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A Study of Free Surface and Viscous Effects on Simulated Rough Open Channel Beds

Julian B. Andersen

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of the requirements for the degree

of

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Approved:

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Major Professor

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Head of Department

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UTAH STATE UNIVERSITY
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NOTATION

A	Area
A_o	Area of orifice opening
A_r	Free surface instability parameter
A_v	Vertical projected bed element area
a	A constant
B	Flume width
C	Chezy coefficient
C_o	Orifice coefficient
C_1, C_2, C_3, C', C''	A constant
C_b	Bed element shape factor
C_s	Shape correction factor
D	Depth of flow
F	Froude number
f	Denotes functional relationship
g	Acceleration due to gravity
I_j, I_1, I_2, i	Roughness spacing ratio
K	Roughness height
K_n	Roughness height were n is percent larger
m	A constant
N	Number of bed elements
n	Constant or a percent larger
P	Parameter denoting a ratio of $C/g^{\frac{1}{2}}$
R	Hydraulic radius
R_D	Reynolds number based on depth
R_K	Reynolds number based on roughness height

NOTATION (continued)

S, S_1, S_2	Slope of free surface and channel bed
u	Uniformity coefficient
V	Mean velocity of flow
x	Longitudinal spacing of grid
y, y_n	Normal depth
z	Lateral spacing of grid
γ	Specific weight
Δp	A pressure difference
θ	Non-dimensional parameter expressing relative spacing of bed elements
κ	The von Karman turbulence coefficient
μ	Viscosity of fluid (dynamic)
Σ	Indicates summation
χ	Roughness density parameter

ABSTRACT

A Study of Free Surface and Viscous Effects on

Simulated Rough Open Channel Beds

by

Julian B. Andersen, Doctor of Philosophy

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Department: Civil Engineering

An experiment was designed to eliminate the free surface from simulated naturally roughened open channel beds from which results were compared to data with a free surface from another study. All other pertinent variables were held constant. From this comparison, a relationship was established for the additional energy loss due to the presence of a free surface in the flow over these channel beds.

$$P = 0.23 - 0.28\ D/K_{25}$$

where P is the proportion that the channel conductance coefficient $(C/g^{\frac{1}{2}})$ is reduced due to presence of a free surface, D is the flow depth, K_{25} is a measurement of roughness height and D/K_{25} is the relative roughness and was varied from 1 to 7.

The channel conductance coefficient was found to be non-dependent upon Reynolds number.

A parameter describing bed element spacing was identified as the ratio of vertical projected area of all bed elements to the total bed area, and was found to be constant for a particular channel bed. Roughness spacing had only a minor effect on the channel conductance parameter.

The channel conductance coefficient was related to the relative roughness by a power function and the following prediction equation was established relating the channel conductance coefficient to the relative roughness and spacing parameter:

$$C/g^{\frac{1}{2}} = 3.0\ (D/K_{16})^{0.317}\ \exp\ (0.007/\theta)$$

where D/K_{16} is the relative roughness and θ is the spacing parameter.

(98 pages)

CHAPTER I

INTRODUCTION

The Problem

Open channel flow has long been of interest to engineers. Antone Chezy presented the first relationship by which open channels of differing cross-section, slope and boundary roughness could be related to one another within a limited range. Other developments and modifications have been made by Bazin, Kutter, Manning, and others.

In the past few years, Albertson, Robinson, Einstein, Sayre, Powell, Morris, and others have presented research papers relating to the effects of boundary roughness using geometrical shaped roughness elements at uniform spacings.

Under the direction of D. F. Peterson at Utah State University, Mohanty, Attieh, Mirajgaoker and Al-Khafaji used various geometric roughness elements in a flume to classify flow regimes and to study boundary drag where bed elements are large in relation to flow depth and gradient is sufficiently high to cause at least localized supercritical flow. Kharrufa extended the research to a simulated idealized natural roughened channel in which gravel elements were glued to the bed and related the mean velocity to the depth of flow, slope, relative roughness height, and a roughness intensity factor. Judd took the problem to the field and made observations on various alluvial rivers and streams in the Wasatch mountain area of northern Utah, and also in Colorado and New Mexico. He related the mean velocity to the depth of flow, relative roughness height and roughness intensity or spacing. In the studies to date, separation of gravity and viscous effects has not been possible. In order to accomplish this, viscosity or gravity would have to be varied and it would be helpful if the free surface effects could be eliminated.

It has been assumed that the resistance coefficient is independent of viscosity based on the grounds that most relevent experiments show no variation with Reynolds number at high Reynolds number. For high relative roughness, most experiments have utilized sharp-edged roughness elements which have a single point of separation for all flows. For flow around rounded objects, the point of separation changes even under conditions of high Reynolds number resulting in a change in the values of the drag coefficient. In natural streams, the bed elements include a wide array of sizes each of which has a different drag-velocity curve. What portion of the resistance originates from free surface conditions such as spills, etc. is also unknown.

The purpose of this project is to study the resistance to flow in naturally roughened open channels where relative roughness effects are important, and to clarify the effects of viscosity on the flow around these rounded, size distributed elements and to attempt to delineate losses associated with the free surface.

Objectives

1. To devise an experiment such that the effects of free surface on channel resistance can be studied and to establish some relationship for the additional amount of energy lost due to the presence of a free surface.

2. To study the significance of viscous effects on the channel drag using large rounded bed elements of graded gravel at fairly high Reynolds numbers.

3. To identify a hydraulically significant parameter describing bed element spacing.

4. To discuss and evaluate the validity of the Chezy equation for use in rough channels, in light of the data taken for this study.

CHAPTER II

REVIEW OF LITERATURE

Open Channel Experiments

In 1768, a French engineer A. Chezy, developed an equation for canal design. This equation contained a constant now known as the Chezy coefficient which has been studied extensively since that time by many investigators trying to simplify and investigate how the coefficient varies under differing conditions. The Chezy formula is

$$V = C\ (RS)^{\frac{1}{2}} \tag{1}$$

where V is the mean velocity, C is the Chezy coefficient, S is the slope and R the hydraulic radius of the channel.

W. R. Kutter published a new formula for C in 1869 which contained a slope correction term. Bazin pioneered open channel research and developed a formula in 1897 which defined C for various design materials. The idea of roughness as a variable was not conceived until nearly the 20th Century. In 1891, R. Manning proposed an equation which gives

$$C = 1.49\ R^{1/6}\ /n \tag{2}$$

where n is a roughness coefficient. This equation is widely used throughout the world. Gauckler, Hagen, Strickler and others have also made investigations and developments.

In more recent times, Prandtl developed a formula showing the relation between momentum and viscosity as expressed by friction factor as a function of Reynolds number for smooth pipes in which smooth pipes were defined as those for which roughness elements did not protrude above the viscous boundary layer. In 1933, J. Nikuradse showed that for flow through rough-walled pipes at high Reynolds numbers the friction factor became independent of Reynolds number and the relative roughness rather than Reynolds number is the dominant factor.

Keulegan (1938) applying these ideas to open channel flow, developed an equation for rough-walled channels using Bazin's results. He attempted to do for open channels what Nikuradse did for pipe flow.

Johnson (1944) tested rectangular channels having rectangular strips fastened to the bottom perpendicular to the direction of flow and observed that maximum resistance occurred when the strips were spaced at about 16 times their height.

Powell (1946) performed similar tests to those of Johnson and developed a formula for Chezy C in the form

$$C = C_s + 40 \log_{10} (R/K) \tag{3}$$

where C_s is a shape factor and K is roughness height.

Robinson and Albertson (1952) published a report on wide rectangular flumes roughened with fixed shape metal baffles under various spacing patterns. They concluded that Chezy C was a function of relative roughness (D/K) alone for a given roughness pattern. They used slopes up to 4 percent and values of D/K from 2.0 to 17.5.

Leopold and Maddock (1953) were the first to propose that for river channels; velocity, depth and width could be expressed as power functions of discharge.

Wolman (1954) proposed a method for sampling coarse river bed material and classifying the material with a frequency distribution and demonstrated its consistency in the field.

Morris (1955) presented a new concept for rough turbulent flow. His assumption was that the energy loss in turbulent flow over rough surfaces is caused by the formation of wakes behind the roughness elements. Longitudinal spacing of the roughness is very important under this concept. In his study, he defines three types of flow: isolated-roughness flow, wake-interference and flow and skimming flow. Equations for the friction factor as a function of Reynolds number and roughness characteristics were derived for each of these types of flow.

The idea that free surface instability is an important factor for energy dissipation became apparent about 1950. Iwagaki (1954) found that the increase in channel resistance with rising Froude number was due to the increasing free surface instability. Chow (1959) in attacking the same problem presents the equation

$$C/g^{\frac{1}{2}} = A_r + 5.75 \log (R/K) \tag{4}$$

where A_r is a function of Froude number. If Froude number is less than 1.0, A_r experiences very little change. If Froude number is greater than 1.0, A_r decreases.

Koloseus (1958) substantiated Iwagaki's conclusion regarding free surface instability and in addition proposed that the resistance coefficient in a rough channel where roll waves form is independent of gravitational effects if the Froude number is less than 1.6.

Blench (1963) suggested that for rough conduits, a more adequate relationship exists in the form

$$V \propto (D/K)^{\frac{1}{4}} (2gDS)^{\frac{1}{2}} \tag{5}$$

where D is the flow depth, K is the roughness height and g is the acceleration due to gravity.

Goncharov (1962) in studying massive roughness in natural streams states that the average roughness height will be determined by the largest 5 percent (by volume) and that

$$C \sim 2.22\ (D/K)^{1/6} \tag{6}$$

Sayre and Albertson (1963) derived an expression for the conductance coefficient from the von Karman-Pradtl equation of logarithmic velocity distribution such that

$$C/g^{\frac{1}{2}} = (2.30/\kappa)\ \log\ (y/\chi) \tag{7}$$

where κ is the von Karman turbulence coefficient, y is the normal depth and χ is a parameter describing roughness by relating size, shape and spacing, i.e.:

$$\chi = f(i)K \tag{8}$$

where i is the ratio of vertical projected area of the roughness strips to the total bed area. They concluded that χ was an adequate definition of roughness spacing or density.

Herbich and Shulits (1964) studied large scale roughnesses at various spacings (large scale in that roughness heights were protruding from surface or nearly so). They tried various dimensionless parameters to describe the height and density of the roughness. One seemed most useful for practical use:

$$\theta = \Sigma A_v/A \tag{9}$$

where θ is the roughness parameter, A_v is the sum of the vertical areas of cubes and A is the horizontal bed area.

Utah State University Experiments

About 1958, a series of studies of steep slope channels with large roughness elements was begun. Mohanty (1959) used bar and cube roughness elements spaced at regular intervals. He was able to classify the resulting flow into three separate regimes: rapid, tumbling and tranquil.

For the rapid and tranquil regimes, the spacing of the roughness elements was important. For the tumbling regime, hydraulic jumps formed behind the roughness elements then the flow became supercritical before the next element was encountered.

Attieh (1961) and Mirajgoaker (1961) ran tests on cubes, hemispheres and circular disks to study the drag, pressure distribution and flow patterns for single elements.

Al-Khafaji (1961) used bar elements in a flume to gather more information about flow regimes. He proposed additional criteria for classifying flow regimes and studied in detail an unstable regime in which traveling roll waves formed.

Beginning with Kharrufa (1962) attention was turned to the problem of large graded natural roughness elements under a wide range of slopes and discharges. Kharrufa cemented these elements to the bed of a laboratory flume. Flow in such an environment becomes very complex. Some of the roughness elements may protrude through the surface, most of the roughness elements extend to an appreciable proportion of the flow depth, the free surface becomes unstable and rough and the velocity distribution is complex and constantly changing with distance along the channel. Energy is dissipated through vortex formation, disruption of flow as it jets between two such roughness elements and hits the face of another and through spills and jumps forming around some of the roughness elements. This type of flow must be treated as being statistically uniform for a given reach if it is to be analyzed at all.

From his study, Kharrufa presented an equation for the rapid regime in the form

$$C/g^{\frac{1}{2}} = f(A^{\frac{1}{2}}/K_{10}) \qquad (10)$$

for D/K_3 from 0.36 to 4.85 and Froude number from 1.2 to 2.48, K_3 and K_{10} are the average heights of the highest three and ten elements in the horizontal bed area A. Further in the tranquil, tumbling and transitional regimes

$$C/g^{\frac{1}{2}} = 2.1\ (D/K_3)^{1/3}\ (A^{\frac{1}{2}}/K_3)^{1/3} \qquad (11)$$

where D/K_3 ranged from 0.36 to 4.85 and Froude number from 0.38 to 1.2, and D is piezometric depth.

Judd (1963) investigated rough high-gradient natural streams in some of the mountainous areas of Utah, New Mexico and Colorado. He related the bed characteristics of such streams to hydraulic parameters. The stream beds were represented by a normal distribution when heights above the mean plane measured from points on a horizontal grid were plotted against cumulative percentile of the sample which was larger. To represent the spacing parameter of these beds, Judd considered a grid system covering area A. At the grid points vertical roughness heights were measured and an arithmetic mean bed height found. Heights above and below the mean plane were calculated and plotted against cumulative percentile larger by number on normal probability paper. These plots show a normal distribution and from them he describes his intensity relationship as

$$I_j = A^{\frac{1}{2}}/K_n N^u \qquad (12)$$

where I_j is a measure of the area associated with one bed element, N is the number of bed elements equal to or greater than K_n in height, u is a uniformity coefficient having a value of $\frac{1}{2}$ if the distribution of bed elements is normal and n is a percentage varying from 0 to 100. I_j remains constant for a particular bed. An equation involving the bed parameters was formulated as

$$C/g^{\frac{1}{2}} = C_1 C_b I_j^{-0.71} (D/W)^{1/3} (D/K_n)^{1/3} \tag{13}$$

where C_1 is a constant C_b is a bed element shape factor and W is the width of the water surface. Froude number varied from 0.2 to 0.7 and slopes varied from 1 to 4 percent.

Abdelsalam (1965) simulated high gradient naturally roughened open channels similar to those of Kharrufa and demonstrated the validity of the Chezy equation for his experiment, and classified his flow into six zones which could be related to Froude number. For each zone, he expressed the conductance coefficient $C/g^{\frac{1}{2}}$ as a function of relative roughness D/K_n and an intensity or spacing parameter I_1. The general form of these equations is

$$C/g^{\frac{1}{2}} = C_2 I_1^m (D/K_{25})^n \tag{14}$$

and

$$C/g^{\frac{1}{2}} = C_3 I_1^m \log_{10} (D/K_{25}) \tag{15}$$

where C_2, C_3, m and n are constant and

$$I_1 = A^{\frac{1}{2}} K_{25}/(N^{\frac{1}{2}} K_n x^{\frac{1}{2}} z^{\frac{1}{2}}) \tag{16}$$

where N is the number of points of height K_n or higher in area A, and x and z are the longitudinal and lateral spacings of the grid used to measure the elements heights and n is the percentile of the fraction by number of the set larger than K_n. I_1 was found to remain constant for any bed regardless of value used for n and A if the sample size was sufficient. Another parameter describing the bed element spacing

$$I_2 = (\Sigma A_v)\, x/AK_{25} \tag{17}$$

was tried by Abdelsalam where A_v is the vertical projection of area of the roughness elements in an area A.

Paralleling the work at Utah State University, Mirajgoaker and Charlu (1963) at Roorkee University studied the effects of large natural roughness in open channel flow. They used uniform-sized gravel elements and placed them according to six different geometric patterns. They found that

$$C/g^{\frac{1}{2}} = 5.28 \log (y_n/\chi) + 1.72 \qquad (18)$$

where y_n is the normal depth of flow and χ is the parameter as used by Sayre and Albertson (1963).

In conclusion, most investigators have found the conductance coefficient to be related to relative roughness but there seems to be two models which can express this relationship: a logarithmic model and a power model. If the relative roughness values are small and the elements are of rounded shapes and spaced without pattern the power model seems to prevail. If on the other hand if D/K values are larger, elements are of geometric regularity and spaced according to some pattern, the logarithmic model more nearly describes the relationship.

CHAPTER III

DESIGN OF EXPERIMENT

Dimensional Analysis

To approach a solution to the questions under study, the following pertinent variables, assuming size and shape of roughness are established:

Symbol	Description
V	Mean velocity
S	Slope of free surface and channel bed
ρ	Mass density of fluid
g	Acceleration due to gravity
B	Flume width
μ	Dynamic viscosity
D	Statistical flow depth
K_n	Roughness height where n is percent larger
θ	A measure of bed element spacing or intensity of areal distribution

$$f_1\ (S, V, D, K_n, \rho, \mu, \theta, B, g) = 0 \qquad (19)$$

Combining variables

$$V/(DSg)^{\frac{1}{2}} = f\ (\rho VD/\mu,\ V/(Dg)^{\frac{1}{2}},\ D/K_n,\ \theta,\ D/B) \qquad (20)$$

or

$$C/g^{\frac{1}{2}} = f\ (R_D,\ F,\ D/K_n,\ \theta,\ D/B) \qquad (21)$$

where $C/g^{\frac{1}{2}} = V/(DSg)^{\frac{1}{2}}$ and C = Chezy coefficient $= V/(DS)^{\frac{1}{2}}$

$\rho VD/\mu = R_D$ = Reynolds number based on depth

$V/(Dg)^{\frac{1}{2}} = F$ = Froude number

D/K_n will be referred to as relative roughness.

The parameter D/B measures the side wall effect of a finite width stream. Because the side walls of the duct used in this experiment were relatively smooth, D/B will be assumed to have a relatively negligible effect upon $C/g^{\frac{1}{2}}$. The foregoing equation may then be reduced to

$$C/g^{\frac{1}{2}} = f\ (R_D,\ F,\ D/K_n,\ \theta) \tag{22}$$

Design of Experiment

The effect of viscosity upon $C/g^{\frac{1}{2}}$ can be studied if all other terms in equation 22 except Reynolds number can be held constant, i.e., by holding depth, discharge, roughness height and spacing constant while varying slope and viscosity. However, as far as surface disturbances are concerned D/K_n, F, θ and possibly viscosity all have some effect.

As spacing is varied, one can expect a different pattern in the forces acting on the boundary which may possibly relate to the Morris concepts of isolated-roughness, wake-interference and skimming flow. Gradation of roughness elements would also be expected to have an influence on drag with changing Reynolds number. If all elements were of the same size and shape, the variation of form drag due to change in point of separation as Reynolds number changes would occur in unison and would be cumulative. With size gradation, however, the drag coefficient will change differently for each element size and the cumulative effect will more closely resemble a uniform noise level so that cumulative Reynolds effects for all of the elements might remain uniform as velocity changes.

In order to study the effects of the free surface, two identical cases could be compared, one with a free surface present and one having the free surface eliminated, but with other parameters in equation 22 unchanged. The open flume experiments could be compared with similar ones using a rectangular conduit of twice the depth with an inverted roughness bed at the top. The difference in the conductance coefficient $C/g^{\frac{1}{2}}$ should then be a measure of the effect of the free surface. Reynolds number can be used as a means of comparison between the two cases.

Briefly, the principle of this comparison can be explained in a simplified manner by the use of figure 1. The difference between S_1 and S_2 will be the difference in specific energy losses for the free surface for the same velocity and roughness, or the parameter $C/g^{\frac{1}{2}}$ in the latter case would be completely attributable to the drag on the boundary through viscosity, i.e., a function of Reynolds number.

It was decided to build and test such a system as shown in figure 1. Open channel flume data were available from the study of Abdelsalam (1965) but since data were being collected simultaneously another set of roughness beds was built to correspond exactly with those of Abdelsalam. For convenience air was used instead of water for testing. Greater velocities are necessary using air in order to obtain a corresponding range of Reynolds numbers which would cause the Froude number range to exceed that of the open channel case. All other variables were tested in the same range as in the open channel study.

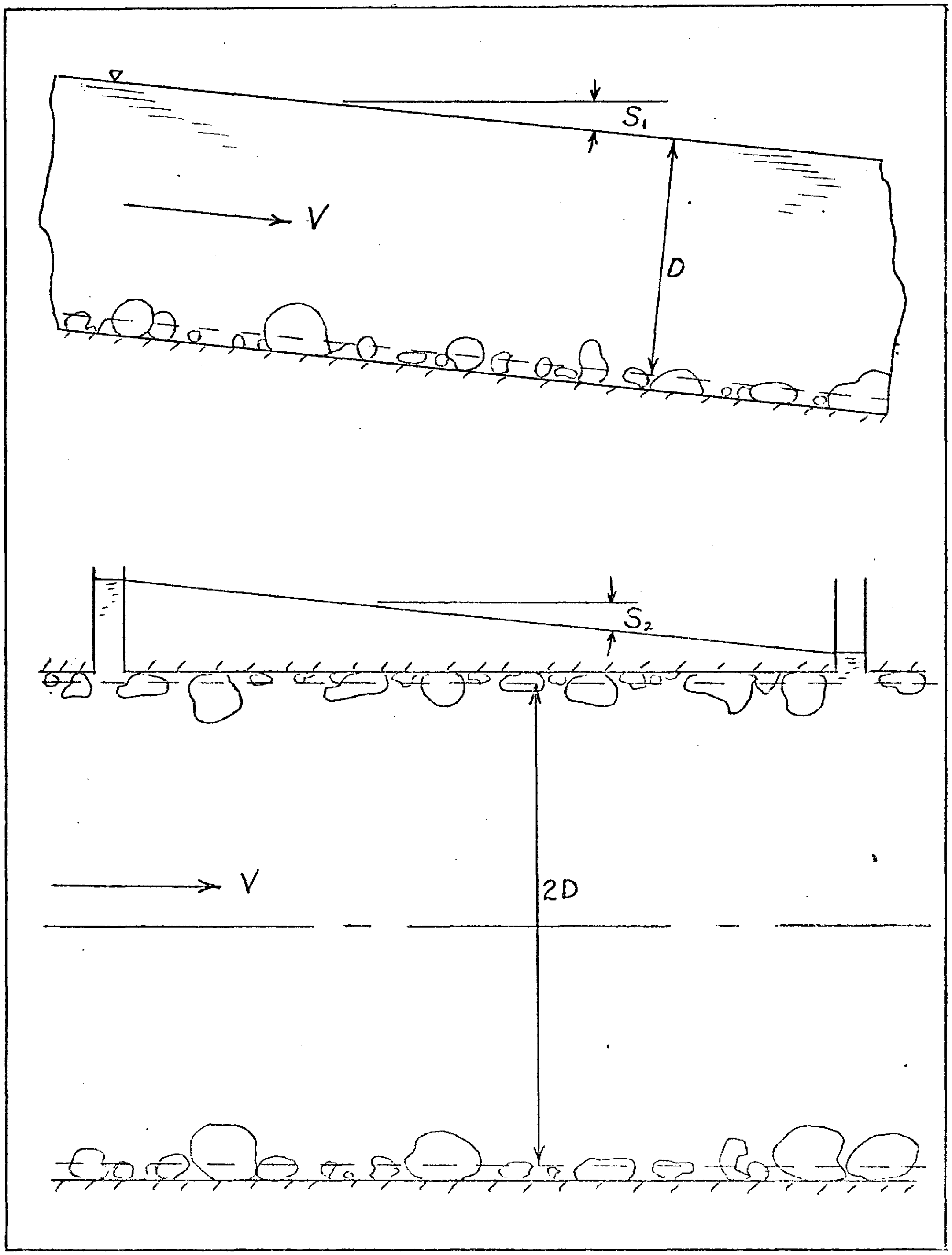


Figure 1. Illustration of experiment with and without free surface. Longitudinal cross-section.

CHAPTER IV

EXPERIMENTAL EQUIPMENT

Air Supply

An 18-inch axial flow fan supplied air to a plenum. The duct entered through an opening in the side of the plenum. The axial flow fan was powered by a $7\frac{1}{2}$-Hp, variable-speed, direct-current motor which in turn was regulated by a speed variator or rheostat. The plenum was 8-feet by 4-feet by 4-feet and contained screen partitions at various levels to scale down turbulence.

The Duct

The duct was 24-feet long by 1-foot high and had a variable width. The sides of the duct contained the gravel elements under study.

Each side of the duct consisted of three 1-foot by 8-feet plywood boards with the gravel elements attached to them. These boards were placed end-to-end. The top and bottom of the duct were fabricated of $3\frac{1}{4}$-inch wide tongue and groove lumber, hence the width (simulating twice the flow depth in the flume), could be varied by the insertion of one or more tongue and groove boards to the top and bottom.

The front of the duct was fitted with a tapered or wedge shaped "leading edge." The sharp leading edge protruded into the plenum leaving approximately an 1/8-inch space around the outside of the duct to allow air to bleed off, thus creating a near uniform velocity profile at the duct entrance (see figures 2 and 3).

