FORMS OF BED ROUGHNESS IN ALLUVIAL CHANNELS

by

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Synopsis

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

and for the rapid flow regime are:

1. Plane bed
2. Symmetrical standing sand and water waves
3. Antidunes.

The forms of bed roughness which develope 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

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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.

Resistance to flow and sediment transportation vary greatly as form of bed roughness changes. Considering two sands with median diameters of 0.46 mm and 0.28 mm which have been thoroughly investigated in a large recirculating flume, when a dune bed configuration developes, the Manning n varies from 0.019 to 0.04 depending on the spacing and amplitude of the dunes, and the corresponding bed material transportation rate ranges from 75 to 1000 ppm. With the antidune condition, Manning n varies from 0.014 to 0.020 depending on the turbulence of the flow, and bed material transportation ranges from 6000 to 42,000 ppm.

Field studies by Simons (1957) and Dawdy (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 break and much of the other variation observed in stage-discharge relationships on those gaged streams where this change of bed configuration occurs.

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

$$Fr = \frac{V}{gD} \qquad (1)$$

in which V is the velocity of flow in fps, and D is the depth in ft.

Normally the mean velocity V and 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 the 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 $0.3 < Fr < 0.55$, 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 $Fr \approx .15$, whereas in a 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 a 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 large separation zone and the turbulence which it generates dissipates considerable energy which increases the resistance to flow with the ripple and dune bed forms.

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 average suspended load concentration. The remainder and by far the largest percentage of the sand moving downstream as bed material load passed the crest of the ripple of dune avalanches 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

