SOME ASPECTS OF ROUGHNESS IN ALLUVIAL CHANNELS

by

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Introduction

For centuries alluvial channels have been constructed to carry water for irrigation, navigation, and river control, but owing to the many factors involved, progress in the science of the design of these channels has been slow. One of the most important factors is the roughness or resistance function which has not yet been determined adequately for alluvial channels.

Although engineers have developed several formulas for the determination of the discharge in a channel, as yet none of these formulas is without important limitations. The difficulty has been in determining for different boundary conditions the extent to which the flow is retarded. In the formulas in present use, the resistance coefficient of a channel has been considered to be constant for a given bed material in a particular condition regardless of the variation of the other variables. Some investigators have shown that this is not the case and have expressed the belief that the resistance coefficient is affected by the slope of the channel, the velocity, the depth of the flow, and the viscosity of the water.

This study is intended to bring together the existing data on the subject and analyze the data briefly to act as a spring-board for future research concerning roughness in alluvial channels.

Previous Developments

Several formulas have been developed to determine the discharge in open channels. However, only two empirical formulas have found general acceptance. The first of these is the Chezy formula which may be stated as

$$Q = C A \sqrt{RS} , \tag{1}$$

where Q is the discharge in cubic feet per second, C is the Chezy discharge coefficient, A is the cross-sectional area of the channel in square feet, R is the hydraulic radius of the channel in feet, and S is the slope of the channel. The other formula is that of Manning's:

$$Q = (1.5/n) \; A \; R^{2/3} \; S^{1/2} , \tag{2}$$

where n is the Manning coefficient of resistance.

Both Chezy's C and Manning's n have been considered by some to be characteristic of the boundary and supposedly constant for a particular type of bed material in a particular state or condition.

The coefficient of resistance to flow in pipes, which is similar in some ways to flow in open channels, has concerned many investigators in the past. The equation for laminar flow in pipes may be stated as

$$C/\sqrt{g} = (Re/2)^{1/2} , \tag{3}$$

where g is the acceleration of gravity and $Re = VR/\nu$ is the Reynolds number. Blasius (11) developed an equation for turbulent flow in pipes with smooth boundaries. This equation is

$$C/\sqrt{g} = 5.99 \quad Re^{1/8} \tag{4}$$

and is applicable for Reynolds numbers as large as 25,000. For Reynolds numbers greater than 25,000, Karman and Prandtl (11) developed the equation

$$C/\sqrt{g} = 5.65 \log_{10} Re/(C/\sqrt{g}) + 3.7 \ . \tag{5}$$

Also they showed that the equation for flow past a rough boundary in pipes is

$$C/\sqrt{g} = 5.65 \log_{10} (r/k) + 4.92 \ , \tag{6}$$

where r is the radius of the pipe and k is the height of the roughness.

Several equations have been developed for flow in open channels with fixed roughness. Keulegan's equation (6) for turbulent flow with a smooth boundary is

$$C/\sqrt{g} = 5.75 \log_{10} Re/(C/\sqrt{g}) + 3.5 \ , \tag{7}$$

and for turbulent flow with a rough boundary is

$$C/\sqrt{g} = 5.75 \log_{10} R/k + 6.25 \ , \tag{8}$$

where k is the roughness measured as the diameter of the equivalent Nikuradse sand particle.

Powell (7, 8, 9) also developed equations for turbulent flow with smooth boundaries and for turbulent flow with rough boundaries.

These equations may be stated as

$$C/\sqrt{g} = 7.4 \log_{10} Re/(C/\sqrt{g}) - 5.58 \quad (9)$$

and

$$C/\sqrt{g} = 7.4 \log_{10} R/\epsilon \quad , \quad (10)$$

where ϵ is the measure of roughness which depends on both the shape of the artificial roughness and the shape of the cross section of the channel. More recently, Robinson and Albertson (10) developed an equation for turbulent flow in wide channels with rough boundaries. This equation is

$$C/\sqrt{g} = 5.75 \log_{10} D/a + 0.5 \quad , \quad (11)$$

where D is the depth of water, and a is the height of a type of roughness made from a system of baffle plates.

