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DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

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PROGRESS REPORT NO. 1 ON STUDY OF NON-SILTING, NON-SCOURING CANAL SECTIONS FOR THE ALL-AMERICAN CANAL

by

E. W. LANE, RESEARCH ENGINEER

Denver, Colorado
September 7, 1933

UNITED STATES

DEPARTMENT OF THE INTERIOR

BUREAU OF RECLAMATION

MEMORANDUM TO CHIEF DESIGNING ENGINEER

SUBJECT: PROGRESS REPORT NO. 1 ON STUDY OF NON-SILTING, NON-SCOURING CANAL SECTIONS FOR THE ALL-AMERICAN CANAL

By E. W. LANE, RESEARCH ENGINEER

Under direction of

J. L. SAVAGE, CHIEF DESIGNING ENGINEER

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SUMMARY

For a canal to be stable the banks must not slough or slide, and the bottom and sides must neither silt nor scour. To obtain these conditions requires the consideration of a number of factors. This report does not deal in detail with sloughing or sliding, since stable slopes for the various soils is comparatively well known.

To prevent silting or scouring of the bed, it is necessary to have a velocity along the bed sufficient to move all of the material which is brought into the canal, and yet not so high as to cause scour of the subgrade of the canal.

The flowing water will not attack the subgrade unless its velocity is more than sufficient to move the material brought into the canal. The excess of velocity over that required to move this material which will attack the canal subgrade depends upon the material of which the subgrade is composed.

In order that the banks may neither silt nor scour, the velocities along them must be sufficient to prevent deposition but not sufficient to cause scour of the material of which they are composed. As a practical matter a slight amount of silting on the sides is not especially detrimental and frequently takes place, so that the important requirement is the prevention of scour and excessive deposition. The maximum allowable velocity along the banks depends upon the material of which they are composed. The material on the sides is also acted upon by the force of gravity, which assists the water in tending to cause motion. The sides will therefore scour under smaller velocities than the bottom.

The ratio between the velocity acting on the sides and that on the bottom depends upon the ratio of the bed width of the canal to the depth. The greater this latter ratio the greater will be the ratio of the velocity acting on the bottom to that acting on the sides. The bed width-depth ratio required for a stable channel is that which will bring the proper ratio of velocity acting on the bottom to that acting on the sides. Conditions which require high velocities acting on the bottom, as compared with those which may be permitted to act on the sides, require high ratios of bed width to depth. For example, canals carrying a heavy bed load in friable material require high velocities on the bed to move the load and low velocities along the banks to prevent cutting them; in other words, a high ratio of bottom velocity to side velocity, and therefore a high bed width-depth ratio. Canals with small bed

loads in friable material do not require such high velocities along the bottom to transport the bed load, and the ratio of this lower velocity, V_B, to the permissible side velocity V_s can therefore be smaller. The correct ratios for other conditions can be determined by the application of these principles.

It is believed that this report outlines the major principles which control stable channel shapes and velocities. Sufficient data is not yet at hand to enable quantitative application of them to be made but this investigation is being continued and it is believed that more definite results will be forthcoming.

SYMBOLS

English system used unless otherwise stated.

V = mean velocity

V_B = velocity near the bottom

V_s = velocity near the sides

B = bed width

d = depth

d_a = average depth

V_o = critical velocity from the standpoint of silting

W = width

W_m = mean width

S = slope (fall ÷ length)

Q = discharge in second feet

f = silt factor = $8\sqrt{\text{particle diameter in inches}}$

R = hydraulic radius

D = diameter of particle in inches

A = area of water cross section

P = wetted perimeter

n = exponent in formula of Kennedy type

C = coefficient in formula of Kennedy type

The following report gives the result of studies made to date on the problem of selecting a non-silting canal section for the All-American Canal. This memorandum extends the study of this subject reported in the memorandum, No. 114, "Notes on the Silt Problem of the All-American Canal," by E. W. Lane, dated December, 1929. Since extra copies of this memorandum are not available, and a wider knowledge of the subject has lead to somewhat changed view-points, some of the material on this subject contained in that report has been worked over and placed in this report with such modifications as the better knowledge of the subject indicated. This report is prepared in order to have available the best possible information for the design of those portions of the All-American Canal which may be constructed under the emergency public works appropriations. Although it is believed that it does contain valuable information and that the conclusions stated are sound as far as they go, it must be recognized that this memorandum is only a report on progress, and that further studies may modify or change entirely some of the less important conclusions. In order to make this report more intelligible to those who may not have an intimate knowledge of the problems of the All-American Canal, a brief statement of the conditions surrounding this large irrigation project is also included.

THE ALL-AMERICAN CANAL

The All-American Canal is planned to take water from the lower Colorado River and carry it to the lands lying in the Imperial and Coachella valleys by a route lying wholly within the United States. The Imperial Valley is now irrigated from the Colorado by a privately-owned canal system, a large part of which lies within the Republic of Mexico. The difficulties of international administration, and the undesirable silt conditions connected with the existing canal has led to the instigation by the U. S. Bureau of Reclamation of the new All-American Canal project which has been approved by Congress and will probably soon be put under construction.

The Colorado River is at present a very silty stream. It has a discharge varying from 2500 to 190,000 second feet and a suspended silt content near the intake of the proposed canal averaging 0.90 per cent by weight, and at times reaching 5.40 per cent. The suspended silt is extremely fine and the bed silt averages about 0.075 mm. (0.003 in.) in diameter. The river slope is approximately 1.2 feet per mile. The use of this very silty water in the Imperial Valley has led to great difficulty and an expense estimated at approximately $1,400,000 per year for dredging, canal cleaning and land leveling.

