably, and, with them, the bed condition—from nearly plane to transitional dunes. The bed-material discharge remained relatively constant. The transitional dunes gradually built up from the plane-bed condition. At first they were long but had small amplitude; then they changed to short but with large amplitude. As the dunes built up, the resistance to flow increased and caused the depth and slope to increase also. The bed was softer than under normal plane-bed conditions.

Run 1.—Plane-bed conditions of flow and transport existed during this run. The resistance to flow was low, and the water surface was relatively smooth. Most sediment transport occurred in close contact with the sand bed. The average bed-material discharge was 3,090 ppm, of which only 12.7 percent was in suspension, in contrast to over 30 percent ordinarily in suspension when dunes and ripples are present. The sand bed was very firm.

Run 9.—The flow condition varied with the size and shape of the dunes formed. At times the dunes were as much as 8–12 feet long, and at other times they averaged 3–4 feet long. The height of the long dunes was about one-half that of the short dunes. The alternating from one kind of dune to another affected slope, depth, and concentration of bed-material discharge. The mean slope for this run was greater than that for run 1, but the velocity and bed-material discharge were much less.

Run 12.—A plane-bed condition very similar to that in run 1 existed as long as the water was kept heated. When the water temperature was allowed to drop to 15°C, the bed condition converted to the one of antidunes.

Run 13.—The increase in slope and shear stress for this run caused the flow velocity and bed-material discharge to be greater than in run 12. The result was a series of standing waves which built up slowly and then gently receded or broke. The sand and water waves were inphase, and the vertical distance between the crest and trough of the water waves was about twice that of the sand waves. None of the dunes upstream from station 40 broke, and only some of those downstream from station 40 broke.

Run 2.—This was a typical antidune run of relatively mild activity. Antidunes formed and broke regularly in the downstream end of the flume, less frequently in the middle of the flume, and only occasionally in the upper end of the flume. The mild activity as the dunes broke did not cause much suspension of sand. After a series of waves broke, the bed usually planed out considerably and low-standing waves developed. The standing waves, in turn, moved upstream as they grew in size and developed into antidunes. Figure 78 illustrates the nature of the standing-waves formed in run 2.

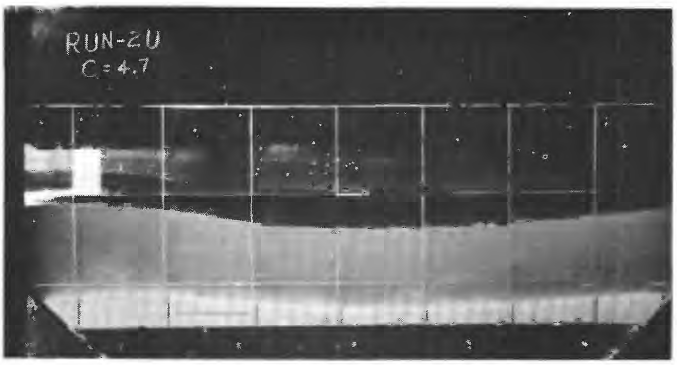


FIGURE 78.—Side view of the standing waves most typical of flow conditions during run 2. Flow is from right to left.

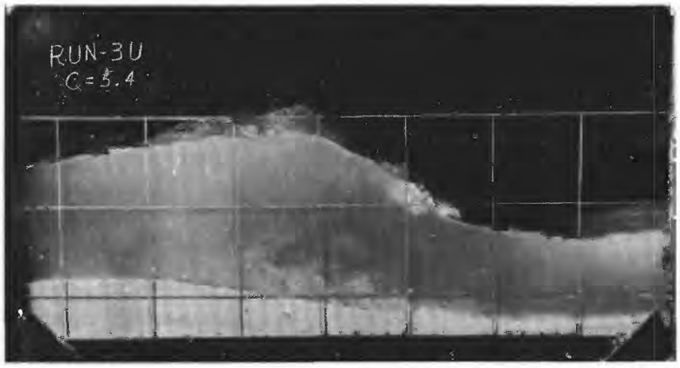


FIGURE 79. Side view of an antidune beginning to break during run 3. Flow is from right to left.

Run 3.—Antidunes were breaking somewhere in the flume at all times during this run, but they generally took longer to break than did those in run 2. The longer breaking time, plus the greatly increased frequency of breaking resulted in a large increase of suspended bed-material discharge over that in run 2. Sediment was deposited on and filled in the upstream slope of the sand waves. During and after breaking of an antidune, such deposition and filling occurred very rapidly. Figure 79 shows an antidune early in the breaking stage. The 0.1-foot-thick highly concentrated layer of sediment became a cloud of sand in the low velocity flow under the breaking crest of the water wave.

Run 14.—Increase in slope over that in run 3 caused greater velocity and more violent activity in the form of breaking antidunes. The bed-material discharge was nearly the same as that of run 3, but the part held in suspension was greater.

RUNS USING 0.33-MM (GRADED) SAND IN 2-FOOT-WIDE FLUME

The 0.33-mm graded sand as described previously, was manufactured or assembled from several size fractions to obtain a nonuniform sand having a median diameter of 0.33 mm. Flow characteristics and bed-material discharge in runs using this sand were recorded for comparison with data for runs using the uniform 0.33-mm sand. The runs in this set are likewise presented in order of increasing slope. The following data were collected during the period July–September 1961. The experimental variables and parameters are given in table 9, and the velocity-profile data, in table 19.

Run 11A.—The bed was planed smooth under several inches of quiet water prior to the beginning of the run. Flow was established at a slope of 0.00022 and a mean velocity of 1.08 fps. Some fine grains moved, mostly to positions at lower levels among coarser grains.

Particles which protruded into the flow were affected by the greatest shear stress and usually were the first to move.

Run 11B.—General movement of all particles was obtained by increasing the slope to 0.00027 and increasing the mean velocity to 1.28 fps. Ripples formed from stations 0 to 20, and some fine-grained particles moved as far as station 24. The remainder of the flume downstream from station 24 remained plane despite considerable particle movement.

Run 16.—Data collection began 36 hours after the run was begun. A uniform pattern of ripples that resembled sand waves formed. It appeared that material finer than the median size was traveling over a bed of material coarser than the median size. Figure 80 shows the bed configuration after the water had been drained from the flume at the end of the run. (Compare the ripples shown in fig. 80 (graded sand) with those shown in fig. 76 (uniform sand of same median diameter). Several samples were taken from the sand waves and from the troughs. Analysis of the composited wave samples gave a median diameter of 0.20 mm and a standard deviation of 1.96, whereas the composited trough samples gave a median diameter of 0.38 mm and a standard deviation of 2.23. This analysis confirmed the visual observation that sorted bed-material discharge existed under this kind of ripple formation.

Run 6.—The ripples formed in run 6 were more fully developed and in a more irregular pattern than those formed in run 16. (See fig. 81.) They caused

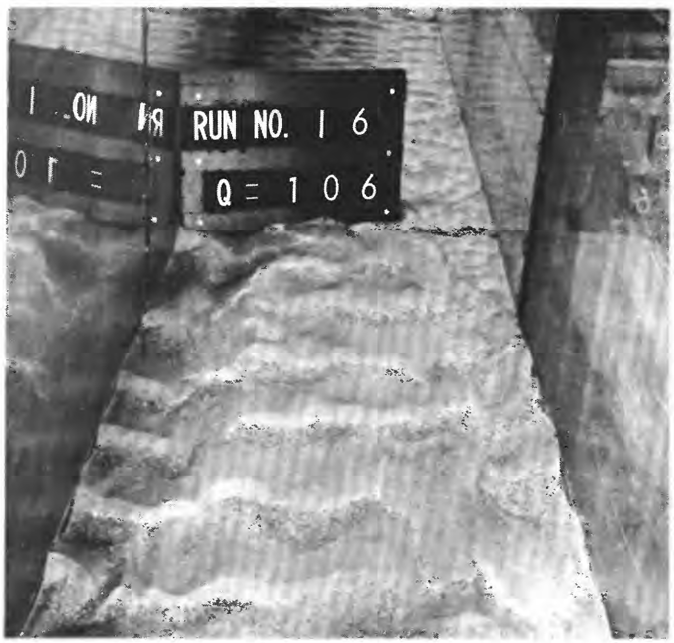


FIGURE 80.—Upstream view of ripples at the end of run 16. Note that the sand in the ripple crests is finer than that in the troughs.

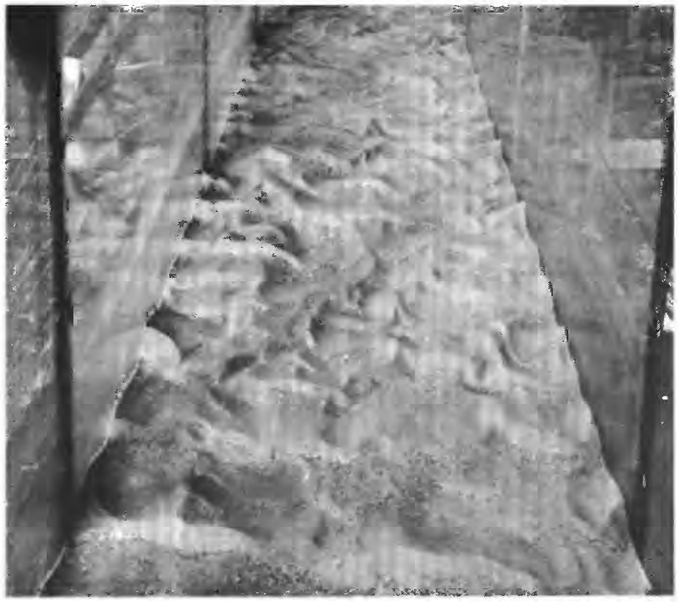


FIGURE 81.—Upstream view of ripples formed during run 6.

greater resistance to flow and somewhat lower mean velocity than those in run 16, even though the slope had been increased from 0.00029 to 0.00047. The water surface was calm. The bed-material discharge (12 ppm) moved in almost continuous contact with the bed.

Run 5.—Slope and discharge were increased over those in run 6. As a result, flow velocity in this run was much greater than that in run 6, and bed-material discharge was somewhat greater. The ripples seemed very small; their growth may have been restricted by the coarse bed material. (See fig. 82.) Sediment moved by sliding or by short hops. A mixture of coarse and fine particles moved near the center of the flume, whereas only fine particles moved closer to the flume walls. The coarser material formed an armor plate, and the fine material moved as ripples. Many coarser particles moved across several ripples without stopping, whereas the fine particles moved from ripple to ripple but had a long rest period between moves.

Run 1.—Long low dunes and a few low ripples formed. (See fig. 83.) Generally, relatively low resistance to flow indicates a low percentage of suspended sediment, but this was not true for this run. The low resistance to flow in run 1 may be explained by the fact that the bed was very soft throughout the depth disturbed by the dune movement.

Run 10.—The bed form in this run was mostly one of ripples superposed on dunes. Long low dunes occasionally formed, moved slowly downstream, and then died away. The bed-material discharge was some-

FIGURE 82.—Upstream view of ripples formed during run 5.

what less than in run 1, and the suspended part was much less.

Run 8.—Small rather rounded dunes formed. Ripples on these dunes were less prominent than on those formed under similar hydraulic conditions in runs using the uniform sand.

Runs 9 and 7.—Low dunes of various sizes formed in both runs. (See fig. 84.) Some dunes had a few superposed ripples during the runs.

FIGURE 83.—Upstream view of the dune-bed configuration at the end of run 1.

FIGURE 84.—Upstream view of the dune-bed configuration formed during run 9. Most of the ripples were caused by flow disturbance during draining of the flume at the end of the run.

Run 2.—Dunes formed that were similar to those of runs 9 and 7 but were somewhat rounded because of the increased slope and velocity in run 2. (See fig. 85.) The dunes moved through the flume very rapidly, so that there was much bed-material discharge.

Run 3.—The flow pattern and bed-material discharge were characteristically those of a run in which the bed condition was transitional between dunes and plane

FIGURE 85.—Upstream view of the dune-bed configuration at the end of run 2.

bed. The bed form varied from almost plane to fast-moving low dunes which rapidly changed form. Some segregation of particles occurred, but generally the sediment was well graded throughout most of the flume.

Run 4.—The mean velocity of flow was 4.00 fps. The transitional dunes of run 3 were washed away, and a plane firm sand bed resulted. Most of the bed-material discharge was in a thin layer close to the bed.

Run 12.—The bed for this run was essentially plane, but some very small standing waves formed. These small waves can be seen in figure 86. Very heavy sediment transport took place near the bed.

Run 13.—The flow conditions for this run resulted in formation of standing waves and slow-moving antidunes, some of which broke.

Run 15.—Violent antidunes broke in series and caused considerable suspension of sediment. The water surface was too rough to allow reliable depth and slope measurements.

Run 14.—This was another antidune run, but the slope was steeper and the velocity lower than in run 15. The antidunes alternately had small and large amplitude. The small antidunes broke gently, and the large ones, vigorously.

RUNS USING 0.47-MM SAND IN 8-FOOT-WIDE FLUME

The 0.47-mm sand used in this set of runs was derived from the 0.45-mm sand by washing away of some of the fine fractions. The main purpose of the set was to determine the effect of fine sediment, C_f, on the mean-flow and bed-material-discharge parameters

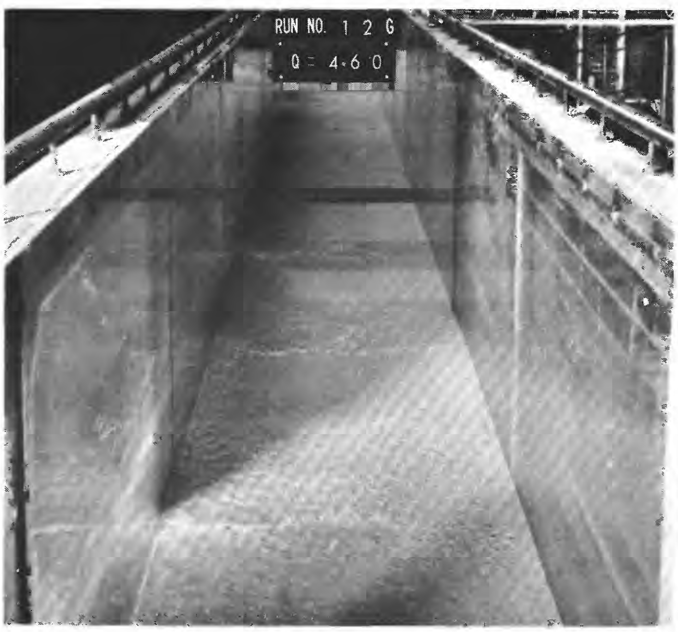


FIGURE 86.—Upstream view of bed conditions at the end of run 12.

for a range of equilibrium-flow conditions similar to those in the set of runs using the 0.45-mm sand.

After equilibrium was established and the data collected for a given run, bentonite was either added to or extracted from the flow to establish a new concentration of fine sediment without stopping the flow. The change in the fine-sediment concentration generally caused a change in the flow and transport conditions, and these changes, in turn, caused a change in bed roughness, depth, slope, and bed-material discharge.

Bentonite was used as the fine sediment because it is commercially available in large quantities. The particle-size distribution of the bentonite down to 2 microns is shown in figure 87. Bentonite is composed of several different clay minerals, as is shown in figure 88. The mean specific gravity of the particles is about 2.8.

As Simons, Richardson, and Haushild (1963) pointed out, aqueous dispersions of bentonite are non-Newtonian; that is, the shearing stress is not directly proportional to the rate of shear. Therefore, the term "apparent" viscosity relates the shearing stress to the rate of shear. Figure 6 shows the relations of apparent kinematic viscosity (ν) and temperature for dispersions of 0, 0.5, 1, 2, 3, 5, and 10 percent bentonite in distilled water as determined using a Stormer viscometer. One part sodium hexametaphosphate to 99 parts bentonite, the ratio used in the flume experiments, prevented flocculation of the clay particles in the dispersions. The apparent kinematic viscosity is given in column 23 of tables 10 and 11 for each run.

After equilibrium had been established in each run, samples for determination of total sediment discharge (bed material plus fine material) were collected into a tank at the end of the flume with a width-depth integrating sampler. Eight samples were taken in the lower flow regime (ripples and dunes) during a 12-hour pe-

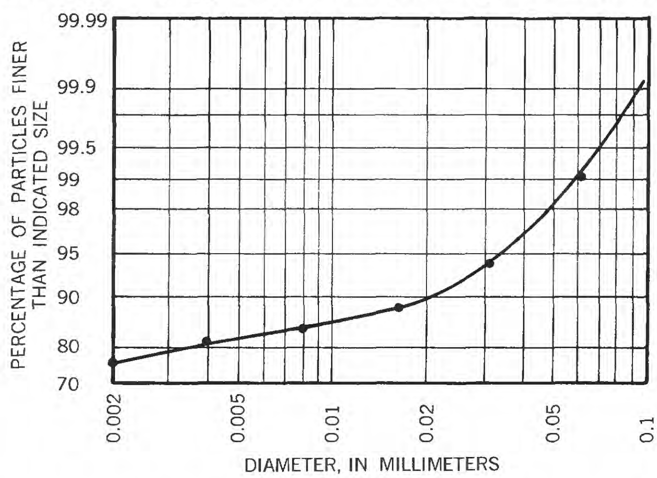


FIGURE 87.—Particle-size distribution of bentonite used in flume studies with the 0.47-mm and 0.54-mm sands. The sample was chemically and mechanically dispersed in water and analyzed by the sieve-pipette method.

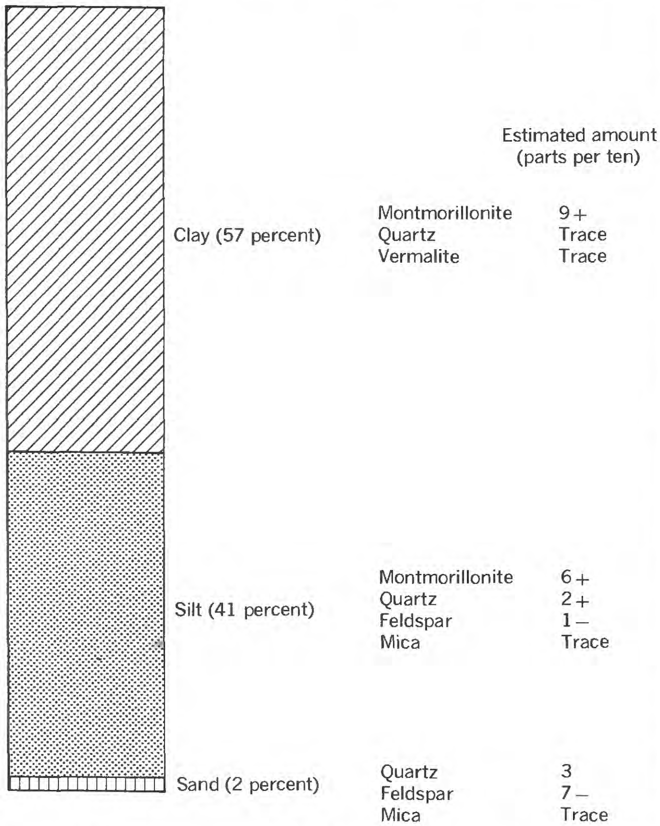


FIGURE 88.—Mineralogy of bentonite for different size classifications as analyzed with an X-ray diffractometer by Paul D. Blackman, U.S. Geological Survey, Denver. The size distribution differs from that shown in figure 87 because no chemical dispersant was used to prevent flocculation after the sample had been mechanically dispersed.

riod, and four samples were taken in the upper flow regime (plane bed, standing waves, and antidunes) during a 1-hour period. Each sample consisted of 70–110 pounds of the water-sediment mixture.

To separate the fine material, or "wash load," from the bed material, the sample was allowed to stand a few minutes so that the sand could settle. After the sand settled, the water-bentonite mixture was drained off, leaving the sand. The remaining fine material in the sand was removed by washing the sand over a No. 230 sieve. The concentration of the fines thus removed was added to the concentration of the fines removed from a pint sample of the water-bentonite mixture drained from the tank containing the flume sample. Then, all material coarser than 0.062 mm was considered bed material, and all finer material was considered fine material. The concentration of fine-material transport is listed in table 10, column 6, and bed-material transport, in column 9. The sum of these is the total concentration of sediment discharge.

Samples of concentration of suspended-sediment (col. 7, table 10) were obtained with the specially designed depth-integrating sampler in the flume section 95–100 feet downstream from the flume entrance. Generally, only one 5- to 8-pound sample was collected by the equal-transit-rate method for each run. Some concentrations were not recorded because the samples contained an excessive amount of bed material from contact of the sampler nozzle with the bed, particularly for the dune runs. Because only a single sample was collected during each run, the standard deviation could not be computed.

This set of experiments was conducted during the period January–May 1958. The experimental variables and parameters are given in table 10, and the velocity-profile data, in table 20.

The order of presenting the runs in table 10 and in the descriptions to follow is based on (a) increasing fine-sediment concentration within a series of runs, (b) increasing slope, and (c) the following order of bed form: ripples, dunes, transitional, plane, and antidunes. The run numbers were continued from the 0.45-mm set because of the close similarity of the bed material.

Runs 46, 47, 48, and 49.—These runs were made using the 0.47-mm sand and clear water. Data collected were meant to fill gaps in the data for the runs using the 0.45-mm sand. Dunes with superposed ripples were formed in all four runs. As was expected, the mean velocity increased as depth increased and as the dunes became lower and longer. Runs 47 and 48 had low shear stress and a low rate of bed-material discharge; thus, there was no suspended-sediment movement, and the sand dunes moved very slowly.

Runs 85, 86, 87, and 88.—The slope for this series of runs ranged from 0.00046 to 0.00049, and the concentration of fine-material discharge was 0, 4,800, 8,400, and 11,400 ppm, respectively. Under these conditions, ripples formed on the bed and flow velocity ranged from 1.13 to 1.20 fps. Fine material near the bottom (about 0.1 foot of flow) blocked visibility of the bed. Through the side window of the flume, however, it could be seen that the fine material was being deposited in the trough of the ripples and that the next ripple from upstream would ride over the lens of fine material; subsequent ripple troughs passed above, through or below the lens deposit. Figure 89, photographed through the window, shows ripples and lenses formed during run 88. The lenses, as well as the shape and velocity of the ripples, seemed to offer some resistance to normal sand transport. When ripples became stationary or nearly so, they became rounded and had about the same slope on the upstream and downstream faces. The stationary ripples resulted from the space between the sand grains at the surface being filled with fine sediment. The fine material definitely caused the

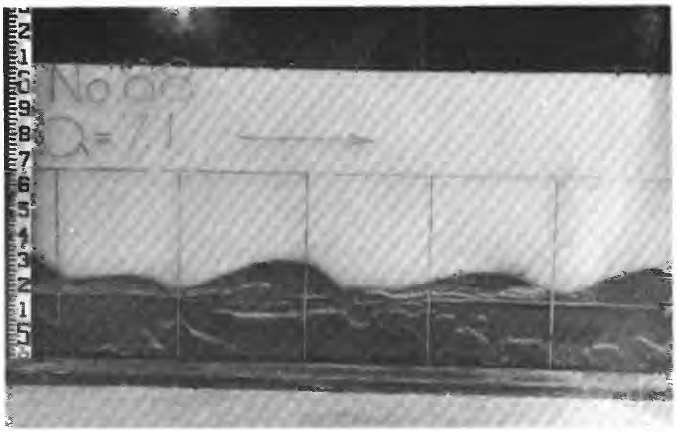


FIGURE 89.—Ripples and lenses of fine material (light colored) in the bed during run 88. The relatively round shape of the ripples can be contrasted with the normal-shaped ripples shown in figure 33.

ripple shapes and patterns to be more irregular than those formed in clear water. In collecting bed-material samples, it was noted that the layer of sand below the normal depth of movement of the ripple waves was much firmer for the fine-material runs than for the clear-water runs.

Runs 90 and 89.—The slope was greater for these runs than for runs 85–88. Both the flow and the ripples were noticeably affected by the stabilization of the bed by the bentonite. In run 89 a crusty layer underlay the ripples throughout most the flume, and the ripples were the same height as those in the previous four runs but were longer and had a higher velocity. The bed was raked smooth to a depth of about 0.15 foot prior to run 90, but it was covered with loose sand ripples riding on a layer of clay-impregnated sand during the run. The sand moved more freely, at least near the windows in run 90, than in run 89.

Runs 93, 92, and 91.—The slope was again increased for these runs and was sufficient to cause dunes and

FIGURE 90.—Upstream view of the bed configuration typical of that formed during runs 93, 92 and 91.

A

B

FIGURE 91.—Upstream views of the water surface during runs 51 (*A*) and 96 (*B*) contrasting the increase in turbulence with increased flow stress and resistance.

overriding ripples to form on the bed. The bed form shown in figure 90 at the end of run 92 was typical for all three runs. The water surface was turbulent, and boils formed downstream from the major dunes. Resistance to the establishment of flow equilibrium due to the fine material in the bed seemed to increase as slope increased. In each run the slope was gradually increased over a period of several hours and then slightly reduced before the final equilibrium was obtained to insure that the more compact sand-clay layer would be below the zone of dune movement.

Runs 82, 51, 52, 73, 74, 76, 75, 53, 77, and 96.—In this series of 10 runs, the slope ranged from 0.00199 to 0.00248, the water discharge ranged from 8.01 to 8.76 cfs, and the bed-material discharge ranged from 429 to 761 ppm. The bed form in all the runs was one of dunes with varying amounts of superposed ripples. The water surface in each run showed evidence of turbulence depending on the amounts of shear stress and resistance to flow. Figure 91 shows the water surface during runs 51 and 96. The dune shape ranged from rough in a relatively regular cross pattern (run 51) to washed out in an irregular pattern (runs 82 and 96). This range in dune shape is shown in figure 92. The resistance to flow in these runs as measured by Manning n ranged from $n=0.034$ (run 82) to $n=0.023$ (run 96).

Many sizes of dunes and ripples were in motion at any given time. The small dunes often moved faster and, hence, caught up with the large dunes and drastically modified their shape, amplitude, and velocity. When a small dune caught up with a larger one, the new dune approximated the sum of the two amplitudes in height. The small dune moved faster than the large one only if it was behind the large dune. The fine sediment seemed to cause the dune form in these runs to be more irregular for a given slope and velocity of flow than that in the clear-water runs, possibly because of the cohesiveness of the mixture.

Run 94.—This was a dune run with almost no fine sediment in the flow. The shape of the dunes was normal; however, the amplitude and the spacing varied considerably. The material on the bed appeared to move more freely than in runs with a large fine-sediment concentration.

Runs 83, 54, 56, 55, 57, 58, and 95.—These runs had slopes ranging from 0.00180 to 0.00259, depths between 0.80 and 0.94 foot, bed-material discharge ranging from 588 to 1,600 ppm, and a bed form of dunes. The discharge of the water-sediment mixture ranged from 15.28 to 15.58 cfs, a variation of only 2.0 percent. Fine-material concentration increased from 0 (run 83) to 28,300 ppm (run 95). Depth, slope, and roughness decreased as concentration of fine sediment increased. The water surface was turbulent and contained many boils caused by eddies downstream from the dune crests. The most turbulent surface flow occurred in run 95. (See fig. 93.) The bed roughness in run 95 became stabilized for brief periods of time (several minutes) and, when this happened, caused choppy waves on the water surface. However, the bed was soft (no lenses of clay), and the turbulence was great enough to cause the clay to act as a wash load, even at this concentration of 28,300 ppm. In run 83 (clear-water condition), dunes had a mean height of 0.43 foot, and some dune troughs exposed the floor of the flume. Water-surface waves and the sand waves were out of phase in all runs in this series; that is, a high (or crown) on the water surface was over a low area (or trough) of the dune, and the low area on the water surface was over a dune crest.

A

B

FIGURE 92.—Upstream views contrasting dune shapes resulting from the flow during runs 82 (*A*) and 96 (*B*).

Run 78.—The flow for this run was in equilibrium with large dunes moving at a rapid rate. Strong eddies from the dune crests caused the water surface to be very turbulent. (See fig. 94.) The water stood high over the trough and low over the crest of dunes, as in the preceding runs, but to an even greater extent. The flow must have been nearly transitional, as indicated by the fact that often no major dunes could be seen near the flume windows.

Run 59.—The flow stress in this run caused the dunes to be washed out; so this run, too, was transitional. The water surface was very irregular, as is shown in figure 95. The washed-out dunes formed a diagonallike crisscross pattern, which was also re-

FIGURE 93.—Upstream view of water surface during run 95. The flow, at a velocity of 2.39 fps, is over a dune-bed form.

FIGURE 94.—Upstream view of water surface during run 78.

peated for the surface waves. The bed was very soft and fluid, particularly near the dunes.

Runs 60 and 61.—These runs had plane-bed conditions. Occasionally a small dunelike form was seen, but these features were generally less than 0.01 foot in amplitude. These minor dunes seemed to extend diagonally across the flume, similar to those observed during run 59. The bed was firm except on the crest of the minor dunes. The character of the flow at the surface is shown in figure 96.

Runs 71, 72, and 70.—The flow was typically that of plane-bed runs. Some small dunes, similar to those formed in runs 60 and 61, formed during run 71; the bed was very plane in run 72; and a few small standing waves formed at the lower end of the flume during run 70. The sand bed was firm, but not as firm as in runs in which higher velocities caused standing waves to form.

Runs 63, 64, 65, 66, and 80.—The flow stress caused formation of bed features ranging from predominately standing waves during run 63 to double-train antidunes during runs 65, 66, and 80. Figure 97 shows a typical water-surface condition for this series of runs. The wave pattern in run 63 developed less vigorously and less frequently than that in run 80, in which the wave trains formed nearly continuously. The sand waves were symmetrical and inphase with the surface waves. The sand bed was firm and smooth except in the area of the breaking antidunes. For a given slope, antidune activity seemed to increase with fine-sediment concentration.

Runs 81, 62, 67, and 79.—The slope ranged from 0.00622 to 0.00651, the depth ranged from 0.53 to 0.55 foot, the mean velocity was about 4.9 fps. Standing waves formed in each run. Figure 98 shows a typical view of the flow for these runs: at times the water

FIGURE 95.—Upstream view of water surface during run 59.

FIGURE 96.—Upstream view of water surface during run 60.

FIGURE 97.—Upstream view of water surface typical of runs 64, 65, and 66.

surface was nearly plane in short reaches, and at other times low- to medium-height standing waves were evident. The bed was plane under the plane-flow areas and wavy under the standing waves with an amplitude of about one-half the amplitude of the water waves. The bed was firm at all locations. Most bed-material discharge occurred within 0.05 foot of the bed. Fine material was in the bed below the zone of sand movement.

Runs 84, 69, and 98.—Varying amounts of antidune activity occurred during this group of runs. Figure 99 illustrates the range of flow condition during run 84—from standing waves to breaking antidunes. The highest concentration of the fine material (42,000 ppm) for this set occurred in run 98. Run 98 also had the largest, most frequent, and most violent antidunes. Figure 100 illustrates the antidune activity during run 98.

Run 68.—A single train of standing waves formed during this run. The standing waves were similar but slightly larger than those of run 67. The water waves had an amplitude of about 0.05 foot and the sand waves had an amplitude of about 0.04 foot. The in-phase water and sand waves were spaced about 4 feet apart. The bed surface was firm.

Runs 100 and 99.—These two runs were nearly identical with respect to slope, depth, and velocity. Run 100 was a continuation of run 99 except that the fine-sediment concentration had been decreased by adding clear water to the flow and wasting the excess of the mixture. Run 100 had 106 ppm of fine sediment and a temperature of 13.3°C, whereas run 99 had 26,900 ppm of fine sediment and a temperature of 19.6°C. Run 100 had a plane bed and a mean bed-material discharge of 8,440 ppm; run 99 had violent antidunes and a mean bed-material discharge of 16,100 ppm. The decrease in antidune activity with the decrease in fine-sediment concentration was very striking.

Run 97.—The slope for this run was much steeper than that for runs 100 and 99, but the mean velocity was much less because of the shallower flow. The antidunes formed in run 97 were not as violent as those in run 99; and, consequently, the bed-material discharge was little more than half that of run 99.

RUNS USING 0.54-MM SAND IN 2-FOOT-WIDE FLUME

This set of runs complemented the previous set (0.47 mm sand in 8-ft-wide flume) in determining the effect of fine sediment on resistance to flow and on sediment transport. The smaller, 2-foot-wide flume, made it practical to use much higher concentrations of bentonite in the flow. The characteristics of the bentonite are described on page I 52.

As in the previous set, equilibrium was established and data were collected for a given run, then without stopping the flow, bentonite was added to or extracted from the flow to establish a new concentration of fine sediment. The change of fine-sediment concentration generally affected the fluidity, which in turn caused a change in bed roughness, velocity, depth, slope, and bed-material discharge.

Samples for determination of total-sediment-transport concentration (bed material plus fine sediment) were collected with a width-depth integrating sampler at the end of the flume. From 8 to 12 samples were taken for the ripple and dune runs, and from 6 to 8 samples were taken for the upper-regime flows. The method of analysis for separation of the fine material and bed material was described on page I 53. Depth-integrated suspended-sediment samples were not obtained for these runs.

FIGURE 98.—View of water surface typical of runs 81, 62, 67, and 79.

A

B

FIGURE 99.—Upstream views of standing waves (*A*) and breaking antidunes (*B*) during run 84.

This set of experiments was conducted during the period April–July 1959. Experimental variables and parameters are given in table 11, and velocity-profile data, in table 21.

The order for presenting this set of runs is identical with that used for presenting runs using the 0.47-mm sand.

Runs 1 and 2.—Particles of sand moved under flow conditions during these runs, but the degree of movement was not sufficient to cause ripples to form. In run 1, particles moved only occasionally; but in run 2, many particles were in motion at any given time. Before run 2 was started, the material on the bed was thoroughly raked and ripples were introduced, but the flow and the characteristics of the sediment particle movement during the run caused the ripples to erode down to a plane bed after about 4 hours.

FIGURE 100.—Downstream view of the antidunes during run 98.

Run 3.—The flow during this run caused considerably more sediment movement than occurred during run 2. Irregular sand waves formed that were very different from ripples.

Run 4.—In spite of the low bed-material discharge of 17 ppm, a rippled bed did not develop. The bed pattern, in general, comprised sand waves; but occasionally it included a very small avalanche face, such as normally would be associated with a dune.

Runs 6 and 5.—The flow conditions in these runs caused normal steep-fronted dunes to form throughout the length of the flume. The dune fronts were continuous across the full width of the flume but were not always normal to the flume wall. If the dunes were diagonal to the flow, however, they were all in the same direction; and if they were normal to the flow, they all were normal. The continuous dune fronts caused increased resistance to flow, but not increased bed-material discharge, in contrast with the data for the 0.47-mm sand in the 8-foot-wide flume.

Run 20.—This run should be classed as transitional, although it could be called a dune run. The dunes were irregular in shape and movement; sometimes there was a long flat area with no dunes. The water surface was generally rough, with choppy waves superposed on longer waves owing to the dunelike bed configuration.

Runs 8, 8A, 8E, 8B, 8C, and 8D.—The discharge for this series of runs ranged from 3.69 to 3.84 cfs, and the fine-material concentration ranged from 0 to 63,700 ppm. Runs 8, 8A, and 8E had bed forms of typical sharp-crested dunes. However, beginning with run 8B the fine-sediment concentration was increased to 20,600 ppm, and the dunes became irregular in shape. The irregularities ranged from long stretches of very low sharp-crested dunes to large round-crested dunes. Also beginning with 8B, some bentonite was layered in the bed by the dune action. The highest concentration of fine material was during run 8D, and the dunes formed during this run were very long and low and had small rounded ripplelike waves superposed. The bed in run 8D was much firmer than that in the dune runs, but not as firm as is expected for the plane-bed condition.

