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Department of Civil Engineering

Colorado Agricultural and Mechanical College Fort Collins, Colorado

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THESIS

SUSPENDED SEDIMENT TRANSPORT IN ALLUVIAL IRRIGATION CHANNELS

> Submitted by Donald Lee Bender

In partial fulfillment of the requirements for the Degree of Master of Science Colorado

Agricultural and Mechanical College Fort Collins, Colorado

December, 1955





COLORADO AGRICULTURAL AND MECHANICAL COLLEGE
December 9 1955
WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUT
SUPERVISION BY DONALD_LEE_BENDER
ENTITLED SUSPENDED SEDIMENT TRANSPORT IN ALLUVIAL
IRRIGATION CHANNELS
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The data were collected by Professor Simons and the writer. Using the complete data, Professor Simons is preparing a Ph.D. dissertation at Colorado A and M College on the subject of stable channels.

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LIST OF SYMBOLS

Symbol	Dimensions	Definition or description
a	L	A reference level above the bed
C	F/F	Concentration of sediment
ca	F/F	Concentration at the reference
C	L₫/T	Chezy discharge coefficient
đ	L	Sediment diameter
D	L	Mean depth of flow
$D_{\mathbf{b}}$	L	Diameter of bed material
g	L/T2	Gravitational acceleration
k		Karman coefficient
K	L	Height of bed roughness
R	L	Hydraulic radius equals area divided by wetted perimeter
Re		Reynolds number
S	L/L	Slope of the energy line
u	L/T	Instantaneous velocity component in x direction
v	L/T	Instantaneous velocity component y
W	L/T	Instantaneous velocity component z
U	L/T	Mean velocity component in x direction
V	L/T	Mean velocity component in y direction

	LIST	OF SYMBOLSContinued
Symbol	Dimensions	Definition or description
W	L/T	Mean velocity component in z direction
u'	L/T	u-U at any instant
v '	L/T	v-V at any instant
w '	L/T	w-W at any instant
x	${f L}$	Longitudinal direction
У	L	Vertical direction
z	L	Transverse direction
Z		Exponent in sediment distribution equation
Zl		Exponent in sediment distribution equation measured from sediment distribution curve
β		Ratio Z_1/Z
እ	F/L3	Specific weight of water
Em	L^2/T	Coefficient of turbulent transfer of momentum
£s	L ² /T	Coefficient of tu rbule nt transfer of sediment
M	FT/L^2	Dynamic viscosity of water
P	FT2/L4	Mass density of water
γ	F/L^2	Shearing stress within the fluid
T.	F/L^2	Shearing stress at the boundary
ប .	L/T	Shear velocity
L	L/T	Fall velocity of the sediment

Chapter I

INTRODUCTION

Irrigation channels are designed to supply definite quantities of water to farmers as efficiently as possible. To accomplish this, the primary purpose of the design engineer is to obtain a stable channel which will have the lowest initial and maintenance costs. The success or failure of many irrigation systems depends upon the amount of money required to keep the canals in satisfactory condition and capable of delivering an adequate amount of water to the farmer. In a stable channel, the effects of the moving water, the bed material and the material being transported by the canal, combine to cause neither silting nor scouring. Thus, to understand thoroughly the problem of stable channels, it is helpful first to study the individual effects of the moving water, the bed material, and the material being transported by the water; and then to combine these individual effects into their overall effect on the channel.

The purpose of this thesis is to study several of the important factors involved in the transport of sediment by water. The data for the investigation are from alluvial irrigation canals. Although these data have rather wide application, this thesis is limited to a study of the transport of suspended material only. An attempt is made to apply the data from the field to theories of suspended sediment transport developed in the laboratory.

The problem

How does the theory of suspended sediment transport apply to existing alluvial irrigation canals?

The problem may be subdivided into the several items that follow:

- 1. To what extent are the theoretical equations for suspended sediment transport supported by data taken from irrigation canals in which the sediment concentration is very small and the slope very flat?
- 2. To what extent are the limitations and assumptions used in the theoretical analysis of sediment transport valid for conditions in such canals?
- 3. What are the limitations of data gathered in such canals?
- 4. What are the most important factors affecting the ability of a fluid to transport suspended sediment?

Chapter II REVIEW OF LITERATURE

Although the problem of determining the amount of sediment being carried in suspension by moving water has received rather wide attention in the past, until recently most of the studies have been limited to laboratory investigations.

In presenting the Review of Literature, the chapter is divided into three major divisions: Development of Suspended Sediment Theory, Effects of Sediment on the Flow Characteristics, and Experiments on Suspended Sediment Distribution. The references are not necessarily presented in chronological order, but in a logical development of the subject.

Development of suspended sediment theory

W. Schmidt (24) 1925 first developed the basic relationship for the vertical transfer of particles by a turbulent fluid in his studies of dust particles in the atmosphere. Assuming the conditions of equilibrium and that the particles are heavier than the fluid, the net upward transfer resulting from turbulent exchange is equal to the rate of settling of the particles due to gravity.

$$wc=-\epsilon s dc/dy$$
 (1)

ry .

where w is the settling velocity of the particle, c is the concentration of the suspended material, y is the vertical distance and \in s is the diffusion coefficient.

O'Brien (18) in 1936 presented a similar theory and equation for the vertical sediment distribution in streams.

Integrating Eq. 1 gives

$$Ln c/ca = -w$$
 $\int_{a} dy/\{s$ (2)
which expresses the relative concentration of the sediment
at any distance y above the bed compared with that at
some reference depth a.

If the sediment transfer coefficient can be expressed as some function of depth, then the integral in the right hand member of Eq. 2 may be evaluated.

Making the assumption that \leftarrow s remains constant with respect to depth, the integral becomes

$$c/ca = e^{-w(y-a)}/\varepsilon s$$
(3)

In 1929 Hurst (9) conducted a series of experiments on the suspension of sediment in a cylindrical column of water agitated uniformily by a series of

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propellers. At various levels in his apparatus he measured the concentration of three well-graded sands for several propeller speeds and found the distribution followed an exponential relationship very similar to Eq. 3.

Rouse (22) in 1938, in a study similar to Hurst's, used a cylindrical glass tank in which a lattice structure oscillated vertically in simple harmonic motion. He stated that the form of Eq. 3 was definitely verified with regard to both the exponential nature of the distribution function and the role played by the settling velocity of the sediment. However, some question still existed as to the strict similarity between the mixing characteristics of the sediment and those of the fluid, for the factor \leq s appeared to vary somewhat with the relative size of the particles in suspension.

If, however, in natural streams, \in s varies with depth, then some function must be found to be used in Eq. 2 which relates \in s and the depth. Various assumptions have been made regarding this relationship. The one most generally used is that the sediment transfer coefficient is equal to the momentum transfer coefficient.

In 1935 Christiansen (6) was able to verify Eq. 2 by summarizing existing Colorado River data. Using the velocity distribution curves and the equation

 $f = \frac{\gamma DS}{dv/dy}$

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(4)

he calculated \in s from which he evaluated the integral on the righthand side of Eq. 2.

Kalinske and Pien (12) 1943 by measuring ϵ s directly in laboratory flume experiments, were also able to demonstrate the general validity of Eq. 2.