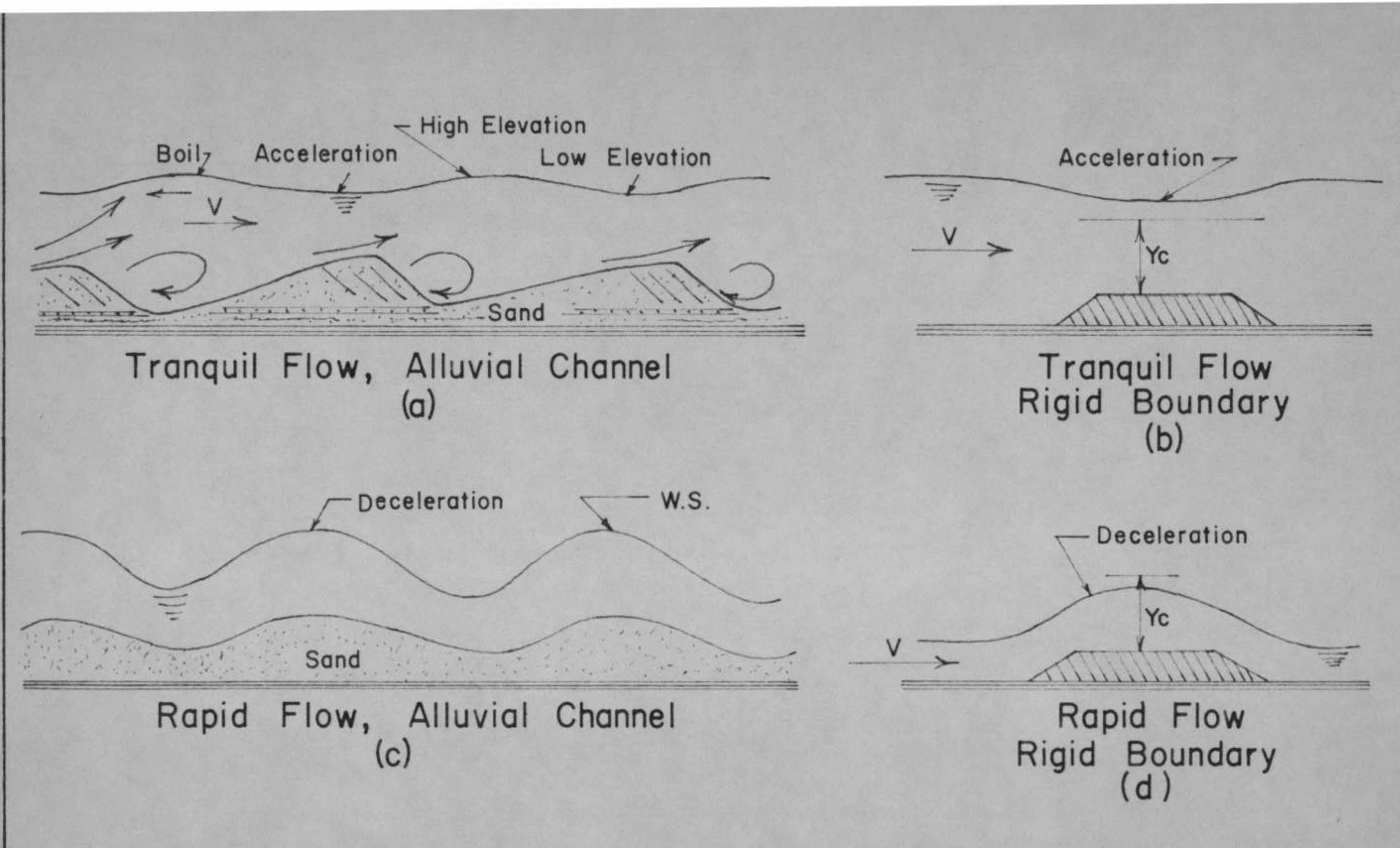

Fig. 1 Relation Between Water Surface and Bed Configuration in the Tranquil Flow and Rapid Flow Regimes.

with limited accuracy by Simons and Richardson (1959). 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. That is, 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 hundreths 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 in their normal order of occurrence are:

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

a. Plane bed prior to the beginning of bed material movement
b. Ripples
c. Dunes with ripples superposed

d. Dunes

e. Washed out dunes (dunes begin to vanish in favor of a plane bed or rapid flow condition depending on the characteristics of the bed material as bed shear is increased).

f. Plane bed (only develops when the bed material is fine, $d \leq 0.4$ mm $\pm$).

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

a. Plane bed (a rather rare condition in the rapid flow regime, a plug flow condition).

b. Standing waves which develop in the initial phase of the rapid flow regime provided the median diameter of the bed material $d \geq 0.4$ mm $\pm$.

c. Antidunes.

d. Extreme antidune activity.

The plane bed developes in the tranquil regime following the transition from dunes when $d \leq .4$ mm 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 the Froude number remains less than one and the plane bed results. The bed will then remain plane until sufficient shear is developed to cause the Froude number to become equal to one. A further increase in shear at this point will develope antidunes in the flow.

There are reports in the literature of a plane bed with bed material movement which developes before ripples. However, based upon experimentation, this seems to be a small flume phenomenon. The major forms of bed roughness which normally develope in the large flume and under field conditions, are illustrated in Fig. 2. 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, while in the Mississippi River sand waves of dune form have been recorded by Carey and Keller (1957) which are spaced several 100 ft apart with amplitudes as large as 40 ft.

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 sand. They usually develope when the median diameter of bed material d is larger than 0.4 mm $\pm$ and the local $Fr > 1$. For the finer sands $d < .4$ mm antidunes form when the local $Fr \geq 1$.