Before the All-American Canal is finished, it is expected that the Boulder Dam, now under construction, 303 miles above the proposed headworks, will be completed. This dam will be 725 feet high and form a reservoir of 30,500,000 acre foot maximum capacity, in which all the silt brought down to the reservoir will be deposited. Another dam will probably soon be built 155 miles above the intake which will stop practically all of the silt coming from above that point. The silt which reaches the intake will therefore be only that picked up from the banks and bed of the river below the lower dam and the small quantity brought in by the tributaries to the river between the lower dam and the intake. The problems to be solved in the design of this canal, which will have a maximum capacity of 15,000 second feet, include prediction of the quantity and quality of silt which in future years will be brought to the canal headworks, the best method of disposing of this silt, and the cross section shape and velocities necessary in the canal in order that it may neither silt nor scour. This report deals with the latter problem only.

HISTORY OF NON-SILTING CANAL SECTION STUDIES

Most of the study of the problem of non-silting canal sections has been made by the British engineers in India, in connection with the large irrigation projects of that country. A certain amount has also been done in Egypt, in connection with the irrigation works on the Nile. Little has so far been contributed by this country. In the last few years, however, a surprising interest in silt problems has developed in this country and it is now being attacked from many angles by a number of research men. Out of this interest will no doubt grow considerable progress.

The first study of non-silting canal sections was made by R. G. Kennedy (Ref. 1). His work is a classic in this field, and has resulted in the saving of millions of dollars in reducing the cost of cleaning out irrigation canals in India and elsewhere. Unfortunately, like most outstanding studies, it came to have such prestige that for many years little further progress along this line was made.

In his paper, Mr. Kennedy gave the result of measurements of bed widths and "full supply" depths on about 22 canals in the Lower Bari Doab canal system in which the channels had become stable and several more which had nearly reached this condition. He also gave the "full supply" discharge and the velocity computed from this discharge and the full supply area. From this data he developed a formula of the type $V_o = Cd^n$ which expressed with reasonable accuracy the relation between the critical mean velocity V_o and the depth d, as indicated by the results of the measurements. For the Lower Bari Doab, C was 0.84 and n was 0.64. Kennedy expected C to vary with the quality and quantity of silt, but thought n would be nearly constant. On Figure 1 is shown a line giving the velocities corresponding to the various depths according to this equation. The local conditions influencing these observations and Mr. Kennedy's conclusions will be given more in detail later in this discussion.

In 1895 Mr. Kennedy issued a set of hydraulic diagrams to aid in the design of non-silting channels. In 1904 he gave a rough rule for the relation of width to depth in non-silting canals (Ref. 5). A second edition of Hydraulic Diagrams (Ref. 6) was issued in 1907, in which Mr. Kennedy reprinted the original paper and added an extended discussion to clear up some of the obscure points and to give the results of his experience since the first paper was printed.

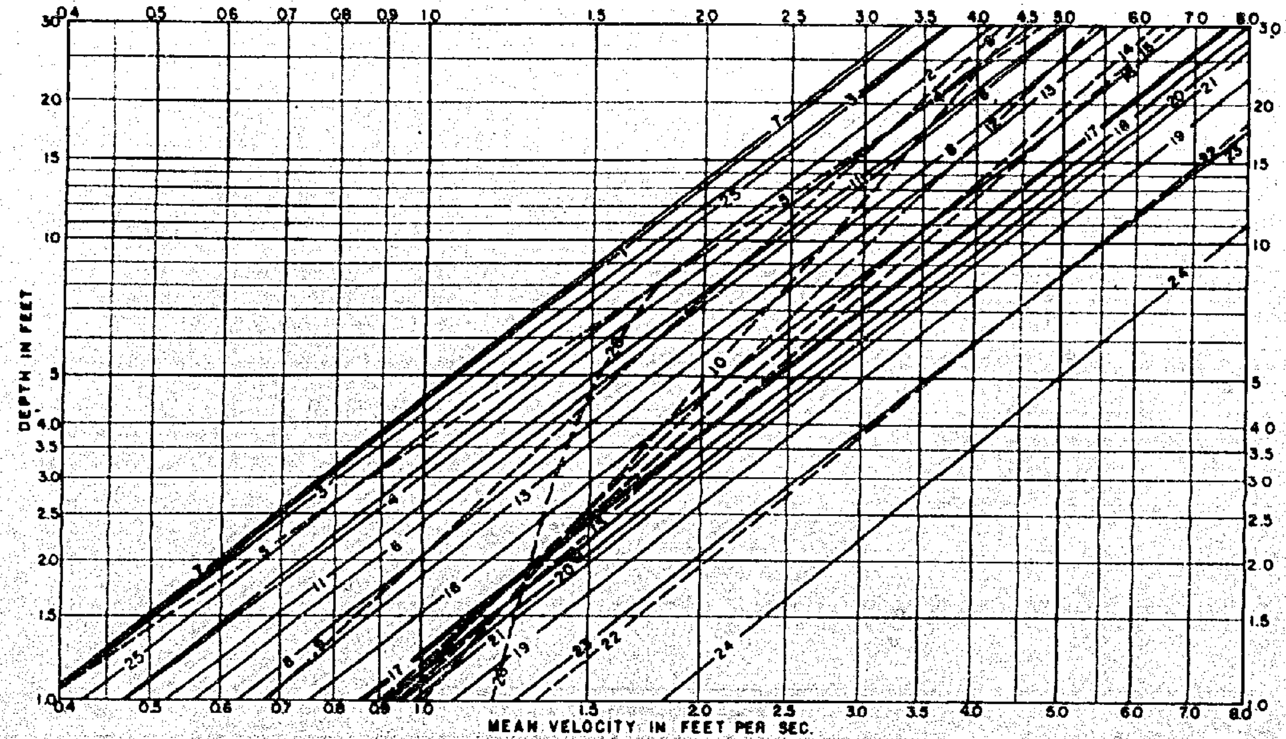
Mr. Kennedy's work soon became extensively used throughout India and observations were made on the ditches of other irrigation systems and a number of other equations of the same type as his were developed, suitable to the various local conditions. One of these was for the Godavari Western Delta and the Kistna Western Delta in Madras (Ref. 7).

In 1913 a set of hydraulic diagrams for the design of channels was put out by Capt. A. Garrett which deals with non-silting channels (Ref. 8) which is extensively used in the United Provinces.

