FORMS OF BED ROUGHNESS IN ALLUVIAL CHANNELS

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January 1960 CER60DBS3

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Synopsis

The forms of bed roughness which develop on the bed of an alluvial channel are intimately related to the regime of flow, the size and gradation of the bed material, the depth of flow, and channel width-depth ratio as well as other less significant variables; such as, viscosity, seepage forces caused by inflow or outflow of water through the fluvial bed, and the concentration of fine material which effects the viscosity and specific weight of the water-sediment mixture.

Based upon laboratory and limited field investigations, the major forms of bed roughness observed in alluvial channels in their normal order of occurrence with increasing shear on the bed for the tranquil flow regime are:

1. Plane bed without bed material movement
2. Ripples
3. Dunes with ripples superposed
4. Dunes
5. Transition
6. Plane bed

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and for the rapid flow regime are:

1. Plane bed
2. Symmetrical standing sand and water waves
3. Antidunes
4. Extreme antidune activity (chutes and pools).

Resistance to flow and sediment transportation vary greatly as form of bed roughness changes. Consider the two sands with median diameters of 0.45 mm and 0.28 mm which have been thoroughly investigated in a large recirculating flume. For a dune bed configuration, the Manning n varies from 0.019 to 0.04, and the corresponding bed material transportation rate ranges from 75 to 1000 ppm. For the antidune condition, Manning n varies from 0.014 to 0.020, and bed material transportation ranges from 6000 to 42,000 ppm.

Field studies by **Colby** (1957) and D. R. Dawdy, Research Section, Surface Water Branch, U.S. Geological Survey (oral communication, 1959) indicate that the behavior of an alluvial channel can be explained more satisfactorily if one is intimately acquainted with the regimes of flow and forms of bed roughness. For example, the change in resistance to flow which occurs when the form of bed roughness changes from dunes to plane bed or standing waves accounts for the discontinuity which has been observed in stage-discharge relationships on certain gaged streams.

REGIMES OF FLOW

Two regimes of flow are commonly recognized in the fields of hydraulics and fluid mechanics. These are the tranquil-flow and rapid flow regimes. These regimes of flow are adequately defined by the specific energy diagram and/or the Froude number, Fr. That is, flow is tranquil when the normal depth is greater than critical depth, and flow is rapid when the depth of flow is less than critical depth. Similarly, when the Froude number $Fr < 1$, flow is tranquil and when $Fr > 1$, flow is rapid. The Froude number is defined, for open channel flow as

$$Fr = \frac{V}{\sqrt{gD}} \tag{1}$$

in which

V is the velocity of flow in fps,

g is the gravitational acceleration in fps^2

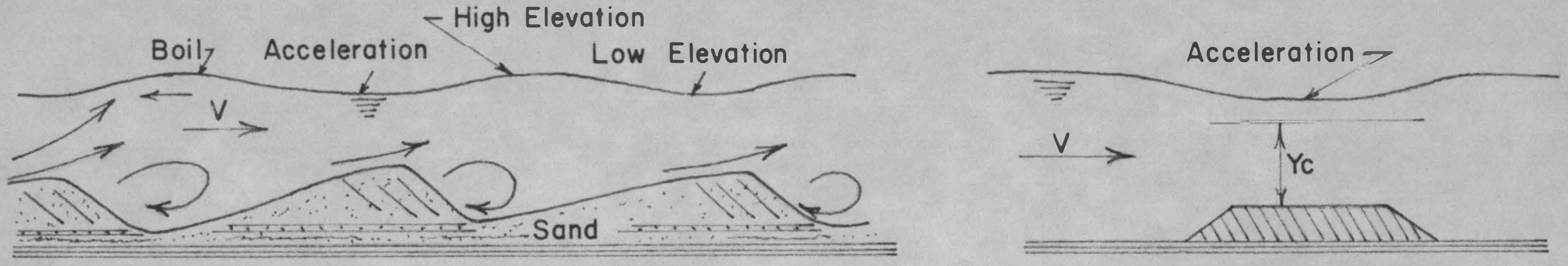
D is the depth in ft.

Normally the mean velocity V and depth D are used in computing Froude number. However, it is important to recognize that with the extreme variability of flow conditions which occur in the cross section of a natural alluvial channel it may, under certain circumstances, be advantageous to consider local values of velocity and depth and the corresponding magnitude of Froude number to help explain observed phenomenon. It is not uncommon, when dealing with alluvial channels, to be confronted with a situation where the Froude number, based on average V and D, is less than unity and yet in the same cross section, the local

Froude number Fr at some points exceed unity. That is, part of the stream is in the rapid flow regime and part is in the tranquil flow regime, and the appearance of the water surface illustrates this fact.

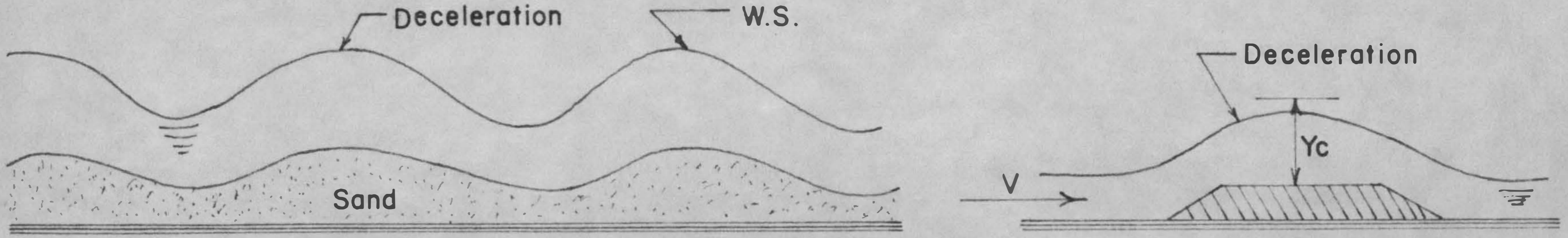
As cited, the local Froude number in an alluvial channel is useful to determine whether the flow is tranquil or rapid. However, the absolute magnitude of the Froude number in either the tranquil or rapid flow regime depends on the scale of the system and is only quantitatively significant for the system under consideration. For instance, in the large recirculating flume which is 8 ft wide, the dunes only occur when $0.3 \leq Fr < 0.55$, whereas in a large deep river, dunes can occur when $Fr < 0.3$. Also in the large flume the beginning of motion occurs at a $Fr \simeq 0.15$, whereas, in a very small flume using the same bed material and width-depth ratio, the beginning of motion may occur at $Fr > 1.0$.

If the Froude number $Fr < 1$, the water accelerates over the artificial or natural humps on the stream bed and decelerates over the depressions or troughs. This is illustrated in Figure 1a and 1b. When $Fr > 1$, the water decelerates over the humps and accelerates in the troughs as illustrated in Figure 1c and 1d. Figure 1a also illustrates a large separation zone and the existence of strong recirculation in the trough area of a natural dune bed and the fact that boils appear on the water surface just downstream of the crests of the sand waves. This type of separation zone and the turbulence which it generates dissipates considerable energy which increases the resistance to flow with the ripple and dune bed forms.