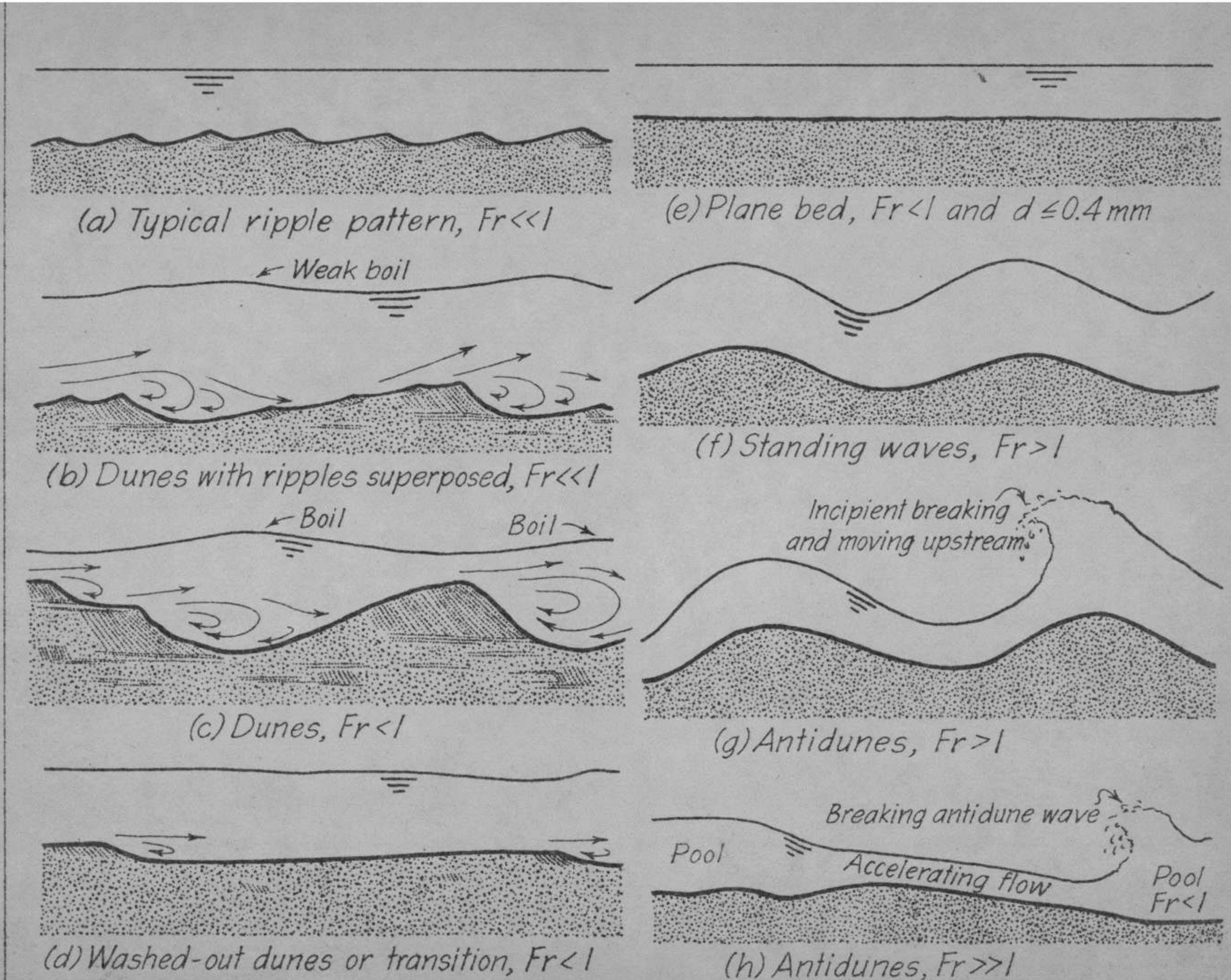

Fig. 2 Forms of Bed Roughness in Alluvial Channels

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 which have bed materials which range in size from fine sand up to and including coarse gravel. Breaking usually occurs when the amplitude of the water wave is twice the amplitude of the sand wave. 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 Froude number is increased, $Fr > 1.2$ for sand with median diameter $d = 0.28$ mm and $Fr > 1.8$ for sand with median diameter $d = 0.45$ mm, the antidune activity is in the form of chutes, in which the water accelerates, and pools in which flow is tranquil 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 this particular time 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 percent.

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

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

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 quite well established, and in a general way, the effect of the characteristics of the bed material (d, σ, and w) and the concentration of fine sediment 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.

Qualitatively, the importance of size of bed material on form of bed roughness is illustrated in Fig. 3. This Figure relates $\frac{V_*}{w}$, $\frac{V_* d}{\nu}$, size of bed material, and the form of bed configuration. The variable V_* in the parameter V_*/w is the shear velocity and