In 1917 F. W. Woods proposed (Ref. 2) the use of definite ratios of depth to width, based on an analysis of data from the Lower Chenab Canal system. In 1919 the results of an extensive analysis of canal dimensions of the Lower Chenab Canal by E. S. Lindley was published (Ref. 3). Mr. Lindley found for these canals a critical velocity relation $V_o = 0.95d^{0.57}$ and a relation of bed width to depth of $B = 3.8d^{1.61}$.

In 1927 Mr. Woods (Ref. 4) proposed a general formula covering velocity, average depth, mean width and slope, as follows:

$$d_a = W_m^{0.434}$$
$$V_o = 1.434 \log_{10} W_m$$
$$S = \frac{1}{2 \times \log_{10} Q \times 1000}$$



Curve No.	LOCALITY	REMARKS
1	Egypt	Lower limit. Buckley
2	Egypt	Upper limit Buckley
3	Egypt	Lower limit. M & Y
4	Egypt	Upper limit. M & Y
5	Egypt	K.D. Ghaleb
6	Egypt	U.S. Dept. Agr. Tech. Bull. No. 67
7	Muzaffargorh	Lower limit, Punjab India
8	Muzaffargorh	Upper limit, Punjab India
8	Sind	India
9	Godaveri, Western	Delta, Madras
10	Rio Negro	Argentina
11	Siam [redacted]	[redacted]
12	Kistna	Madras

Curve No.	LOCALITY	REMARKS
13	Sutlej	India
14	Shwebo, Burma	
15	Chenab, Punjab	
16	Shirhind, Punjab	
17	Bari Doab	Data for Kennedy's Formulae
18	Penner, River	Lower limit
18	Cauvery Delta	Lower limit
19	Penner River	Upper limit
20	Cauvery, Delta	Upper limit
21	Imperial Valley	Rothery
22	Cauvery	Extreme upper limit
23	Imperial Valley	Lower limit. Collings
24	Imperial Valley	Upper limit. Collings

Curve No.	LOCALITY	REMARKS
25	Behera Delta	R G Kinder
26	Jamrao, Sind	W.L.C. Trench

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ALL AMERICAN CANAL
CRITICAL VELOCITY FORMULAE
NON-SILTING, NON-SCOURING VELOCITIES

DRAWN W.M.B. SUBMITTED E.W. Lane
TRACED A.R.U. RECOMMENDED
CHECKED W.M.B. APPROVED
DENVER, COLO. AUG. 16, 1933.

212-D-162

FIG. I

These formulae cover not only the depth and width but also the discharge and slope. According to them, for a given discharge there is a single condition of depth, width and slope which will produce a stable channel.

In 1928 Mr. W. T. Bottomley (Ref. 9) put forward the idea that non-silting, non-scouring irrigation channels would be secured if the slope of the canal was of the same order as that of the parent river regardless of the relation of width to depth and the shape of the channel.

In 1930 an extensive discussion of this subject (Ref. 18) was presented by Mr. Gerald Lacey in which he advanced the proposition that the wetted perimeter of stable channel was a simple function of the square root of the discharge ($P = 2.668Q^{0.5}$) and that the shape of the section depended upon the fineness of the silt carried, coarse silt giving rise to wide shallow sections and fine silt to narrow, deep ones.

He developed the formula $Q f^2 = 3.8 V_o^6$ and $V_o = 1.17 \sqrt{fR}$ in which f is a silt factor, related to the diameter of the bed material by the expression $f = 8 \sqrt{D}$ where D is in inches. From those formulae, knowing the Q of the ditch V_o, A and R can be computed.

The foregoing authorities have developed their ideas almost entirely from experience in India. The result of experience on canals in Egypt is given by Molesworth and Yenidunia (1922) (Ref. 10). They give a general formula in English units:

$$d = (9060S + 0.725) \sqrt{B}$$

as developed from a careful examination of a large number of recognized good Egyptian canals.

As a result of further experience, A. B. Buckley (Ref. 11), develops the adjustment of the formula

$$d = (9060S + 0.725) \sqrt{B}$$

given above, for canals of depths of 1.6 m. (5.26 feet) and less.

$$d = \frac{0.0025\ (100000S + 8)^2\ B}{1.62}$$

The above formula is in English units.

In addition to the general formulae proposed by various investigators, a large number of special formulae of the Kennedy type have been developed. These are listed on Table No. I.

TABLE NO. I

EQUATIONS FOR NON-SILTING, NON-SCOURING VELOCITIES

Curve No.	Equation English Units	Locality	Authority	Limit	Reference
1	$V_o = 0.381d^{0.64}$	Egypt	Buckley	Lower	Irrigation Proj. Dept. of Egypt.
2	$= 0.46d^{0.64}$	"	"	Upper	--ditto--
3	$= 0.39d^{2/3}$	"	Molesworth and Yenidunia	Lower	Molesworth & Yenidunia Irrig.
4	$= 0.475d^{2/3}$	"		Upper	Proc., p. 207.
5	$= 0.391d^{0.727}$	"	K. D. Ghaleb		Proc. Inst., C. E., p. 260, Vol. 229; also p. 285, Vol. 223.
6	$= 0.56d^{0.64}$	"			U. S. Dept. Agr. Tech. Bull. No. 67, p. 44.
7	$= 0.38d^{0.64}$	Mozaffargorh Dist., Punjab, India	C. W. Duthy	Lower	Proc. Punjab Engr. Congress,
8	$= 0.63d^{0.64}$		--ditto--	Upper	pp. 44 and 48, 1919.
8	$= 0.83d^{0.64}$	**Sind**	**F. W. Woods**		Engineer, p. 648, Vol. 143; Parker, Control of Water, p. 678.
9	$= 0.67d^{0.55}$	Godavori Western Delta, Madras	Kennody		Proc. Inst., C. E., p. 260, Vol. 229; Madras P. W. D., Oct. 3, 1912, Dist. 1872.
10	$= 1.01d^{0.44}$	Rio Negro, Argentina	R. E. Ballestor		Proc. Inst., C. E., p. 280, Vol. 225.
11	$= 0.52d^{0.66}$	Siam River, India	-----		U. S. Dept. Agr. Tech. Bull. No. 67, p. 44.
12	$= 0.93d^{0.52}$	Madras (Kistna)	Kennody		Proc. Inst. C. E., p. 260, Vol. 229.
13	$= 0.67d^{0.64}$	Sutlej, India	F. W. Woods		Engineer, 6-17-27, p. 648.
14	$= 0.91d^{0.57}$ (approx.)	Burma (Shwebo)	Kennody		Proc. C. E., p. 260, Vol. 229 (1929-1930); Eng., p. 648; Parker, Control of Water.