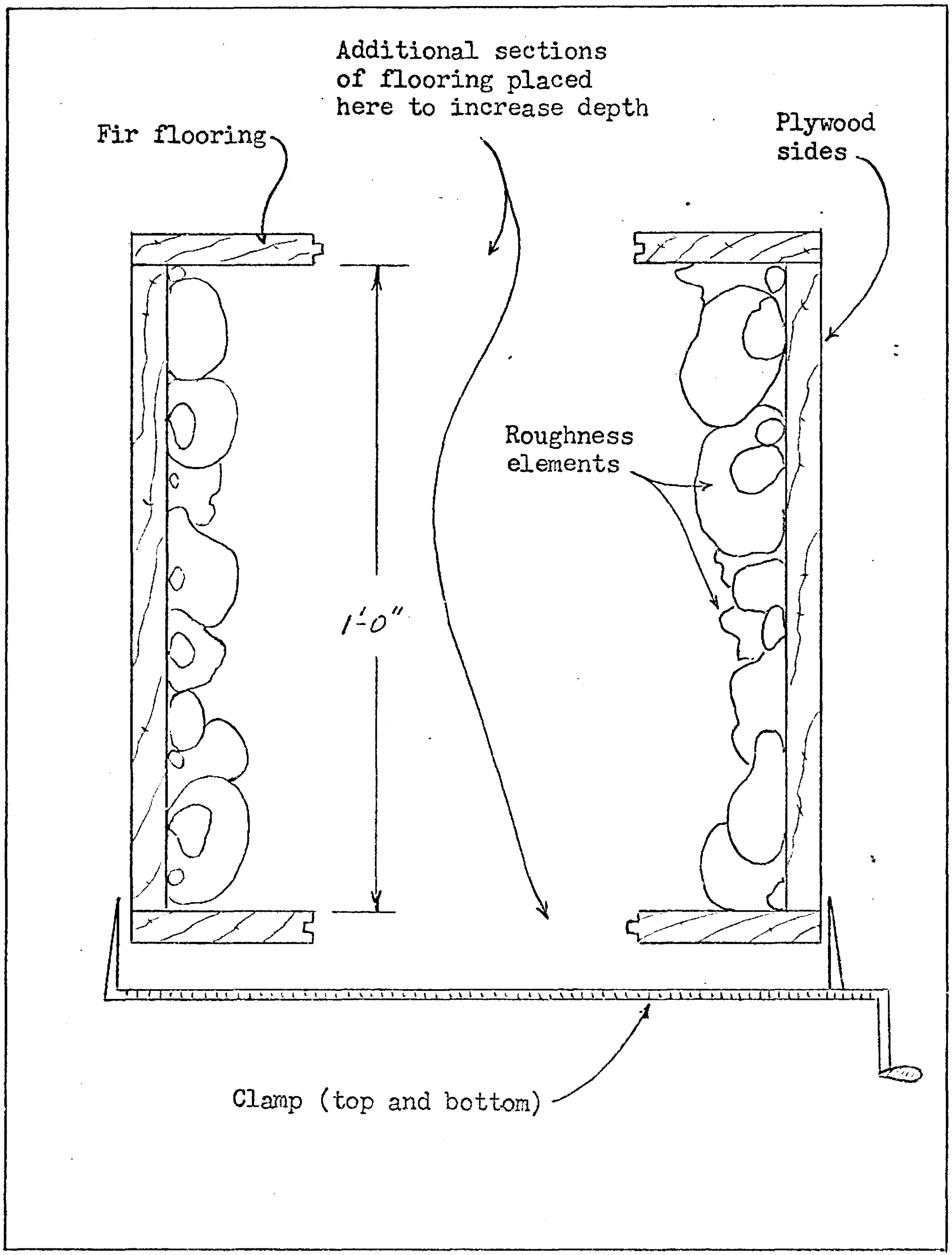


Figure 2. Duct details.

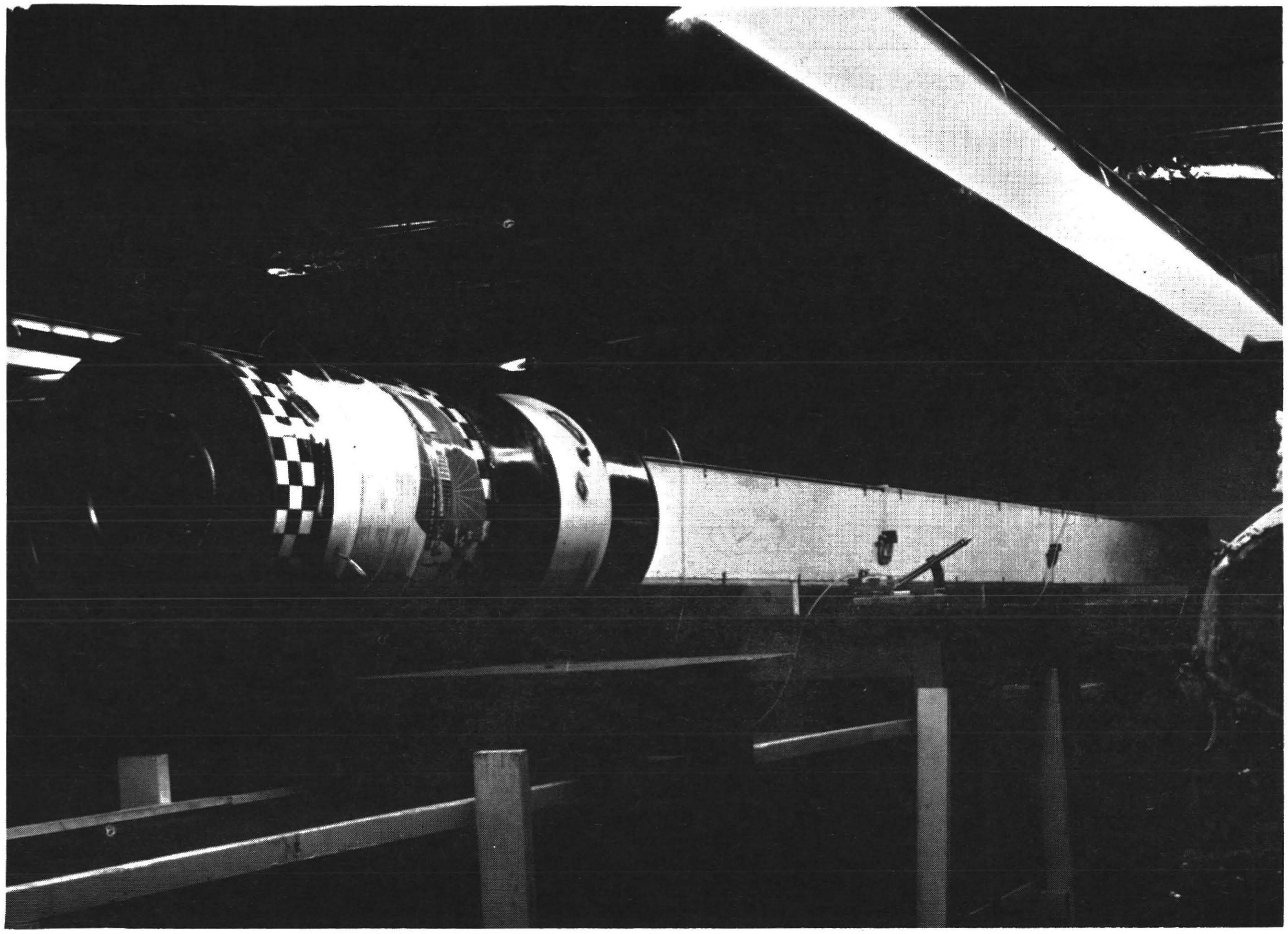


Figure 3. Experimental setup showing orifice meter, duct and air reservoir.

Orifice Meter

An orifice meter was used to measure the flow. The metering device consisted of a large drum which held the sharp-edged orifice plate at one end. Several sizes of orifice plates were used as needed. The other end of the drum was fitted with a plywood mask to fit over the duct. Inside the drum, screens were placed to damp out turbulence and obtain a nearly uniform velocity profile. Four pressure taps were placed around the periphery of the drum so that an integrated pressure inside the drum could be measured (see figure 3). A table of standard orifice coefficients was used for the flow calculations.

Static Pressure Measuring Tubes

Static pressure measuring tubes were used to obtain the pressure drop at 4-foot intervals along the duct. These tubes were constructed from 1/8-inch outside diameter stainless steel tubing. The main tube had five transverse tubes parallel to the mean flow direction and spaced 2-inches apart protruding from it. Each of these transverse tubes had 8 holes (0.010-inch) giving 40 holes with which to measure an integrated pressure at a given cross-section. The tips of these transverse tubes were rounded to hemispheres. See figures 4 and 5.

Point Gage

A point gage was used to measure roughness heights of bed elements attached to the plywood boards. These measurements were taken on a grid pattern at 0.1-foot by 0.2-foot intervals. The point gage was mounted on a carriage so it could be easily placed at the grid points.

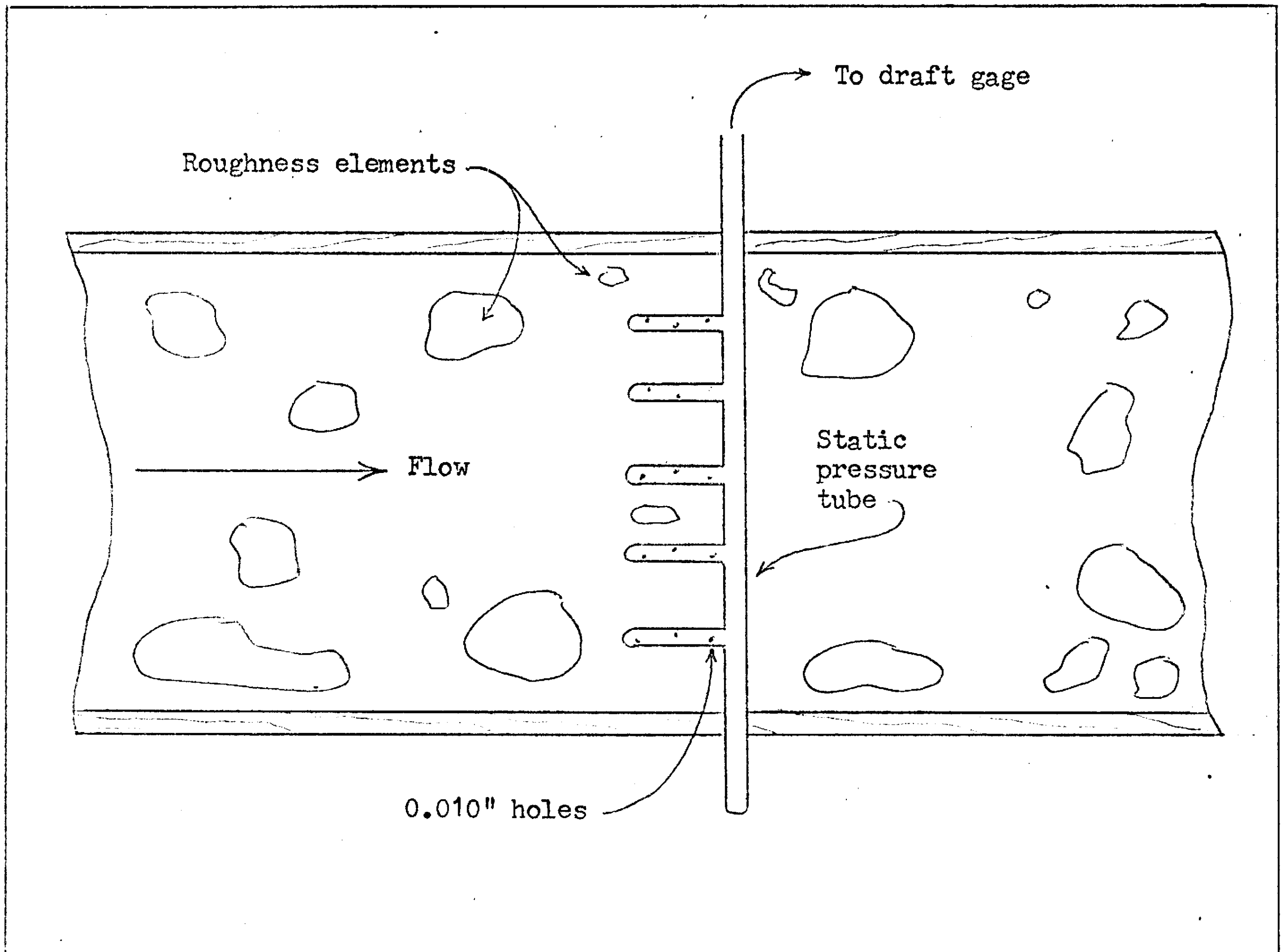


Figure 4. Diagram of static pressure tube placement in duct.

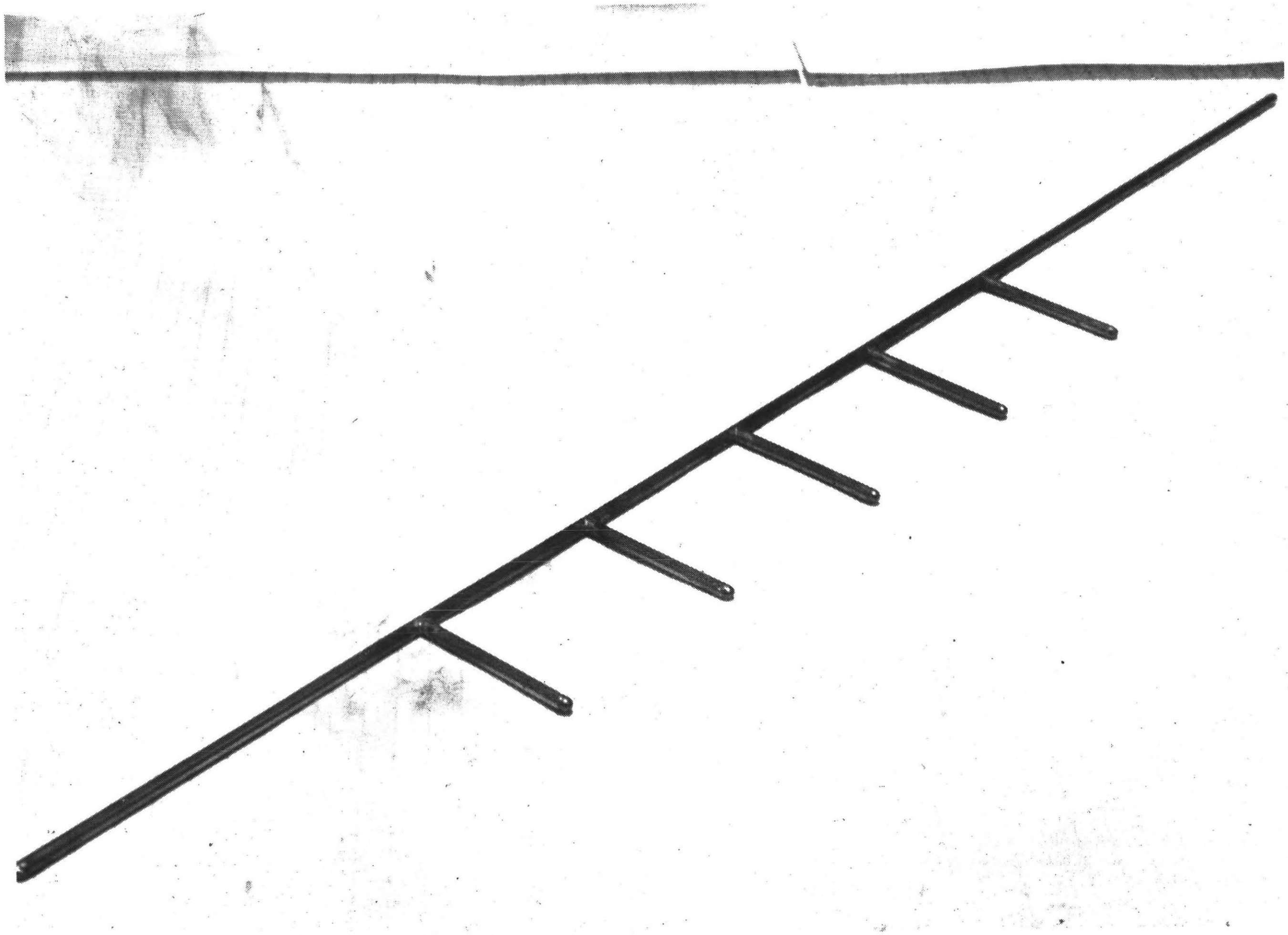


Figure 5. Static pressure measuring tube.

Draft Gages

Variable slope draft gages were used to measure pressure losses along the duct at 4-foot intervals and the pressure difference across the orifice. This gage could measure to an accuracy of 1/25 mm of 0.824 specific gravity oil pressure difference. The draft gage used at the orifice meter could measure to an accuracy of 0.01-inch of water.

Miscellaneous Equipment

A mercury barometer was used to measure barometric pressure for use in calculating air density.

A wet and dry bulb thermometer was used to measure relative humidity also for use in calculating air density. A psychometric chart was used also.

A thermometer was used to measure temperature inside the drum containing the orifice meter for use in determining viscosity, density and humidity.

CHAPTER V

EXPERIMENTAL PROCEDURE AND MEASUREMENTS

Bed and Roughness Elements

Judd (1963) found that in natural large bed element (LBE) high-gradient alluvial channels the grid point measurements of the roughness heights followed a normal distribution by number (not by weight). For this reason the beds were constructed using natural gravel elements such as occur in natural streams and were designed so that the sizes had a normal distribution so they would compare with natural open channels. Size and spacing were both varied. The 5/8-inch plywood beds were painted and the roughness elements attached to them according to the size and spacing designs explained later.

Grading

Two sizes and three spacing levels were used. The two size ranges were 4-inch maximum to a $\frac{1}{2}$-inch minimum and 2-inch maximum to $\frac{1}{4}$-inch minimum.

A design curve for size gradation (figure 6) was drawn to simulate Judd's data taken from natural stream beds. For the 4-inch maximum size beds, 1 percent of the number of roughness elements were larger than 4-inches and 99 percent of these elements were larger than $\frac{1}{2}$-inch. For the 2-inch maximum size beds, 1 percent of the number of roughness elements were larger than 2-inches and 99 percent of them larger than $\frac{1}{4}$-inch.

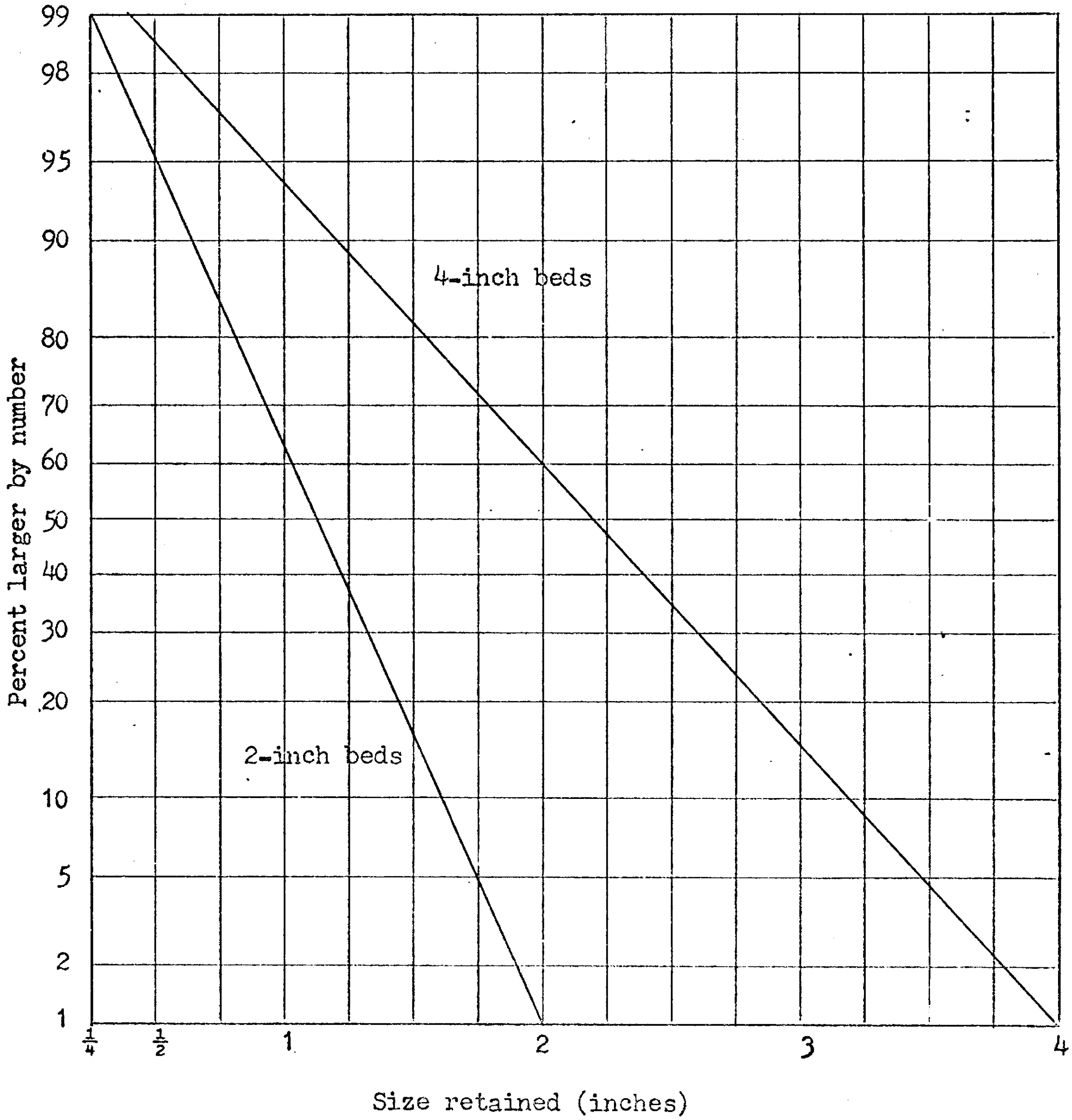


Figure 6. Roughness grading curves.

The roughness elements were sized by United States Standard Sieves of the following sizes: 4, 3, $2\frac{1}{2}$, 2, $1\frac{1}{2}$, 1, 3/4, $\frac{1}{2}$, 3/8, and $\frac{1}{4}$-inches. After sizing, the appropriate number of each size was counted and washed before being attached to the wooden beds.

Fixing Elements

The elements were attached to the plywood beds by means of Marsh Adhesive. Spacing or intensity was determined by finding a standard number (the number of roughness elements of a particular size distribution that could be placed on 1 square foot such that no elements were on top of another yet they were all touching).

The intensities used were: 1 standard number on 1 square foot, 1 standard number on 3 square feet, and 1 standard number on 5 square feet for both 2-inch and 4-inch sizes.

Each panel was subdivided into 100 small rectangles and numbered from 00 to 99. Before an element was attached to the bed, a random number was read from a table of random digits, Snedecor (1956) and placed on a small rectangular subdivision according to the 2 digit random number selected (figures 7 and 8, tables 1 and 2).

The following identification and description was used:

Identification	Description
21	1 standard number on 1 square foot, 2-inch to $\frac{1}{4}$-inch sizes
23	1 standard number on 3 square feet, 2-inch to $\frac{1}{4}$-inch sizes
25	1 standard number on 5 square feet, 2-inch to $\frac{1}{4}$-inch sizes
43	1 standard number on 3 square feet, 4-inch to $\frac{1}{2}$-inch sizes
45	1 standard number on 5 square feet, 4-inch to $\frac{1}{2}$-inch sizes

00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59
60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79
80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99

Figure 7. Panel subdivision for placement of bed elements by random number table.

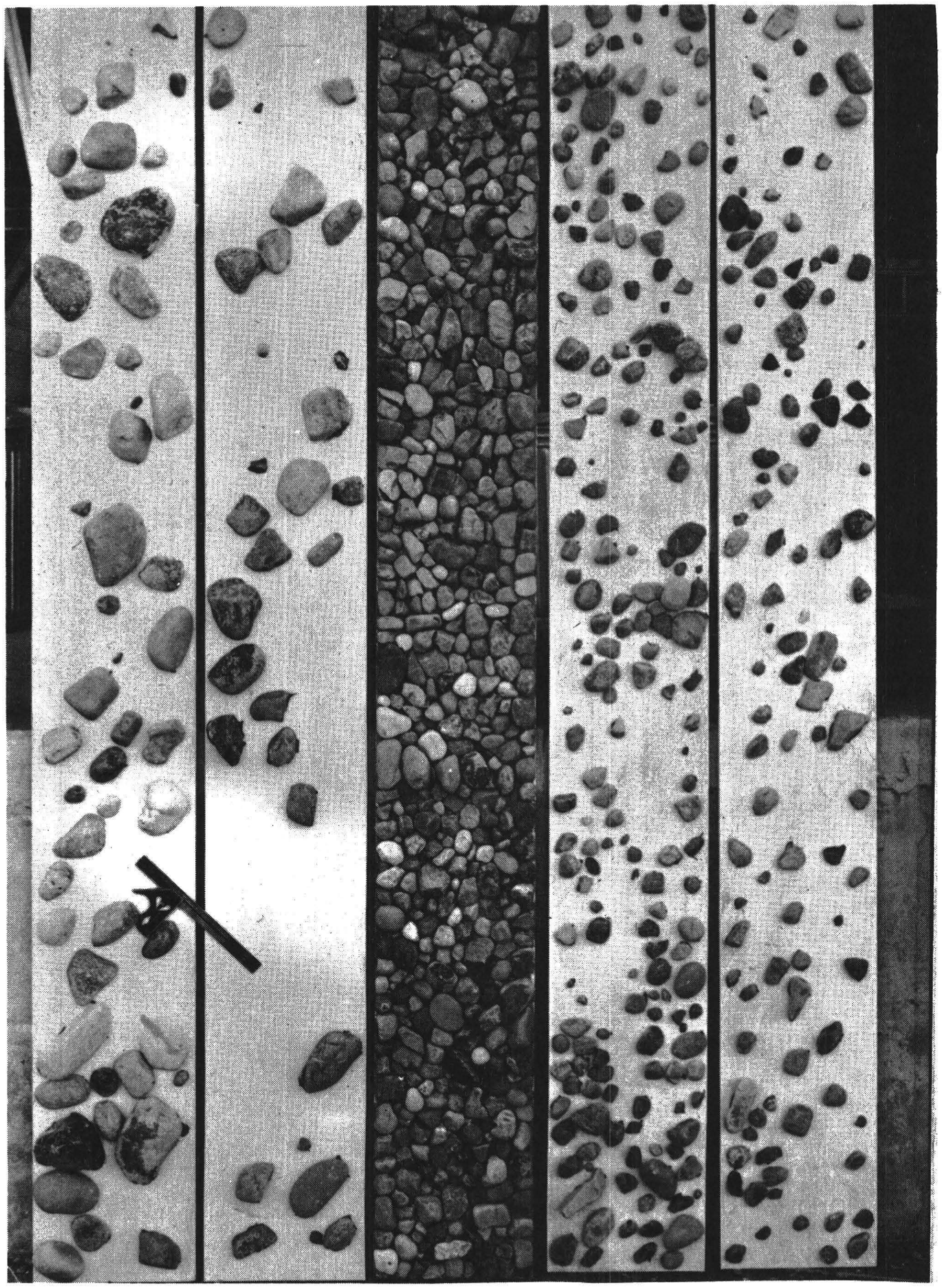


Figure 8. Samples of experimental beds used.