Lane and Kalinske (13) in 1941 by making the assumption the sediment transfer coefficient is equal to the momentum transfer coefficient, showed that ϵ s is a function of depth, it being zero at the top and maximum at mid depth. By using the Prandtl-Karman logarithmic curve for velocity variation in turbulent flow, they expressed ϵ s as

$$\epsilon_{s} = kD \sqrt{qDS} (1-y/D) y/D$$
(5)

where y/D is the relative depth. However, they conclude that the expression obtained using the variation of fs as given in Eq. 4 is not practical for actual engineering applications and that it is more convenient to assume fs is constant with respect to depth and use an average value. This is the equivalent to assuming a parabolic velocity distribution instead of a logarithmic distribution. Thus they obtain Eq. 3 and apply it to open channels. They further present river data to substantiate their assumptions. They point out, however, that the data are for wide rivers and the turbulence developed is due to drag on an unconsolidated sand bed and can not be expected to apply where turbulence is developed due to roughnesses and flow-disturbing items such as rocks, shrubs, trees, or various artificial obstacles.

Vanoni, (29) 1941 conducting experiments on the shape of the curves of velocity distribution for open channels, found that the velocity curve did follow the logarithmic relationship very closely. Therefore, any theoretical approach using this assumption should give results which closely approximate actual variations of $\{s \text{ with depth.}\}$

However, as stated by Chang (5) 1939 and substantiated by Hurst's and Rouse's experiments, a general conclusion can be drawn that whether the velocity distribution is parabolic or logarithmic, the vertical distribution of suspended sediment in turbulent streams is still of the exponential form, as given by Eq. 2.

The equation for sediment distribution in a wide channel with uniform turbulent flow may be stated as

$$c/ca = \left[\left(\frac{D-y}{y} \right) \left(\frac{a}{D-a} \right) \right]$$
(6)

where $Z = \frac{W}{k \cup_*}$, w is the fall velocity, c is the concentration of sediment, and D is the total depth. The equation in this form was first derived about 1936 by A. T. Ippen at the suggestion of Karman and was presented by Rouse (23) in 1937.

Eq. 6 takes into account the variation of \leq s with depth as expressed in Eq. 5 and gives the relative sediment concentration for a given particle size at some arbitrary depth a.

Vanoni (28) in 1946 reporting on experiments on sediment distribution in open channels performed in the laboratory, found that the measured sediment distribution had the same form as Eq. 6 but did not agree quantitatively with it. He stated that this is an indication the basic assumption, that the transfer coefficient for sediment is equal to that for momentum, is somewhat invalid.

Ismail (10) 1952 extending Vanoni's experiments to closed channels carrying sediment, stated that the sediment transfer coefficient varies with the mean sediment size and in his experiments varied from 1.3 to 1.5 times the momentum transfer coefficient.

Einstein and Chien (7) 1952 presented a new method of approach to the suspended sediment theory and substantiate their reasoning by comparing the results from their method to actual river measurements. The method follows closely the derivation of Eq. 6 with an additional assumption concerning the non-symmetry of the mixing length. In this method they have presented certain constants to be determined from the river measurements and applied to the exponent Z of Eq. 6.

Effects of sediment on the flow characteristics

Buckley (4) in 1923, reporting on experiments in the Menufia Canal in Egypt, found that the presence of sediment decreased the roughness and consequently increased the mean velocity. He attributed the decrease in the roughness to the dampening of the drag by the sediment. That is, the sediment did not allow the turbulence to extend up into the main body of the stream and slow it down.

Chang (5) 1939 however, states that unless the concentration is large it will not have an appreciable affect on the mean velocity. He gives the example that a large concentration of 10 percent by weight will change the velocity about 7.4 percent.

Kalinske and Hsia, (11) 1945 conducting studies in the laboratory on the transport of fine sediment of high concentration, found that the presence of sediment did not seem to have any definite effect upon the flow characteristics of the open channel. Furthermore, they checked the mean velocity distribution and found it to follow rather closely the logarithmic distribution. They also found that the numerical value of Karman's

universal coefficient k varied from 0.32 to 0.44 without any regular variation with respect to the sediment concentration. The sediment used in this experiment was very fine, having a mean diameter of 0.011 mm. The size of the suspended sediment was distributed uniformily throughout the cross section for all mean concentrations.

Vanoni (28) 1946 and Ismail (10) 1952, from their experiment in the laboratory on suspended sediment transport, conclude that the value of k decreases as the sediment load increases. The decrease in k indicates a dampening of the turbulence by the sediment. Vanoni obtained k values of 0.317 to 0.394. Ismail's k values were from 0.268 to 0.402. Vanoni also indicated that fine sediment has more effect in reducing k than coarse sediment.

Vanoni (28) 1946 shows that k is directly related to the velocity distribution and that k will reflect any change in the velocity distribution. He also shows that k is directly related to the momentum transfer coefficient by the equation

$$fm = ky \frac{7}{\sqrt{7}}$$
(7)

Barton and Lin (3) 1955 found from laboratory flume experiments that the value of k decreased as the sediment load increased. Their k-values ranged from 0.24 to 0.61. However, they had difficulty with the

entrance conditions at the head of the flume. When this condition was eliminated, their k-values ranged from 0.24 to 0.42.

Rand (21) 1953 in his discussion at the Fifth Hydraulics Conference stated that in some recent experiments he has found that the factor k proved to be a function of roughness size and geometry as well as relative roughness. He found that k increased with an increase of roughness. He obtained values of from 0.3 to 0.4. He also pointed out the curvature of the velocity distribution near the bottom on logarithmic paper could be decreased by the proper choice of bed elevations. By choosing different bed elevations, the value of k can be altered.

Vanoni (27) in 1953, analyzing Nikuradse's data, indicated that for the range of relative roughness in the experiments (r/k from 15 to 507) the value of k did not vary appreciably. He obtained values of k from 0.324 to 0.415 with the average equal to .374.

Morris (16) 1954 in a paper on flow over rough pipe and channel surfaces, discussed the use of a modified k for the flow near the walls. He states that the velocity distribution near the wall should be of the same form as near the center, but that it would need to be modified by an increase in k. His k-values range from 0.33 near the center to 0.42 near the wall,

with 0.36 as an average. He states that the value of k near the wall will be a function of the wall Reynold's number. For his experiments, k decreased with increasing wall Reynold's number.

Powell (20) 1946 and Nemenyi (17) 1946, both citing the work of three independent investigators, Moller (15) 1926 Gibson (8) 1909 and Stearns (26) 1883 seem to agree that secondary flow is in spiral pairs. The spiral pairs are two symmetrical parts, tending toward the middle of the pair at the top and tending outward at the bottom.

Experiments on suspended sediment distribution

Vanoni (28) 1946 in his experiments on sediment transport in open channels in the laboratory, found that the sediment distribution followed the exponential form as given in Eq. 6 but that the values of Zdid not agree with the Z_1 obtained from his concentration profile curves. Using the notation of Z as the calculated value from the equation $Z = \frac{W}{U_{L_{L_{l}}}}$, and Z_{l} as the experimental value figured from the slope of the curve from the logarithmic plot of the concentration versus depth, Vanoni found that Z_1 was less than Z_1 for fine sediment. For the coarsest sediment the values were very nearly equal. He attributed this relationship of $\mathbb{Z}_{\mathbf{1}}$ Z to two conditions which are directly connected and

to the coefficients of momentum and sediment transfer. In the first condition the coefficient of sediment transfer is less than the coefficient of momentum transfer. This condition is for fairly coarse sediment. As the instantaneous fluctuations start, there is a slip between the water and the particle. Thus, the instantaneous velocity of the particle is not as great as that for the water, as it is assumed to be. Therefore, \leq m is greater than \leq s.

