A STUDY OF RESISTANCE TO FLOW IN ALLUVIAL CHANNELS[1]

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SYNOPSIS

This paper presents the initial results of a flume study of alluvial channels currently being conducted by the U. S. Geological Survey at Colorado State University. A detailed classification of the regimes of flow, the forms of bed roughness, and the basic concepts pertaining to resistance to flow are discussed.

INTRODUCTION

The problem of defining roughness in alluvial channels dates back several centuries. The solution of this problem, at least the complete solution, has thus far eluded man. The principle reasons why only limited answers which in some cases are of questionable value, have been developed is that the scope of the problem is broad and the multitude of variables influencing resistance to flow in alluvial channels is great. Alluvial channels are more complex than rigid channels because the form of the bed is a function of the flow. That is, not only do the alluvial channel roughness elements resist the flow, but they in turn are shaped by the flow. Thus far, most scientists working in this

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field have been limited by time, facilities, instrumentation needs, and funds. As a result only small parts of the complete and complex problem have been thoroughly investigated. It is of interest to note, however, that sufficient isolated groups of data have been collected and are being collected so that ultimately it should be possible to combine ideas and data resulting from these separate efforts to determine a general solution superior to any obtained thus far.

The Importance of Roughness in Alluvial Channels

The importance of accurately describing resistance to flow or roughness in alluvial channels becomes immediately apparent when it is realized that the accurate evaluation of channel roughness is essential to the solution of all problems associated either directly or indirectly with water flowing in alluvial material. Citing examples, a more precise knowledge of channel roughness would assist materially in the design of stable channels, and suitable design slopes could be accurately determined consistent with existing conditions. Furthermore, an understanding of the behavior and control of rivers and river systems could be developed. That is, the influence of imposing changes such as cut-offs, increasing or decreasing the sediment load, contractions at bridges, and changing the characteristics of the sediment load could be predicted with greater precision.

In the design of structures which are influenced by alluvial streams, or which influence the behavior of alluvial streams, an improved knowledge of channel roughness is practically a necessity. Here the applicability (or lack thereof) of model study data to the prototype for flood routing, scour problems, backwater curve computations and similar problems depends to a large extent on how accurately channel roughness can be estimated.

The accuracy with which discharge can be determined is a function of the accuracy with which channel roughness can be evaluated. Resistance to flow in alluvial channels varies between wide limits with discharge, temperature and size of bed material, and with the magnitude and type of sediment load. As a result, a change in discharge may occur without a corresponding change in stage. In addition, the accuracy that can be attained in estimating flood flows by any method whatsoever, excluding direct measurement; is directly related to the precision with which roughness can be evaluated. The accuracy with which floods can be measured is directly related to the cost of flood control structures, bridges and soil conservation methods.

These foregoing examples as well as many others such as the influence of roughness on sediment transport, flow problems involving multiple roughness -- all serve to illustrate the need to study and improve the limited knowledge of how and why channel roughness varies and how to evaluate its magnitude for any given set of conditions.

Research Program

A U. S. Geological Survey research project was organized at Colorado State University in September 1956 to study the mechanics of water and sediment movement in alluvial channels. This being an extremely broad and complex field of study, it was further decided to consider only one aspect of the total problem at a time in order to minimize the diffusion of effort. The initial objective of this program was the evaluation of bed roughness in alluvial channels -- a subject of paramount importance as already stated. This objective was further subdivided into a laboratory phase to be followed later by a field phase.

This study is a part of the research program of the Water Resources Division of the U. S. Geological Survey. An advisory council consisting of P. C. Benedict, Chief of Research, QW Branch, Washington, D. C., and R. W. Carter, Chief of Research, SW Branch, Washington, D. C., assist with planning the program and review the results of the research.

The laboratory study of roughness in alluvial channels is being conducted in a recirculating laboratory flume with a sand bed. The flume is described in the section, Experimental Equipment and Procedure.

The investigational program thus far conducted in the flume has involved:

1. Modification of the pumping system to meet the needs of the program.
2. Development of special techniques applicable to the measurement of the independent variables.
3. Selection and placement of a suitable sand to a depth of about 0.7 ft on the bed of the laboratory flume.
4. Collection of data to obtain the following information for the sequence of runs thus far completed:
    a. Discharge
    b. Velocity
    c. Velocity distribution in the vertical
    d. Slope
    e. Temperature
    f. Depth
    g. Bed roughness
    h. Total sediment load
    i. Photographs

5. Collection of data with fine sediment (100 percent passing the 200 mesh sieve) added to the flow to assist in the evaluation of the influence of very fine sediment on channel roughness and sediment transport (Simons and Richardson, 1959).
6. Currently another sequence of runs are being completed using a sand which has a median diameter d of 0.28 mm and a standard deviation σ of 1.8. Data from these runs are not utilized in this report.

THEORY OF FLOW IN ALLUVIAL CHANNELS

An analysis of flow in alluvial channels is extremely complex because of the many variables involved and the difficulty of measuring them. In the U. S. Geological Survey circular by Simons, Richardson, and Albertson (1959) a thorough discussion of the pertinent variables and important dimensionless parameters related to resistance to flow in alluvial channels was presented utilizing the principle of dimensional analysis.

Dimensional Analysis

The equation relating the selected dependent variable D and the independent variables states that

$$D = \phi(B, Sfc, Sfr, V, S, \rho, \mu, \Delta\gamma, C_f, d, w, \sigma, \Delta\gamma_s) \quad (1)$$

in which

D is the depth of flow

B is the channel width

sf_c is the shape factor of the cross section of the channel

sf_r is the shape factor of the reach

V is the average velocity of the flow

S is the slope of energy gradient

ρ is the mass density of the liquid

μ is the dynamic viscosity of the liquid

$\Delta\gamma$ is the difference between the specific weight of the liquid and air

C_f is the concentration of fine sediment in the liquid which has occasionally been referred to by others as wash load

d is the median diameter of bed material

w is the representative fall velocity of the bed material

σ is the standard deviation of the bed material

$\Delta\gamma_s$ is the difference between the specific weight of the sediment and the liquid

Using D, V and ρ as the repeating variables and applying the Pi-theorem.

$$\phi_1\left(\frac{B}{D}, sfc, sfr, S, \frac{Vd\rho}{\mu}, \frac{V^2}{\frac{\Delta\gamma D}{\rho}}, C_f, \frac{d}{D}, \frac{w}{V}, \sigma, \frac{V^2}{\frac{\Delta\gamma_s D}{\rho}}\right) = 0 \qquad (2)$$

The parameters involving μ and $\Delta\gamma$ are the Reynolds number Re and the Froude number Fr respectively. Since $\frac{\Delta\gamma}{\rho} = g$ for flow of water in open channels the Froude number can be expressed in the form

$$Fr = \frac{V}{\sqrt{gD}}$$

The last term in eq 2 is modified to a drag coefficient C_D for the particles by multiplying this parameter by D/d and $(w/V)^2$ and taking it to the minus-one power.

That is,

$$C_D = \frac{d \Delta \gamma_s}{\rho w^2}$$

Eq 2 can now be rewritten as

$$\phi_2\left(\frac{B}{D}, sfc, sfr, S, Re, Fr, C_f, \frac{d}{D}, \frac{w}{V}, \sigma, C_D\right) = 0 \qquad (3)$$

This equation can be simplified by noting that:

1 - The width depth ratio is a term which is probably of secondary importance provided $B/D \geqslant 5$. When $B/D < 5$ the effect of side walls may be appreciable.

2 - The relative standard deviation σ of the size distribution of the bed material undoubtedly influences flow under certain conditions which must ultimately be determined. However, at this stage of the investigation, since only one sand has

been used, σ may be eliminated.

3 - The shape factors for the channel sfa and sfr may be eliminated since the bed is completely alluvial, the cross section is uniformly rectangular except for variation due to bed roughness, and the channel is straight.

Utilizing these simplifications, eq 3 reduces to

$$\phi_3 \left(S, Re, Fr, C_f, \frac{d}{D}, \frac{w}{V}, C_D\right) = 0 \qquad (4)$$

The parameters in eq 4 can be modified to other forms in the same manner that the last term in eq 2 was modified to a drag coefficient C_D.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

The establishment of relationships which exist between the resistance to flow in an alluvial channel and the characteristics of the flow and the sediment requires laboratory experiments in which:

1. Uniform steady flow exists. This is only possible in a statistical sense for with a rough movable boundary the velocity is changing both in magnitude and in direction with time and distance. However, just as turbulent flow, with velocity fluctuations, may be considered steady and uniform in a statistical sense so may flow in alluvial channels. Similarly in terms of scour, the sum of the depositional forces must balance the sum of the aggrading forces. This also is only possible in a statistical sense as the bed at a cross section is continually changing form and the total load fluctuates with time. However, considering a long time average, neither the bed nor the load is changing with time. Possibly equilibrium flow is a more suitable term than steady uniform flow.
2. The variables which describe the flow and sediment characteristics must be measured accurately. The interval of time required to measure precisely a given variable depends

upon the variable involved and how it varies with time. To illustrate, a sediment sample should be collected over a relatively long interval of time in order to average its variation with time. Conversely, the point velocities in a vertical should be measured quickly before the bed condition, and consequently, the form of the velocity profile has had an opportunity to change appreciably.

In addition, the scope of the investigation must simulate the conditions found in nature. That is:

1. Various sizes and gradations of bed material which are found in the field must be used, subject to the limitations of the flume.
2. Slope, depth, and water discharge must be varied enough to cover an adequate range of field conditions.
3. The effect of temperature variation must be investigated.

Thus far, forty-five runs have been completed using one size of bed material with slope, depth, and water discharge varied from run to run. The slope was varied from 0.00014 to 0.01 ft/ft, the discharge was varied from 2 to 21 cfs and the flow conditions ranged from no sediment movement to antidune flow. This is, to our knowledge, the first set of data, excluding Gilbert's (1914) which covers this broad range of flow conditions.

The Flume

The runs were made in a tilting recirculating flume 150 ft long, 8 ft wide, and 2 ft deep as shown in fig. 1. The flume is of wood construction resting on steel I-beams. The slope of the flume was changed and adjusted by mechanical jacks placed every 10 ft along the flume. Any slope can be set between the limits of 0 to 0.013 ft/ft. The flume is constructed so that the water-sediment mixture which leaves the flume is returned to the flume entrance by centrifugal pumps. This procedure of recirculating the water-sediment mixture aids in obtaining equilibrium conditions, and in simulating conditions in an infinitely long channel, because the sediment load and size distribution are varied by the flow -- rather than by mechanical traps and shakers.

Alluvial Bed Material

The flume was filled to a depth of 0.7 ft with a natural river sand. This sand was obtained from a commercial sand and gravel company located on the Cache La Poudre River. Although this sand was supposedly free of particles larger than 1/4-in., a few particles of this size were observed although they were seldom sampled. The sand, principally

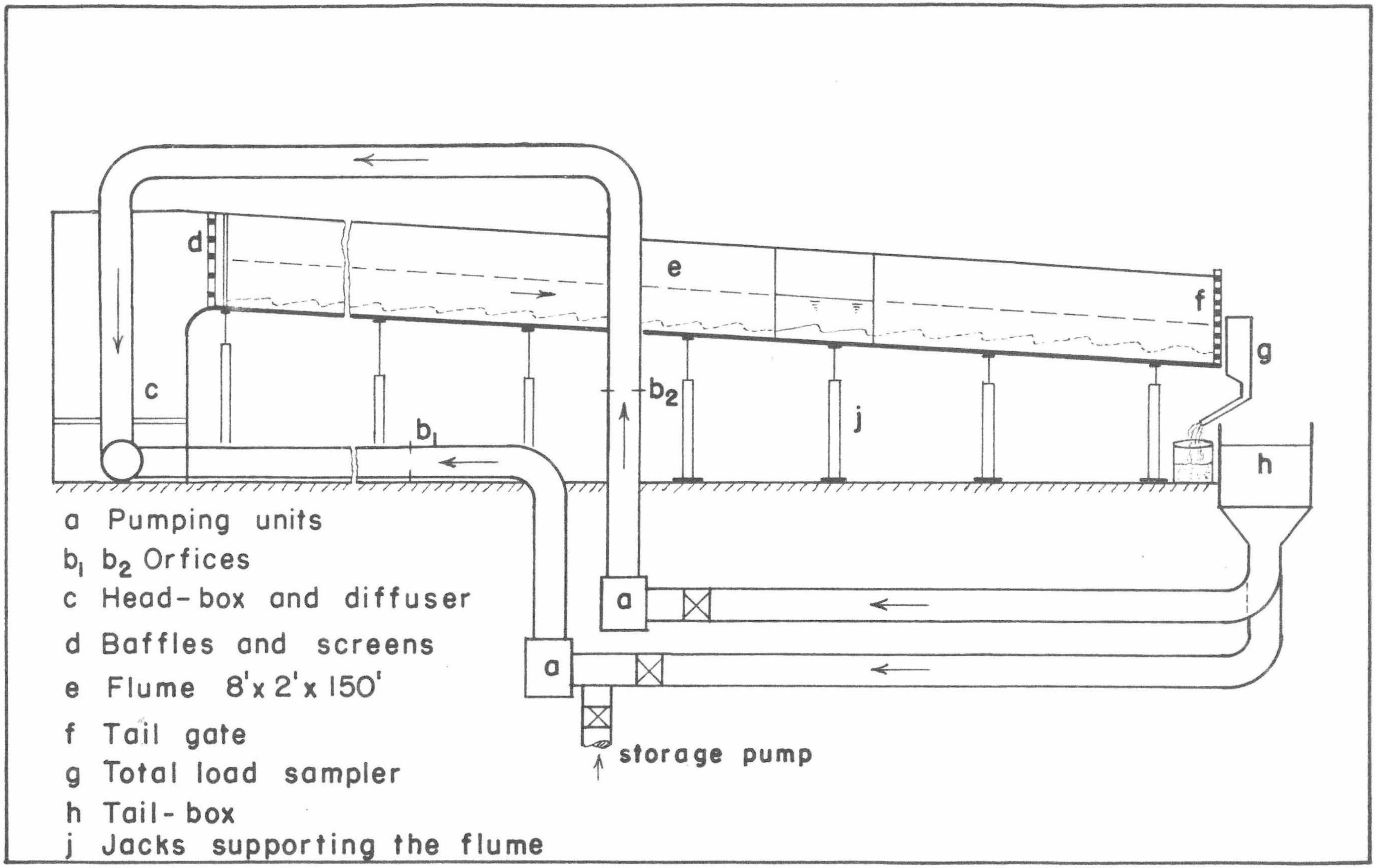


Fig. 1 Schematic diagram of the flume

quartz and feldspar, also contained a small amount of mica. The micaceous particles have a large sieve diameter but small fall diameter. That is, they have a smaller settling velocity than a sand particle of the same sieve diameter. The median fall diameter of the bed material is 0.45 mm based on sample analyses by the visual accumulation apparatus method. The size distribution curve for the bed material is given in fig. 2.