Table 1. Two-inch grading design data by number of elements per 8 square foot panel.

Size	Percentage by Number	Bed Identification Number		
		21	23	25
Number of elements passing 2-inch sieve and retained on 1½-inch sieve	15.0	85	28	17
Number of elements passing 1½-inch sieve and retained on 1-inch sieve	47.0	265	89	53
Number of elements passing 1-inch sieve and retained on 3/4-inch sieve	21.0	120	40	12
Number of elements passing 3/4-inch sieve and retained on ½-inch sieve	11.0	64	22	13
Number of elements passing ½-inch sieve and retained on 3/8-inch sieve	2.5	16	5	3
Number of elements passing 3/8-inch sieve and retained on ½-inch sieve	1.5	10	3	2

Table 2. Four-inch grading design data by number of elements per 8 square foot panel.

Size	Percentage by Number	Bed Identification Number		
		41	43	45
Number of elements passing 4-inch sieve and retained on 3-inch sieve	14.0	22	7	4
Number of elements passing 3-inch sieve and retained on $2\frac{1}{2}$-inch sieve	19.0	29	10	6
Number of elements passing $2\frac{1}{2}$-inch sieve and retained on 2-inch sieve	26.0	40	13	8
Number of elements passing 2-inch sieve and retained on $1\frac{1}{2}$-inch sieve	21.0	32	11	6
Number of elements passing $1\frac{1}{2}$-inch sieve and retained on 1-inch sieve	13.0	20	7	4
Number of elements passing 1-inch sieve and retained on 3/4-inch sieve	3.0	5	2	1
Number of elements passing 3/4-inch sieve and retained on $\frac{1}{2}$-inch sieve	2.0	3	1	1
Number of elements passing $\frac{1}{2}$-inch sieve and retained on $\frac{1}{4}$-inch sieve	1.0	2	1	0

Roughness Measurements

After roughness elements were attached to the beds one panel from each set was selected at random for measurement. It was divided into a grid system 0.2-foot by 0.1-foot and the heights measured with a point gage at the grid points. Three-hundred-and-sixty-one points on each of the 5 different beds were measured.

Miscellaneous

Each of the 5 sets of beds were used at 3 different depths (changing number of tongue and groove boards between panels containing roughness elements). At each depth, the velocity was varied over 15-levels by changing the speed of the fan.

CHAPTER VI

GENERAL OBSERVATIONS

Velocity Direction at Center-line

A pitot tube was used to find the direction of the velocity along the center-line between the roughness elements at 2-inch intervals. The velocity was held at approximately 15-feet per second for each of 15 runs. In every case, the center-line velocity vector was found to deviate not more than 10 degrees from the center-line of the duct, even for relative roughness values near 1.0. This indicates that the precision with which the pressure could be measured in the duct with the static pressure tubes (which were located only on the center-line) should be very good as a pitot tube yields good accuracy up to 15 degrees deviation of flow from its axis of symmetry. However, near the roughness elements, the direction of flow was found to vary continuously from parallel to the duct, to an adverse direction.

Velocity Profiles

Several velocity profiles were taken near the entrance of the duct to check the uniformity of the approaching velocity profile. If the entrance velocity profile was not uniform, the duct was moved in or out to change the amount of air being "bled off" at the leading edge until a uniform profile was obtained. Measurements with a pitot tube showed the velocity profile to be uniform at the center-line but becoming very erratic near the roughness elements. Near the elements, pressure measurements were taken which indicated anything from stagnation velocity to slightly greater than the mean velocity. The velocity at the duct center-line was found to be very near the mean velocity in every case, which gave a check on the flow rate measurements taken with the orifice meter.

CHAPTER VII

ANALYSIS

Parameter Analysis

The parameter $C/g^{\frac{1}{2}}$ is a constant which measures the ability of an open channel to conduct flow of a fluid as depth and slope are varied, therefore, it can be called a conductance coefficient. The conductance coefficient accounts for the resistance due to skin friction as well as the form drag resulting from flow deformation which includes free surface effects associated with gravity, principally gravity waves and spills. $C/g^{\frac{1}{2}}$ decreases with increasing surface waves.

The free surface activity is generally modeled with Froude number, both form drag and skin friction may vary with R_D which also measures the relative importance of viscosity. In consideration of the importance of form drag the roughness height K_n might just as well be used as the length parameter in the Reynolds number, giving R_K. R_D and R_K are proportional for any particular bed.

The relative roughness D/K_n has a great influence upon $C/g^{\frac{1}{2}}$ as it is the primary factor controlling the development of the boundary layer, the amount of flow deformation and surface activity. As D/K_n increases $C/g^{\frac{1}{2}}$ increases also.

The spacing of the roughness elements as measured by θ or I also influences $C/g^{\frac{1}{2}}$. Under idealized roughness and depending upon the spacing and velocity the flow may take one of the following forms:

1. Isolated-roughness flow
2. Wake-interference flow
3. Quasi-smooth flow

as suggested by Morris and shown in figure 9. Isolated-roughness flow occurs when the wake and vortex of each element is dissipated before the next element is encountered. Wake-interference flow occurs when the wake and vortex from one element interferes with one or more elements downstream. The resulting flow pattern becomes very complex. Quasi-smooth flow prevails when the roughness elements are spaced so close that the flow skims the tops of the elements and a hydraulically smooth boundary condition is approximated.

Data Analysis

In addition to the data taken using the air duct, raw data for the open channel phase of the study were taken from Abdelsalam's dissertation. These data included:

1. Discharge
2. Depth D
3. Slope S
4. Viscosity
5. Average roughness height
6. Velocity V
7. Froude number $F = V/(Dg)^{\frac{1}{2}}$
8. Reynolds number $R_D = \rho VD/\mu$ and $R_K = \rho VK_n/\mu$
9. Conductance coefficient $C/g^{\frac{1}{2}} = V/(DSg)^{\frac{1}{2}}$
10. Relative roughness D/K_n

All values of K_n in equations 21 and 22 are K_{25} which is the roughness height for which 25 percent of the roughness heights are larger.

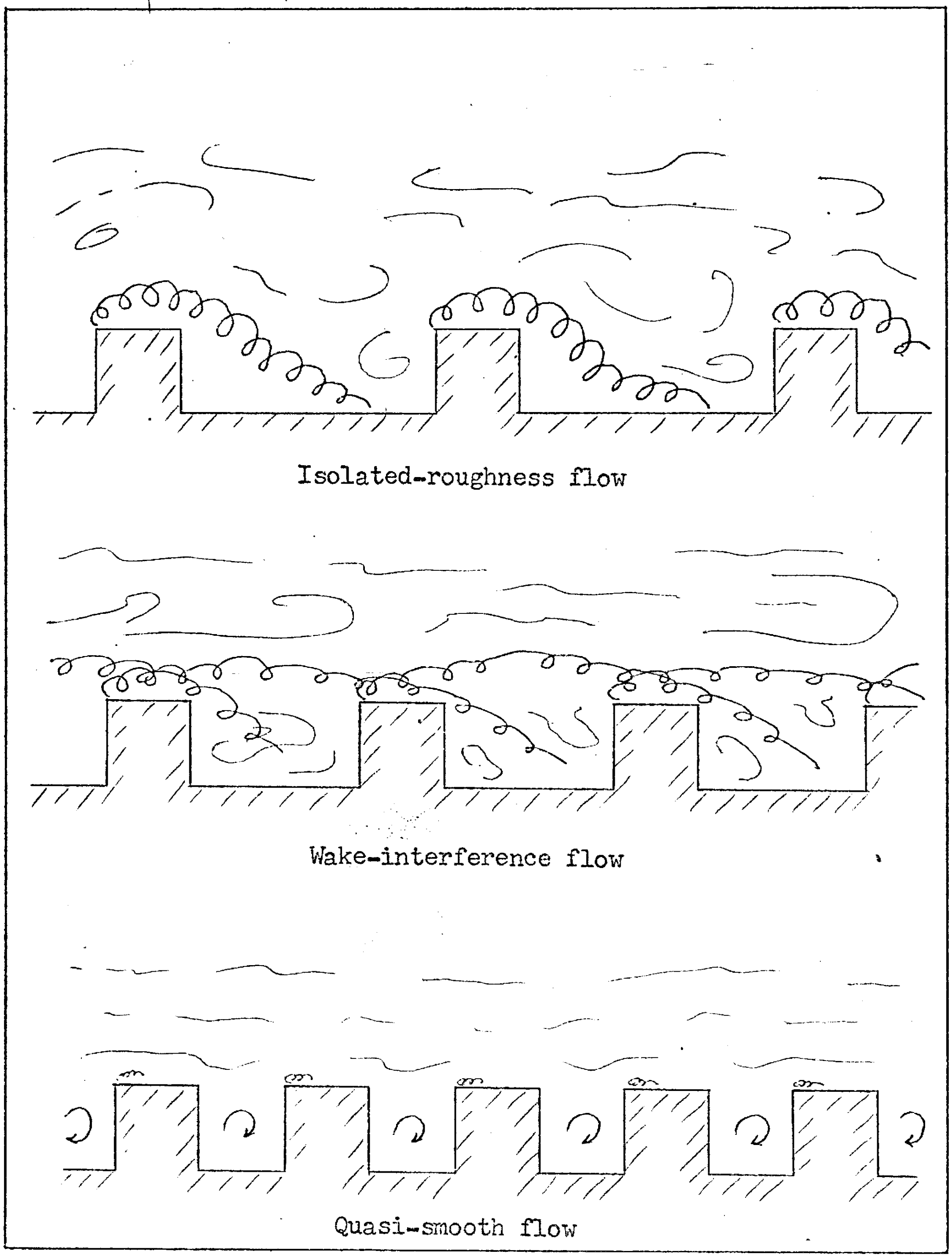


Figure 9. Sketch of the Morris concept of flow over rough surfaces. Adopted from Open Channel Hydraulics by V. T. Chow (1959).

For the closed conduit, the following information was tabulated and analyzed using the IBM 1620 Computer System:

1. Velocity $V = (C_o A_o / A) \quad (2 \Delta p / \rho)$.

2. Depth D = one-half the distance back to back of the boards on which the roughness elements were mounted minus twice the effective roughness height. Effective roughness height is the height of the volume of the roughness elements if they were all melted down to the same level.

3. Area A = D since the width was 1-foot.

4. Air density ρ = specific weight of air/g. Specific weight of air was found by the use of a psychrometric chart knowing the barometric pressure and the wet and dry bulb temperature.

5. Conductance $C/g^{\frac{1}{2}} = V/(D \Delta p/\rho)^{\frac{1}{2}}$ as slope $S = \Delta p$/specific weight of air.

6. Reynolds number $R_D = \rho VD/\mu$ and $R_K = \rho VK_n/\mu$.

7. Slope $S = \Delta p$/specific weight of air.

8. Relative roughness D/K_{25} and D/K_{16}.

The relative roughness D/K_{25} was used so that results could be compared to the free surface case. Abdelsalam's bed element distribution curves were drawn with points of zero height excluded (appendix B) and K_{25} values for each bed were taken from these curves. For the analysis other than the free surface phase, the writer prefers to use the method of Judd in which the bed element distribution curves for the same data are drawn including zero points (appendix A). K_{16} values are obtained from these distributions for each bed. The 16-percent-larger size K_{16} was chosen to be the characteristic bed element height because the higher elements cause most of the disturbance and are therefore more effective in characterizing the flow.

The calculated parameters for the closed conduit experiment are included in appendix C of this dissertation.

CHAPTER VIII

RESULTS AND DISCUSSION

Bed Analysis

The beds were described statistically by using the roughness height measurements taken at the grid points. The average of all points for each bed was calculated, this is the effective roughness height. The effective roughness height was subtracted from the individual readings, then the cumulative percent larger was plotted against the height above and below the mean plane (effective roughness height) on normal probability paper. See appendix A. These plots show straight lines only for the beds having the closest roughness spacing. An inspection of the curves shows that the zero points are causing the non-linearity to occur, so plots were drawn using only the grid points of height greater than zero (appendix B), these show a somewhat normal distribution and are the same as those of Abdelsalam (1965), and similar to the findings of Judd (1963) on natural streams.

The most difficult task involving the spacing parameter is finding a truly descriptive relationship for it. Judd described his spacing relationship as

$$I_j = A^{\frac{1}{2}} / K_n N \qquad (23)$$

where I_j appeared to be a constant for a particular bed. Abdelsalam used two methods to express a spacing parameter

$$I_1 = (A/xzN)^{\frac{1}{2}} K_{25}/K_n \qquad (24)$$

$$I_2 = x \;\; A_v/AK_{25} \qquad (25)$$

and both I_1 and I_2 are constant for a particular bed.

Herbich and Shulits (1964) used a method of measuring roughness spacing for geometrically uniform roughness elements spaced at regular intervals. In this method, the vertical projection of area of all roughness elements is expressed as a ratio to the total bed area

$$\theta = \Sigma A_v/A \tag{26}$$

where θ is the spacing parameter and ΣA_v is the sum of the vertical projected areas of all roughness elements contained in area A. θ is readily evaluated for geometrical shapes but for the rounded natural roughness elements used in this experiment, θ was calculated assuming the roughness elements to be spheres. The number of elements of each size was counted and multiplied by their respective vertical projected areas, these were then summed and divided by the total bed area A.

I_j, I_1 and θ can be written in terms of each other, from equations 23 and 24

$$I_j = I_1 \, (xz)^{\frac{1}{2}}/K_{25} \tag{27}$$

also

$$\theta = \Sigma A_v/A$$

substituting

$$A = I_1^2 \, Nxz \, K_n/K_{25}$$

from equation 24 and

$$A_v \propto NK_n^2$$

$$\theta = C' \, K_n K_{25}/I_1^2 \, xz = C''/I_j^2 \tag{28}$$

Table 3 gives spacing parameter values for each method discussed.

Table 3. Values of various intensity parameters for experimental flume beds.

Bed	I_j	I_1	I_2	θ
21	2.33	2.32	5.47	0.392
23	4.00	4.50	2.02	0.133
25	5.20	4.88	1.74	0.078
43	3.82	3.31	2.27	0.151
45	5.00	4.82	1.17	0.088

The data from this study showed $C/g^{\frac{1}{2}}$ to be at a minimum value when θ is between 0.15 and 0.25 (figure 10). This can be related to the Morris concept of flow over rough surfaces as shown in figure 9. Where θ is a minimum, resistance to flow is maximum. This occurs when the predominant larger elements that control the flow are spaced such that on a statistical basis their wakes are dissipated just before another of these elements is encountered or so that the balanced effect of the spacing produces a maximum resistance to flow through wake and surface activity formation. If the elements are spaced farther apart so that θ approaches zero, channel resistance decreases and in effect an isolated-roughness condition occurs. As the larger elements are placed closer together so that θ exceeds the minimum value, the predominant effect would be that some of the larger element wakes would begin to interfere with flow around downstream elements and again the channel resistance would decrease.

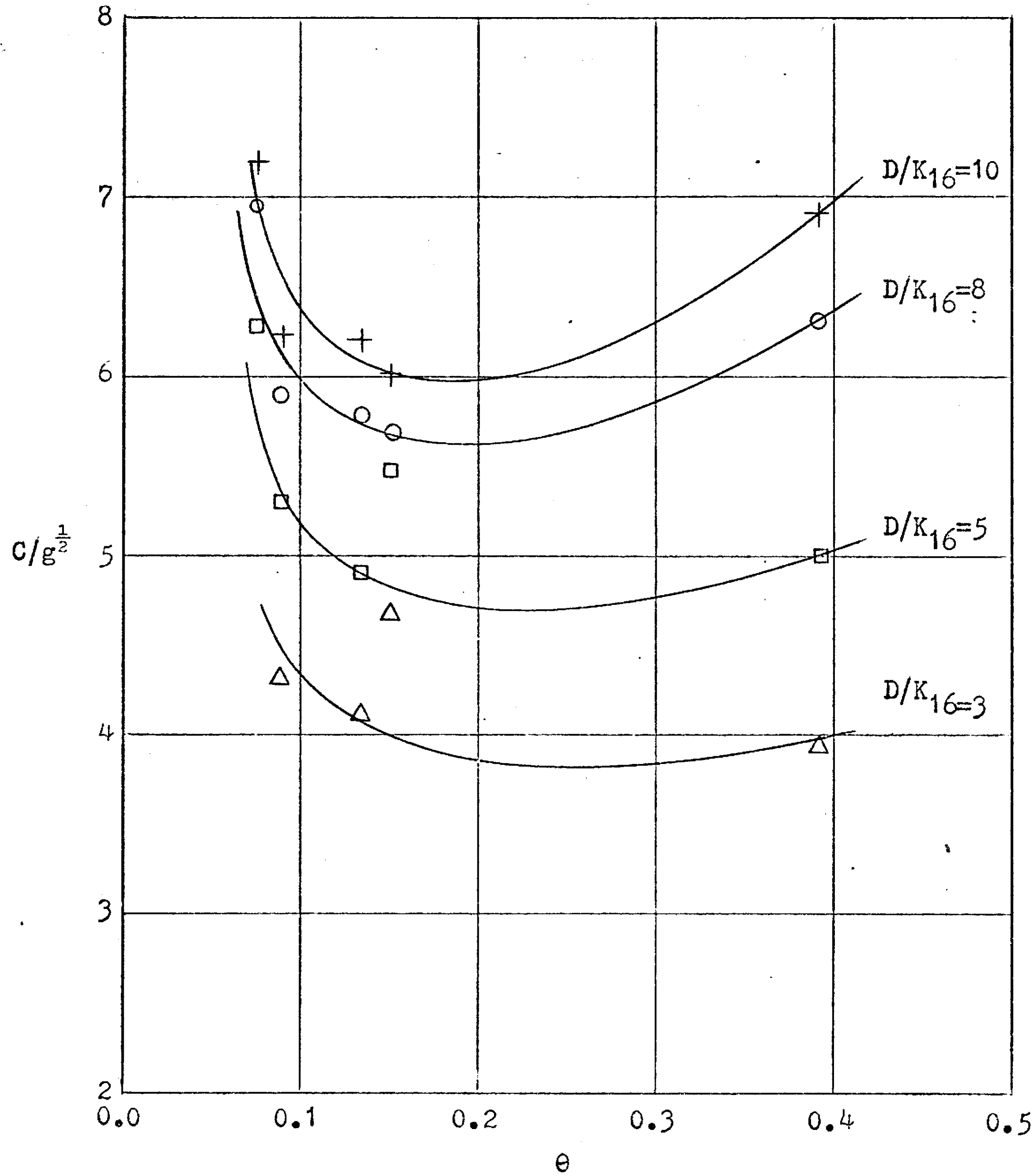


Figure 10. Plot of $C/g^{\frac{1}{2}}$ vs. θ

The shape of the roughness elements has an influence on the wake formed behind them. Spheres and hemispheres seem to cause less wake than irregular and angular elements as born out by the fact that in this experiment when θ was at a minimum value the wake length is about 5K while others have found wake lengths between 10K and 15K for baffles and angular roughness elements.

The larger elements contribute a large amount to the channel resistance. Judd has shown this to be true by establishing good correlations using only the largest elements in the channel.

Flow Analysis

Plots were drawn from experimental values of velocity versus slope at various depths for each of 5 beds tested (figures 11 through 15). These plots of the experimental data show that velocity varies as the square root of the slope, confirming the validity of the Chezy equation.

Energy Dissipation Due to Presence of Free Surface

No free surface existed in this experiment, but all other factors such as Reynolds number, beds and relative roughness were designed to be the same as for the free surface data. Plots were drawn of $C/g^{\frac{1}{2}}$ versus R_K at various values of D/K_{25} (figures 16 through 20). Conductance coefficients between the open channel and closed conduit were compared at corresponding values of R_K and D/K_{25}. Another plot was drawn having the proportion of $C/g^{\frac{1}{2}}$ lost due to the presence of a free surface as the ordinate and D/K_{25} as the abscissa as shown in figure 21. A curve fitting method which minimizes the sum of squared orthogonal deviations was used to fit the data to a line

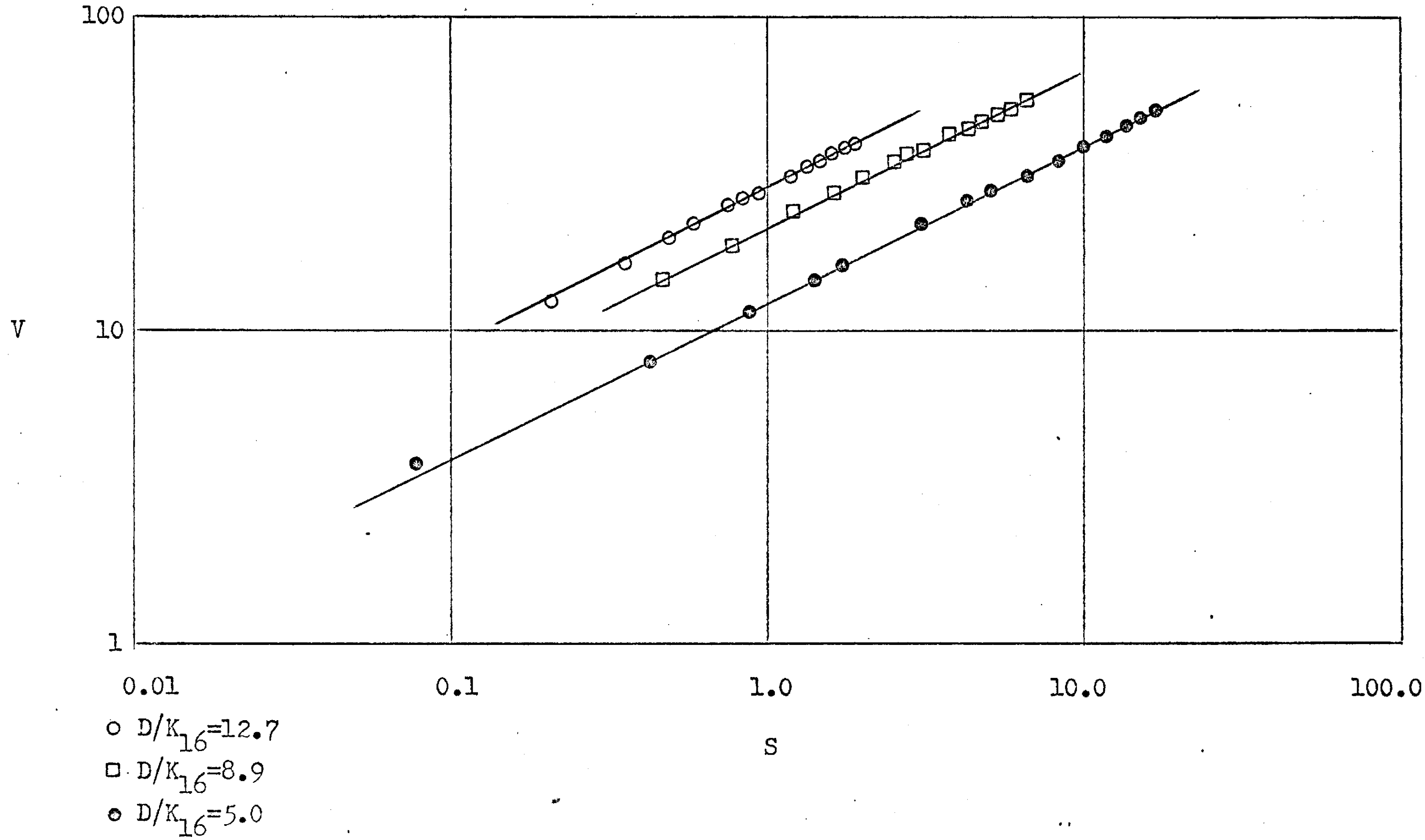


Figure 11. Velocity versus slope for bed 21. Slope of lines 0.501.