In the second condition the sediment transfer coefficient is greater than the momentum transfer coefficient. This condition is for fine sediment.

>for momentum transfer, a correlation is required between the horizontal and vertical turbulent velocity fluctuations and uncorrelated or random fluctuations do not contribute to the momentum transfer. For sediment transfer this kind of correlation is not necessary and the random fluctuations also transfer sediment and tend to make \leq s larger than \leq m.

Thus it is seen that the sediment transfer coefficient is a function of particle size and the assumption that $\epsilon = \epsilon$ is most valid for coarse particle sizes when the two conditions tend to cancel one another.

Vanoni states that his laboratory experiments indicate a tendency for Z_1 to increase with concentration. His concentrations range from 1,000 ppm to 16,000 ppm. Barton and Lin (3) 1955 in their laboratory flume experiments, divided their results into two conditions, (1) flow over a plane bed and (2) flow over a bed with dunes. For the case of flow over a plane bed, the theoretical distribution of sediment as presented by Eq. 6 followed the experimental results very well. However, for flow over a bed with dunes, the actual sediment distribution was always more uniform than that predicted by the theory. Using the notation of Z being the calculated value and Z_1 the experimental value, for a plane bed, Z equals Z_1 and for a bed with dunes Z_1 is smaller than Z. They conclude that the relationship of Z and Z_1 depend to a large extent upon the bed conditions.

Anderson (2) 1942, using suspended sediment data from the Enoree River, found that the data fitted the form of Eq. 6 very well, but that in general the distribution was more uniform than the theory indicated. He also found that this difference increased with the grain size. In the experiment, k was assumed to be 0.4.

Mitchell (14) 1953, at the Fifth Hydraulic Conference in discussing effects of suspended sediment on the flow, states that some data from the Missouri

River indicated a possible decrease in Z_1 with an increase in concentration. The concentrations ranged from 3000 ppm to 8000 ppm.

Chapter III THEORETICAL ANALYSIS

In order to understand suspended sediment transport, it is helpful also to understand the mechanics of turbulent flow. Turbulence makes it possible for streams to carry non-colloidal sediment in suspension and for the particles to be transported from one region to another. The purpose of this chapter is to present theoretical and dimensional considerations for turbulent flow, turbulent transfer of sediment, and sediment distribution in the vertical.

Turbulent flow

For the purpose of this study, let turbulent flow be understood to be flow in which any velocity component at a point fluctuates with respect to time. Let u, v, and w equal the instantaneous velocity components in the directions of x, y, and z. Let U, V, and W equal the corresponding mean velocity and u', v', and w' equal the corresponding velocity fluctuation at any instant.

For a study of steady, uniform flow in wide channels, let x be taken along the axis of the channel,

y be taken vertically, and z be taken across the channel. V and W will be comparatively small and may be neglected. However, v' and w' do not vanish, but cause secondary movements which give rise to mixing of the fluid. In the derivation of the equation for flow in an infinitely wide channel carrying sediment the assumption is made that there is little variation in the conditions of flow with respect to the lateral or longitudinal directions, but that in the vertical direction, due to the presence of a gravitational field, there is a variation of sediment concentration with respect to depth.

The momentum transfer in turbulent flow is characterized by the equation

$$dv/dy = 1/ky \sqrt{\frac{Y_{\bullet}}{\beta}}$$
 (7)

wherein the Karman coefficient k has been found to be approximately equal to 0.4 for certain conditions. However, k is an indication of mixing and if any disturbing factor, other than the usual bottom drag, enters into the flow to increase or decrease the mixing, k might be expected to vary.

As discussed in Chapter II it has been found that an increase in the load of suspended sediment will decrease k. As the sediment load increases, it will take an increasing amount of energy to keep the sediment in suspension. Thus the turbulence will not extend upward into the flow as far as in clear water and the velocity distribution will have a greater variation with depth and k will be smaller than with clear water flow.

Side effects entering into the flow set up a different pattern of mixing than in the two-dimensional system. Normally, these side effects will increase the mixing through secondary circulation. As discussed in Chapter II, secondary circulation seems to be in the form of reverse spiral flow. The strength of the spiral flow and the number of pairs or cells in the channel will depend upon the width, the depth, the bed roughness, the side roughness, and the mean velocity of the flow. The cause of the secondary circulation is not entirely known.

Turbulent transfer of sediment

Consider the condition in which sediment, with a specific gravity greater than that of water, is in the flow. Then, there will be more sediment in the lower part of the channel cross section than in the upper part. Let v' flow upward through a unit area. Because of continuity, there will be downward flow equal to the upward flow. The upward fluctuation will carry more sediment upward than the downward fluctuations will carry downward, because the concentration of sediment is greater in the lower part of the channel. Therefore, the net transfer of sediment by the flow is upward. Under conditions of equilibrium the downward transfer of sediment due to gravity is equal to the net upward transfer by the flow.

The net upward transfer of sediment varies with the gradient of the curve of mean concentration and may be expressed as

where \mathcal{E}_s is the sediment transfer coefficient. For equilibrium, the upward transfer must be balanced by the settling of sediment for which the volume settling through a unit area is $w \ge x \le 1$ where w is the fall velocity of the sediment. The equation for sediment transfer is, therefore,

wc +
$$\epsilon_s dc/dy = 0$$
 (1)

Similar reasoning may be applied to the transfer of momentum, except that the slope of the velocity curve is positive, and the net transfer of momentum is downward. The effect of this transfer of momentum is a forward tangential stress, called turbulent shear, acting on the fluid directly below. The equation for shear in turbulent flow may be written

$$\mathcal{T} = - m \, \rho \, \mathrm{d} \mathbf{v} / \mathrm{d} \mathbf{y} \tag{8}$$

where \in m is the momentum transfer coefficient.

Sediment distribution in a vertical

Let an element of flow in equilibrium be considered. Therefore,

$$d \gamma/dy = - JS \tag{9}$$

where S is the slope of the uniform flow and is the specific weight of the water-sediment mixture. Upon integration

$$\Upsilon = - \gamma Sy \tag{10}$$

Denoting the distance in the vertical as depth D minus the vertical distance y from the bottom

$$\mathcal{T} = \mathcal{J} S(D-y) \tag{11}$$

For the bottom shear

$$\mathcal{T} = \mathcal{Y} DS \tag{12}$$

and

$$\gamma = \mathcal{T}\left(\frac{\mathbf{D}-\mathbf{y}}{\mathbf{D}}\right) \tag{13}$$

From

$$\gamma = \beta \notin m \, dv/dy \tag{14}$$

$$\epsilon m = \gamma / \rho / dv / dy$$
 (15)

According to Karman, in turbulent flow

$$dv/dy = 1/ky \sqrt{\frac{\gamma_{o}}{\rho}}$$
(7)

Substituting gives

$$\mathcal{L} \mathbf{m} = \frac{\frac{\gamma_{o}}{p} \frac{\mathbf{D} - \mathbf{y}}{\mathbf{D}}}{\frac{1}{\mathbf{ky}} \sqrt{\gamma_{o/p}}} = \mathbf{k} \sqrt{\gamma_{o/p}} \left(\frac{\mathbf{D} - \mathbf{y}}{\mathbf{D}}\right) \mathbf{y} \quad (16)$$

Assuming

$$\epsilon s = \epsilon m$$

Eq. 1 gives

$$wc+k\sqrt{\frac{\gamma_{\mu}}{D}}$$
 $y \frac{dc}{dy} = 0$ (17)

Separating variables

$$\int_{C_{a}}^{C} dc/c = - \frac{wD}{k\sqrt{\gamma_{a}}} \int_{a}^{y} \frac{dy}{y(D-y)}$$
(18)

Which leads to

$$c/ca = \left[\left(\frac{D-y}{y} \right) \left(\frac{a}{D-a} \right) \right]^{Z}$$
(6)

Where

$$Z = \frac{W}{k \sqrt{\tau_{o/p}}} = \frac{W}{k \sqrt{gDS}}$$
(19)

Eq. 6 enables one to compute the sediment concentration at any point in the vertical at a distance y above the bed, when the concentration C a at a distance a above the bed is known.