TABLE NO. I (Continued)

Curve No.	Equation English Units	Locality	Authority	Limit	Reference
15	$V_o = 0.95d^{0.57}$	Chenab, Punjab	Lindley		Proc. Inst. C. E., p. 260, Vol. 229; Punjab Eng. Congress, Proc., 1919, p. 63.
16	$= 0.756d^{0.64}$	Sirhind, Punjab	W. B. Harvey		Proc. Punjab Eng. Congress, 1919, p. 58.
17	$= 0.84d^{0.64}$	Bari Doab	Kennedy		Hydraulic Diagrams, Kennedy, Public Works Dept., India, 1907.
18	$= 0.924d^{0.64}$	Penner River	J. M. Lacey	Lower	Proc. Inst. C. E., p. 333, Vol. 229.
18	$= 0.924d^{0.64}$	Couvery Delta	--ditto--	"	
19	$= 1.09d^{0.64}$	Penner River	"	Upper	--ditto--
20	$= 0.966d^{0.64}$	Couvery Delta	"	"	"
21	$= 0.98d^{0.64}$	Imperial Valley	Rothery		Proc. Inst. C. E., p. 179, Vol. CCXVI.
22	$= 1.26d^{0.64}$	Couvery Delta	J. M. Lacey	Extreme upper	Proc. Inst. C. E., p. 333, Vol. 229.
23	$= 1.33d^{0.61}$	Imperial Valley	Collings	Lower	Proc. A. S. C. E., May, 1933.
24	$= 1.83d^{0.61}$	" "	"	Upper	Proc. A. S. C. E., May, 1933.
25	$= 0.42d^{0.64}$	Behera Delta	R. G. Kinder		Proc. Punjab Engineering Congress, 1919, 74j.
26	$= 1.1+.095d$	Jamrao, Sind	W. L. C. Trench		Proc. Inst. C. E., p. 307, Vol. 223, 1926-1927.

Note: "Limit" refers to the upper or lower limit of the data observed, which may spread over a considerable range.

SUMMARY OF PREVIOUS STABLE CHANNEL FORMULAE

The formulae developed for stable channels fall into two classifications: (a) those giving an expression for velocity, and (b) those giving stable channel shapes. Those in the first class take the form of the Kennedy equation $V_o = Cd^n$. In most of these n has been taken as 0.64, the value developed by Kennedy. In all cases the value of C was constant for a given locality or canal system. Kennedy believed that C would vary with both the size and quantity of silt, but did not emphasize the effect of quantity of silt as much as quality and as a result it has been largely lost sight of by other students of the subject. He did not believe that the value of n would change greatly.

A formula of the Kennedy type indicates that the critical velocity increases with the depth, but experience shows that as the depth is increased a velocity is finally reached where the banks begin to erode. Kennedy believed that the limiting velocity was a matter of experience, and gave limiting values which correspond to depths of about 9 to 1-1/2 feet. This had the effect of limiting the depths of canals designed according to his rules to these depths. No data on this limitation are available for the conditions under which any of the other formulae of the Kennedy type were developed.

Of the formulae of the second type, Lindley gives a relation of critical velocity to depth and bed width, but suggests no modifications for quality or quantity of silt. Woods gives relations for mean depth, velocity, and slope, but like Lindley makes no suggestion that these relations might be influenced by quantity or quality of the silt. Lacey gives channel shapes and velocities, bringing in the effect of the size of the silt grain but does not consider the quantity of material to be transported.

COMPARISON OF CRITICAL VELOCITIES

In order to determine what velocities could safely be used in the All-American Canal, Figure 1 was prepared showing the relation of depth to critical velocity, as determined from all available observations on actual ditches. These show at a glance that for a given depth of flow there is a tremendous variation in critical velocity. The line representing Kennedy's data is shown heavier than the remainder. The variations range approximately from 46% to 208% of Kennedy's results, or the highest value over 450% of the lowest.