The size analyses of the bed material and sediment load were made using the visual accumulation apparatus cited in the foregoing paragraph. It was developed by the Inter-Agency Sediment Project at Minneapolis, Minnesota. The theory and application of this apparatus were presented in detail by Colby (1956).

General Procedure

The general procedure followed for each run involved recirculating a given discharge of the water-sediment mixture in the flume at a given slope until equilibrium conditions were established.

Slope selection was accomplished in a general sense. In any flow system where discharge, depth and slope can be varied, only two of the three variables can be considered as independent. In a natural stream the discharge and slope are normally independent with depth dependent.

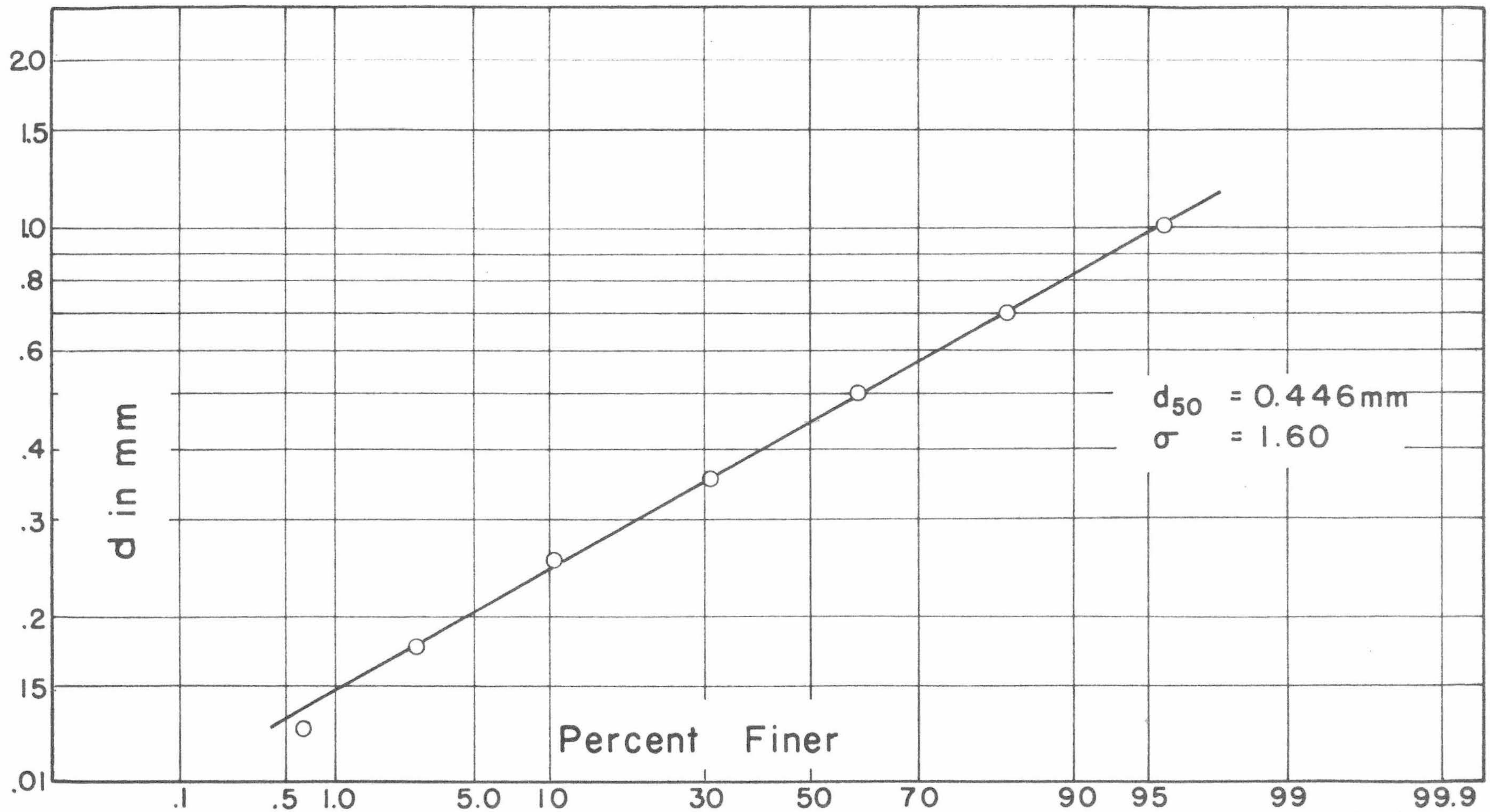


Fig. 2 Size Distribution Curve of the Bed Material

In the flume the discharge was independent, slope was independent within limits, and depth was dependent. The slope was preset at the beginning of a run by adjusting the tail gate. Such adjustment indirectly influences the depth as a dependent variable. Generally, and especially at the flatter slopes (0.0014 to 0.006), the slope of the water surface was adjusted parallel with the bed. With the development of bed configuration, the slope and depth adjusted to the new condition of bed roughness. Thus, for these experiments the slope and depth are a function of Q and the roughness which develops for that regime of flow. The non-uniformity of flow caused by a change in bed roughness was eliminated by continuing the run until the bed slope and the slope of the water surface again became parallel to each other by natural adjustment of the sand bed.

In the tranquil flow regime the mechanics of establishing the desired slope at the beginning of each run was to set first an M1 backwater curve, and then alternately adjust the tail gate and measure the water surface slope until the water surface is gradually adjusted to the desired slope. For the flatter slopes, (0.00014 to 0.0006) the bed was carefully screeded to the desired slope before the run. With the steeper slopes since the increased sand movement assisted in obtaining equilibrium conditions quickly, the bed was only raked to remove the dunes from the previous run before starting the new run. In the rapid flow regime the slope was changed by altering the bed control at the lower end of the flume. The resultant movement of sediment quickly established equilibrium conditions.

Equilibrium flow was considered established if:

1. The same bed configuration was established for the full length of the flume, excluding the section influenced by entrance conditions.
2. The water surface slope remained essentially constant with respect to time $\left(\frac{\partial S}{\partial t} = 0\right)$.

The period of time required to establish equilibrium conditions varied with the slope and the discharge. Some runs with flat slopes required three and four days to achieve equilibrium, whereas, at steeper slopes equilibrium was established in two or three hours. Every run involved continuous flume operation until it was completed. Whether or not equilibrium conditions are established is based on the measured data and the judgment of the experimenter. To insure the achievement of equilibrium conditions most of the experiments were continued longer than the required time as indicated by measurements.

Data Obtained

Water surface slope.--Water surface elevation was measured every 5 ft along the flume using a precision level and a Lory point gage, see fig. 3. As a check on these slope determinations and to facilitate slope control a U. S. Geological Survey bubble gage was utilized to continuously record the difference in elevation of the water surface over a 100 ft interval. Slopes recorded by this means were in excellent agreement with measured slopes.

Discharge.--To obtain the desired range in discharge two pumps were used. One is a 12-in. pump with a maximum discharge capacity of 7.98 cfs and the other is a 15-in. pump with a maximum discharge capacity of 13.38 cfs. Carefully-calibrated orifice meters and water-air manometers, read to the nearest one-hundredth of a foot, were used to measure the discharge.

Water temperature.--Water temperature was measured with a mercury thermometer to the nearest 0.5° C each time discharge was determined.

Depth.--Depth was determined:

1 - By subtracting the actual mean bed elevation from the mean water surface elevation.

2 - By subtracting the bed elevation of a plane screeded reach of channel from the mean water surface elevation corresponding to the reach.

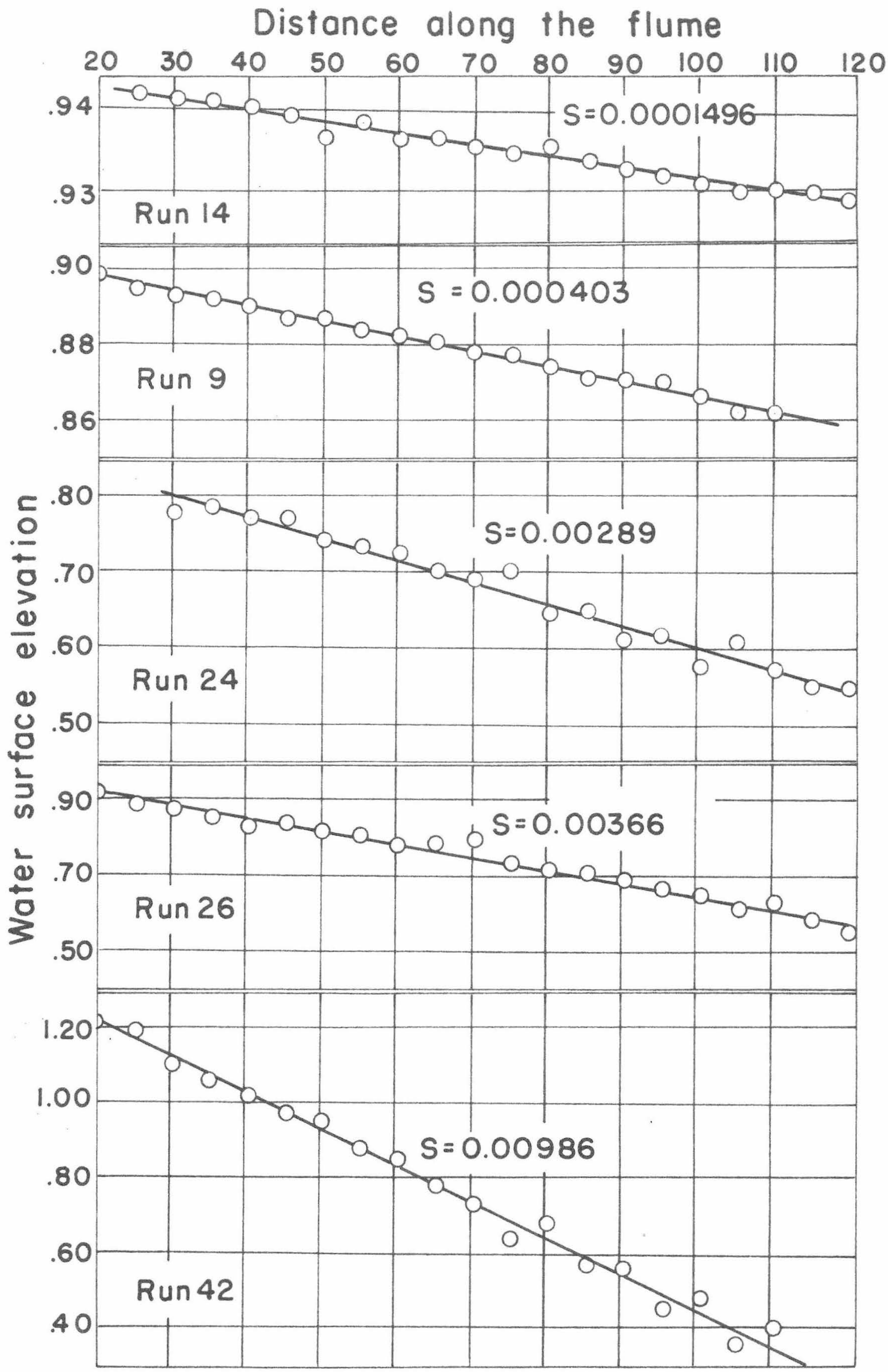


Fig. 3 Typical Water Surface Profiles

3 - By dividing the mean water-sediment discharge by the average velocity of the flow as determined from velocity profiles.

4 - By utilizing a sonic depth sounder to measure the distance to the alluvial bed from a fixed distance below the water surface.