Anderson (2) studied the formation of bed waves in open channels. He concluded that bed waves should not be formed if the Froude number is less than 0.55. Once the value of Froude number becomes greater than 0.55, however, bed waves or sand dunes begin to form. He also concluded that there is a critical Froude number beyond which bed wave formation is destroyed and the bed becomes smooth. This critical value is a function of the sediment size. The larger the sediment, the greater is the critical Froude number.

Theoretical Considerations

Three types of boundary layer may be considered: (a) that which is developed downstream from a leading edge of a flat plate in a fluid of infinite extent, (b) that which is developed in circular pipes, and (c) that which is developed in open channels. In the first type the thickness of the boundary layer increases indefinitely in the downstream direction, while the piezometric head remains constant throughout. In the second and third types, however, the thickness of the boundary layer remains constant, while the piezometric head decreases in the downstream direction. Although there is considerable similarity between flow in open channels and flow in pipes, the similarity is not complete owing to certain differences, such as: (a) cross-sectional shape of flow prism is not the same, and (b) a free surface exists in the open channels. These differences have considerable influence on the pattern of secondary circulation.

In order to relate flow in circular pipes and flow in open channels, equations for flow in wide channels will be developed.

Laminar Flow in Wide Channels

The equation for laminar flow in wide channels can be derived through the use of the equation relating the gradients of shear and pressure

$$\frac{d\tau}{dy} = \frac{dp}{dx} , \qquad (12)$$

and the Newton shear equation

$$\tau = \mu \frac{dv}{dy} . \qquad (13)$$

Combining these equations and integrating yield

$$C/\sqrt{g} = (Re/3)^{1/2} , \qquad (14)$$

which is the equation for laminar flow in wide channels where $Re = \frac{VR}{\nu}$ and the hydraulic radius R equals the depth of flow D .

Turbulent Flow in Open Channels

Following the similarity between flow in pipes and flow in open channels, Keulegan (6), Rouse (11), Powell (8, 9), Robinson and Albertson (10), and others have developed equations for turbulent flow in open channels with fixed roughness, and either smooth boundaries or rough boundaries. They showed that the equation for turbulent flow in open channels with smooth boundaries takes the form of Eq 4 or Eq 5. Also, they showed that the equation for turbulent flow in open channels with rough boundaries takes the form of Eq 6, such as Eqs 8, 10, and 11.

No equations have been developed for rough alluvial channels. However, when such a relationship is developed, it may have certain similarities to these equations for open channels with rigid boundaries.

Dimensional Analysis

In the foregoing analyses it has been difficult, in some cases, to solve theoretically for the boundary drag without making assumptions that have doubtful validity. Therefore, a dimensional analysis may be used to advantage. The variables which govern the mean intensity of shear τ_o along the boundary in an alluvial channel may be stated as:

V = mean velocity of flow in the channel,

R = hydraulic radius,

sf = factor expressing the shape of the channel,

d = mean diameter of bed material,

ρ = density of water,

ρ_s = density of bed material,

μ = viscosity of the water,

$\Delta\gamma$= difference between specific weight of air and water,

σ = standard deviation of diameter of bed material.

The general relationship among these variables may be stated as:

$$\tau_0 = \phi_1 \text{ (sf , V , R , } \rho, \ \rho_s, \ \mu, \ \Delta\gamma, \text{ d , } \sigma) \quad (15)$$

With V , R , and ρ as repeating variables, dimensional analysis yields:

$$\tau_0 = \rho V^2 \phi_2 \text{ (sf , R/d , d/}\sigma \text{ , } \rho_s/\rho \text{ , } V/\sqrt{(\Delta\gamma/\rho)R} \text{ , VR/}\nu \text{ ,} \quad (16)$$

in which $V/\sqrt{(\Delta\gamma/\rho)R}$ is a Froude number Fr and VR/ν is a Reynolds number Re .