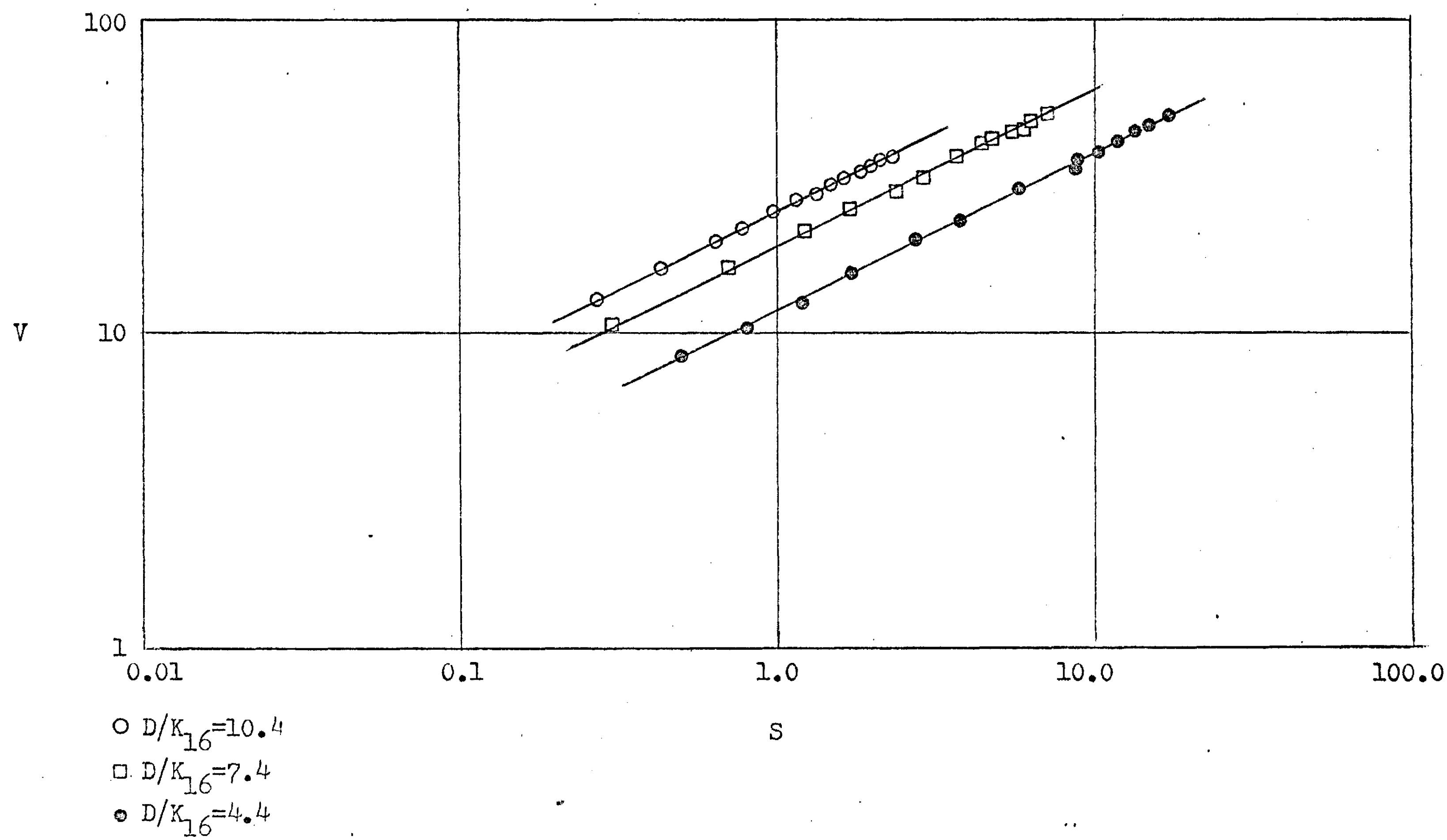


Figure 12. Velocity versus slope for bed 23. Slope of lines 0.501.

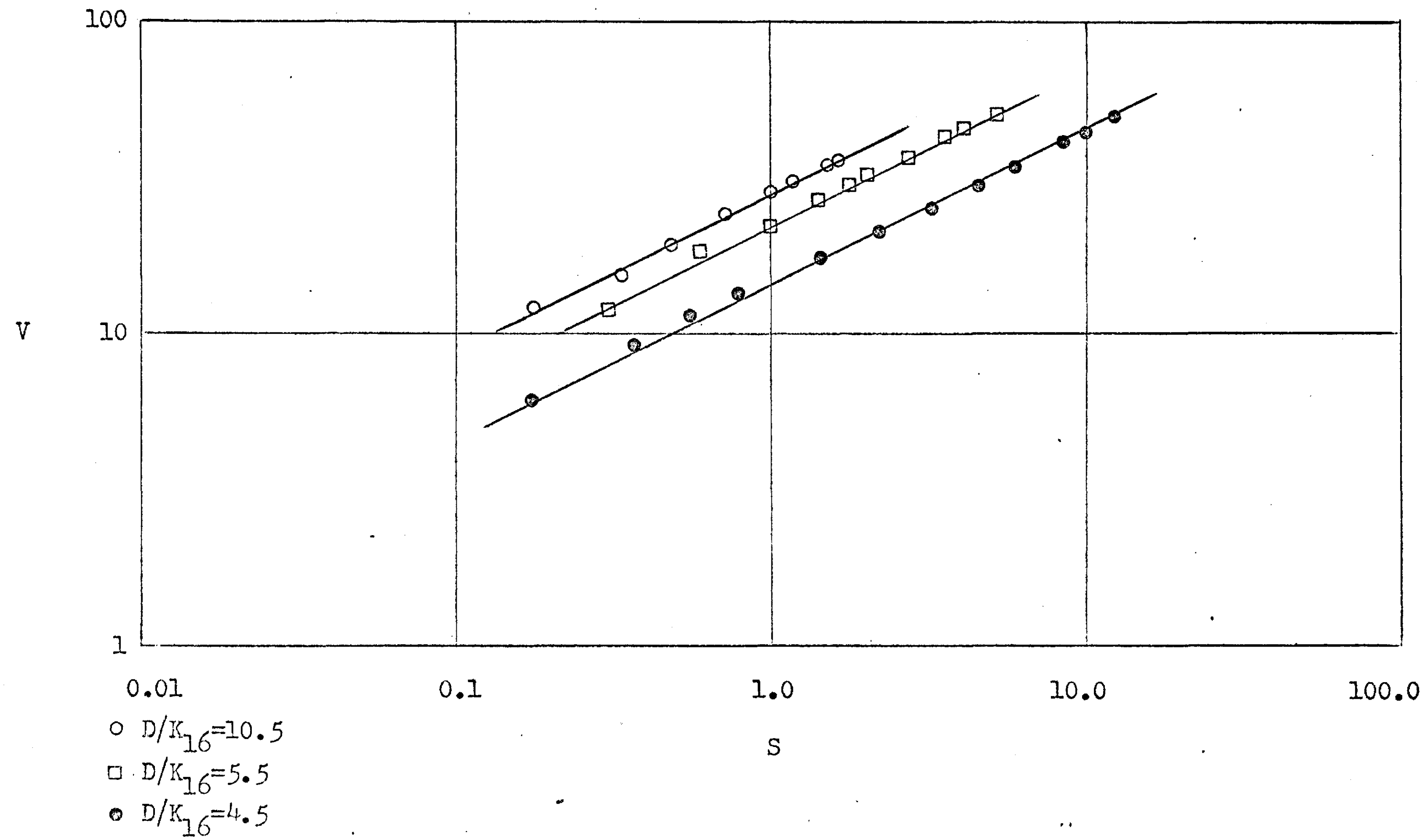
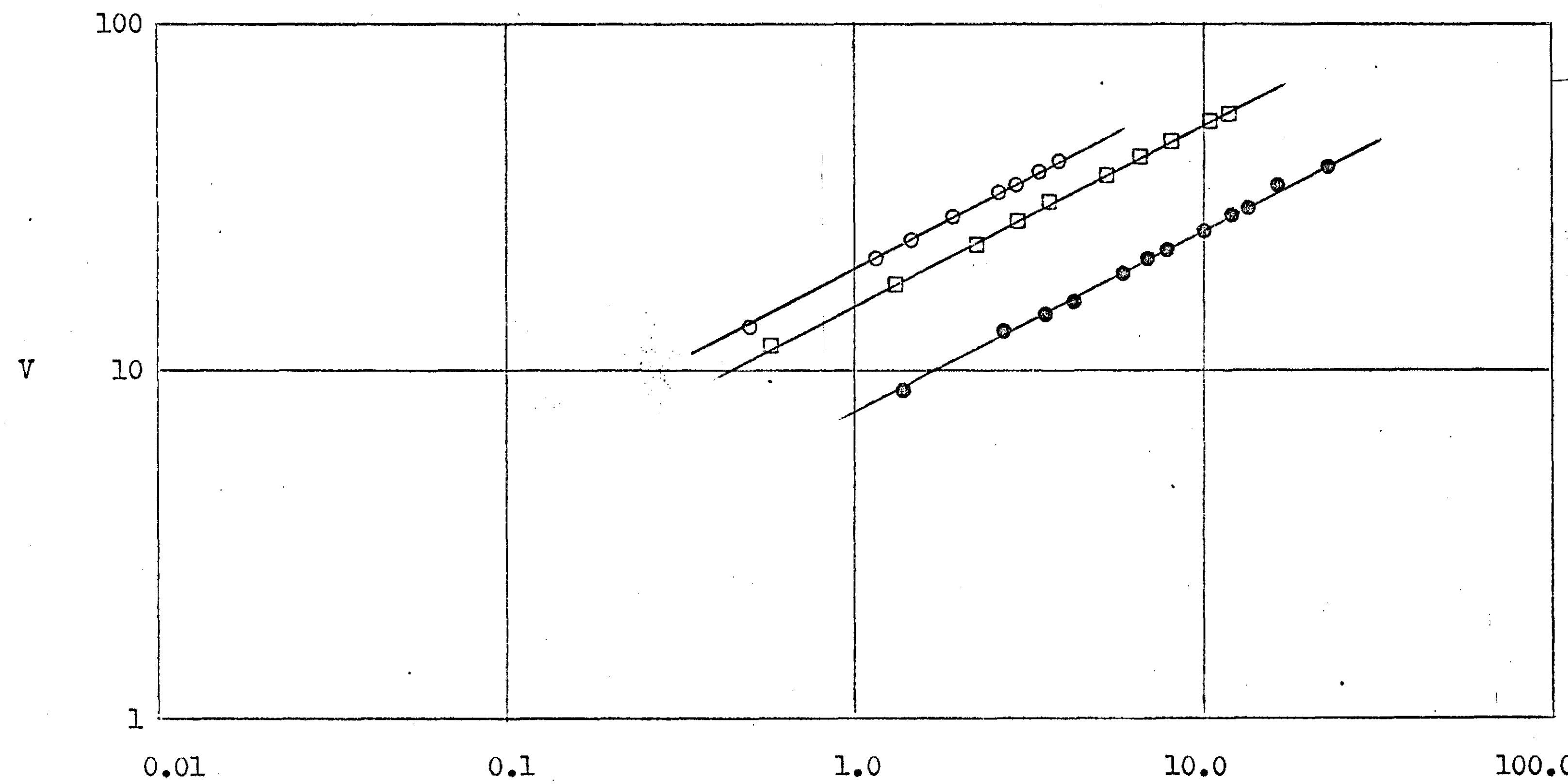


Figure 13. Velocity versus slope for bed 25. Slope of lines 0.501.



○ $D/K_{16}=4.6$
□ $D/K_{16}=3.2$
● $D/K_{16}=1.8$

Figure 14. Velocity versus slope for bed 43. Slope of lines 0.520.

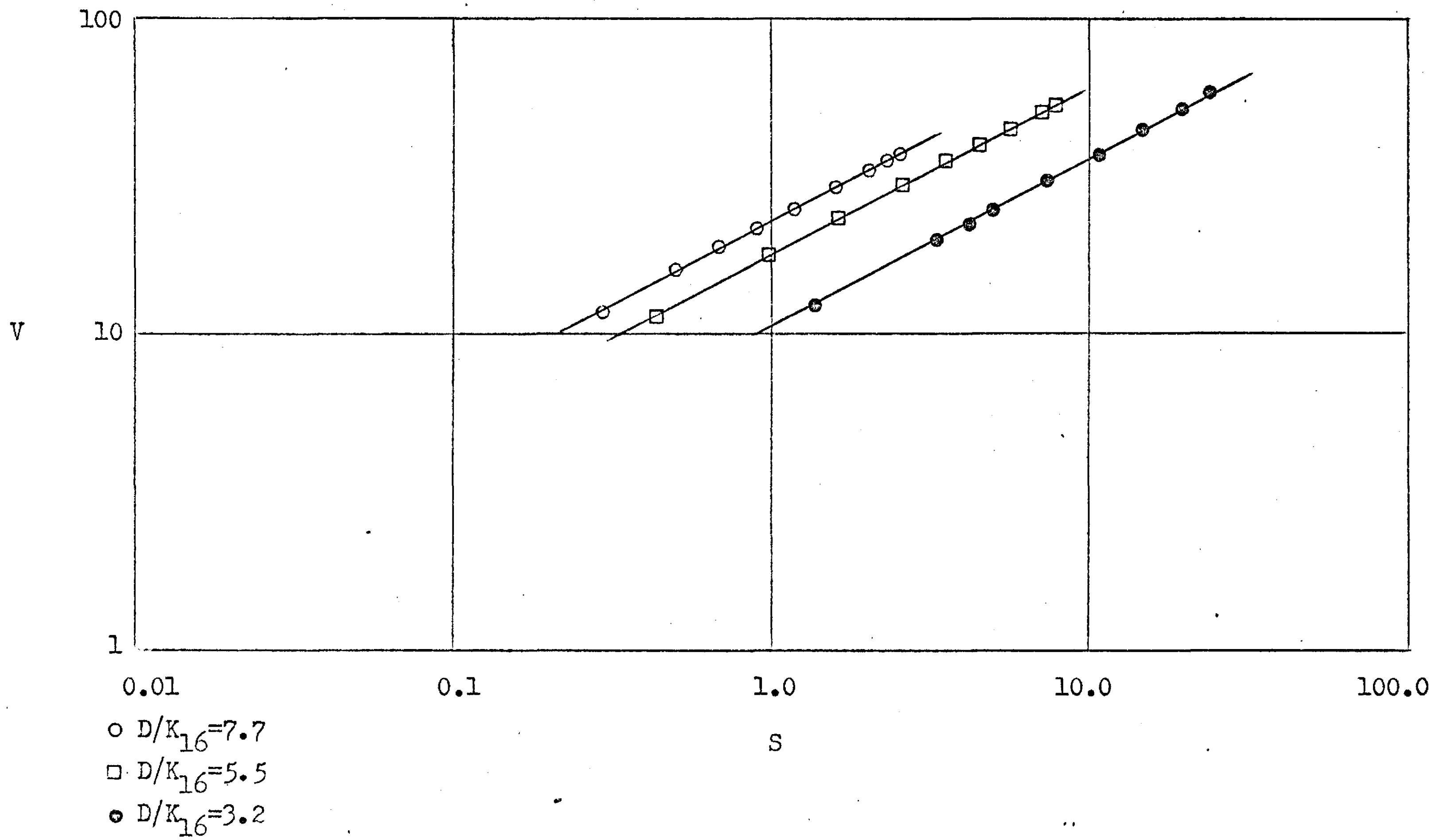


Figure 15. Velocity versus slope for bed 45. Slope of lines 0.522.

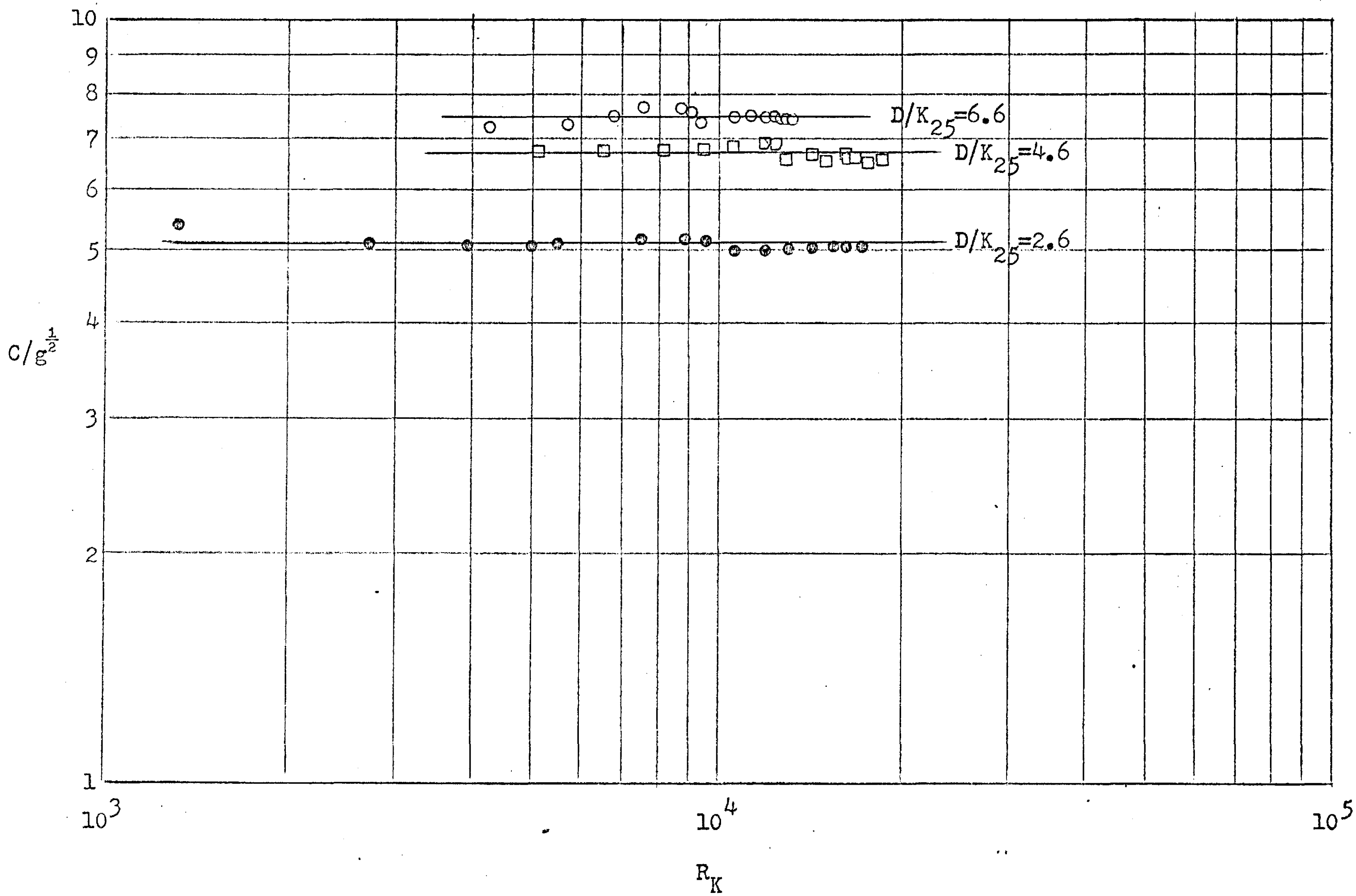


Figure 16. $C/g^{\frac{1}{2}}$ versus R_K for bed 21.

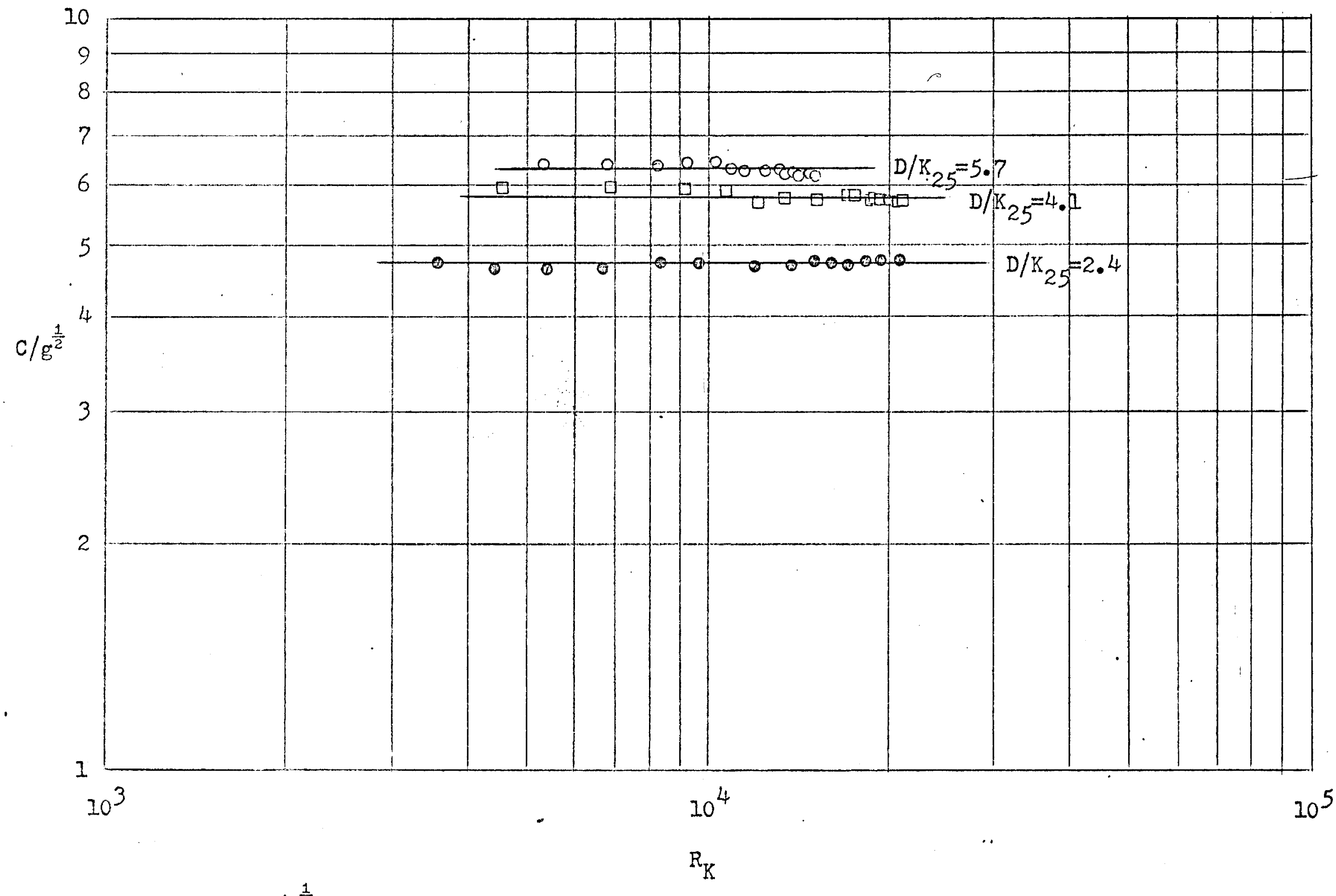


Figure 17. $C/g^{\frac{1}{2}}$ versus R_K for bed 23.