The depths as determined by these methods are in good agreement.

Mean velocity.--The mean velocity was computed from:

1 - The velocity profiles, and

2 - The continuity principle using the depth as computed by methods 1 or 2.

Velocity profiles.--Velocity profiles were obtained by measuring point velocities in the selected verticals with a calibrated pitot tube using a water-air manometer.

Bed material.--Several samples of bed material were collected each run. The size distribution of each sample of bed material was determined using the visual accumulation tube (VA tube). The VA tube (Colby 1956) determines the fall diameters.

Total sediment load.--Total sediment load was determined periodically after equilibrium conditions were established, by using a width-depth integrating total load sampler of special design. A sample of the water-sediment mixture weighing from 100 to 160 lbs was collected 4 or 5 times during a run. From these samples the concentration and size distribution of the total load were determined.

Suspended sediment samples.--Suspended sediment samples were collected at the same cross section as the velocity profile data using the DH-48 hand sampler.

Bed configuration.--The height and length of the various forms of bed roughness were measured initially by the point gage. Later a sonic depth sounder was perfected which was used to measure bed configuration and rate of bed form movement.

Standard deviation.--The standard deviation σ of the bed material and sediment for each run was calculated from the equation

$$\sigma = \frac{1}{2} \left(\frac{d}{d_{16}} + \frac{d_{84}}{d} \right) \qquad (5)$$

in which

d is the median size

d_{16} is the size of material for which 16 percent is smaller

d_{84} is the size of the material for which 84 percent is smaller

The basic variables which were recorded for each run are given in Progress Report No. 1 by Simons, Richardson and Albertson (1959).

OBSERVED FLOW PHENOMENA

The form of bed roughness in alluvial channels is a function of the sediment characteristics and the characteristics of the flow. That is, the bed configuration may be changed by changing any one of discharge (which affects the depth), slope, temperature, or the median diameter or size distribution of the bed material. In the flume experiments the bed material was not changed and the slope, temperature, and depth were varied. Under these conditions the following forms of bed roughness were observed.

Tranquil flow regime, $Fr < 1$

1. Plane bed without movement,
2. Ripples,
3. Dunes,
4. Transition from dunes to rapid flow,

Rapid flow regime, $Fr > 1$

5. Plane bed and water surface,
6. Standing waves,
7. Antidunes,

The major forms of bed roughness are sketched in fig. 4.

Slope and bed material are the dominant parameters which determine the form of bed configuration that will occur.

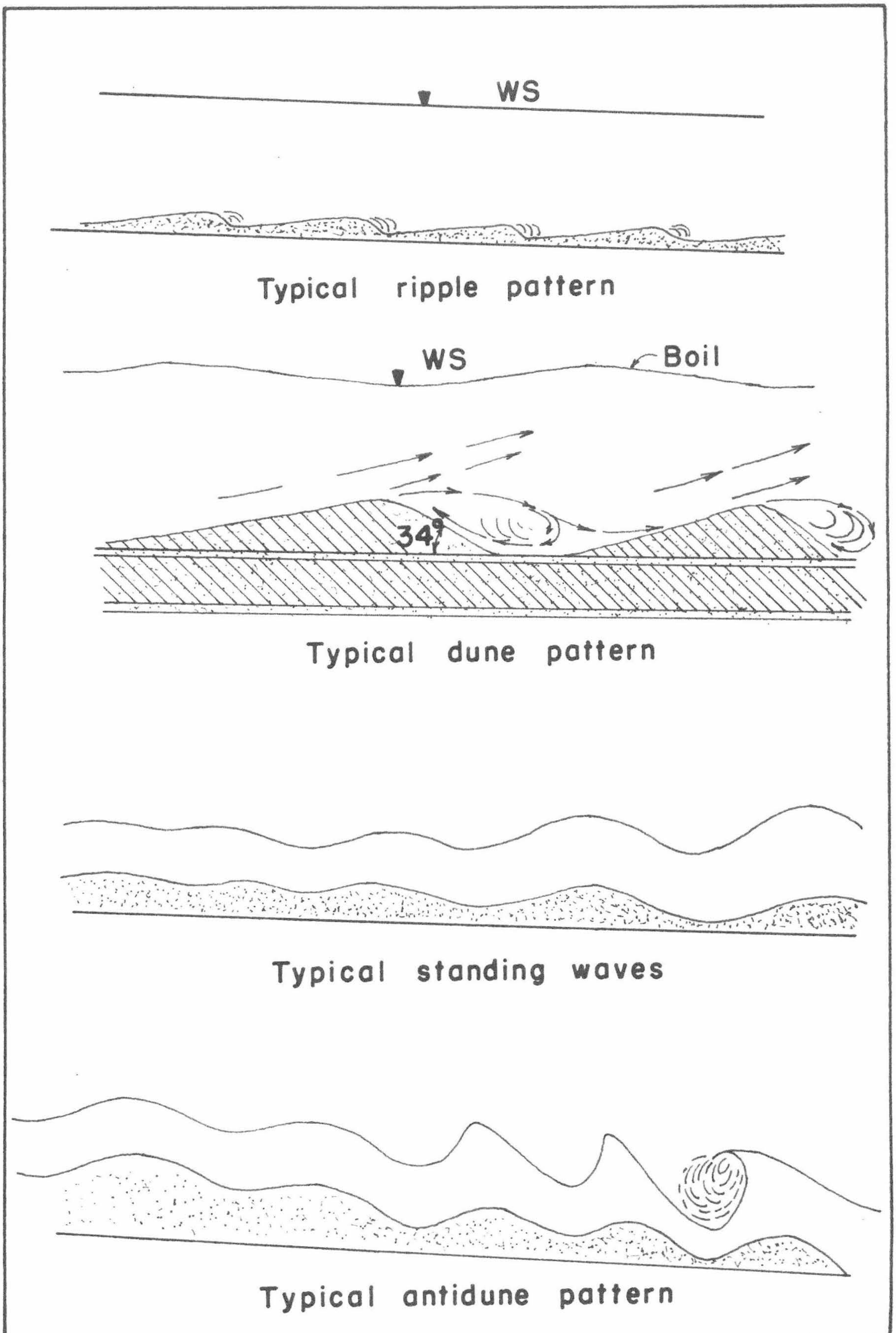


Fig. 4 Major forms of bed roughness

Although, with slope and bed material constant, the form of the bed may be changed by varying depth (changing Q) or changing temperature. However, changing depth or temperature will not change flow from tranquil to rapid unless the slope for a given bed material is close to the critical slope. That is, for a given bed material with a small slope and the dune bed form of roughness it is impossible to change to standing waves by changing depth or temperature. With a given depth and temperature all bed forms can be observed by changing slope when using a sand bed material. This last statement has to be qualified because with shallow depths three-dimensional flow will occur and with it multiple bed roughness forms. It is possible to have a size of bed material which will eliminate some of the bed forms regardless of the depth, slope or water temperature. Fig. 20 in the section Analysis of data illustrates the effect of temperature, slope, depth, and size of material on the forms of bed roughness.

With a given bed material the change from one bed form to another is not necessarily abrupt. Neither does it occur at the same slope (depth and temperature held constant) or the same depth (slope and temperature held constant) if the change is reversed. That is, the change from ripples to dunes may occur at a different slope (depth and temperature held constant) than the change from dunes to ripples. This gradual change and/or hysteresis affect results in a transition from one bed form to another. This transition is of major importance when the flow changes from tranquil to rapid or rapid to tranquil, that is, from dunes to standing sand waves and water waves or from standing waves to dunes. The change in flow regime from tranquil to rapid or rapid to tranquil does occur in many natural rivers. That is, if slope of the energy grade line is close to critical slope a change in stage can cause a change in regime with tranquil flow at low stage and rapid flow at high stage. When this change occurs there is a break in the discharge rating curve for that stream. Because there is a hysteresis in the transition from rapid to tranquil or tranquil to rapid flow the stage where the break in the rating curve occurs depends on whether the stage is rising or falling and also on the rate of change.

It is important to note that the velocity of the flow in an alluvial channel is not zero at the bed. The velocity of the water through the bed even though slow is important, especially when considering seepage force, which is a force or form drag exerted by the liquid on the sand grains within the bed which form the walls of the pore passages. The magnitude of the seepage force per unit of volume of bed material is equal to the hydraulic gradient of the flow and it acts in the direction of flow. When the magnitude of the seepage force is equal in magnitude and opposite in direction the submerged weight of a unit volume of bed material (inflow condition) the effective weight of the bed material tends to zero. Conversely if the seepage force and submerged weight of bed material act in the same direction (outflow or seepage) the effective weight of the bed material is increased. Actually depending upon bed configuration, direction of flow in the bed, water table conditions and regime of flow the direction of flow in the bed can vary from vertically upward to vertically downward. The velocity of this flow in the bed is largest with the dune bed form of roughness since the porosity of the material is relatively large and smallest in the rapid flow regime where the bed material is more closely packed. In the flume, as a result of the floor, the velocity of the flow through the bed was probably smaller than in most natural streams with deep sand beds, consequently, the seepage force is smaller. In a natural stream the velocity, in addition to being larger in the direction of flow, has vertical components of velocity in the bed resulting from inflow or outflow. This inflow or outflow which depends on the position of the water table of the surrounding area can cause large seepage forces. These forces may have a considerable effect on the form of bed roughness and transport of sediment.

Tranquil Flow Regime

Plane bed without movement.--The plane bed, with no movement of bed material, was soft and easily disturbed. The word plane is used to emphasize that the bed was not hydraulically smooth. That is, for a hydraulically smooth rigid bed the magnitude of d/δ' (the ratio of median diameter of bed material to the thickness of the laminar sublayer) must be such that $d/\delta' < 0.25$. The minimum d/δ' for the flume runs was 0.40. Obviously it is possible to obtain a hydraulically smooth boundary without bed movement by decreasing the slope or the depth. However, obtaining a smooth bed or a plane bed without sediment movement in itself has little practical significance. The important factor to consider is at what point will movement of bed material begin when the slope or depth or both are increased. It is interesting to note that the point where movement begins, with this bed material, is not the point where the transition from the hydraulically smooth to the hydraulically rough boundary of rigid boundary hydraulics occurs. That is, the thickness of the laminar sublayer must be decreased beyond that point corresponding to the transition before movement begins. It must be remembered that the bed material utilized is non-uniform and computations are based on a median diameter of the material.

Movement of bed material began with a slope of 0.00015 when the depth was increased (by increasing Q) from 0.61 to 0.71 ft. The d/δ' - value at the beginning of movement of the bed material was between 0.48 and 0.53. The Manning n for the two runs without movement was 0.015, and $C/\sqrt{g}$ varied between 14.0 and 15.0.

When d/δ' approached 0.53 movement of the fine material began and ripples started to form. The ripples formed at the upstream end of the flume and at any small depression or ridge on the bed and then continued to develop in a downstream direction below these points of minor disturbance until the bed was covered. As ripples formed on the bed, the slope and depth in the flume increased from 0.00015 and 0.71 to 0.00023 and 0.80 respectively. The Manning n increased from 0.015 to 0.022 and $C/\sqrt{g}$ decreased from 15.0 to 10.3.

The change from a plane bed, with no sediment movement, to ripples occurred at a definite depth (slope and temperature held constant). As stated in the preceding section the change occurred when the depth was changed from 0.61 to 0.71 ft with a constant slope of 0.00015. With the bed material utilized, ripples started to form when movement began. Other investigators have reported movement with a plane bed without the formation of ripples. Whether this movement without ripples is a physical fact or the result of the experimental procedure and equipment is unknown. For example, movement without ripples may result from using a sorted bed material whereas this bed material is unsorted.

Changing from ripples to the plane bed by altering flow conditions is a physical impossibility unless movement of sediment occurs without the formation of ripples. By chaning depth and/or slope it is possible to stop the movement of sediment. However, the ripples still exist although they may not be as angular in form as when sediment is moving. If d/δ' is a criteria of the change from plane bed to ripples or ripples to plane bed d/δ' must be reduced to less than 0.48 to stop movement of sediment with a ripple bed configuration.

Ripples.--The form of the ripples is illustrated graphically in fig. 4, and a photograph of typical ripple formation is shown in fig. 5. The height of the ripples was less than 0.10 ft and their longitudinal spacing less than 2.0 ft. Their length-height ratio L/h varied from 10 to 20. The ratio of depth of flow to ripple height ranged from 4 to 24

Manning n ranged from 0.019 to 0.027, and $C/\sqrt{g}$ ranged from 7.8 to 12.4. The upper limit of n-values, and the lower limit of $C/\sqrt{g}$, in general, were associated with the shallower depths.

There was little or no suspended sediment movement with the ripple bed form. The water was sufficiently clear so that the bed was visible at all times. The total sediment load ranged from 1 ppm to 101 ppm and the sediment moved in more or less continuous contact with the bed, rolling up over the crest of the ripples and coming to rest on their forward slope. The sediment on the forward slope did not move again until it was exposed in the upstream part of the ripple as the ripple migrated downstream. Thus the movement of the sediment particles takes place in steps. The length of the step and time interval between steps depends on the length of the ripple and ripple velocity.

With ripples the bed was soft but not as soft as with dunes. The water surface was very smooth with little visible difference from the water surface for the plain bed without sediment movement. The separation zone downstream from the crest of the ripple is such that there was little evidence of jet impingement on the downstream ripple. The reverse flow in the trough moved only the finest mica particles and the turbulence was small at the interface between the main current and the separation zone.