Tranquil Flow, Alluvial Channel
(a)

Tranquil Flow
Rigid Boundary
(b)



Rapid Flow, Alluvial Channel
(c)

Rapid Flow
Rigid Boundary
(d)

Fig. 1 Relation Between Water Surface and Bed Configuration in the Tranquil Flow and Rapid Flow Regimes.

Some of the sand streaming off the crest of the sand waves is carried downstream and upward to the water surface in the boil in relatively large concentrations as compared with the average suspended load concentration. However, the largest percentage of the sand moving downstream as bed material load, passes the crest of the ripple or dune and avalances down the face of the ripple or dune causing it to advance downstream in the direction of flow.

Figure 1c shows the existence of symmetrical sand and water waves of sinusoidal form which have been described mathematically with limited accuracy by the writers. These sand and water waves are commonly observed in the rapid flow regime when the median diameter of bed material $d > 0.4$ mm. Standing waves will be defined in greater detail later. There is little separation and recirculation in the rapid flow regime when plane bed and/or standing waves exist. In these cases, the dissipation of energy which is reflected in the resistance to flow is primarily the result of shear on the bed and the formation of waves. With antidunes, which are described later, the resistance to flow is related to the shear on the bed, the formation of waves, and the energy dissipated in the breaking waves which are similar to the hydraulic jump.

Energy is also used on a relatively small scale in alluvial channels to cause water to flow within the sand bed itself. In general, there is a flow in the porous bed material (flume case) in the direction of channel slope. The velocity is quite small, on the order of a few hundredths to a few tenths of a foot per minute, but nevertheless, a source of energy dissipation.

THE FORMS OF BED ROUGHNESS IN ALLUVIAL CHANNELS

Within the two regimes of flow, the forms of bed configuration observed in the laboratory flume, as boundary shear is increased, are:

Tranquil Flow Regime, $Fr < 1$ (Based upon local values of V and D).

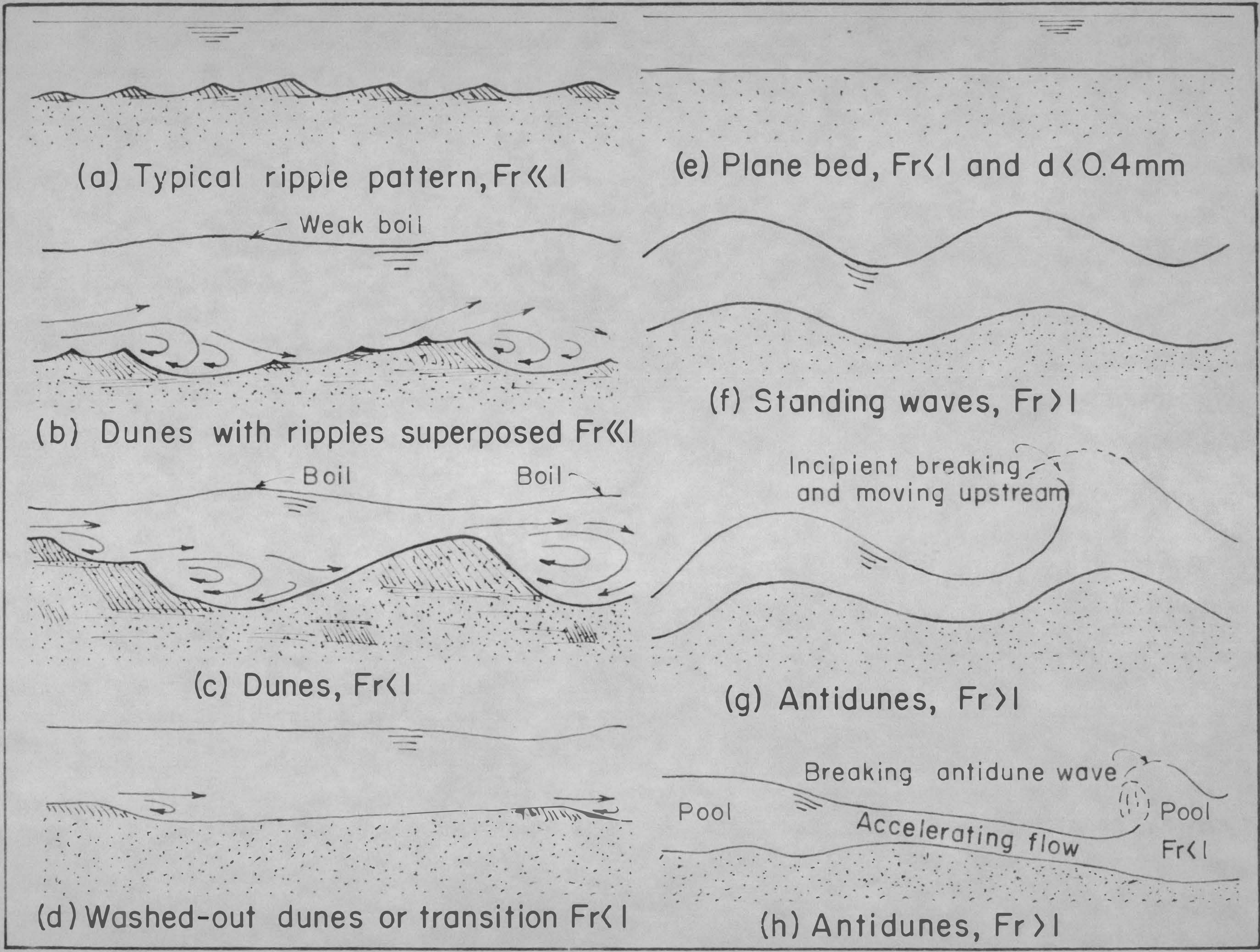
1. Plane bed prior to the beginning of bed material movement
2. Ripples
3. Dunes with ripples superposed
4. Dunes
5. Transition (dunes diminish in amplitude in favor of a plane bed or rapid flow condition depending on the characteristics of the bed material as bed shear is increased).
6. Plane bed (only developed for 0.28 mm sand).

Rapid Flow Regime, $Fr > 1$ (Based upon local values of V and D).

1. Plane bed (a rather rare condition in the rapid flow regime, a plug flow condition).
2. Symmetrical standing sand and water waves which develop in the initial phase of the rapid flow regime with the 0.45 mm sand.
3. Antidunes.
4. Extreme antidune activity (chutes and pools).

The plane bed develops in the tranquil regime following the transition from dunes when $d \geq 0.28$ because of the greater mobility and lack of stability of the bed material. That is, the magnitude of shear, γDS, required to eliminate the dunes is sufficiently small in this size range that when the change in bed roughness occurs, and the plane bed results, the Froude number remains less than one. The bed will then remain plane until the slope is increased enough to cause the Froude number to equal one. A further increase in slope at this point will develop antidunes.

There are reports in the literature of a plane bed with bed material movement which develops before ripples. However, based upon experimentation, this seems to be a small flume phenomenon. The major forms of bed roughness which normally develop in the large flume and under field conditions, are illustrated in Fig. 2, Simons and Richardson (1959). The spacing and amplitude of the ripples are usually on the order of 0.5 - 1.5 ft and 0.01 - 0.1 ft respectively. The spacing of the dunes is usually greater than 2 ft, and their amplitudes range from 0.15 ft to many feet depending on the depth of flow and sediment characteristics of the channel. For example, in small alluvial channels the dunes may be 0.5 - 1 ft high with a spacing of 5-20 ft, whereas, in the Mississippi River sand waves of dune form have been recorded by Carey and Keller (1957) which have lenghts of several hundred (100) ft and amplitudes as large as 40 ft.