The exponent Z can be determined by two methods, (1) from Eq. 19 designated by Z, and (2) from the slope of the log plot of concentration versus depth, designated by Z_1 .

The ratio of the exponent \mathbf{Z}_{l} to the exponent \mathbf{Z} is designated $\boldsymbol{\beta}$.

Several assumptions are made in the derivation of Eq. 6. These assumptions and their possible effects are discussed below.

> 1. The flow is steady, uniform flow. This assumption would probably have its greatest effect on the determination of the slope.

- 2. The density \(\rho\) and the specific weight \(\forall are independent of \(y.) The validity of this assumption will differ with the amounts of sediment in the flow. However, for most practical purposes its variation with depth should be insignificant. This statement does not apply to the unmeasured load where \(\rho\) and \(\forall may vary considerably with depth. \)
- 3. The velocity is proportional to the log of the depth. As stated in Chapter II, this assumption should not introduce any appreciable error. The effective elevation of the channel bottom, however, may need to be adjusted.
- 4. The sediment transfer coefficient ξ_s is equal to the momentum transfer coefficient ξ_m . This assumption is probably the most important one made in the derivation. There is good evidence, as discussed in Chapter II, to show that ξ_s does not equal

 \mathcal{E}_m . It is thought to vary with sediment size, roughness, and secondary circulation. The sediment transfer coefficient can be either greater than or less than the momentum transfer coefficient. Dimensional analysis can be used to contribute to an understanding of the problems of suspended sediment transport.

The factors influencing Z and k include those describing the characteristics of the geometry, the characteristics of the flow, the characteristics of the fluid and the characteristics of the sediment.

The variables representing k may be expressed in equation form as

 $k = f_1 (c, V, R, \rho, \mathcal{U}, K)$

Choosing V, R, as repeating variables

$$k = f_2\left(c, \frac{V R \rho}{m}, \frac{K}{R}\right)$$
(20)

For an alluvial bed K/R can be replaced by D_b/R . Furthermore C/\sqrt{g} is dependent upon Re and D_b/R and can be used in place of either of these terms, which leads to

 $k = f_3 (c, Re, C/\sqrt{g})$ (21)

or

$$k = f_{4}(c, C/\gamma g, D_{b}/R)$$
 (22)

Essentially the same variables may be selected for Z.

101 4.

 $Z = f_5 (c, V, R, \rho, \mathcal{M}, d)$

Choosing V, R, ρ as repeating variables

$$Z = f_6\left(c, \frac{VRP}{u}, d/R\right)$$
(23)

Since C/\sqrt{g} is dependent upon Re and d/R, it can be used in place of either of these terms, co yield

$$Z = f_7 (c, Re, C/\gamma g)$$
 (24)

or

$$Z = f_8 (c, C/\sqrt{g}, d/R)$$
 (25)

Chapter IV EQUIPMENT AND PROCEDURE

The object of this thesis is to relate suspended sediment data collected from irrigation canals to existing theoretical equations. The study has been limited to the measured load of suspended sediment. Extreme caution was used to choose only channels for which the number of variables involved in suspended sediment transport would be at a minimum.

For the reason given above, all the data were taken on irrigation canals. Irrigation canals offered the best opportunities to obtain straight reaches for a sufficiently long distance to eliminate the effects of bends and curves and insure that the flow was in equilibrium. Also irrigation canals offered the best opportunities for finding regular-shaped cross-sections which would be free of obstacles such as rocks, trees, and other flow-disturbing roughnesses.

The size of the canals ranged from 50 cfs to 1800 cfs in discharge capacity. All the canals used had been in operation a sufficiently long time to be considered stable against either scour or deposition.
Visual observation was used to determine if the reaches were stable. Also the canal company records were checked to determine if the section had needed any maintenance in the past. No reach was used where there was a chance of it being in the influence of a backwater curve. The canals were carrying approximately design flows when the data were taken. The canals selected for this study are located in the states of Colorado, Nebraska, and Wyoming. The collection of data extended over the summers of 1953 and 1954.

The data taken for this study included slope of the water surface, velocity distribution, suspended sediment distribution, photographs, temperature of the water, and a general condition of the bed. The sequence in which the data were taken varied on some of the canals, but generally the procedure was as follows.

Slope measurements

The length of reaches over which detailed data were taken varied from 800 to 2000 ft depending on the size and slope of the canal. The upper end of the reach was always a sufficient distance below any curve to eliminate the effects of the curve. Laths were placed in the water and driven into the canal bank approximately $l\frac{1}{2}$ ft from the edge of the canal every 100 ft for the entire length of the reach. The tops of the stakes were driven to approximately 0.1 ft above the water surface. Laths were used because they are fairly inexpensive, plentiful, and easy to drive, yet sturdy enough to withstand a small weight applied to them.

A portable hook gauge, developed by the Bureau of Reclamation, was used to obtain very accurately the elevation of the water surface with respect to the top of the stakes. The elevation readings were repeated until the effects of surges in the canal were eliminated. The portable hook gauge is simply a plastic stilling well with a tube extending into the water to measure the elevation. When the well was filled to the elevation of the water surface, a valve was closed to keep the water from draining out of the well. A hook gauge was then used to determine the relation of the elevation of the water in the well to that of the base of the device. While the well was filling, the base of the device rested on the top of the stake. The elevation of the stakes with respect to some arbitrary bench mark was then obtained by the use of an engineer's level. Care was taken to eliminate the effects of the sun on the instruments by surveying only in the early morning, in the evening, or when the sky was overcast. Also every other station was used as a turning point to further increase the accuracy of the survey. The points were then plotted and a

straight line drawn through them for the slope of the water surface. In special cases where the slope was very small, the number of stations for slope measurements was increased from 11 to 21 to facilitate accurate determination of the slope.

Velocity measurements

On most of the canals, because of their size, it was necessary to use a boat to obtain the velocity and suspended sediment measurements. The boat was a l4-ft aluminum semi-rounded bottom runabout furnished by the Bureau of Reclamation. The boat was fitted with a 3-ft boom which extended upstream. To this boom was attached a U. S. Geological Survey Model A sounding reel. A Price current meter was attached to the end of the sounding reel cable.

The current meter was weighted with a 16-1b sounding weight. Extra fins were attached to the sounding weight to help orientate the current meter in the stream. The current meter was carefully cared for at all times and was calibrated in the calibration channel at Colorado A and M College in the spring and again in the fall to insure the accuracy of the velocity data. The current meter was calibrated with the sounding weight attached.

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The boat was secured by means of a tagline stretched across the canal. The tagline was attached to steel stakes driven into the banks of the canal. The tagline was graduated in feet to facilitate orientation across the canal.