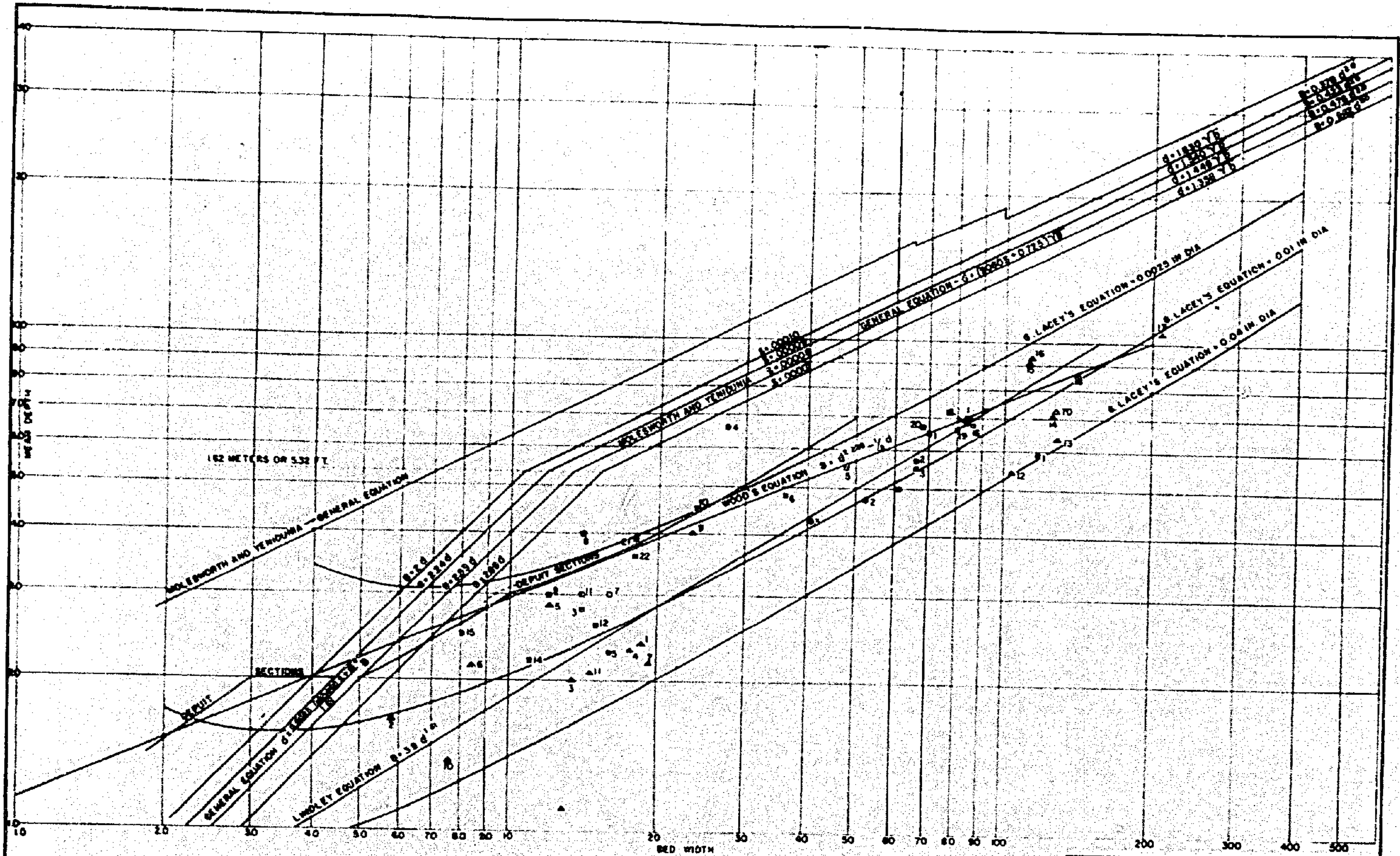
The local conditions under which most of these formulae were developed is not known in detail. In a general way, however, it is believed that the silt of the Nile River is finer than that of Ravi River, from which water is drawn for the Lower Bari Doab Canal, on which Mr. Kennedy's observations were made. The lower velocities found for the Egyptian canals as compared with Kennedy's is therefore consistent with the relation of Lacey's equation $Qf^2 = 3.8\ V_o^6$, that finer material results in lower critical velocities. But it is also known that the silt of the Colorado River and tributary Imperial Valley canals is finer than that of the Ravi, but the critical velocities are higher in the case of the Imperial Valley canals. This is contrary to the relation given by Mr. Lacey.

COMPARISON OF FORMULAE FOR WIDTH-DEPTH RELATION

A comparison similar to that of the critical velocity relations was also made of the various formulae for the relation of bed width to depth. The results are shown on Figure 2, which gives the relation of bed width to depth for the principal formulae and some of the data. The Wood's formula was expressed in terms of mean width, and has been changed to terms of bed width by assuming side slopes 1/2 to 1.

The data for channels as proposed by G. Lacey (using 1/2:1 side slopes) for three sizes of material are also shown. The finest of these, 0.0025 inches in diameter, is for material corresponding in size to the material composing the bottom of the Imperial Valley canals.

The Punjab (Kennedy) data is computed from the data given by Kennedy for the Lower Bari Doab Canal, using vertical side slopes, as reported by him. There are also given data on canals in the Godavari Western Delta and some values obtained from canals in the Imperial Valley. The data from Egypt was in the form of a general equation by Molesworth and Yenidunia, which is independent of the slope, and an equation which is dependent on the slope, four slopes being given. Below 1.62 meters (5.32 feet) a modification of the Molesworth-Yenidunia formula given by A. B. Buckley has been used, based on data which has been collected since the other formula was proposed. The Dupuit section, said to be widely used in Egypt is also shown. Two values are given of canals with 46 foot bed width which illustrates the widely varying depth which will give stable shapes under different conditions.



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ALL AMERICAN CANAL
BED WIDTH - DEPTH RELATION
NON-SILTING NON-SCOURING CANAL

DRAWN C.B.C., V.E.R. SUBMITTED C.W. Lane
TRACED J.P.N. RECOMMENDED
CHECKED W.P.B. APPROVED

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FIG. 2

This data for the bed width-depth relation shows even greater variation than the depth critical-velocity relations shown on Figure 2. For a 5-foot depth, the Molesworth-Yenidunia formula without the slope factor , gives a bed width of 6.4 feet and the Lindley equation gives 50.0 feet or a ratio of maximum to minimum of 781%. Some of the Imperial Valley data indicate even higher ratios than given by the Lindley formula. The wide range does not seem to be due to variation in the size of the silt, for while the Egyptian data is believed to be for finer silt than the Indian data of Woods and Lindley, most of the Imperial Valley data, which are also for fine silt, give even higher bed width-depth ratios than either Lindley or Wood.

FACTORS AFFECTING STABLE CHANNEL SHAPES

As a result of the wide range of critical velocities and bed width-depth relations found on the canals in the different parts of the world, and the lack of any readily apparent consistency in the variations, it was clear that if the factors controlling this variation could not be determined it would not be safe to adopt any of the relations given by existing formulae for the design of the sections of the All-American Canal. Although these formulae no doubt provide workable relations for the conditions for which they were developed, those conditions have not been delineated sufficiently to enable them to be applied elsewhere. In general also they were developed empirically from a very limited range of conditions, and in most cases they omit from consideration factors which are important.