As the slope and/or depth was increased beyond a certain limit the ripples were modified and the appearance of the bed changed. Compare the ripples shown in fig. 5 with the dunes in fig. 6.

The bed changed from the ripple pattern to a dune pattern when the slope and/or depth were changed such that d/δ' was approximately 1.0. The Froude number was approximately 0.28. This change was abrupt and the dunes established themselves over the full length of the flume in a matter of hours. To change from dunes to ripples (Q constant) it was necessary to decrease the slope and/or increase depth from those values at which ripples changed to dunes. With the reduced transport capacity caused by the change in slope and/or depth considerable time is required for the flow to completely convert a dune configuration to ripples. However, ripples superpose themselves on the dunes in short order.

Dunes.--The graphical form of the dunes is illustrated in fig. 4 and a photograph of typical dunes is shown in fig. 6. In the sequence of runs completed, dunes ranged in average height from 0.15 to 0.52 ft and in length from 4.0 to 7.5 ft. The length to height ratio L/h varied from 14 to 28. The ratio of depth of flow to dune height D/h ranged from 15 to 5. Froude number varied from 0.38 to 0.60 with 0.60 fixing the upper limit of the unmodified dune bed form.

Fig. 5. View of ripple configuration, looking upstream. Water-surface slope S = 0.000403 (run 9).

Fig. 6. View of dune configuration, looking upstream. Water-surface slope S = 0.00289 (run 24).

Mannings n varied from 0.018 to 0.033, although, from observing the bed much larger values of Manning n would be expected, see fig. 6. The reason for these smaller n values is that with this large a flume, as with a natural stream, the dunes form in a pattern that allows part of the flow to sideslip or bypass the dune. This sideslippage or meandering of the flow around the dunes is very obvious when a smaller discharge is run over a dune bed formed by a larger discharge.

Dunes move downstream as a result of sediment toppling over the crest and accumulating on the downstream face of the dune. The larger the amplitude h of the dune the more sediment is stored in the dune and the smaller the dune velocity for a constant transport rate. Considering a particular run, dunes with a low amplitude with their higher velocities overtake the larger dunes. This results in a much larger dune and decreases the dune velocity. Velocity of the dunes varied from 0.03 to 0.70 ft per minute. The larger dune velocities were associated with the steeper slopes and shallower depths. Conversely, the larger dunes were associated with flatter slopes and deeper depths. Knowing the average amplitude and velocity of ripples and dunes the bed load transport can be computed. This problem is treated in Progress Report No. 2, Simons and Richardson (1959).

The L/h-ratios for dunes and ripples are similar. The ratios vary from 10 to 24 for ripples and 14 to 28 for dunes. This indicates that there is a correlation between dune height and dune length for a given sediment. That is, if the amplitude of the dune or ripple increases with change in slope or depth the length also increases. The variation in the L/h ratios may be the result of the randomness of the dune configuration -- making it difficult to obtain true average length or height. Some of the variation in L/h may result from including the separation zone in measured lengths of the dunes. That is, the true length of the dune may extend from the end of the separation zone to the down-stream crest. The measured length as used, however, was from crest to crest. The magnitude of the separation zone increases as slope increases until the transition region is reached.

The ratio of depth of flow to dune height or relative roughness D/h is different for ripples than for dunes. Ripples have a larger D/h ratio than dunes. This parameter may help explain why the n values are smaller for ripples than for dunes. Also with the ripple and dune bed forms, the larger n values occurred with the smaller D/h values.

It appears from the flume data that maximum dune height, with two-dimensional flow, is limited by the depth of flow. That is, the dune will only grow until its crest is within a certain relative distance from the water surface unless three-dimensional flow exists. Also with a given slope and a continuous increase in depth the dune height may reach some maximum value for that size of sediment and water temperature, and increasing the depth beyond this limiting depth will not increase the dune height. If this is true, then to predict accurately the resistance to flow in an alluvial channel the point where dune height becomes independent of depth must be determined. This point may be a function of the width of the channel. If dune height becomes independent of depth the n values may decrease with stage. That is, h/D the relative roughness will decrease.

With dunes the bed is very soft and fluid and there is considerable segregation of the bed material. The upstream slope and crest of the dune, which has a negative slope of approximately 2 to 4 degrees, consist of the fine and coarse material moving downstream. This slope of the upstream face was practically the same as that for the upstream face of the ripples. On the upstream face of the dune, at the lower slopes, ripples formed. At the larger slopes these ripples on the dune were not apparent. The downstream face, which has a positive slope between 31 and 39 degrees, consists of the coarser fraction of the bed material. This coarser fraction is the material which could not be swept into suspension at the crest but toppled over the crest and avalanched down the fore slope. It is this avalanching which results in the soft nature of a dune bed. The material is deposited by the force of gravity and has relatively large voids. If it had been deposited by the dynamic force of the fluid it would be packed into place, with relatively small voids ratio. Bagnold (1941, p. 238-240) observed and explained the same phenomena with wind blown dunes. The trough of the dune contains a layer 1/8 to 2 inches thick of the fine material from the bed. Part of the fines in the trough came from the sediment which was swept from the crest and part came from the lower part of the upstream face of the downstream dune where the main current which overrides the separation zone impinges on the bed, see fig. 4. As the water surface slope was increased within the dune form of bed roughness the toe of the downstream dune was more actively blasted and eaten away by the high velocity water impinging on it. This is a source of additional fine material which is deposited in the trough by the reverse flow in the separation zone. Velocities as high as 1.3 ft/sec in the upstream direction were measured in the separation zone.

The slope of the downstream face of the dune, which varied from 31 to 39 degrees with an average of 34 degrees, was clearly defined by lines formed by the dark colored mica particles as the dune moved downstream, fig. 4. The angle of repose in air for dry non-cohesive sand 1 mm in diameter (the bed material in the flume was 95 percent finer than 1 mm) varies from 29 to 32 degrees depending on angularity of the particles, (Simons, 1957). That is, well rounded 1 mm particles have an angle of repose of 29 degrees and very angular particles 32 degrees. It is probable that the angle of the forward face of the dune is increased above that for angle of repose of dry sand in air as a result of the increase in pressure in the separation zone on the fore plain of the dune and the reverse flow in the trough moving up the face of the dune. This is verified by the fact that as the velocity of flow is reduced to zero in the flume the face of the crest of the dune slumps reducing its angle of inclination.

With the dune bed form of roughness the water surface is uneven and turbulent. Over the crest of the dune the water surface is lower than over the trough. This is the result of the acceleration and deceleration of the flow as it contracts over the crest and expands over the trough. This was illustrated for rigid boundaries by Rouse (1946 pp. 135 and 139). The degree of roughness (turbulence) of the water surface increases with increasing bed roughness.

The roughest water surface occurred where there were large water surface boils. These boils stood approximately 0.1 of a foot above the surrounding water surface. However, the roughness of the water surface was not great enough to affect the determination of the water surface slope, see fig. 3. The turbulence created at the interface between the main flow and the flow in the separation zone dissipated considerable energy and normally the disturbance caused by the interference was visible on the water surface downstream. With the dune bed form the suspended sediment concentration, the intensity of the turbulence, the relative roughness, and the velocity of the reversed flow in the trough increased with increasing slope. Along with the dunes, potholes formed which have a depth equal to the height of the dunes. These as well as the dunes caused boils on the water surface which were evident downstream from the dunes. The potholes and boils moved downstream in front of the dunes at the velocity of the dunes. There were normally from 10 to 20 potholes and boils evident in the full length of the flume with this type of bed roughness. The pothole appeared to develop as a result of the increased strength of the secondary circulation in the separation zone. The combination of the velocity in the direction of flow and the secondary circulation causes a vertical circulation similar to a whirlwind.

This rotating motion scours out additional material at a point in the separation zone and produces a pothole. The existence of these potholes is indicated by the formation of very strong boils which visibly transport considerable suspended sediment upward to the water surface.

The segregation of the material by the formation and movement of dunes means that a large number of bed material samples must be obtained and analyzed before the size distribution can be established with confidence. With the flume material 60 samples were needed before another sample would not alter the median diameter a significant amount. This segregation should have some value, though, because in the field ($Fr < 0.6$) it might be possible to determine the characteristics of the bed roughness by core sampling the bed, conditions permitting.

Transition, dunes to rapid flow.--The change from dunes to rapid flow is complex and the form of the bed roughness is erratic. With small changes in depth and/or slope the bed configuration may change from a form typical of dunes to a form typical of rapid flow or some combination of the two. The transition occurs when the depth and/or slope are changed to give $d/\delta' > 2$ and $0.6 < Fr < 1.0$.

There is a definite break in the Froude number when changing from dunes to rapid flow. With dunes the maximum Froude number was 0.60. Obviously, the minimum Froude number is 1.0 with rapid flow. Runs with a Froude number between 0.6 and 1.0 displayed a multiple roughness, that is, a bed form in between dunes and a plane bed consisting of washed out dunes and sand bars.

It is logical that the upper limit of the Froude number, with the dune bed form, is considerably less than 1.0. The change in roughness, and consequently the change in resistance to flow and the dissipation of energy, is large when changing from the plane bed or undulating bed of the rapid flow regime to dunes whereas the change in energy for changes in the Froude number in the vicinity of $Fr = 1$ is small. Thus the velocity and depth, when the bed form changes, are changed considerably resulting in a low Froude number. Conversely, the change from dunes to rapid flow results in smaller loss of energy because of the reduced roughness, resulting in larger velocities, small depths and Froude number ≥ 1.0.

There is a hysteresis effect in the change of bed roughness from dunes to rapid flow and back to dunes. The value of slope and/or depth for the change depends on the bed configuration prior to the change. If the bed is covered with dunes a slope of 0.0035 may be required before rapid flow will occur and the dune configuration is destroyed. If the bed is plane the slope may be decreased to 0.0025 before the flow will change from rapid to tranquil and dunes form. This hysteresis effect may be attributed to the change in energy with change in flow regime from tranquil to rapid or rapid to tranquil. That is, a change from potential to kinetic energy with change from tranquil to rapid or change from kinetic to potential energy with a change from rapid to tranquil. This change in energy results from the large change in roughness associated with the change in flow regime from tranquil to rapid or rapid to tranquil. Dunes have n values ranging from 0.018 to 0.032, whereas with rapid flow the n-values range from 0.010 to 0.015.

The fact that, with this bed material, a typical dune pattern did not occur with a Froude number equal to or greater than 0.60 is important, especially, if it holds true for other bed materials. Runs 40 and 29 had Froude numbers equal to or slightly greater than 0.60. Their bed form is washed out dunes with rather large L/h values. The Manning n values were 0.018 and 0.021 respectively, these are small when compared with n values for dunes, but larger than rapid flow n values. It seems that the magnitude of Manning n increases as the percent of the bed which is covered with dunes increases.

The three other runs (30, 35, 36) with $0.6 < Fr < 1.0$ had long sand bars of small amplitude which were diagonal to the flow. These bars were 20 to 30 ft in length with L/h values between 30 and 50.

Runs (29, 30, 35, 36) had distinctly different types of flow occurring side by side, see fig. 7. This was probably caused by using discharges which were too small with respect to slope which caused three-dimensional flow. This same phenomena was also observed in the antidune range when the discharge was decreased beyond a given value (run 45). With three-dimensional flow the n-values ranged from 0.014 to 0.023, whereas the n-values for standing waves is approximately 0.012.

Three-dimensional flow probably results because in conducting the experiments, discharge and slope were controlled, and with the steeper slopes the small discharges set up conditions favorable for three-dimensional flow. Other experimenters may have experienced this flow condition because of the limited discharge capacity of their flume system and the resultant large width to depth ratio which develops as slope is increased. With the dune bed form the smallest discharge was sufficient to insure two-dimensional flow. Presumably, however, by further decreasing the discharge, three-dimensional flow could also develop.

Fig. 7. Three-dimensional flow with multiple forms of bed roughness (run 35).

Fig. 8. View of the plane bed in the rapid flow regime, looking upstream. Water surface S = 0.00366 (run 26).

Runs 29, 30, 35, and 36 were discounted in analysis of data because they were three-dimensional.

Rapid Flow Regime

With rapid flow, $Fr > 1.0$, three forms of sand bed and water surfaces were observed; plane, standing waves and antidunes.

Plane bed and plane water surface.--A completely plane bed with plane water surface, over the full length of the flume was only produced once in the total sequence of runs, see fig. 8. It was anticipated from existing literature that this would be the most common type of bed configuration between dunes and antidunes. Most experimenters have recorded a larger number of plane bed runs -- particularly when they worked with short flumes. In many of the runs conducted in this study, there was a plane bed and water surface for the first 60 to 70 ft of the flume, but beyond that point standing waves developed. Laursen (1958), in his experiment using a flume 105 ft long and 3 ft wide also reported difficulty in obtaining a plane bed. Based on recent tests using a fine sand it is apparent that whether or not a plane bed develops is intimately related to size of bed material. Using fine sand plane bed runs are a common phenomenon and they develop at $Fr < 1$ in the tranquil flow regime.