The vertical profiles of velocity were spaced from 2 ft to 5 ft apart. This gave approximately 10 to 12 velocity verticals for each canal. The points in the vertical were taken at one tenth, two tenths, four tenths, six tenths, eight tenths, and nine tenths depth, and at a point four tenths of a foot above the bed. When the nine tenths depth point was close to the four tenths of a foot point, it was omitted. The 0.4 ft point was as close to the bottom as the current meter could be placed. The readings were taken for 70 seconds or longer.

Sediment samples

A U.S. DH 48 hand sampler was used to obtain the sediment samples. The sampler was fitted with a nose cap to prevent the filling of the sampler until it reached the desired depth. The sampler was fitted on a 6-ft aluminum bar which was graduated in tenths of feet. The sediment verticals were always at one of the velocity verticals, usually every other one. The points in the sediment verticals were usually at one tenth, two

tenths, four tenths, six tenths, eight tenths, and nine tenths depth and at a point 0.4 ft above the bed. When the nine tenths depth point was close to the 0.4 ft point, it was omitted. The first summer only two pintbottle samples were taken at each point. Because of the extremely low concentrations, it was very difficult for the laboratory to get a size distribution of the material. Therefore, the second summer, four pint-bottle samples were taken at each point.

Photographs

Photographs were taken of all the reaches while they were flowing full and also when they were dry. Photographs were taken looking downstream and looking upstream. They were also taken of any other pertinent features. All the photographs were taken with both the standard 35mm camera and a 35mm stero-camera.

Temperatures

Temperatures of the water were taken every onehalf hour while at the site. This usually extended over the daylight hours for two or three days. Occasionally, additional readings were obtained when revisiting the site. Bed conditions

Whenever possible, the bed of the reach was investigated for the presence of dunes. When dunes were present, the approximate height, spacing and orientation was investigated by probing the bed with a rod. On the smaller canals, waders were used to walk on the bed to determine the height and spacing of the dunes.



Bijou Canal at full supply



Bijou Canal empty

PLATE I



Ft. Morgan III Canal at full supply



Ft. Morgan III Canal empty (note dune pattern)

PLATE II



Portable Hook Gauge



Using the portable hook gauge



Current metering equipment

Chapter V PRESENTATION OF DATA AND DISCUSSION OF RESULTS

There is a very close relationship between the procedures used in determining the parameters and the results obtained from these parameters. Because of this relationship, the procedures are included in some detail in the same chapter as the discussion of results.

The tables and figures are presented near the beginning of the chapter to facilitate reference to them.

The discussion of results includes the Karman coefficient k and the exponents Z and Z_1 .

Procedures used to obtain parameters

Shear velocity.--The shear velocity $U*=\sqrt{gDS}$ was calculated for each vertical. The shear velocity for the channel is the average of all the shear velocities for the verticals.

The 50-percent size of suspended sediment.--The 50-percent size is the median size; 50-percent of the sediment, by weight, is larger than this size and 50percent is smaller than this size. All the suspended

Table 1PARAMETERS USED IN THIS STUDY.*									
Canal	Location	Condition of bed	Slope of water surface	Average sediment concentration ppm	Water temp- eratu- re ^O F				
Farmers	5 mi east of Mitchel, Neb.	Dunes 0.5' high, spaced 4'-8'	0.00013	173	69				
Interstate	1 mi no of Morril, Neb.	Dunes 0.4' high, spaced 4'-8'	0.00012	71	71				
Larimer-Weld	5 mi no.est. of Ft. Collins, Colo.	Dunes 0.4' high, spaced 5'-6'	0.000369	70	63				
Ft. Laramiel	3 mi west Torrington, Wyo.	Dunes 0.4' high, spaced 5'	0.00008	39	72				
Ft. Laramie II	9 mi so. of Lyman, Neb.	Small ripples of sand on clay bottom	0.000063	144	73.8				
Ft. Laramie III	8 mi so of Lyman, Neb.	Smooth clay bottom	0.000074	119	73				
Ft. Morgan I	½ mi west of Ft. Morgan,Colo	Small sand ripples on cohesive bed	0.000135	57	77				
Ft. MorganII	7 mi west of Ft. Morgan,Colo	Heavy dune pattern and pot holes 1.0'	0.00024	52	77				
Ft. MorganII	Il ¹ / ₂ mi west of Ft. Morgan.Colo	Dunes 0.3' spaced 6-7'	0.00019	85	77				
Garland I	10 mi west of Powell, Wyo.	Gravel bottom	0.000181	34	62				
Garland II	4½ mi west of Powell, Wyo.	Gravel bottom	0.000166	57	61.5				
Lucerne I	16 mi west of Torrington, Wyo	Small sand ripples	0.000253	67	69				
Lucerne II	17 ¹ / ₂ mi west of Torrington, Wyo	Small sand ripples	0.000387	42	71				
No. Platte	4 mi west of Torrington, Wyo	Small sand ripples	0.000294	21	70				
Bijou	9 mi west of Ft. Morgan, Colo	Solid smooth sand	0.000302	92	73				
Cozad	¹ / ₂ mi east of Gothenburg, Neb	Small sand ripples	0.000218	104	82				
Dawson	戈 mi east of Cozad, Neb	Dunes 0.5' high, spaced 5'-6'	0.000388	119	83				
Taylor-Ord	र्र mi west of Taylor, Neb	Dunes 0.3' high, spaced 5'-6'	0.000216	120	82				
*The complet obtained by Collins, Co	e field data are being publish addressing correspondence to lorado.	ed in co-operation with the Bur the Civil Engineering Dept., Co	eau of Rec lo. A & M	lamation and ma College, Fort	ıy be				

Canal	C/19	U# ft/sec	50% sed.size mm	Fall velocity ft/sec	K	Z	z ₁	β	<u>u</u> U *
Farmers	17 .19	0.157	0.067	0.0122	0.50	0.22	0.157	1.40	0.078
Interstate	15.52	0.161	0.056	0.0092	0.40	0.163	0.144	1.13	0.057
Larimer-Weld	11.22	0.236	0.0993	0.025	0.49	0.326	0.218	1.50	0.107
Ft. Laramie I	12.16	0.142	0.0455	0.0066	0.57	0.081	0.082	0.99	0.0465
Ft. Laramie II	19.38	0.109	0.0377	0.004458	0.37	0.13	0.114	1.14	0.042
Ft. Laramie III	18.94	0.116	0.0425	0.0066	0.53	0.154	0.0975	1.58	0.0517
Rt. Morgan I	10.40	0.122	0.028	0.00278	0.46	0.078	0.0495	1.58	0.0228
Ft. Morgan II	10.07	0.151	0.0407	0.0060	0.72	0.093	0.055	1.69	0.0397
Ft. Morgan III	10.40	0.133	0.0236	0.0018	0.52	0.078	0.026	3.00	0.0135
Garland I	11.82	0.204	0.0425	0.00475	0.70	0.071	0.0333	2.13	0.0233
Garland II	16.34	0.168	0.0445	0.00514	0.50	0.070	0.062	1.13	0.031
Lucerne I	13.92	0.138	0.0438	0.0055	0.54	0.097	0.080	1.21	0.04
Lucerne II	9.31	0.192	0.0396	0.00512	0.66	0.128	0.0405	3.16	0.0267
North Platte	10.33	0.154	0.0255	0.00184	0.56	0.067	0.0214	3.12	0.012
Bijou	13.91	0.175	0.0321	0.00313	0.72	0.0511	0.025	2.04	0.018
Cozad	10.72	0.145	0.0178	0.00121	0.44	0.07	0.0273	2.48	0.012
Dawson	11.81	0.191	0.0438	0.00745	0.73	0.127	0.0535	2.37	0.039
Taylor-Ord	11.54	0.162	0.091	0.0213	0.43	0.35	0.177	1.96	0.076

sediment samples were analysed for size distribution and concentration by the U. S. Geological Survey at their Lincoln, Nebraska laboratory. The 50-percent size was obtained by plotting the sediment size distribution on log-probability paper. For most canals, however, there was insufficient sediment in the water-sediment samples to give any more than the percentage passing the 0.62 mm sieve. Thus, it was necessary to find a method of extrapolating this one point to the 50-percent size.