Run 7.—This clear-water run had a slope nearly double that for 8D; yet the bed had a rough dune configuration in contrast to the low smooth configuration of run 8D. The average bed-material discharge was 1,250 ppm for run 7 and 521 ppm for run 8D. The relatively high bed-material discharge for run 7 was caused by the rapid movement of the dunes and by the suspension of sediment through the action of large eddies that originate from the dune crests. The water surface over the dunes was very turbulent. Small waves and boils formed over the dune trough and eddy areas and dissipated over the upstream slope of the next dune downstream.

Runs 14, 14A, 14C, and 14B.—The discharge for each of these runs was about 4.8 cfs, and the fine-sediment concentration ranged from 0 to 44,100 ppm. The bed condition varied from one of nearly normal dunes, for clear water (run 14), to plane bed, for the highest concentration of fine material (run 14B). The equilibrium slope decreased as the fine-sediment concentration increased, as in runs 8–8E.

Run 19.—This run was set up to produce dunes at a discharge rate higher than that in run 7. The depth was first set at 0.6 foot but was increased as equilibrium became established. The dunes resulting from this flow had an unusual shape, especially the short ones, in that they were high and well-rounded toward the upper end but drawn down at the lower end, where the crest is ordinarily located. The avalanche face, where present, was less than half as high as the dune. The water surface was extremely rough, because of the turbulence caused by the dunes. A short dune trapped between two relatively long dunes was severely scoured by a jet of flow from the upper dune and, therefore, rapidly changed size and shape. This run was classed as transitional between dunes and plane bed.

Run 9.—This run was transitional between dunes and plane bed. Generally one or more irregularly shaped dunes could be seen in the flume, but the conditions changed constantly. Dunes formed and then were erased by the flow. The roughness of the water surface varied with the roughness of the bed.

Run 10.—The bed in this run was plane more than 90 percent of the time. Sometimes smooth undulations developed throughout the length of flume and lasted 2–3 minutes. Occasionally a very low dune with a small avalanche face formed and moved rapidly through the flume. This kind of flow caused most of the bed-material discharge to slide and to roll along the bed.

Runs 15, 15A, 15B, and 15C.—The discharge for each of these runs was nearly 7.0 cfs, and the concentration of fine material ranged from 0 to 58,600 ppm. The flow in all the runs was considered to have standing wave form, although the waves for run 15 were often poorly defined. Unlike in dune runs 8–8D and 14–14B, an increase in fine-material concentration caused an increase in the equilibrium slope. Most bed-material discharge moved in relatively close contact with the sand bed.

Runs 13 and 11.—These were clear-water runs which had standing-wave patterns of flow. Suspended sediment moving in the cross section of flow was much less a part of the bed-material discharge than that moving close to the bed. With the recirculating system and under these flow conditions, only the top few hundredths of a foot of the bed was disturbed. Specific sand particles from the bed moved downstream, but they were immediately replaced by other particles from the moving layer. The step length and rest period differed greatly for any group of particles or between specific particles.

Runs 18, 18A, 18B, and 18C.—The discharge in this series of runs was about 7.6 cfs, and the fine-sediment concentration ranged from 0 to 58,700 ppm. The flow conditions ranged from standing waves when there was no fine sediment (run 18) to mildly breaking antidunes when the concentration of fine sediment was highest (run 18C). Equilibrium slope increased noticeably, and suspended-sediment concentration considerably, as fine-sediment concentration increased, especially when the flow shifted to the breaking antidunes of run 18C.

Runs 16A, 16B, and 16C.—The discharge in each of these three runs was about 7.8 cfs, and fine-material concentrations ranged from 11,200 to 44,500 ppm. Slopes were considerably steeper than in runs 18–18C. The flow condition was one of antidunes in all three runs. The degree of antidune activity and resistance to flow in the runs increased with increasing fine-material concentration.

Runs 17, 17A, and 17B.—The discharge in this series was nearly the same as in the 16A–C series, but the slope was greater and antidunes formed in all runs. As bentonite was being added between periods of data collection ("runs"), it was noted that antidune activity increased with increasing concentration of the fine material. A similar condition was noted by Langbein (1942) for natural streams. This increased antidune activity caused increased resistance to flow and greater slope to maintain the depth of flow. In run 17B, three or four waves occasionally broke simultaneously, scouring out a 16- to 20-foot-long pool and creating a steep section draining the pool. Run 17B must have been transitional between antidunes and chute-and-pool flow. The increasing antidune activity caused the suspension and total transport of sand to increase rapidly.

Run 12.—This clear-water antidune run was made at high slope to allow comparison with runs having high concentrations of fine sediment.

BASIC DATA

TABLE 2.—*Experimental variables and parameters*

Run	Slope ×10² S	Depth D (ft)	Water discharge Q (cu ft per sec)	Temperature T (° C)	Suspended concentration: Sampled C_s (ppm)	Suspended concentration: Standard deviation C_s (ppm)	Suspended concentration: Particle size d_{50} (ft×10³)	Total bed-material discharge: Concentration C_t (ppm)	Total bed-material discharge: Standard deviation C_t (ppm)	Total bed-material discharge: Particle size d_{50} (ft×10³)	Total bed-material discharge: Gradation σ	Bed material particle size d_{50} (ft×10³)	Sand waves: Length L (ft)	Sand waves: Height H_s (ft)	Sand waves: Velocity V_s (ft per min)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
24	0.0055	0.94	6.52	18.6	0	0	---------	0	0	---------	---------	---------	---------	---------	---------
22A	.010	.48	2.99	17.5	0	0	---------	0	0	---------	---------	---------	---------	---------	---------
2	.015	1.06	6.68	12.3	0	0	---------	0.2	---------	---------	---------	0.656	0.6	0.03	0.00098
22B	.016	.43	2.99	17.8	0	0	---------	0	0	---------	---------	---------	---------	---------	---------
26	.017	.30	2.00	19.2	0	0	---------	0	0	---------	---------	.626	---------	---------	---------
25	.018	.93	6.45	19.2	0	0	---------	.3	.2	---------	---------	.613	.4	.03	---------
22C	.018	.42	2.99	18.0	0	0	---------	0	0	---------		---------	---------	---------	---------
30	.028	1.00	8.91	17.0	7	---------	---------	3.7	.5	0.321	1.80	.626	.6	.03	.024
1	.034	.58	3.42	13.6	0	0	---------	1.2	1.0	.712	1.40	.643	.5	.02	.00085
31	.043	1.02	10.62	18.1	42	---------	0.423	29	3.3	.433	1.59	.623	.6	.04	---------
27	.057	.55	4.08	18.1	---------	---------	---------	4.0	.7	.334	1.61	.623	.5	.03	---------
5	.058	1.03	12.67	16.4	105	11	.462	120	13	.499	1.62	.640	.9	.04	.080
23	.062	.44	2.99	18.1	0	0	---------	2.0	.4	.499	1.38	.597	.4	.03	.0029
32	.066	.95	13.64	18.2	---------	---------	.456	281	17	.456	1.53	.649	4.0	.10	.23
8	.070	.93	14.81	18.3	506	28	.511	519	40	.427	1.67	.630	5.4	.18	.17
28	.079	.54	4.49	18.0	---------	---------	---------	34	4.9	.518	1.32	.623	.6	.04	---------
33	.083	1.06	16.66	17.4	748	86	.482	836	174	.482	1.46	.656	8.0	.65	.13
29	.084	.56	5.08	19.1	31	---------	---------	58	7.2	.558	1.45	.643	.6	.04	---------
3	.092	.55	5.20	12.3	---------	---------	---------	84	18	.528	1.36	.659	.7	.04	.032
11	.099	1.09	20.47	18.9	795	42	.351	1,300	181	.446	1.55	.583	11.6	.39	.21
13	.100	.89	21.98	19.3	772	67	.371	1,240	68	.453	1.54	.590	13.4	.13	.20
14	.106	.86	22.12	19.4	950	56	.413	1,490	168	.522	1.43	.564	18.8	.17	---------
15	.112	.79	21.84	19.3	1,120	84	.482	2,000	71	.561	1.38	.584	20.5	.04	---------
34	.127	.52	7.00	16.6	393	58	---------	503	26	.518	1.36	.653	1.7	.04	.26
12	.130	1.02	21.96	19.7	929	58	.423	1,270	110	.436	1.54	.593	17.7	.32	.20
6	.130	.61	8.14	15.3	550	88	.429	861	157	.489	1.42	.620	5.1	.18	.10
7	.140	.68	9.66	18.0	567	140	.452	1,240	192	.499	1.56	.614	7.4	.31	.24
35	.147	.52	7.52	18.5	729	154	.462	999	131	.531	1.40	.656	4.5	.13	.24
16	.156	.72	22.14	18.8	1,350	116	.528	2,750	296	.620	1.34	.597	---------	---------	---------
10	.170	.51	11.68	19.1	861	157	.433	2,480	316	.548	1.40	.587	24.0	.10	.78
9	.194	.49	8.22	18.6	697	260	.397	1,210	230	.495	1.46	.623	5.2	.20	.15
17	.196	.67	22.19	19.1	4,030	373	.472	4,650	1,770	.544	1.30	.561	4.4	.10	---------
18	.300	.64	22.16	18.9	7,270	473	.478	9,240	820	.522	1.29	.597	4.9	.10	---------
19	.350	.64	22.19	18.7	13,400	562	.495	12,900	3,060	.522	1.33	.564	---------	---------	---------
39	.390	.61	22.33	18.8	20,100	2,080	.521	16,200	3,590	.495	1.30	---------	---------	---------	---------
20	.460	.60	22.17	18.5	23,300	4,620	.485	23,900	3,610	.512	1.33	.590	---------	---------	---------
21	.542	.50	16.13	18.7	21,900	3,690	.469	25,200	4,720	.502	1.26	---------	---------	---------	---------
38	.582	.58	22.00	17.9	31,600	10,000	.508	26,600	7,510	.522	1.33	---------	---------	---------	---------
36	.845	.51	15.54	16.8	38,800	13,900	.518	35,500	4,120	.541	1.31	.676	---------	---------	---------
37	.950	.65	21.84	17.3	57,300	14,500	.561	47,300	10,500	.512	1.31	.689	---------	---------	---------

for 0.19-mm sand in 8-foot-wide flume

Run	Mean velocity V (ft per sec)	Velocity profile		Shear velocity V_* (ft per sec)	Bed-material discharge		Kinematic viscosity $\times 10^5$ ν (sq ft per sec)	Shear stress at bed τ (lb per sq ft)	Reynolds number $\times 10^{-2}$ R	Froude number F	Resistance factor			Bed configuration
		Slope B	Intercept C		Sampled suspended q_s (lb per sec per ft)	Total q_t (lb per sec per ft)					Darcy-Weisbach f	Chezy $C/\sqrt{g}$	Manning n ($ft^{1/6}$)	
(1)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)
24	0.87	0.27	1.19	0.041	0	0	1.12	0.0032	730	0.16	0.174	21.4	0.012	Plane.
22A	.78	----	----	.039	0	0	1.16	.0030	320	.20	.0203	19.8	.012	Do.
2	.79	.38	1.16	.072	0	0	1.33	.0099	625	.14	.0656	11.0	.024	Ripple.
22B	.87	----	----	.047	0	0.000010	1.15	.0043	323	.23	.0234	18.5	.012	Plane.
26	.83	.24	1.18	.041	0	0	1.10	.0032	----	----	----	----	----	Do.
25	.87	.53	1.24	.073	0	.000015	1.10	.010	725	.16	.0570	11.8	.022	Ripple.
22C	.89	.36	1.18	.049	0	0	1.14	.0047	325	.24	.0246	18.0	.013	Plane.
30	1.11	.51	1.52	.095	0.00049	.00026	1.17	.017	949	.20	.0585	11.7	.022	Ripple.
1	.74	.47	1.15	.080	0	.000032	1.28	.012	328	.17	.0928	9.3	.026	Do.
31	1.30	.76	1.86	.119	----	.0024	1.14	.027	1,161	.23	.0669	10.9	.024	Do
27	.93	.53	1.51	.100	----	.00013	1.14	.020	449	.22	.0934	9.3	.026	Do.
5	1.54	1.01	2.15	.139	.0104	.0119	1.19	.037	1,330	.27	.0649	11.1	.024	Do.
23	.85	.34	1.40	.093	0	.000047	1.14	.017	325	.23	.0957	9.1	.025	Do.
32	1.79	.72	2.43	.142	----	.030	1.13	.039	1,499	.32	.0504	12.6	.021	Dune.
8	1.99	.83	2.66	.145	.058	.060	1.13	.041	1,636	.36	.0423	13.7	.019	Do.
28	1.04	.63	1.72	.117	----	.0012	1.14	.027	491	.25	.1016	8.9	.027	Ripple.
33	1.96	.49	2.63	.168	.097	.109	1.16	.055	1,788	.34	.0590	11.6	.023	Dune.
29	1.13	.64	1.77	.123	.00123	.0022	1.11	.029	569	.27	.0949	9.2	.026	Ripple.
3	1.18	.67	1.85	.128	----	.0034	1.33	.032	482	.28	.0936	9.2	.026	Do.
11	2.35	.45	3.13	.186	.127	.21	1.11	.067	2,300	.40	.0503	12.6	.021	Dune.
13	3.09	----	3.85	.169	.132	.21	1.10	.056	1,498	.58	.0240	18.2	.014	Transition.
14	3.22	1.29	4.13	.171	.164	.26	1.10	.057	2,514	.61	.0226	18.8	.014	Do.
15	3.46	1.37	4.50	.169	.191	.34	1.10	.055	2,480	.69	.0190	20.5	.012	Plane.
34	1.68	.77	2.47	.146	.021	.027	1.18	.041	736	.41	.0603	11.5	.020	Dune.
12	2.69	1.33	3.84	.207	.159	.22	1.09	.083	2,514	.47	.0472	13.0	.020	Do.
6	1.67	.80	2.30	.160	.035	.055	1.22	.049	827	.38	.0732	10.4	.023	Do.
7	1.78	.83	2.51	.175	.043	.093	1.14	.059	1,061	.38	.0774	10.2	.024	Do.
35	1.81	.63	2.71	.157	.043	.059	1.12	.048	836	.44	.0601	11.5	.020	Do.
16	3.84	1.40	4.92	.190	.233	.47	1.12	.070	2,473	.80	.0196	20.2	.012	Transition.
10	2.89	1.29	4.22	.167	.078	.23	1.11	.054	1,328	.71	.0267	17.3	.014	Plane.
9	2.10	1.18	3.68	.175	.045	.078	1.12	.059	909	.53	.0555	12.0	.019	Dune.
17	4.14	----	----	.206	.70	.80	1.11	.082	2,502	.89	.0197	20.1	.012	Antidune.
18	4.33	----	----	.249	1.26	1.60	1.11	.120	2,489	.95	.0264	17.4	.014	Do.
19	4.33	----	----	.269	2.32	2.23	1.12	.140	2,475	.95	.0308	16.1	.015	Do.
39	4.58	----	----	.277	3.50	2.82	1.12	.148	2,500	1.03	.0292	16.6	.015	Do.
20	4.62	----	----	.298	4.03	4.13	1.12	.172	2,462	1.05	.0333	15.5	.016	Do.
21	4.03	----	----	.295	2.76	3.17	1.12	.169	1,796	1.00	.0430	13.6	.017	Do.
38	4.74	----	----	.330	5.43	4.57	1.14	.211	2,397	1.10	.0387	14.4	.017	Do.
36	3.81	----	----	.373	4.71	4.30	1.18	.269	1,650	.94	.0765	10.2	.023	Chute-pool.
37	4.20	----	----	.446	9.77	8.06	1.16	.385	2,351	.92	.0902	9.2	.026	Do.

TABLE 3.—*Experimental variables and parameters*

Run	Slope $\times 10^2$ S	Depth D (ft)	Water discharge Q (ft³ per sec)	Temperature T (° C)	Suspended concentration			Total bed-material discharge				Bed material particle size d_{50} (ft$\times 10^3$)	Sand waves		
					Sampled C_s (ppm)	Standard deviation C_s (ppm)	Particle size d_{50} (ft$\times 10^3$)	Concentration C_t (ppm)	Standard deviation C_t (ppm)	Particle size d_{50} (ft$\times 10^3$)	Gradation σ		Length L (ft)	Height H_s (ft)	Velocity V_s (ft per min)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
50A	0.007	0.96	6.09	14.5	0	0	—	—	—	—	—	—	—	—	—
50D	.018	.91	6.09	15.8	0	0	—	0.5	0.2	—	—	0.856	0.4	0.04	0.0002
51	.046	.99	9.86	16.0	9	—	—	12	1.7	0.705	1.71	.889	1.2	.03	.053
52	.065	.94	12.25	16.0	57	8	—	98	16	.696	1.61	.820	1.7	.06	.096
54	.084	.93	13.62	18.3	157	40	—	200	44	.607	1.56	.935	5.1	.17	.055
53	.108	1.02	15.58	16.9	396	100	0.584	358	67	.584	1.49	.902	6.0	.28	.29
57	.126	.48	5.11	13.9	0	0	—	93	16	.771	1.56	.951	.7	.05	.080
56	.126	.75	11.09	15.3	407	297	.591	550	147	.623	1.58	.823	4.9	.20	.16
55	.130	1.08	17.80	18.1	534	203	.689	639	173	.646	1.48	.886	9.2	.36	.13
45	.138	.84	21.84	17.8	679	136	.541	1,270	675	.755	1.76	.951	—	—	—
43	.140	1.13	19.23	17.4	556	112	.640	931	248	.686	1.60	.912	9.7	.44	.13
44	.163	1.03	21.55	16.8	623	151	.820	833	157	.630	1.56	.856	11.1	.41	.18
42	.167	.94	15.68	14.8	416	57	.902	704	70	.656	1.60	.837	8.5	.40	.086
46	.167	.74	21.76	18.5	857	98	.554	1,670	172	.853	1.64	.827	—	—	—
58	.185	.46	6.75	14.2	331	129	.689	753	104	.702	1.53	.902	9.0	.15	.26
47	.280	.63	21.79	13.6	3,770	461	.600	4,760	673	.758	1.73	.863	3.4	.05	—
48	.493	.59	21.69	15.9	10,800	1,150	.662	9,080	1,020	.646	1.53	.856	4.7	.15	—
39	.813	.55	21.71	10.2	34,000	1,710	.627	28,700	9,460	.656	1.46	.787	5.0	.18	—
41	.952	.45	15.41	11.0	43,300	2,020	.715	35,600	7,920	.636	1.42	.955	4.4	.12	—
40	1.022	.60	21.35	10.8	41,400	9,470	.623	35,800	6,150	.656	1.45	1.033	—	.12	—

TABLE 4.—*Experimental variables and parameters*

Run	Slope $\times 10^2$ S	Depth D (ft)	Water discharge Q (cu ft per sec)	Temperature T (° C)	Suspended concentration			Total bed-material discharge				Bed material particle size d_{50} (ft$\times 10^3$)	Sand waves		
					Sampled C_s (ppm)	Standard deviation C_s (ppm)	Particle size d_{50} (ft$\times 10^3$)	Concentration C_t (ppm)	Standard deviation C_t (ppm)	Particle size d_{50} (ft$\times 10^3$)	Gradation σ		Length L (ft)	Height H_s (ft)	Velocity V_s (ft per min)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
7	0.007	1.01	6.61	13.9	0	0	—	0	0	—	—	—	—	—	—
8	.011	1.00	7.76	11.9	0	0	—	0	0	—	—	0.985	—	—	—
9	.023	1.01	7.76	10.9	0	0	—	2.7	1.8	—	—	.985	0.6	0.02	0.029
10	.041	.59	4.16	15.1	0	0	—	1.0	.2	0.902	1.58	.866	.5	.03	.055
5	.045	1.00	10.73	16.5	0	0	—	12	3.5	.850	2.08	.985	.7	.04	.040
13	.063	1.00	13.46	16.4	99	—	—	75	11	.663	1.82	.949	1.2	.06	.31
4	.069	.86	10.73	14.6	0	0	0.649	51	16	.650	2.00	.902	.8	.06	.077
11	.073	.59	4.92	14.9	0	0	—	20	1.8	.906	1.60	.951	.6	.03	.027
33	.090	1.06	15.74	17.6	377	203	.672	330	54	.630	1.60	.853	6.2	.27	.10
[a] 1	.100	.88	12.70	16.7	403	—	.570	405	65	.423	2.13	1.064	7.1	.29	—
12	.108	.57	7.19	16.0	74	7	—	150	14	.751	1.92	.886	.9	.04	.22
14	.116	.62	8.61	15.6	134	—	—	298	55	.725	1.71	.853	1.5	.07	.080
20	.120	1.05	18.14	15.6	347	25	.672	506	105	.607	1.62	.928	9.6	.46	.17
[a] 2	.131	.92	15.19	15.8	583	62	.354	664	158	.554	1.96	.918	11.2	.35	—
21	.131	1.07	20.39	16.5	528	126	.518	732	101	.591	1.64	.866	9.8	.31	.16
19	.134	.65	9.90	14.9	423	82	.655	563	104	.627	1.69	.870	5.8	.20	.123
[a] 16	.134	1.02	17.23	15.8	436	89	.449	549	144	.574	1.74	.820	7.8	.34	.12
23	.134	.91	22.02	15.6	608	81	.492	1,230	248	.656	1.64	.997	11.8	.26	.38
17	.136	.65	10.01	14.7	262	44	.600	505	79	.630	1.72	.892	6.2	.25	.11
[a] 3	.136	.88	15.28	15.2	445	73	.383	733	168	.640	1.91	.843	7.6	.27	.13
18	.141	.61	11.96	14.7	439	189	.485	1,040	200	.699	1.68	.814	11.7	.24	.20
30	.142	.64	15.68	14.5	548	63	.462	1,370	102	.627	1.47	.975	—	.04	—
34	.150	.44	5.50	14.1	—	—	—	480	127	.788	1.69	.951	1.8	.06	.095
22	.153	.60	14.92	12.7	442	53	.511	1,540	59	.755	1.62	.951	—	—	—
[a] 15	.158	.75	12.87	13.0	389	34	.446	789	123	.620	1.68	.837	8.2	.35	.098
24	.172	.82	21.98	15.7	763	375	.475	2,350	351	.689	1.77	.899	16.2	.23	.36
25	.199	.72	21.85	14.7	972	328	.561	2,710	363	.804	1.64	1.031	—	—	—
28	.229	.55	15.72	15.1	750	121	.586	2,760	372	.833	1.51	.873	—	—	—
29	.278	.52	15.70	15.4	1,240	118	.587	3,120	135	.886	1.72	.929	—	—	—
26	.328	.50	15.51	15.0	1,740	133	.573	5,060	1,160	.820	1.62	.886	2.5	.06	—
32	.470	.58	21.76	10.8	9,490	1,360	.590	10,500	1,590	.676	1.71	.846	3.4	.07	—
27	.533	.43	15.47	15.1	8,240	251	.557	11,500	866	.682	1.71	.916	3.1	.14	—
31	.593	.56	21.34	10.2	16,400	634	.613	13,000	2,630	.591	1.34	.906	3.8	.22	—
35	.815	.54	21.33	10.9	31,800	5,080	.619	27,600	3,810	.650	1.46	.903	6.0	.25	—
37	.820	.30	8.34	11.6	7,820	941	.639	19,900	1,690	.885	1.91	.935	3.0	.13	—
38	.930	.40	15.26	11.1	33,800	4,220	.698	36,100	6,650	.656	1.48	.912	4.5	.14	—
36	1.007	.57	21.38	11.5	47,400	8,660	.648	42,400	11,400	.669	1.43	.984	5.7	.12	—

[a] Slope poorly defined.

for 0.27-mm sand in 8-foot-wide flume

Run	Mean velocity V (ft per sec)	Velocity profile		Shear velocity V_* (ft per sec)	Bed-material discharge		Kinematic viscosity $\times 10^5$ ν (ft per sec)	Shear stress at bed τ (lb per ft)	Reynolds number $\times 10^{-2}$ R	Froude number F	Resistance factor			Bed configuration
		Slope B	Intercept C		Sampled suspended q_s (lb per sec per ft)	Total q_t (lb per sec per ft)					Darcy-Weisbach f	Chezy $C/\sqrt{g}$	Manning n ($ft^{1/6}$)	
(1)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)
50A	0.79	0.18	1.23	0.047	0	0	1.25	0.0042	607	0.14	0.0277	17.0	0.015	Plane.
50D	.84	.20	1.27	.073	0	.000024	1.21	.010	631	.16	.0598	11.6	.022	Ripple.
51	1.24	.52	1.70	.121	.0007	.00092	1.20	.028	1,023	.22	.0763	10.2	.026	Do.
52	1.63	.58	2.03	.140	.0055	.0094	1.20	.038	1,277	.30	.0592	11.6	.022	Do.
54	1.83	.66	2.22	.159	.017	.021	1.13	.049	1,506	.33	.0600	11.5	.023	Dune.
53	1.91	.45	2.18	.188	.048	.044	1.17	.069	1,665	.33	.0778	10.1	.026	Do.
57	1.33	.84	1.67	.140	0	.0037	1.27	.038	503	.34	.0881	9.5	.024	Ripple.
56	1.85	.93	2.70	.174	.035	.048	1.22	.059	1,137	.38	.0711	10.6	.024	Dune.
55	2.06	.68	2.63	.213	.074	.09	1.14	.088	1,952	.35	.0852	9.7	.027	Do.
45	3.25	1.24	4.07	.193	.116	.22	1.15	.072	2,374	.62	.0283	16.8	.015	Transition.
43	2.13	.37	2.15	.226	.084	.14	1.16	.099	2,075	.35	.0898	9.4	.029	Dune.
44	2.62	.68	3.24	.233	.105	.14	1.18	.105	2,287	.45	.0630	11.3	.023	Do.
42	2.09	.50	2.26	.225	.051	.086	1.24	.098	1,584	.38	.0926	9.3	.028	Do.
46	3.68	1.40	4.74	.199	.15	.28	1.12	.077	2,431	.75	.0235	18.4	.014	Plane.
58	1.83	.30	2.07	.166	.017	.040	1.26	.053	668	.48	.0655	11.0	.021	Dune.
47	4.32	----------	----------	.238	.64	.81	1.28	.110	2,126	.96	.0243	18.1	.014	Antidune.
48	4.60	----------	----------	.306	1.83	1.54	1.20	.182	2,262	1.06	.0354	15.0	.016	Do.
39	4.93	----------	----------	.379	5.76	4.86	1.40	.279	1,937	1.17	.0474	13.0	.018	Do.
41	4.28	----------	----------	.371	5.21	4.28	1.38	.267	1,396	1.12	.0602	11.5	.020	Chute-pool.
40	4.45	----------	----------	.444	6.91	5.98	1.38	.383	1,935	1.01	.0798	10.0	.024	Do.

for 0.28-mm sand in 8-foot-wide flume

Run	Mean velocity V (ft per sec)	Velocity profile		Shear velocity V_* (ft per sec)	Bed-material discharge		Kinematic viscosity $\times 10^5$ ν (sq ft² per sec)	Shear stress at bed τ (lb per sq ft)	Reynolds number $\times 10^{-2}$ R	Froude number F	Resistance factor			Bed configuration
		Slope B	Intercept C		Sampled suspended q_s (lb per sec per ft)	Total q_t (lb per sec per ft)					Darcy-Weisbach f	Chezy $C/\sqrt{g}$	Manning n ($ft^{1/6}$)	
(1)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)
7	0.82	0.17	0.81	0.048	0	0	1.27	0.0044	652	0.14	0.0271	17.2	0.015	Plane.
8	.97	----------	----------	.060	0	0	1.34	.0069	724	.17	.0301	16.3	.016	Do.
9	.96	.45	.84	.086	0	.00016	1.38	.014	703	.17	.0649	11.1	.024	Ripple.
10	.88	.59	.85	.088	0	.000032	1.23	.015	422	.20	.0804	10.0	.024	Do.
5	1.34	.69	1.41	.120	0	.0010	1.19	.028	1,126	.24	.0646	11.1	.024	Do.
13	1.68	1.01	1.97	.142	.0104	.0079	1.19	.039	1,412	.30	.0566	11.9	.022	Do.
4	1.56	.76	1.80	.138	0	.0043	1.25	.037	1,073	.30	.0628	11.3	.023	Do.
11	1.04	.47	1.04	.118	0	.00077	1.23	.027	499	.24	.1025	8.8	.027	Do.
33	1.86	.36	2.22	.175	.046	.041	1.15	.060	1,714	.32	.0710	10.6	.025	Dune.
1	1.80	.32	2.06	.168	.040	.040	1.18	.055	1,342	.34	.0700	10.7	.024	Do.
12	1.58	.71	1.79	.141	.0042	.0084	1.20	.038	750	.37	.0635	11.2	.021	Ripple.
14	1.74	.71	2.15	.152	.0090	.020	1.21	.045	892	.39	.0612	11.4	.021	Dune.
20	2.16	.55	2.55	.201	.049	.072	1.21	.079	1,874	.37	.0696	10.7	.025	Do.
2	2.06	----------	----------	.197	.069	.079	1.21	.075	1,566	.38	.0732	10.5	.025	Do.
21	2.38	.33	2.41	.212	.084	.116	1.19	.087	2,140	.41	.0637	11.2	.024	Do.
19	1.90	.39	2.19	.167	.033	.043	1.23	.054	1,004	.42	.0622	11.4	.022	Do.
16	2.11	.31	2.28	.210	.059	.074	1.21	.085	1,779	.37	.0791	10.1	.026	Do.
23	3.02	1.07	3.15	.198	.105	.21	1.21	.076	2,271	.56	.0344	15.2	.017	Transition.
17	1.92	.46	1.67	.169	.020	.039	1.24	.055	1,006	.42	.0618	11.4	.021	Dune.
3	2.17	.91	2.53	.196	.053	.087	1.22	.075	1,565	.41	.0655	11.0	.023	Do.
18	2.45	.56	2.51	.166	.041	.097	1.24	.054	1,205	.55	.0369	14.7	.016	Do.
30	3.06	1.06	3.95	.171	.067	.168	1.25	.057	1,567	.67	.0250	17.9	.014	Transition.
34	1.56	.34	2.01	.146	----------	.021	1.26	.041	545	.41	.0699	10.7	.021	Dune.
22	3.11	1.26	3.91	.172	.051	.179	1.31	.057	1,424	.71	.0244	18.1	.013	Plane.
15	2.14	.25	2.57	.195	.039	.079	1.30	.074	1,235	.44	.0667	11.0	.023	Dune.
24	3.35	.82	3.82	.213	.131	.40	1.21	.088	2,270	.65	.0324	15.7	.016	Transition.
25	3.79	1.29	4.89	.215	.166	.46	1.24	.089	2,200	.79	.0257	17.6	.014	Plane.
28	3.57	1.22	4.60	.201	.092	.34	1.23	.079	1,596	.85	.0255	17.7	.014	Do.
29	3.77	1.36	4.97	.216	.152	.38	1.22	.090	1,607	.92	.0262	17.5	.014	Do.
26	3.88	1.87	5.48	.230	.211	.61	1.23	.102	1,577	.97	.0281	16.9	.014	Antidune.
32	4.69	----------	----------	.296	1.61	1.78	1.38	.170	1,971	1.09	.0319	15.8	.015	Do.
27	4.50	----------	----------	.272	.99	1.39	1.23	.143	1,573	1.21	.0292	16.6	.014	Do.
31	4.76	----------	----------	.327	2.73	2.16	1.40	.207	1,904	1.12	.0378	14.6	.016	Do.
35	4.93	----------	----------	.376	5.29	4.60	1.38	.275	1,929	1.18	.0466	13.1	.018	Do.
37	3.48	----------	----------	.281	.51	1.30	1.35	.154	773	1.12	.0523	12.4	.017	Do.
38	4.77	----------	----------	.346	4.03	4.27	1.37	.232	1,393	1.33	.0421	13.8	.016	Chute-pool.
36	4.69	----------	----------	.430	7.91	7.08	1.36	.358	1,966	1.09	.0672	10.9	.022	Do.