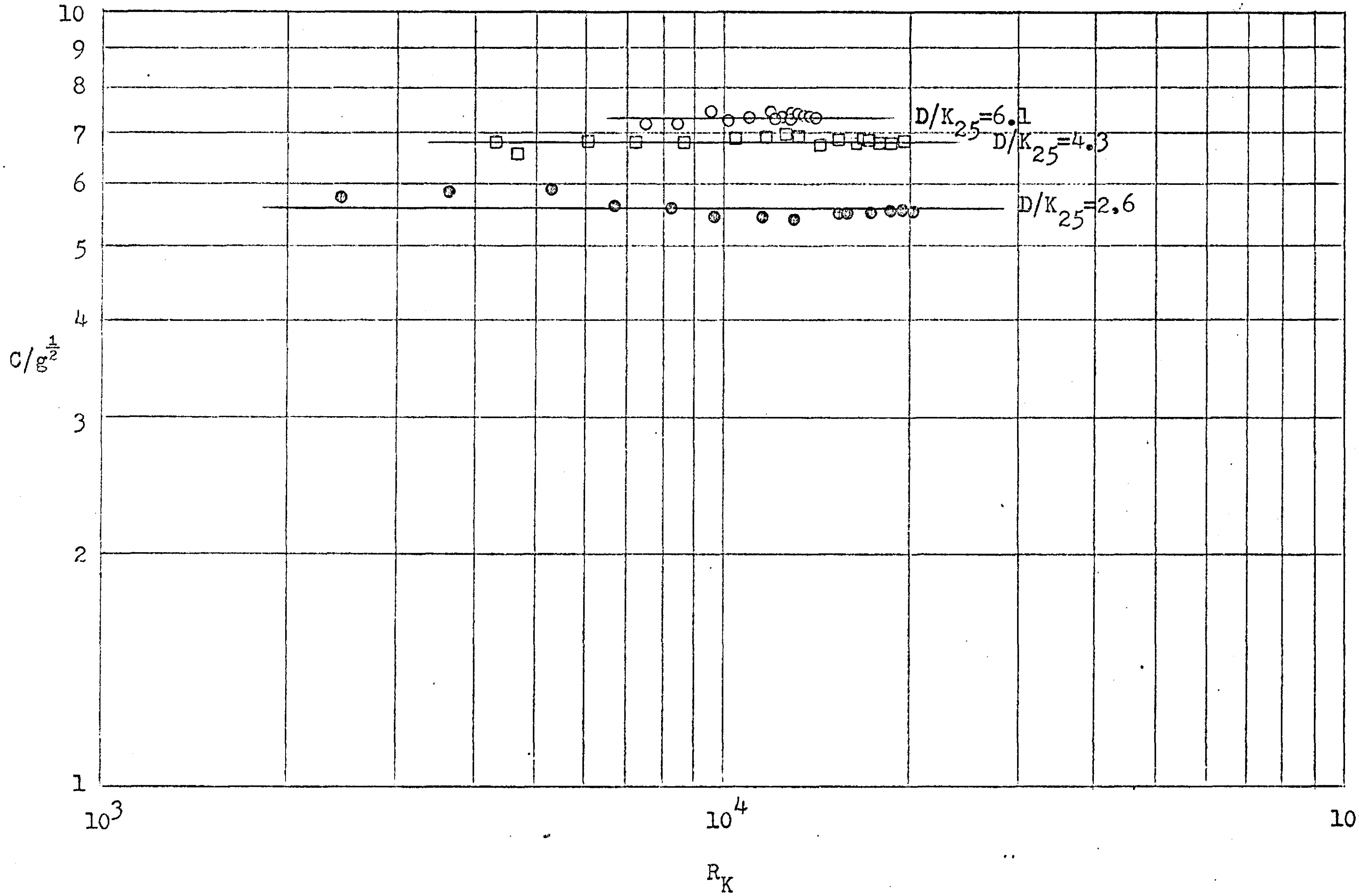


Figure 18. $C/g^{\frac{1}{2}}$ versus R_K for bed 25.

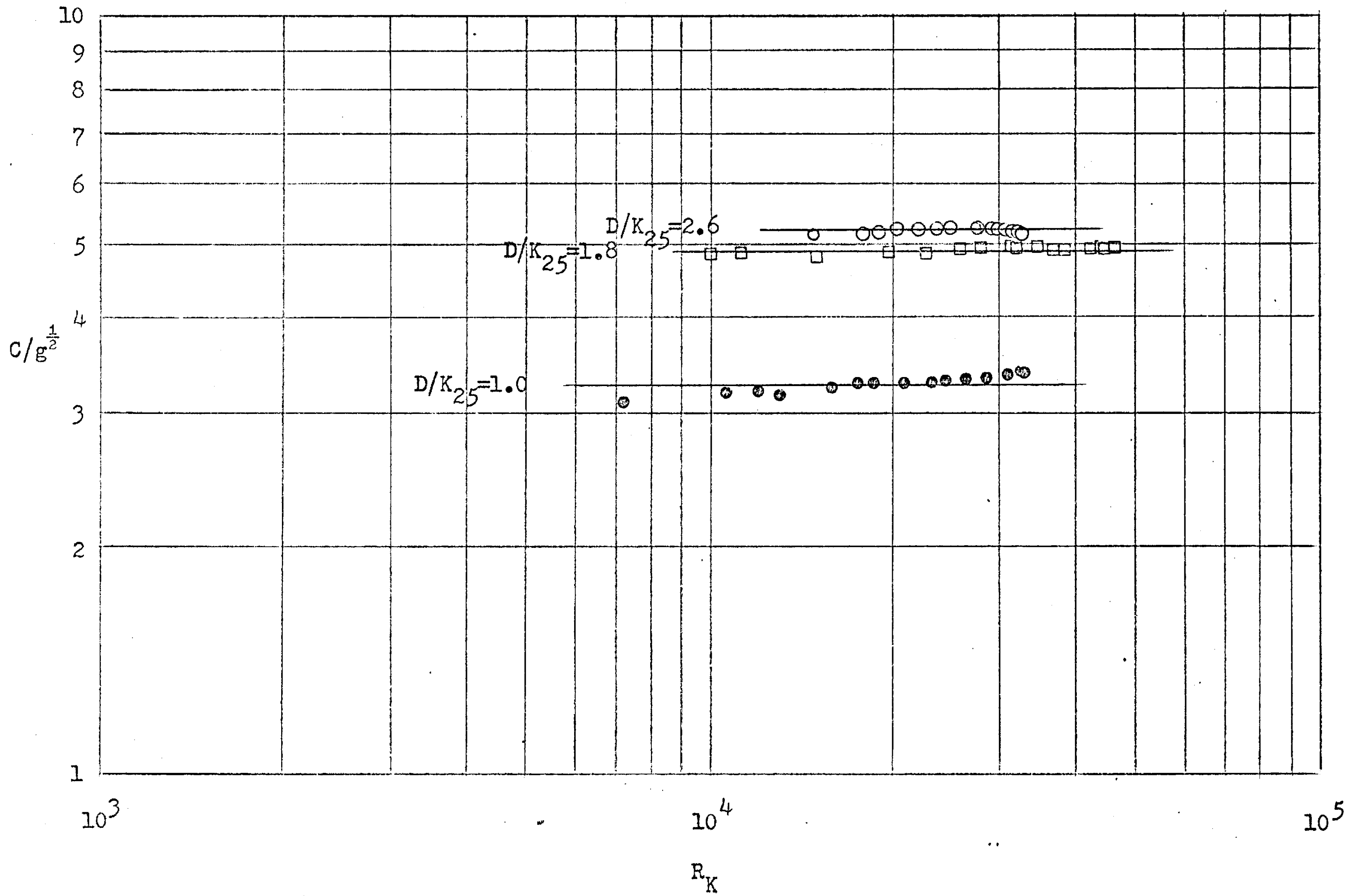


Figure 19. $C/g^{\frac{1}{2}}$ versus R_K for bed 43.

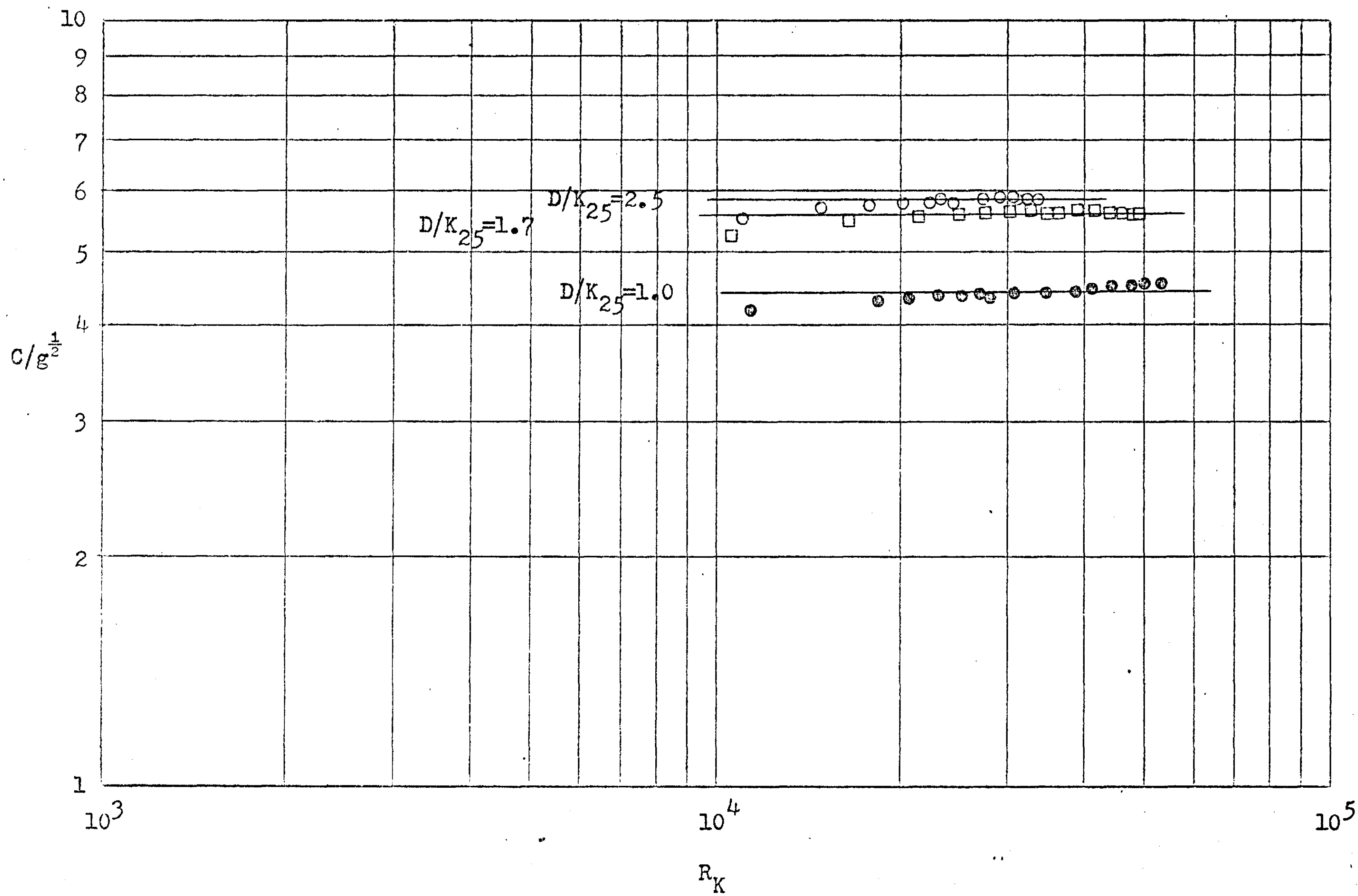


Figure 20. $C/g^{\frac{1}{2}}$ versus R_K for bed 45.

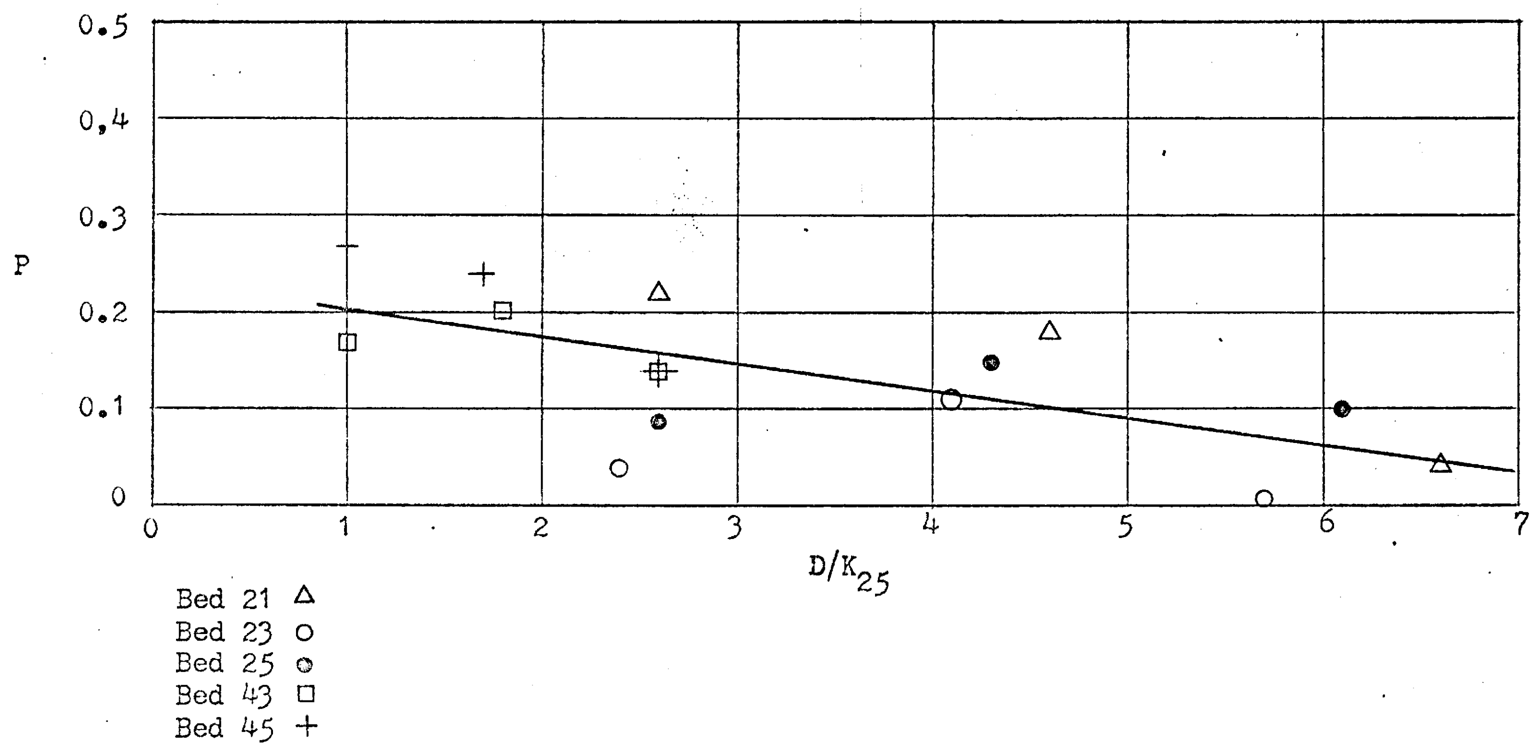


Figure 21. P versus D/K_{25}.

$$P = 0.23 - 0.028\ D/K_{25} \tag{29}$$

where D/K_{25} varied from 1 to 7 and P is the proportion of $C/g^{\frac{1}{2}}$ lost due to presence of a free surface. This model produced a correlation coefficient of 0.66 and an F-test value of 9.8 at 1 and 13 degrees of freedom which is significant at more than 0.99 confidence level. Other models containing the parameter θ were also tested but θ was found to contribute nothing to improve the correlation and in fact decreased the F-test value. When the relative roughness $D/K_{25} \sim 7.0$ there was no appreciable difference in the energy loss between the case with a free surface and the case without a free surface, if relative roughness decreases there is an additional loss of energy in the free surface case caused by breaking surface waves and local spills and jumps. This additional loss of energy appears to be about 20 percent when a relative roughness of 1.0 is reached.

Reynolds Number Analysis

Plots of the conductance coefficient versus R_K and R_D at various D/K_{25} values were made for each of the 5 beds tested (figures 16 through 20 and 22 through 26). These plots show the Reynolds number had no significant effect upon the conductance coefficient in the range of

$$3 \times 10^3 < R_K < 6 \times 10^4$$

$$3 \times 10^3 < R_D < 1 \times 10^5$$

therefore, equation 22 can be written as

$$C/g^{\frac{1}{2}} = F\ (D/K_n,\ \theta) \tag{30}$$

for the closed conduit.

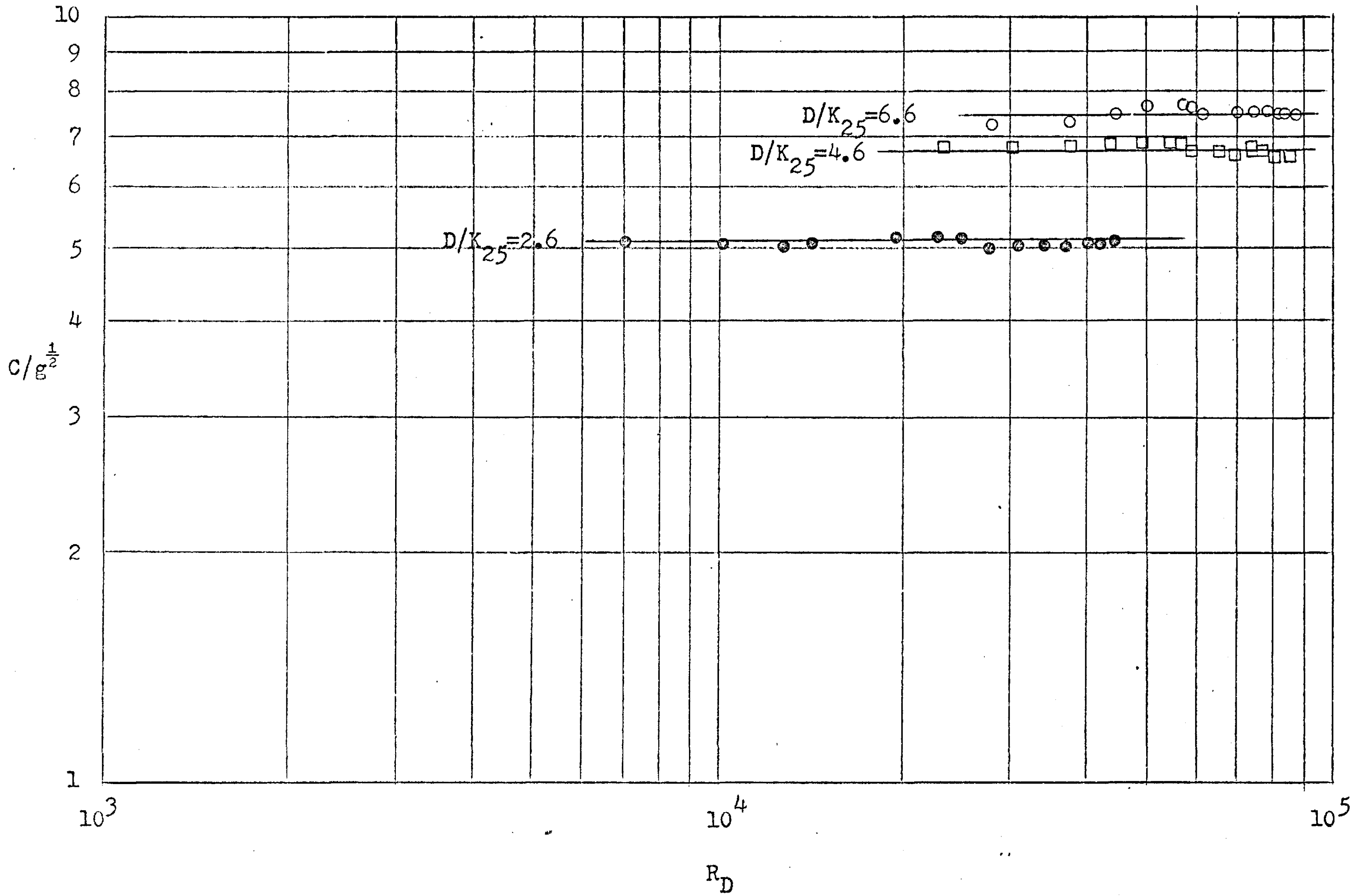


Figure 22. $C/g^{\frac{1}{2}}$ versus R_D for bed 21.

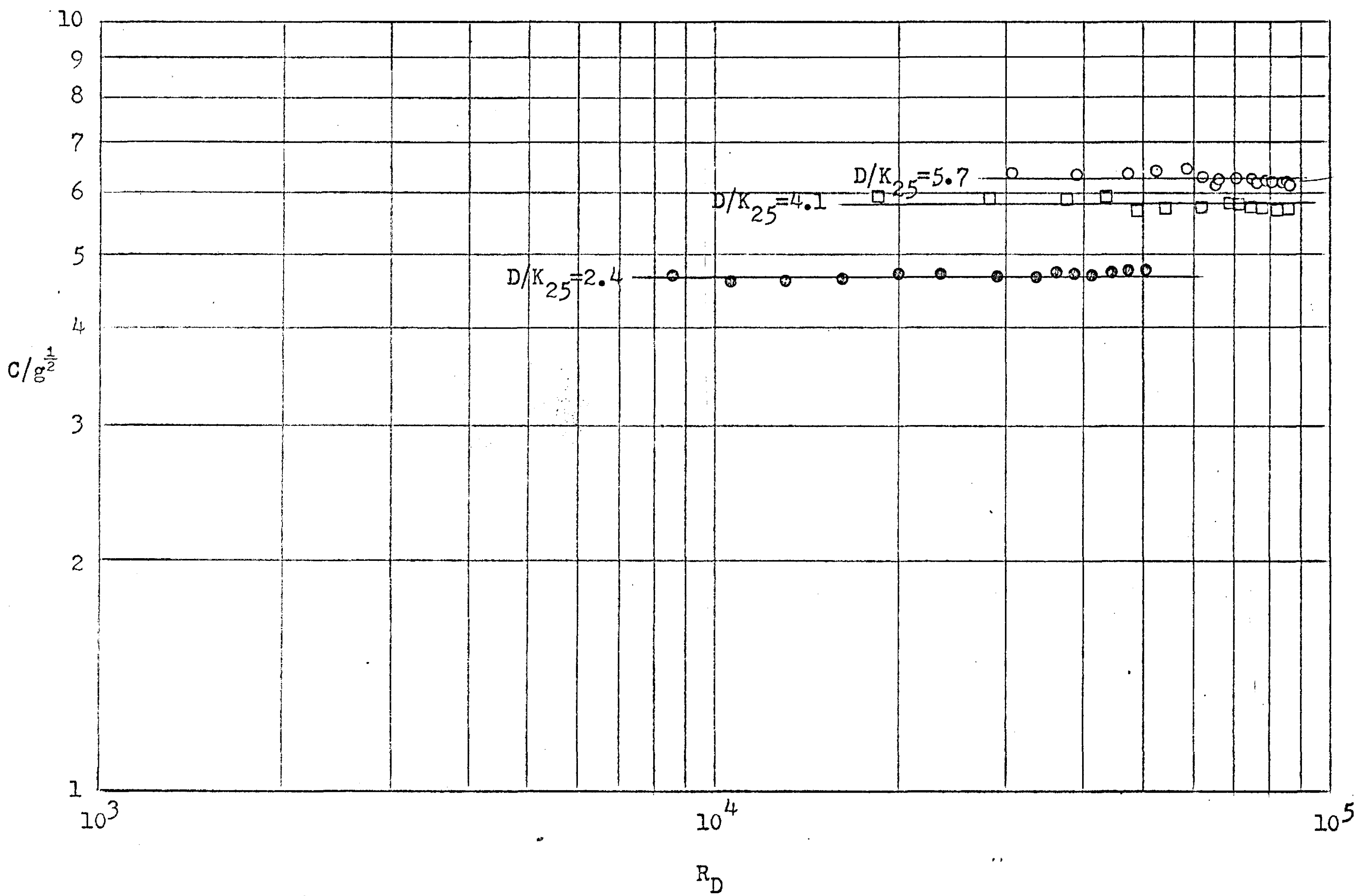


Figure 23. $C/g^{\frac{1}{2}}$ versus R_D for bed 23.

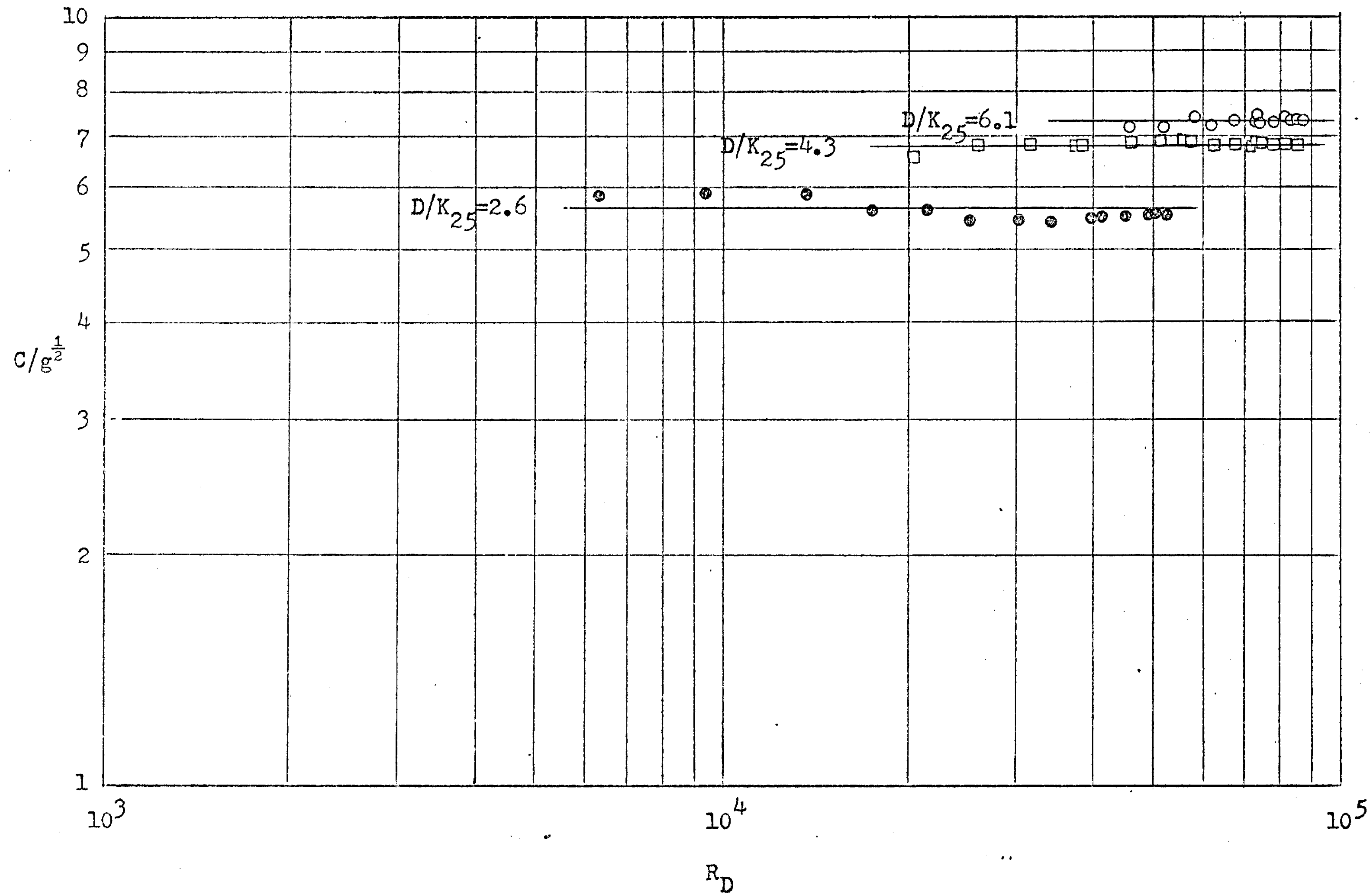


Figure 24. $C/g^{\frac{1}{2}}$ versus R_D for bed 25.

