VELOCITY DISTRIBUTION IN STEEP ROUGH CHANNEL

by

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I. INTRODUCTION

The gross resistance coefficients, in rough channels, are caused by the combined effects of frictional and form resistances. Frictional resistance and form resistances are intimately related to velocity distribution and to analyse a flow, the friction factor must be determined.

Up to the present there has been hardly any investigation on the distribution of velocity in Steep Rough Channels. The aim of this thesis is to provide information concerning the velocity distribution in steep channel with artificial roughness.

In 1959, Peterson and Mohanty classified the flow in steep, rough channels into three regimes, which are tranquil, tumbling and rapid regime. In 1961, Al-Khafaji and Peterson extended this classification into seven regimes: tranquil, rapid, stable and unstable tumbling, transitional rapid, and transitional stable and transitional unstable tumbling. In this thesis the study of velocity distribution will be made only in the three regimes, tranquil regime, stable tumbling regime, and rapid regime. Throughout this thesis, unless otherwise stated, the term "tumbling" will denote stable tumbling.

The data this thesis is based on is taken from Project 405 of the Civil Engineering Department which is sponsored by the Virginia State Highway and the U.S. Bureau of Public Roads.

The object of this thesis is to provide an information concerning the velocity distribution in a steep channel with artificial roughness elements of various sizes and several different shapes. The objectives of this study may be summarized in the following:

1. To study the velocity distribution in the stream under various conditions of flow and roughness geometry.

2. To examine the applicability of the logarithmic law form of velocity distribution under conditions of extreme roughness in the three major regimes.

3. To study the inflection-point of velocity distribution curve in tranquil and rapid flow regime.

4. To determine the velocity coefficients in tumbling flow regime.

5. To study the relation of velocity distributions to the flow classification proposed by Peterson, Mohanty and Al-Khafaji.

II. REVIEW OF LITERATURE

The man who first recognized the effect of boundary roughness on fluid flow was a French engineer, Antoine Chezy. In 1775, according to Ganguillet and Kutter (1) the first recognized formula, giving the mean velocity across a vertical section, for open channels is in form of:

$$V = C\sqrt{RS} \qquad 2\text{-}1$$

where, V is the mean velocity of flow, R is the hydraulic radius of channel, S is the energy slope, and C is Chezy's coefficient. This formula is usually called Chezy's formula. This formula does not take into account the velocity distribution in the section. However, it was the general belief that C is dependent on R and S, as well as upon the degree of roughness of the channel. It was also believed that velocity distribution was parabolic. For determining Chezy's C, many equations have been derived. The most widely used formula is Manning's formula, published in 1890 in the form of:

$$V = \frac{1.486}{n} R^{2/3} S^{1/2} \qquad 2\text{-}2$$

where $C = \frac{1.486}{n} R^{1/6}$, where n depends on channel roughness.

In 1904 and 1925 Prandtl (2) presented his boundary layer theory and a mixing length concept, respectively.

Prandtl had given the expression for the turbulent shear stress at any point in a fluid moving past a solid as follows:

$$\sqrt{\tau/\rho} = \ell \frac{dv}{dy} \qquad 2\text{-}3$$

This can be written in the form of

$$\sqrt{\tau_o/\rho} = \ell \frac{dv}{dy} \sqrt{\tau_o/\tau} \qquad 2\text{-}4$$

which is an approximate law of velocity distribution in the neighborhood of the wall.

Here

τ = the shearing stress at the point

ρ = the density of the fluid

V = the velocity at the point

y = the distance of the point from the wall

ℓ = the so-called mixing length of momentum exchange

τ_0 = the shear in the fluid at the wall

The first rational logarithmic velocity distribution formula of the concepts of turbulent flow which were analytically derived by Prandtl and Von Kármán (3) was in the form:

$$\frac{V}{V_*} = \frac{1}{K} \ln (y/y_o) \qquad 2\text{-}5$$

This is the so-called Karman's law of velocity distribution in the neighborhood of a solid wall, where V_* is shear velocity, y_o is a constant of intergration, K is universal constant.

In 1933, Nikurdse (4), after performing a series of experiments using sand-coated circular pipes, confirmed the law of velocity distribution in the vicinity of a surface covered with closely packed sand grains. The equation is

$$\frac{V}{V_*} = 8.5 + 5.75 \log (y/K_s) \qquad 2\text{-}6$$

K_s is the mean height of the sand grains forming the roughness elements.

In 1936 Schlichting's investigation (5) of roughness for regular geometrical forms showed that the velocity distribution law in the region where the quadratic resistance law holds is given by

$$\frac{V}{V_*} = a_{\tau_o} + 5.75 \log (y/K) \qquad 2\text{-}7$$

which is of the same form as Eq. 2-5. Here a_{τ_o} varies both with the shape and distribution of the roughness elements. For a surface covered with sand $a_{\tau_o} = 8.5$, then Eq. 2-7 equals Eq. 2-6.

In 1938, Keulegan (6) analysed Bazin's experiments and applied the Prandtl-Karman concepts of hydraulic resistance to open channels and was led to the formula

$$\frac{\bar{V}}{\bar{V}_*} = 6.35 + 5.75 \log (R/K_s) \qquad 2\text{-}8$$

where $\bar{V}$ is mean velocity of flow, $\bar{V}_*$ is mean shear velocity, R is hydraulic radius and K_s is the mean height of the sand grains.

In 1939, Taylar (7) stated that: (1) The form of Bakhmetfft's (8) equation, which is as follows:

$$(V_2 - V_1)/\sqrt{\tau_o/\rho} = \frac{2.3}{k} \log (y_2/y_1) \qquad 2\text{-}9$$

where V_2 and V_1 are velocity of the points a distance y_2 and y_1 from wall respectively, may be applied to the velocity distribution near the bed of an open channel, y being measured along a line orthogonal to the lines of equal velocity. (2) The value of k to be used in equation 2-9 is not 0.40 but appears to be dependent upon the geometry of channels.

In 1941, Vanoni (9) tested the Von Karman universal logarithmic velocity distribution law for pipes, $(V - V_{max})/\sqrt{\tau_o/\rho} = \frac{2.5}{K} \log (y/r_o)$, in rectangular open channel for uniform two dimensional flow, established that:

$$\frac{V - V_{max}}{\sqrt{gdS}} = \frac{2.3}{K} \log (y/d) \qquad 2\text{-}10$$

where d is the depth of the flow, S is the slope of the channel, and g is the acceleration of gravity.

Recently, in 1961, Tracy and Lester (10) studied smooth rectangular channels and suggested the following equation:

$$\frac{v - V_c}{V_*} = 2.5 + 5.75 \log y/y_e \qquad 2\text{-}11$$

where v is time-averaged velocity component in x directions. V_c is average velocity in central region of flow, V* is average shear-velocity, $V_* = \sqrt{RS_0g}$, R being the hydraulic radius, S_0 is bed slope of channel.

III. LABORATORY EQUIPMENT

The equipment and apparatus used in this study included water supply, test flume, two dimensional roughness elements, pitot tube, point gauge and equipment to measure the discharge, temperature and slope of the flume.

Water Supply

Water flow to the experimental site is through a closed pumping system. Water is pumped to a head tank, which is approximately 50 feet above the experimental flume, then back down to the flume through six-inch main pipe line.

Experimental Flume

The wooden channel used for this study is 30 feet long and 2 feet deep by 2 feet wide. The channel is fastened to a structural steel frame of bolted construction, which rests on a hinge in such a way that the flume lends itself to slopes ranging from zero to 30 percent.

Head Tank

A structural steel head tank which receives flow from the diffusor contains sufficient guide vances, stream-lining fillets, and baffles to assure a uniform flow approaching the head gate.

Head and Tail Gate

The head tank is provided with a worm-and-rock driven hand-operated headgate. A tail gate is the same type as the head gate, also hand-operated with worm-and-rock drive. Both of these gates permit flexibility of the type of flow desired.

Roughness Elements

Different sizes of artificial wooden roughness bars square in cross-section were used for this study. The length of each bar is exactly two feet so that it fits snugly in the flume perpendicular to the walls of the flume. Also the two inches high roughness elements used for this study have semi-circular, triangular and parallelogram in cross-section, as shown in Figure 3-1.

Pitot Tube

Arrangement was made to hold two plastic tubes, connected with a standard pitot tube mounted on a hand-operated movable carriage, laid on a frame which inclined at an angle of 30° to facilitate the reading of the difference between the static and dynamic head.

Point Gauge

The depth of flow at any particular point, normal to the bed of the flume or the roughness surface, was measured by point gauge. The point gauges used for this study were accurate enough to measure depth up to one-thousandth of a foot.

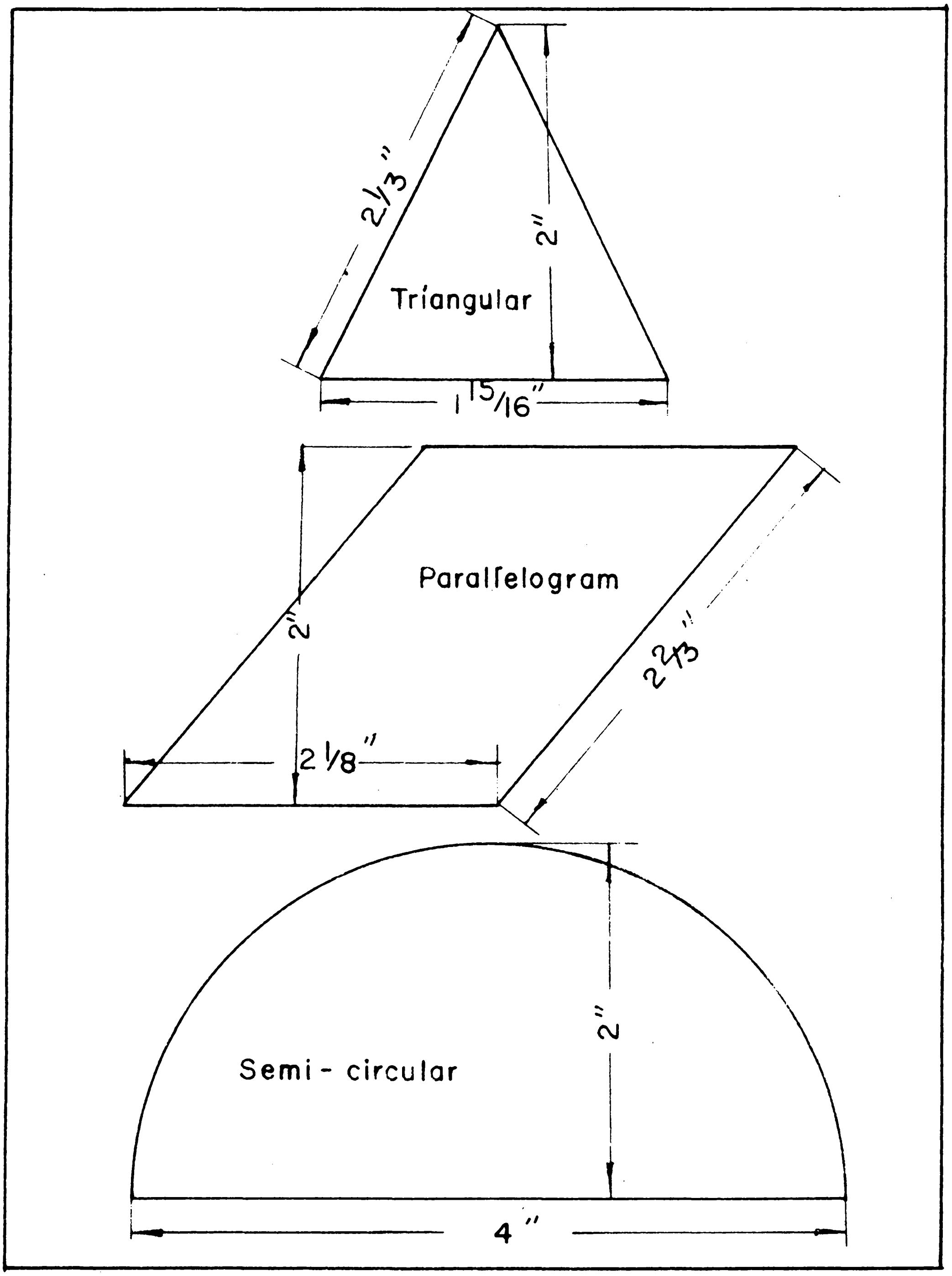

Fig. 3-1 The Shape Of Roughness Elements

Measurement of Slope

A cathotometer was used to measure accurately the slope of the flume. This device consists of a level, a one-meter high steel stand and a base having three small legs. The level rides on the meter steel stand and can be moved up and down conveniently. The stand can rotate to any horizontal angle. The flume bed slope can be computed from the difference of levels on the scale read directly by the level.

Measurement of Temperature

A standard thermometer was used to measure the temperature of the flow.

Measurement of Discharge

The discharge was obtained from readings of a manometer that had previously been calibrated by standard weighing methods. The total range of flow rates in the experimental program ranged from a minimum of 0.132 c.f.s. to a maximum of 1.90 c.f.s.

IV. THEORETICAL CONSIDERATION

The momentum transfer theory of turbulent flow developed by Prandtl, by assuming that the momentum of each fluid particle remains constant during movement from one region to another, leads to an equation for two-dimensional flow:

$$\tau = \rho \ell^2 (dv/dy)^2 \qquad 4\text{-}1$$

where ℓ is the mixing length, τ is tractive force, and ρ is fluid density. By assuming that the mixing length is proportional to the distance from the wall, y, that is $\ell = ky$, then equation 4-1 reduces to:

$$\tau = \rho k^2 y^2 \; (dv/dy)^2 \qquad 4\text{-}2$$

integration of equation 4-2 results in the following:

$$\frac{V}{\sqrt{\tau/\rho}} = \frac{1}{k} \ln y + C \qquad 4\text{-}3$$

From Von Karman's investigation in 1931, that τ is a constant and equal to τ_o, the wall shear stress, then equation 4-3 can be written

$$\frac{V}{\sqrt{\tau_o/\rho}} = \frac{1}{k} \ln y + C \qquad 4\text{-}4$$

Substituting V* for $\sqrt{\tau_o/\rho}$, Eq. 4-4 reduces to:

$$\frac{V}{V*} = \frac{1}{k} \ln y + C \qquad 4\text{-}5$$

For open channel flow, regardless of the effect of free surface, it may be assumed that the maximum velocity occurred at the flow surface. Under this assumption, the integration constant C in equation 4-5 becomes $\frac{Vmax}{V*} - \frac{1}{k} \ln d$, where d is the depth of the flow. Therefore, equation 4-6 can be written as:

$$\frac{V - Vmax}{V*} = \frac{1}{k} \ln (y/d) \qquad 4\text{-}6$$

For rough channel, the depth, d, may be expressed by $y_1 + (K - y_1)$ where K is the height of roughness element, y_1 is the height of inflection point measured from flume bed, and y_1 is the control depth. This effective depth is a function of bed-slope, flow regime, discharge, the length of a cycle, and the shape of roughness element. Since y_1 is also a function of bed-slope, flow regime, discharge the length of a cycle and the shape of roughness element, then $y_1 + (K - y_1)$ may be replaced by C_1y_1, here C_1 is a proportional constant. Eq. 4-6 may be rewritten, by substituting y_1 instead of d, as

$$\frac{V}{V*} = \frac{Vmax}{V*} + \frac{1}{K_1} \ln y/y_1 \qquad 4\text{-}7$$

K_1 is a constant.

Also, for a constant slope, a definite roughness, in same regime y_1 is always proportional to the length of a cycle. Therefore, Eq. 4-7 may be written as

$$\frac{V}{V*} = A + \frac{1}{K_2} \ln y/L \qquad 4\text{-}8$$

where K_2 is an arbitrary constant. A equals Vmax/V*.

From dimensional consideration, the general relationship that exists may be stated as

$$\tau_o = \phi_1(V, K, y_1, \rho, \mu, \gamma, L, Ks) \qquad 4\text{-}9$$

dimensional analysis yields.

$$\frac{\tau_o}{\rho V^2} = \phi_2(y_1/K,\ L/K,\ V/\sqrt{gy_1},\ Vy_1\rho/\mu\ ,\ Ks) \qquad 4\text{-}10$$

where

μ = fluid viscosity

L = the length of a cycle

γ = unit weight of fluid

g = acceleration of gravity

$\frac{V}{\sqrt{gy_1}}$ = a Froude number

$\frac{Vy_1\rho}{\mu}$ = a Reynolds number

Ks = the shape factor of roughness element.

Equation 4-10 may be rearranged as

$$\frac{V}{V_*} = \phi_3\ (y_1/K,\ L/K,\ N_F,\ N_R,\ Ks) \qquad 4\text{-}11$$

Equating 4-11 and 4-8 yield

$$\frac{Vmax}{V*} + \frac{1}{K_2} \ln y/L = \phi_3(y_1/K,\ L/K,\ N_F,\ N_R,\ Ks)$$

or

$$A + \frac{2.3}{K_2} \log_{10} y/L = \phi_3(y_1/K,\ L/K,\ N_F,\ N_R,\ Ks) \qquad 4\text{-}12$$

A is constant equal to Vmax/V*. So A and K_2 are also a function of y_1/k, L/K, N_F, N_R, Ks. Since the parameters are so complex, theoretical analysis seems difficult.

Qualitative study will be made of the various parameters affecting the velocity distribution in tranquil, tumbling and rapid flow regimes.

V. PRESENTATION OF DATA

In this chapter the scope of this thesis will be outlined and briefly discussed. Since the velocity distribution is studied in three flow regimes, it seems advisable to orient the reader about these regimes.

Regime Classification

According to the flow classification proposed by Peterson, Mohanty and Al-Khafaji (11) the flow regimes are a function of channel slope, discharge, and roughness elements. Figure 5-1 is a typical classification curve. From these figures, it obviously indicated that for a given value of roughness parameter, tranquil regime occurred only at a slope of very small value, up to certain value of slope, rapid flow occurred at high discharge, tumbling flow occurred at low discharge. The water surface patterns also differ as shown in Figure 5-2.

Measurement of Data

Systematic measurements of velocity traverses were made at the control depth, middle of the cycle, along the channel bed, along the top of roughness elements and the downstream surface of the roughness. The velocity distribution of the upstream surface of roughness elements, because of the length of the pitot tube, could not be measured very close to the roughness elements, at least two and one-half inches apart.