For the plane bed of fig. 8 the Manning n-value is extremely small (n = 0.0078), the total sediment load is large (4580 ppm), the Froude number is 1.6 and the d/δ' value is only 2.1. This Froude number is the next to the largest recorded even though the slope for this run is not as great as for the runs in the antidune regime. The sand bed was very firm.

Standing waves.--The water surface consists of symmetrical standing waves of small amplitude, fig. 9. The standing waves form and gradually disappear and unlike antidunes they had no tendency to break or migrate upstream. The form of bed roughness observed with standing waves, in the order of increasing slope, were:

(a) a diagonal dune pattern cross-laced like a shoe string, see fig. 10,

(b) a plane bed, see fig. 8,

(c) a symmetrical undulating sand wave similar in form to those observed in the antidune regime, see fig. 15.

The standing wave formed when Froude number was approximately 1.0. The standing water waves with the diagonal cross-laced sand bars shown in fig. 10 formed with this lower Froude number. The standing wave with plane bed was formed at a Froude number of about 1.1 and standing waves with an

Fig. 9. View of standing wave in rapid flow regime looking downstream. Water-surface slope S = 0.00364 (run 39).

Fig. 10. View of cross-laced configuration, looking upstream. Water-surface slope S = 0.00435 (run 27).

undulating sand wave bed developed when $1.2 < Fr < 1.5$. The Manning n for standing waves is relatively small, ranging from 0.012 to 0.015. The water surface waves are 1.5 times as high as the corresponding sand waves. Concurrent measurements of the sand bed waves and the water surface waves are illustrated in fig. 15.

Antidunes.-- When the Froude number, computed on the basis of average velocity and average depth, was greater than 1.3 and d/δ' was greater than 3.0, antidunes formed.

Antidunes are defined as a train of symmetrical sand waves with a corresponding train of symmetrical water surface waves which are in phase with each other. Both trains of waves move upstream and grow in height until they break, see figs. 11-14, resulting in a cyclical fluctuation of the water surface waves and the sand waves. The waves build up from a plane bed with a plane water surface. They grow and move upstream until one or two of the waves become unstable and break as shown in figs. 13 and 14. Normally, when one wave breaks other waves break immediately thereafter for a distance of one or two waves upstream and 4 or 5 waves downstream. That is, depending on discharge and slope, from one to eight waves at a spacing of 1 to 6 ft usually break within a short time interval. This chain reaction that follows the breaking of the first wave is

Fig. 11. Water surface before antidune wave starts to build up, looking upstream. Water-surface slope S = 0.00986 (run 42).

Fig. 12. Looking across the flow at an antidune wave starting to form.

Fig. 13. Antidune wave at point of breaking looking upstream.

Fig. 14. Antidune wave after breaking (run 42).

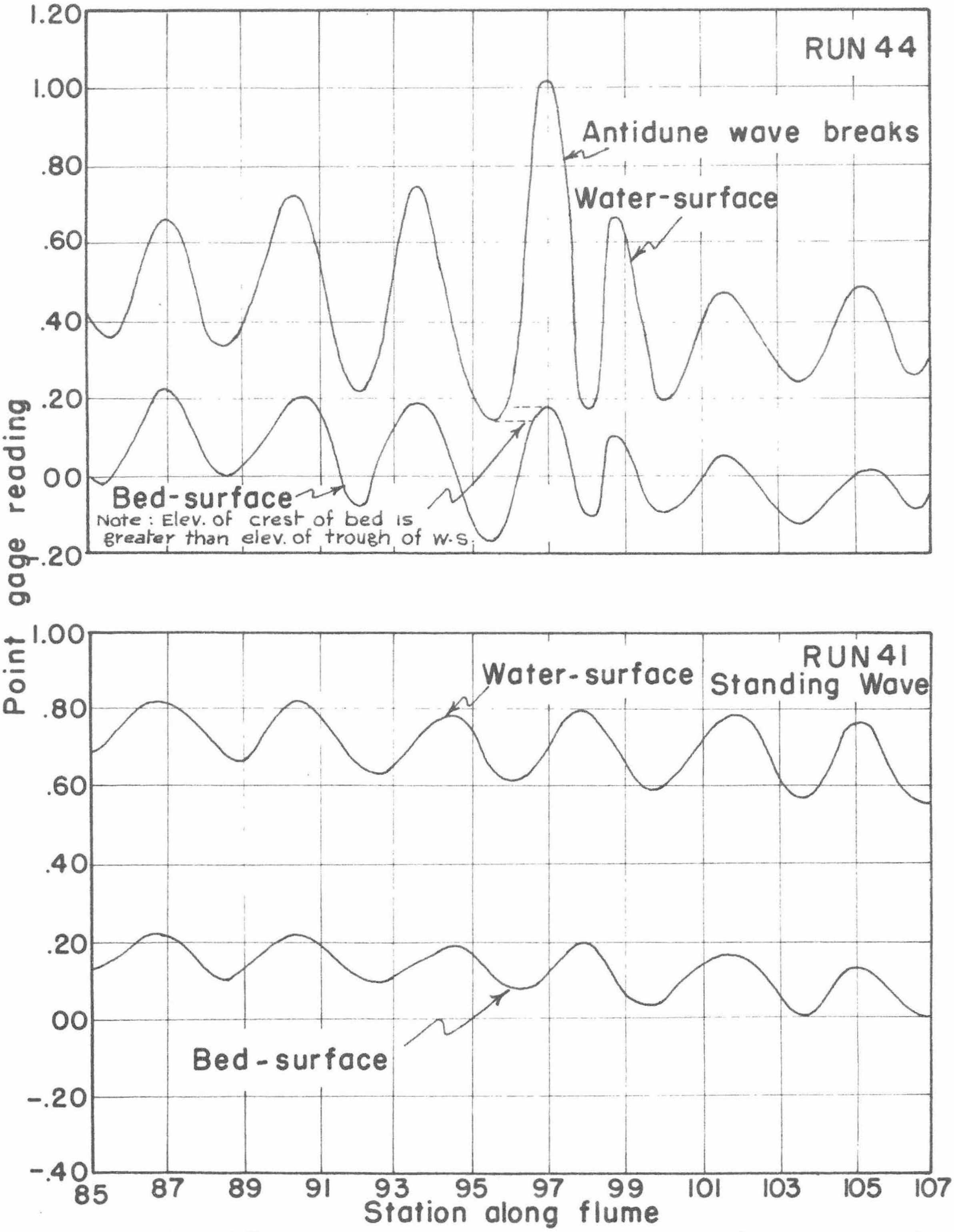


Fig. 15 The actual water surface and bed configuration for runs 44 and 41

apparently triggered by the action of the first wave which breaks.

In making concurrent measurements of the bed and water surface in the troughs and crests of antidunes, it was observed that antidunes become unstable and break when the water surface in the trough of the wave train is approximately the same elevation as the crest of the downstream bed wave, fig. 15. The measurements also indicated that the water waves are 1.7 times larger in amplitude than the corresponding sand waves. The total height of the water surface waves from trough to crest was from 1.0 to 1.5 times the average depth. When the waves started to break their heights were about twice the average depth. The breaking of the waves is very spectacular. There is considerable turbulence, dissipation of energy and mixing of the flow. When they break they sound like the surf in the ocean and there is probably some resemblance in that the ocean wave (as it climbs the sloping beach) also builds up to an unstable height before breaking.

The bed when the antidunes are building up is very firm and there is no separation between the flow and bed. However, when the antidune breaks the crest of the sand wave becomes soft and fluid and seems almost to explode. When the waves break the flow is very turbulent, there is separation, and considerable sediment is thrown into suspension. Normally, most of the sediment load is moved as contact load. Total load concentration is very large ranging from 4240 to 15,000 ppm for these runs. It appears that the movement of the antidunes upstream results from scour on the downstream side of the sand wave and deposition on the upstream side of the wave -- consequently, the wave moves upstream.

Except for run 45, which was considered three-dimensional, there was only one train of waves in the cross section. The train of waves was located off center at about the left 1/3-point in the cross section. In subsequent runs, however, two trains of waves symmetrically located in the flume were observed several times. The wave train was not continuous throughout the entire length of the flume. That is, a train of antidunes would build up and break in one 20 to 40 ft length of flume, then repeat in another 20 to 40 ft reach, or they would build up and break in two or three discontinuous lengths of the flume. The building up and breaking in the different reaches of the flume might be in phase or out of phase.

The period of time it takes for one antidune wave to build up and break, and the number of antidune waves building up at one time, varied with the slope and the discharge. With run 32 only one train of 6 to 8 antidune waves would build up and break at a given time. This train of waves with a total length of about 40 ft, would perhaps build up in the lower section, then next in the middle or upper sections, and again near the original position. Normally, about two complete cycles occurred every hour -- a cycle includes starting with a plain surface, the building up of waves, the breaking of the waves, and the return to a plain surface. For other runs with steeper slopes there were 3 or 4 reaches in the flume in which the train of waves built up and broke in phase and out of phase, almost continuously.

When the antidunes break a considerable amount of water is stored in the flume. Based on observations at the glass-walled section of the flume when an antidune breaks the water in the crest moves upstream, and that water close to the bed almost ceased to move until the breaking wave vanishes, then normal flow is restored. At the larger slopes, run 43, when 3 or 4 series of antidune waves in the train would build up and break simultaneously water was stored in the flume to such an extent that the pumps would surge. In the extreme case, antidune waves would build up and break in phase with the surging of the pumps. This resulted in a fluctuating discharge and an increase in antidune activity. Throughout the full length of the flume so much water was stored in the flume as a result of antidune action, that the tail-water level in the tailbox dropped until the pumps lost their prime. To eliminate this degree of surging of the pumps, the level of the water in the sump was raised and excess water was continuously added to the sump to replace that stored in the flume. When the antidunes were not breaking there was a surplus of water which was discharged through an overflow at the top of the sump.

Storage of water caused by the breaking of the antidune waves probably explains the surging discharge observed in alluvial streams with steep slopes. That is, the antidunes store and release water in the upper reaches of the stream in a random haphazard manner, but as the flow travels downstream this storage and release of storage causes the antidunes to break in a more systematic pattern until surges develop which cause the antidunes to form and break at regular time intervals. Some field examples of surging flow are Muddy Creek near Pavillion, Wyoming and Medano Creek in the Great Sand Dune National Monument, Colorado.

Antidune flow with this bed material, hydraulically speaking, is very efficient. That is, the Manning n ranges from 0.010 to 0.013. Even though the breaking of the antidune dissipates considerable energy the period of time and length of flume that this breaking occupies is small in comparison with the total time and total flume length. This explains the small n values. It was observed that as the antidune activity increased with an increase in slope that there was a larger dissipation of energy with a decrease in discharge coefficient $C/\sqrt{g}$ and an increase in Manning n. Surface velocity measurements, obtained by timing floats along a centerline of a train of antidune waves (when they were not breaking) and along a nearby parallel line where the water surface was smooth, showed that the surface velocity was greater in the train of waves. The velocity in the trough of the dune is considerably greater than that in the crest. It is possible that the dunes break when the velocity and depth over the crest decrease because of increasing wave height until a Froude number less than 1.0 results.

The standing wave and the antidune wave may be compared to the flow regimes of rigid boundary hydraulics illustrated by Rouse (1946). The crisscrossed type bed pattern, fig. 10 which was observed with both standing wave and antidune flow resembles the shock waves which develop with rapid flow ($Fr > 1.0$) when considering rigid boundaries.

ANALYSIS OF DATA

The basic data and the parameters computed therefrom have been utilized to obtain the relationships presented in this section. It should also be borne in mind that these relations excluding fig. 20 are based on only one group of flume data, and that the size and gradation of bed material remained constant except as altered by miscellaneous sorting which may or may not be of significance. That is, d and σ are constant and w varied only because of temperature changes. The relationships presented in this chapter are given in a logical sequence which can be subdivided into four major phases.

1. Relationships of a simple nature which illustrate the interrelationships that exist between flow variables, geometric variables, the form of bed roughness and the regimes of flow.
2. Relationships of a more complex nature which illustrate the variation of the Manning n, tractive force and total sediment load concentration.
3. Relationships which involve roughness in alluvial channels.

4. A plot which utilizes data from both the laboratory and the field to expand the usefulness of the foregoing concepts and to accentuate the existence of two regimes of flow and six major forms of bed roughness.

Appreciable insight to the scope covered by the data collected and the interrelationships existing between flow and geometric variables can be gained by considering a few simple dimensional plots.

Variation of Velocity with Depth

The variation of velocity with depth and their interrelationships with the six major forms of bed roughness are given in fig. 16. Isoclines of Froude number have been superposed on the figure to illustrate the wide scope of the data. Velocities range from those for no movement of bed material to magnitudes far in excess of the critical velocity. That is, V varies from 0.65 to 6.2 ft/sec. Note that the transition roughness includes those runs which have a bed roughness somewhere between dunes and roughnesses associated with rapid flow (washed out dunes or transition). Runs of this type plot just below the critical velocity curve. The lines dividing the plot into forms of bed roughness are based on the observed roughness and the Froude number, Fr.