Combining the following equation

$$\tau_0 = \gamma DS = \gamma RS \quad (17)$$

with Eq 16 gives

$$\gamma RS = \rho V^2 \phi_2 \text{ (sf , R/d , d/}\sigma \text{ , } \rho_s/\rho \text{ , Fr , Re)} \quad (18)$$

or

$$V = \sqrt{g}\, \phi_3 \text{ (sf , R/d , d/}\sigma \text{ , } \rho_s/\rho \text{ , Fr , Re)} \sqrt{RS} \ . \quad (19)$$

Comparing this equation with that of Chezy's, which is

$$V = C \sqrt{RS} \ ,$$

and rearranging Eq 19 give

$$C/\sqrt{g} = \phi_3 \, (sf \, , \, R/d \, , \, d/\sigma \, , \, \rho_s/\rho \, , \, Fr \, , \, Re) \quad . \qquad (20)$$

For flow of water in wide alluvial channels, sf and ρ_s/ρ may be considered constant. Also, the variation and influence of the relative standard deviation d/σ will be assumed of secondary importance. The Froude number will be considered unimportant because conditions of uniform flow and no surface waves will be assumed. Eq 20 therefore simplifies to

$$C/\sqrt{g} = \phi_4 \, (R/d \, , \, Re) . \qquad (21)$$

Discussion of Results

No experimental data were obtained specifically for this study. Instead, all data available to the writers were used -- provided sufficient information was recorded to permit reasonably accurate determination of the parameters involved in Eq 21.

Because the available data included both laboratory and field studies, the range of the variables was considerable as shown in the following tabulation:

$Q = 0.004$ -- $145,000$ cfs

$V = 0.070$ -- 39 ft/sec

$R = 0.012$ -- 13.5 ft

$S = 0.000149$ -- 0.0252

$d = 0.0000328$ -- 0.361 ft

$C/\sqrt{g} = 4.1$ -- 27.6

$R/d = 2.15$ -- $17,900$

$Re = 120$ -- $7,400,000$

Fig. 1 shows that the data obtained by the U. S. Waterways Experiment Station, Sato, Gilbert, and the data from the Missouri River are well suited to the use of Eq 21. Although these data were not taken especially for this study, they included information on all the variables needed. Much of the other data used for this study have a missing or inaccurate variable which it was necessary to estimate. Such deficiencies may be summarized as one or more of the following:

1. Water temperature not recorded,
2. Hydraulic radius calculated as $R = A/T$ instead of $R = A/P$,
3. Water surface slope in a given channel assumed to be the same for different discharges,
4. Mean diameter of bed material not given.
5. Data obtained in reaches of rivers which were not strictly uniform.

Fig. 1 is a plot of the Chezy discharge coefficient $C/\sqrt{g}$ against the Reynolds number with the relative size of bed material R/d as the third variable. On the basis of the data plotted, the lines of constant R/d were located empirically by a process of curve fitting and cross plotting. The field data from the Missouri River and the laboratory data from Gilbert, Kalinski and Hsia, and the U. S. Waterways Experiment Station were used principally to establish these curves. Data obtained more recently have helped to confirm the curves.

After the curves in Fig. 1 were established, they were placed on the transition plot, Fig. 2, wherein it was found that each of the

R/d-curves plotted on a single straight line, except for those portions represented by the lower Reynolds numbers.

In each of the figures, Reynolds number was taken as VR/ν (having a magnitude of one-fourth that for pipes which uses the diameter instead of the hydraulic radius).