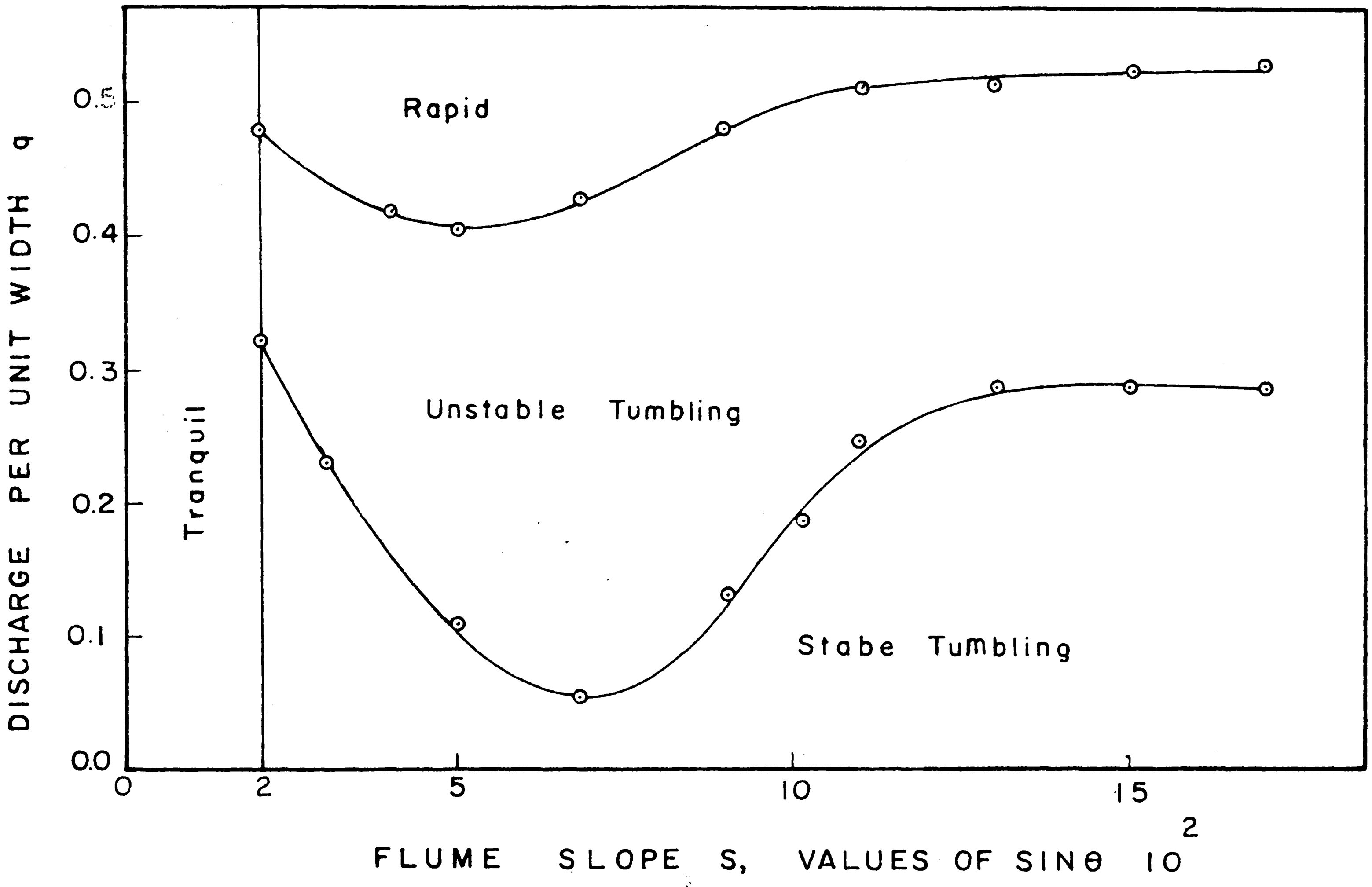

FIG. 5 - I FLOW REGIME DIAGRAM FOR L/ K = 5, K = 2" X 2"

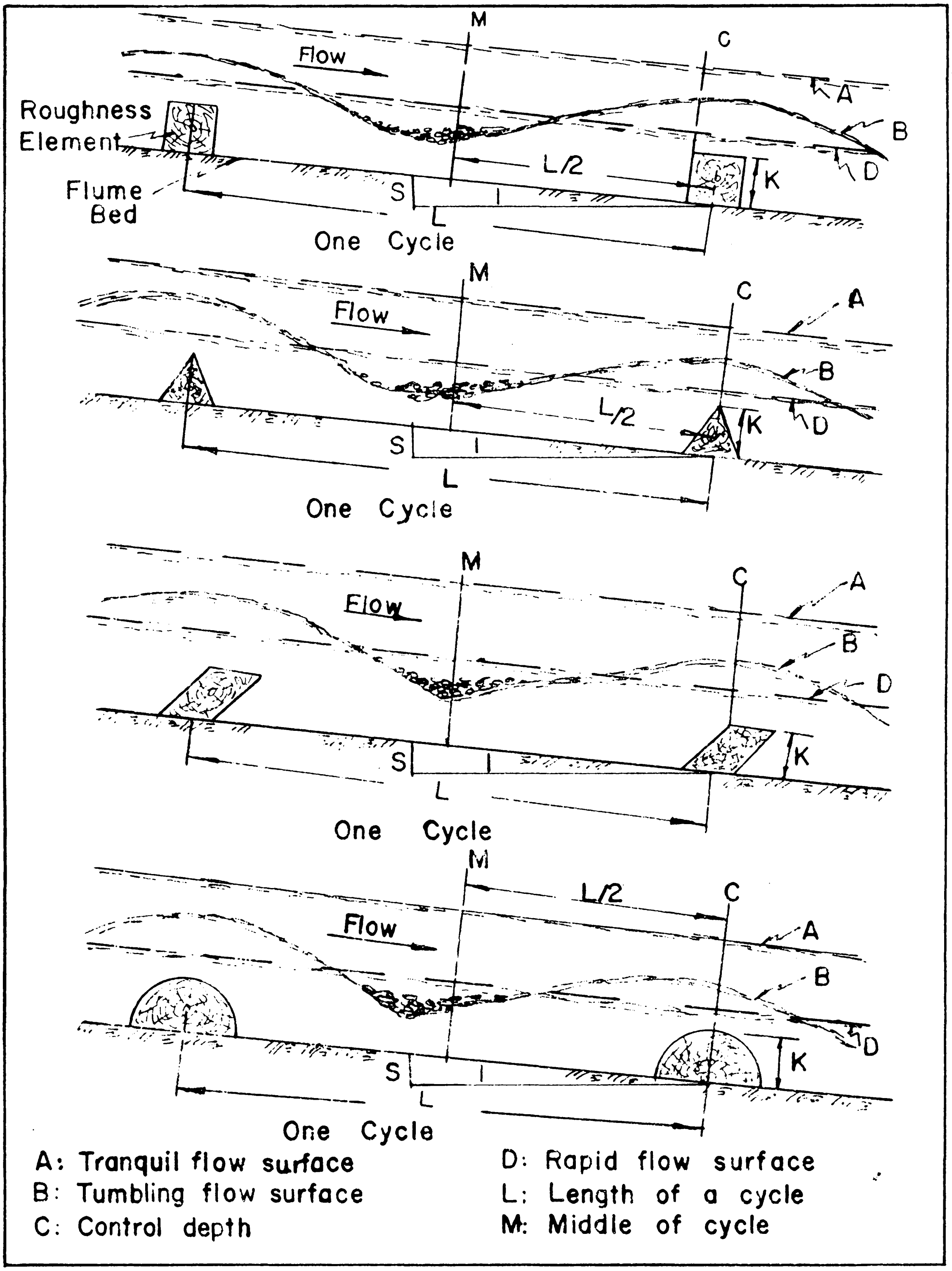

Fig. 5-2 Definition Sketches

Point velocity measurements were made over a section in the middle and near the downstream end of the flume, normal to the flow. The velocity traverses are shown in the tables in the Appendix. Since the flow near the downstream end is fully developed and also the wall effect cannot affect the flow in the middle of the flume, at least the affection is lowest in the whole cross-section.

Definition of Special Terms

Control Depth: The depth at the upstream crest of the roughness elements as shown in Fig. 5-2.

Length of a Cycle: The distance between two neighbor roughness elements from center to center, as shown in Fig. 5-2.

Inflection Point: The point of the velocity distribution curve below which the velocity is constant or nearly so, above which the velocity changed rapidly with the change of depth.

Flume: Rectangular open channel 30 feet long and two feet wide.

VI. VELOCITY DISTRIBUTION IN TRANQUIL AND RAPID FLOW REGIME

In this chapter an attempt will be made to describe velocity distribution around and between roughness elements in tranquil and rapid flow regime in steep rough channel.

Velocity Distribution at Control Depth - Velocity distribution was made directly over the upstream edge of the roughness elements in the central region for all regimes.

The velocity distribution in tranquil regime was found to be logarithmic regardless of the configuration of roughness geometry except the semi-circular roughness elements as shown in Figures 6-1, 6-2, 6-3. Plotting the velocity on semi-logarithmic paper, testing for logarithmic distribution, it was found that the velocity varies linearly against the depth. For semi-circular roughness, the velocity is constant distributed within a certain distance from roughness elements, then changes slightly at the region near water surface. But it may be taken as a constant throughout the section, since the change is very small.

For rapid flow regime, as shown in Figures 6-2, 6-3, 6-4, the velocity was found to be logarithmic for small size of roughness and small spacing, $L/K = 2.5$, for larger spacing; however, this distribution tends to deviate slightly from logarithmic.

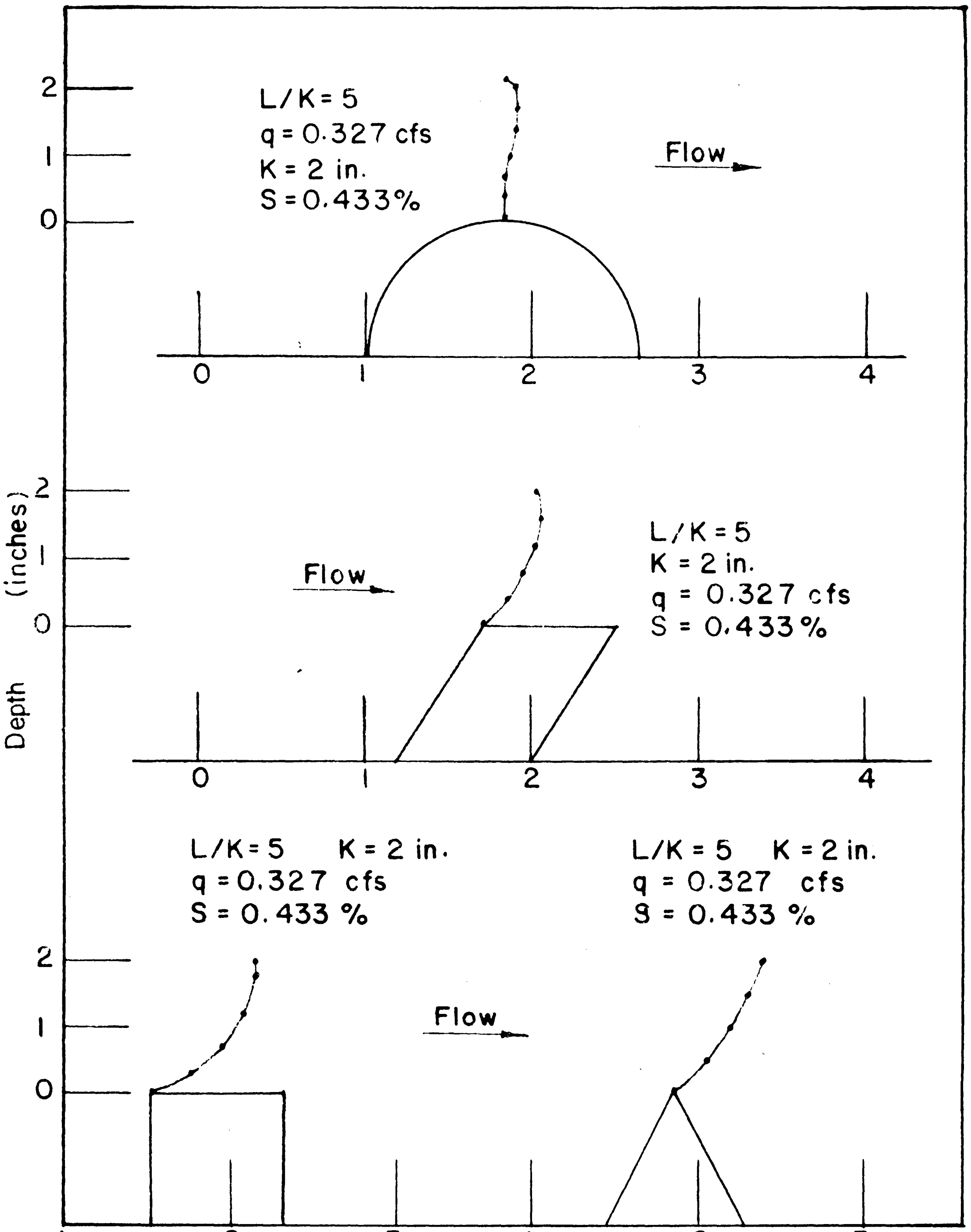

Fig. 6-1 Velocity Distribution Effected By Roughness Shape In Tranquil Flow At Control Depth

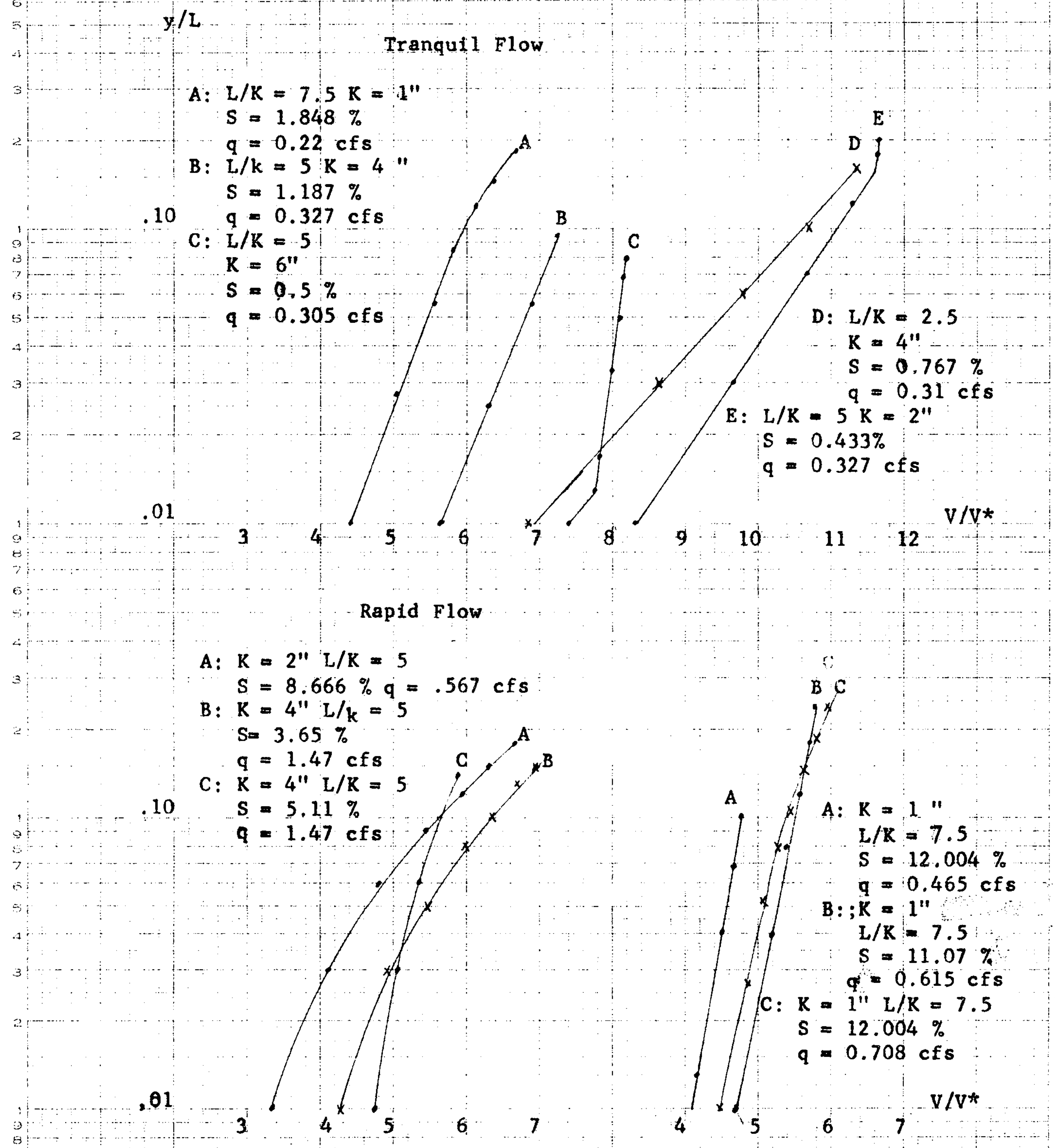

Fig. 6-2 Dimensionless Velocity Distribution For Square Baes At Control Depth In Tranquil And Rapid Flow Regime

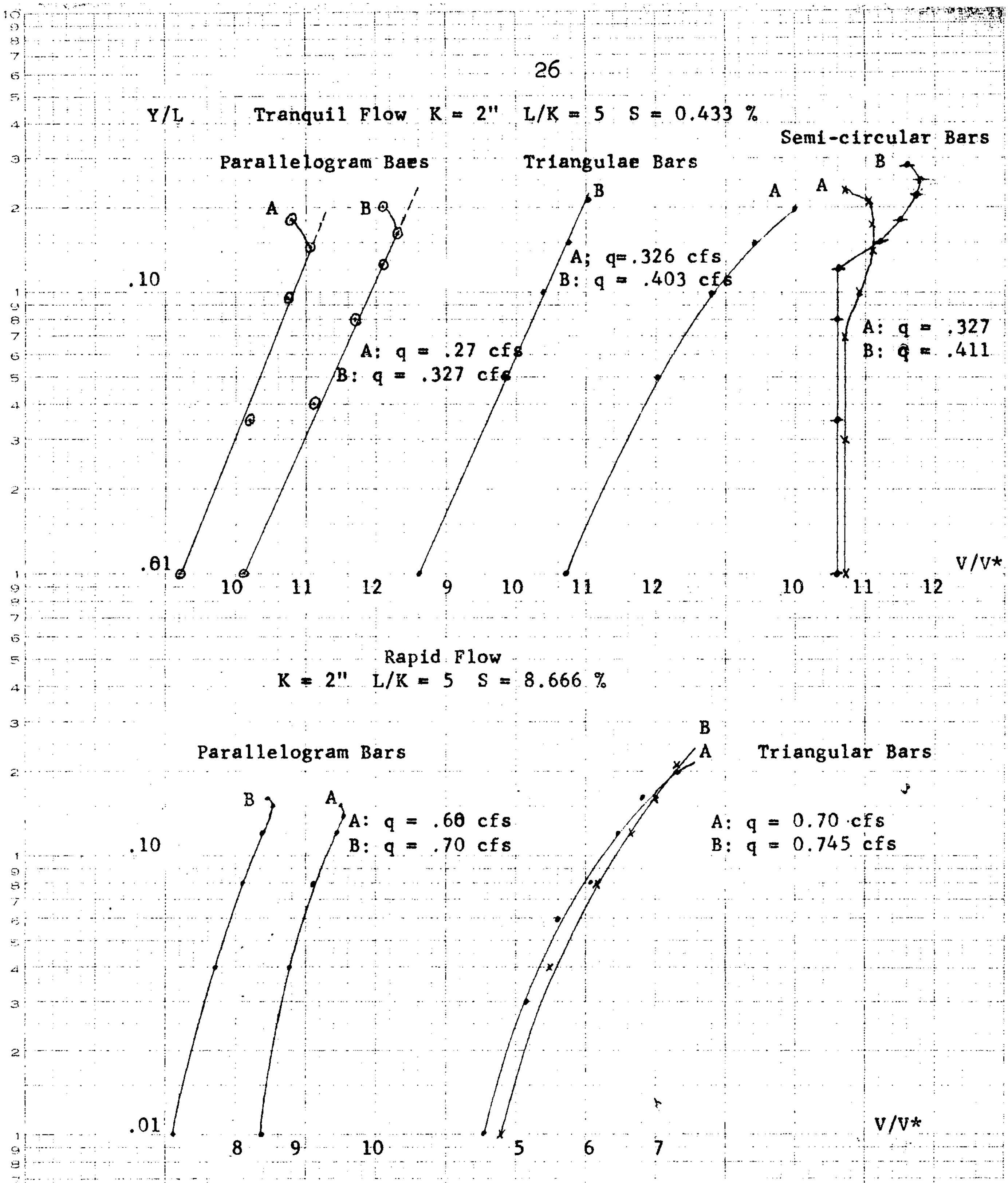

Fig. 6-3 Dimensionless Velocity Distribution In Tranquil and Rapid Regime For Different Shape of Roughness Elements At Control Depth

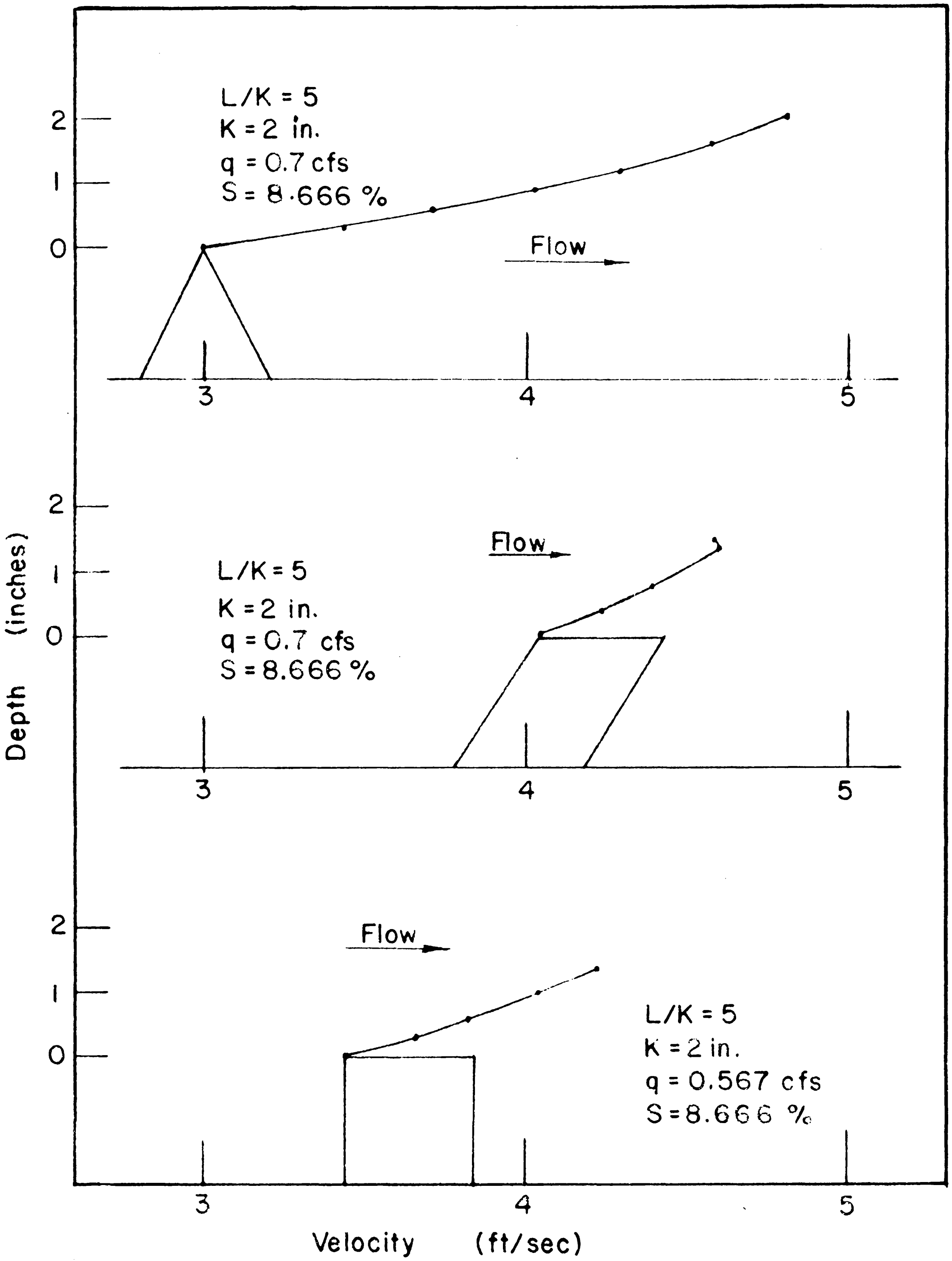

Fig. 6-4 Velocity Distribution Effected By Roughness Shape In Rapid Flow At Control Depth

Velocity Distribution Around Roughness - Velocity distribution around roughness surface was found to be a function of flow regime and the size and shape of roughness elements. Within one regime and given roughness elements, it is a function of discharge and slope. For square roughness elements, the maximum velocity around roughness surface occurred at the downstream crest of the roughness and was constant at downstream surface both for tranquil and rapid flow regime as shown in Figure 6-5. For triangular cross-section roughness as shown in Figure 6-6 the maximum velocity occurred at control depth; this is true also for semi-circular roughness, and the velocity is nearly constant at downstream surface both for tranquil and rapid regime. For semi-circular roughness elements, the velocity at downstream is increased from zero or nearly so at bottom to the maximum at the control depth as shown in Figure 6-7. As for parallelogram roughness the maximum velocity occurred at downstream crest for tranquil flow, upstream crest for rapid flow. The velocity at downstream surface is formed as an upward curve as shown in Figure 6-8. Fluctuation in velocity is due to the occurrence of separation and eddying.