On log-probability paper, a normal size distribution gives a straight line. It was found for the canal which had sufficient sediment for a size distribution, that the log-probability curve had somewhat the shape of a dogleg, see Fig. 3. However, the two slopes of the curve were fairly constant for the entire canal. Therefore, an average for the two slopes could be determined for the sediment in that canal.

The assumption was then made that sediment data from similiar canals in similiar regions would have the same slopes on log-probability paper. These slopes were then used to expand the size distribution to the 50percent size for the canals with only one point on the size distribution curve.

The assumption that like canals in like regions carry sediment with similiar distribution curves may be



Fig. 1 Typical variation of velocity with depth (Ft. Morgan III Canal)



Fig. 1 Typical variation of velocity with depth (Ft. Morgan III Canal)(cont'd)



Fig. 2 Typical variation of concentration with depth (Farmers Canal)



Typical sediment size distribution

Fig. 3















Fig. 7 Variation of k with $\frac{W}{U_{sp}}$

k



Fig. 8 Variation of Z with Z₁



Fig. 9 Variation of Z with $\frac{W}{U_{H}}$



Fig. 10 Variation of Z_1 with $\frac{W}{U*}$





Fig. 12 Variation of Z with C/\sqrt{g}



Fig. 13 Variation of β with c/\sqrt{g}

somewhat questionable. The canals which had enough sediment to make a size distribution analysis had a larger 50-percent size than the canals that carried insufficient sediment for a size distribution. This means the assumption was made that the size distribution was the same for all size ranges.

The Visual Accumulation Tube, commonly called the V. A. Tube, was used to determine the sediment size distribution for the samples which had a sediment size larger than 0.062 mm. The V. A. Tube is a glass settling tube, 120 cm long and 25 mm in diameter. The time it takes the sediment particles to fall the length of the tube is measured and then converted into a particle size. Because of the very small concentrations in the canals, the volume of the sediment samples obtained were not always as large as desirable for an accurate V. A. Tube analysis.

For the sample which had a sediment size smaller than 0.062 mm, the size distribution was obtained by sieves.

The 50-percent size of the sediment in this study ranged from 0.094 mm to 0.0178 mm, with most of the canals having a 50-percent size of approximately 0.04 mm.

As shown by Fig. 4, there is a discontinuity between the sieve analysis and the V. A. Tube analysis. Fig. 4 indicates the V. A. Tube analysis gives a smaller 50-percent size than the sieve. This difference can be explained in part, especially for the smaller size particles, by the shape of the particle. As the particle is falling in the relatively calm water of the V. A. Tube, it will orient its largest cross section perpendicular to the direction of movement. This will make the particle fall slower than a sphere of the same volume, which gives the particle a smaller size than does the sieve.

The concentration effects will probably be greater in the V. A. Tube than in the field. This would tend to cause the V. A. Tube to give a small size determination. However, it may also be that the concentration will have the effect of upsetting the particles so their maximum cross section is not perpendicular to the direction of movement at all times. If these two effects are operative, they would tend to cancel each other.

The 50-percent size was found for each point sample. The 50-percent size was then weighted by multiplying by the concentration at the same point in the vertical. This column of products was totaled for the vertical. The column of concentrations was also totaled

for the vertical. The total of the column of 50-percent size times concentration was divided by the total of the concentration column. This gave a weighted 50-percent size for the vertical. A similiar method was used to determine a weighted 50-percent size for the entire canal.

The fall velocity of the sediment.--By using the 50-percent size and the temperature of the water, the fall velocity of the sediment was determined from the graph on page 97 of the report, "Influence of Shape on the Fall Velocity of Sedimentary Particles" (25). This graph gives the fall velocity for different sizes and temperatures.

<u>Determination</u> of <u>k</u>.--The Karman coefficient k was calculated from the equation

$$k = \frac{2.3U*}{m}$$
(26)

where m is the slope of the line on the semi-log plot of depth versus velocity. The slope is numerically equal to the difference in velocities for one log cycle on the depth scale. A k was calculated for each vertical. The average of the k's for the verticals gave the k for the channel.

Determination of the exponents Z and Z_1 .--The equation $Z = \frac{W}{kU*}$ was used to calculate Z. A Zvalue was calculated for each vertical. However, the Z for the canal is not the average of the verticals, but

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was calculated from the average values of w, k, and U for the channel. This was done so that the average Z would be weighted the same as the average w. The exponent Z_1 is the slope of the line on the log-log plot of concentration versus depth. A Z_1 -value was determined for each vertical and an average of these gave the Z_1 for the canal.

The Karman coefficient

The Karman coefficient k was found from the data of Nikuradse to have a value of about 0.4 which has been in common use for many years. However, as discussed in Chapters II and III, k seems to vary with certain factors. In a laboratory study the number of these factors affecting k can be controlled and kept to a minimum. In the field, however, these factors cannot be controlled. It is necessary, therefore, to evaluate the relative importance of each factor to help understand and interpret the field data.

Local variation.--As seen in Eq. 7, the numerical value of k is an indication of the intensity of mixing and the variation of k across the channel will reflect the variation across the channel of the intensity of mixing. The variation of k across the channel, as shown in Fig. 5, indicates regions of relatively large and

small velocity gradients. As discussed in Chapters II and III, secondary circulation will have a pattern of flow in pairs of spirals. In spiral flow, momentum is transferred more rapidly and over a greater distance than in turbulent flow without secondary circulation. The greatest transfer of momentum will be along the vertical periphery of adjacent spirals, while near the center of the spiral the momentum transfer caused by the secondary circulation is relatively small. Thus, there will be a cyclic variation of mixing with respect to distribution across the channel.

<u>Average k-values</u>.--As seen in Table 1, the average k-values for the channels are generally greater than 0.4. This indicates that the mixing is greater than that which would be caused only by bottom drag in a twodimensional system of turbulent flow.

Secondary circulation, while causing a cyclic variation of mixing across the channel, would also seem to increase the mixing for the entire system. This would be reflected in an increase in the average k for the channel.

As stated in Chapters II and III, the numerical value of k decreases with an increase in suspended sediment. The average measured suspended sediment carried

by the canals investigated was very low, say 80 ppm as compared to Vanoni's 1300 ppm. Based on Vanoni's data, this concentration should have an insignificant effect on the magnitude of k.

There is some evidence, as stated in Chapters II and III, that the sediment size also affects k. It would appear that if the effects of the concentration are to be considered small, the effects of the sediment size would also be small. This may not be entirely true, however, if the effects of sediment size are not always directly connected with concentration, but to some extent with bed roughness through the formation of sand dunes.

The side effects of the channel tend to cause abnormal mixing near the banks. As discussed in Chapters II and III this increase in mixing near the banks will make the k-values near the banks larger than the kvalues near the center. If, in averaging the k-values across the channel, the end k-values are omitted (to give a closer approximation of a two-dimensional system) most of the average k-values are decreased. This is especially true for the very large average k-values. However, the end k-values are for verticals where sediment samples were taken and should not be omitted in computing the average k-values for the entire channel.