To develop a rational design for the canal sections of the All-American Canal it was therefore necessary to attempt to go back to the fundamentals and try to make an analysis of the factors controlling the shape of a stream channel in erodable material, and their relations to each other.

The following is a list of factors which may enter into a determination of stable channel shapes:

<u>Hydraulic factors</u>

- Slope
- Roughness
- Hydraulic radius or depth
- Velocity
    - Mean velocity
    - Velocity distribution
- Temperature

Channel shape

Width

Depth

Side slopes

Nature of material

Material transported

Quality

Size

Shape

Specific gravity

Dispersion

Quantity

Bank and subgrade material

Miscellaneous

Alignment

Uniformity of flow

Aging

In arriving at a rational solution of the problem of stable channels it is necessary to consider all of these factors, and determine as accurately as possible which of them are of major importance, and which of them are minor or negligible. By determining first the relation between major factors, it may be possible to later study the effect of minor factors, but until the major relations are known, the data available is only collection of miscellaneous facts of limited value.

Of the hydraulic factors, the slope, roughness, hydraulic radius and mean velocity are interdependent and with reasonable certainty their relation is known quantitatively through the ordinary velocity formulae. It is true that the effect of the movement of material in suspension and by traction upon the roughness is not definitely known and more information on this point is needed, but compared to the uncertainty existing in other phases of the problem, the relations of these four items is so well known that for the purposes of this study further investigation along those lines is probably unjustified. The relation between these factors and scouring or transportation of solids in channels is not well established and must be further studied.

As will be shown later, it is believed that the velocity distribution, as well as the mean velocity, is of primary importance to the problem and that it together with the channel shape factors of width and depth exercise an important influence on stable shapes. The side slopes are relatively unimportant except as regards sloughing.

Temperature has been suggested as having an important effect because it influences the rate at which solid particles settle through water, because of its effect on the viscosity of the water. That temperature might have some effect cannot be questioned, but it is believed that it is probably small, from the standpoint of stable channel shapes. Most of the data were collected in warm countries, comparable to the locality of the All-American Canal, and the temperature variation while it might cause some difference in settlement rate would ordinarily not be enough when averaged over the year to cause major effects. Moreover, it is probable that the drag force, which is not appreciably affected by temperature, is the most important factor in stable channel shapes, and therefore temperature effects are relatively unimportant. In any event, temperature data is not available, which would enable an analysis of its effect to be made.

Nearly all students of the problem have admitted that the size of the material transported is of major importance. The shape no doubt has an effect, but it is believed to be of secondary importance as laboratory experiments show that angular particles are moved by only slightly higher velocities than rounded ones. In any event, no data on it is available for any of the localities, so that its influence could not be investigated, even if it was desired to do so. Specific gravity of the transported material also has its effect, but since it rarely varies much from 2.65 it is of secondary importance. No data on it would be available, even if it were desirable to study it. The dispersion of the material by virtue of the electrical charges carried by the particles is important in some phases of sedimentation, but it is probably active only in the case of very fine material which is ordinarily not much of a factor in stable channel sections. Here again no data for further study is available.

It is believed that the quantity of solids in motion is an important factor in the shape of stable channel shapes, and has not received attention which its importance warrants. Cases illustrating its importance are numerous. For example, it is a common occurrence in some irrigation systems to have the upper section of the ditch fill during periods of high silt content in the streams from which they draw, and this fill scour out later during periods of clear water flow. In other words, the ditch is unstable, at times being unable to transport all the material brought to it, hence filling up, and other times transporting more material than brought to it, and therefore cutting down its bed. Over long periods the ditches are approximately stable because the two actions counteract each other. Another common example is the change from unstable to stable condition which result when an effective sand trap is applied to a ditch which is filling up. There are also numerous cases where the channel of a natural stream is stable but begins to scour severely when a dam is built on it and cuts off the supply of solid material which formerly came down to renew that which was moved forward by the flowing water.

One of the most important factors controlling stable channel shapes is the nature of the material composing the banks and subgrade. If these are resistant to scour, higher velocities can be used than if the material is friable.

Alignment is another factor which must be considered, for bank scour is more likely to take place on curves. If a canal is apt to be operated a large proportion of the time at part capacity, this must also be considered in the design.

Another factor influencing the stability of an irrigation channel is what is commonly called aging. After water has run for some time in a channel, the particles composing the bed arrange themselves in such a manner that they are more difficult to move than when the water is first turned in. If the water is silty, this material forms a sort of weak cement which binds the bed material together and makes it more resistant.

In addition to the factors listed on pages 14 and 15 another set of relations enter into the selection of the best channel section in any instance, which depend upon the conditions which the canal is designed to meet.

Canals for convoying water for irrigation or power are usually designed to meet one of three sets of conditions. The first type is encountered when it is desired to use the lowest practicable velocity, in order that the slope may be reduced to a minimum. In the case of power canals this is done to obtain the greatest feasible power head, and in irrigation canals it is done to enable the ditch to command as much irrigable area as possible for a given length. A second type of conditions is met in both power and irrigation canals where it is desired to reduce the size of the canal to a minimum, in order to make the cost as small as possible without making the slope steeper than necessary. This requires that the velocity be made as great as can be carried without scouring the banks or bed. A third condition is met in irrigation canals where it is desired to carry the ditch on an alignment which has a slope as steep as possible, in order to reduce the cost of drops. The first of these conditions aims at securing the minimum practical velocity within the limitations of cost and silting. The second aims to secure the highest velocity which the ditch will stand with a shape which will convey the water with a reasonable loss of head. The third aims to use up as much head as possible by making the canal wide and shallow, thus reducing the hydraulic radius to a minimum and the slope for a given velocity to a maximum. The group into which any particular canal falls therefore indicates limitations which are likely to control the best channel shape, which must not be exceeded while still being subject to the influence of the factors listed on pages 14 and 15.