TABLE 5.—*Experimental variables and parameters*

Run	Slope ×10² S	Depth D (ft)	Water discharge Q (cu ft per sec)	Temperature T (° C)	Suspended concentration: Sampled C_s (ppm)	Suspended concentration: Standard deviation C_s (ppm)	Suspended concentration: Particle size d_{50} (ft×10³)	Total bed-material discharge: Concentration C_t (ppm)	Total bed-material discharge: Standard deviation C_t (ppm)	Total bed-material discharge: Particle size d_{50} (ft×10³)	Total bed-material discharge: Gradation σ	Bed material particle size d_{50} (ft×10³)	Sand waves: Length L (ft)	Sand waves: Height H_s (ft)	Sand waves: Velocity V_s (ft per min)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
14	0.015	0.61	3.94	10.2	----------	----------	----------	0	0	----------	----------	----------	----------	----------	----------
13	.019	.35	1.84	9.0	----------	----------	----------	0	0	----------	----------	----------	----------	----------	----------
17	.020	.98	6.22	12.0	----------	----------	----------	.7	.2	----------	----------	----------	0.8	0.04	----------
16	.021	.81	5.11	12.0	----------	----------	----------	1.2	.6	0.728	2.70	----------	.7	.06	----------
15	.023	.80	5.07	11.0	----------	----------	----------	.7	.5	.837	2.68	1.44	----------	----------	----------
18	.031	.58	3.62	11.3	----------	----------	----------	.4	.1	----------	----------	----------	.7	.04	----------
2	.036	.82	7.90	11.0	----------	----------	----------	9.4	.3	.968	2.47	1.35	1.2	.07	----------
3	.039	.85	7.90	11.5	----------	----------	----------	10	5.6	.935	2.79	1.48	1.4	.09	----------
9	.040	.55	3.84	12.0	----------	----------	----------	1.4	.8	.361	3.80	1.54	.7	.06	----------
1	.042	.80	7.85	9.0	----------	----------	----------	23	7	1.160	3.95	1.44	2.0	.10	----------
5	.047	.75	7.93	11.0	----------	----------	----------	27	10	.863	2.77	1.52	1.0	.07	----------
11	.049	.35	1.95	11.5	----------	----------	----------	4.7	3.9	----------	----------	1.46	.8	.06	----------
4	.057	.69	7.94	10.0	----------	----------	----------	92	18	1.030	2.29	1.51	4.2	.15	----------
8	.060	.51	3.83	12.0	----------	----------	----------	7.6	2.5	.846	2.78	1.39	.7	.06	----------
7	.078	.70	7.98	11.5	----------	----------	----------	268	20	.637	3.36	1.46	4.4	.20	----------
10	.088	.33	1.95	10.5	----------	----------	----------	16	4.1	1.400	1.64	1.54	.8	.08	----------
6	.088	.46	3.90	9.5	----------	----------	----------	42	16	1.440	1.86	1.64	1.6	.10	----------
12	.106	.29	1.95	11.7	----------	----------	----------	1.0	.8	.771	3.70	1.54	.9	.06	----------
19	.112	.41	4.24	18.0	----------	----------	----------	208	52	.951	3.28	1.57	6.4	.26	----------
21	.114	.96	12.12	16.0	189	----------	0.31	380	34	.820	2.81	1.36	4.8	.31	----------
22	.124	1.00	13.54	15.7	----------	----------	1.33	554	102	.791	2.58	1.25	7.5	.52	----------
25	.189	.42	4.91	17.0	----------	----------	----------	378	77	1.100	2.03	1.50	6.3	.26	----------
20	.193	.61	8.14	16.4	388	----------	.43	508	61	.663	2.84	1.61	5.4	.36	----------
23	.247	.65	13.34	16.0	558	----------	.46	856	206	.755	2.43	1.40	6.6	.41	----------
24	.289	.62	8.73	17.0	----------	----------	1.11	917	711	.820	2.29	1.23	5.5	.31	----------
40	.301	.81	21.41	19.0	917	----------	.44	2,460	657	.810	1.97	1.41	7.4	.31	----------
39	.364	.55	20.64	19.0	747	----------	.49	3,960	338	1.010	1.92	1.51	3.7	.10	----------
26	.366	.34	14.45	17.0	----------	----------	.44	4,580	275	1.140	1.87	1.54	----------	----------	----------
28	.366	.40	11.19	16.0	3,970	----------	1.08	4,230	594	1.110	1.84	1.65	2.6	.05	----------
29	.369	.30	4.54	17.4	----------	----------	1.31	1,850	241	1.190	2.08	1.48	6.4	.23	----------
31	.432	.44	14.85	17.5	----------	----------	1.51	4,750	409	1.250	1.80	1.58	3.2	.06	----------
27	.436	.33	7.91	18.0	----------	----------	1.12	4,100	291	1.210	1.98	1.66	10.2	.19	----------
36	.446	.19	3.15	19.0	323	----------	.65	1,370	795	1.350	2.10	1.50	.9	.03	----------
41	.466	.54	21.62	18.7	907	----------	.65	4,340	785	1.380	1.76	1.14	3.9	.14	----------
30	.492	.27	5.33	17.2	----------	----------	1.38	3,550	457	1.350	1.85	1.57	6.0	.12	----------
35	.494	.25	5.58	17.0	2,680	----------	1.02	4,610	330	1.330	1.71	1.48	2.2	.07	----------
34	.546	.28	8.44	17.5	682	----------	.59	5,690	1,050	1.450	1.77	1.31	2.5	.08	----------
33	.607	.27	10.02	16.0	----------	----------	1.71	6,810	442	1.360	1.85	1.26	2.8	.10	----------
38	.619	.50	21.38	19.0	732	----------	.68	6,230	844	1.590	1.83	1.36	3.8	.09	----------
37	.620	.43	18.87	18.5	752	----------	.66	5,570	688	1.740	1.83	1.65	3.8	.08	----------
32	.656	.37	14.96	18.0	----------	----------	1.56	6,180	764	1.670	1.84	1.35	3.7	.29	----------
45	.862	.28	5.58	18.9	250	----------	.66	9,630	1,440	1.590	1.61	1.33	1.6	.11	----------
44	.898	.28	10.83	19.4	3,020	----------	.98	15,100	4,160	1.570	1.60	1.74	3.0	.21	----------
42	.986	.31	13.43	20.0	4,520	----------	1.21	11,400	1,890	1.720	1.65	1.30	3.6	.25	----------
43	1.01	.43	21.42	18.5	----------	----------	----------	11,500	232	1.280	1.80	1.57	5.8	.27	----------

for 0.45-mm sand in 8-foot-wide flume

Run	Mean velocity V (ft per sec)	Velocity profile		Shear velocity V_* (ft per sec)	Bed-material discharge		Kinematic viscosity $\times 10^5$ ν (sq ft per sec)	Shear stress at bed τ (lb per sq ft)	Reynolds number $\times 10^{-2}$ R	Froude number F	Resistance factor			Bed configuration
		Slope B	Intercept C		Sampled suspended q_s (lb per sec per ft)	Total q_t (lb per sec per ft)					Darcy-Weisbach f	Chezy $C/\sqrt{g}$	Manning n ($ft^{1/6}$)	
(1)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)
14	0.81	0.221	0.90	0.054	--	0	1.40	0.0057	353	0.18	0.0359	14.9	0.016	Plane.
13	.65	.108	.67	.046	--	0	1.46	.0041	156	.19	.0405	14.0	.016	Do.
17	.80	.161	.92	.071	--	.000034	1.34	.012	585	.14	.0788	10.1	.026	Ripples.
16	.79	.261	.98	.067	--	.000048	1.34	.0086	478	.15	.0568	11.9	.021	Do.
15	.79	.32	.98	.077	--	.000028	1.38	.011	458	.16	.0759	10.3	.025	Do.
18	.78	.22	.86	.076	--	.000011	1.36	.011	333	.18	.0761	10.2	.023	Do.
2	1.20	--	--	.097	--	.00058	1.38	.018	713	.23	.0528	12.3	.021	Do.
3	1.16	.36	1.49	.103	--	.00062	1.36	.021	725	.22	.0635	11.2	.023	Do.
9	.88	.30	1.33	.084	--	.000042	1.34	.014	361	.21	.0732	10.5	.023	Do.
1	1.23	.35	1.68	.104	--	.00141	1.46	.021	674	.24	.0572	11.8	.021	Do.
5	1.32	.41	1.79	.107	--	.00167	1.38	.022	717	.27	.0521	12.4	.020	Do.
11	.70	.30	1.21	.074	--	.000071	1.36	.011	180	.21	.0902	9.4	.024	Do.
4	1.44	.36	1.86	.113	--	.0057	1.41	.025	705	.31	.0489	12.8	.019	Dune.
8	.93	.36	1.40	.099	--	.00023	1.34	.019	354	.23	.0911	9.4	.025	Ripple.
7	1.43	.22	1.80	.133	--	.0167	1.36	.034	736	.30	.0688	10.8	.023	Dune.
10	.75	.38	1.32	.097	--	.00024	1.39	.018	178	.23	.1330	7.8	.028	Ripple.
6	1.07	.64	1.65	.114	--	.00128	1.43	.025	344	.28	.0911	9.4	.025	Do.
12	.85	.41	1.45	.099	--	.000015	1.35	.019	183	.28	.1096	8.5	.025	Do.
19	1.30	.56	1.87	.122	--	.0069	1.14	.029	468	.36	.0700	10.7	.021	Dune.
21	1.58	1.05	1.75	.188	0.0179	.036	1.20	.068	1,264	.28	.1129	8.4	.031	Do.
22	1.70	.61	1.91	.200	--	.058	1.21	.077	1,405	.30	.1105	8.5	.031	Do.
25	1.47	.32	2.25	.160	--	.0145	1.17	.050	528	.40	.0946	9.2	.025	Do.
20	1.68	.61	2.06	.195	.025	.032	1.19	.073	861	.38	.1075	8.6	.028	Do.
23	2.57	.32	2.75	.227	.058	.089	1.20	.100	1,392	.56	.0626	11.3	.022	Do.
24	1.76	.85	2.57	.240	--	.062	1.17	.112	933	.39	.1490	7.3	.033	Do.
40	3.32	.49	3.83	.280	.153	.41	1.11	.152	2,423	.65	.0570	11.8	.022	Do.
39	4.71	1.80	5.90	.254	.120	.64	1.11	.125	2,334	1.12	.0232	18.6	.013	Standing wave.
26	5.38	1.61	5.03	.200	--	.52	1.17	.078	1,563	1.63	.0111	26.9	.008	Plane.
28	3.52	1.60	5.60	.217	.35	.37	1.20	.091	1,173	.98	.0304	16.2	.014	Transition.
29	1.89	1.15	3.35	.189	--	.066	1.16	.069	489	.61	.0798	10.0	.022	Dune.
31	4.24	1.60	5.32	.247	--	.55	1.16	.119	1,608	1.13	.0272	17.1	.013	Standing wave.
27	2.99	1.17	4.32	.215	--	.25	1.14	.090	866	.92	.0415	13.9	.016	Transition.
36	2.04	.73	--	.165	.0079	.034	1.11	.053	349	.82	.0525	12.4	.016	Do.
41	5.05	1.60	6.40	.285	.153	.73	1.12	.157	2,435	1.21	.0254	17.7	.013	Standing wave.
30	2.47	1.70	4.34	.207	--	.148	1.16	.083	575	.84	.0561	11.9	.018	Transition.
35	2.80	2.07	4.93	.199	.117	.201	1.17	.077	598	.99	.0406	14.0	.015	Do.
34	3.73	1.99	5.73	.222	.045	.37	1.16	.095	900	1.24	.0283	16.8	.013	Standing wave.
33	4.60	1.62	5.48	.230	--	.53	1.20	.102	1,035	1.56	.0200	20.0	.011	Do.
38	5.38	1.78	6.70	.316	.122	1.04	1.11	.193	2,423	1.34	.0275	17.0	.014	Do.
37	5.54	1.99	6.15	.293	.111	.82	1.12	.166	2,127	1.49	.0224	18.9	.012	Transition.
32	5.03	1.29	5.95	.280	--	.72	1.14	.151	1,633	1.46	.0247	18.0	.012	Antidune.
45	2.50	1.51	4.75	.279	.0109	.42	1.11	.151	631	.83	.0995	9.0	.024	Do.
44	4.78	1.79	6.80	.285	.255	1.28	1.10	.157	1,217	1.59	.0283	16.8	.013	Do.
42	5.36	2.20	7.20	.314	.47	1.19	1.08	.191	1,539	1.70	.0274	17.1	.013	Do.
43	6.18	--	--	.374	--	1.92	1.12	.271	2,373	1.66	.0292	16.6	.014	Do.

TABLE 6.—*Experimental variables and parameters*

Run	Slope ×10² *S*	Depth *D* (ft)	Water discharge *Q* (cu ft per sec)	Temperature *T* (°C)	Suspended concentration: Sampled C_s (ppm)	Suspended concentration: Standard deviation C_s (ppm)	Suspended concentration: Particle size d_{50} (ft×10³)	Total bed-material discharge: Concentration C_t (ppm)	Total bed-material discharge: Standard deviation C_t (ppm)	Total bed-material discharge: Particle size d_{50} (ft×10³)	Total bed-material discharge: Gradation σ	Bed material particle size d_{50} (ft×10³)	Sand waves: Length *L* (ft)	Sand waves: Height H_s (ft)	Sand waves: Velocity V_s (ft per min)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
19	0.013	1.01	8.06	19.8	0	0	------	0	0	------	------	------	------	------	------
25	.022	1.01	9.88	19.3	0	0	------	0	0	------	------	------	------	------	------
26	.022	1.02	10.80	19.0	0	0	------	0	0	------	------	------	------	------	------
27	.028	1.01	11.86	22.7	0	0	------	2.8	------	------	------	2.79	------	------	------
20	.028	1.03	10.91	19.6	0	0	------	.4	.2	------	------	------	------	------	------
21	.030	1.01	12.06	20.5	0	0	------	.4	------	------	------	------	------	------	------
18	.037	1.01	13.42	18.0	0	0	------	21	3.6	2.64	1.43	3.15	2.1	0.04	0.06
28	.037	1.04	14.53	20.7	0	0	------	28	8.7	2.95	1.37	3.02	3.7	.05	.07
29	.043	.50	4.62	18.9	0	0	------	0	0	------	------	------	------	------	------
22	.043	.49	4.49	19.0	0	0	------	0	0	------	------	------	------	------	------
30	.050	.51	5.06	18.9	0	0	------	------	------	------	------	------	------	------	------
31	.054	.50	5.42	16.8	0	0	------	4.2	.2	------	------	3.22	------	------	------
15	.059	1.05	16.25	19.7	4.1	------	------	65	30	2.58	1.45	3.28	2.6	.09	.14
23	.062	.49	5.10	19.2	0	0	------	------	------	------	------	------	------	------	------
32	.064	.52	6.25	16.7	0	0	------	26	9.8	2.79	1.38	2.98	------	------	------
24	.068	.49	5.71	19.3	0	0	------	15	3.7	------	------	------	------	------	------
14	.071	.58	7.41	17.4	------	------	------	63	17	2.72	1.38	3.25	2.8	.03	.07
34	.080	.54	7.08	19.5	------	------	------	73	20	2.56	1.40	2.82	2.9	.02	.12
16	.112	1.04	16.85	19.4	12	------	------	140	50	2.69	1.44	3.18	3.6	.16	.13
35	.130	.53	7.64	17.1	------	------	------	201	52	2.82	1.48	3.02	2.9	.06	.20
17	.136	1.00	16.83	19.2	30	------	------	211	58	2.89	1.50	3.08	3.5	.18	.18
33	.145	.56	8.18	19.0	14	------	------	253	84	2.53	1.54	2.99	3.3	.08	.18
5	.183	.93	16.41	17.5	80	37	2.62	308	65	2.62	2.42	2.98	5.2	.28	.17
10	.192	.46	6.90	19.0	12	------	------	450	126	2.76	1.53	3.22	3.9	.12	.24
37	.275	1.11	22.58	18.0	260	117	1.38	601	259	2.35	2.40	2.43	6.6	.34	.27
36	.304	.55	8.96	17.3	56	------	------	519	70	2.69	1.62	3.07	3.5	.13	.32
6	.313	1.04	22.30	19.1	281	135	2.23	537	227	2.16	2.81	2.92	5.8	.31	.45
7	.339	.59	10.10	18.3	357	124	1.54	822	199	3.12	1.84	3.38	4.5	.19	.44
38	.356	1.02	22.69	18.9	422	220	.94	1,080	274	2.41	2.14	2.48	6.3	.30	.58
11	.393	.92	22.22	18.3	614	------	------	1,180	630	2.39	2.74	3.15	7.4	.32	.60
8	.430	.57	11.20	17.4	313	121	1.30	1,490	646	2.80	1.53	2.89	5.9	.17	.59
12	.437	.89	22.19	18.5	656	116	2.34	1,900	737	2.49	2.33	3.02	4.8	.23	1.16
13	.587	.82	22.09	18.4	1,190	572	2.79	2,750	840	2.63	1.84	3.02	6.2	.25	2.30
9	.600	.49	11.32	18.5	498	214	2.65	2,620	724	3.05	1.64	3.17	2.7	.12	1.37
3	.65	.60	16.46	17.3	2,820	1,360	2.87	3,110	723	2.85	2.02	3.08	3.2	.19	------
1	.71	.68	22.33	19.3	3,770	529	1.87	4,020	724	2.21	2.28	3.28	------	------	------
2	.92	.53	22.07	18.2	2,320	563	1.79	6,140	2,420	2.82	1.75	3.02	4.9	.31	------
4	.94	.51	15.64	18.0	2,340	875	2.82	5,090	1,600	2.76	2.11	3.08	4.5	.11	------
41	1.12	.44	15.67	21.7	2,230	170	1.48	9,480	785	2.68	1.96	3.41	------	------	------
42	1.16	.44	20.44	20.4	1,610	741	2.16	7,320	1,280	2.95	1.51	2.66	------	------	------
40	1.23	.38	15.53	19.6	1,470	498	1.51	10,200	1,740	3.47	1.34	2.72	------	------	------
43	1.26	.44	20.63	21.0	2,500	488	2.30	7,000	1,060	3.45	1.42	2.49	------	------	------
39	1.28	.43	20.88	20.5	2,300	520	2.10	7,010	460	3.35	1.50	3.35	------	------	------

for 0.93-mm sand in 8-foot-wide flume

Run	Mean velocity V (ft per sec)	Velocity profile		Shear velocity V_* (ft per sec)	Bed-material discharge		Kinematic viscosity $\times 10^5$ ν (sq ft per sec)	Shear stress at bed τ (lb per sq ft)	Reynolds number $\times 10^{-2}$ R	Froude number F	Resistance factor			Bed configuration
		Slope B	Intercept C		Sampled suspended q_s (lb per sec per ft)	Total q_t (lb per sec per ft)					Darcy-Weisbach f	Chezy $C/\sqrt{g}$	Manning n ($ft^{1/6}$)	
(1)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)
19	1.00	0.41	1.52	0.065	0	0	1.09	0.008	927	0.18	0.0335	15.4	0.017	Plane.
25	1.22	.48	1.78	.085	0	0	1.10	.014	1,120	.21	.0384	14.4	.018	Do.
26	1.32	.54	2.00	.085	0	0	1.11	.014	1,212	23	.0330	15.6	.017	Do.
27	1.47	.60	2.02	.095	0	.00026	1.02	.018	1,456	.26	.0337	15.4	.017	Do.
20	1.32	.61	2.07	.097	0	.000034	1.09	.018	1,247	.23	.0432	13.6	.019	Do.
21	1.49	.67	2.22	.098	0	.000038	1.07	.019	1,406	.26	.0345	15.2	.017	Do.
18	1.66	.62	2.26	.110	0	.0022	1.14	.023	1,471	.29	.0349	15.1	.017	Dune.
28	1.75	.58	2.25	.111	0	.0032	1.06	.024	1,717	.30	.0326	15.7	.017	Do.
29	1.16	.40	1.80	.082	0	0	1.11	.013	523	.29	.0400	14.2	.017	Plane.
22	1.15	.42	1.77	.082	0	0	1.11	.013	508	.29	.0410	14.0	.017	Do.
30	1.25	.50	1.93	.090	0	----------	1.11	.016	574	.31	.0418	13.8	.017	Do.
31	1.36	.54	1.99	.093	0	.000177	1.18	.017	576	.34	.0374	14.6	.016	Do.
15	1.93	.58	2.40	.141	.00052	.0082	1.09	.039	1,859	.33	.0428	13.7	.019	Dune.
23	1.30	.57	2.07	.098	0	----------	1.10	.019	579	.33	.0459	13.2	.018	Plane.
32	1.50	.56	2.30	.103	0	.00127	1.18	.021	661	.37	.0381	14.5	.016	Do.
24	1.46	.60	2.30	.104	0	.00067	1.10	.021	650	.37	.0403	14.1	.017	Do.
14	1.60	.68	2.51	.115	----------	.0036	1.16	.026	800	.37	.0414	13.9	.017	Dune.
34	1.64	.73	2.47	.118	----------	.0040	1.10	.027	805	.39	.0413	13.9	.017	Do.
16	2.03	.97	2.59	.194	.00158	.0184	1.10	.073	1,919	.35	.0727	10.5	.025	Do.
35	1.80	.63	2.50	.149	----------	.0120	1.17	.043	815	.44	.0547	12.1	.020	Do.
17	2.10	.82	2.77	.209	.0039	.028	1.10	.085	1,909	.37	.0794	10.0	.026	Do.
33	1.83	.64	2.64	.162	.00089	.0162	1.11	.051	923	.43	.0627	11.3	.021	Do.
5	2.21	.67	2.33	.234	.0102	.039	1.16	.106	1,772	.40	.0898	9.4	.028	Do.
10	1.88	.37	2.79	.169	.00083	.024	1.11	.055	779	.49	.0643	11.2	.021	Do.
37	2.54	1.28	3.34	.313	.046	.106	1.14	.191	2,473	.43	.122	8.1	.033	Do.
36	2.04	.40	2.75	.232	.0039	.036	1.16	.104	967	.48	.103	8.8	.027	Do.
6	2.68	----------	----------	.324	.049	.093	1.11	.203	2,511	.46	.117	8.3	.032	Do.
7	2.14	.27	2.83	.254	.028	.065	1.13	.125	1,117	.49	.112	8.4	.029	Do.
38	2.78	1.58	4.15	.342	.075	.191	1.11	.227	2,555	.49	.121	8.1	.032	Do.
11	3.02	1.10	4.28	.341	.106	.204	1.13	.226	2,459	.56	.102	8.9	.029	Do.
8	2.46	1.26	3.78	.281	.027	.130	1.16	.153	1,209	.57	.104	8.8	.027	Do.
12	3.12	----------	----------	.354	.114	.33	1.12	.243	2,479	.58	.103	8.8	.029	Do.
13	3.37	2.03	5.40	.394	.205	.47	1.13	.300	2,445	.65	.109	8.6	.030	Transition.
9	2.89	1.30	4.38	.308	.044	.23	1.12	.183	1,264	.72	.0941	9.2	.025	Do.
3	3.43	----------	----------	.354	.36	.40	1.16	.243	1,774	.78	.0853	9.7	.025	Do.
1	4.10	----------	----------	.394	.66	.70	1.10	.301	2,535	.88	.0739	10.4	.024	Do.
2	5.20	----------	----------	.396	.40	1.06	1.13	.304	2,439	1.26	.0464	13.1	.018	Do.
4	3.83	----------	----------	.392	.29	.62	1.14	.299	1,713	95	.0841	9.8	.024	Do.
41	4.45	3.97	7.35	.398	.27	1.16	1.04	.308	1,883	1.18	.0640	11.2	.021	Do.
42	5.81	2.96	8.20	.405	.26	1.17	1.07	.319	2,389	1.54	.0389	14.3	.016	Standing wave.
40	5.11	2.49	7.42	.388	.178	1.24	1.09	.292	1,781	1.46	.0461	13.2	.017	Do.
43	5.86	2.64	8.68	.423	.40	1.13	1.05	.346	2,456	1.56	.0415	13.9	.017	Do.
39	6.07	3.34	8.46	.420	.38	1.14	1.07	.344	2,439	1.63	.0474	13.0	.018	Do.

TABLE 7.—*Experimental variables and parameters*

Run	Slope ×10² S	Depth D (ft)	Water discharge Q (cu ft per sec)	Temperature T (° C)	Suspended concentration			Total bed-material discharge				Bed material particle size d_{50} (ft×10³)	Sand waves		
					Sampled C_s (ppm)	Standard deviation C_s (ppm)	Particle size d_{50} (ft×10³)	Concentration C_t (ppm)	Standard deviation C_t (ppm)	Particle size d_{50} (ft×10³)	Gradation σ		Length L (ft)	Height H_s (ft)	Velocity V_s (ft per min)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
1	0.014	0.51	0.91	10.0	0	0	----	0	0	----	----	----	----	----	----
2	.017	.52	.88	23.4	0	0	----	0	0	----	----	----	----	----	----
3	.112	.54	1.31	10.5	0	0	----	55	11	0.886	1.63	----	----	0.20	----
4	.086	.54	1.31	27.8	0	0	----	61	16	.998	1.60	0.854	0.7	.07	----
30	.110	.57	1.56	14.7	24	8.4	----	91	22	.886	1.47	1.021	.6	.07	0.060
29	.103	.56	1.57	33.8	9.1	1.3	----	117	43	1.248	1.43	1.019	3.3	.11	.050
5	.139	.56	1.88	10.2	56	14	0.616	226	62	.782	1.57	.837	1.0	.10	.0050
6	.118	.59	1.88	27.2	33	----	----	168	40	.788	1.48	.854	1.6	.10	.0083
27	.147	.58	2.28	14.3	168	----	.626	455	238	.854	1.36	1.038	4.1	.21	.20
28	.214	.63	2.29	34.3	251	----	.715	787	310	.913	1.48	1.035	4.5	.13	.19
26	.201	.71	2.67	13.1	80	3.1	.649	854	295	.933	1.46	1.071	4.6	.18	.14
25	.210	.66	2.64	33.1	274	101	.655	719	180	.867	1.56	1.019	4.2	.23	.28
21	.184	.58	3.13	12.4	196	49	.538	907	199	.847	1.58	1.035	----	----	----
22	.166	.64	3.13	33.9	498	218	.649	1,150	286	.886	1.63	1.051	6.4	.18	.37
24	.172	.74	3.48	12.1	307	63	.695	706	206	.847	1.52	.969	6.8	.13	.26
23	.261	.73	3.48	32.8	227	72	.646	1,150	359	.894	1.52	.916	6.3	.20	.32
7	.189	.60	3.48	11.9	196	38	.613	1,410	194	.925	1.58	.950	----	----	----
8	.194	.72	3.50	26.9	248	29	.567	1,820	405	.926	1.57	1.003	5.5	.24	.48
20	.566	.55	4.55	12.7	1,520	139	.708	5,600	527	1.012	1.49	1.001	----	----	----
19	.417	.56	4.55	28.4	735	159	.767	4,340	383	.831	1.48	.979	----	----	----
10	.710	.59	4.78	7.0	2,020	602	.636	5,180	1,040	1.015	1.54	1.001	----	----	----
9	.493	.56	4.78	23.5	1,480	86	.688	5,530	870	1.184	1.63	.935	----	----	----
12	.456	.67	5.32	7.9	1,480	384	.652	3,960	288	.923	1.46	1.051	----	----	----
11	.408	.60	5.30	23.8	1,810	310	.672	5,250	812	1.035	1.69	1.051	----	----	----
14	.865	.60	5.70	12.5	5,340	711	.767	12,300	3,500	.906	1.51	1.215	----	----	----
13	.730	.60	5.70	31.7	2,100	111	.737	8,780	1,770	.991	1.43	1.049	----	----	----
15	.835	.63	6.63	11.4	19,000	3,140	.793	26,100	5,810	.801	1.39	1.160	----	----	----
16	.635	.62	6.64	26.7	14,700	4,820	.737	21,000	2,480	.864	1.44	1.527	----	----	----
17	.970	.62	6.79	12.9	29,900	6,060	.816	29,600	5,120	.871	1.42	1.103	----	----	----
18	.656	.61	6.82	27.9	17,400	2,860	.777	20,800	6,620	.886	1.62	1.231	----	----	----
31	1.62	.65	6.71	14.5	41,600	27,800	.836	49,300	7,720	.833	1.47	----	----	----	----

for 0.32-mm sand in 2-foot-wide flume

Run	Mean velocity V (ft per sec)	Velocity profile		Shear velocity V_* (ft per sec)	Bed-material discharge		Kinematic viscosity $\times 10^5$ ν (sq ft per sec)	Shear stress at bed τ (lb per sq ft)	Reynolds number $\times 10^{-2}$ R	Froude number F	Resistance factor			Bed configuration
		Slope B	Intercept C		Sampled suspended q_s (lb per sec per ft)	Total q_t (lb per sec per ft)					Darcy-Weisbach f	Chezy $C/\sqrt{g}$	Manning n ($ft^{1/6}$)	
(1)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)
1	0.90	--------	--------	0.048	0	0	1.41	0.045	325	0.22	0.0227	18.7	0.012	Plane.
2	.86	--------	--------	.053	0	0	1.00	.0055	447	.21	.0305	16.2	.015	Do.
3	1.24	0.49	2.00	.139	0	.0023	1.39	.038	482	.30	.101	8.9	.027	Ripples.
4	1.24	.70	1.88	.122	0	.0025	.91	.029	736	.30	.0777	10.1	.023	Do.
30	1.39	--------	--------	.142	.0012	.0045	1.24	.039	639	.32	.0835	9.8	.024	Do.
29	1.43	--------	--------	.136	.00045	.0058	.80	.036	1,001	.34	.0724	10.5	.023	Dune.
5	1.72	2.14	7.18	.158	.0034	.0136	1.40	.049	688	.41	.0677	10.9	.022	Do.
6	1.62	2.10	6.91	.150	.0020	.0101	.92	.043	1,039	.37	.0683	10.8	.022	Do.
27	2.01	--------	--------	.166	.0122	.033	1.26	.053	925	.47	.0518	12.1	.019	Do.
28	1.85	--------	--------	.208	.0183	.057	.79	.084	1,475	.41	.101	8.9	.027	Do.
26	1.93	--------	--------	.214	.0069	.073	1.30	.089	1,054	.40	.0986	9.0	.028	Do.
25	2.05	--------	--------	.211	.0231	.061	.81	.087	1,670	.44	.0849	9.7	.025	Do.
21	2.74	.88	4.05	.185	.0195	.090	1.32	.067	1,204	.63	.0366	14.8	.016	Transition.
22	2.48	--------	--------	.185	.049	.114	.80	.066	1,984	.55	.0445	13.4	.018	Do.
24	2.39	--------	--------	.202	.034	.078	1.34	.079	1,320	.49	.0573	11.8	.021	Do.
23	2.43	--------	--------	.248	.025	.126	.81	.119	2,190	.50	.0830	9.8	.025	Do.
7	2.95	1.87	4.82	.191	.021	.156	1.34	.071	1,321	.67	.0335	15.4	.016	Do.
8	2.48	.84	4.11	.212	.028	.20	.92	.087	1,941	.52	.0585	11.7	.021	Do.
20	4.23	2.00	6.76	.313	.22	.81	1.31	.194	1,776	1.00	.0448	13.4	.018	Antidune.
19	4.18	3.75	7.50	.273	.107	.63	.90	.146	2,601	.98	.0425	15.3	.016	Plane.
10	4.12	1.70	6.22	.367	.31	.79	1.55	.261	1,568	.95	.0635	11.2	.021	Antidune.
9	4.35	2.91	7.26	.298	.22	.84	1.00	.172	2,436	1.02	.0375	14.6	.016	Do.
12	4.03	1.51	5.80	.314	.25	.67	1.51	.191	1,788	.87	.0484	12.8	.019	Plane.
11	4.51	2.13	6.78	.281	.31	.89	.98	.153	2,761	1.03	.0310	16.1	.015	Antidune.
14	4.86	--------	--------	.408	.97	2.24	1.32	.324	2,209	1.11	.0567	11.9	.020	Do.
13	4.84	--------	--------	.376	.38	1.59	.84	.273	3,457	1.10	.0510	12.9	.013	Do.
15	5.36	--------	--------	.412	4.00	5.49	1.36	.328	2,483	1.19	.0475	13.0	.019	Do.
16	5.42	--------	--------	.357	3.08	4.40	.93	.246	3,613	1.21	.0348	15.2	.016	Do.
17	5.58	--------	--------	.440	6.45	6.38	1.30	.375	2,661	1.25	.0497	12.7	.019	Do.
18	5.73	--------	--------	.359	3.79	4.53	.90	.250	3,884	1.29	.0314	16.0	.015	Do.
31	5.27	--------	--------	.580	8.89	10.54	1.25	.660	2,740	1.15	.0980	9.1	.027	Chute-pool.

TABLE 8.—*Experimental variables and parameters*

Run	Slope ×10² S	Depth D (ft)	Water discharge Q (cu ft per sec)	Temperature T (° C)	Suspended concentration: Sampled C_s (ppm)	Suspended concentration: Standard deviation C_s (ppm)	Suspended concentration: Particle size d_{50} (ft×10³)	Total bed-material discharge: Concentration C_t (ppm)	Total bed-material discharge: Standard deviation C_t (ppm)	Total bed-material discharge: Particle size d_{50} (ft×10³)	Total bed-material discharge: Gradation σ	Bed material particle size d_{50} (ft×10³)	Sand waves: Length L (ft)	Sand waves: Height H_s (ft)	Sand waves: Velocity V_s (ft per min)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
7	0.025	0.50	1.12	20.2	0	0	---------	0	0	---------	---------	---------	---------	---------	---------
8	.087	.50	1.00	20.0	0	0	---------	6.6	2.3	1.000	1.52	1.049	0.8	0.02	0.01
5	.088	.49	1.12	20.0	15	3.5	0.610	47	17	.912	1.68	1.075	.9	.04	.05
11	.102	.52	1.41	20.1	54	5.6	.475	142	8.9	1.009	1.73	1.163	2.3	.05	.10
10	.213	.49	1.69	20.0	568	258	1.016	460	129	1.033	1.50	1.163	2.8	.06	.19
6	.240	.52	1.96	20.0	323	50	.617	732	160	.951	1.53	1.016	3.8	.13	.27
4	.270	.49	3.29	20.0	648	70	---------	2,210	426	.969	1.57	1.020	---------	---------	---------
1	.290	.51	4.01	20.0	393	8.5	---------	3,090	397	1.085	1.18	1.115	---------	---------	---------
9	.320	.52	2.62	19.8	2,070	306	.934	1,960	368	.918	1.50	1.082	4.4	.14	.43
12	.350	.51	4.24	20.0	625	80	.844	3,280	240	1.113	1.25	1.180	---------	---------	---------
13	.620	.50	4.42	20.3	761	171	1.050	4,990	386	1.180	1.25	1.120	---------	---------	---------
2	.800	.50	4.66	20.0	5,140	978	.945	7,110	1,100	1.115	1.26	1.016	5.5	.14	---------
3	.910	.52	5.40	20.3	11,000	1,780	.928	18,400	2,530	.990	1.36	1.049	6.1	.23	---------
14	1.14	.52	6.04	19.9	15,300	2,760	.885	18,400	1,970	1.015	1.46	1.082	---------	---------	---------

TABLE 9.—*Experimental variables and parameters*

Run	Slope ×10² S	Depth D (ft)	Water discharge Q (cu ft per sec)	Temperature T (° C)	Suspended concentration: Sampled C_s (ppm)	Suspended concentration: Standard deviation C_s (ppm)	Suspended concentration: Particle size d_{50} (ft×10³)	Total bed-material discharge: Concentration C_t (ppm)	Total bed-material discharge: Standard deviation C_t (ppm)	Total bed-material discharge: Particle size d_{50} (ft×10³)	Total bed-material discharge: Gradation σ	Bed material particle size d_{50} (ft×10³)	Sand waves: Length L (ft)	Sand waves: Height H_s (ft)	Sand waves: Velocity V_s (ft per min)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
11A	0.022	0.50	1.06	18.3	0	0	---------	0	0	---------	---------	---------	---------	---------	---------
11B	.027	.50	1.25	18.5	0	0	---------	0	0	---------	---------	---------	---------	---------	---------
16	.029	.50	1.05	20.5	0	0	---------	3.5	1.5	0.449	1.90	1.015	0.41	0.02	0.004
6	.047	.51	1.06	22.5	0	0	---------	12	1.7	.443	2.96	.950	.50	.03	.004
5	.063	.52	1.46	22.6	8.1	3.8	---------	85	11	.985	2.14	1.100	.29	.005	.017
1	.097	.50	1.95	22.1	217	---------	0.282	507	137	.575	2.25	1.050	---------	---------	---------
10	.117	.48	1.69	23.4	56	9.9	.335	452	100	.453	2.03	1.170	---------	---------	---------
8	.120	.51	2.11	24.1	372	178	.373	1,030	345	.482	2.31	1.445	4.0	.15	.21
9	.143	.52	2.46	23.0	888	298	.429	1,520	534	.459	2.20	1.335	4.6	.15	.35
7	.163	.53	2.32	23.2	370	19	.370	1,220	391	.540	2.49	1.408	3.4	.12	.21
2	.188	.52	2.62	22.1	1,240	75	.354	2,790	542	.423	2.12	1.110	5.8	.08	.54
3	.343	.52	3.34	21.9	3,370	1,550	.459	4,320	504	.443	1.99	1.016	3.6	.03	.89
4	.433	.51	4.00	21.8	2,560	270	.420	5,100	824	.738	2.12	.950	---------	---------	---------
12	.447	.49	4.60	21.6	3,610	410	.478	7,900	603	.689	2.38	.985	---------	---------	---------
13	.695	.49	5.38	19.6	6,130	64	.443	15,100	1,100	.502	2.68	.919	4.4	.12	---------
15	.910	.52	6.46	19.6	8,820	80	.459	22,500	7,000	.557	2.20	1.082	8.3	.18	---------
14	.980	.51	6.04	19.6	3,770	73	.452	14,600	2,280	.715	2.50	1.147	4.2	.05	---------

for 0.33-mm (uniform) sand in 2-foot-wide flume

Run	Mean velocity V (ft per sec)	Velocity profile		Shear velocity V_* (ft per sec)	Bed-material discharge		Kinematic viscosity $\times 10^5$ ν (sq ft per sec)	Shear stress at bed τ (lb per sq ft)	Reynolds number $\times 10^{-2}$ R	Froude number F	Resistance factor			Bed configuration
		Slope B	Intercept C		Sampled suspended q_s (lb per sec per ft)	Total q_t (lb per sec per ft)					Darcy-Weisbach f	Chezy $C/\sqrt{g}$	Manning n ($ft^{1/6}$)	
(1)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)
7	1.14	----------	----------	0.063	0	0	1.08	0.0078	528	0.28	0.0248	18.0	0.013	Plane.
8	1.02	0.45	1.40	.118	0	.00021	1.08	.027	472	.25	.1076	8.6	.027	Ripple.
5	1.17	.70	1.90	.118	.00052	.0017	1.08	.027	531	.29	.0811	9.9	.023	Do.
11	1.38	----------	----------	.129	.0024	.0064	1.08	.032	664	.34	.0703	10.7	.022	Dune.
10	1.76	----------	----------	.182	.0300	.025	1.08	.064	799	.44	.0855	9.7	.024	Do.
6	1.92	----------	----------	.200	.0198	.046	1.08	.078	924	.47	.0871	9.6	.025	Do.
4	3.43	----------	----------	.206	.066	.23	1.08	.083	1,556	.86	.0289	16.6	.014	Transition.
1	4.02	1.10	5.00	.218	.049	.39	1.08	.092	1,898	.99	.0236	18.4	.013	Plane.
9	2.57	----------	----------	.231	.169	.16	1.09	.104	1,226	.63	.0648	11.1	.021	Dune.
12	4.24	----------	----------	.240	.083	.44	1.08	.111	2,002	1.05	.0256	17.7	.013	Plane.
13	4.52	----------	----------	.316	.105	.70	1.07	.193	2,112	1.13	.0391	14.3	.016	Antidune.
2	4.76	----------	----------	.359	.75	1.06	1.08	.250	2,204	1.19	.0454	13.3	.018	Do.
3	5.30	----------	----------	.390	1.86	3.16	1.07	.295	2,576	1.30	.0434	13.6	.017	Do.
14	5.93	----------	----------	.437	2.88	3.54	1.08	.370	2,855	1.45	.0434	13.6	.017	Do.

for 0.33-mm (graded) sand in 2-foot-wide flume

Run	Mean velocity V (ft per sec)	Velocity profile		Shear velocity V_* (ft per sec)	Bed-material discharge		Kinematic viscosity $\times 10^5$ ν (sq ft per sec)	Shear stress at bed τ (lb per sq ft)	Reynolds number $\times 10^{-2}$ R	Froude number F	Resistance factor			Bed configuration
		Slope B	Intercept C		Sampled suspended q_s (lb per sec per ft)	Total q_t (lb per sec per ft)					Darcy-Weisbach f	Chezy $C/\sqrt{g}$	Manning n ($ft^{1/6}$)	
(1)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)
11A	1.08	----------	----------	0.059	0	0	1.13	0.0069	477	0.27	0.0243	18.16	0.013	Plane.
11B	1.28	----------	----------	.066	0	0	1.12	.0084	569	.32	.0212	19.42	.012	Do.
16	1.07	0.093	1.24	.068	0	.00012	1.07	.0090	501	.27	.0326	15.67	.015	Ripples.
6	1.06	.088	.65	.088	0	.00041	1.02	.015	531	.26	.0549	12.07	.019	Do.
5	1.43	.52	1.60	.103	.00036	.0040	1.02	.020	731	.35	.0412	13.93	.017	Do.
1	1.99	.91	.97	.125	.013	.031	1.03	.030	968	.50	.0315	15.93	.015	Dune.
10	1.80	.68	2.80	.134	.0029	.024	1.00	.035	865	.46	.0446	13.39	.017	Do.
8	2.11	.52	2.40	.140	.024	.069	.98	.038	1,094	.52	.0354	15.04	.016	Do.
9	2.42	.74	2.58	.155	.068	.12	1.01	.046	1,248	.59	.0327	15.65	.015	Do.
7	2.23	.41	2.00	.167	.027	.090	1.00	.054	1,177	.54	.0447	13.38	.018	Do.
2	2.57	.86	3.60	.177	.101	.23	1.03	.061	1,300	.63	.0381	14.49	.016	Transition.
3	3.27	1.17	4.15	.240	.35	.46	1.03	.111	1,648	.80	.0430	13.65	.017	Do.
4	4.00	.95	5.00	.267	.32	.65	1.04	.138	1,971	.99	.0355	15.01	.016	Plane.
12	4.79	2.08	6.70	.265	.52	1.16	1.04	.137	2,259	1.21	.0246	18.05	.013	Standing waves.
13	5.61	----------	----------	.331	1.03	2.59	1.09	.212	2,515	1.41	.0278	16.95	.014	Antidunes.
15	6.34	----------	----------	.390	1.78	4.63	1.09	.295	3,019	1.55	.0303	16.25	.014	Do.
14	6.05	----------	----------	.401	.71	2.81	1.09	.312	2,823	1.49	.0351	15.08	.016	Do.