Velocity Along Flume Bed - Velocity along the bed between roughness elements and about one-eighth of an inch above flume bed was measured for different regimes. The velocity along flume bed in tranquil and rapid flow regime was found

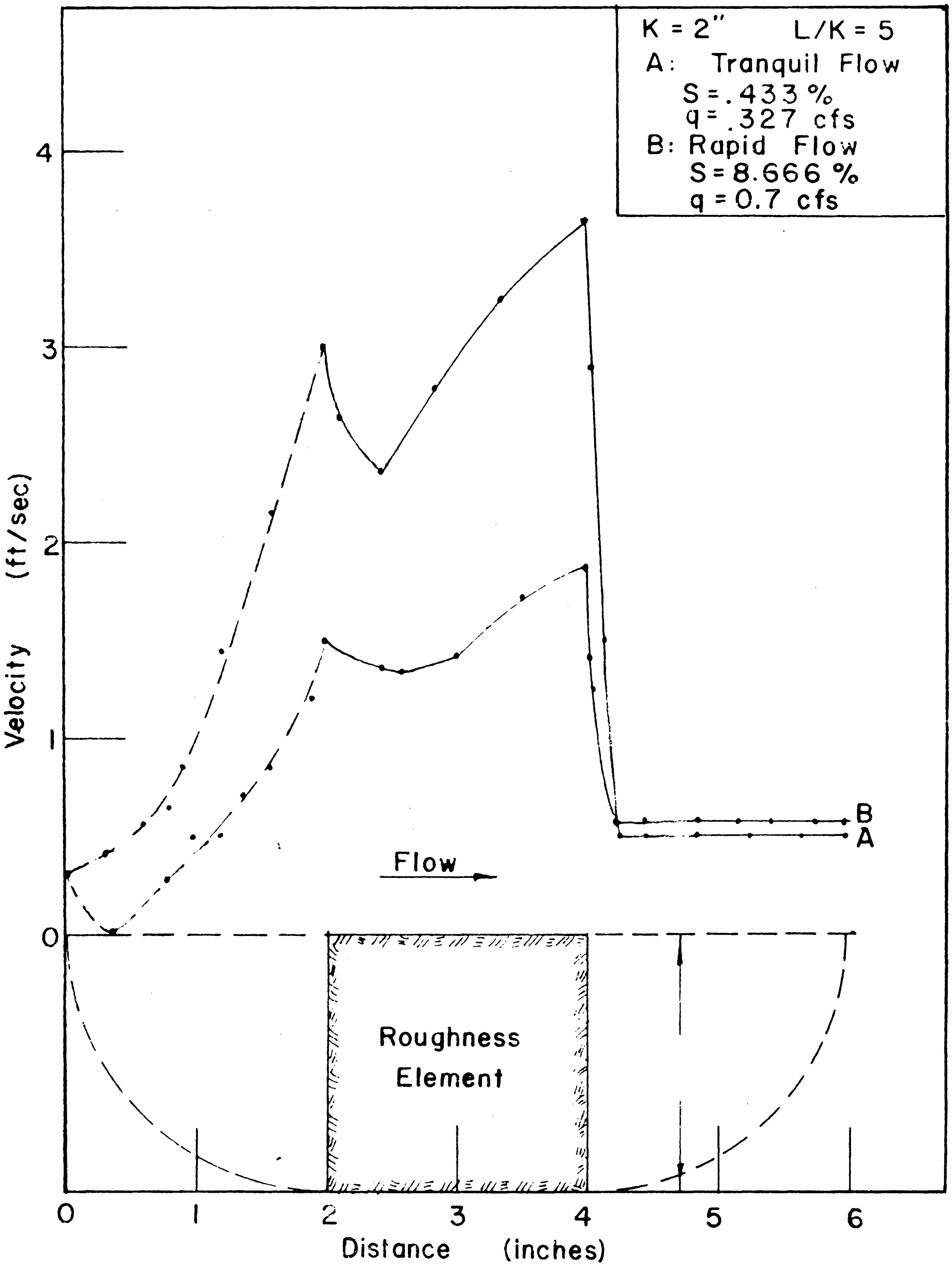

Fig. 6 - 5 The Velocity Distribution Around Square Bars

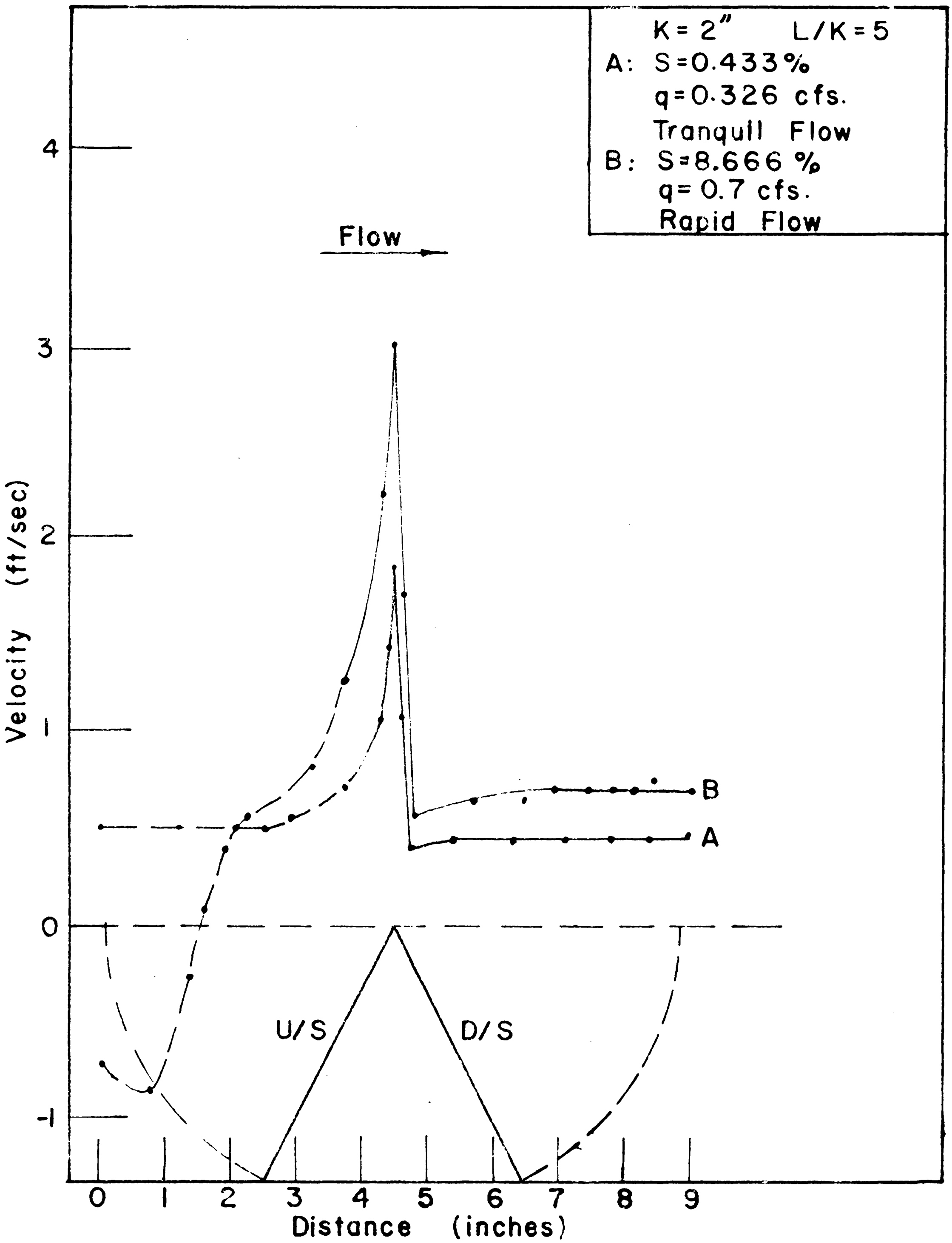

Fig. 6 - 6 The Velocity Distribution Around Triangular Roughness Elements

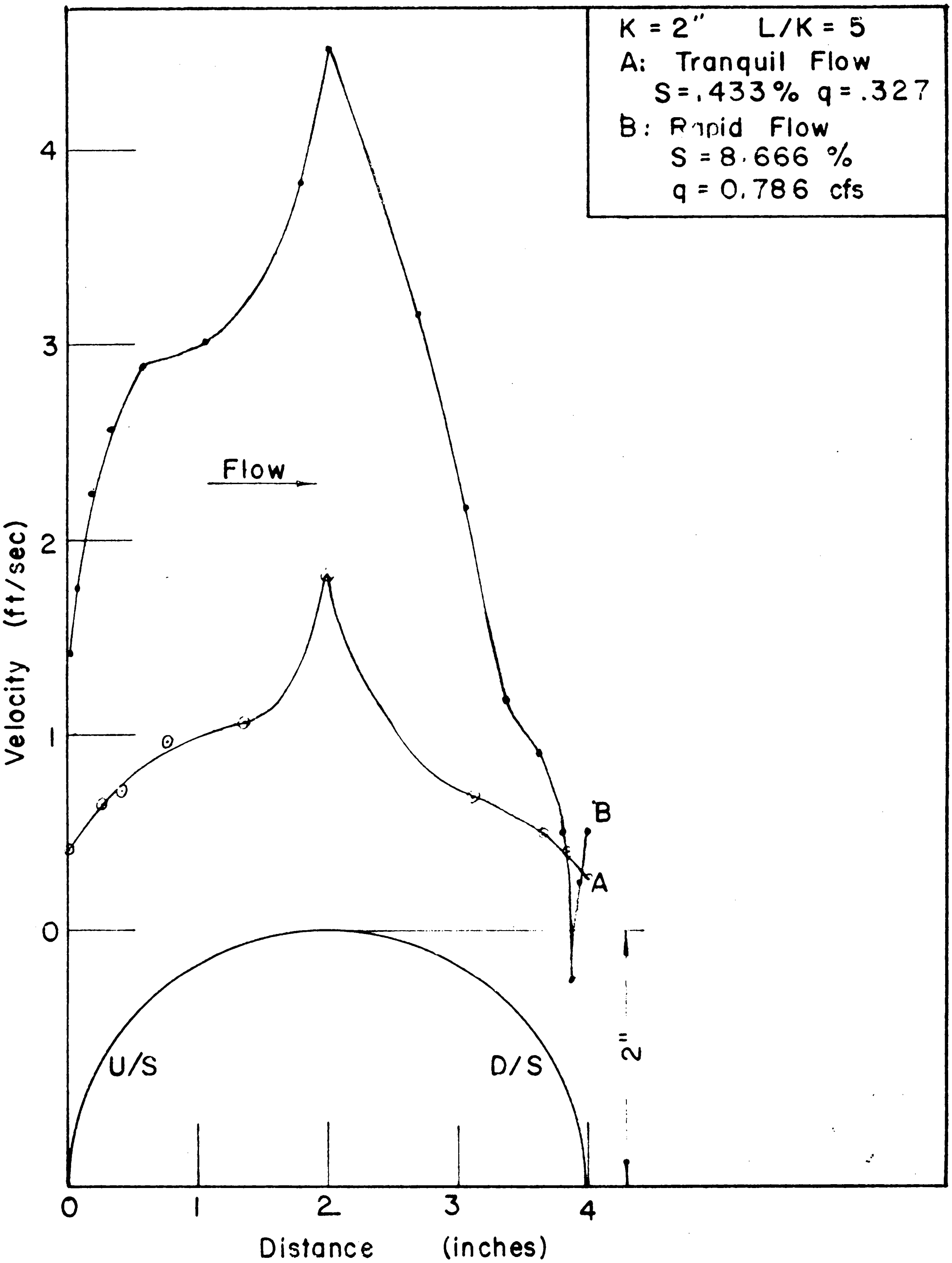

Fig. 6-7 The Velocity Distribution Around Semi-circular Roughness Elements In Tranq. And Rap. Flow

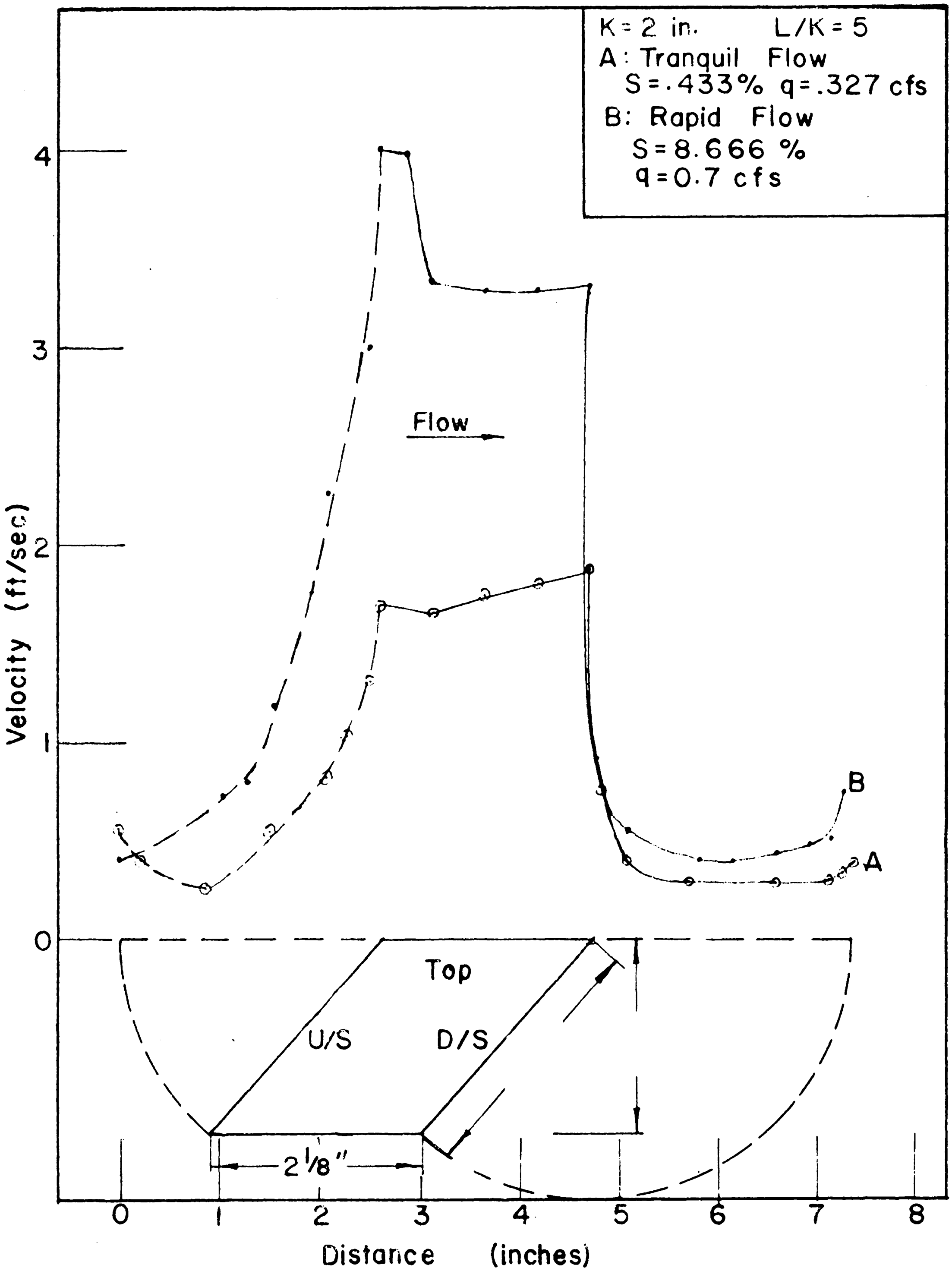

Fig. 6 - 8 Velocity Distribution Around The Parallelogram Bars In Tranquil And Rapid Flow Regimes

to vary very slightly. The variation was due to the confused pattern of eddies.

<u>Velocity Distribution at the Middle of Cycle</u>. Velocity distribution at the middle of a cycle was made to show the order of magnitude of velocities below and above the top of roughness elements.

The velocity distribution at the middle of cycle in rapid and tranquil regime may be said to have the same characteristics. Figure 6-9 shows a typical curve. From this diagram it is seen that velocity distribution in the tranquil flow is logarithmically distributed above the inflection point. Below the inflection point the velocity is constant. This figure also shows that in case of rapid flow the velocity distribution above inflection point deviates slightly from the logarithmic distribution. Below the inflection point the velocity is nearly constant.