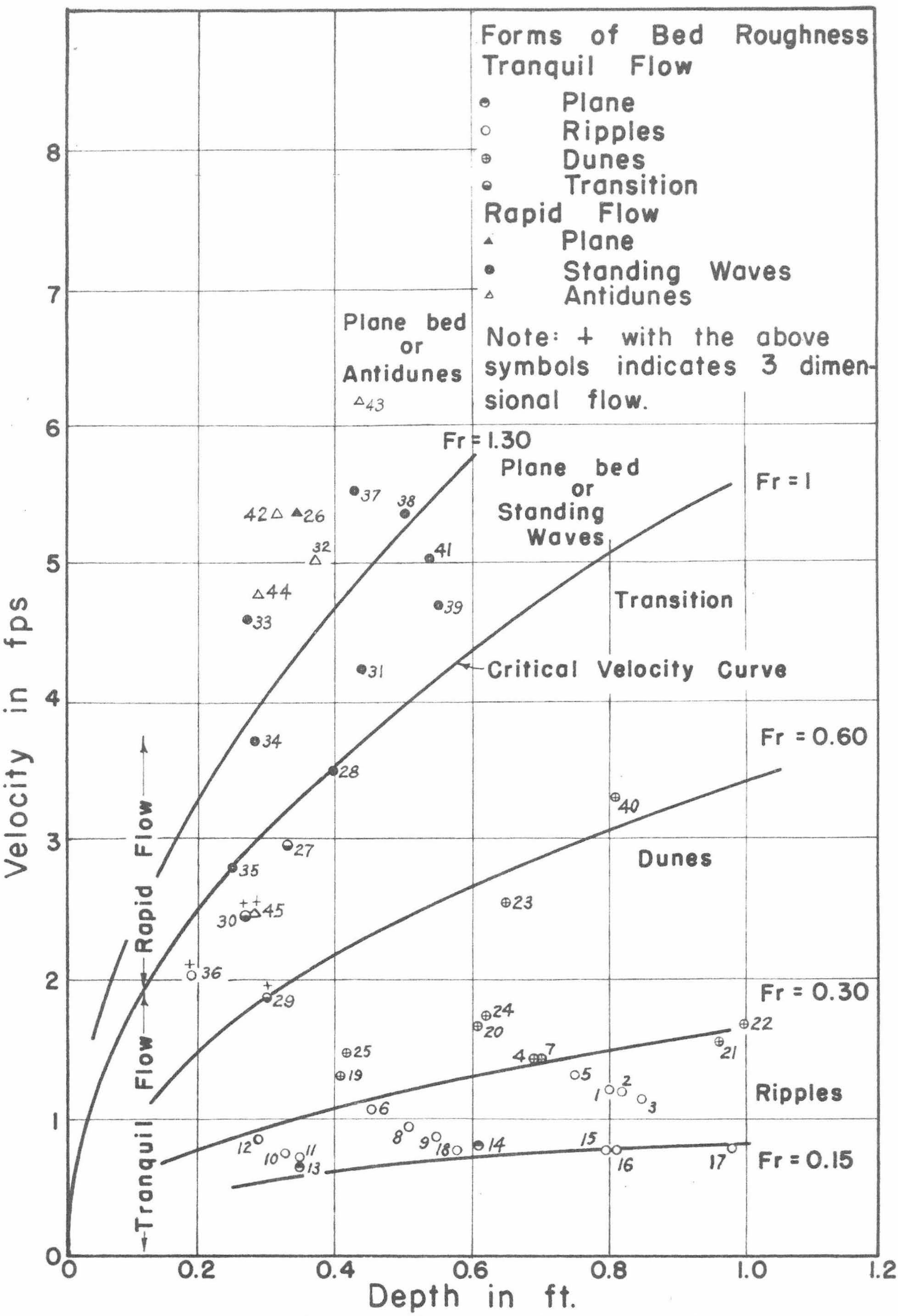


Fig. 16 Variation of velocity V with depth D

A similar relation can be plotted relating D and Q using slope and forms of bed roughness as the other variables. As in the preceding figure, the transition runs will plot just below the critical depth curve.

Variation of Total Sediment Load Concentration with Manning n

Values of Manning n have been computed. The n-values range from 0.008 to 0.033. These n-values have been corrected for side effect in accordance with the procedure presented by Einstein (1951). The magnitude of n increases with increasing V until the regime of flow shifts from the tranquil regime to the rapid flow regime at which point the n's reduce suddenly to approximately 0.012. Undoubtedly, a better relationship of the foregoing type could be obtained by relating Manning n or some other measure of channel roughness with suspended sediment load -- except that with shallow depths it is difficult to sample suspended sediment load with significant accuracy. More often than is desirable when taking the suspended sediment sample, a part of the bed material load and in some cases even a part of a ripple or dune may be intercepted -- particularly when the velocity is relatively large.

By relating the concentration C_T and the Manning n to the regimes of flow these significant conclusions can be reached:

1. As the flow is increased and the bed form changes from a plane (no movement) to ripples, the Manning n increases from about $n = 0.015$ to $n = 0.025$ with no significant discontinuities.
2. With dunes a marked increase in Manning n occurs, $0.020 < n < 0.033$. This increase in n is caused by the extreme size of the dunes at a spacing conducive to maximum roughness.
3. In the transition from tranquil flow to rapid flow the resistance to flow is also in transition. It shifts with small change in depth and slope from large resistance, slightly smaller than for the dunes, to small resistance which is slightly larger than for rapid flow. The value of the resistance to flow is dependent on the area of the bed covered by dunes.
4. In the rapid flow regime there is a significant decrease in Manning n. This extreme decrease in resistance to flow can be attributed to the change from dunes to symmetrical

sand waves. Dunes have a large separation zone with large form drag, whereas, the symmetrical sand wave has no separation zone and only the form drag resulting from the particle. Possibly some of this decrease in Manning n can be attributed to the movement of large quantities of sediment as bed load and not entirely to the elimination of the dunes. Insufficient turbulence is created to hold large quantities of sediment in suspension. Consequently, the sediment load which was carried in suspension with dunes now is carried near the bed. This extreme concentration, in turn, markedly changes the properties of the fluid-sediment mixture which means the fluid is no longer homogeneous and a sort of stratified flow results which inhibits mixing and the effective bed roughness is reduced to extremely small values. The flow has some similarity to plug flow in pipes. For the single run for which $n = 0.0078$ the bed is plane and the resistance caused by the standing waves is not in effect. Under these conditions the plug-flow phenomenon is even more pronounced.

5. The largest C_T-values with standing wave roughness occur just before these waves begin to move upstream as antidunes. With antidunes the C_T-values are even larger. The same extreme concentration of sediment exists near the bed as with standing waves except for the short time period while the antidunes are breaking and the Manning n remains small, $0.011 < n < 0.015$.

Variation of Tractive Force and Total Sediment Load

Fig. 17 is obtained by plotting the tractive force τ_o, which has been calculated by the equation

$$\tau_o = \gamma RS \tag{5}$$

with the total sediment load concentration in ppm. Although there is appreciable scatter, a trend definitely exists. That is, the magnitude of total load C_T increases with increasing magnitude of tractive force τ_o. Each run in fig. 17 has been labeled in accordance with its form of bed

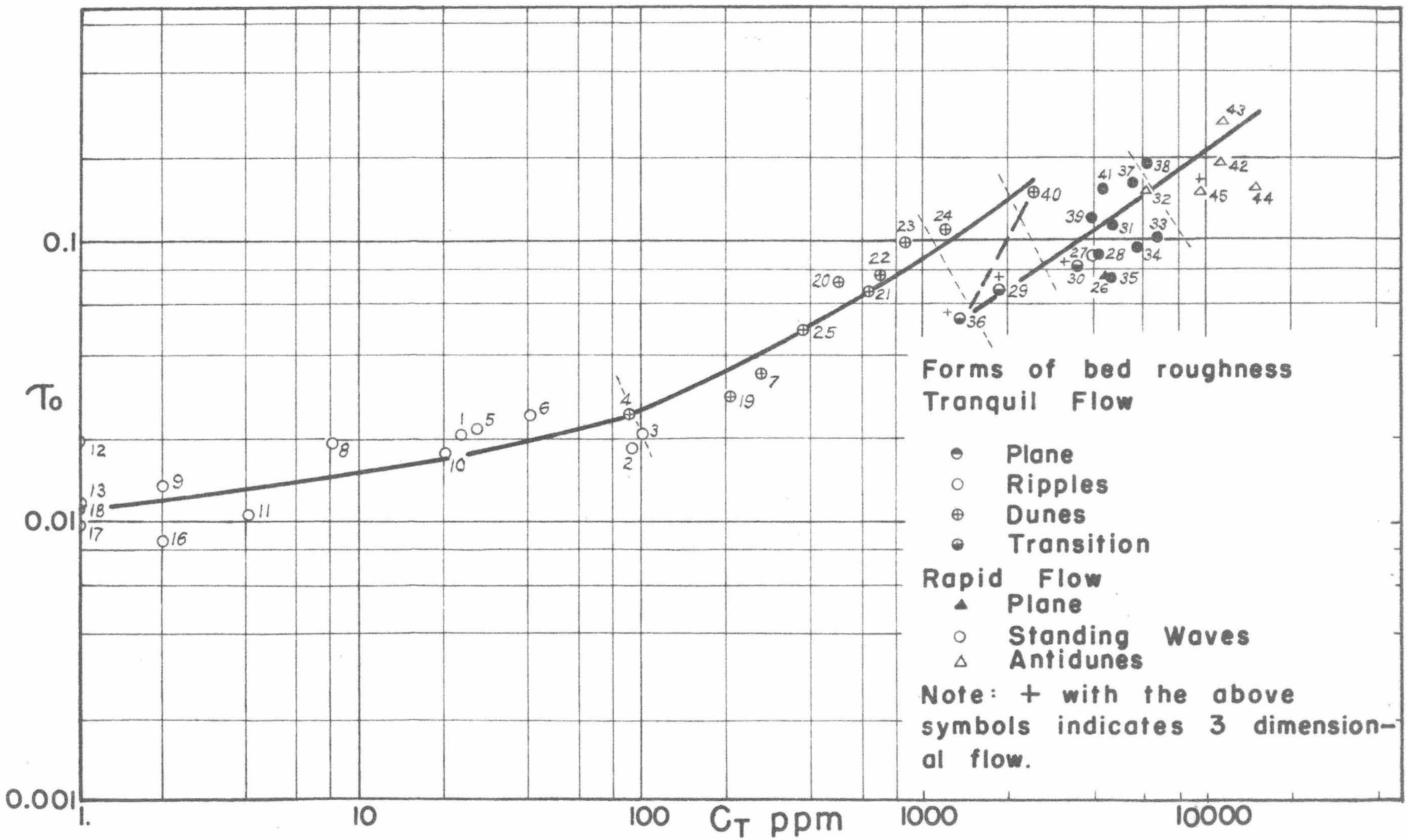


Fig. 17 Variation of τ_0 and C_T ppm

roughness. Using this notation the regimes of flow and forms of bed roughness have been indicated. There is a definite tendency, in this case, for the tranquil flow regime to separate from the rapid flow regime because of the large tractive force associated with runs with large dunes.

The deviation of the runs with dunes from the general trend is a result of an increase in shear τ_o, due to the extreme size of the dunes, without a corresponding increase in concentration C_T. It is significant to note that a sudden decrease in τ_o occurs at about $C_T = 2000$ ppm as the bed changes from dunes to plane bed or standing waves. This is caused by a reduction in roughness which also decreases the ability of the flow to transport sediment. Consequently, C_T is cut in half from run 40 to run 36 -- beyond which point C_T, in the transition regime, steadily increases. No such discontinuity occurs at the change from ripples to dunes or at the change from standing waves to antidunes. There is, however, considerable scatter in the rapid flow regime which shows that another variable is needed to define the phenomenon more completely.

Relationship Between

$\frac{V_* d}{\nu}$, $\frac{V}{V_*}$ $\frac{\tau_o}{\Delta \gamma_s d}$, and $\frac{V}{\sqrt{gD}}$

The relationship between $V_* d/\nu$ and $V\,\tau_o/V_* \Delta \gamma_s d$ was investigated for both regimes of flow, see fig. 18, and the form of bed roughness is the third variable. It is of importance to note the precision with which the relation

$$\frac{V}{V_*} \frac{\tau_o}{\Delta \gamma_s d} = \phi \left(\frac{V_* d}{\nu}\right) \qquad (6)$$

describes all forms of bed roughness. These data plot as a curve on log-log paper. The foregoing figure systematically groups the various forms of bed roughness. This relation can be modified to include the effect of varying size and gradations of materials. It is also significant that either or both Fr and C_T can be utilized as third variables in fig. 18.