$$V_* = \sqrt{gDS} \qquad (3)$$

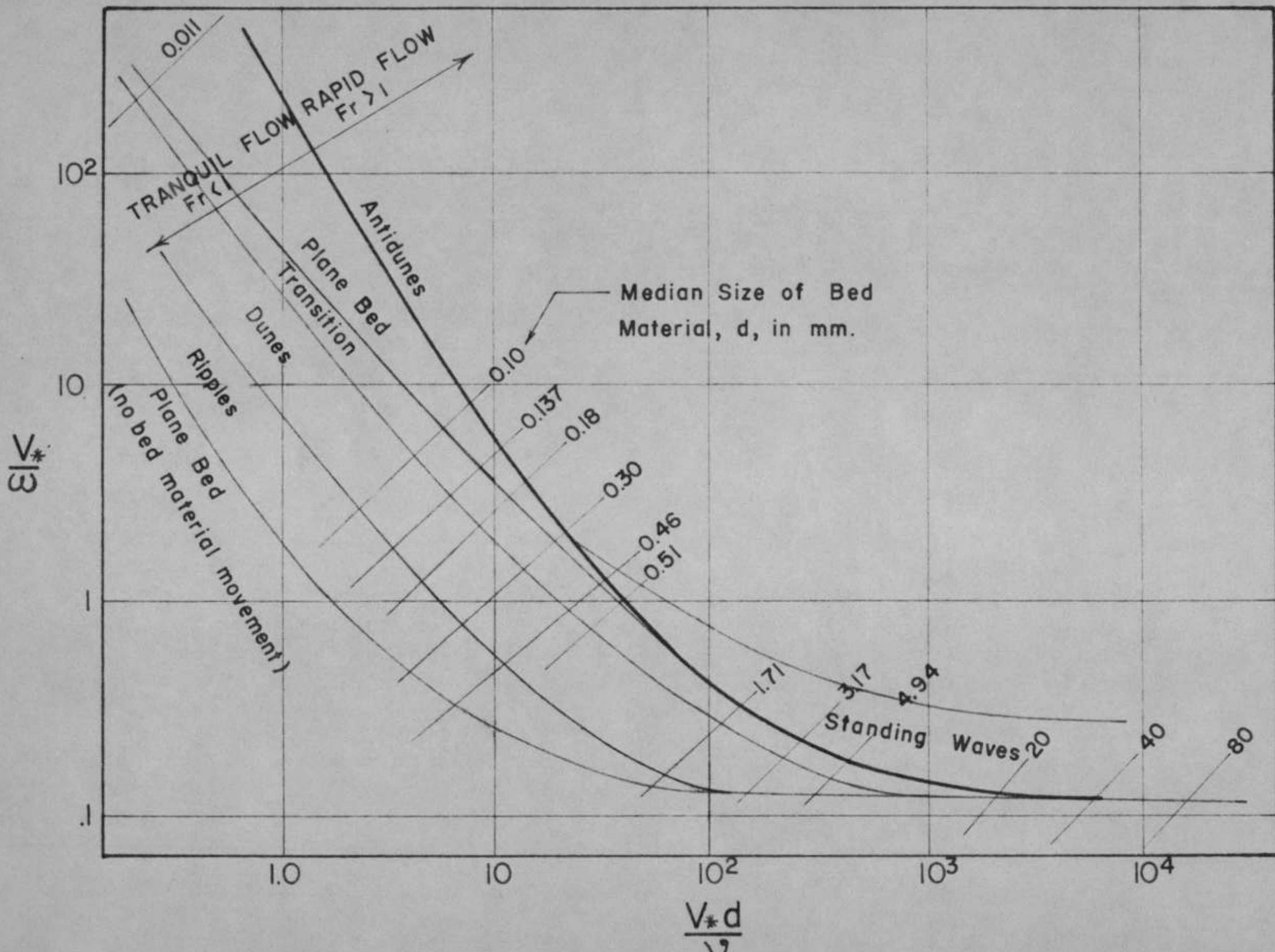

Fig.3 Qualitative Concept of Regimes of Flow and Forms of Bed Roughness in Alluvial Channels.

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

a. 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 depths, 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 developes.

b. For a median diameter $d \geq 2.0$ mm ripples apparently no longer develop. When bed shear is of sufficient magnitude to move this size of bed material, the ripples range of shear has been exceeded and dunes form.

c. For very fine bed material which is cohesive, it is conceivable that ripples may not form. Although, this is not indicated in the figure.

d. Considering dunes, when $d > 5.0 \pm$ mm, dunes no longer develope. 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 cannot be the same as dunes and corresponding flow phenomenon normally observed in the tranquil flow regime.

e. For fine bed material $d < 0.2$ mm the range of shear in which dunes develope is very limited. With very fine sand, dunes may not occur.

f. There is a transition zone following dunes in which the dunes are gradually washed out. With coarser sands $d > 0.4$ mm, the dunes are not completely erased until the rapid flow regime is reached. With the finer sands $d < 0.4$ mm, the dunes are completely erased at a Froude number $Fr < 1.0$ and a plane bed is established.

g. A plane bed condition develops in the tranquil flow regime when the bed material is fine. This is 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 slightly cohesive, it may be possible to squeeze out the ripple and dune zones completely. 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.

h. When $d > 0.4 \pm$ 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. This implies that larger shearing forces must be exerted on the bed material before antidunes can develop.

i. When $d < 0.35\pm$ mm the bed condition which developes following the plane bed with sediment movement is antidunes. At values of $Fr \approx 1$ the antidune activity is very mild. As Fr increases, the violence of the antidune activity also increases until at large values of Fr the chute and pool condition illustrated in Fig. 2h developes.

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 same bed material and flow conditions in a smaller flume which is 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 and the range of Fr within which they occur was appreciably changed. 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 begins, ripples do not form in the small flume. In fact, ripples never developed in this flume with this size of bed material (d = 0.46 mm). 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 and natural channels.

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 percent of the total width of the flume is occupied with antidune activity.

The results of this comparison indicate the many problems that the experimenter 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