<u>Inflection Point</u>. As to the inflection point, it was found to be a function of flow regime, shape of roughness, length of cycle, slope of bed, and also a function of location of the velocity traverse in the cycle. The effect of discharge on the inflection point is very small. It was found to be always higher near the downstream surface of roughness elements and to decrease rapidly within one and a half inches and then to a constant. Figure 6-10 shows the inflection

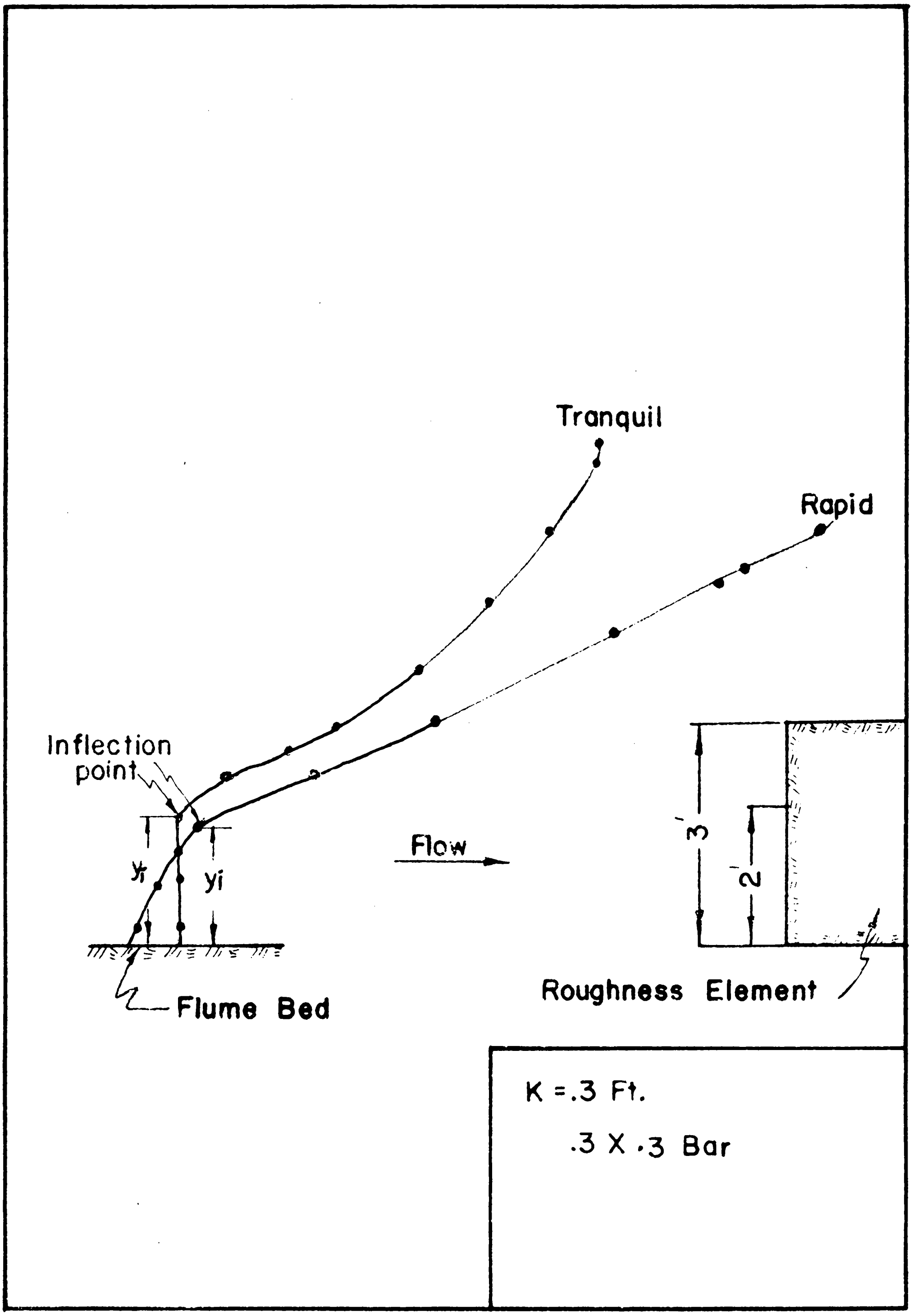

Fig. 6 - 9 Velocity Distribution In Tranquil And Rapid Flow In The Middle Of A Cycle

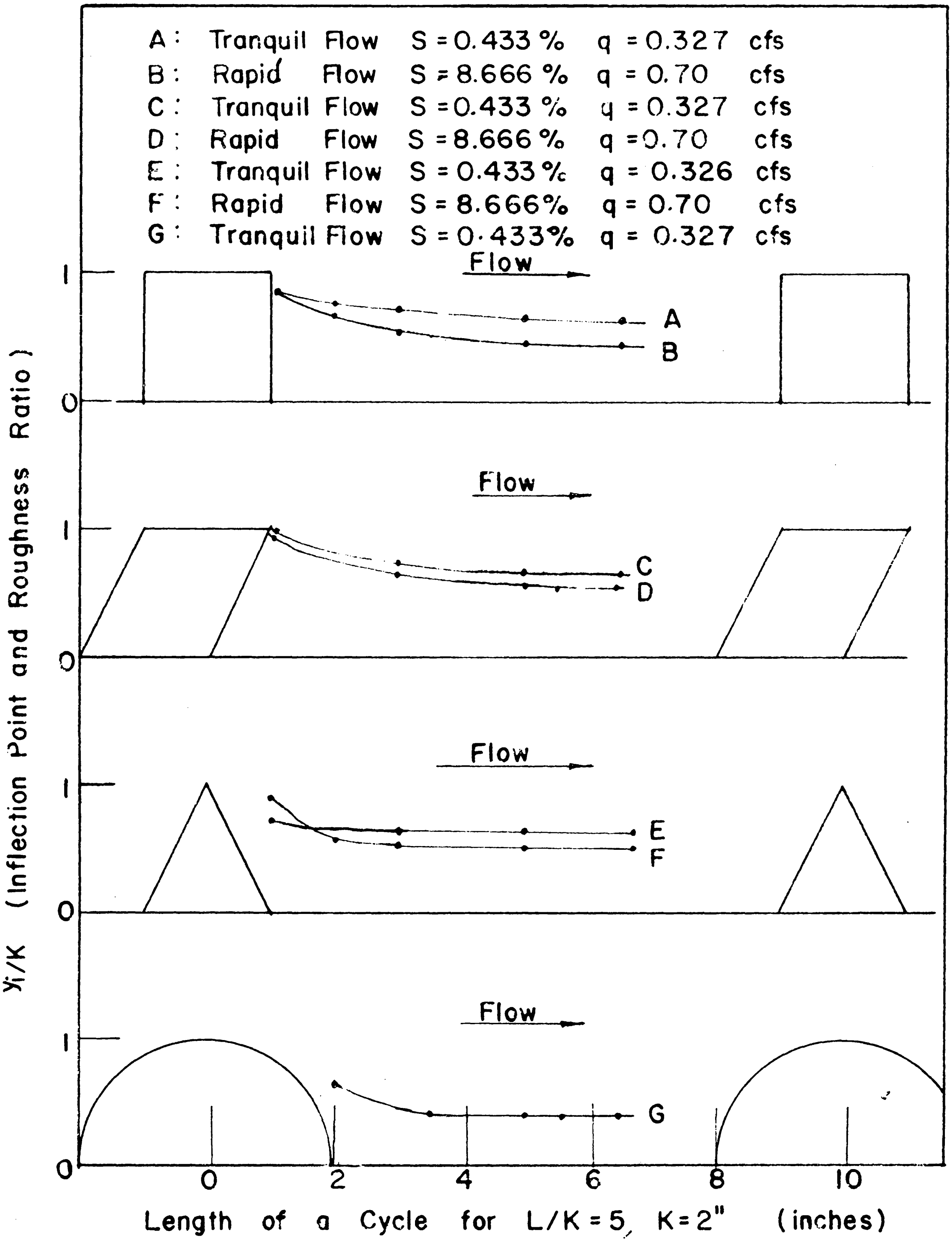

Fig. 6-10 Inflection Points Between Two Roughness Elements

points curve between roughness elements for all shapes of roughness in rapid and tranquil regime. From this diagram, it is shown that the height of inflection points, y_i, of rapid flow always less than the height of inflection points of tranquil flow.

Since the range of slope in tranquil flow regime is only a few percent, the influence may be neglected. By statistical analysis, the height of inflection points in tranquil flow regime for L/K = 5, for square, triangular, parallelogram roughness elements, is 0.65 K. It is very near 2/3 K. As to semi-circular bar the ratio of the height of inflection point to the height of roughness, y_i/K, is about 0.42. In rapid flow this value for L/K = 5 ranged from 0.35 to 0.55.

Applicability of the Logarithmic Law - From the velocity distribution curves it can be concluded that in tranquil flow the velocity is logarithmically distributed. In rapid flow, although the velocity deviates slightly from logarithmic distribution, the logarithmic law may still be applicable.

It is interesting to note that the constant A and k_2 in the logarithmic law, Equation 4-8, are not equal to 8.5 and 0.40, respectively. They did not assume any regularity values but seem to be functions of L/K, y_i/K, N_F, N_R, Ks.

VII. VELOCITY DISTRIBUTION AND VELOCITY COEFFICIENTS IN TUMBLING FLOW REGIME

In this chapter the velocity distribution around and between roughness elements in tumbling flow regime will be described. An attempt will be made also to describe velocity coefficients in tumbling flow regime.

Velocity Distribution Around Roughness Elements Surface: - Owing to the separation, eddy and vortex, there is no regularity of velocity distribution around roughness elements in the tumbling flow regime. The only thing worth mentioning is that the maximum velocity around roughness element occurred at the control depth for triangular and semi-circular bars and at the downstream crest for square and parallelogram roughness as shown in Figures 7-1, 7-2, 7-3, and 7-4.

Velocity Along Flume Bed: - The velocity along the flume bed varied with distance in the cycle as shown in Figure 7-5. This is because of the hydraulic jump which occurred.

Velocity in the Middle of Cycle: - The velocity distribution at the middle of a cycle in tumbling regime depends upon the position of the hydraulic jump. The position of the jump is related to the discharge, the height of the roughness elements, the length of cycle, and the slope of the channel. It is difficult to give any regular form of the velocity distribution at the middle of a cycle in the tumbling regime.

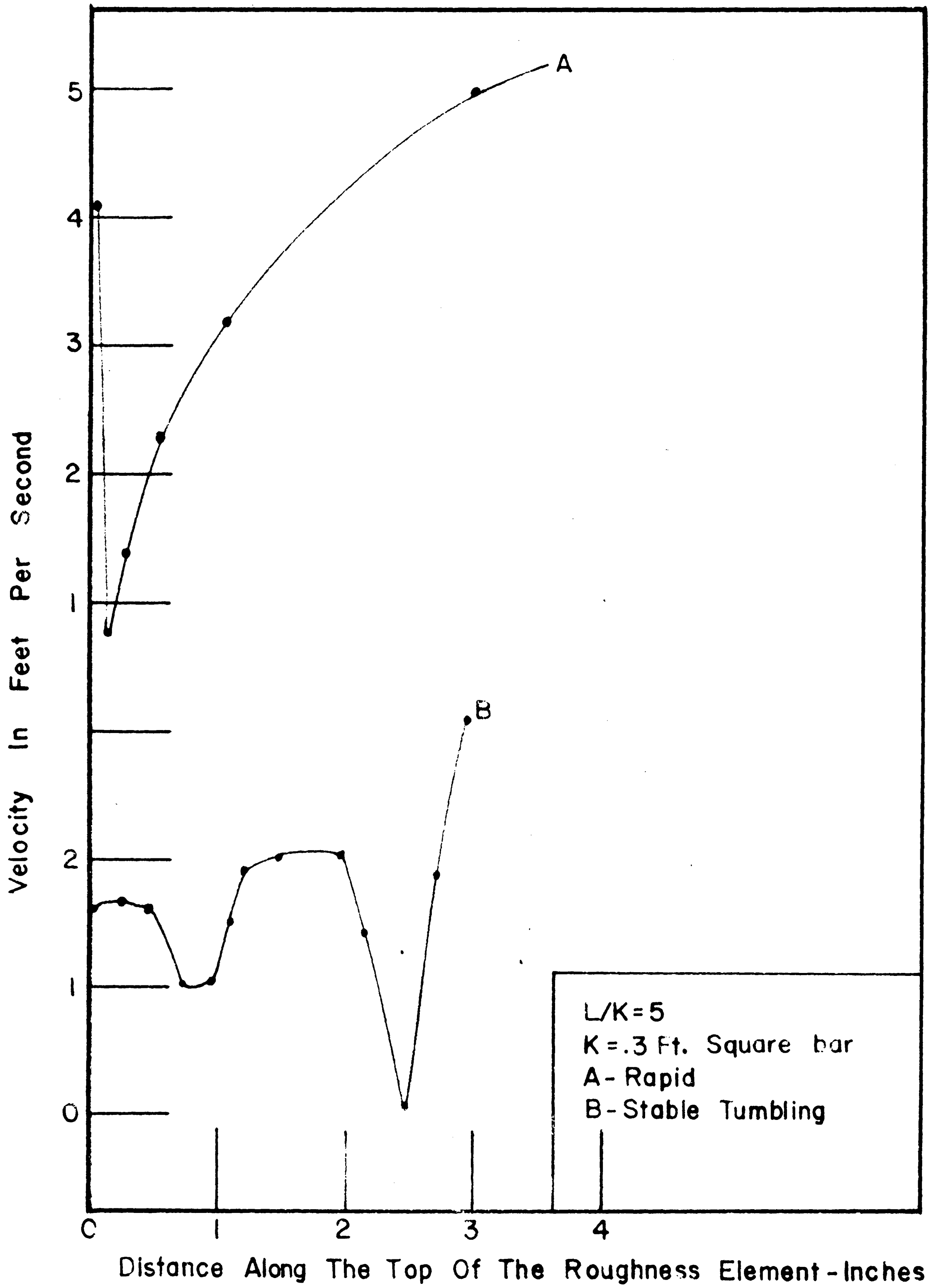

Fig. 7-1 Velocity Along The Top Of The Roughness Element In Rapid And Stable Tumbling

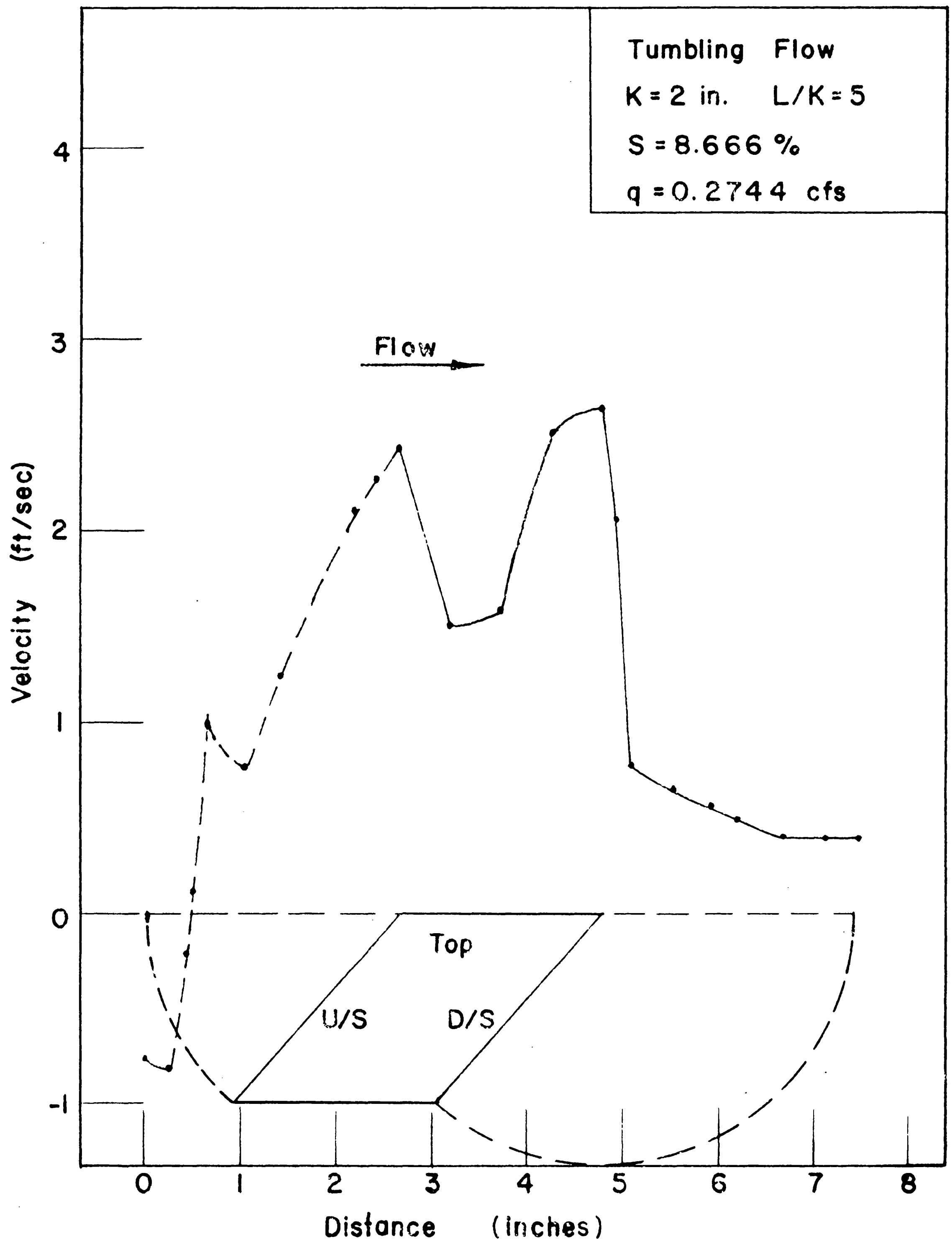

Fig. 7 - 2 Velocity Distribution Around The Parallelogram Roughness Elements in Tumbling Regime

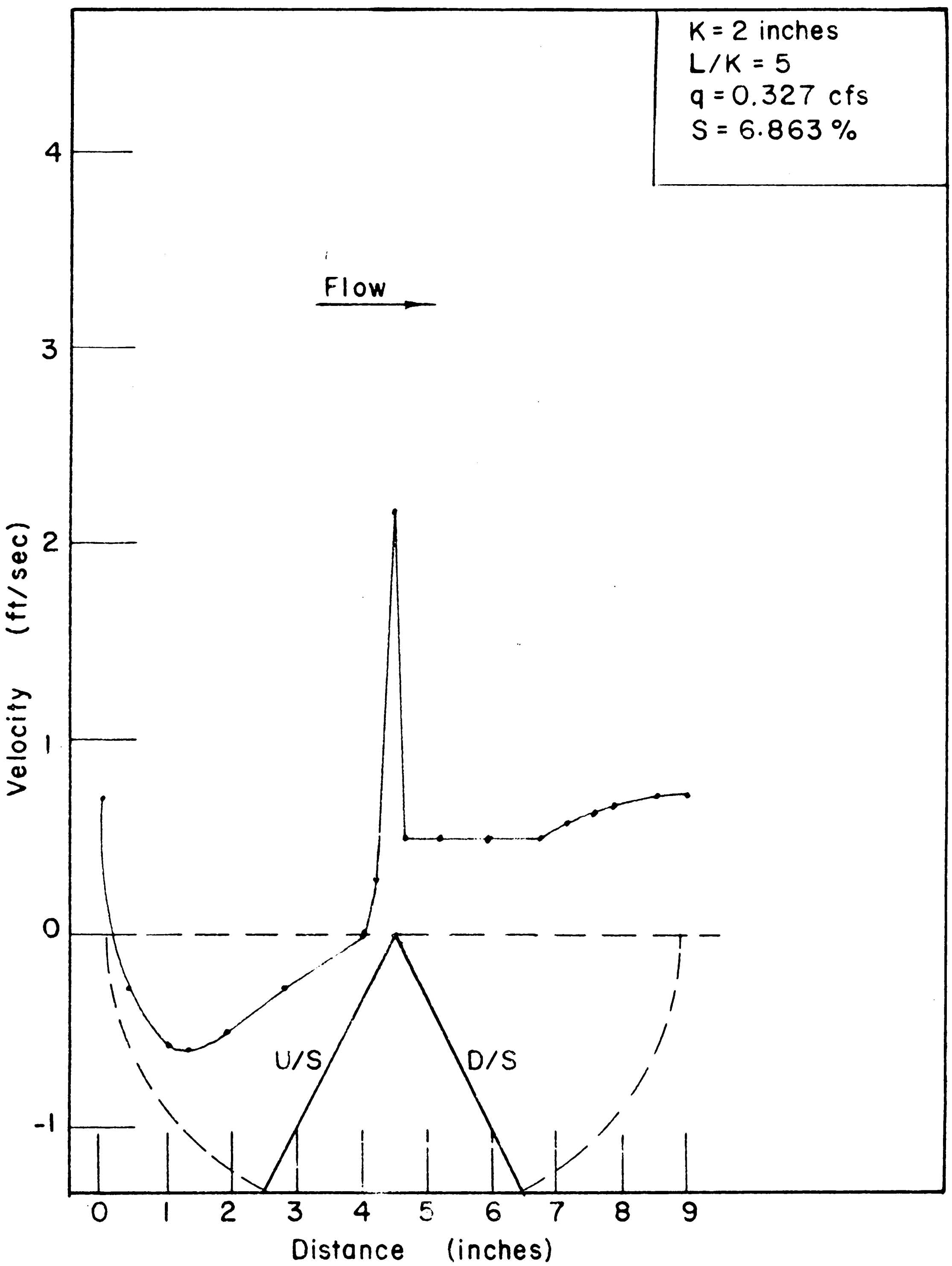

Fig. 7 - 3 The Velocity Distribution Around Triangular Bars In Tumbling Flow Regime