Variation of

$\frac{wdS}{\nu} + \frac{5V^2}{gD}$ with $\frac{V}{V_*}$ $\frac{\tau_o S}{\Delta \gamma_s D}$

Additional study and adjustment of parameters shows that a significant relation from which $C/\sqrt{g}$ can be

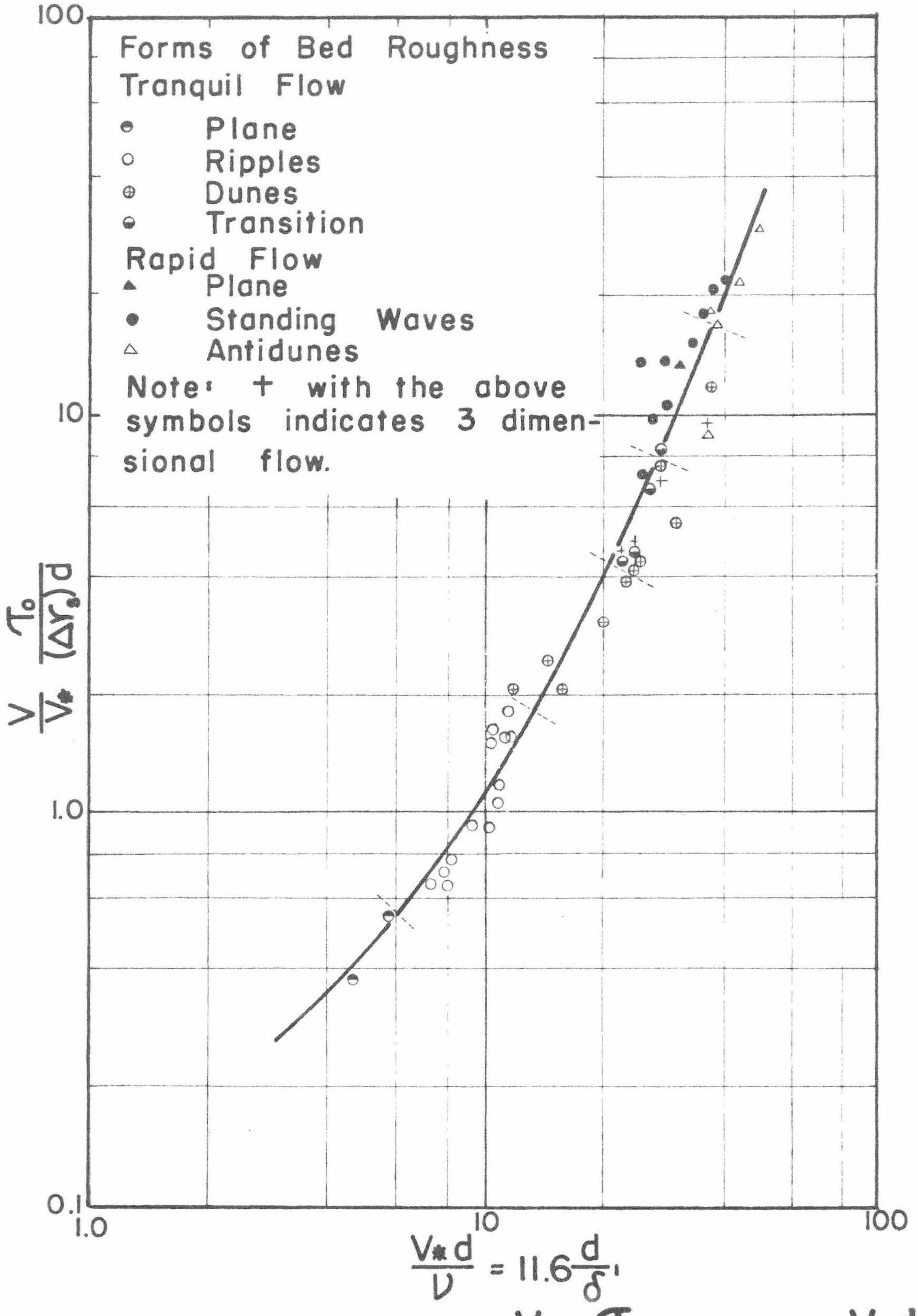


Fig. 18 Variation of $\frac{V}{V_*} \frac{\tau_0}{V_* (\Delta \gamma_s) d}$ with $\frac{V_* d}{\nu}$

computed using this bed material can be obtained by adding the product of a constant and the square of the Froude number Fr to the parameter wdS/ν . This is illustrated in fig. 19 which relates

$$\frac{wdS}{\nu} + \frac{5V^2}{gD} \text{ to } \frac{V\tau_o S}{V_* \Delta\gamma_s D}$$

such that

$$\frac{V\tau_o S}{V_* \Delta\gamma_s D} \times 10^6 = 0.90 \left[\frac{wdS}{\nu} \times 10^2 + \frac{5V^2}{gD}\right]^{1.85} \qquad (7)$$

Solving for V

$$V = 0.90 \times 10^{-6} \left[\frac{wdS}{\nu} \times 10^2 + \frac{5V^2}{gD}\right]^{1.85} \frac{\Delta\gamma_s S}{\gamma}^{-2} \sqrt{gDS} \qquad (8)$$

and

$$\frac{C}{\sqrt{g}} = 0.90 \times 10^{-6} \frac{\Delta\gamma_s}{\gamma S^2} \left[\frac{wdS}{\nu} \times 10^2 + \frac{5V^2}{gD}\right]^{1.85} \qquad (9)$$

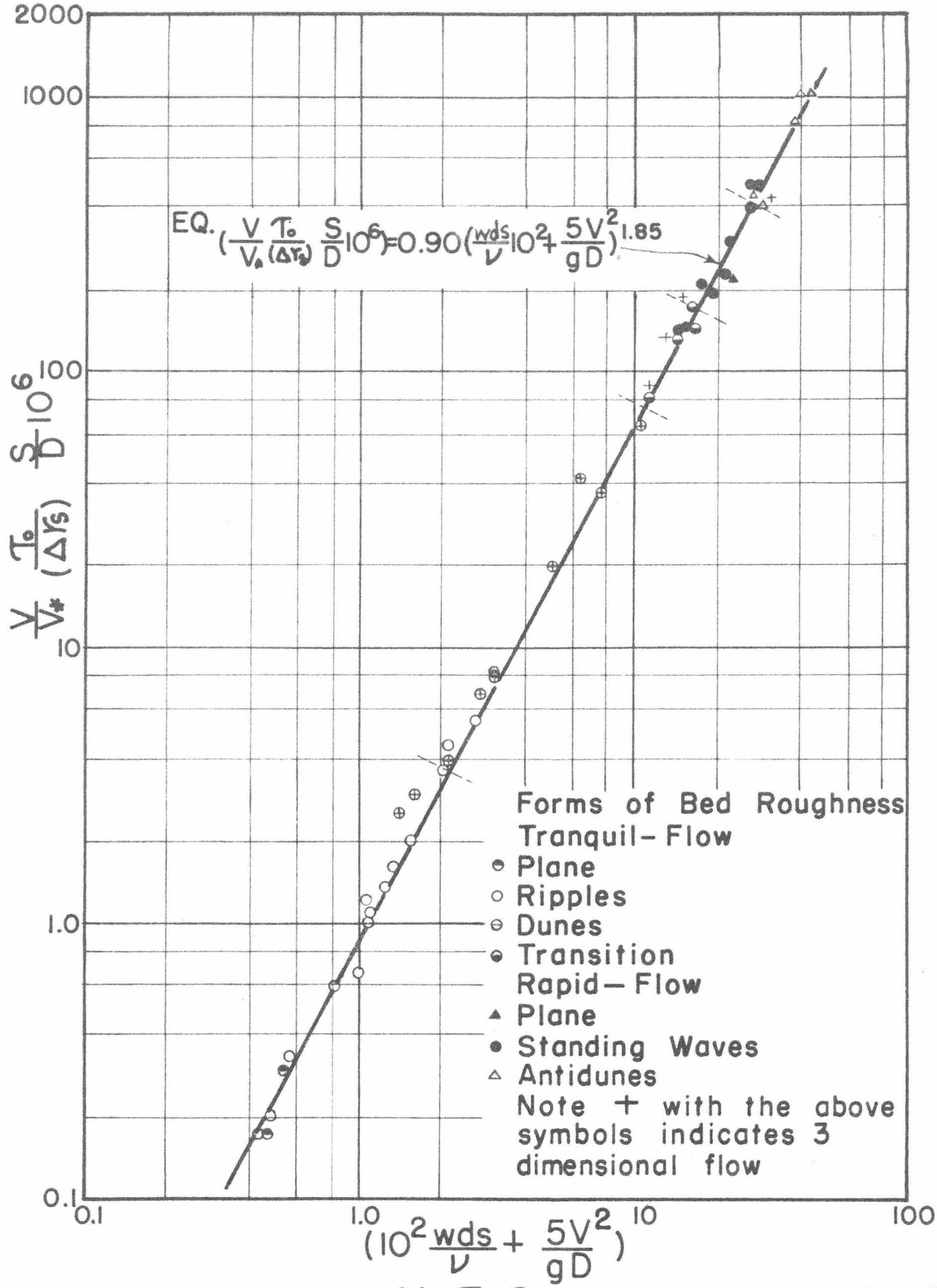


Fig. 19 Variation of $(\frac{V}{V_*} \frac{\tau_0}{(\Delta \gamma_s)} \frac{S}{D}) 10^6$ with $(10^2 \frac{wds}{\nu} + \frac{5V^2}{gD})$

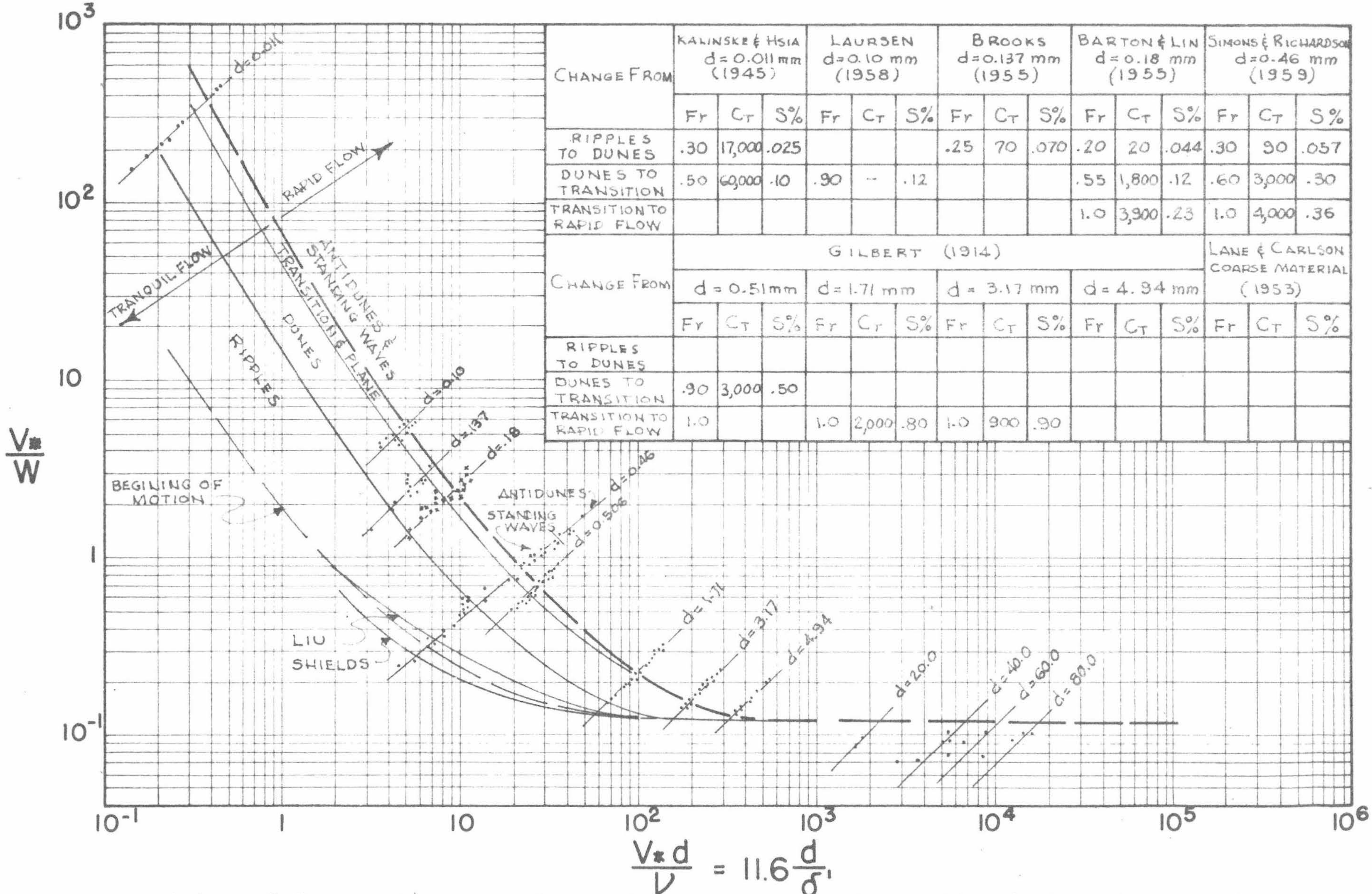
The form of bed roughness plots very well as a third variable except for minor intermingling of ripple and dune runs at the arbitrarily selected dividing line. It is also possible to utilize total sediment load as a third variable with useful accuracy.

Based on a similar approach, but using Re or C_T as the additive term instead of Fr, figures similar to fig. 19 can be obtained which are only slightly less accurate. In fact a figure of this type involving C_T could be used to qualitatively estimate total sediment load in the rapid flow regime.