CONDITIONS REQUIRED FOR STABLE CHANNELS

For a channel to be perfectly stable, it must not fill or scour on either the banks or bed. The banks must also be stable against sloughing or sliding. To accomplish the non-filling requirement, the velocity must be enough to move through all of the solid material which is brought into the section by the flowing water. To fulfill the non-scouring requirement the velocity at the bed or the banks must not be great enough to scour the material of which they are composed. To determine a stable section for a set of conditions it is necessary to work out the various relations which will cause velocities at the banks and bed which will bring these conditions about.

The material carried into a section of canal may be entirely composed of fine material which is easily moved by the water or it may be composed entirely of coarse material which is moved only at relatively high velocities. Usually, however, it has a graded composition varying from coarse to fine. If all the material is very fine, it ordinarily offers little practical difficulty because the velocities required in the ditch to meet conditions of economy are sufficient to keep it in motion. If the material is graded, the fine material moves in suspension and the coarse is rolled along the bed. If all the material is coarse, all of it may be dragged along the bed, and little if any be carried in suspension. Since the amount of the bed material which can be moved depends upon the velocity near the bed, to obtain a stable channel the velocity along the bed must be greater for larger bed loads. This may require a higher velocity along the bed than the material in which the channel was built would stand from clear water, the entire energy of the water on the bottom being expended in dragging along the bottom the material which has been brought down by the water from above. If, however, the velocity along the bottom exceeds that necessary to move the bed load along, it will act on the subgrade of the channel. To have a stable channel, the subgrade material must be sufficiently tenacious to resist this scour. Summarizing this relation, it may be said that the velocity along the bottom of a stable channel must be sufficient to move along the quantity of material supplied to it, but not so great as to scour the subgrade.

The material composing the banks of the canal is acted upon by two forces tending to produce motion. One of these is gravity, which tends to make the material roll or slide down the sides of the ditch. The effective gravity force is the component which acts downward along the side slopes of the ditch. The other force acting is that due to the motion of the water through the canal, which tends to drag or push the material in a downstream direction. The magnitude of this force depends upon the velocity adjacent to the bank. The force of gravity and the force of the stream both act together when water is flowing in the canal, and when the resultant of the two forces is sufficient to dislodge material from the sides, it moves in a diagonal direction to the bed of the stream, or if fine enough, is carried off in suspension by the water. The slope of the bank must be sufficiently flat so that the component along it, of the force of gravity, when combined with the force of the water, is insufficient to dislodge the particles. Flat side slopes, since they cause a smaller component of gravity, therefore have less tendency to scour from this cause.