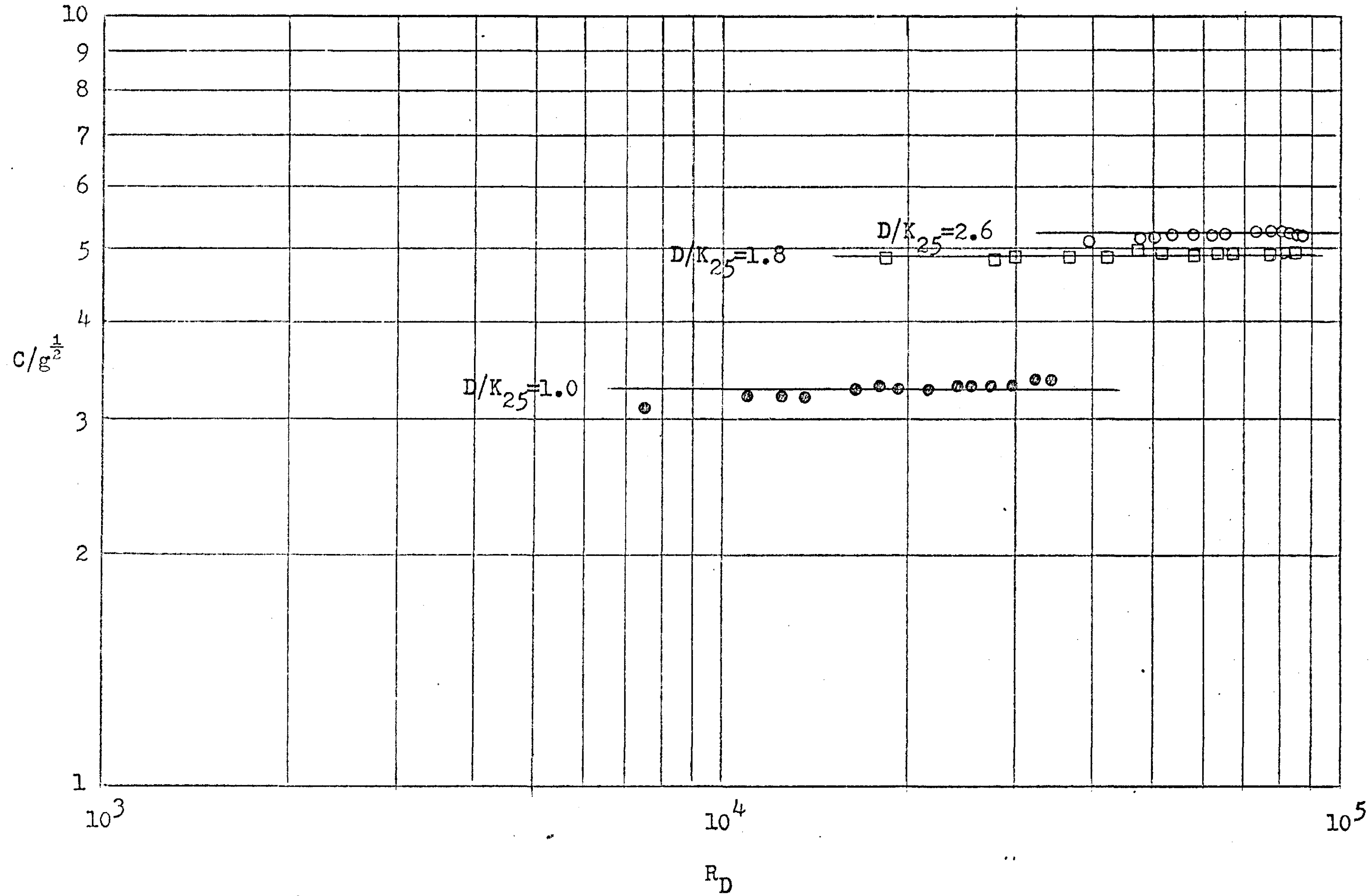


Figure 25. $C/g^{\frac{1}{2}}$ versus R_D for bed 43.

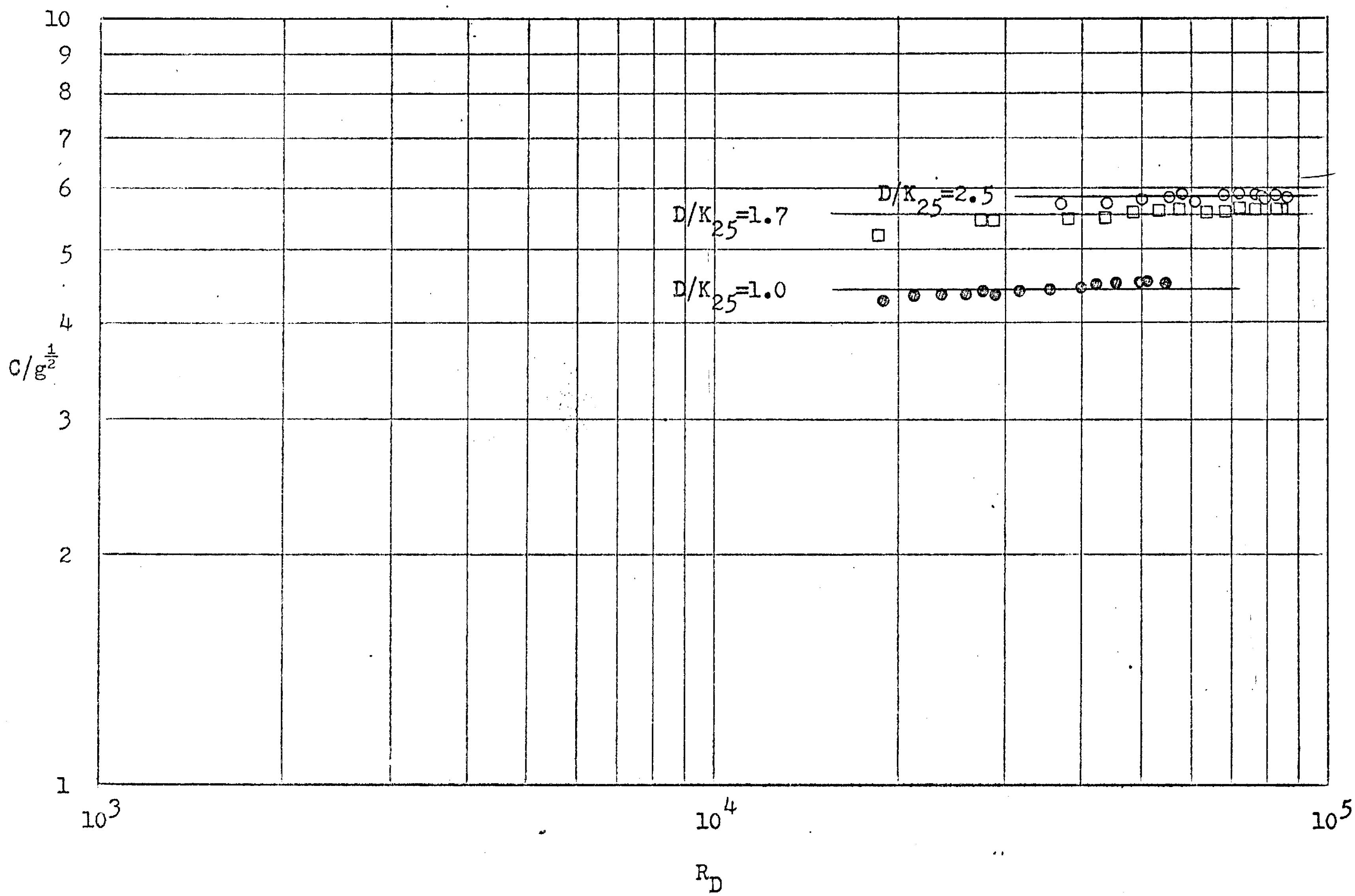


Figure 26. $C/g^{\frac{1}{2}}$ versus R_D for bed 45.

Relative Roughness

The relative roughness ranged between 3.0 and 12.0 based upon K_{16}, a roughness height at which 16 percent of the sample is larger. This value was chosen both because the larger elements are more effective in characterizing the flow due to their shadowing effect on the smaller elements and to follow the precedent set by Judd, although any other value of K_n might have been used. The natural logarithm of the data plot as a family of parallel lines (figure 27). Each of these parallel lines represents a particular value of the spacing parameter θ. $C/g^{\frac{1}{2}}$ plotted against θ^{-1} shows approximate straight lines (figure 28). The data was fit to a surface by the method of minimum sum of squared orthogonal deviations having the form

$$\ln\,(C/g^{\frac{1}{2}}) = a \ln\,(D/K_{16}) + f\,(\theta) \qquad (31)$$

Seven different models were evaluated using the Univac 1108 Computer. The best fit surface can be expressed as

$$\ln\,(C/g^{\frac{1}{2}}) = 0.317 \ln\,(D/K_{16}) + 0.007/\theta + 1.096 \qquad (32)$$

or taking antilog

$$C/g^{\frac{1}{2}} = 3.0\,(D/K_{16})^{0.317} \exp\,(0.007/\theta) \qquad (33)$$

The model produced a correlation coefficient of 0.87 with an F-test value of 25.5 at 2 and 17 degrees of freedom which is significant at a 0.999 confidence level. Models containing θ, θ^2, θ^3 were also tried. Some gave higher correlation coefficients but none were as significant in the F-test. In addition, these terms complicated the relationship. Judd proposed a similar equation for Abdelsalam's beds in a recent unpublished study. His equation is

$$C/g^{\frac{1}{2}} = 4.0\,(D/K_{25})^{0.33}\,f\,(\theta) \qquad (34)$$

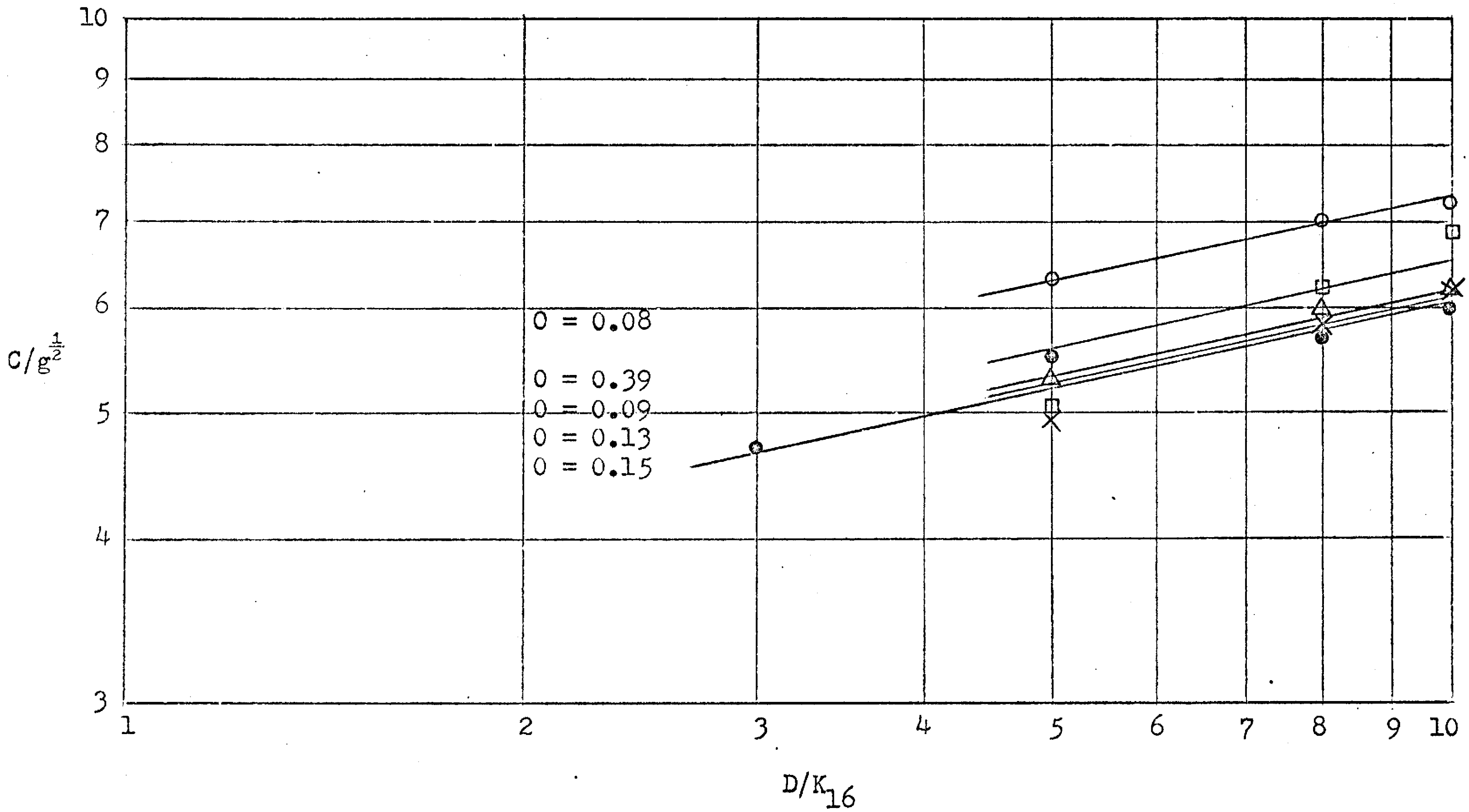


Figure 27. $C/g^{\frac{1}{2}}$ versus D/K_{16}.

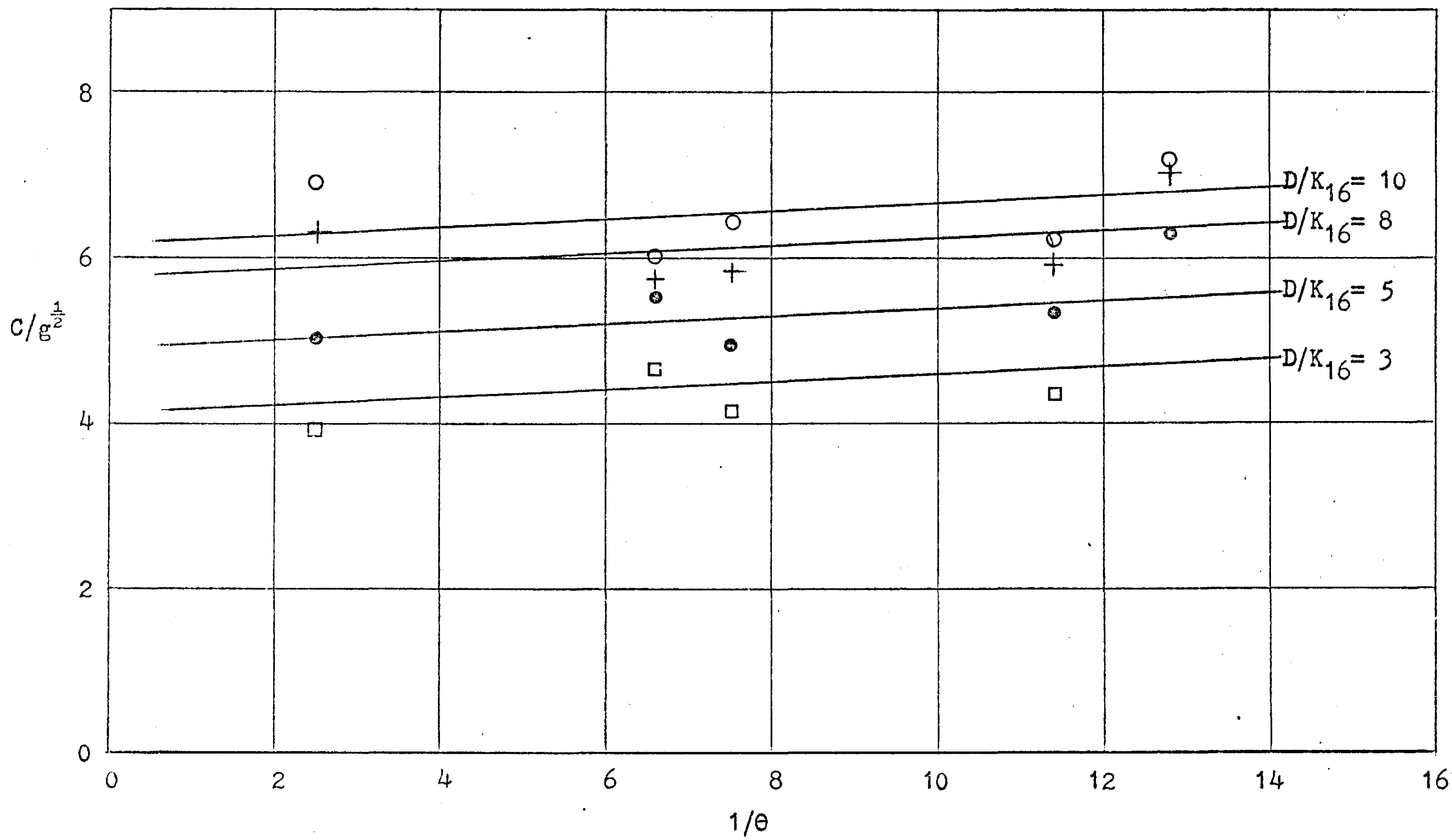


Figure 28. Plot of $C/g^{\frac{1}{2}}$ vs $1/\theta$.

Some investigators have found a logarithmic relationship between $C/g^{\frac{1}{2}}$ and D/K when using roughness elements of a geometric shape spaced at regular intervals, and at large values of D/K. Examination of equation 33 shows that D/K_{16} has the major influence on $C/g^{\frac{1}{2}}$, the contribution of θ the spacing parameter is very small in comparison with that of the relative roughness. This is consistent with the findings of Sayre and Albertson (1963) as reported in their paper on roughness spacing in open channel flumes. They suggest that while the parameter $C/g^{\frac{1}{2}}$ varies appreciably with channel shape and roughness form that roughness spacing causes only minor variations.

CHAPTER IX

SUMMARY

Objectives

The objectives of this dissertation were to establish the relationship for the amount of energy lost due to the presence of a free surface in naturally roughened open channels, to study the significance of viscous effects on channel drag for these channels, and to identify a hydraulically significant parameter describing bed element spacing.

An experiment was designed which eliminated the free surface. From this, the results were compared to data from another study containing a free surface.

From the data gathered, a spacing parameter was identified and a prediction equation was established relating the variables under study and a relationship for energy loss established for the free surface case.

Conclusions

1. The following relationship was established for the amount of energy dissipated because of the presence of a free surface

$$P = 0.23 - 0.028\, D/K_{25} \qquad (35)$$

where P is the proportion the conductance coefficient is reduced due to presence of a free surface, and D/K_{25} varied from 1 to 7. This loss of energy is caused by breaking surface waves and local spills and jumps over roughness elements.

2. The channel conductance coefficient was found to be non-dependent upon R_D through the range $3 \times 10^3 < R_D < 1 \times 10^5$, hence viscous effects were constant.

3. The ratio $\theta = \Sigma A_v/A$ which is the vertical projected area of roughness elements to the total horizontal area of the bed was found to be the best definition of the intensity parameter of those proposed.

4. Roughness spacing causes only a minor effect on the channel conductance coefficient in channels of the type tested herein.

5. The Chezy equation is valid for this experiment as was born out by the fact that the velocity plotted as a function of slope to approximately the 0.5 power.

6. The channel conductance coefficient is related to the relative roughness by a power function if the roughness elements are of a natural rounded type having a normal distribution of size as described in Chapter 5.

7. A relationship among the parameters $C/g^{\frac{1}{2}}$, D/K_{16} and θ was established as

$$C/g^{\frac{1}{2}} = 3.0\ (D/K_{16})^{0.317} \exp\ (0.007/\theta) \qquad (36)$$

For a particular bed, both θ and K_n are constant.

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APPENDIXES

Appendix A

Distribution of Bed Element Heights (Zero Points Included)

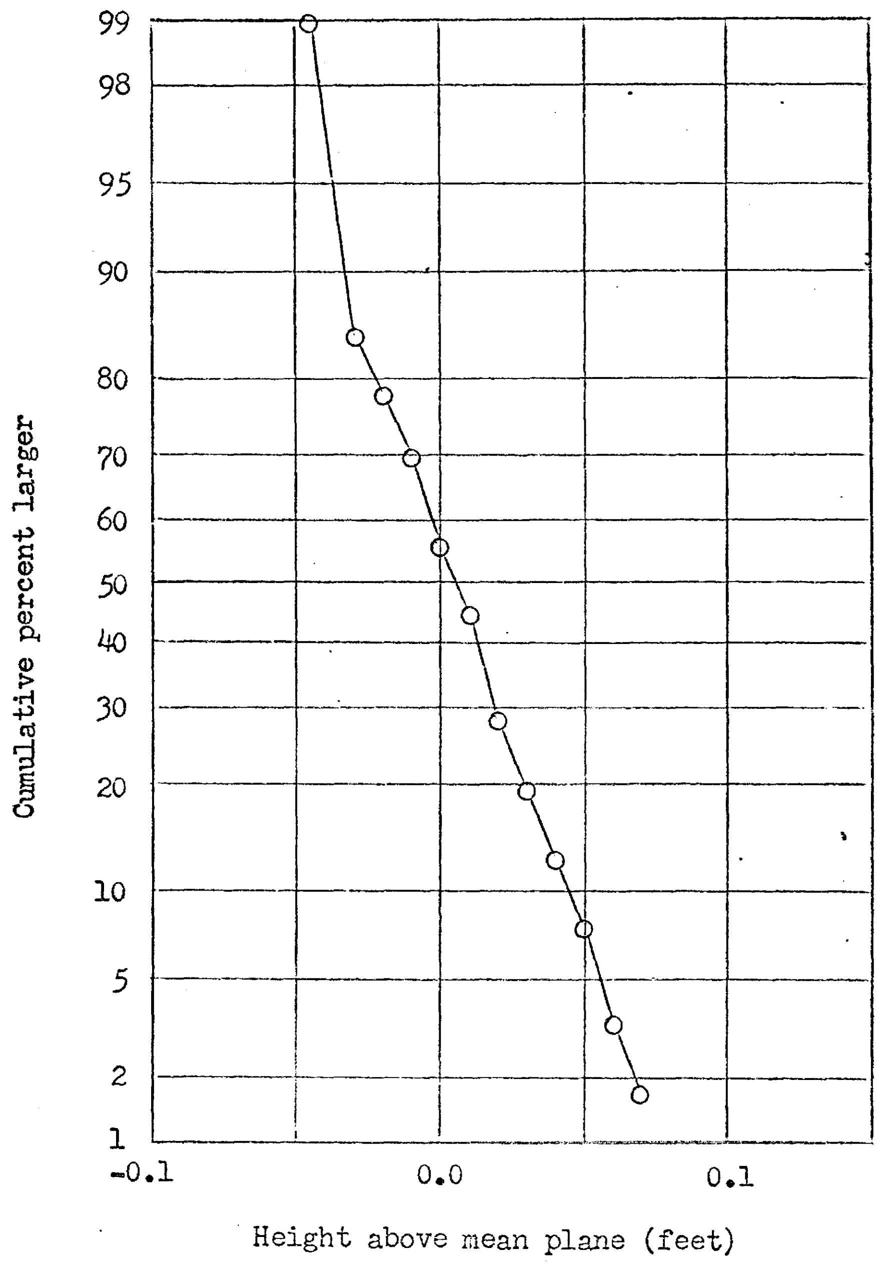

Figure 29. Distribution of bed element heights for bed 21. (zero points included)