(a) Typical ripple pattern, Fr≪1

(b) Dunes with ripples superposed Fr≪1

(c) Dunes, Fr<1

(d) Washed-out dunes or transition Fr<1

(e) Plane bed, Fr<1 and d<0.4mm

(f) Standing waves, Fr>1

(g) Antidunes, Fr>1

(h) Antidunes, Fr>1

Fig. 2. Forms of Bed Roughness in Alluvial Channels

The standing sand and water waves are waves of sinusoidal form which are in phase and which do not move either upstream or downstream with time to any great extent. However, these waves do vary in amplitude with time from plane sand and water surface to a bed with sand and water waves which are several feet high. The amplitude and spacing of these waves depend upon the size and type of stream and the characteristics of the bed material. The water waves are 1.5 - 2 times the amplitude of the sand waves. These waves do not occur for all sizes of bed material. They did occur when the bed material consisted of 0.45 mm sand. They did not occur when the bed material consisted of 0.28 mm sand. These observations imply that standing waves usually develop when the median diameter of the bed material d is larger than 0.4 mm ± and the local $Fr > 1$. For the finer sands, $d < 0.4$ mm, antidunes form when the local $Fr \geq 1$.

The antidunes are very similar to standing waves except the waves continue to grow in amplitude to the point where they break. Antidunes have been observed in natural streams that have bed materials ranging in size from fine sand up to and including coarse gravel. Breaking of the antidune waves usually occurs when the amplitude of the water waves are twice the amplitude of the sand waves. At this time, the water surface in the trough is at approximately the same elevation as the crests of adjacent sand waves. These sand and water waves move upstream prior to breaking. One or two waves may be all that break at one time or there may be a train of several waves which break more or less simultaneously. After antidune waves break, a new train of waves develop and the antidune cycle repeats itself or the waves die out without developing to their breaking point and then reform to break or die out again. As indicated by Langbein (1942) the Froude number, where antidunes first form, increases with increasing size of bed material.

As slope is increased, when $Fr \simeq 1.2$ for 0.28 mm sand and $Fr \simeq 1.8$ for 0.45 mm sand, the antidune activity changes so that it is in the form of chutes and pools. Flow is rapid and is accelerating in the chutes and flow is tranquil in the pools, as illustrated in Fig. 2h. That is, there is a short steep reach which pours water into a pool with breaking waves at its head. This pool is followed by a second steep chute, a pool, and so forth.

The breaking wave phenomenon (antidunes) resemble the hydraulic jump and can be analyzed with some success as such, particularly with two-dimensional flow. Large quantities of sediment are carried into suspension in the breaking antidune wave.

In the breaking wave region and immediately downstream from it, the velocity reduces drastically. The storage of water in these sections where the waves are breaking causes Q to vary with time and this action tends to set up slug flow. For example, in Mendano Creek, which is located in the San Luis Valley of Colorado, antidunes set up slugs of water which travel down the channel spaced at intervals of about 350 feet, traveling at nearly 10 fps. At the time of this observation, the average discharge Q was approximately 120 cfs, the median diameter of the bed material was 0.3 mm, and the channel slope was 1.67 per cent.

THE MAJOR VARIABLES WHICH INFLUENCE FORM OF BED ROUGHNESS

The major variables which apparently influence the form of bed roughness of alluvial channels are indicated in Eq 2, Simons and Richardson (1960).

$$\text{The Form of Bed Roughness} = \phi\,(D, S, d, \sigma, C_f, \rho, \rho_s, \mu, s_f, w, f_s) \qquad (2)$$

in which

D is the depth

S is the slope of energy gradient

d is the median diameter of bed material (some other size may be more representative in graded material)

σ is the standard deviation of bed material

C_f is the concentration of fine sediment

ρ is the mass density of the water

ρ_s is the mass density of the sediment

μ is the dynamic viscosity of the water

s_f is the shape factor of the cross section

w is the fall velocity of the bed material

f_s is the seepage force caused by inflow or outflow to or from the channel.

Investigations to date are not broad enough to determine the full effect of depth of flow and shape factor of the reach on the form of bed roughness. However, the effect of slope on the form of bed roughness is more definitely established, and qualitatively, the effect of the characteristics of the bed material (d, σ, and w) and the concentration of fine sediment C_f on the form of bed roughness have been determined.

The seepage forces are developed as water flows through the porous boundary, and they act in the direction of flow. With outflow, the seepage force increases the effective size of bed material; whereas with inflowing water, the effective size is decreased. With flumes, the seepage forces are relatively small because the flow within the bed material must be set up by the slope of the flume, and the variation in water surface elevation such as that which is associated with dunes or antidunes. In a natural stream there is, in addition, inflow to or outflow from the channel depending on the position of the water table which causes larger seepage forces than those associated with flume flow. For example, with inflow the seepage forces can be large enough to set up a quicksand condition. In this case, the effective weight of the bed material is in equilibrium with the seepage force. Hence, seepage forces can change the effective size of bed material sufficiently to change the form of bed roughness.

The importance of size of bed material on form of bed roughness is illustrated in Fig. 3. Various flume data and limited field data were used to establish this qualitative relation, Albertson and others (1958). This Figure relates V_*/w, V_*d/ν, size of bed material, and the form of bed configuration. This variable V_* in the parameter V_*/w is the shear velocity and

$$V_* = \sqrt{gDS} \tag{3}$$

Utilizing Fig. 3 and the results of extensive laboratory and field observation, it is logical to suggest that:

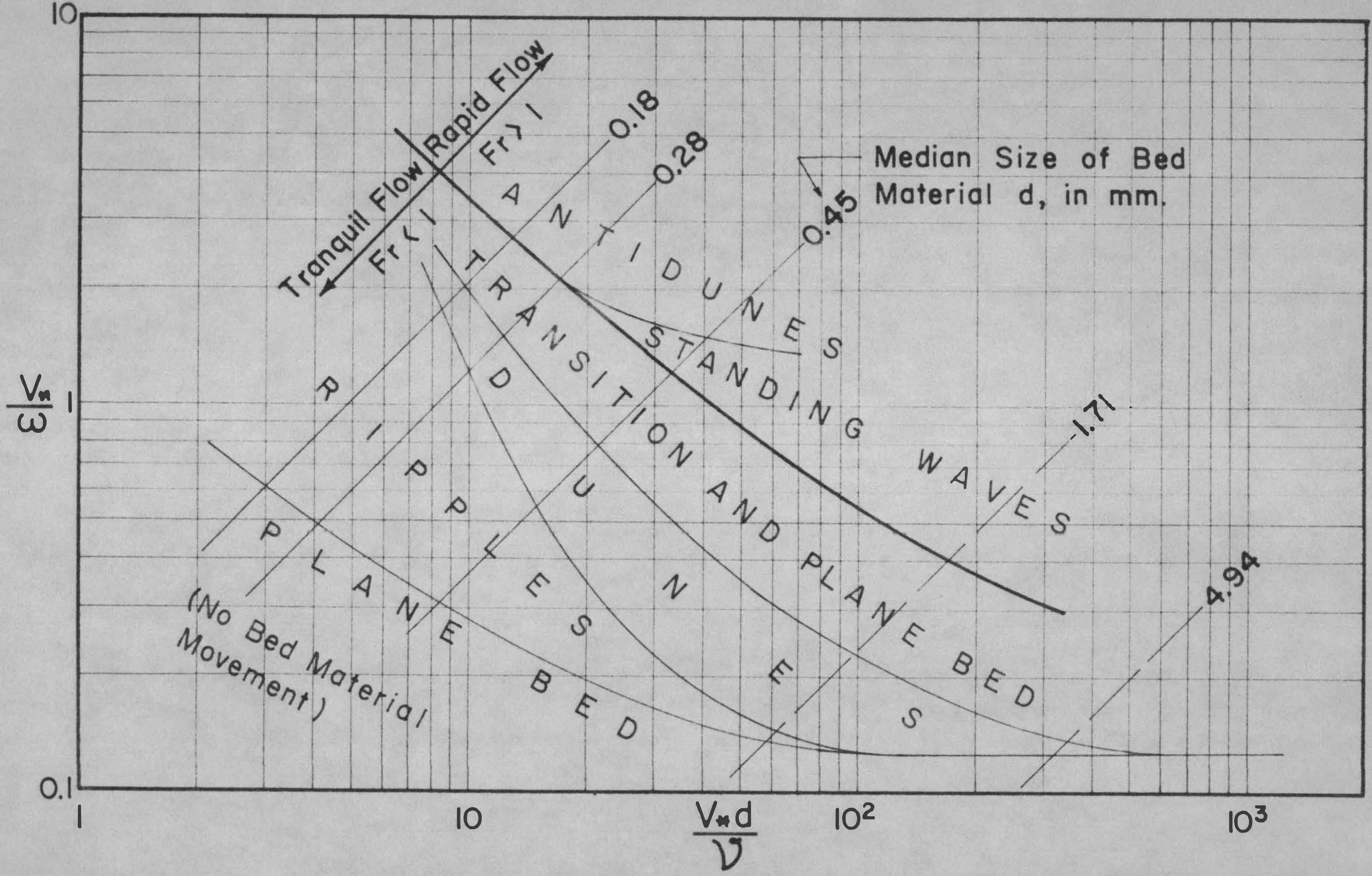


Fig. 3 Qualitative Concept of Regimes of Flow and Forms of Bed Roughness in Alluvial Channels.

1. When bed movement begins, ripples immediately form for the large flume and the field case. With small laboratory flumes, according to Liu (1957) and others, it is possible to have a plane bed on which there is bed material movement prior to the development of ripples. Small flumes yield different results because shallow flows must be used to eliminate or reduce wall effect, which become appreciable when the width-depth ratio is less than 5. With these shallow depth, the slope must be large to obtain the shear ($\tau = \gamma DS$) necessary for beginning of motion. These steeper slopes result in Froude numbers which, for the system, are too large for the occurrence of ripples or dunes and consequently, a plane bed develops.
2. For a median diameter of approximately $d \geq 2.0$ mm ripples apparently no longer develop. When bed shear is of sufficient magnitude to move this size of bed material, the range of shear associated with ripples has been exceeded and dunes form.
3. For very fine bed material which is cohesive, it is conceivable that ripples may not form. Although, this is not indicated in Fig. 3.

4. Considering dunes, when $d > 7.0 \pm$ mm, dunes no longer develop. When sufficient shear occurs to move this size of bed material, $Fr > 1.0$ and dunes are not a phenomena of the rapid flow regime. Based upon investigations conducted in small flumes, various engineers have reported dunes with $Fr > 1$; however, this bed form and associated flow phenomenon may not be the same as the dunes and corresponding flow phenomenon normally observed in the tranquil flow regime.
5. For fine bed material $d < 0.2$ mm the range of shear in which dunes develop is very limited. With very fine sand, dunes may not occur.
6. There is a transition zone following dunes in which the dunes are gradually washed out. With 0.45 mm sand, the dunes were not completely erased until the rapid flow regime was reached. With the finer sands, $d = 0.28$ mm, the dunes were completely erased at a Froude number $Fr < 1.0$ and a plane bed was established.

Because of the reduction in slope and depth due to the reduction in resistance to flow, as the dune form of bed roughness changes to plane bed and the reverse condition; when plane bed changes to dunes, Fig. 3 will not separate the transition dune runs from the plane bed.

7. A plane bed condition developed in the tranquil flow regime when the bed material was fine because of the mobility of the fine material. That is, the finer the bed material, the less the shear required to change the bed configuration from dunes to plane bed and the wider the range of shear in which the plane bed develops. For very fine material, particularly if it is slighty cohesive, it may be possible to squeeze out both the ripple and dune zones. In this case, the only forms of bed configuration in the tranquil zone would be plane bed without bed material movement and plane bed with bed material movement.
8. When $d > 0.30 \pm$ mm, the form of bed roughness which follows the transition zone, in which the dunes are eliminated, is standing waves. That is, there is a zone in which the shear τ is of such magnitude that $Fr > 1.0$ but the bed material is sufficiently stable that antidunes will not form. Larger shearing forces must be exerted on the bed material before antidunes can develop.
9. When $d < 0.30 \pm$ mm, the bed condition which develops following the plane bed with sediment movement is antidunes. At values of shear stress where the $Fr \approx 1$ the antidune activity is mild and the resistance to flow is only slightly greater than for the plane bed. As the shear stress is increased the violence of the antidune activity increases until at large

shear values the chute and pool condition illustrated in Fig 2h develops. With the increase in antidune activity there is an increase in resistance to flow, and the smaller the median size of bed material the greater the increase in resistance for a given measure in shear stress.

THE EFFECT OF SIZE AND SHAPE OF LABORATORY FLUME ON THE FORMS OF BED ROUGHNESS

As a by-product of current studies of resistance to flow and sediment transportation in laboratory flumes it has become apparent, as formerly indicated, that the forms of bed roughness observed with a given alluvial bed material may be quite different in different sizes of flumes, other conditions being essentially the same.

Using a large flume 150 ft long, 8 ft wide, and 2 ft deep, and depth of flow ranging from 0.3 to 1.0 ft, the forms of bed roughness observed in the two regimes of flow were as illustrated in Fig. 2. These forms of bed roughness seem to agree with field conditions. Using the 0.45 mm bed material in a smaller flume which was 60 ft long, 2 ft wide, and 2.5 ft deep, and depth of flow ranging from 0.2 to 1.0 ft, the observed bed configurations were different. More specifically, the plane bed case prior to beginning of motion is the same in the small flume as in the large flume. However, when bed movement began, ripples did not form in the small flume. In fact, ripples never developed in this flume with this size of bed material. When bed shear in the small flume was increased sufficiently, the plane bed was replaced by dunes. These dunes were similar in height and length to those which occur in the large flume, but these dunes never, at any time, had a ripple roughness superposed on them as was the case in the large flume.

In the rapid flow regime conditions are quite similar for both the large and small flume runs. However, the resistance to flow in the small flume was much greater than in the large flume. This results from the smaller width-depth ratio in the small flume whereby a larger per cent of the total width of the flume is occupied with antidune activity.