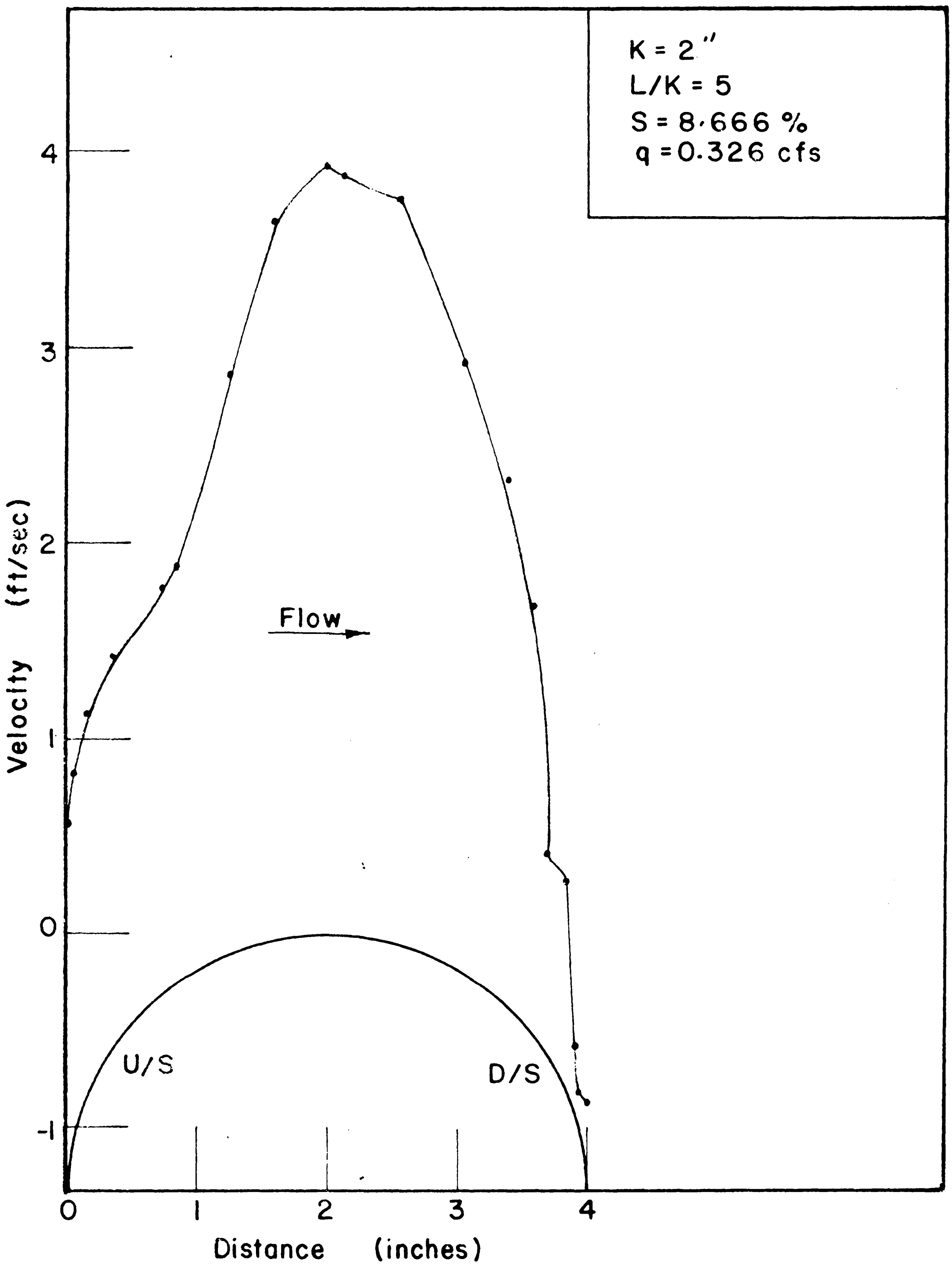

Fig. 7- 4 The Velocity Distribution Around Semi-circular Bars In Tumbling Flow Regime

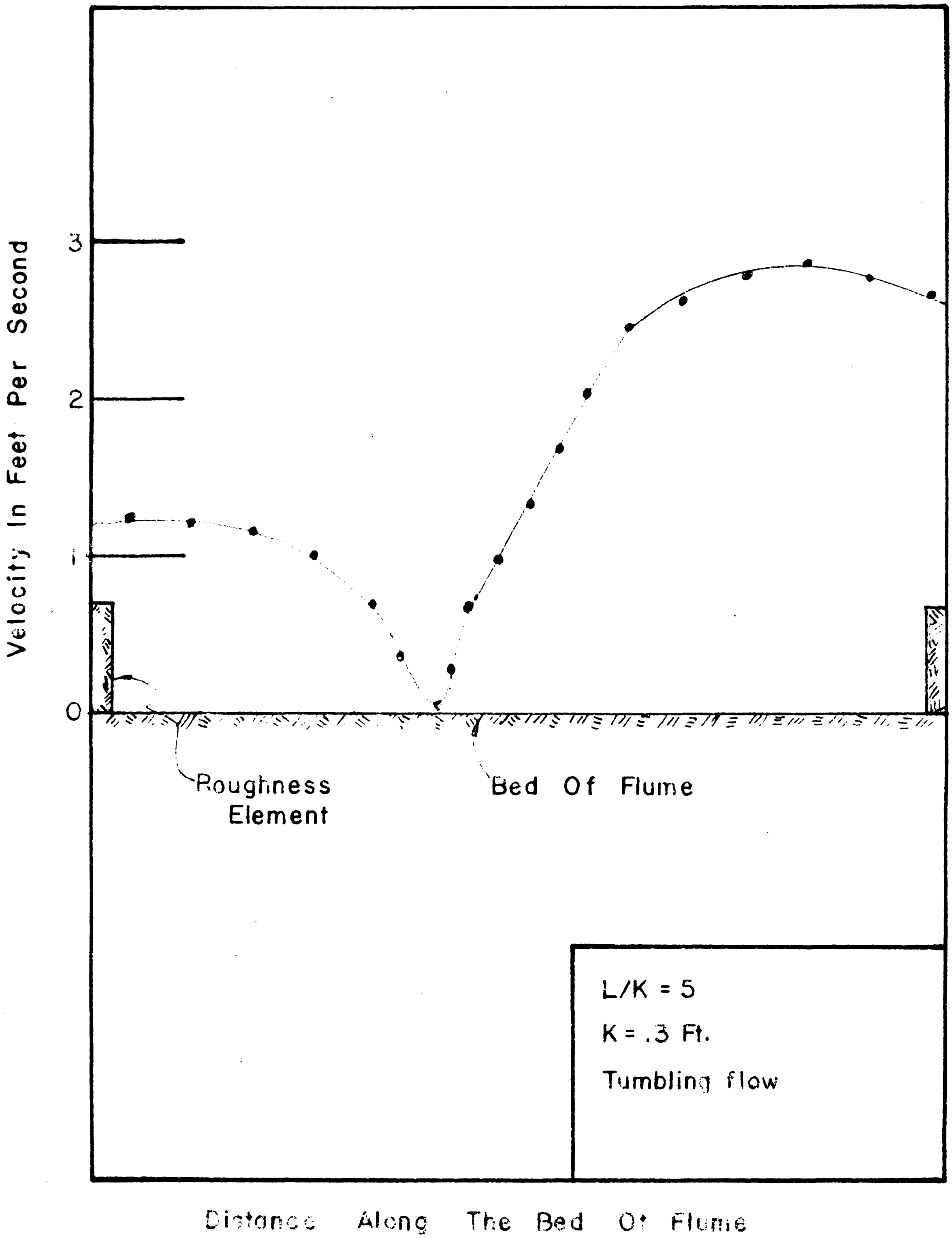

Fig. 7 - 5 Velocity Along The Bed Between Two Consecutive Routhness Elements

<u>Velocity Distribution at Control Depth</u>: - The only regularity of velocity in tumbling flow is the velocity at control depth. Figure 7-6 shows typical curve for different shapes of roughness.

1. Square roughness. - The velocity distribution for square bars in tumbling flow varies from logarithmic to parabolic. For partially developed tumbling flow the velocity approaches logarithmic distribution. For fully developed tumbling flow the velocity was found to be parabolic regardless of the configuration of roughness elements. It was observed that the velocity just above the top of the roughness was low, but within a fraction of about 0.17 y_1 to 0.26 y_1 above the roughness it increases rapidly to a maximum value (refer to Table 7-1). Then above this depth the velocity begins to decrease. An equation which shows the statistical average of the velocity with depth is:

$$V = \left(\frac{1}{k + y}\right)^{5/4} \qquad 7\text{-}1$$

where V is the velocity at a point a distance y above roughness element. K is the height of roughness.

It should be mentioned that the dimension of this equation is not dimensionally homogeneous, and the equation is valid only for points which are above the point of maximum velocity.

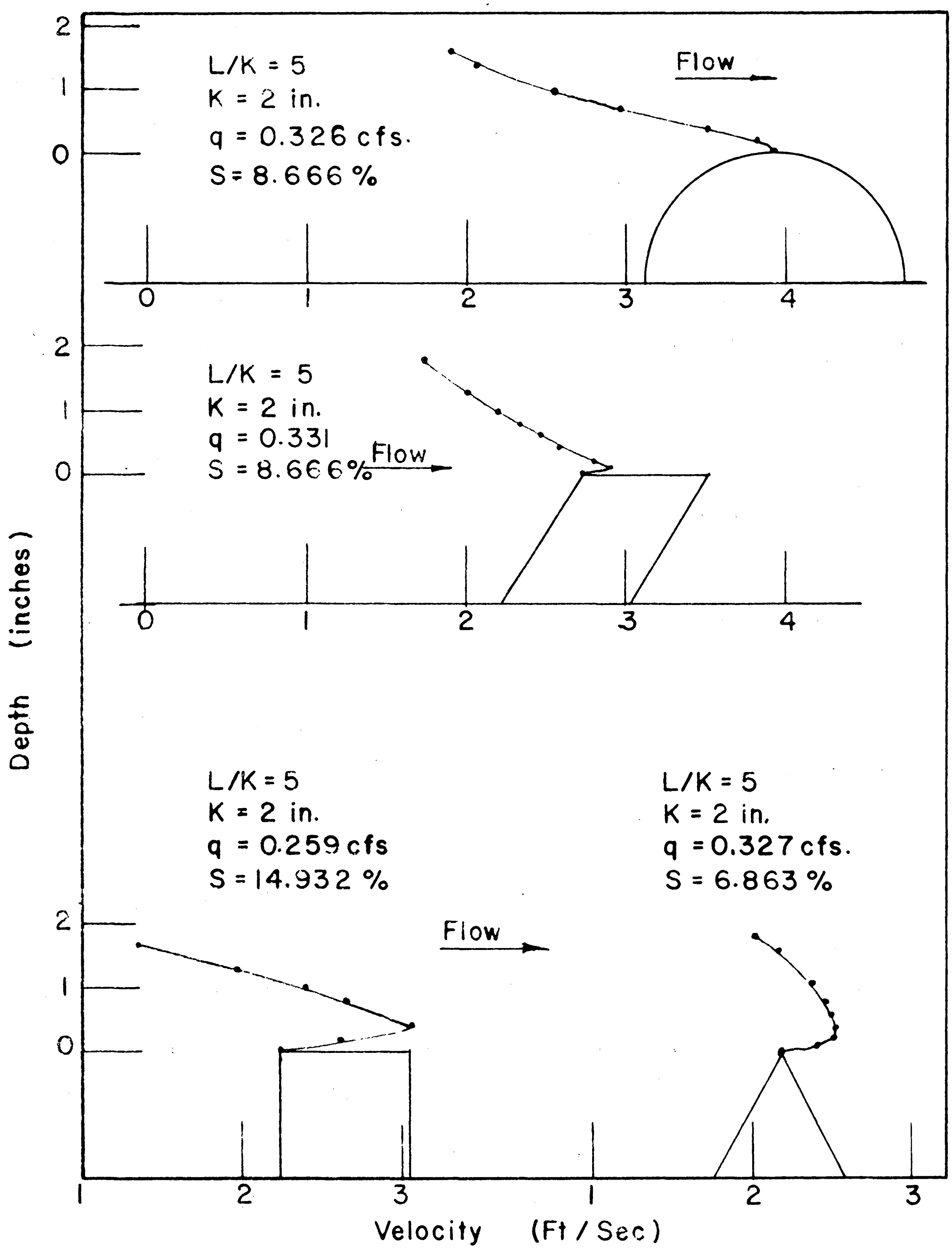

Fig. 7 - 6 Velocity Distribution Effected by Roughness Shapes in Tumbling Regime at Control Depth

Table 7-1. The Point of Maximum Velocity in Tumbling Flow at Control Depth

K in.	L/K	S %	cfs	y_1 ft.	y ft.	y/y_1	Roughness Shape
1	7.5	12.004	.119	.095	.021	.220	Square
1	7.5	12.004	.242	.154	.033	.214	"
2	5.0	14.932	.208	.165	.033	.200	"
2	5.0	14.932	.233	.176	.033	.188	"
2	5.0	14.932	.259	.182	.038	.206	"
4	5.0	10.600	.265	.170	.030	.177	"
4	5.0	13.500	.265	.150	.029	.193	"
4	7.5	7.890	.600	.250	.055	.220	"
4	10.0	2.350	.785	.310	.065	.210	"
6	5.0	10.734	.302	.212	.037	.170	"
6	5.0	13.160	.301	.208	.036	.173	"
2	5.0	6.863	.175	.138	.021	.152	Triangular
2	5.0	6.863	.218	.159	.024	.151	"
2	5.0	6.863	.271	.184	.034	.185	"
2	5.0	6.863	.327	.209	.035	.168	"
2	5.0	8.666	.154	.113	.010		Parallelogram
2	5.0	8.666	.228	.145	.010		"
2	5.0	8.666	.274	.166	.010		"
2	5.0	8.666	.331	.183	.010		"

2. Parallelogram Roughness Elements. - The velocity at control depth for parallelogram roughness, just above the roughness, is low, but it increases rapidly to maximum velocity within a fraction of one-tenth of an inch and then begins to decrease. Figure 7-7 shows the curve.

3. Triangular Roughness Elements. - For triangular bars, the velocity distribution tends to deviate slightly from parabolic. The maximum velocity occurred lower than for square bars. Table 7-1 shows the ratios of y/y_1.

4. Semi-circular Roughness Elements.- For semi-circular bars, the maximum velocity occurred just above the roughness. For a constant slope and same roughness size and constant length of cycle the velocity is proportional to discharge. The decreasing velocity curves are in the same form, as shown in Figure 7-8.

Velocity Coefficients in Tumbling Flow: - For non-uniform distribution of velocity of water flowing in open channels, it is customary to use the velocity head based on the mean velocity and a coefficient. This coefficient is the ratio of either the mean of the squares of the local velocities to the square of the mean which is momentum coefficient or Boussinesq coefficient (12) β, or the mean of the cubes of the local velocities to the cube of the mean velocity which is called energy coefficient or Coriolis Coefficient (13) α.

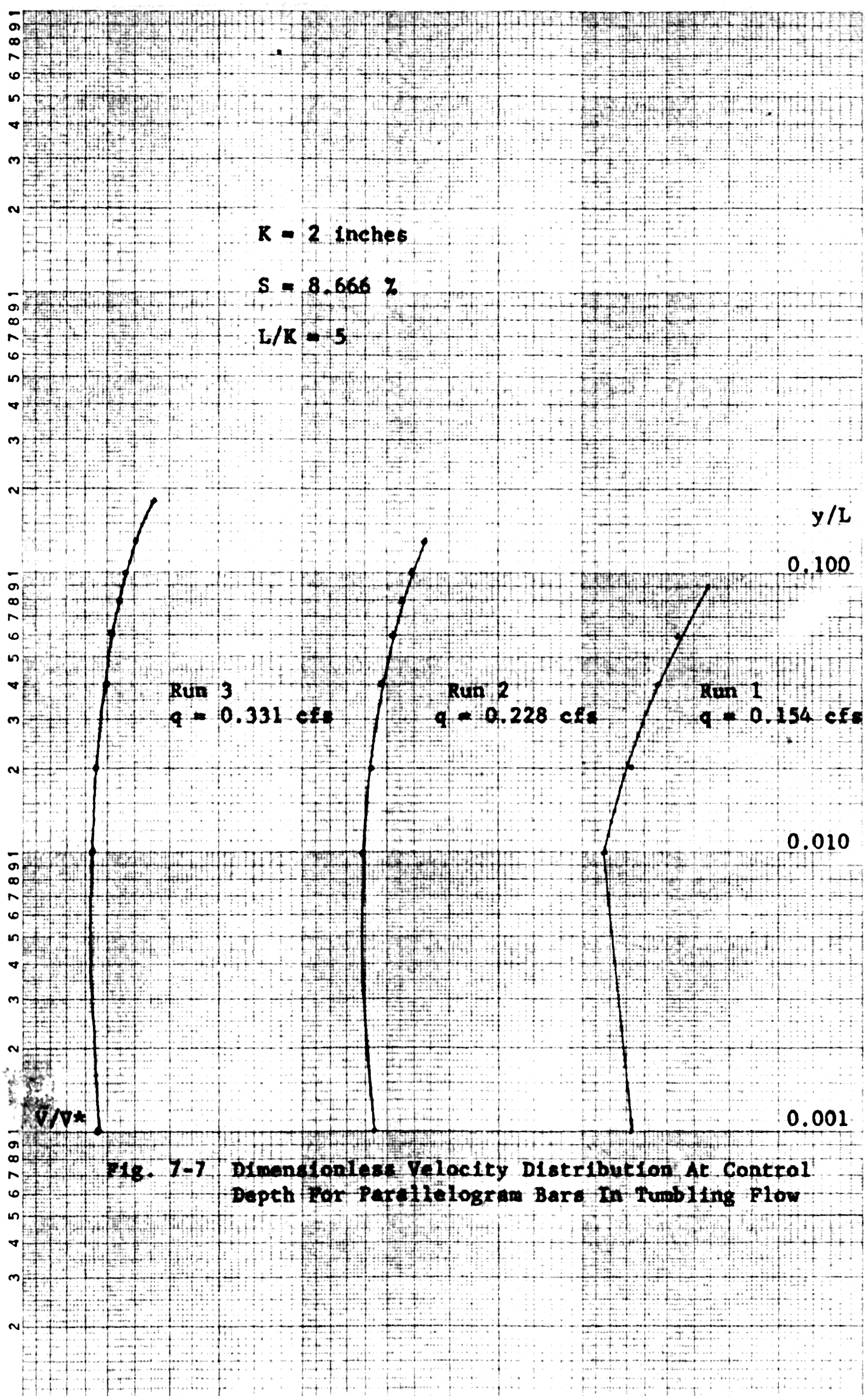

Fig. 7-7 Dimensionless Velocity Distribution At Control Depth For Parallelogram Bars In Tumbling Flow

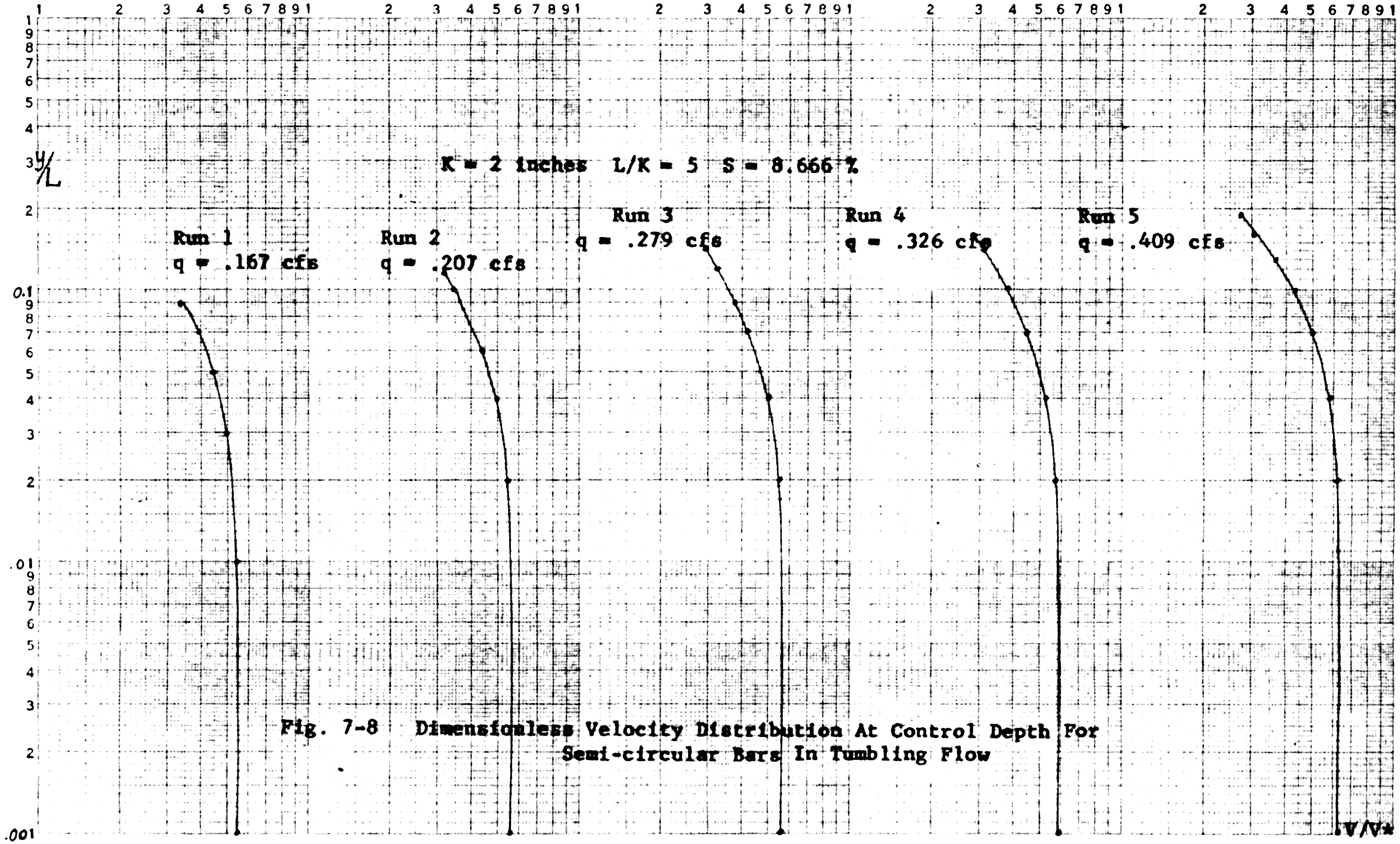

Fig. 7-8 Dimensionless Velocity Distribution At Control Depth For Semi-circular Bars In Tumbling Flow

The velocity coefficients, α and β, for a length of cycle equal to 5 in tumbling flow was given in Table 7-2. It shows that for square and parallelogram roughness α varied from 1.5 to 2.4, β varied from 1.3 to 1.8; for triangular bars, α varied from 2.7 to 3.3, β varied from 1.9 to 2.2; for semi-circular roughness, α varied from 2.1 to 2.5, β varied from 1.65 to 1.85. The coefficient is higher for triangular roughness and lower for parallelogram bars.