As discussed in Chapter II the numerical value of k can be adjusted by choosing different bed elevations. An adjustment of bed elevation in this study would give an increased k. This adjustment of the depth was not made because an increased k was not needed and so little curvature in the velocity profile was found near the bed, see Fig. 1.

Variation of k with roughness.--Fig. 6, shows a general decrease in k with a decrease in the roughness (increase in C/\sqrt{g}). The curve shown in Fig. 6 is the w/U_* 0.05 curve and is representative of the family of curves for w/U_* . Figs. 9 and 12 were used to locate the curve in Fig. 6. Only a representative curve was placed in Fig. 6 because of considerable scattering of the data. As discussed earlier in this chapter, the high k-values in this study may be attributed at least in part to secondary circulation. Furthermore, as the roughness of the bed increases the secondary circulation tends to be decreased. However, the increase in k due to the increase in roughness apparently more than offsets the decrease in k due to a decrease in secondary circulation. Thus, for an increase in roughness, even though the secondary circulation decreases, there is an increase in k.

Rand found that k increases with a decrease in roughness, approaching 0.4. This effect is just the

opposite of that in Fig. 6. However, Rand's roughnesses were much smaller than would be expected in a natural alluvial channel. Furthermore, his k-values were all below 0.4.

Variation of k with the velocity ratio w/U_{\pm} . There is a definite tendency, even though the data scatter considerably, for k to decrease as w/U_{\pm} increases. The curve, shown in Fig. 7 and having a slope of 1/10, was selected to represent the data. Because of the interrelationship of Z and k the slope on Fig. 7 must be compatible with any plot concerning Z and w/U_{\pm} . The equation of the line on Fig. 7 is

$$k = \frac{1}{2.35} (w/U *)^{-1/10}$$
 (27)

The velocity ratio w/U_* gives the particle fall velocity relative to the shear velocity. For the data in this study, w varies through a larger range than U *. Therefore, w/U_* is also an indication of the particle size. Fig. 7 then indicates that k might be a function of the particle size, that is, the smaller the particle, the larger the value of k.

Perhaps the variation of k with particle size may be explained by the relative ease with which turbulence can extend through small particles as compared to larger particles. Perhaps the large particles keep the turbulence confined more to the bed while with smaller particles it can extend further upward into the flow. This would cause k to be a function of particle size, with small particle sizes giving large k-values. Another possible explanation of the apparent variation of k with particle size is the fact that particle size has a strong influence on the bed roughness as found by Ali (1).

However, as stated before, the sediment concentrations are very small and the effects of any sediment parameter may also be small. Vanoni, as discussed in Chapter II, suggested that k might be a function of particle size, but that an increase in particle size gave an increase in k. However, his k-values were all below 0.4.

The exponents Z and Z_1

The exponent Z_1 , as determined from the actual log-log plot of concentration versus depth, expresses the degree of uniformity of sediment distribution in a vertical. Therefore Z_1 is a sediment distribution coefficient. A large Z_1 means the sediment is distributed non-uniformly through the flow in the vertical direction. The smaller the Z_1 , the more uniform the distribution, with Z_1 equal to zero as a limit for complete uniformity.

The exponent Z, calculated from the equation $Z = w/k U_{+}$ (19) actually expresses the ratio of the fall velocity of the sediment to the shear velocity and k. If all the assumptions made in the derivation of Eq. 6, are valid, this ratio should be equal to Z₁.

Determination of Z_1 .--The exponent Z_1 is determined as the slope of the log-log plot of concentration versus depth. The concentration determination is a relatively simple analysis and was determined with considerable accuracy by the U. S. Geological Survey. As discussed in Chapter IV, the field sampling was accomplished with a DH 43 hand sampler fitted with a nose plug. However, the depths in this study were not considered great enough to cause appreciable error.

Theoretically, the log-log plot of concentration versus depth will give a straight line for a small range of particle size. One way of determining if the size range is too large is to plot the log of the concentration against the log of the depth. If the plot does hot produce a straight line, the particle size range is too large and must be reduced until the log-log plot of concentration versus depth does produce a straight line. The sediment concentrations for this study did not have to be separated into size ranges to give a straight line

of the log-log plot of depth versus concentration.

Determination of Z.--The exponent Z is calculated from Eq. 19. As discussed earlier in this chapter, it was possible to determine k and U*with considerable accuracy. However, the fall velocity of the sediment may not have been determined with equal accuracy. If the V. A. Tube analysis gives a smaller particle fall velocity than occurs in the canal, then Z will be smaller than it should be.

<u>The variation of</u> Z with Z_1 .--In all but one canal, Z_1 is greater than Z. This means that the canal is actually carrying less suspended sediment than predicted by the theory, $Z = \frac{\omega}{K U_*}$. This effect is the opposite of what most investigators have found (as discussed in Chapter II). However there are two important differences between this study and those reported in Chapter II: a) the concentrations are very small, b) the size of the sediment is very small.

Fig. 8 seems to have two parts to the curve-the lower part from $Z_1 = 0.06$ to $Z_1 = 0.1$, and the upper part from $Z_1 = 0.1$ to $Z_1 = 0.35$.

The lower part of the curve of Fig. 8 shows a sharp decrease in Z compared to Z1. As discussed earlier in this chapter, this decrease may be due to the V. A. Tube determination of w.
For the upper part of the curve in Fig. 8 the determination of w is probably more accurate than for the lower part of the curve because the 50-percent sizes are larger. However, the curve seems to drift away from the 45-degree line with increasing Z_1 -values. Despite this apparent drift, the number of data in this region are not sufficient to draw conclusions. The broken curve is included in Fig. 8 to show the shape of the curve if it were to continue parallel to the 45-degree line. The gap in Z_1 -values between these data and those available from other experiments is very large, so that accurate interpolation in this gap is not possible. Most of the other available data have Z_1 -values ranging from approximately 0.5 to 4.0 and Z is greater than Z_1 .

As has been discussed, Z_1 will vary somewhat with concentration and size. It then seems possible that Z_1 would equal Z for only one sediment size and one concentration. The ratio $(\beta = Z_1/Z)$ for this case would equal unity. The farther away from this size and concentration, the more β would vary from unity. Experiment has shown β can be either greater or less than unity.

In this study there does not seem to be any tendency for Z_1 to change systematically with concentration. However, the concentrations are very small and

perhaps do not cover a large enough range for significant indications.

Variation of Z and Z_1 across the channel.---As shown in Fig. 5 there is a definite cyclic variation of Z and Z_1 with respect to distance across the channel. This variation is similiar to the variation of k across the channel. It is interesting to note that the variation is detected by two different methods of measurement. One, from which Z was calculated, was the velocity measurements. The other from which Z_1 was determined was the sediment-distribution measurements. As discussed in the variation of k across the channel, the cyclic variation is probably due to effects of secondary circulation.

Variation of Z_1 with w/v_+ .--Fig. 9 actually shows the variation of w/kv_+ with w/v_+ in which w/v_+ cancels so that in effect 1/k is plotted in increasing order of w/v_+ . This means that deviations from the 45-degree line indicate variations in k.