Forms of Bed Roughness as
Indicated by the Variation of

$$\frac{V_*}{w} \text{ with } \frac{V_* d}{\nu} \propto \frac{d}{\delta'}$$

This plot of V_*/w versus $V_* d/\delta'$ (based on flume data and limited field data) which was presented by Albertson, Simons, and Richardson (1958) illustrates the usefulness of a relation of this type to define the regimes of flow and forms of bed roughness. As a result of further study the writers (Simons and Richardson) revised the relationship to conform with the concepts presented in this paper, see fig, 20. The Froude number Fr, the slope S,



Change From	Kalinske & Hsia d = 0.011 mm (1945)			Laursen d = 0.10 mm (1958)			Brooks d = 0.137 mm (1955)			Barton & Lin d = 0.18 mm (1955)			Simons & Richardson d = 0.46 mm (1959)		
	Fr	C_T	S%	Fr	C_T	S%	Fr	C_T	S%	Fr	C_T	S%	Fr	C_T	S%
Ripples to Dunes	.30	17,000	.025				.25	70	.070	.20	20	.044	.30	90	.057
Dunes to Transition	.50	60,000	.10	.90	--	.12				.55	1,800	.12	.60	3,000	.30
Transition to Rapid Flow										1.0	3,900	.23	1.0	4,000	.36

Change From	Gilbert (1914) d = 0.51 mm			Gilbert (1914) d = 1.71 mm			Gilbert (1914) d = 3.17 mm			Gilbert (1914) d = 4.94 mm			Lane & Carlson Coarse Material (1953)		
	Fr	C_T	S%	Fr	C_T	S%	Fr	C_T	S%	Fr	C_T	S%	Fr	C_T	S%
Ripples to Dunes															
Dunes to Transition	.90	3,000	.50												
Transition to Rapid Flow	1.0			1.0	2,000	.80	1.0	900	.90						

Fig. 20 Criteria for Roughness in Alluvial Channels

and the concentration of total load C_T all have some merit as third variables. Which of these is most significant depends, at least to some extent, upon the use of the plot.

Although the relationship between V_*/w, V_*d/ν and the forms of bed roughness shed some light on the mechanics of flow in alluvial channels and on the design of alluvial channels, there are a number of aspects of these problems for which conclusions cannot be quantitatively drawn without further information. For a more detailed discussion of fig. 20 and its advantages and deficiencies refer to the foregoing reference.

CONCLUSIONS

The problem of evaluating the resistance to flow in alluvial channels is extremely complex as a result of:

1. The number of variables involved.
2. The difficulty of measuring these variables with accuracy.
3. The great range in roughness.
4. The various forms of bed roughness.
5. The influence of bank material.
6. The various shapes of channels involved.
7. The two regimes of flow.

8. Non-uniformity of flow.
9. Wind effect.
10. The influence of vegetation.
11. Seepage forces.
12. Temperature effect,

and possibly others. In the case of a flume study, the problem is somewhat simplified in that many of the foregoing factors are eliminated. It must be remembered, however, that ultimately their effects must be considered.

A Summary of the Characteristics of Alluvial Channel Flow

It is apparent that several forms of bed roughness are encountered in fluvial hydraulics. The major ones being:

Tranquil flow regime:

1. Plane bed before movement of bed material begins
2. Ripples
3. Dunes
4. Transition from dunes to rapid flow

Rapid flow regime:

5. Plane bed and plane water surface
6. Symmetrical standing waves
7. Antidunes

In the tranquil flow regime $C/\sqrt{g}$ varied from 14.0 for the plane bed without movement to 7.4 for dunes. $C/\sqrt{g}$, for ripples, varied from 7.8 to 12.4 -- the larger $C/\sqrt{g}$ values occurring with the deeper depths and smaller relative roughness values h/D. With dunes $C/\sqrt{g}$ varied from 7.4 to 12.8, again larger $C/\sqrt{g}$ values were associated with small values of h/D. Smaller values of $C/\sqrt{g}$ probably would have occurred but for the fact that with this large a flume, as with a natural stream, the bed roughness forms so as to allow part of the flow to by-pass the dune.

In the rapid flow regime $C/\sqrt{g}$ varied from 13.9 to 27.0. The smaller $C/\sqrt{g}$ values occurred at the smaller Froude numbers. The largest $C/\sqrt{g}$ value occurred with a plane bed and plane water surface. Standing waves in general had larger values of $C/\sqrt{g}$ than antidunes. This results from the dissipation of energy by the breaking waves. $C/\sqrt{g}$ would be reduced further for antidune flow but for the fact that the period of time and length of flume occupied by the breaking wave is small in comparison with the total time and length of flume.

In the transition from tranquil to rapid flow $C/\sqrt{g}$ varied from 10.0 to 14.1. The magnitude of $C/\sqrt{g}$ increases as the percent of the bed which is covered with dunes decreases. Also, there is a hysteresis in the change-from tranquil to rapid flow which depends on the form of the bed prior to the change. That is, with discharge constant a larger slope is required to change from tranquil to rapid than is required to change from rapid to tranquil.

This change in flow regime from tranquil to rapid or vice versa occurs in natural streams. That is, if the slope of the energy grade line is close to critical slope a change in stage results in a change in regime. When this occurs there is a break in the discharge rating curve. Because there is a hysteresis in the change, the stage where the break occurs varies depending on whether stage is rising or falling and the rate of change.

In the series of runs upon which this report is based, the antidune regime of flow developed when $Fr > 1.3$. This may or may not be the case for other bed materials. For values of $1.0 < Fr < 1.3$, surface waves developed which rarely broke in true antidune fashion and the sand waves underlying the water waves stayed in essentially the same position. There was very little tendency for these waves to move in either the upstream or downstream direction. At values of $Fr = 1.3 \pm$ the water waves developed and broke in a rather systematic manner and the sand waves moved in the upstream direction. The sand waves associated with the water waves were approximately the same shape as the water waves, but to a reduced scale. That is, sand waves were about one-half the amplitude of the water waves. There was a tendency for the magnitude of the sand and water waves to increase in the downstream direction along the flume particularly for those runs having $1.0 < Fr < 1.3 \pm$. The magnitude of the sand and water waves increased with depth. Breaking of the water waves and the sand waves occurred when the elevation of the crest of a sand wave was approximately at the same elevation as the water surface in an adjacent trough. It is apparent that antidunes reforming and breaking result in surging flow observed in some natural streams.

There is a definite break in the Froude number when changing from dunes to rapid flow. The dunes do not occur with this bed material when Froude number is greater than 0.6. Rapid flow starts when $Fr \geq 1.0$. Flow with a Froude number between 0.6 and 1.0 had multiple roughness (a transition condition).

Based on the observed roughnesses, how they develop, and the way in which they move, it may be possible to determine the magnitude and type of bed roughness (particularly dunes) by checking the manner in which the bed material is segregated within the bed. This method could not be employed if the bed material were perfectly uniform and not contaminated with any foreign matter, but this is a rare situation. Also, the appearance of the water surface seems to provide an excellent means of estimating the type and magnitude of bed roughness.

Equations for the Roughness Parameter $\frac{C}{\sqrt{g}}$

The dimensionless form of the Chezy coefficient was adopted as the standard of roughness in this report. However, values of Manning n have also been used to a minor extent.

The usefulness of the various expressions for $C/\sqrt{g}$ at this stage is severely limited by the range of data upon which they are based. As the influence of different bed material, sediment loads, and a wider range of temperature conditions are included as a result of proposed future work, these expressions will undoubtedly need alteration which will make them much more useful to the engineering profession because of the greater range of conditions considered. The possibility of explaining the significance of the parameters involved will also be appreciably enhanced.

It appears that $C/\sqrt{g}$ may consist of a sum of terms each of which may have significance for a particular range or type of resistance to flow.

At a latter stage in the investigation it will be necessary to modify any current expression for $C/\sqrt{g}$ to suit field conditions.

LITERATURE CITED

Albertson, M. L., Simons, D. B., and Richardson, E. V., 1958, Discussion of mechanics of ripple formation: Am. Soc. Civil Engineers Jour., v. 84, no. HY1.

Bagnold, R. A., 1941, The physics of blown sand and desert dunes: Methurn and Co., London.

Barton, J. R., and Lin, P. N., 1955, A study of sediment transport in alluvial channels: Colo. State Univ., Dept. of Civil Engineering, No. 55JRB2, Fort Collins, p. 43.

Brooks, N. H., 1955, Mechanics of streams with movable beds of fine sand: Am. Soc. Civil Engineers Proc., v. 81, no. 668, p. 1-28.

____________, 1957, Closure, Mechanics of streams with movable beds of fine sand: Am. Soc. Civil Engineers Jour., v. 83, no. HY2.

Colby, B. D., and Christensen, R. P., 1956, Visual accumulation tube for size analysis of sand: Am. Soc. Civil Engineers Jour., v. 82, no. HY3.

Einstein, H. A., and Barbarassa, N. L., 1951, River channel roughness: Am. Soc. Civil Engineers Proc., v. 77, no. 78, p. 12.

Gilbert, G. K., 1914, Transportation of debris by running water: U. S. Geol. Survey Prof. Paper 86.

Kalinske, A. A., and Hsia, C. H., 1945, Study of transportation of fine sediments by flowing water: State Univ. Iowa, Studies in Engineering, Bull. no. 29.

Lane, E. W., and Carlson, E. J., 1953, Some factors affecting the stability of canals constructed in coarse granular materials: Internat. Hydr. Conv. Proc., p. 37-48, Minneapolis, Minn.

Laursen, E. M., 1958, Total sediment load of streams: Am. Soc. Civil Engineers Jour., v. 84, no. HY1.

Liu, H. K., 1957, Mechanics of sediment-ripple formation: Am. Soc. Civil Engineers Jour., v. 83, no. HY2.

Rouse, H., 1946, Elementary mechanics of fluids: John Wiley and Sons, New York.

Simons, D. B., 1957, Theory and design of stable channels in alluvial materials: Colo. State Univ., Dept. of Civil Engineering, Ph. D. Thesis, Fort Collins.

Simons, D. B., Richardson, E. V., and Albertson, M. L., 1959, A study of roughness in alluvial channels: U. S. Geol. Survey Circ. (in preparation).

Simons, D. B., and Richardson, E. V., 1959, A study of the effect of fine sediment on flow in alluvial channels, U. S. Geol. Survey Progress Report No. 2 (in preparation).

GLOSSARY OF TERMS

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

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

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

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

Equal Transite Rate (ETR): A method of sampling suspended sediment to obtain the mean concentration of the water-sediment mixture in the flume. By this method the depth integrating sampler (DH-48) is traversed though equally-spaced verticals at an equal transite rate for each vertical.

<u>Fall Diameter</u>: The diameter of a sphere that has a specific gravity of 2.65 and also has the same terminal uniform settling velocity as the particle (any specific gravity) when each is allowed to settle alone in quiescent distilled water of infinite extent and at a temperature of 24° C.

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

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

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

<u>Sand Wave</u>: A ridge (such as ripples, dunes, or symmetrical undulations) on the bed of an alluvial channel formed by the movement of the bed material.

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

<u>Sediment Concentration</u>: The ratio of dry weight of sediment to total weight of the water-sediment mixture, usually expressed in parts per million (ppm).

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

<u>Suspended Load</u>: The sediment moving in suspension in a fluid as a result of turbulent currents and/or by colloidal suspension.

<u>Total Load</u>: The total amount of sediment that is transported by water in a given length of time.

LIST OF SYMBOLS

Symbol	Description	Dimensions	Units
B	Width of channel	L	ft
$C/\sqrt{g}$	Chezy coefficient of discharge in dimensionless form which is equivalent to V/V_*.	0	--
C_D	Drag coefficient for the particle	0	--
C_T	Concentration of total load	ppm	0
C_f	Concentration of fine material	ppm	0
d	Median fall diameter of bed material	L	ft
D	Average depth of flow	L	ft
Fr	Froude number	0	--
h	Average height of bed roughness	L	ft
K	Any constant	0	--
L	Average spacing of bed roughness	L	ft
n	Mannings coefficient of roughness	$L^{1/6}$	$ft^{1/6}$
n_b	Mannings coefficient of roughness (Einstein)	$L^{1/6}$	$ft^{1/6}$
Q	Discharge of water-sediment mixture	L^3/T	ft^3/sec
Re	Reynolds number	0	--
sf_c	Shape factor of the channel cross section	0	--
sf_r	Shape factor for the reach of the stream	0	--
S	Slope of energy gradient equal to water surface slope in steady, uniform flow	0	--

	Description	Dimensions	Units
	Time	T	sec
V	Average velocity based on continuity principal	L/T	ft/sec
V_*	Shear velocity which is $\sqrt{gDS}$, $\sqrt{\tau_o/\rho}$	L/T	ft/sec
W	Fall velocity of sediment particles	L/T	ft/sec
γ	Specific weight of water	F/L^3	lbs/ft^3
γ_s	Specific weight of sediment	F/L^3	lbs/ft^3
$\Delta\gamma$	Difference between specific weights of air and water	F/L^3	lbs/ft^3
$\Delta\gamma_s$	Difference between specific weights of sediment and water	F/L^3	lbs/ft^3
δ'	Thickness of laminar sublayer	L	ft
ν	Kinematic viscosity	L^2/T	ft^2/sec
μ	Dynamic viscosity	Ft/L^2	$lb\text{-}sec/ft^2$
ρ	Mass density of water	Ft^2/L^4	$Slug/ft^3$
ρ_s	Mass density of sediment	Ft^2/L^4	$Slug/ft^3$
σ	Relative standard deviation of the size distribution of the sediment	0	--
τ_o	Tractive or shear force developed on the bed, γDS	F/L^2	lbs/ft^2