Table 7-2. Velocity Coefficient in Tumbling Flow at Control Depth

cfs	y_1 ft.	K in.	L/K	S %	Vm ft/sec	V ft/sec			Roughness Shape
.302	.216	6	5	9.420	1.398	1.801	2.137	1.659	Square
.302	.212	6	5	10.734	1.425	1.745	1.858	1.500	"
.302	.208	6	5	13.160	1.452	1.735	1.706	1.428	"
.265	.170	4	5	10.600	1.559	1.801	1.541	1.325	"
.265	.150	4	5	13.500	1.766	2.033	1.525	1.334	"
.208	.158	2	5	14.932	1.316	1.730	2.268	1.726	"
.233	.172	2	5	14.932	1.355	1.773	2.316	1.711	"
.259	.182	2	5	14.932	1.423	1.891	2.347	1.766	"
.154	.113	2	5	8.666	1.363	1.569	1.525	1.325	Parallelo-gram
.228	.145	2	5	8.666	1.575	1.747	1.561	1.346	"
.274	.166	2	5	8.666	1.653	1.928	1.585	1.300	"
.331	.183	2	5	8.666	1.807	2.161	1.706	1.428	"
.175	.138	2	5	6.863	1.268	1.806	2.889	2.029	Triangular
.218	.159	2	5	6.863	1.372	2.023	3.202	2.172	"
.271	.184	2	5	6.863	1.473	2.091	2.862	2.016	"
.327	.209	2	5	6.863	1.566	2.185	2.719	1.948	"
.167	.102	2	5	8.666	1.639	2.181	2.357	1.771	Semi-cir-cular
.207	.115	2	5	8.666	1.800	2.348	2.219	1.701	"
.279	.140	2	5	8.666	1.994	2.577	2.159	1.671	"
.326	.158	2	5	8.666	2.063	2.679	2.190	1.687	"
.409	.186	2	5	8.666	2.198	2.966	2.457	1.826	"

VIII. CONCLUSION

After a careful study and analysis of the experimental data of velocity distribution, using various sizes and different shapes of artificial roughness elements in rectangular open channel, the following conclusions may be drawn:

1. For tranquil and rapid flow regime, the logarithmic law may be applied with modification in the constant for all shapes of roughness except at the control depth of semi-circular one.

2. The velocity at control depth of semi-circular roughness may be taken as a constant velocity throughout the section.

3. For tumbling flow regime, the velocity varied every inch between roughness elements. At control depth, it is nearly parabolic distributed for triangular and rectangular roughness. As to parallelogram and semi-circular roughness elements the velocity is a decreasing velocity.

4. The effective depth between roughness elements which is equal to the total depth, measured from flume bed to water surface, minus the height of inflection point, may be used.

5. The height of inflection point is a function of the height of roughness, the shape of roughness, the length of a cycle, the slope of flume bed and the flow regime.

6. For tranquil flow, when L/K ranged within 5 to 10 for rectangular, triangular and parallelogram roughness elements, the height of inflection point may be used as 2/3 times the height of roughness elements above the flume bed. For semi-circular bars it may be used as 2/5 times the roughness element height.

7. For rapid flow, the height of inflection point is less than that for tranquil flow, ranging from 0.35 to 0.55 times the height of roughness for rectangular, triangular and parallelogram roughness elements.

8. The energy and momentum coefficients for tumbling flow are higher for triangular bars and lower for parallelogram roughness elements. It ranged from 1.5 to 3.3 for energy coefficient and from 1.3 to 2.2 for momentum coefficient.

IX. GLOSSARY

The letter symbols in this thesis are defined where they first appear and are assembled for convenience of reference in the following:

A	constant, Vmax/V*
C	integrating constant
C_1	arbitrary constant
d	depth of flow, measured from flume bed, ft.
g	acceleration of gravity, γ/ρ, ft./sec.^{2}
k	universal constant for Karman's equation, .40
k_1, k_2	arbitrary constant
K	height of roughness elements, in.
Ks	shape factor of roughness elements
l	mixing length
L	length of a cycle, from roughness center to center
ln	logarithm symbol base of e
log	logarithm symbol base of 10
N_F	Froude number, $V/\sqrt{gy_1}$
N_R	Reynolds number, $Vy_1\rho/\mu$
q	discharge per unit width, c.f.s.
S	slope of flume bed
V	velocity of flow, ft./sec.
Vm	mean velocity of flow, Q/A, ft./sec.
Vmax	maximum velocity of flow, ft./sec.
V*	shear velocity, $\sqrt{\tau_0/\rho}$, ft./sec.

y — depth measured from flume bed or from the top of roughness elements, ft.

y_1 — control depth, measured from the upstream crest of roughness element to water surface, ft.

y_i — the height of inflection points, measured from flume bed to the inflection point, ft.

ρ — fluid mass density, lb.sec.^{2}/ft.^{4}

μ — fluid dynamic viscosity, lb-sec./ft.^{2}

γ — unit weight of fluid, lb./ft.^{3}

τ — tractive force, lb-sec./ft.^{2}

τ_o — wall shear stress, lb-sec./ft.^{2}

α — energy coefficient, V^3/Vm^3

β — momentum coefficient, V^2/Vm^2

D/S — downstream surface

U/S — upstream surface

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XI. BIBLIOGRAPHY

1. Ganguillet, E. and Kutter, W. R., 1889. "A general formula for uniform flow of waters in rivers and other channels." New York, John Wiley and Sons, p. 240.
2. Prandtl, L., 1926. "Uber die ausgels, ldete turbulenz." 2nd International Congress for Applied Mechanics, Zurich.
3. Von Karman, T., 1930. "Mechanische ah leinchkeit and turbulenz." Proc. 3rd International Congress for Applied Mechanics. Stockholm, pp. 85-93.
4. Nikuradse, J., 1933. "Gesetzmässigkeiten der turbutenten Strömung in glatten Rohren" Ver. Dent. Ing., Forschungsheft 356 .
5. Schlichting, H., "Experimentelle Untersuchungen zum Rauhigkeits problem." Ing.-Archiv. 7, 1936.
6. Keulegan, G. H., 1938. "Law of turbulent flow in open channels." U.S. National Bureau of Standards Journal of Research, Vol. 21, pp. 707-741.
7. Taylar, E. H., 1939. "Velocity Distribution in Open Channels." American Geophysical Union Trans. pp. 641-643.
8. Bakhmeteft, B. A., "The mechanics of turbulent flow." Princeton Univ. Press, 1936.
9. Vanoni, V. A., Assoc. M., A.S.C.E., "Velocity Distribution in Open Channels." Civil Engineering, Vol. 11, 1941, pp. 356-357.

10. Tracy, H. J. and Lester, C. M., 1961. "Resistance Coefficients and Velocity Distribution, Smooth Rectangular Channel." U.S. Geological Survey Water-Supply Paper 1592-A.

11. Al-Khafaji, A. N., "The Dynamics of Two-Dimensional Flow in Steep, Rough, Open Channels." Ph.D. Thesis, Utah State University, Logan, Utah, pp. 132, 1961.

12. Boussinesq, J., "Essai sur la théórie des eaux courantes (On the Theory of Flowing Waters). Mémoires présentés par divers savants a l'Académie des Science, Paris, 1877.

13. Coriolis, G., "Sur l'éstablissement de la formule qui donne la figure des remous, et sur la correction qu'on doit y introduire pour tenir compte des différences de vitesse dans les divers points d'une méme section d'un courant." (On the backwater-curve equation and the corrections to be introduced to account for the difference of the velocities at different points on the same cross-section.) Mémoire, No. 268, Annales des ponts et chaussees, Vol. 11, Ser. 1, pp. 314-335, 1836.

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APPENDIX

TABLE I

Velocity Distribution in Open Channel with Artificial Roughness Bar of Square Cross-Section at Control Depth

A TRANQUIL FLOW

Run	V Pt. Vel. Ft/sec.	y Depth Above Roughness In.	q Disch. per ft. width c.f.s.	y_1 Control Depth Ft.	S Bed Slope in percent	K Roughness Height In.	L Length of a Cycle	V_* Shear Vel. Ft/sec.	Y/L	V/V_*	F° Temp
1	2	3	4	5	6	7	8	9	10	11	12
1	.76	0	.066	.074	1.848	1	7.5K	.198	0	3.839	70°
	.80	.14							.019	4.041	
	.82	.24							.032	4.142	
	.83	.40							.053	4.192	
	.84	.56							.075	4.243	
	.845	.60							.080	4.268	
2	.71	0	.144	.115	1.848	1	7.5K	.262	0	2.71	70°
	.95	.10							.013	3.626	
	1.18	.31							.041	4.504	
	1.36	.61							.081	5.191	
	1.55	1.0							.133	5.916	
3	1.36	0	.220	.160	1.848	1	7.5K	.308	0	4.415	70°
	1.56	.20							.027	5.064	
	1.70	.42							.056	5.518	
	1.79	.64							.085	5.810	
	1.90	.91							.121	6.167	
	1.98	1.09							.145	6.427	
	2.06	1.38							.184	6.687	
1	1.12	0	.1543	.137	.433	2	5K	.138	0	8.116	70.6°

TABLE I (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
	1.34	.25	.1543	.137	.433	2	5K	.138	.025	9.710	70.6°
	1.45	.50							.050	10.507	
	1.51	.80							.080	10.941	
	1.56	1.2							.12	11.304	
2	1.23	0	.2364	.186	.433	2	5K	.161	0	7.640	71°
	1.48	.25							.025	9.192	
	1.65	.60							.060	10.248	
	1.85	1.6							.16	11.490	
3	1.53	0	.3272	.242	.433	2	5K	.184	0	8.316	71.8°
	1.78	.30							.03	9.674	
	1.96	.70							.07	10.653	
	2.08	1.20							.12	11.305	
	2.15	1.80							.18	11.685	
	2.14	2.0							.20	11.631	
4	1.69	0	.435	.275	.433	2	5K	.196	0	8.622	71.8°
	1.84	.30							.030	9.388	
	2.01	.70							.070	10.255	
	2.14	1.15							.115	10.918	
	2.25	1.60							.16	11.480	
	2.34	2.10							.21	11.939	
	2.42	2.54							.254	12.347	
1	1.4	0	.327	.245	.36	4	5K	.168	0	8.333	78.5°
	1.58	.60							.03	9.404	
	1.68	1.20							.06	9.999	
	1.80	1.80							.09	10.714	

TABLE I (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
	1.86	2.40	.327	.245	.36	4	5K	.168	.12	11.071	78.5°
2	1.59	0	.327	.208	1.187	4	5K	.282	0	5.638	78.5°
	1.79	.50							.025	6.347	
	1.94	1.10							.055	6.879	
	2.04	1.9							.095	7.234	
3	1.61	0	.327	.189	2.082	4	5K	.356	0	4.522	78.5°
	1.83	.4							.02	5.140	
	2.0	.8							.04	5.618	
	2.17	1.4							.07	6.096	
4	1.64	0	.256	.159	2.082	4	5K	.326	0	5.031	79°
	1.81	.4							.02	5.552	
	1.95	.8							.04	5.981	
	2.09	1.3							.65	6.411	
5	1.56	0	.181	.136	2.082	4	5K	.302	0	5.165	79°
	1.69	.4							.02	5.596	
	1.79	.8							.04	5.927	
	1.85	1.1							.055	6.125	
1	1.27	0	.163	.112	.767	4	2.5K	.166	0	7.650	73.5°
	1.59	.2							.02	9.578	
	1.81	.5							.05	10.903	
	1.98	1.0							.10	11.928	
2	1.23	0	.227	.140	.767	4	2.5K	.186	0	6.612	74°
	1.5	.20							.02	8.064	
	1.81	.50							.05	9.731	
	2.03	.80							.08	10.913	
	2.23	1.20							.12	11.988	
3	1.4	0	.310	.173	.767	4	2.5K	.206	0	6.796	74.5°
	1.78	.30							.03	8.640	
	2.02	.60							.06	9.805	

TABLE I (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
	2.21	1.0	.310	.173	.767	4	2.5K	.206	.10	10.727	
	2.34	1.6							.16	11.358	
4	1.36	0	.461	.225	.767	4	2.5K	.235	0	5.787	75°
	1.78	.30							.03	7.574	
	2.11	.60							.06	8.978	
	2.43	1.10							.11	10.340	
	2.61	1.60							.16	11.106	
	2.67	2.10							.21	11.361	
1	1.16	0	.160	.153	.50	6	5K	.157	0	7.389	77°
	1.26	.4							.013	8.025	
	1.33	.8							.027	8.471	
	1.37	1.2							.040	8.726	
	1.39	1.5							.050	8.853	
2	1.30	0	.227	.195	.5	6	5K	1.77	0	7.345	77°
	1.41	.5							.017	7.966	
	1.49	1.0							.033	8.418	
	1.54	1.5							.050	8.701	
	1.59	2.0							.067	8.983	
3	1.47	0	.305	.243	.5	6	5K	.198	0	7.424	77°
	1.54	.5							.017	7.778	
	1.58	1.0							.033	7.980	
	1.60	1.5							.05	8.081	
	1.61	2.0							.067	8.131	
	1.62	2.4							.080	8.182	

TABLE I (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
4	1.23	0	.305	.250	.11	6	5K	.094	0	13.085	77°
	1.36	.6							.02	14.468	
	1.43	1.2							.03	15.212	
	1.46	1.8							.06	15.531	
	1.47	2.4							.08	15.638	
	1.48	3.0							.10	15.744	
5	1.69	0	.305	.20	1.443	6	5K	.304	0	5.559	77°
	1.75	.5							.017	5.757	
	1.80	1.0							.033	.5.921	
	1.85	1.5							.05	6.086	
	1.89	2.0							.067	6.217	
B	RAPID FLOW										
1	3.54	0	.615	.215	8.128	1	7.5K	.765	0	4.627	78.5°
	3.77	.3							.04	4.928	
	3.95	.6							.08	5.163	
	4.10	.90							.12	5.360	
	4.23	1.20							.16	5.595	
	4.35	1.55							.207	5.686	
	4.36	2.0							.267	5.699	
2	4.00	0	.615	2.02	11.07	1	7.5K	.847	0	4.722	78.6°
	4.41	.30							.04	5.206	
	4.54	.60							.08	5.360	
	4.69	..90							.12	5.537	
	4.81	1.35							.180	5.679	
	4.9	1.75							.233	5.785	

TABLE I (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
1	2.8	0	.465	.170	12.004	1	7.5K	.81	0	3.306	79°
	3.5	.10							.013	4.132	
	3.81	.30							.04	4.498	
	3.94	.50							.067	4.652	
	4.01	.78							.104	4.734	
2	3.44	0	.527	.183	12.004	1	7.5K	.839	0	4.100	79°
	3.95	.20							.027	4.708	
	4.18	.40							.053	4.982	
	4.33	.60							.08	5.161	
	4.44	.80							.107	5.292	
	4.52	1.0							.133	5.387	
3	3.84	0	.615	.199	12.004	1	7.5K	.875	0	4.388	79°
	4.47	.30							.04	5.108	
	4.79	.60							.08	5.474	
	5.00	.9							.12	5.714	
	5.11	1.1							.147	5.840	
4	4.18	0	.708	.220	12.004	1	7.5K	.924	0	4.524	79.1°
	4.49	.20							.027	4.860	
	4.73	.40							.053	5.119	
	4.91	.60							.080	5.314	
	5.05	.80							.107	5.466	
	5.22	1.10							.147	5.650	
	5.36	1.40							.187	5.801	
	5.49	1.70							.227	5.942	
1	3.42	0	.567	.185	8.666	2	5K	.717	0	4.770	71°
	3.65	.30							.03	5.091	
	3.82	.60							.06	5.328	
	4.04	1.00							.10	5.635	
	4.22	1.40							.14	5.886	

TABLE I (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
1	2.15	0	1.47	.35	3.65	4	5K	.641	0	3.354	76°
	2.63	.6							.03	4.103	
	3.08	1.20							.06	4.805	
	3.47	1.80							.09	5.414	
	3.80	2.40							.12	5.928	
	4.05	3.00							.15	6.318	
	4.25	3.60							.18	6.630	
2	3.08	0	1.48	.315	5.11	4	5K	.718	0	4.290	76.3°
	3.56	.50							.03	4.958	
	3.96	1.00							.05	5.515	
	4.30	1.50							.08	5.989	
	4.57	2.00							.10	6.365	
	4.80	2.50							.13	6.685	
	5.00	3.00							.15	6.964	
C	TUMBLING FLOW										
1	1.72	0	.119	.095	12.004	1	7.5K	.606	0	2.838	77°
	1.93	.15							.020	3.185	
	1.95	.25							.033	3.218	
	1.89	.40							.053	3.119	
	1.80	.50							.067	2.970	
	1.65	.60							.080	2.723	
	1.25	.70							.093	2.063	
2	1.16	0	.242	.154	12.004	1	7.5K	.77	0	1.506	77°
	2.08	.10							.013	2.701	
	2.38	.20							.027	3.091	
	2.50	.35							.047	3.247	
	2.50	.40							.053	3.247	

TABLE I (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
	2.45	.50	.242	.154	12.004	1	7.5K	.77	.067	3.182	
	2.24	.65							.087	2.909	
	1.92	.75							.100	2.494	
	1.85	.80							.107	2.403	
1	2.04	0	.208	.158	14.932	2	5K	.886	0	2.302	71.7°
	2.70	.20							.020	3.047	
	2.86	.40							.040	3.228	
	2.60	.60							.060	2.934	
	2.31	.80							.080	2.607	
	1.96	1.00							.10	2.212	
	1.48	1.30							.130	1.670	
2	2.12	0	.233	.172	14.932	2	5K	.92	0	2.302	72°
	2.81	.20							.020	3.051	
	2.95	.40							.040	3.203	
	2.70	.60							.060	2.932	
	2.42	.80							.080	2.628	
	2.10	1.00							.100	2.280	
	1.61	1.30							.130	1.748	
	1.22	1.50							.150	1.325	
3	2.22	0	.259	.182	14.932	2	5K	.935	0	2.374	72°
	2.60	.20							.02	2.781	
	3.06	.40							.04	3.273	
	2.87	.60							.06	3.069	
	2.63	.80							.08	2.813	
	2.38	1.00							.10	2.545	
	1.97	1.30							.13	2.107	
	1.36	1.60							.16	1.455	

TABLE I (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
1	1.59	0	.216	.17	10.6	4	5K	.78	0	2.108	70°
	2.07	.15							.008	2.744	
	2.25	.30							.015	2.983	
	2.28	.46							.023	3.023	
	2.11	.70							.035	2.797	
	1.90	1.00							.05	2.519	
	1.61	1.40							.07	2.134	
	1.30	1.70							.085	1.723	
2	1.74	0	.216	.15	13.5	4	5K	.807	0	2.156	70°
	2.05	.15							.008	2.540	
	2.21	.35							.018	2.738	
	2.17	.70							.035	2.689	
	1.97	1.10							.055	2.441	
	1.68	1.60							.080	2.082	
1	1.92	0	.302	.216	9.42	6	5K	.81	0	2.370	75°
	2.24	.15							.005	2.765	
	2.42	.35							.012	2.987	
	2.35	.50							.017	2.901	
	2.18	.80							.027	2.691	
	2.00	1.10							.037	2.469	
	1.81	1.40							.047	2.234	
	1.59	1.70							.057	1.963	
	1.42	2.00							.067	1.753	
	1.24	2.30							.077	1.531	
2	1.83	0	.302	.212	10.734	6	5K	.856	0	2.138	75°
	2.12	.15							.005	2.477	
	2.22	.30							.010	2.593	