TABLE 10.—*Experimental variables and parameters*

Run	Slope ×10² S	Depth D (ft)	Water discharge Q (cu ft per sec)	Temperature T (° C)	Suspended concentration: Fine Material C_f (ppm)	Suspended concentration: Sampled C_s (ppm)	Suspended concentration: Particle size d_{50} (ft×10³)	Total bed-material discharge: Concentration C_t (ppm)	Total bed-material discharge: Standard deviation C_t (ppm)	Total bed-material discharge: Particle size d_{50} (ft×10³)	Total bed-material discharge: Gradation σ	Bed material particle size d_{50} (ft×10³)	Sand waves: Length L (ft)	Sand waves: Height H_s (ft)	Sand waves: Velocity V_s (ft per min)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
[a] 46	0.084	1.11	14.54	13.1	---	---	---	181	28	---	---	---	6.0	0.41	---
[a] 47	.042	.75	9.59	11.5	---	0	---	23	15	1.141	1.85	---	8.2	.22	0.035
[a] 48	.052	1.23	15.26	11.5	---	0	---	59	11	1.148	1.85	---	6.2	.32	.030
[a] 49	.173	1.33	21.32	11.0	---	---	---	585	169	.823	1.96	---	7.3	.35	.080
85	.047	.78	7.11	12.7	0	0	---	6.0	4.9	1.364	1.66	1.502	1.2	.07	.0074
86	.046	.76	6.92	17.0	4,800	4,070	---	1.6	.3	.249	3.19	1.437	1.0	.06	.0033
87	.046	.75	6.96	19.1	8,400	7,100	---	2.3	1.4	.210	4.37	1.521	.9	.06	.0055
88	.049	.74	7.10	18.3	11,400	10,000	---	2.5	1.2	.417	3.04	1.640	1.0	.07	.0015
[b] 90	.053	.60	6.97	17.1	6,950	6,690	---	37	6.2	1.345	1.70	1.355	1.6	.06	.027
[b] 89	.065	.60	7.08	18.5	9,000	7,490	---	31	8	1.361	2.50	1.509	1.6	.06	.030
93	.072	.62	7.20	14.7	1	53	---	99	21	1.482	1.55	1.742	6.0	.17	.039
92	.090	.63	7.14	18.5	6,070	5,350	---	106	52	1.509	1.93	1.619	4.6	.25	.050
91	.117	.58	7.12	18.0	8,400	8,050	---	195	44	1.443	1.90	1.610	4.3	.25	.084
82	.248	.64	8.16	23.2	133	235	---	429	98	1.463	1.64	1.679	4.1	.28	.17
51	.236	.62	8.11	13.1	584	553	---	545	145	1.351	1.66	---	5.6	.20	.19
52	.222	.55	8.01	16.0	1,620	1,830	---	578	137	1.456	1.63	1.417	5.3	.26	.18
73	.222	.61	8.20	20.7	5,670	8,670	---	662	138	1.509	1.83	1.565	5.4	.29	.26
74	.215	.65	8.18	21.0	7,970	23,800	---	534	151	1.420	2.08	1.627	5.5	.34	.17
76	.203	.63	8.49	20.0	9,330	9,520	---	463	122	1.387	2.00	1.456	5.7	.30	.16
75	.204	.64	8.24	21.2	9,460	22,900	---	625	184	1.574	1.84	1.443	4.4	.28	1.5
53	.235	.57	8.01	17.2	10,700	2,750	---	571	191	1.361	1.65	1.564	5.8	.34	.11
77	.199	.65	8.76	19.1	12,500	22,900	---	639	154	1.246	2.91	1.581	5.1	.29	.091
96	.201	.53	8.31	18.6	25,000	28,600	---	761	135	1.066	2.66	1.588	4.3	.24	.20
94	.237	.81	11.30	13.5	7	56	---	480	146	1.404	1.77	1.624	5.2	.32	.28
83	.200	.91	15.58	16.2	0	503	---	588	170	1.151	1.74	1.633	5.8	.43	.16
54	.240	.92	15.36	16.6	1,940	2,590	---	657	271	1.253	1.74	1.469	6.5	.41	.33
56	.242	.90	15.36	22.1	2,860	---	---	1,100	466	1.148	1.70	---	5.3	.29	.20
55	.237	.94	15.36	18.5	4,060	3,140	---	765	202	1.164	1.88	1.692	5.9	.27	.23
57	.259	.87	15.39	21.3	4,320	5,010	---	761	204	1.325	1.91	1.518	5.1	29	.29
58	.233	.90	15.28	20.1	5,270	4,220	---	807	204	1.210	1.94	1.535	5.4	.26	.21
95	.180	.80	15.38	18.7	28,300	43,400	---	1,640	239	1.099	2.42	1.771	8.6	.33	.31
78	.320	.72	11.52	20.3	12,000	13,300	---	1,510	310	1.089	2.88	1.453	7.4	.39	.34
59	.326	.65	15.36	21.7	4,570	5,820	---	2,920	820	1.312	1.73	1.535	7.50	.07	.72
60	.342	.62	21.35	21.1	3,600	4,390	---	3,290	457	1.427	1.64	1.699	---	---	---
61	.355	.61	21.32	23.2	6,170	7,910	---	3,390	564	1.440	1.68	1.722	---	---	---
71	.531	.32	8.22	21.4	3,600	3,040	---	5,250	1,178	1.525	1.68	1.673	---	---	---
72	.550	.32	8.26	20.2	7,100	7,490	---	5,680	261	1.505	1.55	1.588	---	---	---
70	.640	.30	8.14	20.2	3,910	3,840	---	6,310	156	1.476	1.60	1.515	---	---	---
63	.570	.43	15.50	21.2	3,020	4,540	---	5,360	358	1.633	1.60	1.535	3.4	.23	---
64	.578	.41	15.61	21.2	6,440	8,400	---	5,480	302	1.630	1.60	1.601	3.4	.20	---
65	.571	.42	15.60	21.6	9,090	11,600	---	5,160	445	1.584	1.64	1.506	3.4	.20	---
66	.575	.45	15.52	23.0	12,300	16,600	---	5,130	836	1.647	1.76	1.526	3.3	.20	---
80	.643	.39	15.27	21.8	12,100	14,000	---	7,140	37	1.624	1.76	1.594	3.4	.26	---
81	.634	.55	21.35	10.7	7	3,380	---	4,480	672	2.076	1.61	1.584	4.4	.04	---
62	.622	.54	21.23	24.5	4,790	7,320	---	4,490	428	2.030	1.54	1.647	---	---	---
67	.646	.53	20.87	22.7	11,200	11,400	---	4,390	202	1.994	1.57	1.620	4.0	.10	---
79	.651	.55	21.31	21.0	12,400	15,200	---	5,760	1,038	2.204	1.82	1.355	3.9	.08	---
84	.740	.41	15.36	15.0	7	3,700	---	7,100	135	1.410	1.39	1.640	3.6	.21	---
69	.734	.43	15.54	22.4	7,020	9,890	---	8,280	782	1.601	1.71	1.430	3.7	.26	---
98	.821	.44	15.80	19.0	42,000	57,700	---	17,700	2,620	1.237	1.90	1.440	3.1	.24	---
68	.740	.53	20.94	23.5	7,620	12,400	---	6,760	461	2.181	1.55	1.738	4.0	.05	---
100	.790	.51	21.42	13.3	106	4,240	---	8,440	681	2.322	1.40	1.561	---	---	---
99	.806	.50	21.27	19.6	26,900	42,300	---	16,100	2,000	1.361	1.93	1.492	4.0	.31	---
97	.960	.37	12.01	19.5	5,800	6,300	---	8,960	2,310	2.165	1.50	1.597	3.4	.16	---

[a] Run made to supply missing slope and depth data in the 0.45-mm set.
[b] Bed stabilized by bentonite.
[c] Computed on the basis of kinematic viscosity for distilled water.

for 0.47-mm sand in 8-foot-wide flume

Run	Mean velocity V (ft per sec)	Velocity profile		Shear velocity V_* (ft per sec)	Bed-material discharge		Kinematic viscosity $\times 10^5$ ν (sq ft per sec)	Shear stress at bed τ (lb per sq ft)	Reynolds number $\times 10^{-3}$ R_e	Froude number F	Resistance factor			Bed configuration
		Slope B	Intercept C		Sampled suspended q_s (lb per sec per ft)	Total q_t (lb per sec per ft)					Darcy-Weisbach f	Chezy $C/\sqrt{g}$	Manning n ($ft^{1/6}$)	
(1)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)
[a] 46	1.64	0.50	1.97	0.173	----	0.021	1.30	0.058	1,400	0.27	0.0893	9.5	0.028	Dunes.
[a] 47	1.60	.43	1.94	.101	0	.0017	1.36	.020	882	.33	.0317	15.9	.016	Do.
[a] 48	1.55	.30	1.91	.144	0	.0070	1.36	.040	1,402	.25	.0686	10.8	.025	Do.
[a] 49	2.00	----	----	.272	----	.098	1.38	.144	1,928	.31	.1482	7.4	.038	Do.
85	1.13	.52	1.51	.109	0	.00033	1.31	.023	673	.23	.0740	10.4	.024	Ripple.
86	1.14	.56	1.50	.107	.22	.0000087	1.32	.022	741	.23	.0693	10.7	.024	Do.
87	1.16	.53	1.46	.105	.38	.000:2	1.37	.022	784	.24	.0660	11.0	.023	Do.
88	1.20	.64	1.52	.108	.56	.00014	1.50	.023	786	.25	.0649	11.1	.023	Do.
[b] 90	1.45	.59	1.97	.101	.36	.0020	1.39	.020	744	.33	.0390	14.3	.017	Do.
[b] 89	1.47	.62	1.81	.113	.41	.0017	1.42	.024	788	.33	.0465	13.1	.018	Do.
93	1.45	.46	2.05	.120	.0030	.0056	1.24	.028	725	.32	.0547	12.1	.020	Dunes.
92	1.43	.82	1.94	.135	.30	.0059	1.33	.035	804	.32	.0714	10.6	.023	Do
91	1.53	.71	1.96	.148	.45	.0108	1.42	.042	778	.35	.0747	10.4	.023	Do.
82	1.60	.56	2.20	.226	.015	.027	1.00	.099	1,024	.35	.1597	7.1	.034	Do.
51	1.62	.53	2.40	.217	.035	.034	1.28	.091	785	.36	.1436	7.5	.032	Do.
52	1.81	.42	2.30	.198	.114	.036	1.26	.076	833	.43	.0960	9.1	.026	Do.
73	1.67	----	----	.209	.55	.042	1.24	.085	961	.38	.1251	8.0	.030	Do.
74	1.58	.38	2.33	.212	1.52	.034	1.31	.087	978	.35	.1442	7.4	.033	Do.
76	1.69	.37	2.50	.203	.63	.031	1.38	.080	986	.38	.1153	8.3	.029	Do.
75	1.60	----	----	.205	1.47	.040	1.36	.081	975	.35	.1314	7.8	.031	Do.
53	1.77	.71	2.42	.208	.172	.036	1.52	.084	870	.41	.1101	8.5	.028	Do.
77	1.68	----	----	.204	1.57	.044	1.52	.081	984	.37	.1181	8.2	.030	Do.
96	1.94	.68	2.84	.185	1.85	.049	1.93	.066	918	.47	.0729	10.5	.023	Do.
94	1.74	----	----	.249	.0049	.042	1.28	.120	1,101	.34	.1633	7.0	.036	Do.
83	2.14	.65	2.50	.242	.072	.071	1.19	.114	1,636	.40	.1024	8.8	.029	Do.
54	2.08	----	----	.267	.31	.079	1.25	.138	1,622	.38	.1315	7.8	.033	Do.
56	2.14	1.36	3.03	.265	----	.132	1.11	.136	1,870	.40	.1225	8.1	.032	Do.
55	2.04	----	----	.268	.38	.092	1.26	.139	1,348	.37	.1378	7.6	.034	Do.
57	2.20	1.55	2.94	.269	.60	.092	1.19	.141	1,823	.42	.1199	8.2	.031	Do.
58	2.11	.47	2.83	.260	.50	.096	1.25	.131	1,758	.39	.1213	8.1	.032	Do.
95	2.39	1.30	2.89	.215	5.21	.197	2.03	.090	1,707	.47	.0649	11.1	.023	Do.
78	2.00	.76	3.18	.272	1.19	.136	1.41	.144	1,346	.42	.1484	7.3	.034	Do.
59	2.96	1.51	4.75	.261	.70	.35	1.20	.132	1,850	.65	.0623	11.3	.022	Transition.
60	4.28	2.52	6.05	.261	.73	.55	1.18	.132	2,503	.96	.0298	16.4	.015	Plane.
61	4.36	1.80	5.90	.264	1.32	.56	1.20	.135	2,660	.98	.0293	16.5	.015	Do.
71	3.21	1.90	5.43	.234	.195	.34	1.18	.106	988	1.00	.0425	13.7	.016	Do.
72	3.26	1.87	5.20	.238	.48	.37	1.31	.110	966	1.02	.0427	13.1	.016	Do.
70	3.41	1.35	5.21	.249	.24	.40	1.20	.120	947	1.10	.0425	13.7	.016	Do.
63	4.48	2.77	6.53	.281	.55	.65	1.16	.153	1,835	1.20	.0315	16.0	.014	Antidune.
64	4.76	1.95	6.26	.276	1.02	.67	1.26	.148	1,859	1.31	.0269	17.2	.013	Do.
65	4.63	3.20	6.83	.278	1.41	.63	1.34	.150	1,870	1.26	.0288	16.7	.014	Do.
66	4.34	3.02	6.53	.289	2.00	.62	1.38	.161	1,934	1.14	.0354	15.0	.015	Do.
80	4.91	1.20	5.45	.284	1.67	.85	1.43	.156	1,841	1.39	.0268	17.3	.013	Do.
81	4.85	2.27	7.17	.335	.56	.75	1.38	.218	1,933	1.15	.0382	14.5	.016	Standing wave.
62	4.89	2.35	7.13	.329	1.21	.74	1.12	.210	2,694	1.17	.0362	14.9	.016	Do.
67	4.91	2.20	6.67	.332	1.85	.71	1.36	.214	2,551	1.19	.0366	14.8	.016	Do.
79	4.82	2.60	7.30	.340	2.53	.96	1.46	.223	2,525	1.15	.0397	14.2	.017	Do.
84	4.67	2.40	7.10	.313	.44	.85	1.23	.189	1,557	1.29	.0358	14.9	.015	Antidune.
69	4.48	----	----	.319	1.20	1.00	1.24	.197	1,889	1.20	.0405	14.0	.016	Do.
98	4.51	----	----	.341	7.11	2.18	2.46	.225	1,788	1.20	.0457	13.2	.017	Do.
68	4.95	2.20	7.43	.355	2.02	1.10	1.23	.245	2,624	1.20	.0412	13.9	.017	Standing wave.
100	5.28	2.69	7.94	.360	.71	1.41	1.29	.251	2,087	1.30	.0372	14.7	.016	Plane.
99	5.32	4.46	9.41	.360	7.02	2.67	1.96	.251	2,440	1.33	.0367	14.8	.016	Antidune.
97	4.07	3.21	7.69	.338	.59	.84	1.29	.221	1,369	1.18	.0552	12.0	.019	Do.

TABLE 11.—*Experimental variables and parameters*

Run	Slope ×10² S	Depth D (ft)	Water discharge Q (cu ft per sec)	Temperature T (° C)	Suspended concentration: Fine material C_f (ppm)	Suspended concentration: Sampled C_s (ppm)	Suspended concentration: Particle size d_{50} (ft×10³)	Total bed-material discharge: Concentration C_t (ppm)	Total bed-material discharge: Standard deviation C_t (ppm)	Total bed-material discharge: Particle size d_{50} (ft×10³)	Total bed-material discharge: Gradation σ	Bed material particle size d_{50} (ft×10³)	Sand waves: Length L (ft)	Sand waves: Height H_s (ft)	Sand waves: Velocity V_s (ft per min)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
1	0.016	0.61	1.06	15.9	0	---------	---------	0	0	---------	---------	---------	---------	---------	---------
2	.019	.60	1.12	17.4	0	---------	---------	0	0	---------	---------	---------	---------	---------	---------
3	.026	.62	1.21	16.9	0	---------	---------	.6	.2	---------	---------	1.585	0.5	0.03	0.0001
4	.038	.59	1.59	18.0	0	---------	---------	17	5.8	1.647	1.34	1.526	---------	.10	.0004
6	.170	.72	2.45	18.6	0	---------	---------	387	124	1.539	1.66	1.640	4.6	.35	.0047
5	.201	.81	3.12	19.2	0	---------	---------	408	217	1.499	1.60	1.575	5.0	.26	.0080
20	.338	.72	4.74	20.2	0	---------	---------	2,620	785	1.621	1.52	1.716	4.3	.17	.036
8	.351	.78	3.82	18.9	0	---------	---------	1,200	370	1.585	1.55	1.903	3.6	.23	.012
8A	.331	.84	3.82	18.7	5,740	---------	---------	1,050	---------	1.417	1.58	1.699	3.8	.20	.012
8E	.248	.88	3.69	23.3	14,500	---------	---------	720	194	1.673	1.47	1.968	3.6	.19	.0073
8B	.293	.85	3.84	21.5	20,600	---------	---------	904	362	1.483	1.67	1.949	3.6	.20	.010
8C	.294	.86	3.83	22.4	24,300	---------	---------	1,100	349	1.594	1.75	1.772	4.4	.24	.011
8D	.198	.72	3.77	25.0	63,700	---------	---------	521	78	1.787	2.92	1.706	---------	---------	---------
7	.388	.72	3.42	20.6	0	---------	---------	1,250	415	2.224	1.55	1.804	3.3	.17	.012
14	.399	.89	4.77	19.3	0	---------	---------	1,790	475	1.667	1.45	1.903	4.0	.20	.021
14A	.366	.82	4.78	24.3	9,580	---------	---------	1,970	697	1.532	1.64	1.837	5.8	.20	.030
14C	.377	.87	4.80	22.2	22,400	---------	---------	1,950	556	1.739	1.64	1.837	5.8	.19	.034
14B	.339	.70	4.84	22.3	44,100	---------	---------	2,960	316	1.296	2.91	1.837	---------	---------	---------
19	.408	.76	3.82	21.5	0	---------	---------	1,200	323	1.463	1.56	1.788	4.2	.16	.018
9	.433	.72	4.16	17.7	0	---------	---------	1,520	404	1.421	---------	1.549	4.2	.18	.022
10	.486	.64	5.33	20.3	0	---------	---------	2,690	945	1.706	---------	1.824	---------	---------	---------
15	.551	.74	6.94	21.7	0	---------	---------	3,330	416	1.821	1.53	1.732	---------	---------	---------
15A	.550	.75	6.99	22.5	14,200	---------	---------	4,350	350	1.519	1.88	1.854	---------	---------	---------
15B	.537	.75	6.96	23.7	40,900	---------	---------	4,710	449	1.476	3.17	1.837	---------	---------	---------
15C	.628	.73	6.99	24.0	58,600	---------	---------	7,640	1,330	1.247	2.69	1.722	---------	---------	---------
13	.565	.72	6.37	18.1	0	---------	---------	3,350	299	1.847	1.60	1.713	---------	---------	---------
11	.768	.66	7.48	19.9	0	---------	---------	5,690	931	2.067	1.46	1.509	---------	---------	---------
18	.520	.71	7.62	22.6	0	---------	---------	3,330	717	1.870	1.61	1.870	---------	---------	---------
18A	.508	.76	7.57	22.5	13,200	---------	---------	3,400	349	1.804	1.62	1.837	---------	---------	---------
18B	.790	.69	7.59	23.3	37,900	---------	---------	9,730	3,990	1.558	1.61	1.837	---------	---------	---------
18C	.900	.70	7.59	23.7	58,700	---------	---------	22,300	5,420	1.421	1.40	1.919	---------	---------	---------
16A	.980	.67	7.82	23.5	11,200	---------	---------	5,600	520	2.198	1.33	---------	---------	---------	---------
16B	1.075	.66	7.84	25.0	31,500	---------	---------	10,300	1,720	1.496	1.73	1.713	---------	---------	---------
16C	1.305	.65	7.86	25.1	44,500	---------	---------	15,800	1,940	1.132	2.22	1.837	---------	---------	---------
17	1.175	.65	7.89	22.5	0	---------	---------	9,180	945	1.460	1.74	1.690	---------	---------	---------
17A	1.365	.65	7.83	22.3	39,600	---------	---------	21,800	2,400	1.214	1.63	1.837	---------	---------	---------
17B	1.928	.68	7.86	24.0	51,900	---------	---------	50,000	1,900	1.460	1.30	2.100	---------	---------	---------
12	1.438	.64	7.84	16.9	0	---------	---------	26,000	10,300	1.486	1.74	1.847	---------	---------	---------

[a] Computed on the basis of kinematic viscosity for distilled water.

for 0.54-mm sand in 2-foot-wide flume

Run	Mean velocity V (ft per sec)	Velocity profile		Shear velocity V_* (ft per sec)	Bed-material discharge		Kinematic viscosity $\times 10^5$ ν (sq ft per sec)	Shear stress at bed τ (lb per sq ft)	Reynolds number $\times 10^{-2}$ R^a	Froude number F	Resistance factor			Bed configuration
		Slope B	Intercept C		Sampled suspended q_s (lb per sec per ft)	Total q_t (lb per sec per ft)					Darcy-Weisbach f	Chezy $C/\sqrt{g}$	Manning n (ft $^{1/6}$)	
(1)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)
1	0.89	0.295	1.25	0.056	-----	0	1.20	0.0061	449	0.20	0.0315	16.0	0.015	Plane.
2	.96	.294	1.34	.061	-----	0	1.16	.0071	495	.22	.0320	15.8	.015	Do.
3	1.00	.422	1.45	.072	-----	.000023	1.17	.010	526	.22	.0413	13.9	.018	Ripple.
4	1.37	.428	1.95	.085	-----	.000864	1.14	.014	711	.31	.0309	16.1	.015	Do.
6	1.74	.825	3.13	.198	-----	.030	1.12	.076	1,115	.37	.1040	8.8	.028	Dune.
5	1.95	.645	2.62	.230	-----	.040	1.10	.102	1,438	.38	.1108	8.5	.030	Do.
20	3.36	.329	6.00	.280	-----	.40	1.08	.152	2,245	.70	.0555	12.0	.021	Transition.
8	2.51	.238	4.40	.297	-----	.146	1.11	.170	1,755	.50	.1117	8.5	.030	Dune.
8A	2.33	1.90	4.15	.299	-----	.128	1.31	.173	1,741	.45	.1313	7.8	.033	Do.
8E	2.15	-----	-----	.265	-----	.085	1.46	.136	1,884	.40	.1213	8.1	.032	Do.
8B	2.30	.98	3.64	.283	-----	.110	1.70	.155	1,878	.44	.1213	8.1	.032	Do.
8C	2.28	1.79	4.20	.285	-----	.134	1.79	.158	1,914	.43	.1249	8.0	.032	Do.
8D	2.65	-----	-----	.215	-----	.063	3.20	.089	1,985	.55	.0524	12.4	.020	Transition.
7	2.44	.370	3.15	.299	-----	.136	1.06	.173	1,640	.51	.1200	8.2	.030	Dune.
14	2.74	-----	-----	.338	-----	.272	1.10	.221	2,207	.51	.1214	8.2	.032	Transition.
14A	2.95	-----	-----	.312	-----	.30	1.27	.188	2,480	.57	.0893	9.5	.027	Do.
14C	2.82	-----	-----	.325	-----	.298	1.74	.204	2,386	.53	.1060	8.7	.030	Do.
14B	3.51	-----	-----	.277	-----	.46	2.41	.149	2,413	.74	.0499	12.7	.020	Plane.
19	2.58	.99	4.16	.315	-----	.146	1.04	.192	1,871	.52	.1192	8.2	.031	Transition.
9	2.93	.85	3.91	.317	-----	.201	1.15	.195	1,841	.61	.0938	9.2	.027	Do.
10	4.30	2.88	6.88	.315	-----	.46	1.07	.193	2,545	.95	.0430	13.6	.018	Plane.
15	4.75	2.96	7.42	.363	-----	.74	1.04	.256	3,408	.97	.0468	13.1	.019	Standing waves.
15A	4.76	-----	-----	.365	-----	.97	1.47	.258	3,508	.97	.0470	13.0	.019	Do.
15B	4.73	2.13	6.90	.360	-----	1.04	2.27	.251	3,573	.96	.0464	13.1	.019	Do.
15C	4.85	-----	-----	.385	-----	1.70	2.98	.287	3,606	1.00	.0504	12.6	.020	Do.
13	4.52	3.34	7.51	.362	-----	.68	1.14	.254	2,862	.94	.0513	12.5	.020	Do.
11	5.80	4.38	8.40	.403	-----	1.36	1.08	.314	3,507	1.26	.0386	14.4	.017	Do.
18	5.44	1.78	6.60	.346	-----	.81	1.02	.231	3,814	1.14	.0323	15.7	.016	Do.
18A	5.11	-----	-----	.352	-----	.82	1.44	.240	3,796	1.04	.0379	14.5	.017	Do.
18B	5.62	-----	-----	.419	-----	2.35	1.70	.340	3,870	1.19	.0446	13.4	.018	Do.
18C	5.54	-----	-----	.450	-----	5.39	3.00	.392	3,894	1.17	.0527	12.3	.020	Antidune.
16A	5.92	-----	-----	.461	-----	1.39	1.35	.412	4,002	1.27	.0485	12.8	.019	Standing waves.
16B	6.03	-----	-----	.480	-----	2.57	1.93	.446	4,160	1.30	.0506	12.6	.020	Antidune.
16C	6.14	-----	-----	.524	-----	3.95	2.32	.532	4,168	1.34	.0582	11.7	.021	Do.
17	6.21	-----	-----	.495	-----	2.31	1.02	.475	3,949	1.36	.0509	12.5	.020	Do.
17A	6.17	-----	-----	.535	-----	5.43	2.27	.554	3,917	1.35	.0600	11.5	.021	Do.
17B	5.87	-----	-----	.651	-----	12.51	2.60	.820	4,060	1.25	.0983	9.0	.027	Do.
12	6.27	-----	-----	.543	-----	6.49	1.17	.571	3,400	1.39	.0599	11.6	.021	Do.