The results of this comparison indicate the many problems that the experimentor faces who tries to effectively utilize the data collected by various investigators from their flumes of different size and design.

VARIATION OF RESISTANCE TO FLOW WITH FORM OF BED ROUGHNESS USING THE LARGE FLUME DATA

The influence of size of bed material on the form of bed roughness and resistance to flow is illustrated in Fig. 4 which relates Manning n, the Froude number Fr, and size of bed material d.

The two sets of data upon which this relation is based were collected in a recirculating flume 150 ft long, 8 ft wide, and 2 ft deep with adjustable slope S and variable discharge Q. The sand bed in the flume was approximately 0.6 ft deep. For more shallow sand beds, in the large flume, depth of sand influenced the form of bed roughness and dunes could not fully develop.

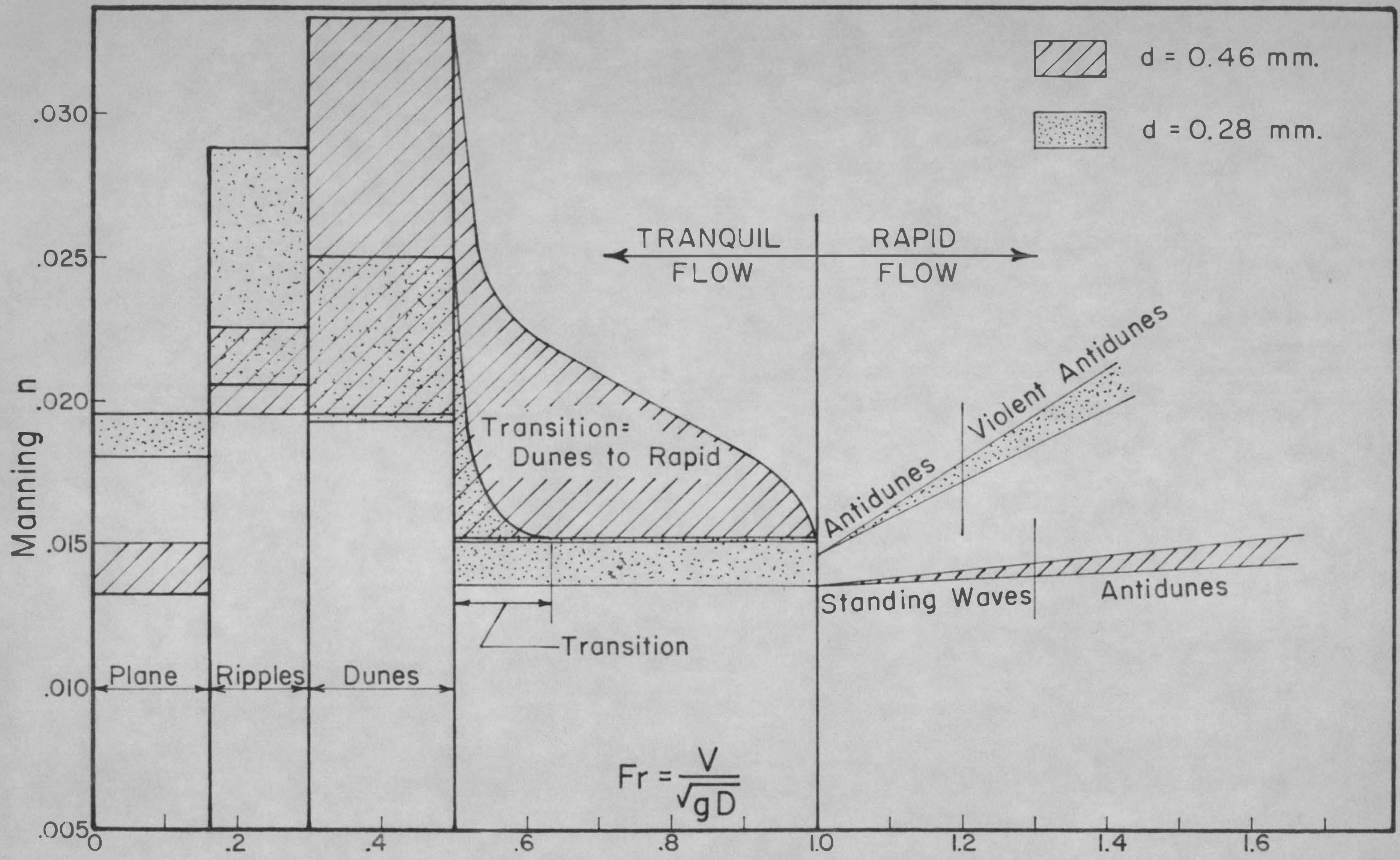


Fig. 4 Effect of Size of Bed Material on Form of Bed Roughness and Manning n

The range of Froude number (based on average velocity and depth) in which the plane bed without sediment movement, and the ripples and the dunes occur was approximately the same for both sands. However, the various forms occurred at much flatter slopes for the 0.28 mm sand than for the 0.45 mm sand. With the 0.45 mm sand the transition zone (zone of washed out dunes) extended over a relatively broad range of Froude number Fr. That is, from $Fr = 0.5$ to $Fr = 1$ at which time the flow regime changed from tranquil to rapid. With the 0.28 mm sand, the transition zone was of limited range. Care had to be exercised in order not to miss the transition phenomenon completely. Beyond the transition zone, still considering the 0.28 mm sand, there was a plane bed configuration with bed material movement which extended from $0.55 \leq Fr \leq 1.0$ as previously indicated.

In the rapid flow regime, using the 0.45 mm sand, standing waves developed when $1.0 < Fr < 1.3$. When $Fr > 1.3$, antidunes developed which grew more violent and increased in size as Fr was increased. With the 0.28 mm sand, antidunes actually developed as soon as $Fr \geq 1$ and the degree of antidune activity increased with increasing Froude number Fr. However, there was an upper limit to the magnitude of the Froud number. Because as the shear stress was increased by increasing slope the antidune activity increased with a corresponding rapid increase in dissipation of energy. This increase in energy dissipation caused the velocity and the Froude number to decrease. It appeared that for the large flume the upper limit of the Froude number for the 0.45 mm sand was 1.7 and for the 0.28 mm sand it was 1.2. With the 0.28 sand, at the maximum shear stress, the chute and pool phenomenon illustrated in Fig. 2h had developed and the Froude number had decreased to less than 1.2. With the 0.45 mm sand at the maximum shear stress obtained, the chute and pools had not developed. However, it is anticipated that at larger slopes chutes and pools would develop.

In the plane bed range, prior to ripples, the Manning n is larger for the d = 0.28 mm sand, than for the d = 0.45 mm sand. This can be explained, at least partially, by considering the gradation of two sands. The sand with the smaller median diameter had a larger standard deviation. Some particles were 3 - 4 mm in diameter. The largest size of material in the 0.45 mm sand was 2.0 mm. Hence, the grain roughness was larger for the fine sand because of the small per cent of large particles which it contained and which extended into the flow in the plane bed case. In the ripple zone the n values are also larger for the 0.28 mm sand. This is attributed to the fact that the ripple spacing was slightly smaller than for the 0.45 mm sand.