The slope of the curve in Fig. 9 was determined in conjunction with Fig. 7. The relationship between Z and k for the plots with $w/v \star is$

 $Z = w/k u \ll (w/u \ll)^n$

and

$$1/k \sim (w/v*)^{n-1}$$

Therefore, if Fig. 7 has a slope of 1/10, the curve in Fig. 9 must have a slope of 1/1.1. This slope does fit the data and makes the plots compatible. The equation for the line is

$$Z = 2.37 (w/u_{*})^{1.1}$$
(28)

Variation of Z_1 with w/u_x .--The line for Eq. 2^8 , was placed on Fig. 10. This line is generally below the data. The curve was placed on Fig. 10 by using Figs. 8 and 9. The broken curve corresponds to the broken curve on Fig. 8. It is not known if the curve should actually become asymptotic to the broken line which is parallel to the curve from Fig. 9. This would mean that for large values of w/v_* , Z and Z_1 are related to w/v_* by the same functions, and the broken line on Fig. 8 is the correct line. Furthermore, the broken line would be more reasonable when considering the problem of extrapolating to the data of other experiments. If, however, Z and Z_1 are not related to w/v_* by the same function, as is indicated by the curve in Fig. 10, the upper half of the curve in Fig. 8 is probably correct.

The upward drift of the curve in Fig. 10 is fairly well established, both by the data and Fig. 8.

Comparing Figs. 9 and 10, it is seen that at some small value of w/υ_* , Z_1 will probably become independent of w/υ_* , while Z does not become independent of w/υ_* . Thus, it might be the difference in the relationships of Z and Z_1 to w/υ_* which is causing the sharp deviation of Z from Z_1 for small values of w/υ_* .

Fig. 10 does indicate that there is a direct relationship between Z_1 and w/U* for the values given, showing that Z_1 is at least indirectly influenced by the particle size.

Variation of (β) with w/U_{\pm} .--Fig. 11 also shows an increasing deviation of Z and Z_1 for decreasing values of w/U_{\pm} . Thus, it is indicated once again that Z_1 becomes independent of w/V_{\pm} for small values of w/U_{\pm} . The curve in Fig. 11 is compatible with the curves in Figs. 9 and 10. The broken line in Fig. 11 corresponds to the broken lines in Figs. 8 and 10.

Variation of Z with bed roughness.--For large values of C/\sqrt{g} , Z is independent of C/\sqrt{g} . For smaller values there is a slight downward trend with decreasing C/\sqrt{g} . The velocity ratio w/u+ has been included in Fig. 12 as a third variable. Because of the relationship of Z and k, Figs. 12 and 6 must be

compatible. The exponent Z is the inverse of k and the plots do show k decreasing with increasing C/\sqrt{g} and Z decreasing with increasing C/\sqrt{g} . The position and spacing of the w/U_{*} curves are determined from Fig. 9 with which they must be compatible. The curves in Fig. 12 do fit the data well.

Variation of β with bed roughness.--In Fig. 13, there should be a family of curves for w/U*, because Z and Z₁ have been shown to vary with w/U* However, the actual w/U* curves were not put in because the w/U* curves were not well enough defined in the Z₁ versus C/ \sqrt{g} plot (not shown). The curve in Fig. 13 is just a representative curve showing the general trend.

The ratio $\beta = Z_1/Z$ shows a marked increase for small values of C/\sqrt{g} which means that C/\sqrt{g} affects one of the Z exponents more than the other. On Fig. 12 there is a tendency for Z to decrease with decreasing C/\sqrt{g} . On a plot of Z_1 versus C/\sqrt{g} (not shown) the data scatter considerable, but there does not seem to be the tendency for Z_1 to decrease as Z does in Fig. 12. In fact there seems to be a slight increase in Z_1 for a decrease in C/\sqrt{g} . This would explain why increases for decreasing values of C/\sqrt{g} .

The variation of β with $C/\gamma g$ is reasonable, however, if the origin and meaning of both Z and Z_1

are kept in mind. The exponent Z reflects the uniformity of the velocity distributions. A rough boundary will cause a large k, as shown in Fig. 6. This will make Z small. However, Z_1 indicates the actual sediment distribution. Therefore, it seems reasonable that for a rough boundary, although the turbulence may extend upward into the flow a considerable distance, the greatest increase in potential carrying power of the flow is near the bed. Thus the sediment gradient near the bed is large and consequently Z_1 should be large.

Chapter VI

SUMMARY AND CONCLUSIONS

Summary

1. The cyclic variation of k with respect to distance across the channel is attributed to the effects of secondary circulation.

2. The generally high average values of k for the channels are attributed to the side effects of the channel, roughness of the bed, and secondary circulation.

3. The reduction of k with an increase in sediment concentration, as noted by other experimenters, is insignificant for this study because of the very low sediment concentrations.

4. There is a decrease in k with a decrease in the bed roughness (increasing C/\sqrt{g}). Although a decrease in bed roughness may increase the secondary circulation, this increase in secondary circulation (which will increase k) is apparently not sufficient to overcome the decrease in k due to the decrease in bed roughness.

5. There is a general decrease in k for an increase in w/U_* , which indicates k will vary inversely with the particle fall velocity. One possible explanation for this variation may be that the larger particles require more energy from the turbulence to remain suspended than the smaller particles, and therefore the turbulence is confined closer to the bed.

6. For all but one channel, Z_1 is larger than Z. The values of Z_1 ranged from 0.05 to 0.35.

7. Both Z and Z_1 are a function of particle size. However, for small values of w/U_* , Z_1 tends to become independent of w/U_* . Throughout the range of the data, Z does not become independent of w/U_* . This causes a sharp deviation of Z from Z_1 for the smaller values of Z and Z_1 . The effects of techniques of laboratory size analysis upon this deviation have not been established.

8. No tendency was noted for Z₁ to vary systematically with the concentration. However, this may be due to the small range of concentrations.

9. The exponent Z_1 varies with both concentration (noted by other experimenters) and sediment size. It then seems possible that Z_1 would equal Z for only one concentration and sediment size, or perhaps one range of concentrations and sediment sizes. 10. There is a cyclic variation of Z and Z_1 with respect to distance across the channel. This variation is attributed to the effects of secondary circulation and may be detected both by the velocity measurements and by the sediment measurements.

11. Although for small bed roughness (large C/\sqrt{g}), Z_1 and Z are independent of C/\sqrt{g} , the relationship does not hold for large bed roughness where Z tends to decrease with decreasing C/\sqrt{g} .

12. The different effect of bed roughness on Z and Z_1 may be explained by the actual meaning of Z and Z_1 . For a rough bed, turbulence extends upward into the flow and causes a uniform velocity distribution. The more uniform the velocity distribution, the larger k will be, which in turn causes Z to be small. However, the turbulence causes a greater increase in the sediment carrying capacity of the flow near the bed than higher in the flow. Therefore, the concentration gradient is increased near the bed, which would at least keep Z_1 from decreasing, and probably cause Z_1 to increase. Conclusions

1. Secondary circulation has a large effect upon k, and Z and Z_1 .

2. The Karman coefficient k may vary with concentration, bed and side roughness, and the suspended sediment size. The Karman coefficient may also be larger than 0.4.

3. The sediment size has an effect upon Z and Z_1 .

4. The ratio $\beta = Z_1/Z$ can be greater than unity.

5. The suspended sediment and water samples were not sufficiently large to give unquestionable accuracy in determining the sediment size distribution.

6. Additional study is needed on the subject of sediment transport in open channels. It is hoped that this study may be helpful as a guide in setting up the scope, objectives, and procedures for future field studies on suspended sediment.

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