TABLE 12.—*Velocity-profile data for 0.19-mm sand in 8-foot-wide flume*

[The lateral section used for measuring was 95-115 ft. from the headbox. w.s.=water surface]

Run	2.0 ft from left wall of flume		4.0 ft from left wall of flume		6.0 ft from left wall of flume	
	Distance above sand bed (*ft*)	Velocity (fps)	Distance above sand bed (*ft*)	Velocity (fps)	Distance above sand bed (*ft*)	Velocity (fps)
24			0.936	w.s.		
			.910	1.24		
			.810	1.19		
			.710	1.15		
			.610	1.12		
			.510	1.10		
			.410	1.05		
			.310	1.05		
			.260	1.02		
			.210	1.02		
			.160	.97		
			.110	.94		
			.080	.91		
			.050	.86		
			.020	.76		
2	1.030	w.s.	1.025	w.s.	1.050	w.s.
	1.000	1.08	1.000	1.16	.983	1.11
	.800	1.11	.800	1.15	.783	1.10
	.600	1.08	.600	1.11	.583	1.03
	.400	.99	.400	1.03	.385	1.00
	.200	.87	.200	.96	.185	.84
	.100	.78	.100	.80	.085	.78
	.075	.78	.070	.69	.043	.75
	.050	.71	.050	.46	.023	.71
	.025	.68	.025	.35		
26			.274	w.s.		
			.250	1.05		
			.230	1.03		
			.190	1.00		
			.150	.98		
			.110	.93		
			.080	.90		
			.050	.84		
			.020	.77		
25	.909	w.s.	.890	w.s.	.912	w.s.
	.859	1.23	.864	1.26	.901	1.27
	.709	1.22	.764	1.22	.801	1.21
	.559	1.10	.614	1.13	.651	1.12
	.409	1.04	.464	1.13	.501	1.07
	.309	.98	.364	.99	.351	1.07
	.259	.94	.214	1.01	.251	.91
	.209	.88	.164	.87	.201	.92
	.159	.82	.114	.89	.151	.83
	.109	.78	.084	.81	.121	.76
	.079	.73	.054	.70	.091	.67
	.049	.69	.024	.68	.071	.62
	.019	.63			.051	.58
22C	.415	w.s.	.401	w.s.	.418	w.s.
	.390	.93	.375	1.11	.405	1.12
	.360	.84	.325	1.07	.305	1.03
	.310	.84	.275	1.01	.255	.99
	.260	.83	.225	.99	.205	.95
	.210	.83	.175	.96	.145	.92
	.160	.79	.125	.90	.105	.87
	.110	.77	.100	.88	.080	.79
	.085	.73	.075	.84	.055	.75
	.060	.70	.050	.77	.030	.69
	.035	.62	.010	.66	.010	.62
	.010	.58				
30	1.027	w.s.	.971	w.s.	.972	w.s.
	.988	1.52	.910	1.55	.940	1.48
	.818	1.53	.810	1.53	.870	1.52
	.718	1.55	.660	1.50	.720	1.39
	.618	1.49	.510	1.40	.570	1.43
	.518	1.41	.410	1.31	.420	1.30
	.418	1.32	.310	1.25	.320	1.19
	.318	1.24	.210	1.16	.220	1.06
	.218	1.16	.160	1.12	.150	.98
	.168	1.13	.110	.98	.100	.91
	.118	1.14	.070	.50	.060	.83
	.078	1.04			.030	.70
	.048	1.03				
	.018	.95				
1	.564	w.s.	.535	w.s.	.523	w.s.
	.547	.88	.506	1.15	.492	1.09
	.447	.76	.406	1.07	.392	1.09
	.347	.76	.306	.91	.292	.91
	.247	.68	.206	.91	.192	.84
	.197	.68	.156	.77	.142	.76
	.147	.58	.106	.77	.092	.80
	.097	.52	.056	.52	.042	.76
	.047	.52	.006	.38		
31	1.048	w.s.	1.028	w.s.	.976	w.s.
	1.020	1.82	.980	1.86	.910	1.85
	.950	1.82	.880	1.80	.810	1.83
	.850	1.76	.730	1.78	.710	1.77
	.750	1.74	.580	1.76	.560	1.71
31—Con.	0.650	1.64	0.480	1.60	0.410	1.61
	.550	1.61	.380	1.60	.310	1.56
	.450	1.53	.280	1.48	.210	1.41
	.350	1.34	.180	1.39	.160	1.30
	.250	1.20	.130	1.31	.110	1.23
	.200	1.14	.080	1.19	.070	1.15
	.150	1.11	.040	.97	.040	1.11
	.110	.88			.020	1.07
	.090	.64				
	.070	.40				
	.040	.31				
27	.479	w.s.	.516	w.s.	.517	w.s.
	.429	1.34	.472	1.35	.455	1.31
	.379	1.31	.422	1.31	.405	1.28
	.329	1.31	.372	1.28	.355	1.23
	.279	1.26	.322	1.23	.305	1.19
	.229	1.16	.272	1.19	.255	1.14
	.179	1.15	.222	1.15	.205	1.08
	.129	1.08	.192	1.06	.155	1.05
	.079	.93	.162	1.08	.105	.92
	.049	.84	.132	1.02	.075	.85
	.019	.80	.102	.92	.045	.85
			.072	.84	.015	.86
			.042	.66		
5	1.063	w.s.	1.028	w.s.		
	1.028	2.11	.998	2.00		
	.828	2.10	.798	2.02		
	.628	1.96	.598	1.92		
	.428	1.79	.398	1.74		
	.328	1.68	.298	1.68		
	.228	1.54	.198	1.50		
	.128	1.42	.148	1.43		
	.078	1.24	.098	1.24		
	.028	1.07	.073	1.19		
			.048	.93		
23	.372	w.s.	.371	w.s.	.365	w.s.
	.350	1.24	.344	1.32	.348	1.36
	.300	1.19	.294	1.29	.298	1.29
	.250	1.08	.244	1.25	.248	1.23
	.200	1.05	.194	1.16	.198	1.20
	.150	1.03	.144	1.12	.148	1.16
	.100	.92	.094	1.06	.098	1.12
	.075	.90	.069	1.02	.073	1.06
	.050	.82	.044	.98	.048	1.03
	.025	.79	.019	.90	.023	.98
32	.868	w.s.	.922	w.s.	.893	w.s.
	.820	2.41	.890	2.47	.860	2.43
	.720	2.39	.790	2.41	.780	2.40
	.620	2.36	.690	2.40	.680	2.36
	.520	2.29	.590	2.33	.580	2.30
	.420	2.02	.490	2.23	.480	2.15
	.320	1.96	.390	2.16	.380	2.10
	.220	1.90	.290	2.07	.280	2.00
	.170	1.86	.240	2.02	.180	1.82
	.120	1.76	.190	1.95	.130	1.72
	.080	1.70	.140	1.90	.090	1.53
	.050	1.56	.110	1.80	.050	1.35
	.020	1.46	.080	1.70	.020	1.30
			.050	1.67		
			.020	1.37		
8	.990	w.s.	.812	w.s.	.926	w.s.
	.948	2.48	.775	2.69	.900	2.61
	.898	2.48	.625	2.63	.800	2.61
	.748	2.39	.425	2.50	.700	2.59
	.548	2.33	.225	2.29	.500	2.45
	.348	2.12	.125	2.07	.300	2.32
	.248	1.95	.075	1.98	.200	2.27
	.148	1.68	.050	1.88	.100	1.91
	.098	1.44	.025	1.38	.050	1.66
	.048	1.38			.025	1.33
	.023	1.30				
28	.557	w.s.	.460	w.s.	.475	w.s.
	.455	1.49	.430	1.50	.445	1.48
	.335	1.34	.380	1.48	.395	1.44
	.255	1.28	.330	1.46	.345	1.37
	.205	1.15	.280	1.47	.295	1.33
	.155	1.08	.230	1.43	.245	1.31
	.105	.93	.180	1.31	.195	1.26
	.075	.79	.130	1.21	.145	1.18
	.045	.55	.080	1.17	.095	1.09
			.030	1.08	.065	.97
			.020	.97	.035	.93
					.010	.87
33	.980	w.s.	.870	w.s.		
	.920	2.57	.820	2.62		
	,820	2.59	.720	2.57		
	.720	2.56	.620	2.50		

TABLE 12.—*Velocity-profile data for 0.19-mm sand in 8-foot-wide flume*—Continued

Run	2.0 ft from left wall of flume: Distance above sand bed (ft)	2.0 ft from left wall of flume: Velocity (fps)	4.0 ft from left wall of flume: Distance above sand bed (ft)	4.0 ft from left wall of flume: Velocity (fps)	6.0 ft from left wall of flume: Distance above sand bed (ft)	6.0 ft from left wall of flume: Velocity (fps)
33—Con.	0.620	2.54	0.520	2.47		
	.520	2.52	.420	2.44		
	.420	2.49	.320	2.40		
	.320	2.45	.220	2.23		
	.220	2.37	.170	2.18		
	.120	2.26	.120	2.08		
	.070	2.04	.090	2.03		
	.030	1.43	.060	1.94		
			.030	1.90		
29	.513	w.s.	.480	w.s.	.528	w.s.
	.490	1.60	.445	1.58	.495	1.60
	.440	1.59	.345	1.55	.395	1.49
	.339	1.55	.245	1.42	.295	1.31
	.340	1.52	.195	1.30	.245	1.28
	.290	1.44	.145	1.26	.195	1.17
	.240	1.35	.095	1.12	.145	1.11
	.190	1.29	.065	1.09	.095	.98
	.140	1.19	.035	1.00	.065	.83
	.100	1.12	.010	.91	.035	.65
	.060	1.08			.015	.46
	.030	1.01				
	.010	.92				
3	.516	w.s.	.490	w.s.	.575	w.s.
	.475	1.58	.444	1.60	.547	1.61
	.375	1.55	.344	1.57	.447	1.59
	.275	1.47	.244	1.44	.347	1.51
	.175	1.35	.144	1.15	.247	1.47
	.125	1.25	.094	1.02	.197	1.40
	.075	1.07	.069	.97	.147	1.38
	.050	.95	.044	.97	.132	1.26
	.025	.40	.019	.97	.097	1.20
					.072	1.09
11	.793	w.s.	.948	w.s.	1.236	w.s.
	.721	3.09	.885	3.07	1.180	3.20
	.621	3.07	.785	2.98	1.080	3.18
	.421	3.05	.685	3.03	.880	3.15
	.221	3.03	.485	2.91	.680	3.03
	.121	2.88	.285	2.91	.480	2.86
	.071	2.75	.185	2.86	.280	2.75
	.046	2.60	.135	2.75	.180	2.66
	.021	2.44	.085	2.64	.130	2.60
			.050	2.45	.080	2.49
			.025	2.29	.055	2.37
					.030	2.12
13	.900	w.s.	.886	w.s.	.851	w.s.
	.800	3.69	.850	3.74	.798	3.80
	.650	3.65	.750	3.70	.698	3.77
	.450	3.60	.650	3.70	.598	3.69
	.350	3.48	.450	3.64	.398	3.64
	.250	3.27	.350	3.50	.298	3.49
	.150	3.06	.250	3.40	.198	3.24
	.100	2.88	.150	3.17	.098	2.97
	.050	2.50	.100	2.98	.048	2.41
	.025	2.20	.050	2.63	.023	2.26
			.025	2.42		
14	.856	w.s.	.872	w.s.	.890	w.s.
	.807	3.90	.810	4.11	.810	3.98
	.707	3.84	.710	4.00	.710	3.91
	.507	3.68	.510	3.86	.510	3.75
	.307	3.43	.310	3.54	.310	3.43
	.207	3.27	.210	3.30	.210	3.07
	.107	3.09	.110	2.87	.110	2.80
	.057	2.73	.060	2.13	.060	2.44
	.027	2.43	.030	.95	.030	2.20
15	.780	w.s.	.785	w.s.	.745	w.s.
	.710	4.13	.710	4.49	.710	4.33
	.610	3.97	.610	4.31	.610	4.29
	.410	3.70	.410	4.14	.510	4.20
	.310	3.54	.310	3.95	.310	3.80
	.210	3.25	.210	3.71	.210	3.54
	.110	3.05	.110	3.20	.110	3.34
	.060	2.54	.060	2.91	.060	3.00
	.030	2.23	.030	2.17	.030	2.73
34	.498	w.s.	.495	w.s.	.485	w.s.
	.450	2.24	.450	2.29	.460	2.24
	.370	2.02	.380	2.24	.360	2.12
	.300	1.88	.310	2.20	.310	2.07
	.230	1.85	.260	2.01	.260	1.98
	.180	1.80	.210	1.81	.210	1.81
	.130	1.86	.170	1.73	.160	1.75

Run	2.0 ft from left wall of flume: Distance above sand bed (ft)	2.0 ft from left wall of flume: Velocity (fps)	4.0 ft from left wall of flume: Distance above sand bed (ft)	4.0 ft from left wall of flume: Velocity (fps)	6.0 ft from left wall of flume: Distance above sand bed (ft)	6.0 ft from left wall of flume: Velocity (fps)
34—Con.	0.090	1.72	0.130	1.70	0.120	1.58
	.060	1.44	.100	1.83	.080	1.51
	.030	1.38	.070	1.85	.050	1.43
			.030	1.76	.020	1.29
12	.924	w.s.	.859	w.s.	1.162	w.s.
	.875		.800		1.100	3.43
	.775		.700	3.93	1.050	3.41
	.675		.600	3.64	.850	3.31
	.575	3.60	.400	3.45	.650	3.26
	.475	3.51	.200	3.03	.450	3.16
	.375	3.37	.100	2.55	.250	2.76
	.275	3.26	.050	2.11	.150	2.55
	.175	3.02	.025	1.39	.100	2.39
	.075	2.41			.050	2.21
	.025	2.10			.025	2.16
6	.641	w.s.	.511	w.s.	.620	w.s.
	.622	2.52	.490	2.46	.600	2.33
	.522	2.42	.390	2.46	.550	2.24
	.422	2.28	.290	2.40	.450	2.30
	.322	2.21	.240	2.36	.250	2.00
	.222	2.07	.190	2.23	.050	1.84
	.122	1.78	.140	2.10		
	.072	1.38	.090	1.86		
	.047	1.15	.040	1.59		
	.022	.75	.015	.87		
7	.727	w.s.	.647	w.s.	.651	w.s.
	.697	2.27	.621	2.30	.625	2.50
	.597	2.25	.521	2.26	.525	2.47
	.397	2.00	.321	2.06	.425	2.36
	.297	1.84	.221	1.96	.325	2.23
	.197	1.79	.171	1.88	.225	2.08
	.147	1.83	.121	1.84	.125	1.64
	.097	1.60	.071	1.77	.075	1.48
	.047	1.43	.021	.91	.050	1.39
	.012	1.07			.025	.64
35	.349	w.s.	.522	w.s.	.522	w.s.
	.317	2.68	.480	2.25	.475	2.40
	.297	2.73	.410	2.16	.405	2.22
	.267	2.75	.340	2.13	.335	2.14
	.237	2.82	.280	2.13	.265	2.06
	.207	2.79	.240	2.10	.205	2.00
	.177	2.77	.200	2.15	.165	1.97
	.147	2.68	.160	2.11	.125	1.84
	.117	2.63	.120	1.93	.085	1.68
	.087	2.49	.090	1.97	.055	1.53
	.057	2.22	.060	1.98	.025	1.36
	.027	2.09	.030	1.78		
16	.700	w.s.	.705	w.s.	.695	w.s.
	.625	4.70	.650	4.75	.625	4.64
	.500	5.00	.550	4.63	.525	5.02
	.300	4.09	.400	5.01	.375	4.28
	.200	3.82	.300	4.18	.275	4.02
	.150	3.82	.200	3.95	.175	3.90
	.100	3.68	.150	3.82	.125	3.68
	.075	3.37	.100	3.52	.075	3.28
	.050	3.28	.075	3.37	.050	3.12
	.025	2.74	.050	3.20	.025	2.60
			.025	2.69		
10	.452	w.s.	.438	w.s.	.458	w.s.
	.393		.425		.395	3.66
	.323		.325	3.68	.325	3.52
	.223	3.60	.225	3.43	.225	3.42
	.173	2.39	.175	3.31	.175	3.19
	.123	3.17	.125	3.13	.125	3.06
	.073	2.96	.100	2.98	.100	2.98
	.048	2.66	.075	2.80	.075	2.85
	.023	2.12	.050	2.76	.050	2.64
			.025	2.58	.025	2.57
9	.411	w.s.	.441	w.s.	.385	w.s.
	.400	2.95	.397	3.30	.350	3.15
	.350	2.99	.347	3.25	.300	3.09
	.300	2.94	.247	3.04	.200	2.81
	.250	2.86	.197	2.87	.150	2.68
	.200	2.67	.147	2.67	.100	2.49
	.150	2.67	.122	2.54	.075	2.38
	.125	2.59	.097	2.31	.050	2.28
	.100	2.51	.072	2.15	.025	2.04
	.075	2.43	.047	1.98		
	.050	2.35	.022	1.73		
	.025	2.15				

TABLE 13.—*Velocity-profile data for 0.27-mm sand in 8-foot-wide flume*

[The lateral section used for measuring was 95-115 ft from the headbox. w.s.=water surface]

Run	2.0 ft from left wall of flume		4.0 ft from left wall of flume		6.0 ft from left wall of flume	
	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)
50A	0.965	w.s.	0.960	w.s.	0.975	w.s.
	.920	1.25	.925	1.22	.920	1.24
	.600	1.21	.600	1.15	.600	1.19
	.400	1.18	.400	1.15	.400	1.15
	.300	1.14	.300	1.13	.300	1.12
	.200	1.11	.200	1.07	.200	1.10
	.150	1.05	.150	1.06	.150	1.07
	.100	1.04	.100	1.05	.100	1.06
	.075	1.03	.075	1.03	.075	1.02
	.050	.98	.050	1.02	.050	.99
	.025	.96	.025	.96	.025	.96
50D	.890	w.s.	.900	w.s.	.915	w.s.
	.835	1.28	.845	1.25	.860	1.23
	.600	1.23	.600	1.25	.600	1.23
	.400	1.21	.400	1.22	.400	1.22
	.300	1.16	.300	1.19	.300	1.19
	.200	1.13	.200	1.15	.200	1.14
	.150	1.09	.150	1.12	.150	1.10
	.100	1.07	.100	1.09	.100	1.09
	.075	1.05	.075	1.07	.075	1.06
	.050	1.03	.050	1.03	.050	.94
	.025	.99	.025	.99	.025	.92
51	.995	w.s.	.960	w.s.	--	--
	.950	1.69	.920	1.67	--	--
	.800	1.64	.800	1.66	--	--
	.600	1.58	.600	1.60	--	--
	.400	1.49	.400	1.52	--	--
	.300	1.36	.300	1.48	--	--
	.200	1.27	.200	1.41	--	--
	.150	1.16	.150	1.38	--	--
	.100	1.08	.100	1.36	--	--
	.075	1.05	.075	1.28	--	--
	.050	1.01	.050	1.24	--	--
	.025	.99	.025	1.24	--	--
52	.965	w.s.	1.100	w.s.	.940	w.s.
	.925	1.68	.970	--	.890	2.07
	.800	1.66	.800	1.98	.600	1.98
	.600	1.60	.600	1.84	.400	1.86
	.400	1.41	.400	1.66	.300	1.80
	.300	1.36	.300	1.60	.200	1.74
	.200	1.23	.200	1.54	.150	1.67
	.150	1.19	.150	1.49	.100	1.61
	.100	1.05	.100	1.47	.075	1.31
	.075	1.05	.075	1.45	.050	1.36
	.050	1.03	.050	1.38	.025	1.17
	.025	1.00	.025	1.40	--	--
54	.830	w.s.	.890	w.s.	1.050	w.s.
	.800	2.26	.870	2.16	1.000	2.24
	.600	2.20	.800	2.12	.800	2.15
	.400	2.20	.600	2.10	.600	2.08
	.300	2.07	.400	2.04	.500	2.04
	.200	2.07	.300	1.99	.400	1.95
	.150	2.07	.200	1.76	.300	1.76
	.100	2.05	.150	1.76	.200	1.65
	.075	1.94	.100	1.76	.150	1.58
	.050	1.83	.050	1.70	.100	1.40
	.025	1.80	.025	1.70	.075	1.36
	--	--	--	--	.050	1.24
	--	--	--	--	.025	1.24
53	.940	w.s.	.950	w.s.	1.130	w.s.
	.700	2.14	.800	2.19	1.020	2.27
	.650	2.14	.600	2.17	1.000	2.23
	.400	2.11	.400	2.13	.800	1.99
	.300	2.04	.300	2.08	.600	1.98
	.200	1.88	.200	1.99	.400	1.82
	.150	1.82	.150	1.90	.300	1.67
	.100	1.79	.100	1.64	.200	1.64
	.075	1.75	.075	1.30	.150	1.59
	.050	1.65	.050	1.21	.100	1.57
	.025	1.41	.025	.70	.075	1.52
	--	--	--	--	.050	1.49
	--	--	--	--	.025	1.49
57	.489	w.s.	.494	w.s.	.444	w.s.
	.445	1.42	.450	1.27	.400	1.48
	.300	1.20	.300	1.12	.300	1.43
	.200	1.10	.200	.85	.200	1.35
	.150	1.01	.150	.70	.150	1.13
	.100	.74	.100	.63	.100	.88
	.075	.66	.075	.52	.075	.90
	.050	.82	.050	.37	.050	.74
	.025	.60	.025	.30	.025	.66
56	.800	w.s.	.750	w.s.	.730	w.s.
	.760	2.30	.725	2.57	.700	2.58
	.600	2.30	.600	2.57	.500	2.56
	.400	2.27	.400	2.37	.400	2.19
	.300	2.23	.300	2.26	.300	1.89
	.200	2.13	.200	2.11	.200	1.49
	.150	1.96	.150	1.71	.150	1.30
	.100	1.89	.100	.92	.100	.96

Run	2.0 ft from left wall of flume		4.0 ft from left wall of flume		6.0 ft from left wall of flume	
	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)
56—Con.	0.075	1.86	0.075	1.23	0.075	0.86
	.050	1.52	.050	1.96	.050	.70
	.025	1.31	.025	1.58	.025	.60
55	1.540	w.s.	.980	w.s.	.930	w.s.
	1.500	2.52	.910	2.47	.875	2.48
	1.350	2.47	.800	2.48	.675	2.46
	1.150	2.41	.600	2.56	.475	2.44
	.950	2.41	.400	2.59	.375	2.28
	.750	2.39	.300	2.60	.275	2.35
	.550	2.30	.200	2.60	.175	2.42
	.450	2.23	.150	2.59	.125	2.46
	.350	1.91	.100	2.53	.075	2.26
	.300	1.88	.075	2.40	.025	2.35
	.250	1.76	.050	2.24	--	--
	.200	.96	.025	1.73	--	--
	.150	1.00	--	--	--	--
	.100	1.03	--	--	--	--
	.075	1.00	--	--	--	--
	.050	1.00	--	--	--	--
	.025	1.00	--	--	--	--
45	.785	w.s.	.810	w.s.	.815	w.s.
	.720	4.04	.760	3.77	.765	3.86
	.550	3.95	.550	3.71	.550	3.68
	.400	3.78	.400	3.58	.400	3.53
	.300	3.56	.300	3.34	.300	3.39
	.200	3.26	.200	3.25	.200	3.26
	.150	3.17	.150	2.85	.150	3.05
	.100	3.05	.100	2.57	.100	2.81
	.075	2.84	.075	2.39	.075	2.65
	.050	2.73	.050	2.21	.050	2.56
	.025	2.32	.025	1.72	.025	2.41
43	.670	w.s.	1.470	w.s.	1.315	w.s.
	.525	2.24	1.450	2.04	1.295	2.37
	.400	1.95	1.350	2.00	1.175	2.36
	.300	1.86	1.150	1.97	.975	2.34
	.200	1.84	.950	1.94	.775	2.33
	.150	1.82	.750	1.90	.575	2.31
	.100	1.90	.550	1.53	.375	2.26
	.075	1.90	.350	1.61	.275	2.18
	.050	1.90	.250	1.55	.175	2.11
	.025	1.90	.150	1.55	.125	1.91
	--	--	.100	1.55	.075	1.69
	--	--	.075	1.56	.050	1.66
	--	--	.050	1.54	.025	1.65
	--	--	.025	1.48	--	--
44	.784	w.s.	.945	w.s.	.860	w.s.
	.700	2.77	.875	--	.750	2.86
	.600	2.95	.675	3.33	.650	2.82
	.400	3.11	.475	3.14	.450	2.77
	.300	3.13	.275	3.04	.350	2.64
	.200	3.11	.175	2.89	.250	2.56
	.150	3.08	.125	2.69	.200	2.43
	.100	3.00	.100	2.68	.150	2.31
	.075	2.82	.075	2.33	.100	2.19
	.050	2.27	.050	2.23	.075	2.08
	.025	2.15	.025	2.23	.050	2.05
	--	--	--	--	.025	2.05
42	.915	w.s.	.890	w.s.	.925	w.s.
	.885	--	.855	2.05	.890	2.33
	.700	2.20	.600	1.68	.600	2.34
	.500	2.18	.400	1.68	.400	2.33
	.400	2.18	.300	1.76	.300	2.29
	.300	2.05	.200	1.77	.200	2.18
	.200	2.09	.150	1.79	.150	2.01
	.150	2.09	.100	1.79	.100	1.82
	.100	1.98	.075	1.75	.075	1.54
	.075	1.90	.050	1.68	.050	1.16
	.050	.95	.025	1.38	.025	1.14
	.025	1.07	--	--	--	--
46	.687	w.s.	.717	w.s.	.682	w.s.
	.660	4.77	.700	4.60	.600	4.13
	.600	4.64	.600	4.50	.400	3.96
	.400	4.39	.400	4.17	.300	3.85
	.300	4.17	.300	4.09	.200	3.54
	.200	3.96	.200	3.63	.150	3.40
	.150	3.68	.150	3.40	.100	3.21
	.100	3.68	.100	3.10	.075	3.09
	.075	3.54	.075	2.94	.050	2.90
	.050	3.30	.050	2.82	.025	2.70
	.025	2.88	.025	2.23	--	--
58	.440	w.s.	.370	w.s.	--	--
	.430	1.97	.350	--	--	--
	.300	2.06	.300	--	--	--
	.200	2.10	.200	1.65	--	--
	.150	2.16	.150	1.62	--	--
	.100	2.07	.100	1.69	--	--
	.075	1.99	.075	1.58	--	--
	.050	1.77	.050	1.59	--	--
	.025	1.61	.025	1.51	--	--

TABLE 14.—*Velocity-profile data for 0.28-mm sand in 8-foot-wide flume*

[The lateral section used for measuring was 95–115 ft from the headbox. w.s.=water surface]

Run	2.0 ft from left wall of flume		4.0 ft from left wall of flume		6.0 ft from left wall of flume	
	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)
7	0.985	w.s.	0.990	w.s.	0.985	w.s.
	.970	0.82	.890	0.86	.970	0.80
	.940	.81	.790	.76	.940	.80
	.840	.82	.690	.74	.840	.80
	.740	.76	.490	.73	.740	.78
	.540	.68	.390	.72	.540	.77
	.340	.67	.290	.70	.340	.75
	.240	.58	.240	.70	.240	.72
	.140	.51	.190	.68	.140	.71
	.090	.51	.140	.68	.090	.69
	.040	.50	.090	.66	.040	.66
	.010	.46	.065	.64	.010	.50
			.040	.58		
			.030	.54		
			.020	.52		
			.010	.49		
9	.980	w.s.	1.000	w.s.	1.015	w.s.
	.900	.84	.950	.78	.965	.85
	.700	.78	.700	.74	.775	.79
	.550	.76	.550	.68	.625	.76
	.400	.73	.400	.65	.475	.68
	.300	.71	.300	.60	.375	.59
	.200	.66	.200	.47	.275	.55
	.150	.53	.150	.37	.175	.50
	.100	.43	.100	.33	.150	.44
	.075	.35	.075	.30	.100	.37
	.050	.35	.050	.30	.075	.34
	.025	.34	.025	.30	.050	.28
					.025	.25
10	.580	w.s.	.580	w.s.	.580	w.s.
	.530	.70	.540	.74	.540	.71
	.400	.58	.450	.65	.450	.63
	.300	.49	.350	.52	.350	.61
	.250	.44	.250	.50	.250	.51
	.200	.43	.200	.42	.200	.44
	.175	.38	.150	.40	.150	.35
	.150	.25	.100	.34	.100	.30
	.125	.21	.075	.26	.075	.23
			.050	.23	.050	.19
			.025	.21	.025	
5	1.025	w.s.	.982	w.s.		
	.950	1.35	.940	1.39		
	.750	1.27	.750	1.35		
	.550	1.18	.550	1.29		
	.400	1.08	.400	1.20		
	.300	.98	.300	1.02		
	.200	.76	.200	.85		
	.150	.61	.150	.78		
	.100	.50	.100	.75		
	.075	.48	.075	.75		
	.050	.50	.050	.71		
	.025	.57	.025	.70		
13	1.020	w.s.	1.013	w.s.	.993	w.s.
	.960	1.81	.960	1.87	.930	1.88
	.750	1.77	.750	1.79	.750	1.86
	.550	1.56	.550	1.63	.550	1.77
	.400	1.53	.400	1.60	.400	1.72
	.300	1.43	.300	1.55	.300	1.49
	.200	1.08	.200	1.29	.200	1.28
	.150	.74	.150	1.18	.150	1.02
	.100	.64	.100	1.05	.100	.72
	.075	.72	.075	1.05	.075	.62
	.050	.48	.050	1.05	.050	.58
	.025	.35	.025	1.05	.025	.55
4	.820	w.s.	.895	w.s.	.885	w.s.
	.780	1.66	.850	1.75	.835	1.69
	.650	1.62	.700	1.72	.700	1.66
	.500	1.56	.550	1.64	.550	1.60
	.350	1.51	.400	1.46	.400	1.50
	.250	1.49	.300	1.27	.300	1.28
	.200	1.38	.200	1.09	.200	1.14
	.150	1.35	.150	.95	.150	1.04
	.100	1.33	.100	.59	.100	.93
	.075	1.31	.075	.57	.075	.86
	.050	1.30	.050	.46	.050	.73
	.025	1.30	.025	.43	.025	.61
11	.521	w.s.	.644	w.s.	.522	w.s.
	.480	.88	.600	.88	.480	.94
	.400	.87	.450	.86	.400	.93
	.300	.82	.350	.76	.300	.85
	.200	.70	.250	.66	.200	.76
	.150	.62	.200	.60	.150	.72
	.100	.58	.150	.52	.100	.64
	.075	.54	.100	.51	.075	.59
	.050	.50	.075	.50	.050	.55
	.025	.48	.050	.47	.025	.51
			.025	.44		
33	1.005	w.s.	0.930	w.s.	1.035	w.s.
	.950	2.11	.875	2.12	.970	2.15
	.800	2.11	.600	1.98	.800	2.24
	.600	2.09	.400	2.00	.600	2.24
	.400	2.09	.300	1.95	.400	2.16
	.300	2.09	.200	1.94	.300	2.10
	.200	2.07	.150	1.86	.200	2.00
	.150	2.01	.100	1.86	.150	1.77
	.100	1.93	.075	1.75	.100	1.68
	.075	1.86	.050	1.70	.075	1.65
	.050	1.82	.025		.050	1.59
	.025	1.66			.025	1.51
1	.740	w.s.	1.010	w.s.	.892	w.s.
	.690	2.04	.960	1.69	.870	1.89
	.590	2.04	.860	1.74	.770	1.85
	.490	2.00	.760	1.80	.670	1.94
	.390	2.06	.660	1.85	.620	1.62
	.340	2.08	.560	1.79	.570	1.73
	.290	2.08	.460	1.72	.520	1.74
	.240	2.08	.360	1.69	.470	1.69
	.190	2.02	.260	1.48	.420	1.74
	.140	1.93	.210	.96	.370	1.74
	.090	1.84			.320	1.73
	.040	1.70			.270	1.54
					.220	1.61
					.170	1.55
					.120	1.29
					.070	1.13
					.020	1.03
12	.628	w.s.	.601	w.s.	.580	w.s.
	.580	1.58	.550	1.66	.530	1.65
	.500	1.51	.400	1.48	.450	1.57
	.400	1.43	.300	1.40	.350	1.48
	.300	1.24	.200	1.19	.250	1.39
	.200	1.18	.150	1.16	.200	1.33
	.150	1.15	.100	1.08	.150	1.27
	.100	1.09	.075	.84	.100	1.10
	.075	.99	.050	.73	.075	.99
	.050	.84	.025	.70	.050	.99
	.025	.82			.025	.99
14	.580	w.s.	.610	w.s.	.580	w.s.
	.530	1.95	.550	1.86	.530	1.94
	.450	1.86	.450	1.77	.450	1.94
	.350	1.84	.350	1.66	.350	1.91
	.250	1.82	.250	1.46	.250	1.78
	.200	1.78	.200	1.40	.200	1.65
	.150	1.72	.150	1.33	.150	1.61
	.100	1.47	.100	1.32	.100	1.56
	.075	1.44	.075	1.33	.075	1.39
	.050	1.28	.050	1.36	.050	1.30
	.025	1.15	.025	1.35	.025	1.16
20	.960	w.s.	1.030	w.s.	.960	w.s.
	.930	2.46	.990	2.51	.920	2.31
	.750	2.50	.750	2.47	.750	2.30
	.500	2.51	.550	2.41	.550	2.21
	.400	2.41	.400	2.21	.400	2.15
	.300	2.36	.300	2.08	.300	2.18
	.200	2.10	.200	2.02	.200	2.21
	.150	1.86	.150	1.91	.150	2.06
	.100	1.72	.100	1.72	.100	2.08
	.075	1.48	.075	1.60	.075	2.07
	.050	1.25	.050	1.46	.050	1.93
	.015	.57	.025	1.30	.025	1.85
21	.855	w.s.	1.025	w.s.	1.025	w.s.
	.815	2.67	.980	2.46	.960	2.33
	.575	2.67	.750	2.39	.800	2.36
	.375	2.71	.550	2.39	.600	2.33
	.275	2.67	.400	2.39	.400	2.35
	.175	2.67	.300	2.39	.300	2.32
	.125	2.67	.200	2.31	.200	2.23
	.075	2.65	.150	2.29	.150	2.10
	.050	2.48	.100	2.22	.100	1.98
	.025	2.16	.075	2.21	.075	1.97
			.050	2.09	.050	1.88
			.025	1.70	.025	1.13
19	.515	w.s.	.510	w.s.	.615	w.s.
	.490	1.98	.475	2.10	.580	2.05
	.400	1.95	.400	2.11	.400	2.04
	.300	1.97	.300	2.08	.300	2.01
	.200	1.91	.200	2.02	.200	1.93
	.150	1.91	.150	2.00	.150	1.85
	.100	1.84	.100	1.98	.100	1.81
	.075	1.77	.075	1.97	.075	1.80
	.050	1.64	.050	1.91	.050	1.73
	.025	1.47	.025	1.88	.025	1.46

TABLE 14.—*Velocity-profile data for 0.28-mm sand in 8-foot-wide flume*—Continued

Run	2.0 ft from left wall of flume		4.0 ft from left wall of flume		6.0 ft from left wall of flume	
	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)
16	0.915	w.s.	0.875	w.s.	0.895	w.s.
	.850	2.21	.800	2.45	.800	2.10
	.600	2.15	.600	2.47	.600	2.02
	.450	2.18	.450	2.43	.450	1.84
	.300	2.20	.300	2.34	.300	1.81
	.200	2.15	.200	2.32	.200	1.83
	.150	2.14	.150	2.29	.150	1.74
	.100	2.10	.100	2.31	.100	1.68
	.075	2.01	.075	2.22	.075	1.54
	.050	1.51	.050	2.10	.050	1.47
	.025	1.40	.025	1.80	.025	1.42
23	.950	w.s.	.945	w.s.	1.158	w.s.
	.900	3.13	.900	3.14	1.100	3.18
	.700	3.02	.700	2.98	1.000	3.16
	.500	2.91	.550	2.85	.900	3.10
	.400	2.80	.400	2.70	.800	3.08
	.300	2.75	.300	2.64	.700	2.98
	.200	2.55	.200	2.57	.600	2.90
	.150	2.13	.150	2.51	.500	2.70
	.100	1.93	.100	2.31	.400	2.61
	.075	1.76	.075	2.23	.300	2.44
	.050	1.56	.050	2.14	.200	2.10
			.025	2.12	.100	1.34
					.050	.30
					.025	.30
17	.925	w.s.	.595	w.s.	.690	w.s.
	.870	1.84	.540	1.72	.635	1.62
	.700	1.66	.400	1.70	.550	1.50
	.500	1.58	.300	1.56	.400	1.48
	.400	1.57	.200	1.52	.300	1.14
	.300	1.54	.150	1.52	.200	1.10
	.250	1.36	.100	1.46	.150	1.08
	.200	1.29	.060	1.35	.100	1.07
	.175	1.28	.050	1.03	.075	1.04
	.150	1.27	.025	.98	.050	1.04
	.125	.54			.025	1.03
	.100	.52				
3	1.180	w.s.	.805	w.s.	.870	w.s.
	1.015	2.50	.750	2.33	.800	2.21
	.815	2.50	.600	2.33	.700	2.21
	.665	2.50	.450	2.26	.550	2.21
	.465	2.40	.300	2.21	.400	2.18
	.365	2.21	.200	2.16	.300	2.04
	.265	1.95	.150	2.12	.200	1.95
	.200	1.28	.100	1.90	.150	1.88
	.150	.63	.075	1.78	.100	1.80
	.100	.74	.050	1.74	.075	1.60
	.075	.58	.025	1.74	.050	1.55
	.050	.62			.025	1.55
	.025	.66				
18	.740	w.s.	.750	w.s.	.600	w.s.
	.700	2.16	.720	2.84	.560	2.85
	.550	2.05	.600	2.81	.450	2.84
	.400	1.60	.500	2.76	.300	2.80
	.300	1.37	.400	2.56	.200	2.73
	.200	1.59	.350	2.47	.150	2.69
	.150	1.59	.300	2.03	.100	2.57
	.100	1.23	.275	1.70	.075	2.45
	.075	1.25	.250	1.19	.050	2.33
	.050	1.26	.225	.79	.025	2.13
	.025	1.25				
30	.665	w.s.	.625	w.s.	.720	w.s.
	.620	3.76	.580	3.68	.675	3.76
	.500	3.59	.400	3.68	.500	3.76
	.400	3.40	.300	3.49	.400	3.49
	.300	3.30	.200	3.40	.300	3.40
	.200	3.10	.150	3.20	.200	3.20
	.150	2.88	.100	2.99	.150	2.64
	.100	2.70	.075	2.76	.100	2.07
	.075	2.64	.050	2.51	.075	1.70
	.050	2.51	.025	2.07	.050	1.70
	.025	2.23			.025	1.48
34	.450	w.s.	.395	w.s.	.345	w.s.
	.425	1.79	.360	1.98	.320	1.96
	.325	1.78	.300	1.96	.250	1.94
	.225	1.68	.250	1.87	.200	1.90
	.175	1.55	.200	1.87	.150	1.75
	.125	1.39	.150	1.77	.100	1.66
	.100	1.35	.10C	1.72	.075	1.64
	.075	1.36	.075	1.61	.050	1.64