In the dune range the opposite condition prevails. The Manning n is larger for the 0.45 mm sand bed than for the 0.28 mm sand.bed. The increase in resistance to flow with increasing sand size (dunes) is contrary to the trend reported by Leopold and Maddock (1953). This increase in resistance is explained by the difference in the spacing and irregularity of the dunes. The dunes observed while experimenting with the 0.28 mm sand were spaced considerably further apart than the dunes for the corresponding conditions using the 0.45 mm sand. The amplitudes of the dunes were about the same for both sands. However, the downstream face of the dunes were of a flatter more rounded nature for the 0.28 mm sand than for the 0.45 mm sand, and the recirculation in the trough was considerably weaker. The large spacing between the dunes and the smaller intensity of recirculation and turbulence in the troughs accounts for the fact that some ripple runs exhibited a larger n value than the dune runs where the 0.28 mm sand was used. The flow over the long plane backs of these dunes was quite efficient, reducing the overall resistance to flow to a value less than that computed for the ripple case.

Using the 0.45 mm sand, the dunes gave much larger n values than the ripples because of the relatively close spacing of the dunes, the stronger circulation in the dune troughs, and the greater magnitude of turbulence.

In the transition zone there is a rapid reduction of resistance to flow which continued to decrease with increasing Fr until the plane bed or small standing wave case is reached. These forms of roughness have a minimum n values.

In the antidune range n values increase with increasing Fr. However, the rate of increase is much more rapid for the 0.28 mm sand than for the 0.45 mm sand. This increase in resistance with increasing Fr is reflected directly by the scale and form of antidune activity and the magnitude of sediment load. That is for a given value of $Fr > 1$, the resistance to flow and bed material transport increases as the median size of bed material is decreased.

EFFECT OF FINE SEDIMENT ON THE FORM OF BED ROUGHNESS

A series of equilibrium runs were made by the writers in the recirculating flume to determine the effect of fine sediment (bentonite clay) on resistance to flow and bed material transportation. The bed material utilized had a median diameter d = 0.45 mm. Bentonite clay, which passed a number 200 sieve, was added to the water until the desired concentration of fine sediment was obtained. The concentrations of clay investigated ranged from 0 to 42,000 ppm. There was a problem associated with the study of effect of fine sediments. In order to hold the concentration of fine sediment constant, additional clay had to be continuously added to replace the clay which was transferring from sediment mixture above the sand bed to the interstitial water in the bed material. The interstitial water in turn lost some of its fine sediment load as a result of deposition on the flume floor. That is, at the contact between the sand bed and the flume floor, some of the bentonite attached itself to the rigid boundary and slowly built up a layer of clay which increased in thickness with time and reduced the concentration of bentonite in suspension in the flume.

As a result of this study, it is possible to evaluate the qualitative effects of the presence of the clay in the water-sediment complex on the forms of bed roughness. In the ripple zone when the concentration of clay was on the order of 2000 ppm, the bed was partially stabilized. The ripples were altered to a rounded more streamlined form, and the water surface was covered with minute ripples above those portions of the bed which were stabilized, such as one observes when water flows over a stable gravel bed.

In the dune zone there was an increase in the spacing of the dunes and an effect on shape, but there was no appreciable effect on the amplitude or movement of the dunes with concentrations of fine sediment up to 30,000 ppm. At a concentration of 40,000 ppm fine material, the resistance to flow was reduced as much as 40 per cent. The decrease in resistance to flow can be explained by the increase in spacing and the change in shape of the dunes resulting from the reduced effective size or decreased fall velocity of bed material. Specifically, concentrations of fine sediment on the order of 100,000 ppm will increase the apparent viscosity of the water sediment mixture over that of water alone by 900 per cent, increase the specific weight of the water-sediment mixture to about 67 lb per cu ft, and reduce the effective size of bed material approximately 50 per cent.

The effect of the presence of fine sediment was essentially the same for the transition zone as for dunes.

In the rapid flow regime the addition of a few thousand ppm of fine sediment converted plane bed and standing wave runs into antidune runs. This process was reversible. If the fine sediment was flushed from the flume system, the run returned to its original plane bed or standing wave form. This result is again probably due to the reduced effective size of the bed material, the change in viscosity and the change in momentum transfer caused by the presence of the fine sediment. The presence of the fine sediment in concentrations less than 42,000 ppm had little effect on resistance to flow and bed material transportation in the rapid flow regime.

VARIATION OF BED MATERIAL LOAD AS A FUNCTION OF BED FORM

The range of magnitude of the total concentration of bed material load is directly related to the form of bed roughness. In the large flume the concentration in ppm for ripples and dunes was practically the same for the two sands investigated. Whereas, in the rapid flow regime, the maximum concentration of the total load for the 0.28 mm sand was about three times greater than the maximum concentration of the total load for the 0.45 mm sand. However, it must be remembered that the change from one bed form to another occurred at much flatter slopes and smaller shears for the 0.28 mm sand than the 0.45 mm sand, everything else kept constant. A summary of the foregoing data is given in Table I.

TABLE 1 - Variation of Total Sediment Concentration, Manning n , the Froude number and Slope of Energy Gradient with Regimes of Flow and Forms of Bed Roughness.

		Bed Material is 0.28 mm,sand				Bed Material is 45 mm.sand			
Tranquil Flow Regime	Forms of Bed Roughness	Concentration of Total Load	n	Fr	$S \times 10^2$	Concentration of Total Load	n	Fr	$S \times 10^2$
	Plane	0	0.016	0.15	.011	0	0.015	0.18	0.015
	Ripples	1 to 150	.022 to .028	.17 to .37	.023 to .11	1 to 100	.018 to .026	.14 to .28	.016 to .11
	Dunes	150 to 1,000	.021 to .025	.34 to .42	.09 to .15	100 to 1,000	.017 to .040	.30 to .40	.06 to .30
	Trans.	1,000 to 2,000	.014 to .017	.56 to .67	.13 to .17	1,000 to 4,000	.014 to .020	.60 to .99	.30 to .50
	Plane	1,500 to 3,000	.013 to .014	.60 to .92	.15 to .28	---	---	---	---
Rapid Flow Regime	Standing Waves	---	---	---	---	4,000 to 7,000	.010 to .015	1.0 to 1.6	.36 to .62
	Antidunes	5,000 to 42,000	.014 to .24	1.0 to 1.3	.33 to 1.0	6,000 to 15,000	.012 to .013	1.4 to 1.7	.66 to 1.0

PREDICTION OF FORM OF BED ROUGHNESS

Thus far, no completely adequate method of predicting form of bed roughness has been developed. Using the parameters indicated in Fig. 3, Albertson and others (1958) presented a method suitable for predicting bed forms for the laboratory case, but it was not completely satisfactory for the field case. As another possibility, consider Fig. 5 which is similar to that presented by Garde (1959). This Figure relates the Shield's parameter $\gamma/\Delta\gamma d$, the Froude number, Fr, the regime of flow, and form of bed roughness. As compared to Fig. 3, Fig. 5 is inferior for the laboratory case but slightly superior for the field case. Until additional data are available which cover an adequate range of depth, D, it will be difficult to develop the criterion necessary to predict form of bed roughness in alluvial channels with confidence.