In Fig. 1, Eq 14 for laminar flow in wide channels has been plotted. It may be seen that the experimental data lie on or above the line defined by Eq 14. Evidently, the resistance observed in experimental channels is higher than that given by Eq 14, which is to be expected in view of the finite width of the experimental channels. With laminar flow the relative influence of the walls or banks may be greater than with turbulent flow. Eqs 4, 7, and 9, which are also plotted, are expressions for turbulent flow in open channels with smooth boundaries. Because there is no detailed information on the conditions of flow for the plotted data, it is difficult to discuss the relations which exist in this range. However, some of the data of Kalinske and Hsia, Sato and the Waterways Experiment Station lie close to the curves representing the smooth boundary, and as the Reynolds number is increased they deviate from these curves.

From Fig. 1 it is quite obvious that Reynolds number is of considerable importance in the analysis of flow in alluvial channels. When the data follow near the curve for a smooth boundary, Reynolds number has an influence which might be expected from rigid boundary hydraulics. However, as Reynolds number increases for a given R/d-value, the data rapidly deviate from the smooth boundary curves, rise markedly to a peak, and then descend almost back to the smooth boundary curve.

The exact cause of the foregoing occurrence is not known, but it is known that for turbulent flow along smooth rigid boundaries, a laminar sub-layer exists which plays a major role in the resulting boundary resistance. The thickness δ' of this laminar sub-layer, in turn, has been shown to be a function of the Reynolds number. Because of these facts for rigid boundaries, it is logical to assume that the laminar sub-layer may play an important role in alluvial channel hydraulics for large as well as small Reynolds numbers. The possible nature of this role will be discussed later.

The relative size of bed material R/d is seen in both Figs. 1 and 2 to be of major importance. For a given Reynolds number the Chezy discharge coefficient may vary more than 300 per cent, as R/d varies from 10,000 to 1,000. At small values of R/d (say 50), wherein the bed material is relatively large, the Chezy coefficient varies only about 60 per cent from its initial departure from the smooth boundary curve until it descends again. For the large values of R/d (say 10,000), however, the variation is approximately 900 per cent, which shows a much greater latitude for the development of dunes with the relatively smaller bed material, or in other words, a relatively deep channel.

The development of sand waves such as ripples, dunes, and bars on the bed of an alluvial channel is evidently very much dependent upon both the Reynolds number and the relative size of the bed material R/d. Furthermore, these waves in turn control the Chezy discharge coefficient. A logical objective, therefore, is to attempt to analyze the sequence and nature of development of these waves. The following analysis has evolved from a study of the various investigations quoted herein, and in some cases the evidence supporting the analysis is quite limited. Nevertheless, the analysis is presented for the consideration of the profession.

Regardless of the magnitude of R/d, when Re is sufficiently small, there is a laminar film or sub-layer at the bed (in the case of laminar flow this layer extends throughout the entire depth of flow) which covers the bed material -- protecting it from the turbulent flow above. Within the turbulent flow, eddies and other velocity fluctuations continually penetrate into the laminar sub-layer where they are damped and die out before they affect the bed. As the Reynolds number increases, however, the laminar sub-layer becomes thinner, due to the increased activity of the turbulence, until there is insufficient thickness to protect the bed from the pulsations and surges caused by periodic eddies and velocity fluctuations. As a result of these surges and pulsations in flow at the bed, small sand waves or ripples develop within the laminar sub-layer. These ripples and sand waves, in turn, set up their own systematic local flow pattern which accentuates the rhythmic formation of the sand waves.

When the ripples within the laminar sub-layer are sufficiently high to penetrate through it, the laminar sub-layer (in its usual form) is destroyed and dunes and roughness develop very rapidly with increasing Reynolds number -- see rising broken lines for $R/d = 100$, 200, and 10,000. This dune development consists of an increase in both height and spacing, until the maximum roughness possible has been reached for the given value of R/d, at which point the hydrodynamic roughness decreases despite the fact that the height of the dunes may be increasing slightly. In this connection it is well to remember that Johnson (5), Powell (7), and Benedict, Matejka, and Albertson (4) all found that the bed roughness is decreased if the spacing of strips across the bed is either increased or decreased from approximately twelve strip heights.