Run	2.0 ft from left wall of flume		4.0 ft from left wall of flume		6.0 ft from left wall of flume	
	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)
34—Con.	0.050	1.36	0.050	1.61	0.025	1.61
	.025	1.37	.025	1.61		
22	.630	w.s.	.610	w.s.	.595	w.s.
	.580	3.55	.560	3.59	.560	3.43
	.500	3.50	.500	3.58	.500	3.33
	.400	3.38	.400	3.50	.400	3.27
	.300	2.98	.300	3.31	.300	3.12
	.200	2.87	.200	3.07	.200	2.94
	.150	2.85	.150	2.92	.150	2.75
	.100	2.67	.100	2.73	.100	2.55
	.075	2.56	.075	2.66	.075	2.43
	.050	2.31	.050	2.40	.050	2.14
	.025	1.93	.025	2.20	.025	1.89
15	.810	w.s.	.595	w.s.	.515	w.s.
	.750	2.32	.550	2.47	.470	2.43
	.550	2.29	.400	2.44	.400	2.40
	.400	2.18	.300	2.38	.300	2.31
	.300	2.01	.200	2.31	.200	2.25
	.200	1.83	.150	2.25	.150	2.25
	.150	1.85	.100	2.14	.100	2.25
	.100	1.89	.075	2.07	.075	2.19
	.075	1.94	.050	1.88	.050	2.16
	.050	1.94	.025	1.82	.025	2.10
	.025	1.90				
24	.650	w.s.	.810	w.s.	.800	w.s.
	.610	3.68	.760	3.70	.750	3.56
	.550	3.78	.550	3.70	.550	3.42
	.400	3.82	.400	3.68	.400	3.17
	.300	3.78	.300	3.62	.300	3.09
	.200	3.68	.200	3.48	.200	3.07
	.150	3.45	.150	3.29	.150	2.97
	.100	3.23	.100	3.10	.100	2.78
	.075	2.96	.075	2.98	.075	2.74
	.050	2.64	.050	2.79	.050	2.61
	.025	2.31	.025	2.48	.025	2.43
25	.670	w.s.	.670	w.s.	.700	w.s.
	.550	4.74	.650	4.74	.650	4.46
	.400	4.46	.550	4.53	.550	4.46
	.300	4.39	.400	4.46	.400	4.24
	.200	4.17	.300	4.24	.300	4.09
	.150	4.01	.200	4.01	.200	3.93
	.100	3.85	.150	3.85	.150	3.85
	.075	3.40	.100	3.50	.100	3.59
	.050	3.20	.075	3.40	.075	3.40
	.025	2.76	.050	3.20	.050	2.88
			.025	2.88	.025	2.76
28	.550	w.s.	.550	w.s.	.550	w.s.
	.500	4.39	.500	4.32	.500	4.32
	.400	4.24	.400	4.16	.400	4.08
	.300	4.08	.300	4.08	.300	3.93
	.200	3.93	.200	4.01	.200	3.85
	.150	3.76	.150	3.68	.150	3.59
	.100	3.40	.100	3.59	.100	3.49
	.075	3.30	.075	3.30	.075	3.30
	.050	3.10	.050	3.10	.050	3.20
	.025	2.76	.025	2.64	.025	2.76
29	.540	w.s.	.490	w.s.	.490	w.s.
	.490	4.24	.440	4.67	.440	4.81
	.440	4.39	.400	4.32	.400	4.39
	.400	4.39	.300	4.32	.300	4.39
	.300	4.16	.250	4.24	.250	4.16
	.250	4.08	.200	4.08	.200	4.01
	.200	4.01	.150	3.93	.150	4.08
	.150	3.76	.100	3.59	.100	3.68
	.100	3.49	.075	3.40	.075	3.59
	.075	3.10	.050	3.20	.050	3.40
	.050	3.20	.025	2.76	.025	3.10
	.025	2.88				
26	.505	w.s.	.485	w.s.	.475	w.s.
	.470	4.81	.430	4.81	.410	4.60
	.400	4.46	.300	4.53	.300	4.46
	.300	4.46	.200	4.32	.200	4.32
	.200	3.93	.150	4.16	.150	4.08
	.150	3.76	.100	3.49	.100	3.93
	.100	3.59	.075	3.40	.075	3.76
	.075	3.10	.050	3.30	.050	3.40
	.050	2.64	.025	2.07	.025	2.88
	.025	2.37				

TABLE 15.—*Velocity-profile data for 0.45-mm sand in 8-foot-wide flume*

[The lateral section used for measuring was 95-115 ft from the headbox. w.s.=water surface]

Run	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)
	2.6 ft from left wall of flume		*4.0 ft from left wall of flume*		*6.8 ft from left wall of flume*	
14	0.613	w.s.	0.613	w.s.	0.621	w.s.
	.563	0.84	.563	0.86	.571	0.83
	.463	.83	.463	.84	.471	.85
	.363	.81	.363	.80	.371	.82
	.263	.76	.263	.79	.271	.77
	.213	.75	.213	.76	.221	.75
	.163	.73	.163	.75	.171	.73
	.113	.69	.113	.70	.121	.69
	.063	.59	.063	.64	.071	.65
	.013	.46	.013	.41	.021	.47
13	.356	w.s.	.363	w.s.	.353	w.s.
	.306	.63	.313	.63	.303	.56
	.256	.62	.263	.62	.253	.56
	.206	.61	.213	.61	.203	.56
	.156	.60	.163	.59	.153	.53
	.106	.58	.113	.58	.103	.52
	.081	.57	.088	.57	.078	.49
	.056	.56	.063	.57	.053	.47
	.031	.53	.038	.54	.028	.46
	.006	.48	.013	.45	.003	.40
17	.902	w.s.	.937	w.s.	.938	w.s.
	.852	.91	.887	.92	.888	.90
	.802	.91	.837	.92	.838	.89
	.602	.90	.637	.91	.638	.89
	.402	.87	.437	.90	.438	.87
	.202	.81	.237	.83	.238	.86
	.152	.79	.187	.78	.188	.83
	.102	.75	.137	.74	.138	.80
	.077	.74	.112	.74	.113	.78
	.052	.73	.087	.73	.088	.75
	.027	.71	.062	.72	.063	.74
	.002	.70	.037	.70	.038	.74
	-----	-----	.012	.69	.013	.68
	1.2 ft from left wall of flume					
16	0.792	w.s.	.787	w.s.	.813	w.s.
	.742	0.97	.737	.94	.763	.98
	.692	.98	.687	.94	.713	.98
	.492	.96	.487	.92	.513	.87
	.292	.87	.287	.88	.313	.80
	.192	.82	.187	.80	.213	.74
	.142	.78	.137	.79	.113	.65
	.092	.73	.087	.77	.063	.60
	.067	.69	.062	.69	.138	.53
	.042	.67	.037	.67	.013	.45
	.017	.62	.012	.60	.413	.86
	.010	.60	-----	-----	-----	-----
	2.6 ft from left wall of flume					
15	0.776	w.s.	.804	w.s.	.771	w.s.
	.726	0.95	.754	.97	.721	.94
	.676	.90	.704	.92	.671	.94
	.476	.87	.604	.90	.471	.92
	.276	.86	.504	.90	.271	.82
	.176	.75	.404	.86	.171	.77
	.126	.73	.304	.82	.121	.71
	.101	.69	.204	.77	.096	.63
	.076	.65	.104	.65	.071	.58
	.051	.63	.079	.52	.046	.58
	.026	.67	.054	.46	.021	.46
	-----	-----	.029	.43	.010	.35
	-----	-----	.004	.30	-----	-----
					5.4 ft from left wall of flume	
18	.673	w.s.	.697	w.s.	0.656	w.s.
	.623	.74	.647	.80	.606	.82
	.573	.78	.597	.80	.556	.79
	.473	.78	.497	.79	.456	.79
	.373	.77	.397	.78	.356	.79
	.273	.72	.297	.77	.256	.76
	.173	.67	.197	.68	.156	.74
	.073	.60	.097	.58	.106	.69
	.048	.52	.072	.51	.056	.62
	.023	.49	.047	.49	.031	.57
	.010	.39	.022	.43	.010	.46
	1.8 ft from left wall of flume					
2	0.703	w.s.	-----	-----	-----	-----
	.603	1.34	-----	-----	-----	-----
	.503	1.32	-----	-----	-----	-----
	.403	1.27	-----	-----	-----	-----
	.303	1.25	-----	-----	-----	-----
	.203	1.24	-----	-----	-----	-----
	.103	1.22	-----	-----	-----	-----
	4.0 ft from left wall of flume				*4.0 ft from left wall of flume*	
[a] 2	0.727	w.s.	.861	w.s.	0.758	w.s.
	.627	1.44	.761	1.44	.658	1.44
	.527	1.38	.661	1.43	.558	1.43
	.427	1.29	.561	1.39	.458	1.46
	.327	1.29	.461	1.31	.358	1.42
	.227	1.26	.411	1.27	.258	1.37

Run	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)
	4.0 ft from left wall of flume		*4.0 ft from left wall of flume*		*4.0 ft from left wall of flume*	
[a] 2—Con.	0.127	1.24	0.361	1.28	0.158	1.28
	-----	-----	.261	1.24	.058	.87
	-----	-----	.161	1.09	-----	-----
	-----	-----	.061	.95	-----	-----
3	.741	w.s.	-----	-----	-----	-----
	.641	1.42	-----	-----	-----	-----
	.577	1.43	-----	-----	-----	-----
	.513	1.43	-----	-----	-----	-----
	.449	1.38	-----	-----	-----	-----
	.385	1.29	-----	-----	-----	-----
	.321	1.29	-----	-----	-----	-----
	.257	1.29	-----	-----	-----	-----
	.193	1.20	-----	-----	-----	-----
	.161	1.16	-----	-----	-----	-----
	.129	1.13	-----	-----	-----	-----
	.097	1.16	-----	-----	-----	-----
	.065	1.11	-----	-----	-----	-----
	.033	1.02	-----	-----	-----	-----
	1.2 ft from left wall of flume		*2.6 ft from left wall of flume*			
9	0.551	w.s.	0.587	w.s.	0.543	w.s.
	.501	1.25	.537	1.20	.493	1.20
	.401	1.23	.437	1.18	.393	1.11
	.351	1.20	.337	1.13	.343	1.08
	.301	1.18	.287	1.05	.293	1.02
	.251	1.18	.237	.99	.243	.97
	.201	1.16	.187	.97	.193	.90
	.151	1.11	.137	.94	.143	.87
	.101	.99	.087	.84	.093	.84
	.051	.87	.037	.55	.043	.84
	.026	.84	.012	.49	.018	.80
	5.4 ft from left wall of flume		*6.8 ft from left wall of flume*			
9	0.581	w.s.	0.540	w.s.	-----	-----
	.531	1.22	.490	1.25	-----	-----
	.431	1.11	.390	1.23	-----	-----
	.381	1.08	.290	1.16	-----	-----
	.331	1.05	.240	1.11	-----	-----
	.281	1.02	.190	1.08	-----	-----
	.231	.90	.140	1.05	-----	-----
	.181	.87	.090	1.02	-----	-----
	.131	.80	.040	.97	-----	-----
	.081	.73	.015	.87	-----	-----
	2.0 ft from left wall of flume		*4.0 ft from left wall of flume*		*6.0 ft from left wall of flume*	
1	0.650	w.s.	0.650	w.s.	0.650	w.s.
	.625	1.62	.625	1.63	.625	1.62
	.525	1.59	.525	1.60	.525	1.62
	.425	1.55	.425	1.49	.425	1.55
	.325	1.50	.325	1.45	.325	1.52
	.225	1.41	.225	1.39	.225	1.44
	.125	1.36	.125	1.35	.125	1.30
	.025	1.33	.025	1.34	.025	1.01
	2.5 ft from left wall of flume				*5.5 ft from left wall of flume*	
5	0.737	w.s.	.667	w.s.	0.743	w.s.
	.637	1.65	.567	1.70	.643	1.78
	.537	1.62	.467	1.63	.543	1.70
	.437	1.57	.367	1.62	.443	1.70
	.337	1.57	.317	1.60	.343	1.70
	.287	1.51	.267	1.60	.243	1.53
	.237	1.45	.217	1.57	.193	1.55
	.187	1.43	.167	1.49	.143	1.49
	.137	1.25	.117	1.42	.093	1.35
	.087	1.13	.067	1.33	.043	1.25
	.037	.94	.042	1.25	-----	-----
	7.0 ft from left wall of flume					
5	0.757	w.s.	-----	-----	-----	-----
	.657	1.68	-----	-----	-----	-----
	.557	1.67	-----	-----	-----	-----
	.457	1.65	-----	-----	-----	-----
	.357	1.65	-----	-----	-----	-----
	.257	1.62	-----	-----	-----	-----
	.207	1.55	-----	-----	-----	-----
	.157	1.35	-----	-----	-----	-----
	.107	1.29	-----	-----	-----	-----
	.057	1.02	-----	-----	-----	-----
	1.2 ft from left wall of flume		*2.6 ft from left wall of flume*		*4.0 ft from left wall of flume*	
11	0.310	w.s.	0.357	w.s.	0.314	w.s.
	.260	1.00	.311	1.00	.274	1.02
	.210	.97	.261	1.02	.224	.97
	.160	.90	.211	.84	.174	.94
	.135	.90	.186	.90	.149	.90
	.110	.87	.161	.84	.124	.90
	.085	.87	.136	.80	.099	.84
	.060	.80	.111	.77	.074	.80
	.035	.77	.086	.77	.049	.80
	.010	.69	.061	.74	.024	.77
	-----	-----	.036	.74	-----	-----
	-----	-----	.011	.60	-----	-----

See footnote at end of table, p. I86.

TABLE 15.—*Velocity-profile data for 0.45-mm sand in 8-foot-wide flume*—Continued

Run	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)
	5.4 ft from left wall of flume		*6.8 ft from left wall of flume*		*4.0 ft from left wall of flume*	
11—Con.	0.390	w.s.	0.271	w.s.		
	.340	1.00	.221	0.99		
	.290	.90	.171	.97		
	.240	.90	.121	.90		
	.215	.90	.096	.87		
	.190	.87	.071	.84		
	.165	.87	.046	.80		
	.140	.80	.021	.80		
	.115	.84	.001	.49		
	.090	.77				
	.065	.77				
	.040	.77				
	.015	.69				
	1.2 ft from left wall of flume		*2.5 ft from left wall of flume*			
4	0.648	w.s.	0.648	w.s.	0.661	w.s.
	.548	1.87	.548	1.81	.561	1.76
	.448	1.84	.448	1.79	.461	1.76
	.348	1.79	.348	1.78	.361	1.72
	.298	1.81	.298	1.73	.261	1.55
	.248	1.76	.248	1.78	.211	1.57
	.198	1.72	.198	1.72	.161	1.53
	.148	1.65	.148	1.62	.111	1.53
	.098	1.51	.098	1.62	.061	1.49
	.048	1.47	.048	1.58	.011	1.47
	5.5 ft from left wall of flume		*7.0 ft from left wall of flume*			
4	0.665	w.s.	0.678	w.s.		
	.565	1.73	.578	1.55		
	.465	1.73	.478	1.53		
	.365	1.70	.378	1.43		
	.265	1.62	.278	1.42		
	.215	1.53	.228	1.42		
	.165	1.51	.178	1.35		
	.115	1.45	.128	1.33		
	.065	1.29	.078	1.31		
	.015	1.25	.028	1.29		
	1.2 ft from left wall of flume		*2.6 ft from left wall of flume*			
8	0.461	w.s.	0.444	w.s.	.493	w.s.
	.411	1.29	.393	1.33	.450	1.25
	.311	1.27	.293	1.31	.350	1.22
	.261	1.20	.243	1.27	.300	1.20
	.211	1.08	.193	1.25	.250	1.18
	.161	1.05	.143	1.16	.200	1.11
	.111	.99	.093	1.11	.150	1.02
	.061	.87	.043	1.02	.100	.99
	.011	.73			.050	.84
	5.4 ft from left wall of flume		*6.8 ft from left wall of flume*			
8	0.421	w.s.	0.511	w.s.		
	.419	1.25	.461	1.27		
	.319	1.22	.361	1.25		
	.219	1.18	.261	1.11		
	.169	1.08	.211	1.08		
	.119	1.02	.161	1.02		
	.069	.97	.111	.99		
	.019	.84	.061	.90		
			.011	.35		
	2.5 ft from left wall of flume		*4.0 ft from left wall of flume*		*6.1 ft from left wall of flume*	
7	0.632	w.s.	0.698	w.s.	0.606	w.s.
	.532	1.60	.598	1.88	.506	1.75
	.432	1.62	.498	1.93	.406	1.65
	.332	1.60	.398	1.79	.306	1.65
	.232	1.62	.298	1.84	.206	1.62
	.182	1.53	.198	1.82	.156	1.60
	.132	1.58	.158	1.84	.106	1.49
	.082	1.57	.098	1.79	.056	.84
	.032	1.29	.058	1.78	.006	.49
	1.2 ft from left wall of flume		*2.6 ft from left wall of flume*		*4.0 ft from left wall of flume*	
10	0.279	w.s.	0.302	w.s.	0.245	w.s.
	.229	1.08	.252	0.99	.195	1.18
	.179	1.02	.202	.94	.145	1.11
	.154	.99	.177	.90	.120	1.05
	.129	.94	.152	.90	.095	.97
	.104	.90	.127	.84	.070	.94
	.079	.87	.102	.84	.045	.90
	.054	.80	.077	.80	.020	.87
	.029	.35	.052	.80	.010	.73
	.004	.28	.027	.77		
			.002	.35		
	5.4 ft from left wall of flume		*6.8 ft from left wall of flume*			
10	0.273	w.s.	0.346	w.s.		
	.223	1.13	.296	1.08		
	.173	1.11	.246	1.08		
	.148	1.08	.196	.99		
	.123	1.02	.171	.99		
	.098	.99	.146	.97		
	.073	.97	.121	.94		
	.048	.90	.096	.87		
	.023	.80	.071	.84		
	.008	.65	.046	.69		
			.021	.42		

Run	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)
	1.2 ft from left wall of flume		*2.5 ft from left wall of flume*		*4.0 ft from left wall of flume*	
6	0.445	w.s.	0.500	w.s.	0.457	w.s.
	.395	1.45	.450	1.47	.350	1.42
	.345	1.43	.400	1.45	.250	1.31
	.295	1.42	.350	1.38	.200	1.23
	.245	1.40	.300	1.33	.150	1.16
	.195	1.33	.250	1.29	.100	1.02
	.145	1.31	.200	1.23	.050	.97
	.095	1.02	.175	1.20	.025	.69
	.070	.84	.150	1.11		
	.045	.65	.125	1.05		
			.100	.90		
	5.5 ft from left wall of flume		*7.0 ft from left wall of flume*			
6	0.477	w.s.	0.486	w.s.		
	.427	1.38	.436	1.31		
	.377	1.33	.386	1.23		
	.327	1.33	.336	1.27		
	.277	1.20	.286	1.18		
	.227	1.16	.236	1.20		
	.177	1.11	.186	1.13		
	.127	.99	.136	1.05		
	.102	.94	.086	.94		
	.077	.87	.061	.84		
	.052	.69	.036	.65		
	4.0 ft from left wall of flume					
12	0.237	w.s.				
	.189	1.22				
	.139	1.16				
	.114	1.11				
	.089	1.08				
	.064	1.05				
	.039	.97				
	.014	.90				
	2.0 ft from left wall of flume		*4.0 ft from left wall of flume*		*6.0 ft from left wall of flume*	
19	0.423	w.s.	0.433	w.s.	0.285	w.s.
	.408	1.49	.418	1.42	.270	1.58
	.308	1.58	.318	1.53	.170	1.67
	.208	1.51	.268	1.55	.120	1.63
	.158	1.42	.218	1.42	.095	1.51
	.108	1.33	.193	1.55	.070	1.45
	.083	1.22	.168	1.47	.045	1.33
	.058	1.20	.143	1.42	.020	1.20
	.033	.80	.118	1.35	.010	.94
			.093	1.25		
			.068	1.16		
			.043	1.18		
			.018	1.18		
21	1.016	w.s.	.760	w.s.	1.095	w.s.
	.916	1.58	.660	1.92	.995	1.70
	.866	1.60	.560	1.86	.895	1.75
	.816	1.60	.460	1.75	.795	1.70
	.716	1.58	.360	1.58	.745	1.65
	.516	1.62	.260	1.51	.695	1.61
	.416	1.67	.160	1.51	.595	1.60
	.316	1.20	.060	1.38	.495	1.55
	.266	1.11	.010	1.27	.395	1.22
	.216	.73			.295	1.22
	.166	.55			.195	1.22
	.116	.49			.145	.99
					.095	.69
20	.555	w.s.	.740	w.s.	.655	w.s.
	.540	1.81	.720	1.70	.635	1.75
	.440	1.84	.620	1.88	.535	1.90
	.340	1.79	.520	1.85	.435	1.91
	.240	1.58	.470	1.79	.335	1.91
	.140	1.47	.420	1.72	.285	1.85
	.090	1.35	.370	1.72	.235	1.73
	.040	1.20	.320	1.68	.185	1.63
	.015	.97	.270	1.68	.160	1.65
			.220	1.57	.135	1.55
			.170	1.43	.110	1.47
			.145	1.60	.085	1.38
			.120	1.56	.060	1.29
			.095	1.38	.035	1.16
			.070	1.40	.010	1.05
			.045	1.13		
			.010	.87		
23	.660	w.s.	1.080	w.s.	.700	w.s.
	.610	2.78	1.030	2.44	.650	2.62
	.510	2.88	.930	2.44	.550	2.68
	.410	2.82	.830	2.50	.450	2.70
	.310	2.86	.730	2.48	.350	2.60
	.210	2.78	.630	2.46	.250	2.76
	.160	2.76	.580	2.40	.200	2.70
	.110	2.70	.530	2.37	.150	2.64
	.060	2.62	.480	2.40	.100	2.60
	.035	2.60	.455	2.54	.050	2.31

TABLE 15.—*Velocity-profile data for 0.45-mm sand in 8-foot-wide flume*—Continued

Run	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)
	2.0 ft from left wall of flume		*4.0 ft from left wall of flume*		*6.0 ft from left wall of flume*	
23—Con.	0.010	2.37	0.430	2.40	0.025	2.16
			.405	2.37	.010	1.88
			.330	2.44		
			.230	2.29		
			.130	2.42		
22	.965	w.s.	1.088	w.s.	1.114	w.s.
	.865	1.75	.988	1.95	1.014	1.98
	.765	1.85	.888	1.92	.914	1.94
	.665	1.75	.788	1.94	.814	2.05
	.465	1.68	.588	1.79	.714	2.03
	.265	1.67	.388	1.72	.514	1.73
	.215	1.60	.288	1.65	.464	1.63
	.165	1.55	.238	1.62	.414	1.33
	.115	1.55	.188	1.35	.314	1.27
	.065	1.55	.138	1.51	.214	1.20
			.088	1.47	.114	1.13
			.038	1.22	.010	.84
25	.484	w.s.	.351	w.s.	.270	w.s.
	.409	1.78	.301	2.02	.220	2.11
	.384	1.78	.251	1.98	.170	2.09
	.334	1.76	.201	1.91	.120	2.10
	.284	1.68	.151	1.94	.070	2.09
	.234	1.73	.126	1.92	.045	1.91
	.184	1.78	.101	1.91	.020	1.73
	.159	1.76	.076	1.76	.005	1.67
	.134	1.79	.051	1.72		
	.109	1.78	.026	1.58		
	.084	1.72				
	.059	1.55				
	.034	1.45				
24	.570	w.s.	.750	w.s.	.294	w.s.
	.470	2.80	.650	1.95	.194	2.94
	.370	2.82	.600	1.82	.144	2.92
	.320	2.66	.500	1.68	.094	2.70
	.270	2.56	.400	1.67	.044	2.50
	.220	2.48	.300	1.79	.019	2.05
	.170	2.48	.250	1.76		
	.120	2.36	.200	1.68		
	.070	2.22	.150	1.20		
	.020	2.12	.100	.77		
			.050	.73		
			.023	.60		
40	1.300	w.s.	.936	w.s.	.728	w.s.
	1.280	3.96	.900	3.08	.650	3.42
	1.180	3.83	.700	3.36	.600	3.67
	.980	3.64	.500	3.30	.550	3.60
	.780	3.87	.400	3.34	.450	3.44
	.580	3.45	.300	3.08	.350	3.75
	.480	2.15	.200	3.18	.250	3.79
	.380	1.82	.100	3.05	.150	3.71
	.280	.00	.050	2.62	.100	3.32
	.180	.00	.025	2.05	.050	2.92
					.025	2.56
39	.570	w.s.	.540	w.s.	.640	w.s.
	.550	5.45	.500	5.60	.600	5.40
	.500	5.19	.400	5.34	.550	5.10
	.400	5.22	.300	5.20	.450	5.00
	.300	5.04	.200	4.59	.350	4.80
	.200	4.85	.100	4.04	.250	4.74
	.100	4.27	.050	3.63	.150	4.20
	.050	3.74	.025	2.52	.100	3.85
	.025	2.54			.050	3.41
					.025	1.18
26	.500	w.s.	.460	w.s.	.485	w.s.
	.480	4.71	.450	4.47	.455	4.53
	.410	4.26	.350	4.48	.405	4.62
	.310	3.83	.250	4.23	.305	4.27
	.210	3.73	.200	4.07	.205	4.21
	.160	3.65	.150	3.98	.155	3.78
	.110	3.50	.100	3.50	.105	3.61
	.060	2.98	.050	3.24	.055	3.19
	.040	2.46	.030	2.96	.035	2.62
	.020	1.35	.010	1.25	.015	2.68
28	.408	w.s.	.343	w.s.	.395	w.s.
	.358	5.10	.323	4.25	.345	4.35
	.308	5.10	.273	3.85	.295	4.17
	.258	4.32	.223	3.86	.245	3.89
	.208	4.55	.173	3.74	.195	3.75
	.158	3.87	.123	3.73	.145	3.58
	.108	3.98	.073	3.71	.120	3.39
	.058	3.49	.023	3.09	.095	3.35
					.070	3.21
					.045	2.78
					.020	1.35
29	.304	w.s.	.370	w.s.	.325	w.s.
	.254	2.70	.320	2.96	.275	2.44
	.204	2.60	.270	2.64	.225	2.35
	.154	2.54	.270	2.35	.175	2.42
	.129	2.31	.220	2.37	.125	2.24
	.104	2.40	.170	2.66	.100	1.98

Run	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)
	2.0 ft from left wall of flume		*4.0 ft from left wall of flume*		*6.0 ft from left wall of flume*	
29—Con.	0.079	1.97	0.145	2.52	0.075	1.98
	.054	1.78	.120	2.40	.050	1.92
	.029	1.35	.095	2.38	.025	1.31
	.004	.73	.070	2.19		
			.045	1.92		
			.020	1.60		
31			.335	w.s.	.370	w.s.
			.325	4.87	.300	4.61
			.275	4.84	.250	4.38
			.225	4.61	.200	4.38
			.175	4.60	.150	3.91
			.125	4.38	.100	4.09
			.075	3.87	.050	3.64
			.050	3.33	.025	3.50
			.025	2.29		
27	.293	w.s.	.323	w.s.	.319	w.s.
	.243	3.75	.273	3.71	.269	3.83
	.193	3.55	.223	3.64	.169	3.19
	.143	3.41	.173	3.51	.119	2.78
	.093	3.24	.123	3.46	.069	2.28
	.068	3.02	.073	2.74	.044	1.79
	.043	2.82	.048	2.39	.019	1.25
	.018	2.00	.023	2.36		
36	.190	w.s.	.170	w.s.	.160	w.s.
	.130	1.97	.150	2.44	.140	2.31
	.115	2.06	.130	2.24	.115	2.44
	.090	1.87	.105	2.08	.090	2.42
	.065	1.95	.080	1.87	.065	2.42
	.040	1.53	.055	1.67	.040	2.21
	.020	1.53	.030	1.05	.020	2.31
	.010	1.47	.020	1.38	.010	1.73
			.010	1.55		
	2.5 ft from left wall of flume					
41	0.614	w.s.	.510	w.s.	.499	w.s.
	.550	5.50	.490	6.09	.479	5.74
	.500	5.50	.450	5.82	.450	5.65
	.400	5.40	.350	5.61	.350	5.30
	.300	5.19	.250	5.39	.250	5.35
	.200	4.86	.200	5.02	.200	5.03
	.150	4.80	.150	4.82	.150	4.75
	.100	4.17	.100	4.38	.100	4.43
	.050	3.74	.050	3.77	.050	3.85
	.025	1.45	.025	2.64	.025	3.35
	2.0 ft from left wall of flume					
30	0.225	w.s.	.281	w.s.	.265	w.s.
	.175	3.06	.231	3.31	.225	3.13
	.150	2.90	.181	3.27	.200	2.72
	.125	2.62	.131	2.90	.175	3.06
	.100	2.60	.081	2.54	.150	2.98
	.075	2.46	.056	2.60	.125	2.97
	.050	2.12	.031	1.87	.100	2.76
	.025	1.68	.006	2.25	.075	2.60
					.050	2.12
					.025	1.25
35	.260	w.s.	.203	w.s.	.229	w.s.
	.200	3.76	.173	3.12	.200	3.45
	.175	3.71	.173	3.57	.175	3.23
	.150	3.52	.148	3.17	.150	3.28
	.125	3.25	.123	3.16	.125	3.01
	.100	3.40	.098	3.18	.100	2.86
	.075	2.54	.073	2.82	.075	2.64
	.050	2.44	.048	2.12	.050	1.90
	.025	2.06			.025	1.72
34	.280	w.s.	.250	w.s.	.300	w.s.
	.200	4.33	.200	4.53	.250	4.23
	.150	3.97	.150	4.27	.200	4.20
	.100	3.58	.100	3.60	.150	3.90
	.050	3.44	.050	3.27	.100	3.59
	.025	3.39	.025	2.54	.050	3.16
					.025	2.52
33	.340	w.s.	.305	w.s.	.300	w.s.
	.280	4.34	.225	4.52	.250	4.40
	.230	4.45	.175	4.30	.190	4.40
	.180	4.08	.125	3.85	.150	4.33
	.130	3.97	.075	3.50	.100	3.76
	.080	3.74	.050	3.10	.050	3.50
	.055	3.52	.025	2.83	.025	3.06
	.030	3.10				
38	.510	w.s.	.500	w.s.	.490	w.s.
	.450	6.13	.450	5.57	.450	6.13
	.400	6.08	.350	5.70	.400	6.06
	.300	5.70	.250	5.50	.350	6.19
	.200	5.19	.200	5.33	.250	5.69
	.150	5.18	.150	5.02	.200	5.45
	.100	5.09	.100	4.89	.150	5.30
	.050	5.02	.050	4.73	.100	4.83
	.025	3.89	.025	3.56	.050	4.56
					.025	3.44

TABLE 15.—*Velocity-profile data for 0.45-mm sand in 8-foot-wide flume*—Continued

Run	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)
	2.0 ft from left wall of flume		*4.0 ft from left wall of flume*		*6.0 ft from left wall of flume*	
37	0.500	w.s.	0.500	w.s.	0.480	w.s.
	.450	6.10	.450	5.65	.425	5.20
	.350	5.81	.425	5.71	.400	5.20
	.250	5.75	.325	5.54	.350	5.49
	.200	5.75	.225	5.15	.300	5.49
	.150	5.20	.125	4.66	.200	4.95
	.100	4.57	.075	4.38	.100	4.56
	.050	3.77	.050	3.60	.050	4.32
	.025	1.58	.025	3.15	.025	4.06
32			.345	w.s.	.380	w.s.
			.275	5.44	.340	5.03
			.225	5.24	.290	5.25
			.175	4.93	.240	5.25
			.125	4.81	.190	4.85
			.075	4.53	.140	4.62
			.050	4.29	.090	4.53
			.025	3.95	.050	4.03
					.025	2.60
45	.185	w.s.	.190	w.s.	.215	w.s.
	.160	3.94	.160	4.08	.200	3.97
	.135	3.95	.135	3.85	.175	3.87
	.110	3.79	.110	3.79	.150	3.68
	.085	3.58	.085	3.52	.125	3.50

Run	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)
	2.0 ft from left wall of flume		*4.0 ft from left wall of flume*		*6.0 ft from left wall of flume*	
45—Con.	0.060	3.49	0.060	3.63	0.100	3.26
	.035	3.34	.035	3.31	.075	2.98
	.010	2.94	.010	2.72	.050	2.48
					.025	1.65
44	.302	w.s.	.300	w.s.	.255	w.s.
	.200	5.70	.239	5.40	.210	5.29
	.175	5.70	.214	5.30	.185	5.11
	.125	4.81	.189	5.45	.135	4.93
	.075	5.20	.164	5.02	.085	4.66
	.050	4.45	.139	5.15	.060	4.79
	.025	4.36	.089	4.39	.035	3.97
			.064	4.25		
			.039	4.15		
			.024	3.67		
42					.295	w.s.
					.275	5.85
					.225	5.84
					.175	5.21
					.150	5.20
					.125	5.42
					.100	5.31
					.075	4.76
					.050	4.23
					.025	3.68

[a] These profiles taken 80, 100, and 124 feet from headbox.