In the meantime, the possibility of predicting the bed configuration based upon the appearance of the water surface should be considered. This method is not applicable to design but is extremely useful for analysis. However, some training is required on the part of the individual before he can apply it effectively. As with other methods, there is a lack of information on effect of depth on the appearance of the water surface, but in this case, this deficiency of data is not so crucial.

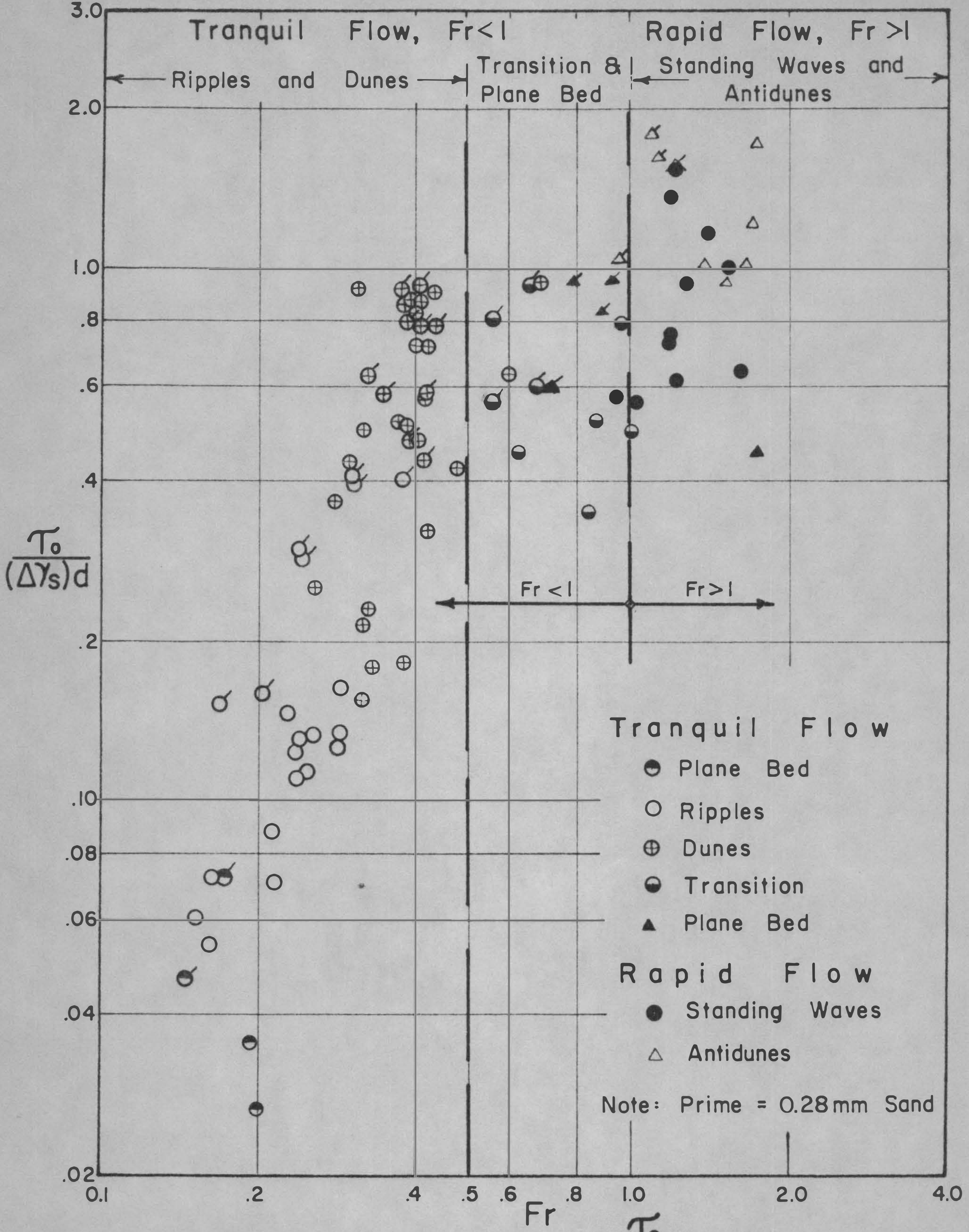


Fig. 5 Variation of $\frac{\tau_0}{(\Delta\gamma_s)d}$ with Fr and Forms of Bed Roughness

The regime of flow can be determined by observing the direction of travel of an artifically induced water surface ripple or wave using the wave celarity concept. If the disturbance generated to oppose flow moves upstream with respect to a fixed point of observation, flow is tranquil, and if it is swept downstream, flow is rapid. It is also possible to make this determination in an alluvial channel by observing the condition of the water surface.

If the flow regime is rapid, there will be some evidence of standing waves and/or antidunes as illustrated in Fig. 2f, 2g, and 2h. If these waves are in evidence, they immediately fix the general form of bed roughness which exists and the water surface and accompanying sand waves are in phase. If the flow regime is tranquil, the major rises in water surface (usually boils) will be out of phase with the sand waves. For a rippled bed, the water surface will be quite plane and placid except for very shallow flow at which time small ripples are generated on the water surface by the sand ripples. With a dune bed configuration, there will be turbulence generated at the water surface in the form of boils downstream of the dunes. Usually the color of the water is different in the boil area due to the large concentration of suspended sediment carried to the water surface within the boil. The strength of the boil activity is dependent on the magnitude, spacing and shape of the dunes, and the depth of flow. In the transition zone the water surface will be rather plane with minor boils appearing on the water surface and velocities will exceed 2.5 fps, except in the case of very fine bed material. Within the plane bed range, velocity of flow will be relatively larger than for transition condition. The water surface will be quite plane except for possible surface waves which are generated by disturbances along the sides of the channel.

Application of this information, when it is available, makes possible a more significant interpretation of stage-discharge relations and other flow phenomenon observed in alluvial channels.

FIELD PROBLEMS

As indicated, the conditions obtained using the large flume agree quite well with conditions observed in the field, except the field case is much more complex. In the field more than one form of bed roughness can exist side by side within a given reach. In the extreme it is conceivable that ripples may develop near the banks of a stream, dunes may exist inside the ripple zones, and plane bed or perhaps standing wave, depending on the characteristics of the bed material, may develop down the central section of the channel or wherever maximum velocity occurs in the channel. Considering the flume, usually only one form of bed roughness existed. However, two forms of bed roughness could be set up simultaneously by operating the flume at a relatively steep slope and shallow depth.

In the field, the slope of energy gradient through a given reach of channel varies within narrow limits as the discharge Q changes. However, the depth varies greatly. In contrast, referring to flume studies, slope can be varied widely at will; but depth variations are small due to the physical limitations of the pumping plant and the flume. Because of the limited range of depth in most data, knowledge of the effect of depth variation on bed roughness is meager. However, there is ample evidence that a change in depth can shift the form of bed roughness from dunes to transition, plane bed, and antidunes. The reduction in resistance to flow which occurs as dunes are eliminated, accounts for the discontinuity in stage discharge relations which have been observed in the laboratory and for many natural streams. Typical qualitative stage-discharge curves which illustrate the effect of change of bed roughness on stage are presented in Fig 6.