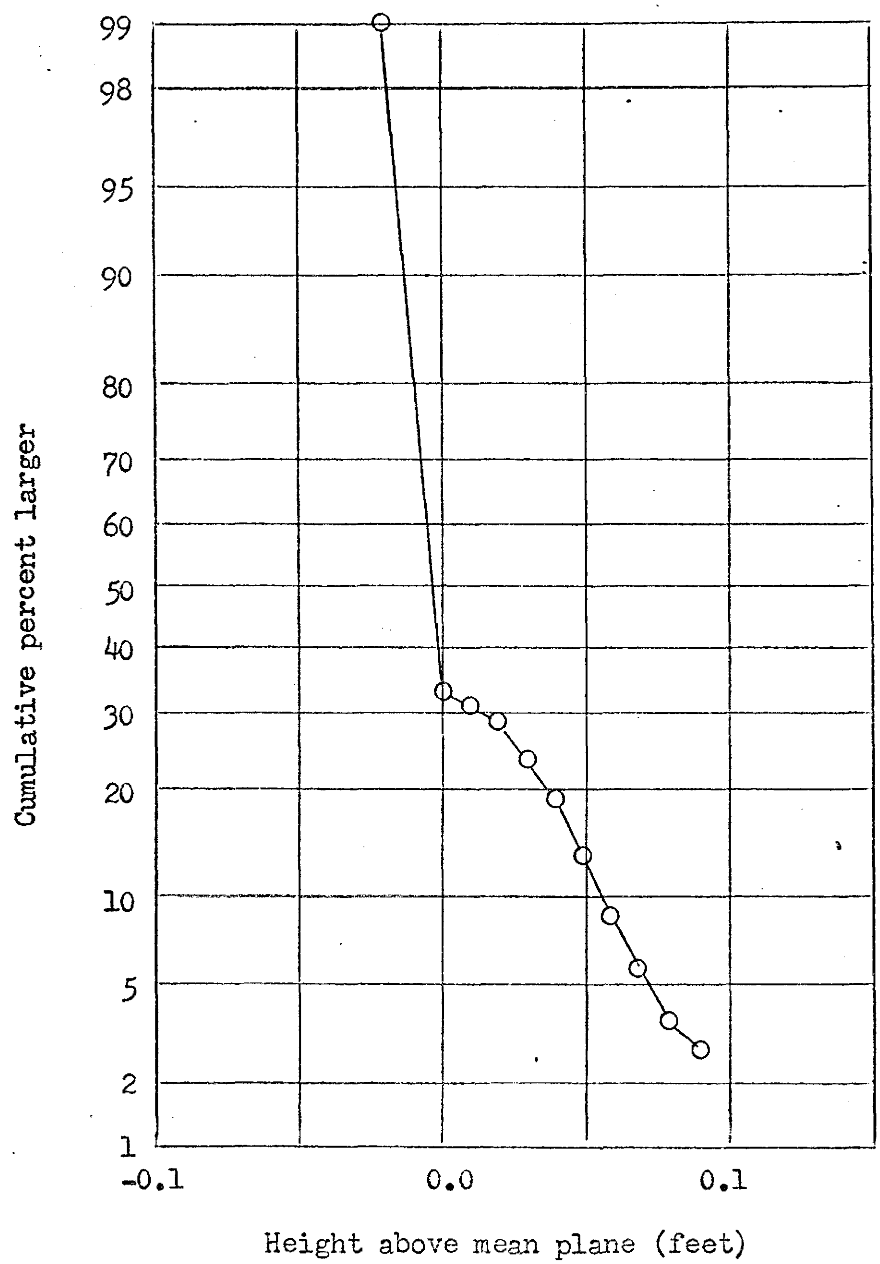

Figure 30. Distribution of bed element heights for bed 23. (zero points included)

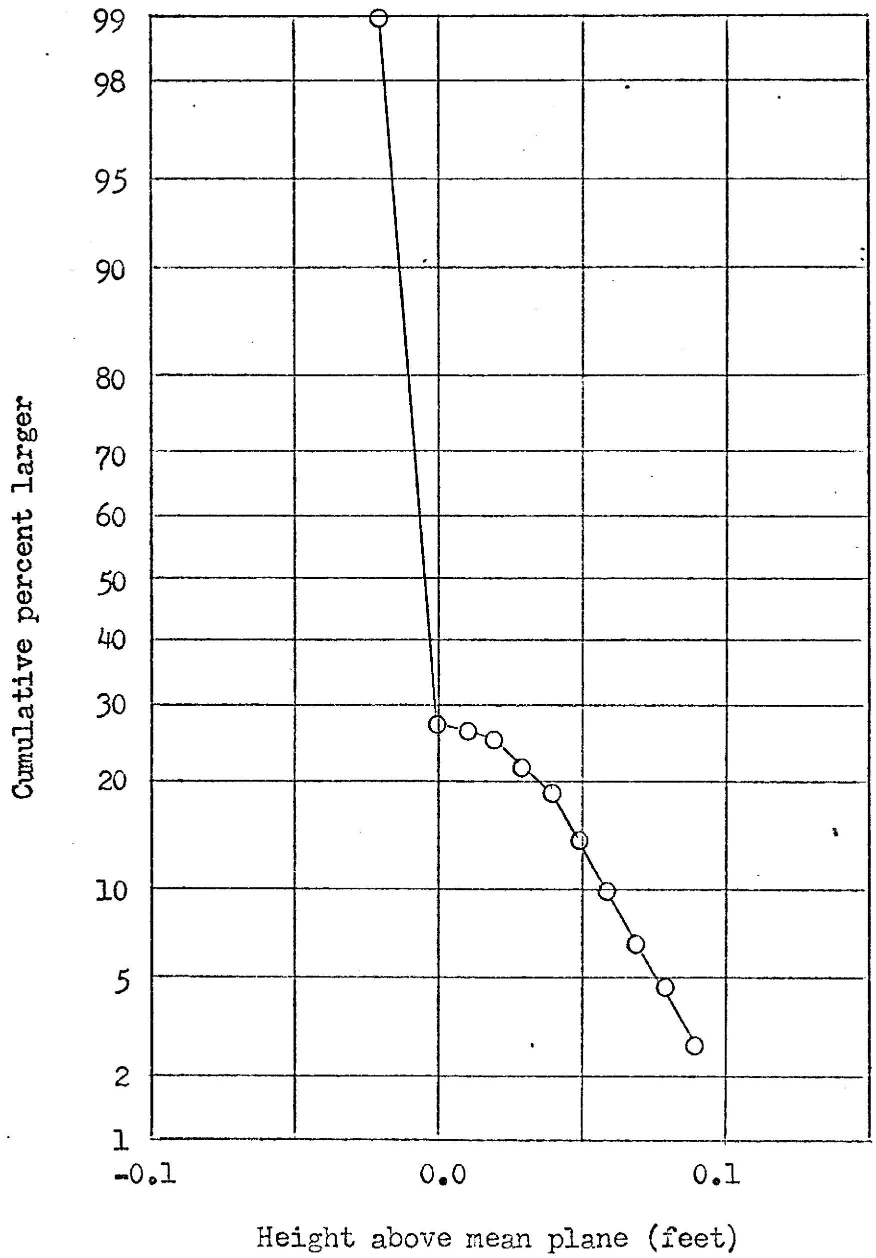

Figure 31. Distribution of bed element heights for bed 25. (zero points included)

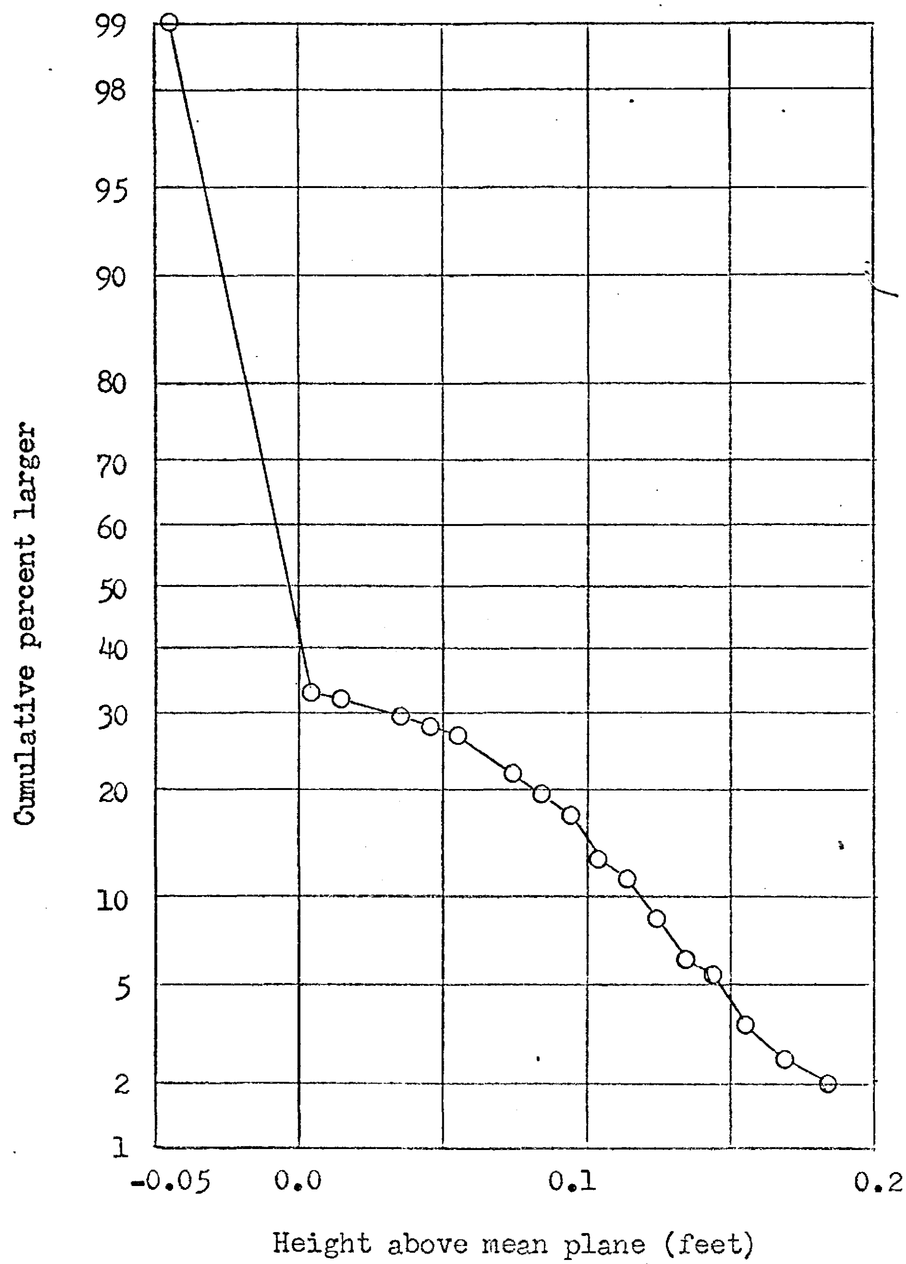

Figure 32. Distribution of bed element heights for bed 43. (zero points included)

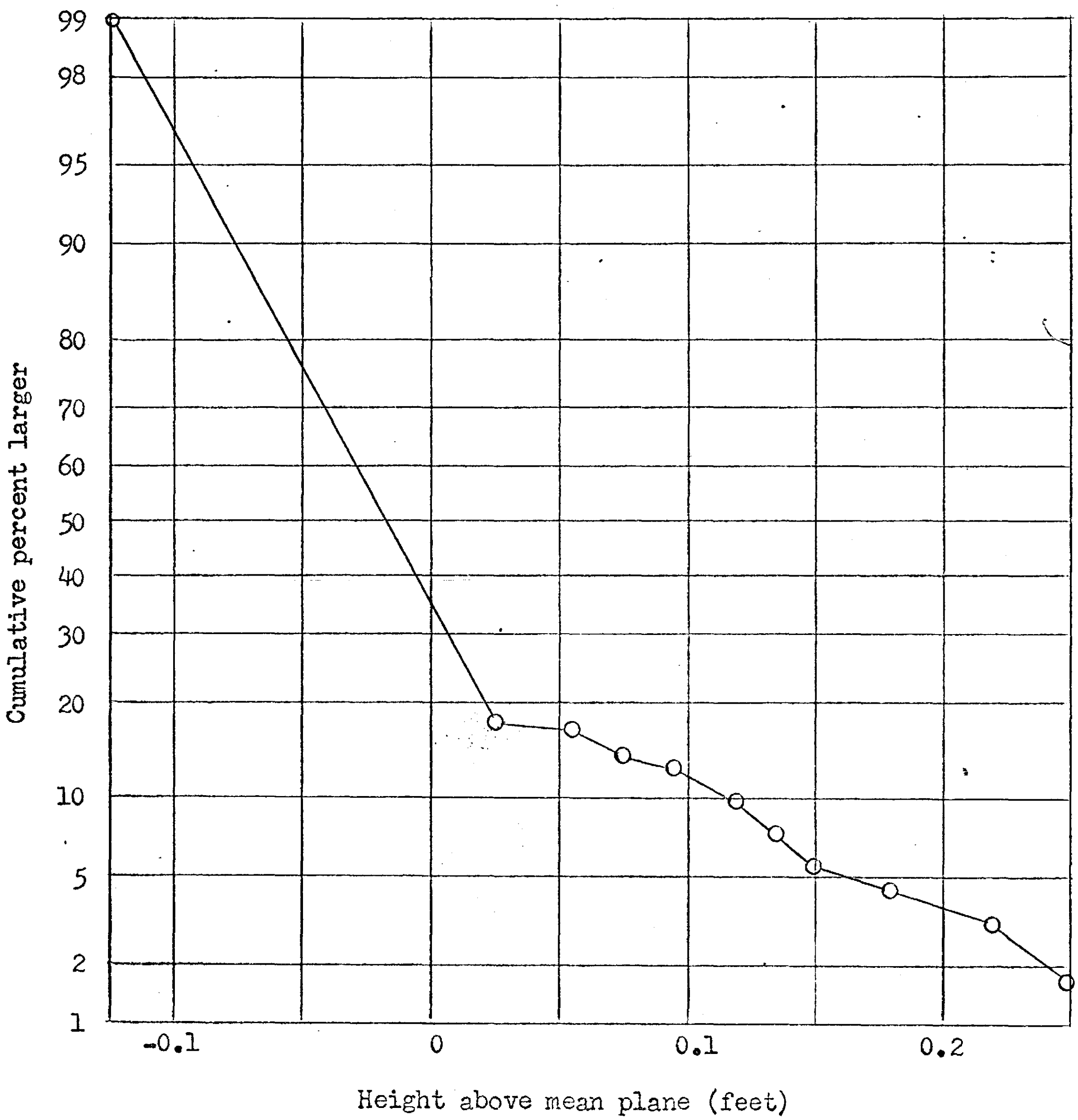

Figure 33. Distribution of bed element heights for bed 45. (zero points included)

Appendix B

Distribution of Bed Element Heights

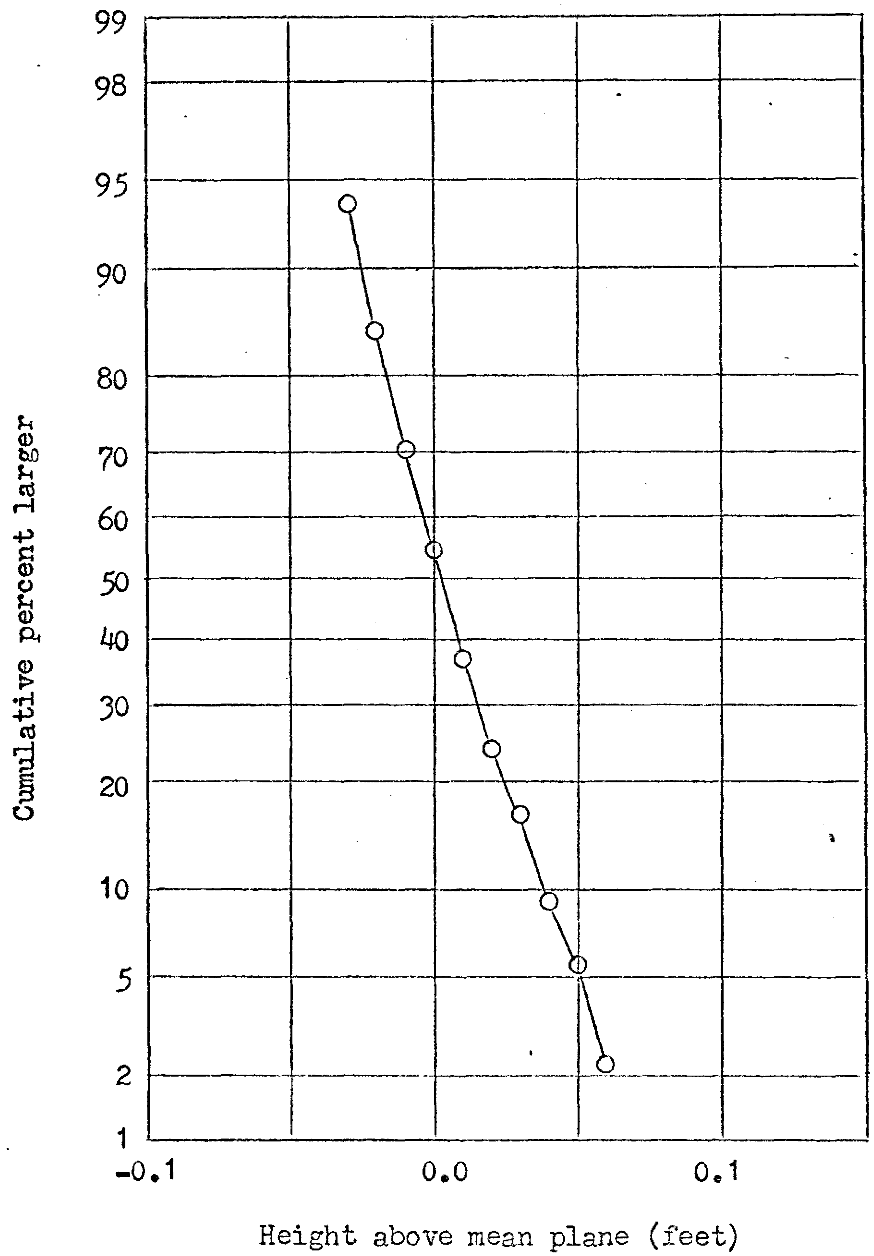

Figure 34. Distribution of bed element heights for bed 21.

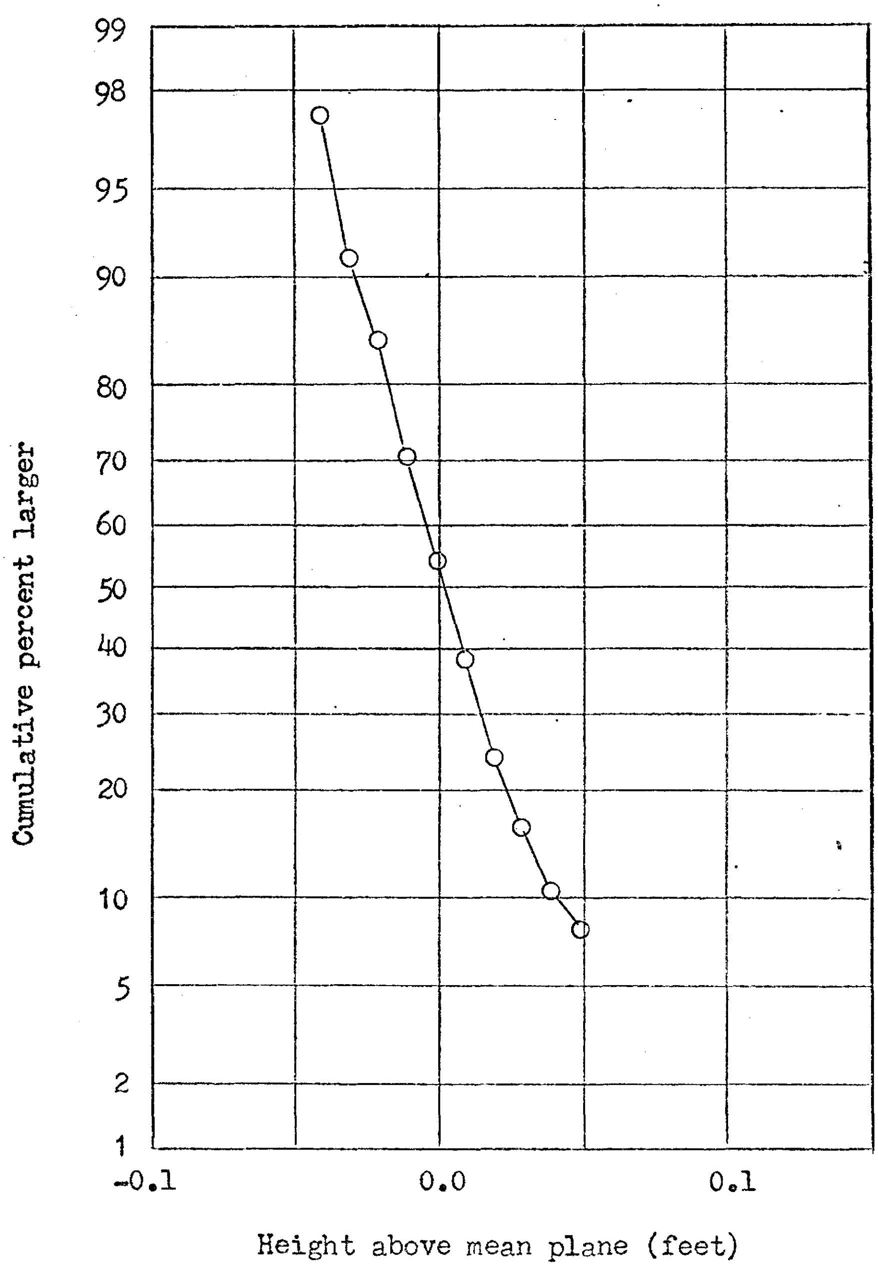

Figure 35. Distribution of bed element heights for bed 23.

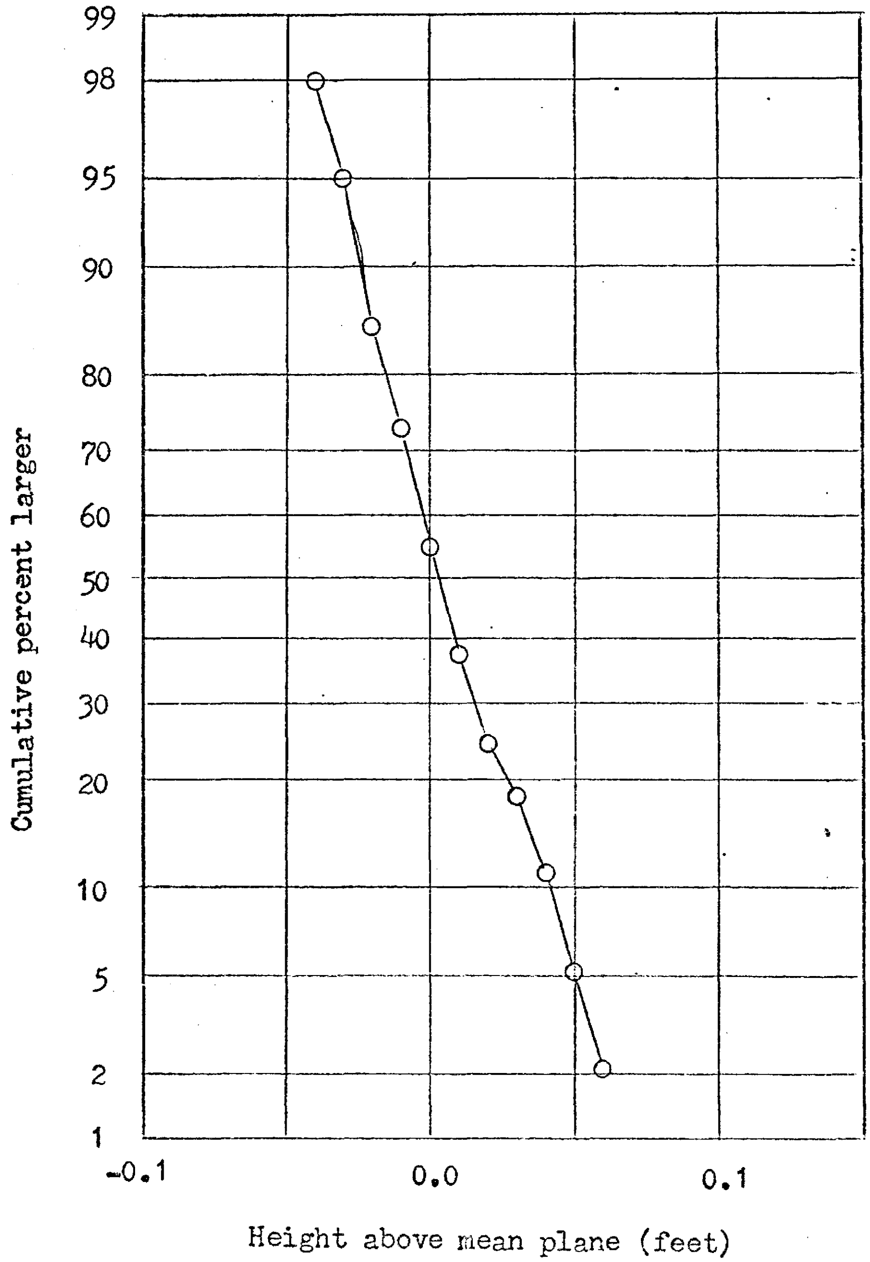

Figure 36. Distribution of bed element heights for bed 25.