TABLE I (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
	2.26	.50	.302	.212	10.734	6	5K	.856	.017	2.640	
	2.19	.70							.023	2.558	
	2.09	.90							.030	2.442	
	1.93	1.20							.040	2.255	
	1.71	1.50							.050	1.998	
	1.37	1.90							.063	1.600	
	1.01	2.30							.077	1.180	
3	1.36	0	.302	.208	13.16	6	5K	.939	0	1.448	75°
	1.97	.15							.005	2.098	
	2.25	.40							.013	2.396	
	2.19	.70							.023	2.332	
	2.07	1.00							.033	2.205	
	1.89	1.30							.043	2.013	
	1.71	1.60							.053	1.821	
	1.33	2.10							.070	1.416	

Velocity Distribution in Open Channel with Artificial Roughness Bar of Parallelogram Cross-Section at Control Depth

A TRANQUIL FLOW

Run	V Point Velocity Ft/sec.	y Depth above Rough- In.	q Disch. per.ft. width c.f.s.	y_1 Control Depth Ft.	S Bed Slope in percent	K Rough-ness Height In.	L Length of a cycle	V_* Shear Velocity Ft/sec.	y/L	V/V_*	F° Temp.
1	2	3	4	5	6	7	8	9	10	11	12
1	1.28	0	.175	.137	.433	2	5K	.138	0	9.275	68.5°
	1.41	.30							.03	10.217	
	1.50	.65							.065	10.869	
	1.57	1.00							.10	11.376	
	1.54	1.40							.14	11.159	

TABLE I (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
2	1.45	0	.270	.178	.433	2	5K	.158	0	9.177	69°
	1.61	.40							.04	10.190	
	1.70	.95							.095	10.759	
	1.74	1.45							.145	11.012	
	1.70	1.80							.180	10.759	
3	1.69	0	.327	.20	.433	2	5K	.167	0	10.120	69°
	1.85	.40							.04	11.078	
	1.96	.80							.08	11.736	
	2.02	1.20							.12	12.096	
	2.05	1.60							.16	12.275	
	2.02	2.00							.20	12.096	
4	1.54	0	.405	.234	.433	2	5K	.180	0	8.556	69°
	1.83	.60							.06	10.722	
	2.06	1.20							.12	11.444	
	2.12	1.60							.16	11.778	
	2.15	2.10							.21	11.944	
B	RAPID FLOW										
1	4.04	0	.6	.184	8.666	2	5K	.482	0	8.382	70.7°
	4.23	.40							.04	8.776	
	4.39	.80							.08	9.108	
	4.55	1.20							.12	9.440	
	4.6	1.40							.14	9.544	
	4.58	1.50							.15	9.502	
2	4.04	0	.70	.204	8.666	2	5K	.569	0	7.100	70.5°
	4.37	.40							.04	7.680	
	4.62	..80							.08	8.120	
	4.79	1.20							.12	8.418	
	4.85	1.50							.15	8.524	
	4.80	1.60							.16	8.436	

TABLE I (Continued)

C TUMBLING FLOW

1	2	3	4	5	6	7	8	9	10	11	12
1	2.11	0	.154	.113	8.666	2	5K	.315	0	6.698	71°
	2.65	.10							.01	8.413	
	2.11	.20							.02	6.698	
	1.72	.40							.04	5.460	
	1.45	.60							.06	4.603	
	1.12	.90							.09	3.556	
2	2.27	0	.228	.145	8.666	2	5K	.404	0	5.618	70.5°
	2.46	.10							.01	6.089	
	2.30	.20							.02	5.693	
	2.12	.40							.04	5.247	
	1.94	.60							.06	4.802	
	1.79	.80							.08	4.430	
	1.65	1.00							.10	4.084	
	1.48	1.30							.13	3.663	
3	2.75	0	.331	.183	8.666	2	5K	.510	0	5.392	70.5°
	2.89	.10							.01	5.667	
	2.79	.20							.02	5.471	
	2.57	.40							.04	5.039	
	2.46	.60							.06	4.824	
	2.33	.80							.08	4.569	
	2.20	1.00							.10	4.314	
	2.02	1.30							.13	3.961	
	1.73	1.80							.18	3.392	

TABLE I (Continued)

Velocity Distribution in Open Channel with Artificial Roughness Bar of Triangular Cross-Section At Control Depth

A TRANQUIL FLOW

Run	V Point Velocity Ft/sec	y Depth above Rough-ness In.	q Disch per.ft. Width c.f.s.	y_1 Control Depth Ft.	S Bed Slope in Percent	K Rough-ness Height In.	L Length of a cycle	V_* Shear Velocity Ft/sec.	y/L	V/V_*	F° Temp.
1	2	3	4	5	6	7	8	9	10	11	12
1	1.42	0	.170	.141	.433	2	5K	.139	0	10.215	70°
	1.58	.30							.03	11.367	
	1.67	.60							.06	12.014	
	1.69	.90							.09	12.158	
	1.70	1.30							.13	12.230	
2	1.56	0	.257	.184	.433	2	5K	.160	0	9.750	70.2°
	1.71	.40							.04	10.688	
	1.83	.80							.08	11.438	
	1.92	1.30							.13	12.000	
	1.98	1.80							.18	12.375	
3	1.85	0	.326	.21	.433	2	5K	.171	0	10.819	70.3°
	2.05	.50							.05	11.988	
	2.19	1.00							.10	12.807	
	2.30	1.50							.15	13.450	
	2.40	2.00							.20	14.035	
4	1.64	0	.403	.263	.433	2	5K	.191	0	8.586	70.3°
	1.87	.50							.05	9.791	
	1.99	1.00							.10	10.419	
	2.06	1.50							.15	10.785	
	2.12	2.10							.21	11.099	

TABLE I (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
B RAPID FLOW											
1	2.99	0	.70	.227	8.666	2	5K	.661	0	4.523	73°
	3.43	.30							.03	5.189	
	3.70	.60							.06	5.597	
	4.02	.90							.09	6.081	
	4.28	1.20							.12	6.475	
	4.57	1.60							.16	6.913	
	4.81	2.00							.20	7.277	
2	3.16	0	.745	.236	8.666	2	5K	.658	0	4.803	73°
	3.58	.40							.04	5.441	
	4.02	.80							.08	6.110	
	4.38	1.20							.12	6.657	
	4.60	1.60							.16	6.991	
	4.78	2.10							.21	7.265	
C TUMBLING FLOW											
1	1.94	0	.175	.138	6.863	2	5K	.305	0	6.459	72°
	2.11	.10							.01	6.918	
	2.17	.20							.02	7.115	
	2.17	.30							.03	7.115	
	2.03	.60							.06	6.656	
	1.84	.90							.09	6.033	
	1.69	1.10							.11	5.541	
2	2.18	0	.218	.159	6.863	2	5K	.351	0	6.211	72°
	2.28	.20							.02	6.496	

TABLE I (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
	2.27	.40	.218	.159	6.863	2	5K	.351	.04	6.467	
	2.18	.60							.06	6.211	
	2.09	.80							.08	5.954	
	2.02	1.00							.10	5.755	
	1.93	1.20							.12	5.499	
	1.85	1.40							.14	5.271	
3	2.16	0	.271	.184	6.863	2	5K	.406	0	5.320	72°
	2.32	.20							.02	5.714	
	2.34	.40							.04	5.764	
	2.30	.60							.06	5.665	
	2.22	.80							.08	5.468	
	2.17	1.00							.10	5.345	
	2.06	1.30							.13	5.074	
	1.98	1.50							.15	4.877	
4	2.18	0	.327	.209	6.863	2	5K	.462	0	4.719	73°
	2.40	.10							.01	5.195	
	2.50	.20							.02	5.411	
	2.52	.40							.04	5.455	
	2.49	.60							.06	5.390	
	2.46	.80							.08	5.325	
	2.38	1.10							.11	5.152	
	2.16	1.60							.16	4.675	
	2.01	1.80							.18	4.351	

TABLE I (Continued)

Velocity Distribution in Open Channel with Artificial Roughness Bar of Semi-Circular Cross-Section At Control Depth

A TRANQUIL FLOW

Run	V Point Velocity Ft/sec.	y Depth Above Roughness Inches	q Disch. per ft Width c.f.s.	y_1 Control Depth Ft.	S Bed Slope in percent	K Roughness Height Inches	L Length of a Cycle	V* Shear Velocity Ft/sec.	y/L	V/V_*	F° Temp.
1	2	3	4	5	6	7	8	9	10	11	12
1	1.45	0	.160	.130	.433	2	5K	.135	0	10.74	69°
	1.45	.30							.03	10.74	
	1.45	.60							.06	10.74	
	1.45	1.00							.10	10.74	
	1.47	1.30							.13	10.888	
2	1.45	0	.214	.159	.433	2	5K	.149	0	9.732	69°
	1.45	.30							.030	9.732	
	1.45	.60							.060	9.732	
	1.45	.95							.095	9.732	
	1.49	1.10							.110	10.00	
	1.58	1.30							.130	10.604	
	1.62	1.50							.150	10.872	
	1.59	1.65							.165	10.671	
3	1.83	0	.327	.21	.433	2	5K	.171	0	10.702	70°
	1.83	.40							.04	10.702	
	1.83	.70							.07	10.702	
	1.87	1.00							.10	10.936	
	1.90	1.40							.14	11.111	
	1.91	1.70							.17	11.169	
	1.90	2.05							.205	11.111	
	1.83	2.15							.215	10.702	

TABLE I (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
4	1.97	0	.411	.245	.433	2	5K	.185	0	10.649	70°
	1.97	.40							.040	10.649	
	1.97	.80							.080	10.649	
	1.97	1.20							.120	10.649	
	2.07	1.50							.150	11.189	
	2.13	1.80							.180	11.514	
	2.17	2.20							.220	11.730	
	2.19	2.50							.250	11.838	
	2.17	2.80							.280	11.730	
B	TUMBLING FLOW										
1	2.94	0	.167	.102	8.666	2	5K	.533	0	5.515	70.5°
	2.91	.10							.010	5.546	
	2.66	.30							.030	4.990	
	2.37	.50							.050	4.446	
	2.10	.70							.070	3.940	
	1.81	.90							.090	3.396	
2	3.18	0	.207	.115	8.666	2	5K	.566	0	5.618	70.5°
	3.09	.20							.020	5.459	
	2.81	.40							.040	4.964	
	2.47	.60							.060	4.364	
	1.96	1.00							.100	3.463	
	1.80	1.15							.115	3.180	
3	3.62	0	.279	.14	8.666	2	5K	.641	0	5.647	70.5°
	3.54	.20							.02	5.522	
	3.20	.40							.04	4.992	
	2.70	.70							.07	4.212	
	2.44	.90							.09	3.806	
	2.07	1.20							.120	3.229	

TABLE I (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
	1.89	1.40	.279	.14	8.666	2	5K	.641	.140	2.948	
4	3.93	0	.326	.158	8.666	2	5K	.664	0	5.919	71°
	3.82	.20							.020	5.753	
	3.49	.40							.040	5.256	
	2.96	.70							.070	4.458	
	2.54	1.00							.100	3.825	
	2.05	1.40							.140	3.087	
	1.90	1.60							.160	2.861	
5	4.52	0	.409	.186	8.666	2	5K	.719	0	6.287	71°
	4.46	.20							.020	6.204	
	4.20	.40							.040	5.842	
	3.62	.70							.070	5.035	
	3.12	1.00							.100	4.340	
	2.64	1.30							.130	3.672	
	2.21	1.60							.160	3.074	
	1.98	1.90							.190	2.754	

TABLE II

Velocity Distribution in Open Channel with Artificial Roughness Bar of Square Cross-Section At Middle of Cycle

A TRANQUIL FLOW

Run	V Point Velocity Ft/sec	y Depth Above Flume Bed In.	q Disch. per.ft. width c.f.s.	yi Height of In- flection Point In.	S Bed Slope in percent	K Rough- ness Height In.	L Length of a cycle	V_* Shear Velocity Ft/sec.	Y/L	V/V_*	y_i/K
1	2	3	4	5	6	7	8	9	10	11	12
1	.55	0	.066		1.848	1	7.5K	.198	0	2.778	
	.55	.28							.037	2.778	
	.55	.58							.077	2.778	
	.71	.79							.105	3.586	
	.81	.98							.131	4.091	
	.82	1.10							.147	4.141	
	.84	1.40							.187	4.242	
	.85	1.58		.587					.211	4.293	.587
2	.90	0	.144		1.848	1	7.5K	.262	0	3.435	
	.91	.30							.040	3.473	
	.92	.58							.077	3.512	
	1.12	.80							.107	4.275	
	1.23	1.00							.133	4.695	
	1.38	1.34							.179	5.267	
	1.49	1.65							.220	5.687	
	1.61	2.00		.586					.267	6.145	.586
3	.62	0	.220		1.848	1	7.5K	.308	0	2.013	
	.62	.34							.045	2.013	
	.62	.58							.077	2.013	
	.86	.83							.111	2.792	

TABLE II (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
	1.12	1.08	.220		1.848	1	7.5K	.308	.144	3.636	
	1.35	1.42							.189	4.382	
	1.54	1.74							.232	4.999	
	1.69	2.08							.277	5.486	
	1.77	2.39		.585					.319	5.745	.585
1	0	0	.154		.433	2	5K	.138	0	0	
	0	.70							.070	0	
	0	1.30							.130	0	
	.40	1.50							.150	2.898	
	.76	1.80							.180	5.507	
	1.03	2.20							.220	7.463	
	1.25	2.70							.270	9.058	
	1.43	3.20		1.35					.320	10.362	.675
2	.50	0	.226		.433	2	5K	.161	0	3.106	
	.50	.60							.060	3.106	
	.50	1.30							.130	3.106	
	.64	1.50							.150	3.975	
	.96	1.90							.190	5.963	
	1.27	2.30							.230	7.888	
	1.48	2.80							.280	9.192	
	1.65	3.65		1.34					.365	10.248	.67
3	.501	0	.327		.433	2	5K	.184	0	2.723	
	.501	.50							.050	2.723	

TABLE II (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
	.501	1.00	.327		.433	2	5K	.184	0	2.723	
	.501	1.35							.135	2.723	
	.82	1.55							.155	4.457	
	1.18	1.90							.190	6.413	
	1.44	2.35							.235	7.826	
	1.65	2.90							.290	8.968	
	1.80	3.55							.355	9.783	
	1.87	4.00							.400	10.163	
	1.82	4.07		1.35					.407	9.892	.675
4	-.29	0	.435		.433	2	5K	.196	0	-1.480	
	-.29	.70							.070	-1.480	
	-.29	1.34							.134	-1.400	
	0.07	1.50							.150	.357	
	0.40	1.75							.175	2.041	
	0.75	2.10							.210	3.827	
	1.08	2.50							.250	5.510	
	1.43	3.00							.300	7.296	
	1.67	3.50							.350	8.520	
	1.87	4.20							.420	9.541	
	1.97	4.80		1.34					.480	10.051	.670
1	.29	0	.327		.36	4	5K	.168	0	1.726	
	.29	.80							.040	1.726	
	.29	1.60							.080	1.726	
	.29	2.60							.130	1.726	
	.63	3.00							.150	3.750	
	.91	3.60							.180	5.416	
	1.15	4.20							.210	6.845	
	1.36	4.80							.240	8.095	
	1.58	5.60							.280	9.404	
	1.74	6.40		2.6					.320	10.356	.65

TABLE II (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
2	.57	0	.327		1.187	4	5K	.282	0	2.021	
	.57	.90							.045	2.021	
	.57	1.80							.090	2.021	
	.57	2.50							.128	2.021	
	.88	3.20							.160	3.120	
	1.18	3.80							.190	4.184	
	1.52	4.50							.225	5.390	
	1.78	5.10							.255	6.312	
	2.08	5.90		2.54					.295	7.376	.64
3	.501	0	.327		2.082	4	5K	.356	0	1.407	
	.501	.90							.045	1.047	
	.501	1.80							.090	1.047	
	.501	2.20							.110	1.047	
	.57	2.60							.130	1.601	
	.98	3.10							.155	2.753	
	1.38	3.60							.180	3.876	
	1.72	4.10							.205	4.831	
	2.02	4.70							.235	5.674	
	2.32	5.40		2.52					.270	6.517	.63
4	.71	0	.256		2.082	4	5K	.326	0	2.178	
	.71	.9							.045	2.178	
	.71	1.8							.090	2.178	
	.74	2.6							.130	2.270	
	.89	3.0							.150	2.730	
	1.17	3.6							.180	3.589	
	1.50	4.0							.200	4.601	
	1.95	4.5							.225	5.981	
	2.43	5.2		2.54					.260	7.454	.635

TABLE II (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
5	.65	0	.181		2.082	4	5K	.302	0	2.152	
	.65	.9							.045	2.152	
	.65	1.8							.090	2.152	
	.70	2.6							.130	2.318	
	.91	3.1							.155	3.013	
	1.09	3.6							.180	3.609	
	1.53	4.1							.205	5.066	
	1.77	4.6							.230	5.860	
	1.93	5.1		2.55					.255	6.390	.64
1	.71	0	.163		.767	4	2.5K	.166	0	4.277	
	.71	1.0							.10	4.277	
	.71	2.0							.20	4.277	
	.71	3.0							.30	4.277	
	.71	3.5							.35	4.277	
	1.00	3.9							.39	6.024	
	1.47	4.1							.41	8.855	
	1.75	4.4							.44	10.542	
	2.01	5.0		3.5					.50	12.108	.875
2	.65	0	.227		.767	4	2.5K	.186	0	3.494	
	.65	1.0							.10	3.494	
	.65	2.0							.20	3.494	
	.65	3.0							.30	3.494	
	.65	3.4							.34	3.494	
	.78	3.6							.36	4.193	

TABLE II (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
	1.18	4.0	.227		.767	4	2.5K	.186	.40	6.344	
	1.60	4.3							.43	8.602	
	1.88	4.7							.47	10.107	
	2.05	5.2		3.45					.52	11.021	.86
3	.64	0	.310		.767	4	2.5K	.206	0	3.107	
	.64	1.0							.10	3.107	
	.64	2.0							.20	3.107	
	.64	3.0							.30	3.107	
	.64	3.35							.335	3.107	
	.82	3.6							.36	3.980	
	1.26	3.9							.39	6.116	
	1.66	4.2							.42	8.059	
	2.05	4.8							.48	9.951	
	2.30	5.6		3.37					.56	11.164	.843
4	.51	0	.461		.767	4	2.5K	.235	0	2.170	
	.51	1.0							.10	2.170	
	.51	2.0							.20	2.170	
	.51	3.0							.30	2.170	
	.51	3.1							.31	2.170	
	.54	3.3							.33	2.298	
	.74	3.6							.36	3.149	
	1.01	3.8							.38	4.298	
	1.50	4.0							.40	6.383	
	1.89	4.2							.42	8.042	
	2.28	4.6							.46	9.701	
	2.56	5.2							.52	10.978	
	2.73	6.1		3.24					.61	11.616	.81

TABLE II (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
1	.57	0	.160		.5	6	5K	.157	0	3.631	
	.57	1.5							.05	3.631	
	.57	3.0							.10	3.631	
	.57	4.0							.133	3.631	
	.65	4.6							.153	4.140	
	.74	5.2							.173	4.713	
	.87	5.9							.197	5.541	
	1.04	6.5							.217	6.624	
	1.22	7.1							.237	7.771	
	1.38	7.5		4.03					.250	8.790	.672
2	.30	0	.227		.5	6	5K	.177	0	1.695	
	.30	1.5							.05	1.695	
	.30	3.0							.10	1.695	
	.30	4.0							.133	1.695	
	.56	4.5							.150	3.164	
	.79	5.2							.173	4.463	
	.96	5.9							.197	5.424	
	1.12	6.6							.220	6.328	
	1.24	7.3							.243	7.006	
	1.36	8.05		4.0					.268	7.684	.667
3	.41	0	.305		.5	6	5K	.198	0	2.071	
	.41	1.5							.05	2.071	
	.41	3.0							.10	2.071	
	.41	3.95							.132	2.071	
	.51	4.6							.153	2.576	
	.71	5.2							.173	3.586	
	.88	5.8							.193	4.444	
	1.02	6.4							.213	5.152	
	1.17	7.2							.240	5.909	