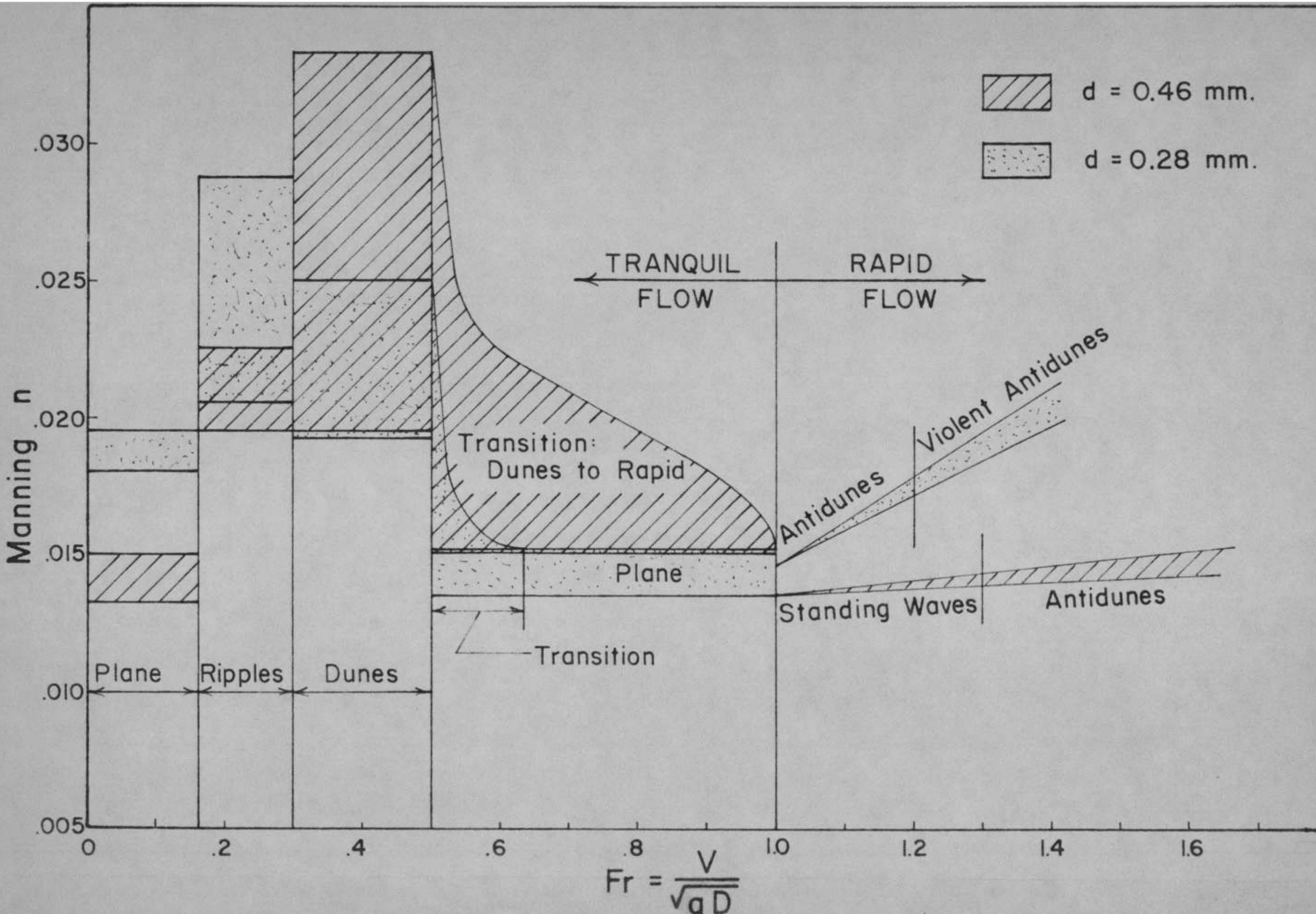

Fig. 4 Effect of Size of Bed Material on Form of Bed Roughness and Manning n

2 ft. deep with adjustable slope S and variable discharge Q . The sand bed in the flume was approximately 0.6 ft. deep. For shallower sand beds in the large flume, depth of sand influenced the form of bed roughness and dunes could not fully develop.

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 is approximately the same for both sands. However, the various forms occurred at much flatter slopes for the .28 mm sand than for the .45 mm sand. With the coarse sand the transition zone or zone of washed out dunes extends over a relatively broad range of Froude number Fr. That is, from $Fr = 0.5$ to $Fr = 1$ at which time the flow regime changes from tranquil to rapid. With the fine sand, the transition zone is of limited range. Care must be exercised in order not to miss the transition phenomenon completely. Beyond the transition zone, still considering the fine sand, there is a plane bed configuration with bed material movement which extends from $.55 \leq Fr \leq 1.0$ as previously indicated.

In the rapid flow regime, using the coarse 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 fine sand antidunes actually developed as soon as $Fr > 1$ and the degree of antidune activity increased with increasing Froude number Fr. In fact, at $Fr > 1.2$, the form of antidune activity took on the chute and pool appearance illustrated in Fig. 2h. It is anticipated that the same phenomenon would occur, using the coarse sand, provided Fr was increased beyond its current range, say to $Fr \geq 1.8$.

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 coarse sand was 2.0 mm. Hence, the grain roughness is larger for the fine sand because of the small percent of large particles which it contains and which extend into the flow in the plane bed case. In the ripple zone the n values are also larger for the fine sand. This is attributed to the fact that slightly larger ripples formed.