With increasing Reynolds number, beyond the point of maximum roughness, the dunes take on quite different patterns. The principal reason for decreasing roughness is the increase in the spacing and a change in the pattern of the dunes. Eventually, some of the dunes seem to travel more rapidly then others (Barton and Lin (3)) and long transverse sand bars develop. Under these conditions the resistance to flow is considerably decreased, but the water surface is so irregular that accurate determination of depth is extremely difficult.

Finally, as Reynolds number is increased still further, the bars disappear and a plane bed develops. At this point, the R/d-value is approximately equal to the relative roughness R/k of Nikuradse -- an occurrence which might be expected since the visual appearance of the plane bed is quite similar to that of Nikuradse's sand-treated pipe walls.

Of particular interest is a further comparison of the different roughness standards (Nikuradse, Powell, and Robinson) with R/d as Reynolds number varies. The curve of constant R/d seems to depart from the smooth boundary curve at about the same value of the Chezy coefficient as that at which it reaches a plane boundary. As the roughness increases for a given R/d-value, the magnitude of the corresponding R/k-value increased many-fold. For example, when R/d = 10,000 the magnitude of R/k decreases to less than 1.0 -- a situation which obviously is impossible. The reason for this apparent inconsistency is the height and spacing of the dunes. This means that, using a Nikuradse-type of roughness, the material in a plane bed would have to be greater in diameter than the depth of flow to give as much resistance to the flow as dunes where $R/d = 10,000$ and $Re = 100,000$. In other words, the Nikuradse standard of roughness R/k is inadequate for flow in alluvial channels when dunes exist. As pointed out previously, when the bed is plane R/d and the equivalent R/k approach each other and R/k is an effective standard. Likewise, for small R/d-values when dunes do not form, the equivalent R/k is approximately equal to R/d.

When dunes exist on the bed, a more appropriate roughness standard is that of Powell or Robinson where the length terms for the roughness (a and ϵ) would then be compared with the average heights of the dunes.

As stated earlier, the laminar sub-layer should play some part in the development of the dunes. This possibility is further supported by Fig. 2 wherein the abscissa d/δ' is the size of the bed material relative to the thickness of the laminar sub-layer. On the one hand, for very small bed material relative to depth, such as for the data of Kalinske and Hsia, the particles are so fine that the turbulence in the flow above the laminar sub-layer is able to reach the bed with sufficient force to move them and ripples develop. On the other hand, if the particles are relatively large, such as $R/d = 20$ for the Waterways Experiment Station data, they are sufficiently stable to resist the surging action until the laminar sub-layer is almost destroyed and a plane bed is developed -- hence, only small dunes are developed.

It is quite probable that throughout the development of the dunes the laminar sub-layer is still in existance on certain parts of the dunes so that a part of the bed resistance is a result of shear in this sub-layer. However, the dunes themselves cause large-scale form drag to exist and contribute a major portion of the resistance. The fact that for a plane bed the equivalent R/k approaches R/d indicates that, as the plane bed forms, the effect of the laminar sub-layer is finally eliminated completely. Nevertheless, since no measurements of the velocity and turbulence distribution very near a dune are known, there is insufficient information to prove directly the existance of a laminar sub-layer throughout the dune development sequence.

Although the relative size of the bed material plays a very important part in the initial formation of ripples, and hence the point of deviation of a given R/d-curve from the smooth boundary curve, the relative thickness of the laminar sub-layer d/δ', which is proportional to the parameter $Re/(R/d)(C/\sqrt{g})$, seems to control completely the reduction in roughness and the eventual destruction of the bed waves. This is evidenced in Fig. 2 by the single sloping line to which all R/d-curves greater than 50 become tangent. The equation of this line has been determined empirically to be

$$\frac{C/\sqrt{g}}{\sqrt{8}} - 2 \log_{10} 2R/d = 12.4 \log \frac{\sqrt{32}\,Re}{(R/d)(C/\sqrt{g})} - 24.17 \quad . \qquad (22)$$

This equation seems to be applicable from the point where the bed material is half the thickness of the laminar sub-layer to the point where the bed material is twice the thickness of the laminar sub-layer. Beyond this range either the bed is plane or anti-dunes form as discussed in the following paragraph.