TABLE II (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
	1.29	8.0	.305		.5	6	5K	.198	.267	6.515	
	1.33	8.6		3.98					.287	6.717	.663
4	0	0	.305		.11	6	5K	.094	0	0	
	0	1.5							.05	0	
	0	3.0							.10	0	
	0	4.1							.137	0	
	.20	4.5							.150	2.128	
	.50	5.0							.167	5.319	
	.83	5.7							.190	8.830	
	1.05	6.5							.217	11.170	
	1.19	7.4							.247	12.659	
	1.27	8.1							.270	13.510	
	1.33	9.0		4.14					.300	14.149	.69
5	.62	0	.305		1.443	6	5K	.304	0	2.039	
	.62	1.5							.050	2.039	
	.62	3.0							.100	2.039	
	.62	3.9							.130	2.039	
	.84	4.6							.153	2.763	
	1.12	5.4							.180	3.684	
	1.40	6.3							.210	4.605	
	1.63	7.1							.237	5.362	
	1.78	8.0		3.90					.267	5.855	.65
B	RAPID FLOW										
1	1.94	0	.761		5.015	1	7.5K	.624	0	3.110	
	1.96	.3							.040	3.142	

TABLE II (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
	2.02	.5	.761		5.015	1	7.5K	.624	.067	3.238	
	2.22	.7							.093	3.559	
	2.52	1.0							.133	3.956	
	3.08	1.4							.187	4.937	
	3.61	1.8							.240	5.787	
	3.92	2.1							.280	6.284	
	4.35	2.6							.347	6.973	
	4.74	3.3		.475					.440	7.598	.475
2	1.77	0	.835		5.015	1	7.5K	.642	0	2.757	
	1.79	.30							.040	2.788	
	1.81	.48							.064	2.819	
	1.92	.60							.080	2.991	
	2.19	.90							.120	3.411	
	2.51	1.20							.160	3.910	
	2.98	1.50							.213	4.642	
	3.40	2.00							.267	5.296	
	3.80	2.50							.333	5.919	
	4.16	3.00							.400	6.480	
	4.32	3.60		.48					.480	6.729	.48
3	1.68	0	.863		5.015	1	7.5K	.65	0	2.585	
	1.74	.30							.040	2.677	
	1.83	.50							.067	2.815	
	2.17	.70							.093	3.339	
	2.60	1.00							.133	4.000	
	2.96	1.30							.173	4.554	
	3.40	1.70							.227	5.231	
	3.75	2.10							.280	5.769	
	4.10	2.60							.347	6.308	
	4.33	3.10		.475					.413	6.662	.475

TABLE II (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
1	1.36	0	.615		8.128	1	7.5K	.765	0	1.778	
	1.40	.30							.040	1.830	
	1.42	.41							.055	1.856	
	1.72	.60							.080	2.248	
	2.18	.90							.120	2.850	
	2.62	1.20							.160	3.425	
	3.25	1.50							.200	4.248	
	3.86	2.00							.267	4.579	
	4.36	2.50							.333	5.699	
	4.70	3.00		.412					.400	6.144	.412
2	1.55	0	.615		11.07	1	7.5K	.847	0	1.830	
	1.58	.20							.027	1.865	
	1.62	.40							.053	1.913	
	2.10	.60							.080	2.479	
	2.66	.90							.120	3.140	
	3.17	1.20							.160	3.743	
	3.68	1.50							.200	4.345	
	4.26	2.00							.267	5.029	
	4.51	2.50		.400					.333	5.325	.400
3	1.74	0	.615		15.01	1	7.5K	.955	0	1.749	
	1.80	.30							.040	1.809	
	1.85	.40							.053	1.859	
	2.03	.60							.080	2.040	
	2.67	.90							.120	2.683	
	3.65	1.20							.160	3.668	
	4.33	1.50							.200	4.352	
	4.93	2.00		.35					.267	4.955	.35

TABLE II (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
1	1.33	0	.465		12.004	1	7.5K	.81	0	1.642	
	1.38	.20							.027	1.704	
	1.44	.40							.053	1.778	
	2.05	.70							.093	2.531	
	2.80	1.00							.133	3.457	
	3.40	1.40							.187	4.197	
	3.75	1.80		.40					.240	4.629	.40
2	1.51	0	.528		12.004	1	7.5K	.839	0	1.800	
	1.58	.20							.027	1.883	
	1.63	.39							.052	1.943	
	1.82	.50							.067	2.169	
	2.48	.80							.107	3.056	
	3.15	1.10							.147	3.754	
	3.77	1.40							.187	4.493	
	4.18	1.80							.240	4.970	
	4.28	2.00		.395					.267	5.101	.395
3	1.26	0	.615		12.004	1	7.5K	.875	0	1.440	
	1.32	.20							.027	1.508	
	1.41	.40							.053	1.611	
	1.83	.60							.080	2.091	
	2.34	.80							.107	2.674	
	2.92	1.00							.133	3.337	
	3.58	1.30							.173	4.091	
	4.06	1.60							.213	4.640	
	4.60	2.00		4.0					.267	5.257	4.0
4	1.02	0	.709		12.004	1	7.5K	.924	0	1.104	
	1.13	.20							.027	1.223	
	1.26	.39							.052	1.364	

TABLE II (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
	2.00	.60	.709		12.004	1	7.5K	.924	.080	2.165	
	2.56	.80							.107	2.771	
	3.08	1.00							.133	3.333	
	3.84	1.30							.173	4.156	
	4.35	1.60							.213	4.708	
	4.69	2.00							.267	5.076	
	5.00	2.60		.395					.347	5.412	.395
1	.501	0	.567		8.666	2	5K	.718	0	.698	
	.67	.50							.05	..933	
	.86	.90							.09	1.198	
	1.25	1.10							.11	1.741	
	1.82	1.40							.14	2.535	
	2.45	1.70							.17	3.412	
	2.99	2.00							.20	4.164	
	3.70	2.50							.25	5.153	
	4.25	3.00							.30	5.919	
	4.59	3.40	.567	.92					.34	6.392	.46
2	.501	0	.635		8.666	2	5K	.745	0	.672	
	.61	.50							.05	.819	
	.82	.90							.09	1.101	
	1.10	1.05							.105	1.477	
	1.45	1.20							.120	1.946	
	2.10	1.50							.150	2.819	
	2.67	1.80							.180	3.584	
	3.12	2.10							.210	4.188	
	3.67	2.50							.250	4.926	
	4.12	2.90							.290	5.530	
	4.41	3.20		.925					.320	5.920	.463
3	.05	0	.70		8.666	2	5K	.77	0	.065	

TABLE II (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
	.22	.5	.70		8.666	2	5K	.77	.05	.286	
	.501	.92							.092	.651	
	1.01	1.2							.12	1.312	
	1.69	1.5							.15	2.195	
	2.5	1.8							.18	3.247	
	3.1	2.1							.21	4.026	
	3.7	2.4							.24	4.805	
	4.2	2.7		.93					.27	5.455	.465
4	.03	0	.775		8.666	2	5K	.797	0	.038	
	.20	.5							.05	..251	
	.41	.92							.092	.514	
	.54	1.1							.11	.678	
	1.36	1.3							.13	1.706	
	1.94	1.5							.15	2.434	
	2.93	1.8							.18	3.676	
	3.37	2.1							.21	4.228	
	4.07	2.4							.24	5.107	
	4.6	2.7		.93					.27	5.772	.465
1	.40	0	1.48		3.65	4	5K	.641	0	.624	
	.52	.6							.03	.811	
	.63	1.2							.06	.983	
	.80	1.8							.09	1.248	
	.92	2.0							.10	1.435	
	1.17	2.4							.12	1.825	
	2.06	3.0							.15	3.214	
	2.67	3.6							.18	4.165	
	3.22	4.2							.21	5.024	
	3.7	4.8							.24	5.772	
	4.16	5.4							.27	6.490	

TABLE II (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
	4.65	6.0	1.48		3.65	4	5K	.641	.30	7.254	
	5.20	6.6							.33	8.113	
	5.50	6.9		1.99					.345	8.581	0.498
2	-.15	0	1.48		5.11	4	5K	.718	0	-.209	
	0	.6							.03	0	
	.17	1.2							.06	.237	
	.40	1.9							.095	.557	
	1.15	2.6							.130	1.602	
	2.30	3.2							.160	3.203	
	3.15	3.8							.190	4.387	
	3.74	4.4							.22	5.209	
	4.2	5.0							.25	5.850	
	4.62	5.6							.28	6.435	
	5.00	6.0		1.9					.30	6.964	.475

TABLE II (Continued)

Velocity Distribution in Open Channel with Artificial Roughness Bar of Parallelogram Cross-Section At Middle Of Cycle

A TRANQUIL FLOW

Run	V Point Velocity Ft/sec.	y Depth above Flume Bed In.	q Disch. per ft. width c.f.s.	y_i Height of Inflection Point In.	S Bed Slope in percent	K Roughness Height In.	L Length of a Cycle	V_* Shear Velocity Ft/sec.	y/L	V/V_*	y_i/K
1	2	3	4	5	6	7	8	9	10	11	12
1	.40	0	.175		.433	2	5K	.138	0	2.898	
	.40	.80							.080	2.898	
	.40	1.40							.140	2.898	
	.50	1.65							.165	3.623	
	.77	1.80							.180	5.579	
	1.00	2.05							.205	7.246	
	1.19	2.40							.240	8.623	
	1.34	3.00							.300	9.710	
	1.39	3.50		1.42					.350	10.072	.71
2	.43	0	.270		.433	2	5K	.158	0	2.721	
	.43	.60							.060	2.721	
	.43	1.20							.120	2.721	
	.50	1.40							.140	3.165	
	.70	1.60							.160	4.430	
	1.08	2.00							.200	6.835	
	1.40	2.40							.240	8.861	
	1.62	3.00							.300	10.530	
	1.69	3.80		1.34					.380	10.696	.67
3	.58	0	.327		.433	2	5K	.167	0	3.473	
	.58	.600							.600	3.473	

TABLE II (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
3	.58	1.30	.327		.433	2	5K	1.67	.130	3.473	
	.61	1.45							.145	3.653	
	1.06	1.75							.175	6.347	
	1.53	2.00							.200	9.162	
	1.62	2.40							.240	9.701	
	1.84	2.80							.280	11.018	
	1.96	3.15							.315	11.736	
	2.05	3.80		1.3					.380	12.275	.65
4	.65	0	.405		.433	2	5K	.180	0	3.611	
	.65	.60							.06	3.611	
	.65	1.25							.125	3.611	
	1.06	1.50							.150	5.889	
	1.46	1.90							.190	8.111	
	1.64	2.40							.240	9.111	
	2.25	3.00							.300	12.500	
	2.48	3.50							.350	13.778	
	2.70	4.10		1.25					.410	15.000	.625
B	RAPID FLOW										
1	.72	.50	.6		8.666	2	5K	.482	.05	1.494	
	.75	.70							.07	1.556	
	.80	.90							.09	1.660	
	.85	1.05							.105	1.763	
	1.14	1.30							.130	2.365	
	1.80	1.60							.160	3.734	
	2.88	2.00							.200	5.975	
	3.64	2.40							.240	7.552	
	4.33	3.00							.300	8.983	
	4.93	3.80		1.08					.380	10.228	.54

TABLE II (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
2	.70	.50	.677		8.666	2	5K	.547	.05	1.280	
	.73	.70							.07	1.335	
	.77	.90							.09	1.408	
	.82	1.05							.105	1.499	
	1.04	1.20							.120	1.901	
	1.51	1.50							.150	2.761	
	2.17	1.80							.180	3.967	
	2.86	2.0							.20	5.229	
	3.49	2.2							.22	6.380	
	4.02	2.5							.25	7.349	
	4.43	3.0							.30	8.100	
	4.63	3.5							.35	8.465	
	4.74	4.0		1.06					.40	8.666	.53
3	.43	.5	.7		8.666	2	5K	.569	.05	.756	
	.50	.7							.07	.879	
	.66	1.0							.10	1.160	
	.88	1.2							.12	1.547	
	1.51	1.5							.15	2.654	
	2.15	1.7							.17	3.779	
	3.01	2.0							.20	5.290	
	4.01	2.4							.24	7.048	
	4.49	2.9							.29	7.891	
	4.62	3.6		1.05					.36	8.120	.525
4	.71	.5	.785		8.666	2	5K	.608	.05	1.168	
	.73	.7							.07	1.201	
	.77	.9							.09	1.266	
	.80	1.0							.10	1.316	
	.98	1.2							.12	1.612	
	1.45	1.5							.15	2.385	

TABLE II (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
	2.28	1.8	.785		8.666	2	5K	.608	.18	3.750	
	3.24	2.1							.21	5.329	
	4.23	2.5							.25	6.957	
	4.74	3.0							.30	7.796	
	5.04	3.5							.35	8.289	
	5.13	3.8		1.04					.38	8.437	.52

Velocity Distribution in Open Channel with Artificial Roughness Bar of Triangular Cross-Section at Middle of Cycle

A. Tranquil flow

Run	V Point Velocity Ft/sec.	y Depth Above Flume Bed In.	q Disch. per ft. Width c.f.s.	y_i Height of Inflection Point In.	S Bed Slope in percent	K Roughness Height In.	L Length of a Cycle	V_* Shear Velocity Ft/sec.	y/L	V/V_*	y_i/K
1	2	3	4	5	6	7	8	9	10	11	12
1	.501	0	.170		.433	2	5K	.139	0	3.604	
	.501	.50						.	.050	3.604	
	.501	1.10							.110	3.604	
	.501	1.30							.130	3.604	
	.720	1.70							.170	5.180	
	.910	2.00							.200	6.547	
	1.100	2.30							.230	7.913	
	1.280	2.60							.260	9.208	
	1.440	3.00							.300	10.359	
	1.560	3.40		1.33					.340	11.223	.665
2	.470	0	.257		.433	2	5K	.160	0	2.938	
	.470	.50							.050	2.938	

TABLE II (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
	.470	1.10	.257		.433	2	5K	.160	.110	2.938	
	.500	1.30							.130	3.125	
	.600	1.50							.150	3.750	
	.730	1.70							.170	4.563	
	.880	1.90							.190	5.500	
	1.150	2.30							.230	7.188	
	1.360	2.70							.270	8.500	
	1.610	3.10							.310	10.063	
	1.970	3.80		1.3					.380	12.313	.65
3	.501	0	.326		.433	2	5K	.171	0	2.930	
	.501	.60							.060	2.930	
	.501	1.20							.120	2.930	
	.570	1.40							.140	3.333	
	.840	1.70							.170	4.912	
	1.160	2.10							.210	6.784	
	1.450	2.50							.250	8.479	
	1.710	3.00							.300	10.000	
	1.910	3.50							.350	11.169	
	2.080	4.10		1.28					.410	12.164	.64
4	.650	0	.403		.433	2	5K	.191	0	3.403	
	.650	.40							.040	3.403	
	.650	.90							.090	3.403	
	.650	1.25							.125	3.403	
	.780	1.50							.150	4.084	
	1.060	1.80							.180	5.550	
	1.340	2.10							.210	7.016	
	1.700	2.50							.250	8.901	
	2.100	3.00							.300	10.995	

TABLE II (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
	2.440	3.50	.403		.433	2	5K	.191	.350	12.775	
	2.750	4.00		1.27					.400	14.398	.635
B	RAPID FLOW										
1	-.64	0	.70		8.666	2	5K	.661	0	-.968	
	-.49	.60							.060	-.741	
	-.38	1.00							.100	-.875	
	.10	1.20							.120	.151	
	.80	1.50							.150	1.210	
	1.48	1.80							.180	2.239	
	2.05	2.00							.200	3.101	
	2.88	2.30							.230	4.357	
	3.41	2.60							.260	5.159	
	3.90	3.00							.300	5.900	
	4.28	3.40							.340	6.475	
	4.67	4.00		1.04					.400	7.065	.52
2	-.64	0	.745		8.666	2	5K	.658	0	-.973	
	-.52	..50							.050	-.790	
	-.48	1.00							.100	-.730	
	-.08	1.10							.110	-.122	
	.40	1.30							.130	.608	
	1.00	1.60							.160	1.520	
	1.70	1.90							.190	2.584	
	2.60	2.30							.230	3.951	
	3.13	2.60							.260	4.757	
	3.70	2.90							.290	5.623	
	4.19	3.20							.320	6.368	
	4.58	3.50							.350	6.961	
	4.92	4.00		1.04					.400	7.477	.52

TABLE II (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
3	-.64	0	.80		8.666	2	5K	.689	0	-.929	
	-.56	.50							.050	-.813	
	-.40	1.05							.105	-.581	
	-.02	1.20							.120	-.029	
	.69	1.50							.150	1.001	
	1.40	1.80							.180	2.032	
	2.31	2.20							.220	3.353	
	3.07	2.60							.260	4.456	
	3.75	3.00							.300	5.443	
	4.28	3.50		1.06					.350	6.212	.53
4	-.58	0	.86		8.666	2	5K	.733	0	-.791	
	-.49	.50							.500	-.668	
	-.31	1.05							.105	-.423	
	-.03	1.20							.120	-.041	
	.50	1.50							.150	.682	
	1.31	1.80							.180	1.787	
	2.01	2.10							.210	2.742	
	2.82	2.50							.250	3.847	
	3.59	3.00							.300	4.898	
	4.15	3.50							.350	5.662	
	4.46	4.00		1.07					.400	6.085	.535

Velocity Distribution in Open Channel with Artificial Roughness Bar of Semi-Circular Cross-Section at Middle of Cycle

A TRANQUIL FLOW

Run	V Point Velocity Ft/sec.	y Depth Above Flume Bed In.	q Disch. per ft. width c.f.s.	y_i Height of In-flection Point In.	S Bed Slope in percent	K Rough-ness Height In.	L Length of a Cycle	V_* Shear Velocity Ft/sec.	y/L	V/V	y_i/K
1	2	3	4	5	6	7	8	9	10	11	12
1	-.68	0	.16		.433	2	5K	.135	0	-5.037	

TABLE II (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
	-.68	.4	.16		.433	2	5K	.135	.040	-5.037	
	-.68	.8							.080	-5.037	
	-.56	1.0							.100	-4.148	
	-.28	1.2							.120	-2.074	
	.18	1.5							.150	1.333	
	.50	1.8							.180	3.704	
	.77	2.2							.220	5.704	
	.97	2.6							.260	7.185	
	1.13	3.0							.300	8.370	
	1.23	3.3							.330	9.111	
	1.18	3.4		.85					.340	8.741	.425
2	.29	0	.214		.433	2	5K	.149	0	1.946	
	.29	.4							.04	1.946	
	.29	.8							.08	1.946	
	.36	1.0							.10	2.416	
	.48	1.2							.12	3.221	
	.63	1.5							.15	4.228	
	.79	1.8							.18	5.302	
	.98	2.2							.22	6.577	
	1.17	2.6							.26	7.852	
	1.30	3.0							.30	8.725	
	1.38	3.4							.34	9.262	
	1.42	3.8		.85					.38	9.530	.415
3	.08	0	.327		.433	2	5K	.171	0	.468	
	.12	.4							.04	.702	
	.16	.8							.08	.936	

TABLE II (Continued)

1	2	3	4	5	6	7	8	9	10	11	12
	.43	1.0	.327		.433	2	5K	.171	.10	2.515	
	.66	1.3							.13	3.860	
	.91	1.7							.17	5.322	
	1.08	2.1							.21	6.316	
	1.22	2.5							.25	7.135	
	1.33	3.0							.30	7.778	
	1.42	3.5							.35	8.304	
	1.48	4.0							.40	8.655	
	1.51	4.3							.43	8.830	
	1.49	4.5		.82					.45	8.714	.41
4	-.24	0	.411		.433	2	5K	.185	0	-1.297	
	-.19	.4							.04	-1.029	
	-.14	.8							.08	-.757	
	.20	1.0							.10	1.081	
	.56	1.3							.13	3.027	
	.79	1.6							.16	4.270	
	1.02	2.0							.20	5.514	
	1.25	2.5							.25	6.757	
	1.42	3.0							.30	7.676	
	1.56	3.5							.35	7.892	
	1.70	4.0							.40	9.189	
	1.79	4.4							.44	9.676	
	1.86	4.7		.81					.47	10.546	.405

Abstract

VELOCITY DISTRIBUTION IN STEEP ROUGH CHANNEL

by

Chiang Tsung-Ting

This thesis consists of an experimental study of the velocity distribution in tranquil, stable tumbling and rapid flow regimes in a steep rectangular channel with artificial roughness elements.

Four shapes of roughness elements, rectangular, parallelogram, triangular, and semi-circular, were used. Effects on velocity distribution due to variations in discharge, flume slope and roughness geometry were studied for each shape of roughness element. The applicability of logarithmic law was examined and the inflection points in tranquil and rapid flow regime were studied. Also the velocity coefficients in tumbling regime were studied.

The findings were confirmed through the analysis of data taken from project 405 of the Civil Engineering Department.

A review of literature on this subject and a bibliography are included.