TABLE 16.—*Velocity-profile data for 0.93-mm sand in 8-foot-wide flume*

[The lateral section used for measuring was 95-115 ft from the headbox. w.s.=water surface]

Run	2.0 ft from left wall of flume		4.0 ft from left wall of flume		6.0 ft from left wall of flume	
	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)
19	0.980	w.s.	0.974	w.s.	0.972	w.s.
	.930	1.47	.894	1.58	.930	1.49
	.830	1.50	.697	1.55	.830	1.51
	.680	1.50	.547	1.52	.680	1.48
	.530	1.44	.397	1.41	.530	1.45
	.380	1.38	.297	1.35	.380	1.40
	.230	1.32	.197	1.30	.280	1.36
	.130	1.22	.147	1.25	.180	1.27
	.080	1.11	.097	1.13	.130	1.25
	.040	1.04	.057	1.00	.080	1.13
	.020	.94	.027	.93	.050	1.02
					.020	.91
25			.982	w.s.		
			.905	1.82		
			.855	1.81		
			.755	1.75		
			.655	1.74		
			.555	1.70		
			.455	1.66		
			.355	1.62		
			.255	1.51		
			.155	1.47		
			.105	1.33		
			.065	1.28		
			.030	1.10		
26			1.008	w.s.		
			.955	1.98		
			.855	1.97		
			.755	1.92		
			.655	1.91		
			.555	1.86		
			.455	1.78		
			.355	1.70		
			.255	1.67		
			.155	1.55		
			.105	1.47		
			.065	1.39		
			.030	1.15		
27			1.005	w.s.		
			.975	2.02		
			.875	1.97		
			.775	1.97		
			.625	1.93		
			.525	1.87		
			.475	1.83		
			.375	1.77		
			.275	1.71		
			.175	1.67		
			.125	1.55		
			.075	1.35		
			.035	1.09		
			.005	.69		
20			.980	w.s.		
			.950	2.00		
			.900	2.00		
			.800	2.01		
			.700	1.96		
			.600	1.92		
			.500	1.86		
			.400	1.81		

Run	2.0 ft from left wall of flume		4.0 ft from left wall of flume		6.0 ft from left wall of flume	
	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)
20—Con.			0.300	1.75		
			.200	1.64		
			.150	1.57		
			.100	1.44		
			.050	1.25		
			.030	1.16		
			.010	.80		
21					0.985	w.s.
					.955	2.23
					.905	2.21
					.805	2.17
					.705	2.14
					.605	2.10
					.505	2.06
					.405	1.99
					.305	1.86
					.205	1.80
					.165	1.79
					.125	1.68
					.085	1.53
					.045	1.31
					.025	1.19
					.015	1.01
18	.900	w.s.	1.060	w.s.	1.012	w.s.
	.870	2.23	1.030	2.23	.982	2.29
	.770	2.22	.900	2.22	.882	2.30
	.670	2.18	.750	2.13	.782	2.27
	.520	2.10	.650	2.13	.682	2.25
	.370	2.06	.550	2.06	.582	2.22
	.270	1.94	.450	1.97	.482	2.16
	.170	1.81	.350	1.92	.382	2.07
	.120	1.72	.250	1.88	.282	1.98
	.070	1.63	.200	1.84	.182	1.91
	.020	1.06	.150	1.74	.132	1.81
			.100	1.49	.082	1.68
			.060	1.37	.052	1.65
			.030	1.23	.022	1.41
28	1.045	w.s.	1.040	w.s.	1.025	w.s.
	.995	2.25	.950	2.33	.975	2.30
	.895	2.21	.750	2.27	.825	2.30
	.695	2.15	.550	2.19	.675	2.25
	.495	2.06	.400	2.12	.575	2.17
	.395	2.00	.300	2.02	.475	2.13
	.295	1.97	.200	1.90	.375	2.09
	.195	1.84	.150	1.83	.275	2.00
	.145	1.78	.100	1.72	.175	1.85
	.095	1.72	.060	1.60	.125	1.75
	.055	1.56	.030	1.40	.075	1.64
	.025	1.44			.035	1.46
29			.480	w.s.		
			.450	1.65		
			.400	1.64		
			.350	1.63		
			.300	1.60		
			.250	1.53		
			.200	1.49		
			.150	1.45		
			.100	1.40		
			.070	1.34		
			.040	1.21		

TABLE 16.—*Velocity-profile data for 0.9-3mm sand in 8-foot-wide flume*—Continued

Run	2.0 ft from left wall of flume		4.0 ft from left wall of flume		6.0 ft from left wall of flume	
	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)
29—Con.			0.020	1.10		
			.010	1.01		
22			.459	w.s.		
			.429	1.65		
			.379	1.62		
			.329	1.61		
			.279	1.59		
			.229	1.54		
			.179	1.52		
			.129	1.41		
			.079	1.32		
			.044	1.25		
			.024	1.16		
30			.496	w.s.		
			.466	1.78		
			.416	1.75		
			.366	1.74		
			.316	1.68		
			.266	1.66		
			.216	1.61		
			.166	1.56		
			.116	1.49		
			.076	1.38		
			.046	1.28		
			.026	1.13		
			.008	.99		
31	0.485	w.s.	.505	w.s.	0.500	w.s.
	.450	1.80	.470	1.80	.470	1.80
	.420	1.78	.400	1.76	.420	1.78
	.370	1.76	.340	1.74	.370	1.77
	.320	1.74	.290	1.68	.320	1.77
	.270	1.72	.240	1.63	.270	1.68
	.220	1.64	.190	1.60	.220	1.68
	.170	1.62	.140	1.48	.170	1.62
	.120	1.49	.090	1.43	.130	1.55
	.080	1.45	.050	1.23	.090	1.45
	.050	1.29	.020	1.08	.060	1.37
	.020	.96			.040	1.24
					.020	1.12
15	.935	w.s.	1.013	w.s.	1.077	w.s.
	.900	2.48	.950	2.50	1.050	2.60
	.750	2.51	.750	2.41	.950	2.52
	.550	2.51	.550	2.26	.750	2.39
	.400	2.40	.400	2.26	.550	2.30
	.300	2.24	.300	2.01	.400	2.14
	.200	2.18	.200	1.91	.300	2.08
	.150	2.13	.150	1.91	.200	1.98
	.100	2.09	.100	.88	.150	1.93
	.060	1.87	.060	1.85	.100	1.80
	.030	1.82	.030	1.83	.060	1.73
					.030	1.75
23					.480	w.s.
					.450	1.87
					.400	1.83
					.350	1.82
					.300	1.76
					.250	1.70
					.200	1.64
					.150	1.62
					.120	1.55
					.090	1.48
					.060	1.40
					.030	1.20
					.010	.95
32	.510	w.s.	.490	w.s.	.500	w.s.
	.490	2.03	.470	2.08	.470	2.01
	.440	2.03	.430	2.06	.420	2.02
	.390	2.05	.380	2.00	.370	2.00
	.340	2.01	.330	1.97	.320	1.98
	.290	1.99	.280	1.95	.270	1.95
	.240	1.97	.230	1.90	.220	1.92
	.190	1.91	.180	1.84	.170	1.85
	.140	1.86	.130	1.75	.130	1.80
	.100	1.76	.090	1.67	.100	1.71
	.070	1.65	.060	1.55	.070	1.63
	.040	1.51	.030	1.29	.040	1.47
	.030	1.39	.010	1.22	.010	1.21
	.010	1.23				
24					.490	w.s.
					.460	1.98
					.410	2.01
					.360	1.92
					.310	1.91
					.260	1.88
					.210	1.78
					.160	1.73
					.110	1.60
					.070	1.49
					.040	1.37
					.020	1.21

Run	2.0 ft from left wall of flume		4.0 ft from left wall of flume		6.0 ft from left wall of flume	
	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)
14	0.562	w.s.	0.548	w.s.	0.577	w.s.
	.540	2.16	.530	2.17	.560	2.13
	.480	2.13	.480	2.18	.520	2.14
	.430	2.10	.430	2.16	.470	2.14
	.380	2.06	.380	2.13	.420	2.09
	.330	2.03	.330	2.08	.370	2.08
	.280	1.94	.290	1.99	.320	1.99
	.240	1.92	.250	1.98	.280	1.98
	.200	1.85	.210	1.97	.240	1.92
	.160	1.80	.180	1.89	.200	1.86
	.130	1.72	.150	1.84	.160	1.79
	.100	1.66	.120	1.77	.130	1.70
	.070	1.56	.090	1.68	.100	1.62
	.040	1.35	.060	1.62	.070	1.54
	.020	1.26	.030	1.49	.040	1.41
					.020	1.37
34	.540	w.s.	.530	w.s.	.510	w.s.
	.510	2.21	.500	2.28	.480	2.30
	.460	2.20	.450	2.24	.430	2.27
	.410	2.18	.400	2.18	.380	2.24
	.360	2.15	.350	2.13	.330	2.12
	.310	2.10	.300	2.11	.280	2.04
	.260	2.02	.250	1.99	.230	2.04
	.210	1.98	.200	1.90	.180	1.92
	.160	1.88	.150	1.86	.130	1.82
	.110	1.78	.110	1.79	.080	1.71
	.060	1.66	.070	1.58	.050	1.60
	.030	1.47	.040	1.38	.030	1.45
	.010	1.31	.020	.96	.010	1.22
16	1.006	w.s.	.993	w.s.	.995	w.s.
	.950	2.55	.966	2.71	.900	2.74
	.800	2.46	.866	2.66	.700	2.66
	.700	2.44	.666	2.60	.500	2.50
	.600	2.39	.466	2.36	.400	2.40
	.500	2.26	.316	2.13	.300	2.23
	.400	2.15	.216	1.94	.250	2.30
	.300	2.00	.166	1.88	.200	2.07
	.200	1.90	.116	1.83	.150	2.02
	.150	1.76	.066	1.75	.100	1.95
	.100	1.57	.016	1.43	.060	1.94
	.060	1.37			,030	1.79
	.030	1.30				
35	.580	w.s.	.560	w.s.	.550	w.s.
	.540	2.20	.510	2.43	.520	2.42
	.490	2.21	.460	2.42	.470	2.44
	.440	2.28	.410	2.34	.420	2.36
	.390	2.24	.360	2.32	.370	2.32
	.340	2.25	.310	2.36	.320	2.29
	.290	2.16	.260	2.26	.270	2.14
	.240	2.16	.210	2.20	.220	2.06
	.190	2.12	.160	1.98	.170	1.97
	.140	2.00	.110	1.47	.120	1.78
	.110	1.86	.070	1.12	.070	1.58
	.080	1.81	.040	.98	.040	1.48
	.050	1.56	.010	.93	.010	1.33
	.010	.74				
17	1.196	w.s.	.948	w.s.	.890	w.s.
	1.160	2.67	.900	2.66	.860	2.99
	1.060	2.62	.800	2.65	.790	2.96
	.960	2.55	.700	2.57	.690	2.91
	.860	2.51	.600	2.55	.590	2.90
	.760	2.47	.500	2.55	.490	2.87
	.660	2.44	.400	2.47	.390	2.84
	.560	2.34	.300	2.33	.290	2.71
	.460	2.21	.200	2.12	.240	2.60
	.360	2.11	.150	2.00	.190	2.37
	.310	2.11	.100	2.02	.140	2.32
	.260	2.08	.060	1.99	.090	2.18
	.210	1.88	.030	1.84	.060	2.11
	.160	.84			.030	1.85
	.160	.64				
	.060	.58				
33	.500	w.s.	.460	w.s.	.510	w.s.
	.470	2.34	.420	2.63	.450	2.56
	.440	2.30	.370	2.67	.400	2.52
	.390	2.31	.320	2.65	.350	2.48
	.340	2.26	.270	2.61	.300	2.30
	.290	2.23	.220	2.53	.250	2.31
	.240	2.18	.170	2.42	.200	2.18
	.190	2.15	.120	2.36	.150	2.16
	.140	2.15	.080	2.20	.100	2.01
	.090	2.05	.050	2.08	.060	2.00
	.050	1.88	.020	1.79	.030	1.80
	.020	1.62				
5	1.105	w.s.	1.025	w.s.	.955	w.s.
	1.050	2.85	1.000	2.74	.875	2.71
	.950	2.75	.845	2.65	.675	2.76
	.750	2.52	.695	2.61	.525	2.64
	.600	2.52	.545	2.40	.375	2.47
	.500	2.48	.395	2.26	.275	2.51

TABLE 16.—*Velocity-profile data for 0.93-mm sand in 8-foot-wide flume*—Continued

Run	2.0 ft from left wall of flume		4.0 ft from left wall of flume		6.0 ft from left wall of flume	
	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)
5—Con.	0.400	2.44	0.295	2.13	0.175	2.36
	.300	.71	.195	1.95	.125	2.23
	.200	.52	.145	1.58	.075	2.01
	.150	.51	.095	.58	.050	1.98
	.100	.41	.055	.58	.025	2.14
	.060	.45	.025	.73	-----	-----
	.030	.49	-----	-----	-----	-----
10	.380	w.s.	.452	w.s.	-----	-----
	.350	2.63	.390	2.72	-----	-----
	.300	2.63	.340	2.70	-----	-----
	.250	2.60	.300	2.67	-----	-----
	.210	2.59	.260	2.70	-----	-----
	.170	2.56	.220	2.47	-----	-----
	.140	2.53	.180	2.47	-----	-----
	.110	2.49	.140	2.49	-----	-----
	.080	2.37	.100	2.49	-----	-----
	.050	2.32	.070	2.47	-----	-----
	.020	2.25	.030	2.52	-----	-----
37	-----	-----	.950	w.s.	-----	-----
	-----	-----	.860	3.26	-----	-----
	-----	-----	.760	3.10	-----	-----
	-----	-----	.610	3.03	-----	-----
	-----	-----	.460	2.99	-----	-----
	-----	-----	.310	2.69	-----	-----
	-----	-----	.210	2.50	-----	-----
	-----	-----	.110	2.07	-----	-----
	-----	-----	.060	1.29	-----	-----
	-----	-----	.030	1.09	-----	-----
36	.425	w.s.	.450	w.s.	0.425	w.s.
	.380	2.67	.420	2.24	.370	1.66
	.330	2.69	.390	2.66	.320	2.70
	.280	2.76	.340	2.52	.270	2.61
	.230	2.49	.290	2.35	.220	2.27
	.180	2.58	.240	2.36	.170	2.43
	.130	2.51	.190	2.36	.120	2.61
	.080	2.47	.140	2.26	.080	2.55
	.050	2.43	.090	2.43	.050	2.51
	.020	2.15	.050	2.12	.020	2.80
	-----	-----	.020	2.05	-----	-----
6	1.010	w.s.	.965	w.s.	-----	-----
	.950	3.53	.900	3.20	-----	-----
	.800	3.53	.700	3.11	-----	-----
	.650	3.37	.550	3.20	-----	-----
	.500	3.11	.400	2.94	-----	-----
	.460	2.64	.300	3.11	-----	-----
	.300	1.74	.200	2.64	-----	-----
	.200	2.42	.150	2.85	-----	-----
	.150	2.08	.180	2.42	-----	-----
	.100	2.16	.050	1.70	-----	-----
	.060	2.04	-----	-----	-----	-----
	.030	2.23	-----	-----	-----	-----
7	.411	w.s.	.505	w.s.	.555	w.s.
	.350	3.19	.470	3.23	.520	2.81
	.300	3.18	.420	3.19	.420	2.75
	.250	3.13	.370	2.98	.320	2.76
	.200	3.06	.320	2.82	.220	2.70
	.150	3.03	.270	2.54	.170	2.57
	.100	2.57	.220	2.44	.120	2.66
	.060	2.30	.170	1.97	.080	2.60
	.030	2.40	.120	1.53	.050	2.55
	-----	-----	.100	1.82	.020	2.48
	-----	-----	.060	1.84	-----	-----
	-----	-----	.030	1.76	-----	-----
38	-----	-----	1.010	w.s.	-----	-----
	-----	-----	.880	3.64	-----	-----
	-----	-----	.800	4.02	-----	-----
	-----	-----	.650	3.68	-----	-----
	-----	-----	.500	3.52	-----	-----
	-----	-----	.350	3.39	-----	-----
	-----	-----	.200	2.60	-----	-----
	-----	-----	.100	2.41	-----	-----
	-----	-----	.060	.51	-----	-----
11	.870	w.s.	.900	w.s.	.830	w.s.
	.750	4.09	.850	3.90	.750	3.34
	.700	4.09	.700	4.09	.650	3.98
	.550	3.75	.550	4.02	.450	4.16
	.400	3.98	.400	3.90	.300	3.59
	.300	3.82	.300	3.75	.200	2.70
	.200	3.59	.200	3.53	.150	2.55
	.150	3.53	.150	3.57	.100	1.34
	.100	3.06	.100	3.18	.060	1.80
	.060	2.60	.060	3.34	.030	1.75
	.030	0.80	.030	2.88	-----	-----
8	0.550	w.s.	0.422	w.s.	0.372	w.s.
	.500	3.20	.390	3.52	.350	3.20
	.450	3.24	.340	3.52	.300	3.20
	.410	3.31	.300	3.52	.250	3.52
	.370	3.23	.260	3.20	.210	3.12
	.330	3.07	.220	3.08	.170	3.12
	.290	3.00	.180	2.77	.130	2.94
	.250	2.91	.140	2.60	.090	3.20
	.210	2.94	.100	2.41	.060	3.28
	.170	2.71	.060	2.37	.030	.76
	.130	2.61	.030	2.41	-----	-----
	.090	2.35	-----	-----	-----	-----
	.060	2.07	-----	-----	-----	-----
	.030	.88	-----	-----	-----	-----
13	.410	w.s.	.750	w.s.	.540	w.s.
	.350	5.92	.550	4.85	.450	4.96
	.250	5.42	.450	4.85	.350	4.63
	.150	4.52	.350	4.09	.250	3.95
	.100	4.29	.250	4.22	.150	3.54
	.050	4.22	.150	3.52	.100	3.52
	-----	-----	.100	3.37	.050	3.12
	-----	-----	.050	2.64	-----	-----
9	-----	-----	-----	-----	.500	w.s.
	-----	-----	-----	-----	.450	3.75
	-----	-----	-----	-----	.400	3.52
	-----	-----	-----	-----	.350	3.83
	-----	-----	-----	-----	.300	3.45
	-----	-----	-----	-----	.250	3.52
	-----	-----	-----	-----	.200	2.42
	-----	-----	-----	-----	.150	2.65
	-----	-----	-----	-----	.100	2.93
	-----	-----	-----	-----	.060	3.03
	-----	-----	-----	-----	.030	2.75
41	.440	w.s.	.400	w.s.	.420	w.s.
	.410	6.72	.360	5.64	.350	5.96
	.360	6.24	.310	5.78	.300	5.17
	.310	5.21	.260	5.56	.250	4.85
	.260	3.95	.210	4.85	.200	5.12
	.210	3.60	.160	4.58	.150	4.70
	.160	3.25	.110	3.94	.100	4.46
	.120	2.52	.060	2.94	.060	3.82
	.090	2.05	.030	2.18	.030	3.20
	.060	1.14	-----	-----	-----	-----
	.030	2.17	-----	-----	-----	-----
42	.430	w.s.	.430	w.s.	.470	w.s.
	.390	6.88	.380	7.20	.430	7.35
	.340	6.80	.330	6.88	.380	7.13
	.290	6.61	.280	6.68	.330	6.95
	.240	6.38	.230	6.49	.280	6.74
	.190	6.12	.180	6.21	.230	6.46
	.140	5.82	.130	5.74	.180	6.25
	.100	5.42	.090	5.17	.130	5.63
	.060	4.96	.060	3.95	.090	4.02
	.030	3.52	.030	1.36	.060	1.12
	-----	-----	-----	-----	.030	0.38
40	.360	w.s.	.340	w.s.	.300	w.s.
	.310	6.17	.300	6.61	.280	6.53
	.260	5.92	.260	6.25	.260	5.79
	.210	5.60	.210	6.08	.210	5.37
	.160	5.01	.160	5.74	.160	5.17
	.110	3.95	.110	5.32	.110	4.70
	.060	2.66	.060	4.75	.060	4.19
	.030	1.36	.030	2.18	.030	1.36
43	.410	w.s.	.420	w.s.	.400	w.s.
	.380	7.02	.380	7.23	.360	7.61
	.330	6.91	.330	7.23	.310	7.44
	.280	6.76	.280	7.02	.260	7.30
	.230	6.53	.230	6.65	.210	7.02
	.180	6.37	.180	6.27	.160	6.63
	.130	5.87	.130	5.92	.110	6.04
	.080	5.27	.090	5.52	.060	5.01
	.030	3.12	.060	4.40	.030	3.45
	-----	-----	.030	5.13	-----	-----
39	.470	w.s.	.410	w.s.	.450	w.s.
	.430	7.09	.390	7.35	.420	7.41
	.390	6.84	.340	7.16	.400	7.37
	.340	6.63	.290	6.99	.350	7.23
	.290	6.76	.240	6.68	.300	7.06
	.240	6.41	.190	6.30	.250	6.64
	.190	6.16	.140	5.87	.200	6.37
	.140	5.64	.100	5.46	.150	5.78
	.100	5.32	.060	4.22	.100	4.64
	.060	2.64	.030	2.18	.060	3.89
	.030	1.36	-----	-----	.030	.58

TABLE 17.—*Velocity-profile data for 0.32-mm sand in 2-foot-wide flume*

[w.s.=water surface]

Run	0.5 ft from left wall of flume		1.0 ft from left wall of flume		1.5 ft from left wall of flume	
	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)
3	0.522	w.s.	----	----	0.500	w.s.
	.480	2.04	----	----	.450	1.76
	.410	2.04	----	----	.350	1.66
	.310	2.04	----	----	.250	1.54
	.210	2.04	----	----	.150	1.30
	.110	2.04	----	----	.100	1.22
	.060	2.04	----	----	.050	1.10
	.035	2.04	----	----	.025	.91
	.023	1.95	----	----	----	----
	.010	1.94	----	----	----	----
4	.600	w.s.	0.610	w.s.	.550	w.s.
	.550	1.49	.510	1.73	.500	1.59
	.450	1.56	.410	1.72	.400	1.61
	.350	1.45	.310	1.58	.300	1.57
	.250	1.40	.210	1.52	.200	1.31
	.150	1.28	.180	1.54	----	----
	.125	1.24	.135	1.24	----	----
	.100	1.17	.110	1.13	----	----
	.075	1.05	.080	.97	----	----
	.040	1.09	.060	.90	----	----
	.025	.85	.019	.74	----	----
5	.570	w.s.	.575	w.s.	.660	w.s.
	.520	6.57	.525	6.63	.610	5.90
	.420	6.68	.425	6.69	.510	6.20
	.320	6.28	.325	6.41	.410	5.98
	.220	6.02	.225	6.21	.310	5.69
	.120	5.29	.125	5.12	.210	5.20
	.095	4.85	.075	4.12	.160	5.16
	.070	4.70	.050	4.28	.110	4.07
	.045	4.60	.025	4.60	.085	3.80
	.024	4.64	----	----	.060	3.64
	----	----	----	----	.025	2.81
6	.595	w.s.	.675	w.s.	.650	w.s.
	.545	5.88	.625	6.56	.600	5.75
	.445	5.96	.525	6.60	.500	5.97
	.345	5.86	.425	6.68	.400	5.91
	.245	5.72	.325	6.42	.300	5.86
	.145	5.30	.225	6.07	.200	5.56
	.095	5.18	.175	5.60	.150	5.24
	.045	2.76	.150	5.25	.125	4.35
	.020	1.42	.125	4.78	.100	4.15
	----	----	.100	4.45	.075	3.96
	----	----	.075	3.64	.050	3.72
	----	----	.050	2.88	.021	2.76
	----	----	.026	2.29	----	----
21	----	----	.545	w.s.	----	----
	----	----	.495	3.80	----	----
	----	----	.445	3.69	----	----
	----	----	.345	3.64	----	----
	----	----	.245	3.44	----	----
	----	----	.195	3.28	----	----
	----	----	.145	3.29	----	----
	----	----	.120	3.01	----	----
	----	----	.095	3.28	----	----
	----	----	.070	3.07	----	----
	----	----	.045	2.75	----	----
	----	----	.020	1.75	----	----
7	.615	w.s.	.600	w.s.	.610	w.s.
	.565	3.96	.550	3.96	.565	3.67
	.465	4.05	.450	4.14	.465	3.99
	.365	3.70	.350	4.06	.365	3.98
	.265	3.68	.250	3.99	.265	3.63
	.165	3.36	.150	3.47	.165	3.21
	.115	3.37	.100	3.28	.115	2.86
	.090	3.00	.075	2.96	.090	2.63
	.065	2.86	.050	2.94	.065	2.75
	.040	2.60	.022	2.13	.040	2.27
	.019	.87	----	----	.019	1.05
8	.562	w.s.	.620	w.s.	.675	w.s.
	.512	3.65	.570	3.60	.625	2.88
	.412	3.97	.520	3.69	.525	3.14
	.312	3.98	.470	4.41	.425	3.57
	.212	3.51	.420	4.35	.325	3.84
	.112	3.61	.320	4.01	.225	3.32

Run	0.5 ft from left wall of flume		1.0 ft from left wall of flume		1.5 ft from left wall of flume	
	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)
8—Con.	0.062	3.26	0.220	3.88	0.175	3.35
	.037	3.15	.120	3.70	.125	3.33
	.019	2.27	.070	3.69	.075	3.21
	----	----	.045	3.00	.050	2.62
	----	----	.020	2.62	.025	2.20
20	.511	w.s.	.506	w.s.	.592	w.s.
	.500	5.63	.450	6.03	.440	5.93
	.400	5.76	.400	5.98	.400	5.79
	.300	5.66	.300	6.08	.300	5.68
	.200	5.27	.200	5.80	.200	5.11
	.150	5.27	.150	5.36	.150	5.01
	.100	4.74	.100	4.91	.100	4.64
	.075	4.53	.075	4.77	.075	4.50
	.050	4.06	.050	4.31	.050	3.92
	.025	3.39	.025	3.31	.025	3.64
	.010	2.50	.012	2.60	.009	2.85
19	----	----	.585	w.s.	----	----
	----	----	.535	5.93	----	----
	----	----	.435	5.86	----	----
	----	----	.335	5.63	----	----
	----	----	.235	5.36	----	----
	----	----	.185	5.13	----	----
	----	----	.135	4.55	----	----
	----	----	.085	4.09	----	----
	----	----	.060	2.48	----	----
	----	----	.035	1.56	----	----
	----	----	.010	1.98	----	----
10	.531	w.s.	.540	w.s.	.529	w.s.
	.450	5.81	.475	5.21	.475	5.80
	.350	5.70	.375	5.15	.375	5.61
	.250	5.24	.275	4.83	.275	5.29
	.150	4.91	.175	4.80	.175	4.96
	.100	4.85	.125	4.58	.125	4.66
	.050	4.18	.075	4.48	.075	4.48
	.025	3.66	.050	3.96	.050	4.08
	.012	2.17	.025	3.05	.025	3.38
	----	----	.009	2.16	.008	2.36
9	.585	w.s.	.544	w.s.	.544	w.s.
	.535	5.77	.486	6.14	.444	5.81
	.435	5.85	.436	6.00	.344	5.61
	.335	5.83	.386	6.09	.294	5.48
	.285	5.76	.336	6.07	.244	5.47
	.235	5.63	.286	5.82	.194	5.30
	.210	5.38	.236	5.91	.144	5.08
	.185	5.28	.186	5.68	.219	4.65
	.160	5.26	.136	5.31	.094	4.36
	.135	4.93	.111	5.18	.074	3.96
	.110	4.62	.086	4.82	.050	3.04
	.085	4.42	.061	4.20	.025	2.11
	.060	3.78	.036	3.16	.011	1.85
	.035	1.92	.011	1.75	----	----
	.008	1.15	----	----	----	----
12	.643	w.s.	.632	w.s.	.642	w.s.
	.575	5.20	.575	5.25	.575	5.22
	.475	5.27	.475	5.26	.475	5.28
	.375	5.16	.375	5.24	.375	5.21
	.275	4.96	.275	5.18	.275	5.02
	.175	4.80	.175	4.98	.175	4.74
	.125	4.56	.125	4.60	.125	4.46
	.075	4.04	.075	4.26	.075	4.12
	.050	3.70	.050	3.84	.050	3.81
	.025	3.20	.025	3.41	.025	3.13
	.010	2.30	.011	2.27	.009	2.40
11	.546	w.s.	.562	w.s.	.540	w.s.
	.525	5.98	.525	6.03	.525	6.01
	.475	6.07	.475	5.86	.475	6.14
	.375	6.09	.375	5.61	.375	6.03
	.275	5.86	.275	5.45	.275	5.88
	.175	5.37	.175	5.08	.175	5.48
	.125	5.24	.125	4.80	.125	5.61
	.075	4.59	.075	4.40	.075	4.97
	.050	4.05	.050	3.90	.050	4.58
	.025	2.89	.025	3.15	.025	3.61
	.010	1.88	.012	2.60	.009	1.68

TABLE 18.—*Velocity-profile data for 0.33-mm (uniform) sand in 2-foot-wide flume*

[w.s.=water surface]

Run	0.5 ft from left wall of flume		1.0 ft from left wall of flume		1.5 ft from left wall of flume	
	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)
8			0.435	w.s.		
			.390	1.29		
			.340	1.24		
			.290	1.26		
			.240	1.17		
			.190	1.17		
			.140	.95		
			.090	.90		
			.065	.80		
			.040	.71		
			.015	.72		
5			.456	w.s.		
			.420	1.66		
			.400	1.62		
			.350	1.58		
			.250	1.44		
			.200	1.35		
5 Con.			0.150	1.31		
			.100	1.25		
			.060	1.13		
			.030	.83		
1			.520	w.s.		
			.495	4.60		
			.445	4.70		
			.395	4.60		
			.345	4.55		
			.295	4.49		
			.245	4.40		
			.195	4.19		
			.145	4.06		
			.095	3.83		
			.045	3.42		
			.020	3.11		

TABLE 19.—*Velocity-profile data for 0.33-mm (graded) sand in 2-foot-wide flume*

[w.s.=water surface]

Run	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)
	0.5 ft from left wall of flume		*1.0 ft from left wall of flume*		*1.5 ft from left wall of flume*	
16			0.510	w.s.		
			.490	1.25		
			.450	1.25		
			.400	1.19		
			.350	1.16		
			.300	1.13		
			.250	1.13		
			.200	1.10		
			.150	1.10		
			.100	1.10		
			.060	1.10		
			.040	1.19		
			.020	1.22		
6			.548	w.s.		
			.528	0.62		
			.493	.63		
			.480	.60		
			.430	.60		
			.380	.61		
			.330	.59		
			.280	.58		
			.230	.58		
			.180	.56		
			.130	.53		
			.090	.52		
			.060	.52		
			.040	.51		
			.020	.50		
	1.0 ft from left wall of flume					
5	0.493	w.s.	.533	w.s.		
	.490	1.40	.510	1.39		
	.460	1.36	.460	1.37		
	.410	1.42	.410	1.44		
	.360	1.39	.360	1.38		
	.310	1.34	.310	1.33		
	.260	1.30	.260	1.28		
	.210	1.26	.210	1.25		
	.160	1.14	.160	1.20		
	.110	1.07	.110	1.11		
	.070	.93	.070	1.05		
	.040	.79	.040	.90		
	.020	.68	.020	.77		
	0.5 ft from left wall of flume					
1	0.480	w.s.	.498	w.s.	0.530	w.s.
	.430	2.62	.460	2.63	.490	2.51
	.380	2.62	.410	2.66	.440	2.64
	.330	2.59	.360	2.66	.390	2.67
	.280	2.51	.310	2.56	.340	2.64
	.230	2.43	.260	2.56	.290	2.61
	.180	2.33	.210	2.50	.240	2.49
	.130	2.23	.160	2.38	.190	2.36
	.080	1.98	.110	2.25	.140	2.15
	.050	1.83	.060	2.07	.090	2.02
	.030	1.56	.020	1.89	.050	1.77
	.020	1.38	.010	1.64	.030	1.36
					.020	1.15
	1.0 ft from left wall of flume		*1.0 ft from left wall of flume*		*1.0 ft from left wall of flume*	
10	0.444	w.s.				
	.425	2.51				
	.375	2.51				
	.325	2.43				
	.275	2.47				
	.225	2.37				
	.175	2.30				
	.125	2.31				
	.075	1.95				
	.060	1.99				
	.040	1.90				
	.020	1.62				
8	.515	w.s.	0.640	w.s.		
	.495	2.59	.620	1.94		
	.440	2.69	.550	1.85		
	.390	2.66	.500	1.78		
	.340	2.59	.450	1.74		
	.290	2.51	.400	1.68		
	.240	2.44	.350	1.67		
	.190	2.37	.300	1.63		
	.140	2.36	.250	1.54		
	.090	2.15	.200	1.49		
	.050	1.90	.150	1.44		
	.030	1.78	.100	1.43		
	.020	1.62	.060	1.43		
			.040	1.43		
			.020	1.43		
9	.534	w.s.	.560	w.s.	0.621	w.s.
	.514	1.98	.540	2.66	.601	2.06
	.490	2.09	.490	2.81	.540	2.08
	.440	2.11	.440	3.00	.490	2.08
	.390	2.11	.390	2.88	.440	2.04
	.340	2.11	.340	2.97	.390	2.04
	.290	2.15	.290	2.98	.340	1.98
	.240	2.13	.240	3.02	.290	1.96
	.190	2.00	.190	2.97	.240	1.92
	.140	1.91	.140	2.75	.190	1.61
	.090	1.78	.100	2.39	.140	1.60
	.060	1.65	.060	2.14	.090	1.39
	.040	.99	.040	1.97	.060	1.36
	.020	1.14	.020	1.80	.040	1.31
					.020	1.33
7	.630	w.s.				
	.600	1.93				
	.540	1.92				
	.490	1.85				
	.440	1.81				
	.390	1.77				
	.340	1.75				
	.290	1.72				
	.240	1.72				
	.190	1.64				
	.140	1.60				
	.090	1.58				
	.060	1.58				
	.040	1.41				
	.020	1.31				

TABLE 19.—*Velocity-profile data for 0.33-mm (graded) sand in 2-foot-wide flume*—Continued

Run	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)
	1.0 ft from left wall of flume		*1.0 ft from left wall of flume*		*1.5 ft from left wall of flume*	
2			0.528	w.s.		
			.485	3.40		
			.450	3.36		
			.400	3.23		
			.350	3.12		
			.300	3.09		
			.250	2.96		
			.200	2.94		
			.150	2.97		
			.100	2.85		
			.060	2.73		
			.040	2.61		
			.020	2.08		
3			0.540	w.s.		
			.490	3.88		
			.440	3.75		
			.390	3.82		
			.340	3.45		
			.290	3.52		
			.240	3.52		
			.190	3.45		
			.140	3.12		
			.090	2.84		
			.040	2.64		
			.020	2.18		

TABLE 20.—*Velocity-profile data for 0.47-mm sand in 8-foot-wide flume*

[The lateral section used for measuring was 95-115 ft from the headbox. w.s.=water surface; r.f., reversed flow as indicated by negative pressure on manometer]

Run	2.0 ft from left wall of flume		4.0 ft from left wall of flume		6.0 ft from left wall of flume	
	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)
46	0.938	w.s.	1.489	w.s.	1.576	w.s.
	.843	1.94	1.400	2.24	1.481	2.05
	.743	1.95	1.200	2.27	1.381	2.05
	.643	1.92	1.000	2.26	1.181	1.86
	.543	1.86	.800	2.10	.981	1.68
	.443	1.74	.600	r.f.	.781	1.62
	.343	1.23	.225	r.f.	.581	1.62
	.293	0.96	.050	r.f.	.481	1.31
	.243	1.00	.025	.35	.381	.25
	.193	0.94			.281	r.f.
	.143	1.56			.081	r.f.
	.093	1.49			.006	r.f.
	.068	1.22				
	.043	1.31				
	.018	1.30				
47	.710	w.s.	.659	w.s.	.803	w.s.
	.673	1.78	.618	1.98	.753	1.92
	.573	1.74	.518	1.95	.653	1.88
	.473	1.70	.418	1.94	.553	1.87
	.373	1.65	.318	1.92	.453	1.78
	.273	1.63	.268	1.89	.353	1.72
	.223	1.62	.218	1.82	.303	1.74
	.173	1.55	.168	1.81	.253	1.70
	.148	1.46	.118	1.80	.228	1.65
	.123	1.44	.093	1.80	.203	1.63
	.098	1.44	.068	1.77	.178	1.62
	.073	1.56	.043	1.69	.153	1.58
	.048	1.56	.018	1.62	.128	1.56
	.023	1.48			.103	1.53
					.078	1.38
					.053	1.18
					.028	1.15
48	1.232	w.s.	1.247	w.s.	1.011	w.s.
	1.147	1.91	1.157	1.81	.918	1.84
	1.047	1.88	.957	1.81	.718	1.86
	.847	1.85	.757	1.79	.518	1.84
	.647	1.81	.557	1.75	.318	1.89
	.447	1.79	.357	1.75	.218	1.77
	.347	1.78	.257	1.49	.168	1.75
	.247	1.70	.207	1.30	.118	1.74
	.197	1.71	.157	1.08	.093	1.69
	.147	1.69	.132	.90	.068	1.66
	.122	1.66	.107	.77	.043	1.56
	.097	1.58	.082	.79	.018	1.28
	.072	1.51	.057	.92		
	.047	1.43	.032	1.05		
	.022	1.28				
49	1.240	w.s.	1.220	w.s.	1.710	w.s.
	1.180	3.02	1.160	2.93	1.675	3.21
	1.130	3.07	1.100	2.93	1.475	3.21
	.930	2.99	.900	2.97	1.075	3.12
	.730	2.89	.700	2.97	.875	2.86
	.530	2.81	.500	2.87	.675	
	.430	2.51	.300	2.58	.575	
	.330	1.84	.200	2.34	.475	
	.286	1.10	.150	2.16	.425	
	.255	.96	.100	2.20	.375	
	.230	.63	.075	2.41	.350	
	.205	.63	.050	1.86	.325	
	.180	.42			.275	
	.130	r.f.			.075	
	.030	r.f.			.035	
85	.795	w.s.	.770	w.s.	.775	w.s.
	.750	1.47	.700	1.43	.700	1.43
	.600	1.36	.550	1.36	.550	1.36