There are some data (Barton and Lin (3)) which indicate that as Reynolds number is increased beyond the plane bed development, anti-dunes are formed wherein the Froude number would play an important part due to the surface waves.

The transition function Fig. 2 is applicable not only to sands but to gravel and cobbles as well. The data of Van't Hul (13) and the U. S. Bureau of Reclamation are for large gravel and cobbles wherein no bed material is moving and no dunes have formed. In this case the bed roughness is similar to that of the Nikuradse roughness.

In comparing the transition function for alluvial channels with that for rigid boundaries, it may be observed that for great depths of flow $(R/d > 50)$ a systematic difference exists. For smaller R/d-values, however, the alluvial channels follow very closely to the rigid boundaries -- in fact there may be no movement of bed material except at large values of $\sqrt{32}\ Re/(R/d)(C/\sqrt{g})$. In studying the data of Van't Hul, one notes that no appreciable movement exists except when $\sqrt{32}\ Re/(R/d)(C/\sqrt{g}) > 100{,}000$ and then no dunes are formed. This leads to the speculation that on plane beds only anti-dunes (and not the usual bed waves) are formed once $\sqrt{32}\ Re/(R/d)(C/\sqrt{g})$ exceeds approximately 200.

Despite the fact that most of the data available to the writers seem to support the arguments presented herein, important questions might be raised for which no answers are known. The data of Kalinske and Hsia remain close to the curve of Blasius for smooth boundaries which indicates that the laminar sub-layer and hence the resistance to the flow is influenced very little if any by the ripples and dunes which were formed. However, instead of the dunes continuing to increase in size, with increasing Reynolds number, their Run No. 11 for which Reynolds number was the greatest had a smooth bed. It is possible that, if Reynolds number had been increased still further, the bed wave sequence of ripples, dunes, bars, and plane bed would have been established and data would have been available to fill in the gap between the data of Kalinske and Hsia and the Missouri River data where, in each case, R/d is approximately equal to 10,000.

Another question which is not answered is why the data of the Nacimiento and Salinas rivers deviate so markedly from the other data. This is particularly noticeable in Fig. 2.

For each of the foregoing questions an attempt was made unsuccessfully to find an explanation through either the Froude number or the standard deviation of the size distribution.

Despite the foregoing questions and inconsistencies, however, the available data in the main support to a remarkable extent the analyses presented herein.

Summary of Conclusions

1. Eq 21: $C/\sqrt{g} = \emptyset\,(Re, R/d)$ is adequate to express the roughness in alluvial channels -- at least as a first approximation.
2. The equations of Blasius and Keulegan fit the data well for a smooth boundary and turbulent flow.
3. The laminar sub-layer and the Reynolds number play an important role in the initial development, evolution, and eventual disappearance of the bed waves.

4. A laminar sub-layer of some type (or at least conditions usually associated with its existence in rigid boundary hydraulics) appears to be necessary for the development of bed waves other than anti-dunes.

5. As the relative size of bed material increases, the influence of the laminar sub-layer decreases.

6. The sequence of development of dunes appears to be

   a. formation of ripples,

   b. formation of dunes and greatly increased roughness,

   c. formation of bars and decreased roughness,

   d. disappearance of all bed waves, and formation of a plane bed, and

   e. eventual formation of anti-dunes,

   provided R/d is sufficiently large to permit bed movement.

7. Owing to the formation of large bed waves, the roughness of the channel may be much greater when the relative size of bed material is small than when the relative size is large.

8. Additional data are badly needed either to prove or to disprove completely the validity of the analyses presented herein -- particularly for the rising portion of each R/d-curve where the bed waves are rapidly developing, and for the region of anti-dunes.