In the dune range the opposite condition prevails. The Manning n is larger for the coarse sand bed than for the fine sand bed. This is because of the difference in the spacing and irregularity of the dunes. The dunes observed while experimenting with the fine sand were spaced considerably further apart than the dunes for the corresponding circumstances using the coarse sand. The amplitudes of the dunes were about the same for both sands. The downstream face of the dunes were of a flatter more rounded nature for the fine sand than for the coarse sand, and the recirculation in the trough was considerably weaker. The large spacing between the dunes and the smaller amount 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 fine 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 coarser 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 continues with increasing Fr until the plane bed or small standing wave case is reached. These forms of roughness have minimum n values.

In the antidune range n values increase with increasing Fr. However, the rate of increase is much more rapid for the fine sand than for the coarse 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 runs were made 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 $d = 0.47$ 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 investigated ranged from 0 to 42,000 ppm. A problem associated with the study of effect of fine sediments results because if the concentration is to remain constant, additional bentonite must be continuously added to replace the continuous movement of clay from the water sediment mixture above the sand bed to the interstitial water in the bed material, which in turn is loosing some of its fine sediment load. That is, at the contact between the sand bed and the flume floor, some of the bentonite attaches itself to the rigid boundary and slowly builds up as a layer which increases in depth with time.

As a result of this study, it is possible to site the qualitative effects of the presence of the clay in the water-sediment complex on form 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 and an effect on slope, 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 the highest concentration of fine material the resistance to flow was reduced as much as 40 percent. The decrease in resistance to flow can be explained by the increase in spacing and the change in slope of the dunes, and the reduced effective weight 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 100 percent, increase the specific weight to about 67 psf and reduce the effective size of bed material about 50 percent.

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 converts plane bed and standing wave runs into antidune runs. This process is reversible. If the fine sediment is flushed from the flume system, the run returns 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. Considering momentum transfer, the fine sediment causes a more rapid rate of change of velocity with respect to distance above the bed making possible larger average velocities and smaller average depths in the stream, other conditions remaining the same, which yields a larger Froude number and partially justifies the observed change. The presence of the fine sediment in concentrations up to 42,000 ppm had little effect on bed roughness 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 finer sand was about three times greater than the maximum concentration of the total load for the coarse sand. However, it must be remembered that the change from one bed form to another occurred at much flatter slopes for the fine sand than the coarse sand, everything else kept constant. The foregoing concepts are summarized in Table 1.

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			
	Forms of Bed Roughness	Concentration of Total Load	n	Fr	S x 10^2	Concentration of Total Load	n	Fr	S x 10^2
Tranquil Flow Regime	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, Simons and Richardson (1959) 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 relates the Shield's parameter $\frac{\tau}{\Delta\gamma d}$, the Froude number Fr, the regime of flow, and form of bed roughness. Based upon available data this figures 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 bed roughness 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.

The regime of flow can be determined by observing the direction of travel of some artificially induced water surface ripple or wave using the wave celarity concept. That is, if the disturbance generated to oppose flow moves upstream with respect to a fixed point of observation, flow is