Run	2.0 ft from left wall of flume		4.0 ft from left wall of flume		6.0 ft from uleft wall of fl me	
	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)
85 Con.	0.450	1.28	0.400	1.31	0.400	1.30
	.350	1.22	.300	1.23	.300	1.28
	.250	1.15	.200	1.16	.200	1.13
	.200	1.03	.150	1.08	.150	1.12
	.150	.93	.100	.99	.100	1.05
	.100	.86	.080	.97	.080	1.01
	.080	.93	.060	.86	.060	.99
	.060	.93	.040	.78	.040	.90
	.040	.89	.020	.72	.020	.82
	.020	.93				
86	.800	w.s.	.810	w.s.	.800	w.s.
	.750	1.40	.750	1.43	.750	1.41
	.550	1.40	.550	1.32	.550	1.31
	.400	1.24	.400	1.24	.400	1.22
	.300	1.21	.300	1.21	.300	1.16
	.200	1.13	.200	1.07	.200	1.02
	.150	1.02	.150	1.02	.150	.98
	.100	.91	.100	.99	.100	.87
	.080	.77	.080	.96	.080	.85
	.060	.65	.060	.92	.060	.84
	.040	.51	.040	.34	.040	.71
	.020	.57	.020	.34	.020	.30
87	.785	w.s.	.775	w.s.	.770	w.s.
	.750	1.45	.750	1.41	.740	1.59
	.550	1.34	.550	1.26	.550	1.45
	.400	1.25	.400	1.15	.400	1.36
	.300	1.13	.300	1.16	.300	1.28
	.200	1.03	.200	1.05	.200	1.14
	.150	.98	.150	1.05	.150	1.07
	.100	.90	.100	.88	.100	1.03
	.080	.92	.080	.86	.080	.99
	.060	.74	.060	.83	.060	r.f.
	.040	.45	.040	.80	.040	r.f.
	.020	.00	.020	.74	.020	r.f.
88	.780	w.s.	.775	w.s.	.740	w.s.
	.730	1.49	.725	1.48	.710	1.49
	.550	1.43	.550	1.39	.550	1.44
	.400	1.29	.400	1.33	.400	1.28
	.300	1.24	.300	1.20	.300	1.14
	.200	1.09	.200	1.06	.200	1.09
	.150	1.01	.150	.91	.150	.97
	.100	.93	.100	.78	.100	.82
	.075	.88	.075	.73	.075	.74
	.050	.72	.050	.56	.050	.61
	.025	.50	.025	.61	.025	.51
90	.600	w.s.	.595	w.s.	.570	w.s.
	.550	1.65	.550	1.84	.530	1.95
	.400	1.59	.400	1.76	.400	1.91
	.300	1.55	.300	1.62	.300	1.83
	.200	1.49	.200	1.63	.200	1.79
	.150	1.45	.150	1.52	.150	1.74
	.100	1.38	.100	1.45	.100	1.56
	.075	1.35	.075	1.37	.075	1.47
	.050	1.12	.050	1.24	.050	1.26
	.025	.90	.025	1.57	.025	.63
89	.625	w.s.	.630	w.s.	.620	w.s.
	.600	1.58	.600	1.69	.590	1.79
	.500	1.53	.500	1.65	.500	1.76
	.400	1.41	.400	1.63	.400	1.72
	.300	1.36	.300	1.59	.300	1.69
	.200	1.23	.200	1.47	.200	1.57
	.150	1.12	.150	1.36	.150	1.52
	.100	1.08	.100	1.25	.100	1.46
	.075	.97	.075	1.19	.075	1.34

TABLE 20.—*Velocity-profile data for 0.47-mm sand in 8-foot-wide flume*—Continued

Run	2.0 ft from left wall of flume		4.0 ft from left wall of flume		6.0 ft from left wall of flume	
	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)
89—Con.	0.050	0.51	0.050	1.08	0.050	1.22
	.025	.42	.025	.50	.025	1.03
93	.640	w.s.	.540	w.s.	.530	w.s.
	.600	1.80	.500	1.95	.500	2.07
	.500	1.81	.400	1.93	.350	2.00
	.400	1.79	.300	1.86	.250	1.86
	.300	1.74	.200	1.82	.150	1.78
	.200	1.67	.150	1.76	.100	1.67
	.150	1.62	.100	1.72	.075	1.43
	.100	1.64	.075	1.68	.050	.99
	.075	1.57	.050	1.60	.025	.88
	.050	1.48	.025	1.46		
	.025	1.40				
92	.755	w.s.	.740	w.s.	.515	w.s.
	.700	1.84	.700	1.79	.470	1.80
	.550	1.81	.500	1.74	.400	1.78
	.450	1.68	.400	1.63	.300	1.74
	.350	1.31	.300	1.46	.200	1.58
	.250	1.08	.200	1.32	.150	1.22
	.200	1.06	.150	1.27	.100	.73
	.150	1.06	.100	1.23	.075	.76
	.100	1.10	.075	1.12	.050	.82
	.075	.96	.050	.97	.025	.86
	.050	.90	.025	.88		
	.025	.95				
91	.605	w.s.	.530	w.s.	.660	w.s.
	.550	1.84	.490	1.50	.620	1.93
	.450	1.78	.350	1.53	.500	1.90
	.350	1.64	.250	1.51	.400	1.82
	.250	1.28	.200	1.43	.300	1.76
	.200	1.28	.150	1.35	.200	1.66
	.150	.97	.100	1.19	.150	1.62
	.100	.71	.075	1.05	.100	1.55
	.075	1.03	.050	.98	.075	1.45
	.050	.82	.025	.74	.050	1.38
	.025	.92			.025	1.19
82	.765	w.s.	.795	w.s.	.620	w.s.
	.740	2.03	.750	2.12	.560	2.37
	.600	1.84	.550	2.13	.450	2.44
	.500	1.72	.400	2.13	.350	2.44
	.400	1.64	.300	1.91	.250	2.36
	.350	1.68	.200	1.80	.200	2.41
	.300	1.53	.150	1.74	.150	2.16
	.250	.81	.100	1.82	.100	.99
	.200	.00	.075	1.78	.075	.33
	.150	.00	.050	1.46	.050	.48
	.100	.00	.025	.59	.025	.30
	.075	.39				
	.050	.61				
	.025	.63				
51	.364	w.s.	.417	w.s.	.550	w.s.
	.304	2.62	.357	2.12	.520	2.11
	.254	2.63	.307	2.05	.470	2.13
	.204	2.53	.257	1.97	.420	2.10
	.154	2.61	.207	2.22	.370	2.23
	.104	2.39	.157	2.22	.320	2.08
	.079	2.23	.107	2.25	.270	2.10
	.054	.88	.082	1.97	.220	2.13
	.029	.69	.057	1.54	.170	2.10
			.042	.76	.120	2.23
			.027	.69	.095	2.08
					.070	1.81
					.045	1.65
					.020	1.51
52	.897	w.s.	.560	w.s.	.507	w.s.
	.847	2.09	.500	2.08	.490	2.17
	.697	1.77	.350	2.09	.460	2.13
	.597	1.64	.250	2.13	.410	2.23
	.497	1.19	.200	2.02	.360	2.12
	.397	.59	.150	1.98	.310	2.12
	.347	.86	.100	1.85	.260	2.11
	.297	.84	.075	1.61	.210	2.07
	.272	.72	.050	1.30	.160	2.04
	.247	.79	.025	.80	.110	1.97
	.222	.90			.060	1.95
	.197	1.14			.035	1.96
	.147	.00			.015	1.93
	.097	r.f.				
	.047	r.f.				
	.022	r.f.				
73	.802	w.s.	.482	w.s.	.402	w.s.
	.750	2.23	.430	2.23	.350	2.48
	.650	2.26	.400	2.57	.300	2.50
	.550	2.16	.300	2.41	.250	2.47
	.450	2.08	.200	2.33	.200	2.59
	.350	1.93	.150	2.29	.150	2.56
	.300	1.51	.100	2.20	.125	2.51
	.250	.37	.080	1.90	.100	2.50

Run	2.0 ft from left wall of flume		4.0 ft from left wall of flume		6.0 ft from left wall of flume	
	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)
73—Con.	0.200	0.37	0.060	1.59	0.075	2.27
	.150	.35	.040	.58	.050	2.27
	.125	.38	.020	.50	.025	1.48
	.100	.44				
	.075	.41				
	.050	.41				
	.025	.41				
74	.695	w.s.	.635	w.s.	.570	w.s.
	.640	2.40	.600	1.98	.520	2.23
	.570	2.55	.450	1.97	.400	2.20
	.470	2.57	.350	1.74	.300	2.15
	.370	2.55	.250	1.68	.250	2.08
	.320	2.50	.200	1.66	.200	1.97
	.270	2.29	.150	1.58	.150	1.93
	.220	.37	.100	1.39	.100	1.97
	.170	.35	.080	.66	.080	2.00
	.130	.35	.060	.57	.060	1.93
	.100	.35	.040	.57	.040	1.80
	.080	.33	.020	.62	.020	1.66
	.060	.31				
	.040	.30				
	.020	.28				
76	.625	w.s.	.625	w.s.	.690	w.s.
	.580	2.29	.580	2.33	.650	2.44
	.460	2.43	.460	2.36	.530	2.39
	.360	2.46	.360	2.33	.430	2.29
	.260	2.53	.260	2.30	.330	2.30
	.210	2.34	.160	2.26	.280	2.27
	.160	2.10	.110	2.13	.230	.61
	.135	1.93	.085	2.13	.180	.74
	.110	1.62	.060	2.05	.130	.65
	.085	.53	.040	1.94	.100	.55
	.060	.44	.020	1.90	.075	.55
	.040	.43			.050	.67
	.020	.53			.025	.73
75	.655	w.s.	.640	w.s.	.630	w.s.
	.590	2.16	.590	1.84	.600	2.26
	.500	2.24	.550	1.76	.500	2.23
	.400	2.23	.450	1.70	.400	2.20
	.300	2.31	.350	1.66	.300	1.91
	.250	2.30	.250	1.86	.250	1.62
	.225	2.21	.200	2.02	.200	.84
	.200	1.66	.150	1.98	.150	.74
	.175	.43	.100	1.76	.125	1.07
	.150	.43	.075	.69	.100	.51
	.125	.43	.050	.47	.075	.52
	.100	.41	.025	.61	.050	.58
	.080	.41			.025	.63
	.060	.39				
	.040	.44				
	.020	.50				
53	.600	w.s.	.464	w.s.	.472	w.s.
	.570	2.33	.434	2.31	.437	2.24
	.490	2.39	.364	1.95	.367	2.24
	.390	2.35	.314	1.75	.317	2.19
	.290	1.97	.264	1.63	.267	2.06
	.240	1.71	.214	1.67	.217	1.94
	.190	1.78	.164	1.64	.167	2.09
	.140	1.71	.114	1.76	.117	2.08
	.100	1.64	.089	1.71	.092	1.96
	.075	.83	.064	1.63	.067	1.89
	.050	.35	.039	1.53	.042	1.67
	.025	0	.014	1.21	.017	.54
77	.690	w.s.	.895	w.s.	.510	w.s.
	.620	2.36	.855	2.13	.470	2.48
	.450	2.36	.825	2.10	.400	2.48
	.350	2.27	.725	2.07	.300	2.46
	.250	2.21	.625	1.97	.250	2.43
	.200	2.07	.525	1.97	.200	.51
	.150	1.90	.425	1.78	.150	.50
	.125	1.64	.325	1.64	.125	.50
	.100	1.51	.275	1.57	.100	.75
	.080	.52	.225	1.25	.080	.67
	.060	.43	.175	.54	.060	.67
	.040	.42	.135	.54	.040	.66
	.020	.43	.100	.50	.020	.57
			.075	.50		
			.050	.51		
			.025	.54		
96	.350	w.s.	.525	w.s.	.545	w.s.
	.315	2.39	.495	2.56	.500	2.44
	.250	2.38	.400	2.55	.400	2.34
	.200	2.37	.300	2.40	.300	2.37
	.150	2.36	.200	1.55	.200	2.44
	.100	2.33	.150	.96	.150	2.36
	.075	2.27	.100	.50	.100	2.24
	.050	2.00	.075	.57	.075	2.15
	.025	1.28	.050	.79	.050	1.78
			.025	.84	.025	1.16

TABLE 20.—*Velocity-profile data for 0.47-mm sand in 8-foot-wide flume*—Continued

Run	2.0 ft from left wall of flume		4.0 ft from left wall of flume		6.0 ft from left wall of flume	
	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)
94	0.745	w.s.	0.755	w.s.	0.840	w.s.
	.680	2.59	.700	2.13	.800	2.02
	.550	2.57	.550	2.21	.700	1.98
	.400	2.56	.400	2.15	.550	2.02
	.300	2.52	.300	2.04	.400	2.13
	.200	2.37	.200	2.04	.300	2.20
	.150	2.07	.150	1.90	.200	2.04
	.100	.87	.100	1.68	.150	2.11
	.075	.80	.075	.81	.100	1.98
	.050	.80	.050	.63	.075	1.86
	.025	.99	.025	.69	.050	1.78
					.025	.79
83	1.095	w.s.	.845	w.s.	.965	w.s.
	1.015	1.00	.800	2.43	.900	2.81
	.845	.99	.650	2.43	.800	2.80
	.645	.92	.500	2.45	.650	2.77
	.545	.90	.400	2.45	.500	2.65
	.445	2.53	.300	2.48	.400	2.46
	.395	2.02	.200	2.48	.300	2.27
	.345	.49	.150	2.33	.250	1.25
	.295	.43	.100	2.23	.200	.92
	.270	.45	.075	2.26	.150	.72
	.245	.50	.050	2.04	.100	.46
	.220	.66	.025	.96	.075	.41
	.170	.29			.050	.79
	.130	.39			.025	.66
	.100	.54				
	.075	.74				
	.050	.58				
	.025	.58				
54	.873	w.s.	.815	w.s.	.888	w.s.
	.833	3.01	.755	2.53	.825	2.88
	.733	3.01	.655	2.42	.775	2.80
	.533	2.93	.555	2.47	.725	2.87
	.433	2.61	.455	2.59	.675	2.78
	.333	2.51	.355	2.43	.575	2.86
	.283	1.37	.255	2.07	.475	2.76
	.233	1.00	.205	1.60	.375	2.71
	.183	1.71	.155	1.46	.275	2.57
	.133	1.23	.105	.65	.225	2.27
	.083	1.56	.080	.65	.175	1.90
	.058	.61	.055	.80	.125	1.23
	.033	.68	.030	1.08	.075	1.23
	.018	.96			.050	.96
					.025	.69
56	.830	w.s.	.690	w.s.	1.015	w.s.
	.800	2.61	.650	2.56	.975	2.62
	.750	2.46	.600	2.76	.900	2.71
	.600	2.46	.550	2.94	.800	2.71
	.500	2.22	.500	3.02	.700	2.76
	.400	2.00	.400	3.02	.500	2.71
	.300	1.44	.300	2.94	.400	2.78
	.250	1.48	.200	2.82	.300	2.85
	.200	1.48	.150	2.60	.200	2.64
	.150	1.44	.100	2.41	.150	2.01
	.125	1.25	.050	2.02	.100	.50
	.100	.92	.025	1.84	.075	.41
	.075	.41			.050	.30
	.050	.57			.025	.41
	.025	.79				
55	1.054	w.s.	.585	w.s.	1.060	w.s.
	1.024	2.64	.535	2.50	1.030	3.28
	.874	2.52	.485	2.67	.830	3.25
	.724	2.41	.385	2.66	.630	3.20
	.574	2.46	.285	2.50	.530	3.13
	.474	2.13	.235	2.42	.430	2.75
	.374	1.91	.185	2.32	.380	2.50
	.324	1.66	.135	2.32	.330	1.23
	.274	1.48	.100	2.30	.280	1.28
	.224	1.62	.075	2.37	.230	1.28
	.174	1.46	.050	1.51	.180	1.36
	.124	1.72	.025	1.38	.130	1.07
	.099	1.91			.105	1.07
	.074	2.02			.080	1.42
	.049	2.08			.055	1.42
	.024	1.84			.030	1.50
57	.885	w.s.	.970	w.s.	1.250	w.s.
	.825	2.66	.880	2.60	1.160	2.89
	.625	2.57	.680	2.34	.960	2.50
	.425	2.46	.480	2.37	.760	2.29
	.325	2.34	.380	2.30	.560	2.15
	.225	1.90	.330	2.36	.460	1.88
	.175	1.62	.280	2.33	.360	2.00
	.125	1.91	.230	1.93	.310	.69
	.100	2.61	.180	.50	.260	.45
	.075	.84	.130	.50	.210	.45
	.050	.88	.105	.63	.160	.41
	.025	.84	.080	.63	.120	.41
			.055	.72	.090	.41
			.030	.96	.060	.45
57—Con.					0.025	0.30
58	0.720	w.s.	0.960	w.s.	.900	w.s.
	.680	2.74	.920	2.87	.860	2.76
	.550	2.82	.700	2.63	.730	2.67
	.450	2.78	.500	2.51	.630	2.67
	.350	2.89	.400	2.33	.430	2.60
	.250	2.65	.300	2.48	.330	2.29
	.200	2.73	.250	2.37	.230	2.26
	.150	2.73	.200	2.07	.180	2.21
	.100	2.65	.150	2.10	.155	1.93
	.075	2.57	.125	1.98	.130	.88
	.050	2.24	.100	1.91	.105	.45
	.025	2.20	.075	2.04	.080	.50
			.050	2.04	.055	.41
			.025	1.84	.030	.57
95	.680	w.s.	.630	w.s.	1.130	w.s.
	.630	2.96	.580	2.66	1.080	2.97
	.550	2.98	.400	2.65	.900	2.87
	.400	2.89	.300	2.59	.700	2.64
	.300	2.92	.200	2.19	.550	2.34
	.200	2.87	.150	1.90	.400	2.13
	.150	2.80	.100	1.86	.300	2.02
	.100	2.80	.075	1.72	.200	1.78
	.075	2.54	.050	1.74	.150	1.44
	.050	2.11	.025	1.46	.100	1.16
	.025	1.90			.075	1.10
					.050	.99
					.025	.96
78	.870	w.s.	.625	w.s.	.610	w.s.
	.800	2.61	.530	2.99	.560	2.29
	.650	2.61	.500	2.92	.400	2.33
	.500	2.65	.400	2.84	.300	2.26
	.400	2.65	.300	2.75	.200	2.20
	.300	2.56	.200	2.81	.150	2.60
	.250	2.30	.150	2.78	.100	2.67
	.200	1.51	.100	2.59	.075	2.67
	.175	1.19	.075	2.20	.050	2.60
	.150	1.19	.050	.92	.025	1.22
	.125	1.25	.025	.92		
	.100	1.07				
	.075	1.04				
	.050	1.19				
	.025	1.19				
59	.510	w.s.	.535	w.s.	.640	w.s.
	.490	4.13	.495	4.17	.610	3.50
	.440	4.01	.415	4.05	.550	2.99
	.340	3.93	.315	3.85	.450	2.99
	.290	3.81	.265	4.01	.350	3.20
	.240	3.68	.215	3.77	.300	3.30
	.190	3.85	.165	3.68	.250	3.63
	.150	3.77	.115	3.20	.200	3.50
	.125	3.50	.090	2.07	.150	2.88
	.100	3.35	.065	2.64	.125	2.99
	.075	3.10	.040	2.64	.100	2.94
	.050	2.51	.015	1.22	.075	2.88
	.025	0.00			.050	.74
					.025	.88
60	.635	w.s.	.605	w.s.	.590	w.s.
	.605	5.69	.565	5.42	.560	5.42
	.505	5.69	.465	5.24	.460	5.24
	.405	5.47	.365	5.24	.360	4.93
	.305	4.99	.265	4.87	.260	4.74
	.255	4.60	.215	4.67	.210	4.32
	.205	4.53	.165	4.53	.160	4.31
	.155	4.01	.135	4.31	.110	3.93
	.105	3.50	.105	4.17	.085	3.59
	.080	2.99	.080	3.77	.060	3.10
	.060	2.37	.055	1.90	.040	2.76
	.040	.88	.035	.88	.020	1.48
	.020	.88	.015	.88		
61	.590	w.s.	.550	w.s.	.600	w.s.
	.560	5.58	.540	5.42	.560	5.24
	.460	5.51	.460	5.33	.460	5.21
	.360	5.30	.360	5.12	.360	4.93
	.260	4.99	.260	4.93	.260	4.60
	.210	4.90	.210	4.67	.210	4.43
	.160	4.60	.160	4.46	.160	4.28
	.110	4.31	.110	4.39	.110	4.17
	.085	4.09	.085	4.39	.085	3.35
	.060	3.54	.060	4.24	.060	3.50
	.040	3.50	.040	3.89	.040	2.99
	.020	3.20	.020	3.40	.020	1.90
71	.340	w.s.	.286	w.s.	.345	w.s.
	.310	4.46	.230	4.31	.310	4.31
	.280	4.31	.190	4.31	.280	4.21
	.230	4.31	.160	4.17	.230	4.17
	.180	4.09	.130	4.01	.180	3.89
	.140	3.93	.100	4.17	.140	3.68
	100	3.50	.080	3.77	.100	3.20
	.080	3.10	.060	3.63	.080	2.88

TABLE 20.—*Velocity-profile data for 0.47-mm sand in 8-foot-wide flume*—Continued

Run	2.0 ft from left wall of flume		4.0 ft from left wall of flume		6.0 ft from left wall of flume	
	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)	Distance above sand bed (ft)	Velocity (fps)
71—Con.	0.060	1.90	0.040	3.50	0.060	2.64
	.040	.63	.020	3.20	.040	1.90
	.020	.63	.020	2.99	.020	.00
72	.310	w.s.	.320	w.s.	.360	w.s.
	.270	4.39	.275	4.31	.330	4.17
	.220	4.24	.225	4.17	.300	4.17
	.170	4.17	.175	4.01	.250	3.93
	.130	3.96	.125	3.85	.200	3.81
	.100	3.93	.100	3.85	.160	3.68
	.080	3.63	.080	3.68	.130	3.50
	.060	3.30	.060	3.50	.100	3.20
	.040	2.23	.040	3.20	.080	2.99
	.020	1.48	.020	1.70	.060	2.64
					.040	.00
					.020	.00
70	.305	w.s.	.260	w.s.	.275	w.s.
	.290	4.46	.240	4.53	.240	4.39
	.240	4.39	.200	4.46	.200	4.31
	.200	4.39	.160	4.31	.160	4.09
	.160	4.39	.130	4.09	.130	4.01
	.130	4.17	.100	4.01	.100	3.93
	.100	4.09	.080	3.77	.080	3.77
	.080	3.77	.060	3.68	.060	3.68
	.060	3.68	.040	3.20	.040	3.50
	.040	3.40	.020	2.51	.020	3.30
	.020	2.76				
63	.400	w.s.	.450	w.s.	.405	w.s.
	.350	4.80	.400	4.93	.355	5.12
	.300	4.53	.350	4.31	.255	5.64
	.250	4.31	.300	4.93	.205	5.06
	.200	4.67	.250	3.77	.155	4.74
	.150	4.53	.210	5.24	.105	5.06
	.100	3.68	.180	4.24	.085	4.67
	.080	3.85	.150	3.68	.065	4.81
	.060	2.64	.120	3.59	.045	4.09
	.040	..00	.100	1.90	.025	1.90
	.020	1.48	.080	2.23		
			.060	0		
			.040	0		
			.020	0		
64	.320	w.s.	.255	w.s.	.250	w.s.
	.270	4.87	.205	5.36	.200	5.96
	.220	4.31	.155	6.01	.150	4.60
	.170	4.60	.105	5.24	.100	4.60
	.120	3.68	.095	4.93	.080	4.74
	.090	4.01	.075	4.39	.060	4.60
	.060	3.20	.055	4.46	.040	4.39
	.040	4.60	.035	4.93	.020	4.09
	.020	.88	.015	3.40		
65	.325	w.s.	.355	w.s.	.425	w.s.
	.305	5.12	.305	4.74	.355	5.42
	.255	4.67	.255	4.81	.305	5.06
	.205	5.30	.205	4.31	.255	4.87
	.155	3.68	.155	4.09	.205	4.67
	.105	3.93	.105	3.85	.155	4.24
	.075	3.40	.075	4.60	.105	3.59
	.055	3.10	.055	3.30	.075	4.46
	.035	2.76	.035	.88	.055	1.22
	.015	0	.015	.63	.035	.63
					.015	.63
66	.330	w.s.	.345	w.s.	.405	w.s.
	.300	4.81	.295	4.93	.350	5.47
	.270	5.06	.245	4.74	.300	4.46
	.240	4.57	.195	4.39	.250	4.99
	.200	4.24	.145	3.40	.200	5.64
	.160	4.60	.120	4.17	.150	4.09
	.130	4.24	.095	4.24	.125	4.24
	.100	4.81	.070	3.68	.100	3.68
	.080	4.24	.045	1.90	.075	1.70
	.060	3.93	.020	2.07	.050	0.00
	.040	2.07			.025	0.00
	.020	2.07				
80	.295	w.s.	.430	w.s.	.395	w.s.
	.250	5.18	.400	6.20	.375	5.65
	.200	4.40	.350	5.10	.275	5.50
	.150	4.50	.300	4.90	.225	5.10
	.125	4.50	.250	4.50	.175	5.80
	.100	3.70	.200	5.38	.125	5.20
	.075	4.30	.150	4.70	.100	3.85
	.050	4.00	.100	4.25	.075	3.00
	.025	3.82	.075	.85	.050	.64
			.050	.85		
			.025	3.65		
81	.500	w.s.	.505	w.s.	.545	w.s.
	.485	6.45	.420	6.38	.515	6.36
	.385	6.31	.360	6.31	.435	6.16
	.285	6.21	.260	6.01	.335	5.91
	.185	5.42	.210	5.96	.235	5.53
	.135	5.06	.160	5.64	.185	5.47
	.085	4.53	.110	5.47	.135	4.93
	.060	4.09	.085	5.18	.085	4.39
81—Con.	0.035	3.77	0.060	4.60	0.060	4.31
	.015	0	.035	4.67	.035	3.10
			.015	3.77	.015	.63
62	.535	w.s.	.540	w.s.	.530	w.s.
	.505	6.45	.500	6.01	.490	6.11
	.435	6.26	.440	6.31	.430	6.01
	.335	6.06	.340	6.01	.330	5.75
	.235	5.80	.240	5.53	.230	5.64
	.185	5.58	.190	5.36	.180	5.36
	.150	5.91	.140	4.87	.130	5.12
	.125	5.53	.105	4.67	.105	4.87
	.100	4.99	.080	4.09	.080	4.87
	.075	4.67	.060	3.77	.060	4.31
	.055	4.39	.040	1.70	.040	3.93
	.035	4.17	.020	1.22	.020	1.36
	.015	3.93				
67	.465	w.s.	.480	w.s.	.515	w.s.
	.430	6.41	.445	6.21	.480	6.16
	.380	6.11	.345	6.11	.430	6.01
	.330	6.06	.295	5.91	.330	5.59
	.280	5.85	.245	5.80	.280	5.47
	.230	5.53	.195	5.59	.230	5.36
	.180	5.42	.145	5.47	.180	5.12
	.130	4.87	.095	4.99	.130	4.81
	.105	4.60	.070	4.09	.100	4.67
	.080	3.77	.045	4.24	.075	4.09
	.060	3.59	.025	.63	.050	3.30
	.040	1.90			.025	.87
	.020	.87				
79	.520	w.s.	.565	w.s.	.550	w.s.
	.480	6.50	.475	6.31	.480	6.31
	.400	6.36	.400	6.01	.430	6.41
	.300	6.21	.300	5.96	.330	6.01
	.250	6.06	.250	6.01	.280	5.85
	.200	5.53	.200	5.58	.230	5.53
	.150	5.06	.150	5.58	.180	5.58
	.100	4.24	.100	4.99	.130	5.30
	.075	4.24	.075	4.74	.080	4.53
	.050	.88	.050	4.53	.060	4.46
	.025	1.07	.025	.63	.040	3.77
					.020	3.10
84	.340	w.s.	.385	w.s.	.285	w.s.
	.300	6.15	.350	5.90	.250	5.15
	.250	6.50	.300	5.85	.200	4.50
	.200	6.05	.250	5.65	.150	5.25
	.150	5.50	.200	5.65	.100	4.10
	.100	5.40	.150	4.91	.080	4.10
	.080	5.30	.100	4.50	.060	3.60
	.060	4.90	.080	4.40	.040	3.10
	.040	4.25	.060	3.30	.020	.65
	.020	1.38	.040	1.45		
			.020	.65		
68	.404	w.s.	.458	w.s.	.500	w.s.
	.380	6.69	.430	6.64	.480	6.31
	.330	6.69	.380	6.36	.430	6.31
	.280	6.69	.330	6.26	.380	6.16
	.230	6.26	.280	6.31	.330	6.06
	.180	6.21	.230	6.11	.280	6.01
	.130	5.75	.180	5.85	.230	5.80
	.100	6.06	.130	5.53	.180	5.53
	.080	5.69	.100	5.12	.130	5.06
	.060	5.36	.080	5.06	.100	4.74
	.040	5.24	.060	4.99	.080	4.39
	.020	4.31	.040	4.09	.060	3.59
			.020	.69	.040	3.77
					.020	1.48
100	.470	w.s.	.515	w.s.	.515	w.s.
	.430	7.38	.450	7.05	.450	6.69
	.300	6.61	.300	6.65	.300	6.46
	.200	6.31	.200	6.26	.200	6.01
	.150	6.06	.150	6.06	.150	5.47
	.100	5.69	.100	5.36	.100	5.24
	.075	5.18	.075	4.74	.075	4.60
	.050	4.31	.050	3.77	.050	3.85
	.025	2.76	.025	1.49	.025	3.77
99	.400	w.s.	.520	w.s.	.480	w.s.
	.300	7.43	.500	7.05	.350	7.00
	.200	7.05	.400	7.17	.250	5.91
	.150	7.35	.300	6.65	.150	5.85
	.100	5.53	.200	4.60	.100	5.85
	.050	4.24	.150	5.18	.050	1.23
			.100	4.17		
			.050	r.f.		
97	.302	w.s.	.250	w.s.	.311	w.s.
	.287	5.18	.232	5.58	.251	5.36
	.237	5.06	.182	5.30	.201	5.24
	.187	4.67	.132	5.12	.151	5.06
	.137	5.47	.082	4.60	.101	4.74
	.087	5.91	.052	2.99	.076	4.01
	.057	4.74	.022	2.07	.051	3.93
	.017	3.30			.020	2.37

TABLE 21.—*Velocity-profile data for 0.54-mm sand in 2-foot-wide flume*

[w.s.=water surface. Measurement taken 1.0 ft from left wall of flume]

Run	Distance above sand bed (ft)	Velocity (fps)
1	0.605	w.s.
	.565	1.22
	.500	1.16
	.400	1.14
	.300	1.06
	.200	1.02
	.150	.96
	.100	.94
	.075	.90
	.050	.81
	.025	.74
	.010	.63
2	.600	w.s.
	.565	1.26
	.500	1.22
	.400	1.22
	.300	1.18
	.200	1.13
	.150	1.11
	.100	1.07
	.075	1.01
	.050	.99
	.025	.88
	.010	.75
3	.610	w.s.
	.581	1.46
	.575	1.50
	.500	1.31
	.400	1.26
	.300	1.25
	.200	1.13
	.150	1.07
	.100	1.02
	.075	.99
	.050	.90
	.025	.77
	.010	.60
4	.548	w.s.
	.530	1.85
	.520	1.78
	.500	1.78
	.400	1.77
	.300	1.73
	.200	1.65
	.150	1.57
	.100	1.47
	.075	1.46
	.050	1.41
	.025	1.29
	.010	1.16
6	.622	w.s.
	.600	2.07
	.569	2.16
	.500	2.28
	.400	2.30
	.300	2.69
	.200	2.61
	.150	2.99
	.100	3.20
	.075	2.77
	.050	2.04
	.025	1.56
6 Con.	0.010	1.36
5	.774	w.s.
	.745	2.36
	.500	2.42
	.400	2.40
	.300	2.38
	.200	2.24
	.150	2.12
	.100	2.13
	.075	2.11
	.050	1.82
	.025	1.28
	.010	1.19
20	.700	w.s.
	.682	4.67
	.600	5.36
	.500	5.30
	.400	5.12
	.300	4.60
	.200	3.85
	.150	3.30
	.100	2.88
	.075	1.48
	.050	1.22
	.025	1.22
8	.808	w.s.
	.770	2.99
	.700	3.40
	.600	3.59
	.500	3.77
	.400	3.68
	.300	3.40
	.200	3.10
	.150	2.64
	.100	.88
	.075	.88
	.050	1.48
	.025	2.64
8A	.796	w.s.
	.760	3.40
	.700	3.10
	.600	3.30
	.500	3.50
	.400	3.68
	.300	3.10
	.200	2.99
	.150	2.76
	.100	2.07
	.075	2.37
	.050	2.23
	.025	.88
8B	.833	w.s.
	.785	2.51
	.700	2.76
	.600	2.76
	.500	3.10
	.400	3.20
	.300	3.10
	.200	2.76
	.150	2.76
	.100	3.20
8B Con.	0.075	3.20
	.050	2.99
	.025	.88
8C	.832	w.s.
	.780	3.20
	.700	3.20
	.600	3.50
	.500	3.50
	.400	3.40
	.300	3.20
	.200	3.30
	.150	3.20
	.100	3.20
	.075	2.51
	.050	1.22
	.025	.88
7	.558	w.s.
	.510	3.05
	.400	3.04
	.300	2.96
	.200	2.81
	.150	2.76
	.100	2.75
	.075	2.76
	.050	2.75
	.025	2.56
	.010	2.02
19	.643	w.s.
	.605	3.59
	.570	3.97
	.500	4.00
	.400	4.05
	.300	4.41
	.200	3.47
	.150	3.40
	.100	3.23
	.075	2.99
	.050	2.82
	.025	2.64
	.010	2.12
9	.630	w.s.
	.610	3.30
	.500	3.40
	.400	3.30
	.300	3.30
	.200	3.54
	.150	3.40
	.100	3.25
	.075	3.10
	.050	2.82
	.025	2.37
10	.638	w.s.
	.600	5.80
	.500	5.96
	.400	5.91
	.300	5.75
	.200	5.36
	.150	5.18
	.100	4.53
	.025	3.96
	.050	2.15
10 Con.	0.025	1.36
15	.748	w.s.
	.680	6.41
	.600	6.50
	.500	6.46
	.400	6.41
	.300	6.21
	.200	5.91
	.150	5.42
	.100	4.93
	.075	4.09
	.050	3.30
	.025	2.07
15B	.754	w.s.
	.670	6.06
	.600	6.06
	.500	6.11
	.400	6.11
	.300	6.06
	.200	5.75
	.150	5.58
	.100	4.99
	.075	4.46
	.050	4.01
	.025	3.20
13	.707	w.s.
	.672	6.26
	.600	6.31
	.500	6.36
	.400	6.36
	.300	6.21
	.200	5.30
	.150	5.47
	.100	4.74
	.075	3.85
	.050	2.07
	.025	1.22
11	.664	w.s.
	.636	7.67
	.600	7.63
	.500	7.50
	.400	7.20
	.300	7.01
	.200	6.16
	.150	5.52
	.100	3.48
	.075	2.60
	.050	1.51
	.025	1.53
18	.752	w.s.
	.670	6.16
	.600	6.16
	.500	6.16
	.400	6.11
	.300	5.85
	.200	5.36
	.150	5.12
	.100	4.39
	.075	3.59
	.050	4.66
	.025	4.60

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