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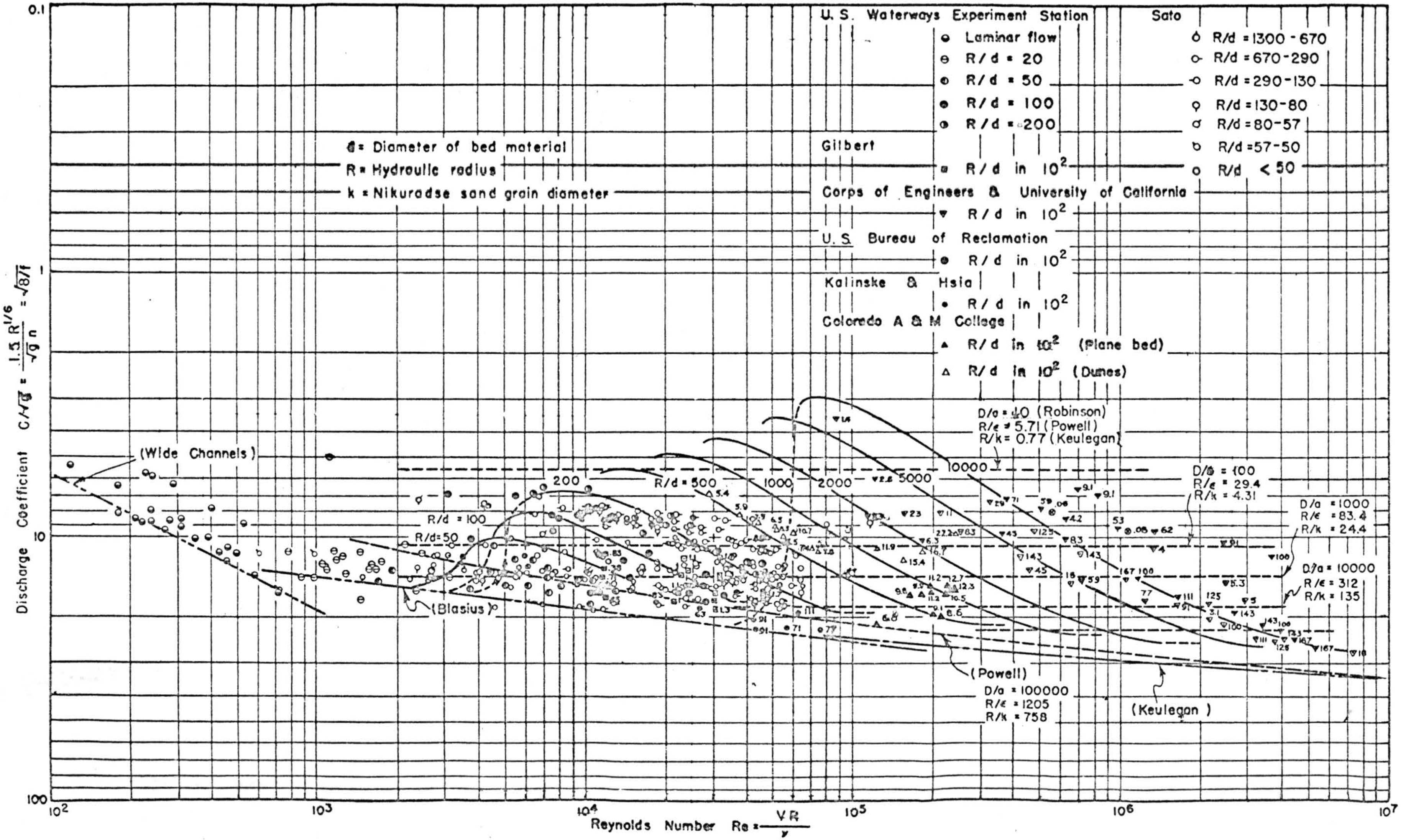

Fig. 1 Variation of Discharge Coefficient with Reynolds Number — Relative Roughness as Third Variable