In Fig. 6a the break which is shown is caused by a change in bed roughness from dunes to plane bed or standing waves. Einstein and Chien (1958) in their discussion of Brook's paper (1958) recognized that the break in the depth-discharge curve could occur. However, contrary to present evidence, they thought the break would only rarely if ever occur in nature. The break occurs on the rising stage at a larger Q than on the falling stage. There is usually greater scatter around the lower leg of the relationship due to the wide variation of resistance to flow with ripples and dunes on the bed. Under certain circumstances, this variation can be explained. For example, in Fig. 6b the

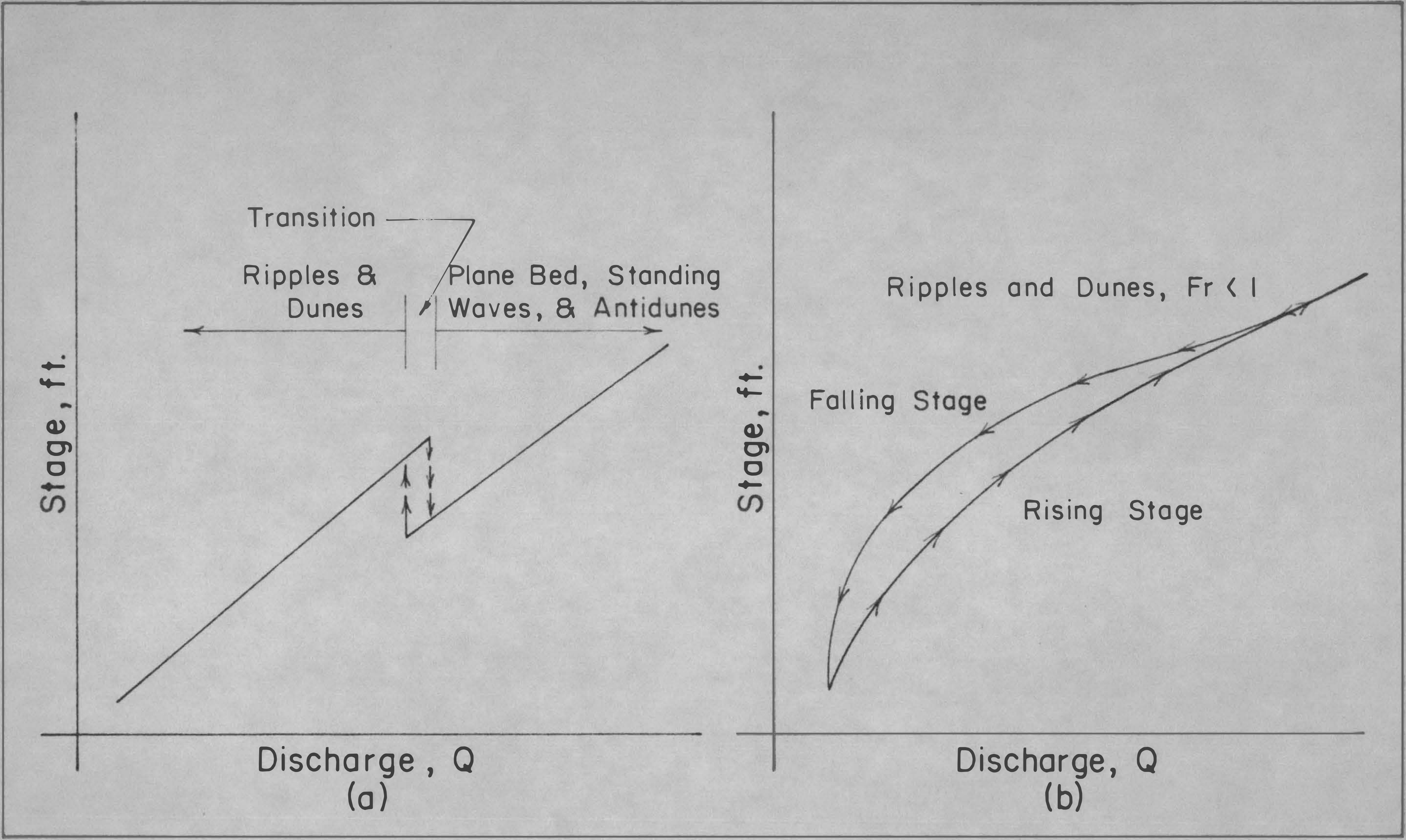


Fig. 6 Typical Qualitative Stage-Discharge Curves for Alluvial Channels.

magnitude of resistance to flow lags the actual discharge Q. That is, the change of bed roughness lags the change of Q; hence, this results in a smaller resistance to flow and smaller depth than would normally occur for equilibrium flow. The reverse occurs on the falling stage. In this instance, at the peak discharge, the form of bed roughness is assumed to be large dunes. As discharge decreases, the large dunes are not altered as fast as the discharge changes, and the resistance and depth are larger than for equilibrium flow on the falling leg of the hydrograph. This results in a loop type of stage-discharge curve which resembles a hysteresis curve.

The loop curve illustrated in Fig. 6b may be reversed with the falling stage points plotting below the rising stage points; or the two curves may coincide with the falling stage points plotting on the same curve as the rising stage points, or the rising and falling stage curves may cross. The form of the curve which results depends upon the rate of change of Q with respect to time, the magnitude of the discharge, the characteristics of the bed material, the effect of the fine sediment load, and the characteristics of the channel.

CONCLUSION

The forms of bed roughness observed in a 150 ft long recirculating flume are essentially the same as the forms of bed roughness observed in natural and artificial channels. The variables which effect form of bed roughness are given in Eq 2:

Form of Bed Roughness = $\emptyset$ (D, S, d, σ, C_f, ρ, ρ_s, μ, s_f, w, f_s (2)

A comprehensive analysis of the data collected indicate that

1. Ripples may not form when $d \geq 2.0$ mm.
2. Dunes may not form when $d \geq 7.0$ mm.
3. When $d \leq 0.2$ mm, the range of bed shear (γDS) within which dunes develop is very limited and if the sand is very fine, dunes may not form at all.
4. A transition zone follows dunes in which dunes are gradually washed out as bed shear is increased.
5. When $d \geq 0.45$ mm the transition zone is not eliminated until $Fr \approx 1$.
6. When $d \leq 0.30$ mm, the transition zone terminates at a $Fr < 1$ and a plane bed condition exists thereafter until $Fr \approx 1$.
7. When $d \leq 0.3$ mm and $Fr \geq 1$ antidunes develop.
8. When $d = 0.45$ mm and $1 < Fr < 1.2$ standing waves develop.
9. At large Froude numbers, $Fr > 1.2$ for the 0.28 mm sand and $Fr > 1.8$ for the 0.45 mm sand, the chute and pool type of antidunes develop.

Information on the effect of bed form on resistance to flow for the field situation is limited. Furthermore, contrary to flume experiments where slope may be varied greatly and depth hardly at all, in the natural stream slope varies but slightly and depth varies greatly. However, in many natural streams a change in bed form with stage has been observed. This change in bed form has, in some instances, resulted in a break in the stage-discharge relationship and in others a loop stage-discharge curve.

To broaden the scope of the information presented herein, additional studies should be conducted in the field and laboratory to determine, more precisely, the effect of depth of flow D, size of bed material d, gradation of the bed material σ, and channel shape on the forms of bed roughness, regimes of flow, sediment transportation phenomenon, resistance to flow, and varied flow in alluvial channels.

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