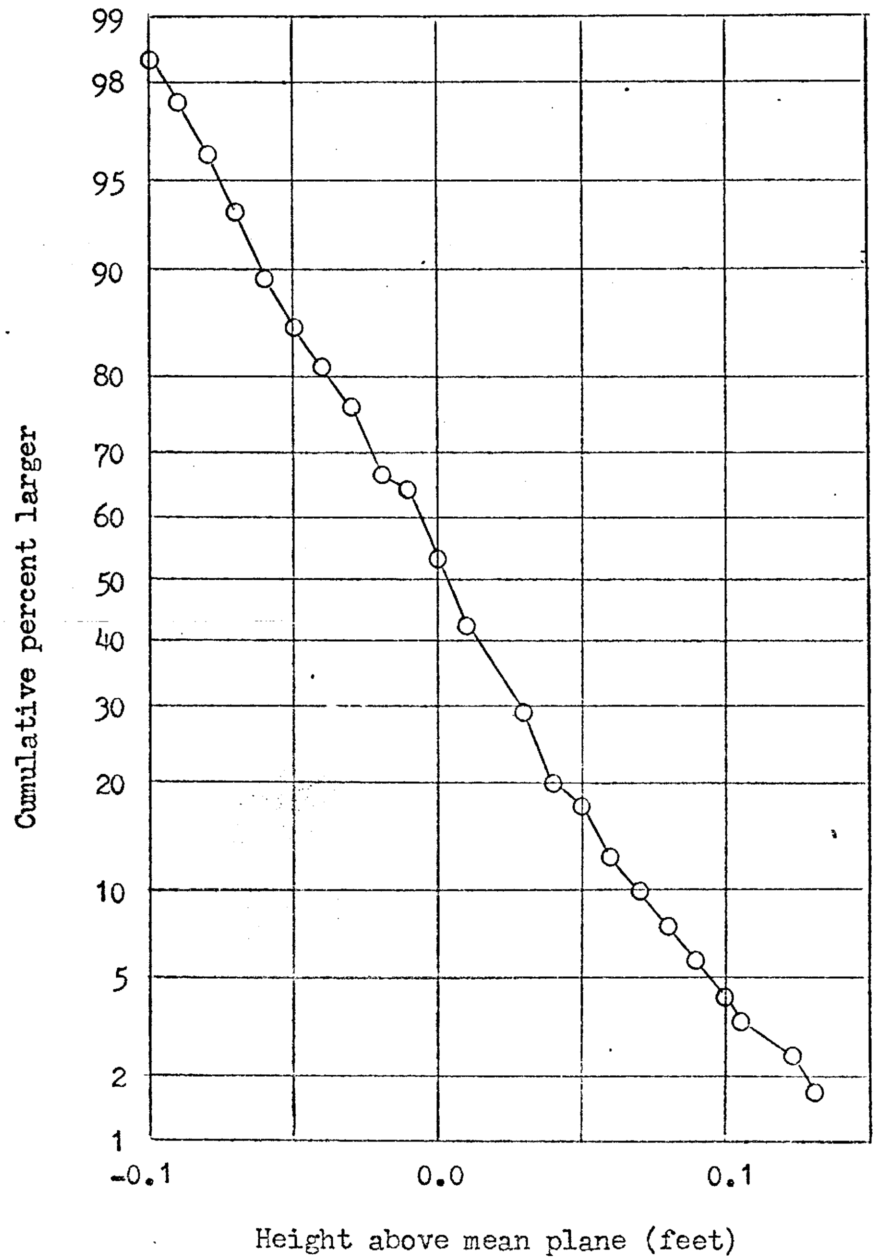

Figure 37. Distribution of bed element heights for bed 43.

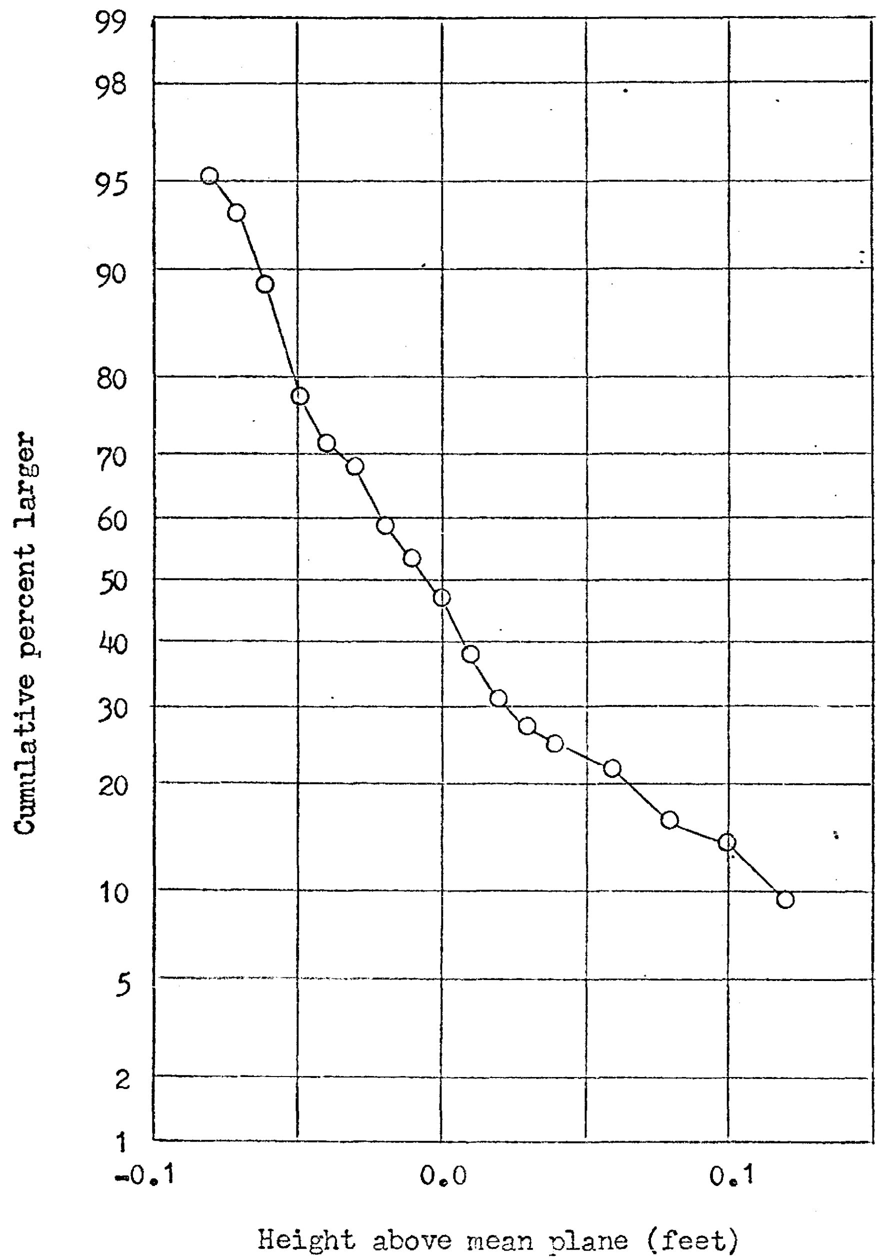

Figure 38. Distribution of bed element heights for bed 45.

Appendix C

Data for Closed Conduit

Table 4. Data for closed conduit

Bed	V	D	S	$C/g^{\frac{1}{2}}$	D/K_{16}	D/K_{25}	R_D	R_K
21	3.80	0.175	0.083	5.54	5.0	2.6	3423	1332
21	7.82	0.175	0.419	5.09	5.0	2.6	7033	2737
21	11.31	0.175	0.888	5.06	5.0	2.6	10172	3958
21	14.23	0.175	1.424	5.03	5.0	2.6	12806	4983
21	15.79	0.175	1.726	5.06	5.0	2.6	14203	5527
21	21.57	0.175	3.100	5.16	5.0	2.6	19403	7550
21	25.36	0.175	4.291	5.16	5.0	2.6	22818	8879
21	27.51	0.175	5.112	5.13	5.0	2.6	24755	9633
21	30.46	0.175	6.704	4.96	5.0	2.6	27402	10663
21	34.31	0.175	8.380	5.00	5.0	2.6	30866	12011
21	37.63	0.175	9.973	5.02	5.0	2.6	33860	13176
21	40.93	0.175	11.817	5.02	5.0	2.6	36829	14331
21	44.40	0.175	13.788	5.04	5.0	2.6	39818	15494
21	46.49	0.175	15.133	5.04	5.0	2.6	41694	16224
21	49.51	0.175	16.983	5.06	5.0	2.6	44405	17279
21	14.54	0.310	0.467	6.73	8.9	4.6	23303	5107
21	18.63	0.310	0.768	6.72	8.9	4.6	29859	6544
21	23.37	0.310	1.203	6.74	8.9	4.6	37445	8207
21	27.17	0.310	1.604	6.79	8.9	4.6	43549	9544
21	30.41	0.310	2.005	6.79	8.9	4.6	48731	10680
21	34.08	0.310	2.472	6.86	8.9	4.6	54613	11969
21	35.53	0.310	2.706	6.83	8.9	4.6	56938	12479
21	40.70	0.310	3.759	6.64	8.9	4.6	65232	14296
21	46.04	0.310	4.762	6.68	8.9	4.6	73786	16171
21	48.06	0.310	5.263	6.63	8.9	4.6	77016	16879
21	36.91	0.310	3.174	6.55	8.9	4.6	59144	12962
21	42.96	0.310	4.310	6.55	8.9	4.6	68846	15089
21	46.54	0.310	5.012	6.58	8.9	4.6	74578	16345
21	49.99	0.310	5.848	6.54	8.9	4.6	80118	17559
21	52.91	0.310	6.516	6.56	8.9	4.6	84785	18582
21	12.23	0.446	0.202	7.18	12.7	6.6	27919	4261
21	16.33	0.446	0.353	7.25	12.7	6.6	37285	5690
21	19.43	0.446	0.471	7.47	12.7	6.6	44370	6771
21	21.86	0.446	0.572	7.63	12.7	6.6	49910	7617
21	25.02	0.446	0.741	7.67	12.7	6.6	57118	8717
21	25.95	0.446	0.808	7.62	12.7	6.6	59258	9043
21	27.17	0.446	0.946	7.37	12.7	6.6	61830	9436
21	30.75	0.446	1.182	7.47	12.7	6.6	69994	10681
21	32.86	0.446	1.334	7.51	12.7	6.6	74786	11413
21	34.68	0.446	1.486	7.51	12.7	6.6	78931	12045
21	34.80	0.446	1.520	7.45	12.7	6.6	79212	12088
21	35.70	0.446	1.588	7.48	12.7	6.6	81258	12401
21	36.26	0.446	1.655	7.44	12.7	6.6	82525	12594
21	37.39	0.446	1.757	7.45	12.7	6.6	85103	12987
21	38.32	0.446	1.875	7.39	12.7	6.6	87209	13309

Table 4. Continued

Bed	V	D	S	$C/g^{\frac{1}{2}}$	D/K_{16}	D/K_{25}	R_D	R_K
23	5.47	0.199	0.168	5.27	4.4	2.4	5580	2302
23	8.47	0.199	0.504	4.71	4.4	2.4	8637	3564
23	10.47	0.199	0.807	4.61	4.4	2.4	10685	4408
23	12.88	0.199	1.210	4.63	4.4	2.4	13136	5420
23	15.89	0.199	1.824	4.65	4.4	2.4	16132	6656
23	19.88	0.199	2.770	4.72	4.4	2.4	20181	8326
23	23.15	0.199	3.784	4.70	4.4	2.4	23501	9696
23	28.77	0.199	5.942	4.67	4.4	2.4	29068	11993
23	33.07	0.199	7.809	4.68	4.4	2.4	33406	13783
23	35.90	0.199	8.998	4.73	4.4	2.4	36267	14963
23	38.32	0.199	10.356	4.71	4.4	2.4	38712	15972
23	40.98	0.199	11.884	4.70	4.4	2.4	41398	17080
23	44.10	0.199	13.581	4.73	4.4	2.4	44552	18381
23	46.76	0.199	15.109	4.76	4.4	2.4	47244	19492
23	49.99	0.199	17.317	4.75	4.4	2.4	50506	20838
23	10.86	0.334	0.303	6.01	7.4	4.1	18588	4561
23	16.39	0.334	0.707	5.94	7.4	4.1	28062	6886
23	21.71	0.334	1.246	5.93	7.4	4.1	37177	9123
23	25.43	0.334	1.684	5.97	7.4	4.1	43548	10686
23	28.58	0.334	2.357	5.67	7.4	4.1	48935	12008
23	31.67	0.334	2.863	5.71	7.4	4.1	54231	13308
23	36.16	0.334	3.717	5.72	7.4	4.1	61716	15144
23	40.23	0.334	4.494	5.78	7.4	4.1	68666	16850
23	41.71	0.334	4.832	5.78	7.4	4.1	71197	17471
23	44.69	0.334	5.575	5.77	7.4	4.1	76286	18719
23	43.84	0.334	5.491	5.70	7.4	4.1	74836	18364
23	45.50	0.334	5.913	5.70	7.4	4.1	77669	19059
23	47.48	0.334	6.420	5.71	7.4	4.1	81045	19887
23	48.71	0.334	6.758	5.71	7.4	4.1	83151	20404
23	49.92	0.334	7.180	5.68	7.4	4.1	85204	20908
23	12.87	0.470	0.272	6.34	10.4	5.7	30620	5347
23	16.46	0.470	0.442	6.36	10.4	5.7	39161	6838
23	19.82	0.470	0.647	6.34	10.4	5.7	47168	8237
23	22.07	0.470	0.783	6.41	10.4	5.7	52509	9169
23	24.85	0.470	0.987	6.43	10.4	5.7	59128	10325
23	26.31	0.470	1.158	6.29	10.4	5.7	62601	10931
23	27.78	0.470	1.328	6.20	10.4	5.7	66093	11541
23	29.89	0.470	1.498	6.28	10.4	5.7	71109	12417
23	31.50	0.470	1.669	6.27	10.4	5.7	74956	13089
23	32.85	0.470	1.839	6.23	10.4	5.7	78167	13649
23	31.95	0.470	1.771	6.17	10.4	5.7	76016	13274
23	33.83	0.470	1.975	6.19	10.4	5.7	80508	14058
23	35.11	0.470	2.112	6.21	10.4	5.7	83539	14588
23	35.96	0.470	2.214	6.21	10.4	5.7	85567	14942
23	36.30	0.470	2.316	6.13	10.4	5.7	86365	15081

Table 4. Continued

Bed	V	D	S	$C/g^{\frac{1}{2}}$	D/K_{16}	D/K_{25}	R_D	R_K
25	6.14	0.202	0.168	5.86	4.5	2.6	6327	2446
25	9.26	0.202	0.371	5.96	4.5	2.6	9541	3689
25	11.46	0.202	0.557	6.02	4.5	2.6	11809	4566
25	13.41	0.202	0.777	5.97	4.5	2.6	13824	5345
25	17.18	0.202	1.452	5.59	4.5	2.6	17506	6768
25	21.22	0.202	2.221	5.59	4.5	2.6	21623	8360
25	24.86	0.202	3.246	5.41	4.5	2.6	25328	9792
25	29.75	0.202	4.613	5.43	4.5	2.6	30310	11719
25	33.60	0.202	5.980	5.39	4.5	2.6	34237	13237
25	38.90	0.202	7.797	5.47	4.5	2.6	39960	15449
25	40.50	0.202	8.458	5.46	4.5	2.6	41265	15954
25	44.28	0.202	9.996	5.49	4.5	2.6	45116	17443
25	47.84	0.202	11.619	5.51	4.5	2.6	48744	18845
25	49.79	0.202	12.473	5.53	4.5	2.6	50735	19615
25	51.67	0.202	13.499	5.52	4.5	2.6	52650	20355
25	11.85	0.337	0.304	6.52	5.5	4.3	20409	4721
25	18.45	0.337	0.675	6.81	5.5	4.3	31769	7349
25	22.11	0.337	0.979	6.78	5.5	4.3	38076	8808
25	26.65	0.337	1.385	6.87	5.5	4.3	45898	10618
25	29.72	0.337	1.723	6.87	5.5	4.3	51179	11840
25	32.33	0.337	1.993	6.95	5.5	4.3	55676	12880
25	33.52	0.337	2.162	6.92	5.5	4.3	57725	13354
25	36.39	0.337	2.682	6.74	5.5	4.3	62364	14427
25	39.30	0.337	3.055	6.82	5.5	4.3	67361	15583
25	42.36	0.337	3.497	6.87	5.5	4.3	72596	16794
25	43.42	0.337	3.701	6.85	5.5	4.3	74417	17215
25	45.15	0.337	4.074	6.79	5.5	4.3	77388	17903
25	41.77	0.337	3.531	6.75	5.5	4.3	71598	16563
25	47.36	0.337	4.516	6.76	5.5	4.3	81169	18777
25	49.95	0.337	5.059	6.74	5.5	4.3	85605	19804
25	10.98	0.473	0.170	6.82	10.5	6.1	26292	4339
25	15.53	0.473	0.340	6.82	10.5	6.1	37183	6137
25	19.16	0.473	0.476	7.11	10.5	6.1	45887	7574
25	21.77	0.473	0.613	7.13	10.5	6.1	52129	8604
25	24.35	0.473	0.715	7.38	10.5	6.1	58317	9625
25	25.91	0.473	0.851	7.20	10.5	6.1	62037	10239
25	28.26	0.473	0.987	7.29	10.5	6.1	67668	11169
25	30.63	0.473	1.107	7.46	10.5	6.1	73346	12106
25	30.99	0.473	1.192	7.27	10.5	6.1	74203	12247
25	32.72	0.473	1.328	7.28	10.5	6.1	78346	12931
25	30.84	0.473	1.192	7.24	10.5	6.1	73842	12187
25	33.62	0.473	1.362	7.38	10.5	6.1	80508	13288
25	34.63	0.473	1.464	7.33	10.5	6.1	82921	13686
25	35.44	0.473	1.532	7.34	10.5	6.1	84862	14006
25	36.36	0.473	1.635	7.29	10.5	6.1	87057	14369

Table 4. Continued

Bed	V	D	S	$C/g^{\frac{1}{2}}$	D/K_{16}	D/K_{25}	R_D	R_K
43	8.59	0.175	1.396	3.06	1.8	1.0	7606	7312
43	12.60	0.175	2.827	3.16	1.8	1.0	11159	10727
43	14.22	0.175	3.508	3.20	1.8	1.0	12588	12102
43	15.46	0.175	4.258	3.16	1.8	1.0	13689	13161
43	18.70	0.175	5.961	3.23	1.8	1.0	16558	15919
43	20.54	0.175	6.983	3.28	1.8	1.0	18187	17485
43	21.97	0.175	7.920	3.29	1.8	1.0	19457	18705
43	24.58	0.175	10.049	3.27	1.8	1.0	21767	20927
43	27.36	0.175	12.263	3.29	1.8	1.0	24226	23290
43	28.71	0.175	13.455	3.30	1.8	1.0	25419	24437
43	31.01	0.175	15.669	3.30	1.8	1.0	27455	26395
43	33.35	0.175	17.883	3.32	1.8	1.0	29534	28393
43	36.50	0.175	20.949	3.36	1.8	1.0	32320	31071
43	38.55	0.175	22.823	3.40	1.8	1.0	34136	32817
43	38.82	0.175	23.504	3.38	1.8	1.0	34377	33049
43	11.70	0.310	0.572	4.89	3.2	1.8	18589	10068
43	17.38	0.310	1.313	4.80	3.2	1.8	27629	14965
43	22.91	0.310	2.223	4.86	3.2	1.8	36413	19722
43	26.39	0.310	2.930	4.88	3.2	1.8	41950	22722
43	29.84	0.310	3.637	4.95	3.2	1.8	47434	25692
43	32.35	0.310	4.277	4.95	3.2	1.8	51417	27850
43	36.11	0.310	5.288	4.97	3.2	1.8	57399	31089
43	36.95	0.310	5.660	4.91	3.2	1.8	58537	31706
43	40.10	0.310	6.589	4.94	3.2	1.8	63525	34408
43	42.62	0.310	7.518	4.92	3.2	1.8	67523	36573
43	44.18	0.310	8.110	4.91	3.2	1.8	69994	37911
43	48.68	0.310	9.799	4.92	3.2	1.8	77117	41769
43	50.89	0.310	10.560	4.95	3.2	1.8	80618	43666
43	52.02	0.310	11.151	4.93	3.2	1.8	82420	44642
43	53.59	0.310	11.827	4.93	3.2	1.8	84900	45985
43	13.08	0.446	0.505	4.86	4.6	2.7	29865	11260
43	17.29	0.446	0.808	5.08	4.6	2.7	39483	14886
43	20.89	0.446	1.145	5.15	4.6	2.7	47687	17979
43	22.07	0.446	1.280	5.15	4.6	2.7	50391	18999
43	23.49	0.446	1.431	5.18	4.6	2.7	53635	20222
43	25.50	0.446	1.684	5.19	4.6	2.7	58232	21955
43	27.52	0.446	1.959	5.19	4.6	2.7	62627	23612
43	28.83	0.446	2.128	5.22	4.6	2.7	65608	24736
43	32.02	0.446	2.601	5.24	4.6	2.7	72868	27473
43	34.08	0.446	2.939	5.25	4.6	2.7	77574	29248
43	33.63	0.446	2.872	5.24	4.6	2.7	76548	28861
43	35.47	0.446	3.210	5.23	4.6	2.7	80725	30435
43	36.35	0.446	3.379	5.22	4.6	2.7	82734	31193
43	37.39	0.446	3.632	5.18	4.6	2.7	85103	32086
43	38.14	0.446	3.784	5.18	4.6	2.7	86812	32730

Table 4. Continued

Bed	V	D	S	$C/g^{\frac{1}{2}}$	D/K_{16}	D/K_{25}	R_D	R_K
45	12.11	0.193	1.396	4.11	3.2	1.0	11829	11538
45	19.60	0.193	3.406	4.26	3.2	1.0	19146	18674
45	21.94	0.193	4.172	4.31	3.2	1.0	21429	20901
45	24.27	0.193	5.024	4.35	3.2	1.0	23700	23116
45	26.58	0.193	6.012	4.35	3.2	1.0	25962	25322
45	28.42	0.193	6.727	4.40	3.2	1.0	27759	27075
45	29.74	0.193	7.545	4.35	3.2	1.0	29047	28331
45	32.44	0.193	8.686	4.42	3.2	1.0	31686	30905
45	36.55	0.193	11.036	4.42	3.2	1.0	35693	34813
45	40.89	0.193	13.625	4.45	3.2	1.0	39932	38948
45	43.40	0.193	15.158	4.47	3.2	1.0	42392	41347
45	46.74	0.193	17.458	4.49	3.2	1.0	45650	44525
45	50.47	0.193	20.098	4.52	3.2	1.0	49294	48079
45	52.44	0.193	21.460	4.54	3.2	1.0	51219	49957
45	56.09	0.193	24.611	4.54	3.2	1.0	54778	53428
45	11.27	0.328	0.444	5.20	5.5	1.7	18653	10686
45	17.58	0.328	0.992	5.43	5.5	1.7	29088	16664
45	22.86	0.328	1.643	5.49	5.5	1.7	37832	21673
45	26.33	0.328	2.122	5.56	5.5	1.7	43564	24956
45	29.48	0.328	2.635	5.59	5.5	1.7	48787	27949
45	32.15	0.328	3.114	5.60	5.5	1.7	53206	30480
45	34.83	0.328	3.628	5.62	5.5	1.7	57629	33014
45	36.84	0.328	4.120	5.58	5.5	1.7	60764	34810
45	38.54	0.328	4.550	5.56	5.5	1.7	63565	36415
45	41.36	0.328	5.151	5.61	5.5	1.7	68217	39080
45	43.88	0.328	5.700	5.65	5.5	1.7	72379	41464
45	46.54	0.328	6.524	5.61	5.5	1.7	76770	43979
45	48.61	0.328	7.074	5.62	5.5	1.7	80183	45935
45	50.50	0.328	7.640	5.62	5.5	1.7	83304	47723
45	51.42	0.328	7.950	5.61	5.5	1.7	84821	48592
45	11.63	0.464	0.303	5.47	7.7	2.5	27629	11205
45	15.70	0.464	0.505	5.71	7.7	2.5	37285	15120
45	18.60	0.464	0.707	5.72	7.7	2.5	44189	17920
45	21.25	0.464	0.909	5.77	7.7	2.5	50470	20467
45	23.29	0.464	1.077	5.81	7.7	2.5	55331	22439
45	24.51	0.464	1.178	5.84	7.7	2.5	58232	23615
45	25.82	0.464	1.351	5.75	7.7	2.5	61140	24794
45	28.78	0.464	1.622	5.85	7.7	2.5	68149	27636
45	30.48	0.464	1.807	5.87	7.7	2.5	72185	29273
45	32.25	0.464	2.027	5.86	7.7	2.5	76378	30974
45	33.41	0.464	2.196	5.83	7.7	2.5	79110	32082
45	32.85	0.464	2.128	5.83	7.7	2.5	77780	31542
45	34.23	0.464	2.314	5.82	7.7	2.5	81045	32866
45	35.11	0.464	2.433	5.83	7.7	2.5	83151	33720
45	36.41	0.464	2.635	5.80	7.7	2.5	86212	34962

VITA

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Doctor of Philosophy

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