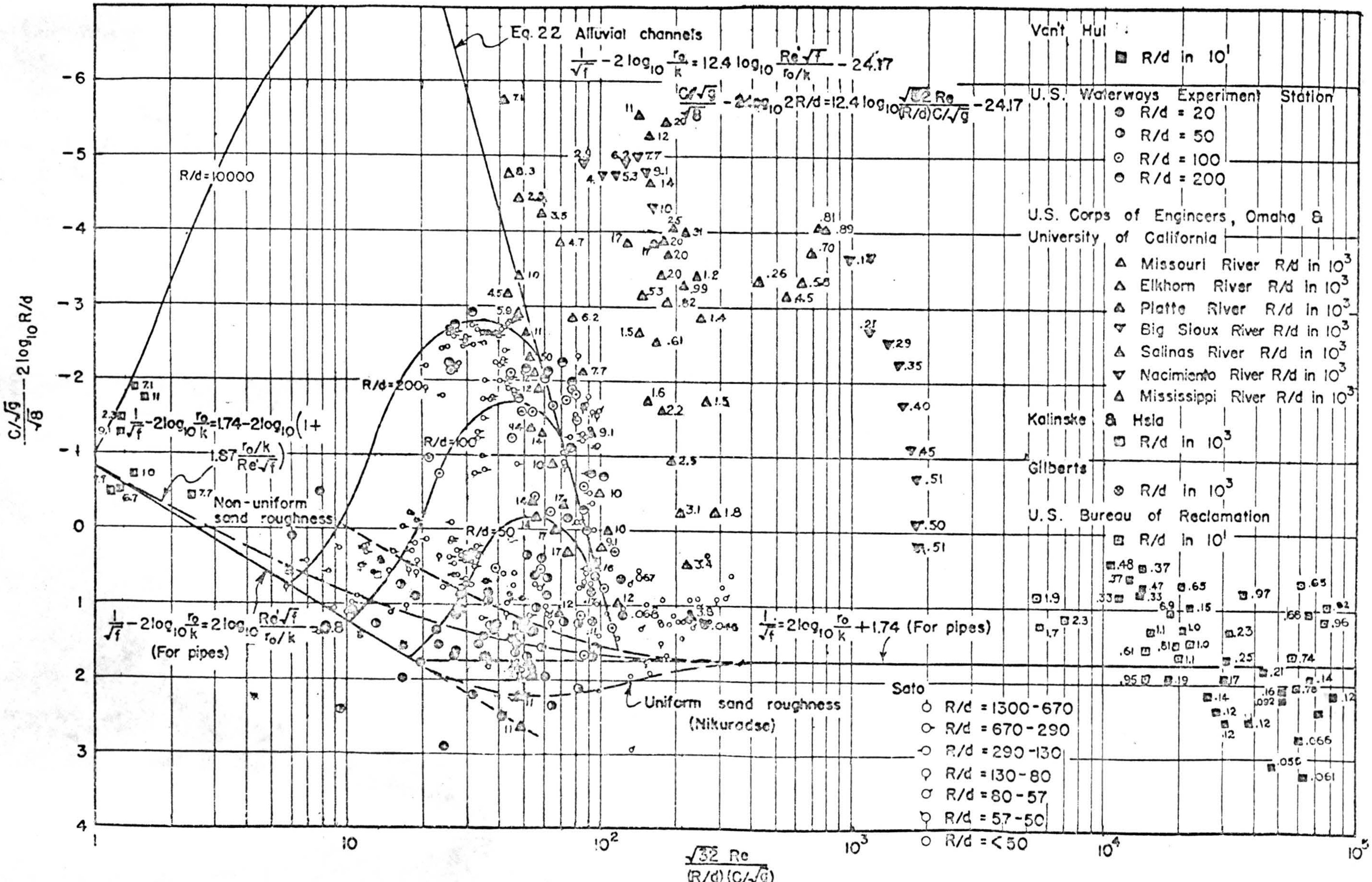

Fig. 2 Transition from smooth to rough boundary for wide alluvial channels