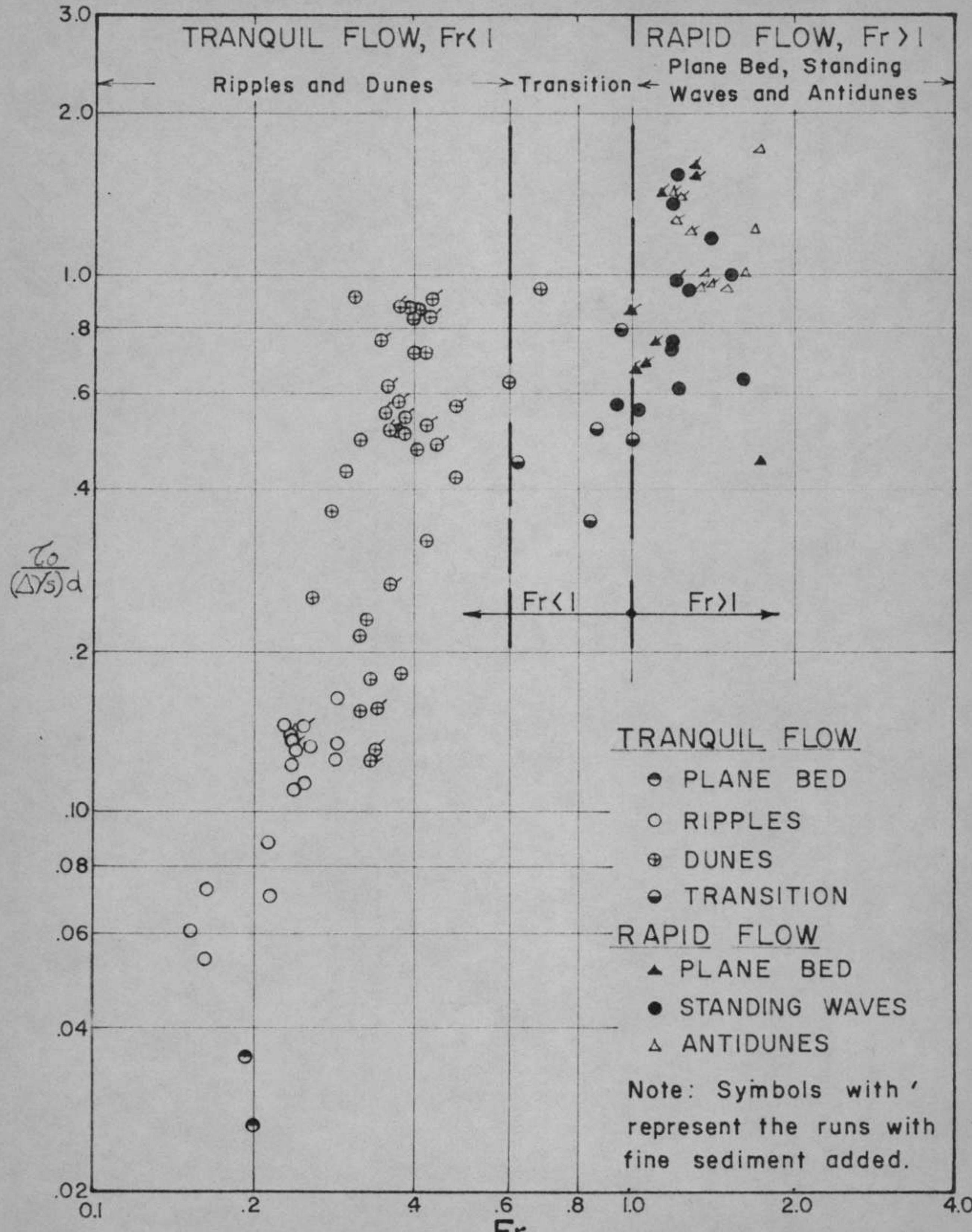

Fig. 5 Variation of $\frac{\tau_o}{(\Delta\gamma_s)d}$ with Fr and Forms of Bed Roughness

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. 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 extra sediment load being carried to the 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 conditions; and 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 of 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. That is, 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 develope near the banks of a stream, dunes may exist inside the ripple zones, and plane bed or perhaps standing waves, depending on the characteristics of the bed material, may develope down the central section or wherever maximum velocity occurs in the channel. Considering the flume, usually only one form of bed roughness exists. However, two forms of bed roughness can be set up simultaneously by operating the flume at 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 qualitative 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 relation which has been observed in the laboratory and for many natural streams. Typical qualitative stage-discharge curves which illustrate the effect of bed roughness on stage are presented in Fig. 6.

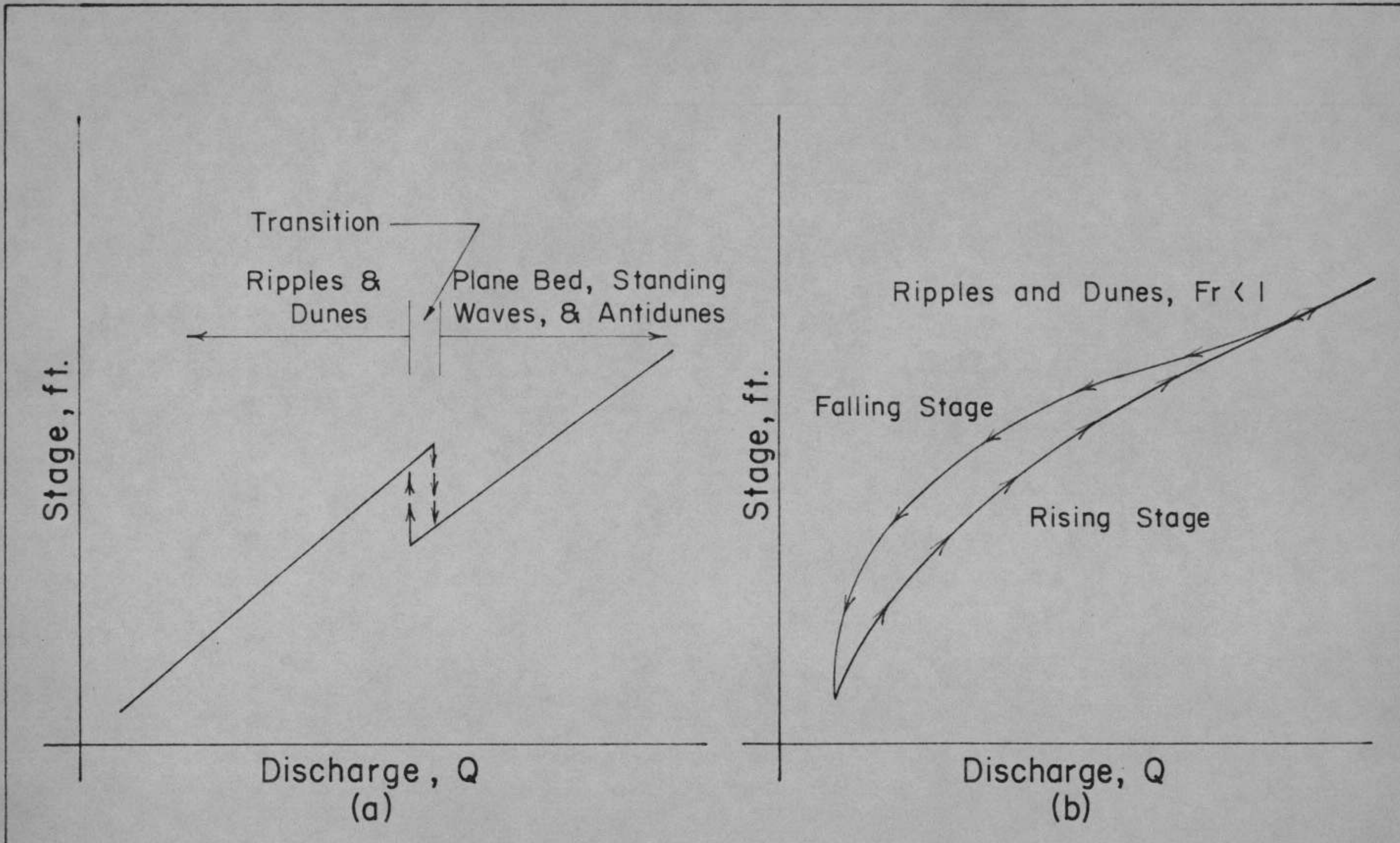

Fig. 6 Typical Qualitative Stage–Discharge Curves for Alluvial Channels.

In Figure 6a the break which is shown is caused by a change in bed roughness from dunes to plane or standing waves. On the rising stage, the break occurs 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 Figure 6b the magnitude of resistance to flow lags the actual discharge Q. That is, the development of bed roughness lags Q; hence, this results in a smaller resistance to flow and smaller depth than would normally occur for equilibrium flow. The opposite is the case on the falling stage. In this instance, at the peak discharge, the form of bed roughness can be 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.

In many cases, the scatter in the lower leg of a breaking stage discharge relation curve, Figure 6a, can be explained in a manner similar to the way the loop curve of Figure 6b was explained. However, one must keep in mind that with the breaking relation and considering the lower curve; the falling stage points may, under some circumstances, plot below the rising stage points, or approximately on them, or the rising and falling stage curves may cross. This complexity is related to the rate of change of Q with respect to time, the characteristics of the bed material, the effect of the sediment load, and the characteristics of the channel.

CONCLUSION

In the two regimes of flow, tranquil and rapid, the following forms of bed roughness occur in artificial and natural alluvial channels:

Tranquil Flow Regime, $Fr < 1$ (Fr is based upon local V and D values)

- Plane bed without bed movement
- Ripples
- Dunes with ripples superposed
- Dunes
- Washed out dunes or transitions
- Plane Bed

Rapid Flow Regime, $Fr \geq 1$ (Fr is based upon local V and D values)

- Plane Bed
- Standing Waves
- Antidunes.

Resistance to flow and sediment transport are intimately related to the form of bed roughness and each can change drastically from one bed form to another. In the flume case, using 0.45 mm sand, the Manning n will change from a value of 0.014 for plane bed without movement, to a value as large as 0.040 for dunes and then decrease to values of .012 for antidunes. Sediment transport rates for the same sand ranges from 100 to 1 000 ppm for the dune bed configuration and from 4 000 to 20,000 for antidunes. This upper limit of 20,000 ppm could be increased by further increasing the shear on the channel boundary. With finer sand, the range of concentrations in the rapid flow regime are larger for given values of Froude number.

The major variables which influence the form of bed roughness are depth of flow, the characteristics of the bed material, the slope of the energy gradient, and the shape of the cross-section. Water temperature, concentration of fine material, and seepage forces which result from the inflow or outflow of water through the boundary of the alluvial channel also influence the bed form by increasing or decreasing the effective weight of the alluvial material.

It is not possible at this time, to rigorously predict what bed form will exist in a natural channel. However, some indication can be obtained from a relationship between the Froude number and Shield's mobility parameter.

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 in loop stage-discharge curves. 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 , 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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