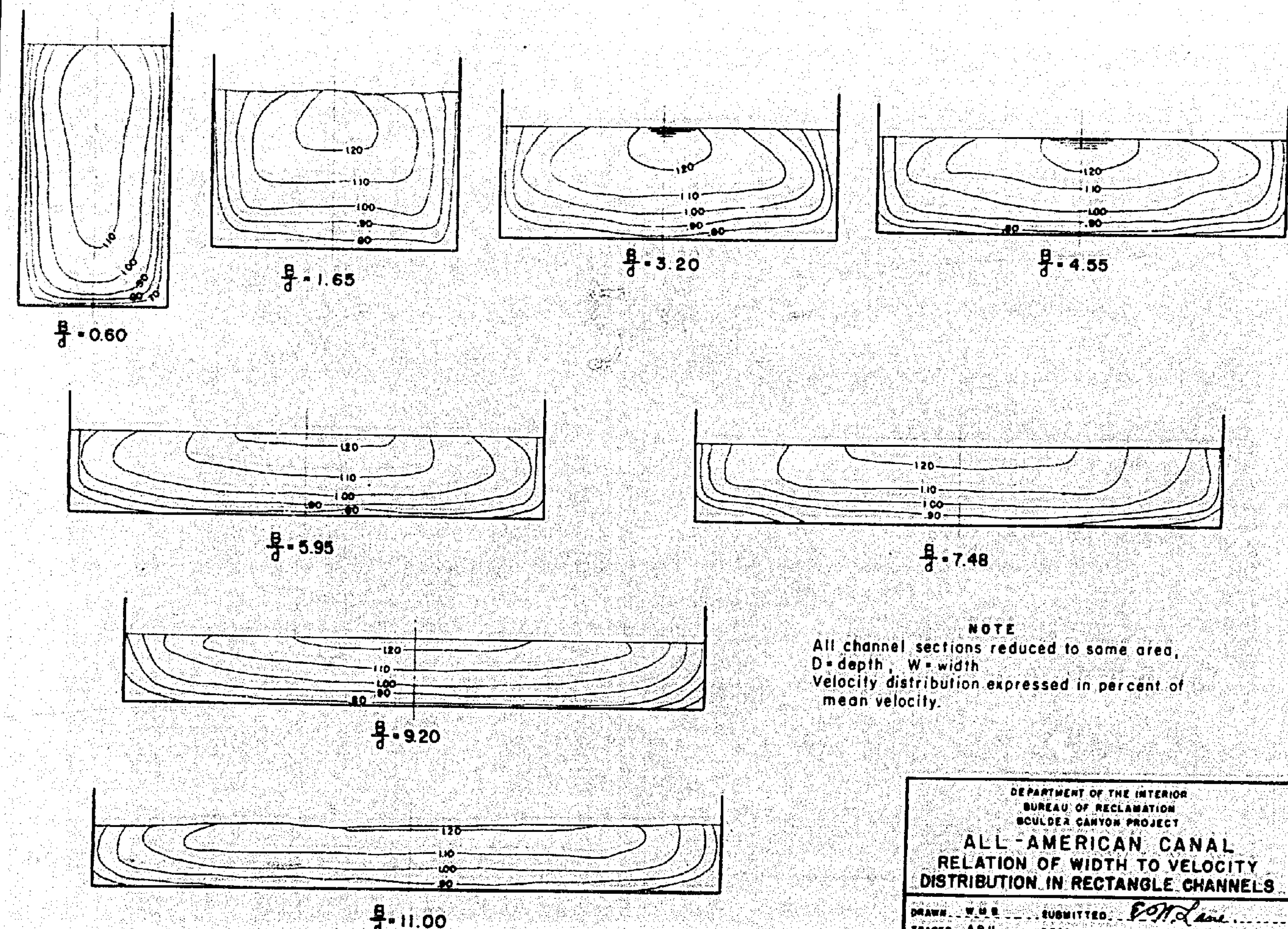
STABLE CHANNELS FOR CLEAR WATER

The simplest cases of determination of stable channel sections are those required to convey clear water. When the water carries silt in suspension or drags a load along the bottom, there are added complications. The simplest cases, with clear water, will therefore be considered first. When the smallest practical slope is desired, it is usually considered that the cheapest channel is secured when the wetted perimeter is least in proportion to the area. In trapezoidal channels this occurs with a ratio of bed width to depth ranging from 2.0 to 0.472 for side slopes between the vertical and 2:1. These values give the most efficient hydraulic section, but since this consideration neglects any excavation above the water line the flattest slope for a given quantity of excavation for a channel in cut is given by cross sections where the ratio of bed width to depth is less than those given above. Thus maximum economy will result from very low W/d ratios. In channels in earth, however, experience has shown that such channels are not stable.

A stable channel for clear water must have banks with sufficiently flat side slopes to keep the material from sloughing or rolling in, and sufficiently low velocities to keep the banks and bed from scouring. As previously stated, since the material on the banks is acted upon by the force of gravity, as well as that due to the motion of the water, it will not resist as high a force from the motion of the water as will the bottom, where gravity does not tend to produce motion.

If the mean velocity in a narrow, deep channel is low enough that the forces acting on the side material are insufficient to move it, and the sides are stable from sloughing, the channel will be stable. In other words, narrow, deep channels can be used with clear water and low velocities. Ordinarily, however, considerations of cost prevent the use of the large canals necessary to produce low velocities. For such a channel a cross section must be selected which will give velocities along the bottom which will not move the bottom material, and velocities along the sides which will not move the side material. Since the side material, due to the action of gravity, will move at a lower velocity than that on the bottom, to obtain the maximum possible mean velocity without scour the velocity along the sides must be enough less than that along the bottom to offset the gravity effect. This reduction of side velocity, as compared with bottom velocity, is secured by increasing the ratio of bed width to depth.

On Figure 3 are shown the velocity distributions in a number of rectangular channels having the same cross sectional area. Most of this data was secured from the results of the experiments of D'Arcy and Bazin. The velocities are indicated by the "isovels" or lines of equal velocity, expressed in terms of the mean velocity. (These data were obtained with different discharges for many of the examples. Although it is probable that the positions of the isovels would change somewhat with different velocities, such changes would be relatively small and would not change the main relations.) Since the areas of all water cross sections are equal, the lines giving the same ratio to mean velocity in all the diagrams represent the same velocity for any given discharge. A study of the velocity distribution in these sections will show that high velocities come in closer to the sides in the narrow, deep cross sections than in the broad, shallow ones. The science of hydrodynamics has not yet progressed to the point where the relation between the velocity distribution adjacent to a surface can be quantitatively related to the drag of the water along the surface or the velocity "gradient" adjacent to the surface, but progress along this line is rapid, and the near future may bring



NOTE

All channel sections reduced to same area,
D = depth, W = width
Velocity distribution expressed in percent of mean velocity.

DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
BOULDER CANYON PROJECT

ALL-AMERICAN CANAL
RELATION OF WIDTH TO VELOCITY DISTRIBUTION IN RECTANGLE CHANNELS

DRAWN W.H.B. SUBMITTED E.W. Lane
TRACED A.R.U. RECOMMENDED
CHECKED W.H.B. APPROVED

DENVER, COLO. AUG. 24, 1933 212-D-163

FIG. 3

sufficient advancement in this field to enable more exact analysis to be made. For the present, however, it is sufficient to say that when the high velocities come close to a surface the pushing or dragging force of water on the surface is greater than if these velocities close to the surface are low.

In a very narrow, deep section, the velocities close to the sides are as high or higher than those close to the bottom. If the velocity in such a channel is gradually increased, due to the added force of gravity on the side material, motion would occur first on the sides.

The design of a channel to fit the first type of conditions mentioned on page 19; i. e., where it is desired to obtain the smallest practicable slope, therefore, consists from the hydraulic standpoint of securing the smallest ratio of bed width to depth which will not produce scour on the sides, provided such ratio is not smaller than that which will give the smallest wetted perimeter for a given earthwork quantity. This latter qualification will probably rarely control. The design of a channel for the second type of conditions, where the highest practicable mean velocity is to be secured, is obtained by so proportioning the ratio of width to depth that the forces tending to produce movement both on the sides and bottom is the maximum they will stand without motion. For canals in the third class, where it is desired to make the ditch as steep as possible without producing scour, it is customary to make the section wide and shallow in order to reduce the hydraulic radius and thus lower the velocity. For such very wide ditches the scour would be greatest on the bottom, and this condition would control the slope which might be used. Theoretically, there is no limit to the slope a ditch might be given because the velocity could be reduced to any desired value by making it sufficiently wide and shallow. As a practical matter, however, it has been found that when the depth is made very small, the irregularities of construction are such that scour starts in the slightly deeper portions of the channel and enlarges them, causing a progressively greater concentration and scour until the beneficial effect of the widening is lost. This action has been noted in ditches with steep slopes 8 to 10 feet wide and 0.6 to 0.8 feet deep.

CHANNELS CARRYING SOLIDS IN SUSPENSION

It is now pretty generally agreed that material can be carried by a stream in suspension because of the vertical currents which occur in flowing water and carry the solid material upward at a greater rate than the force of gravity causes them to fall. The ability of a stream to transport material in suspension should therefore be proportional to its turbulence, which in turn is probably proportional to the energy expended. The concentration of a given quality of solids which a stream could support would therefore be proportional to the energy expended per unit of volume of the water. This energy is proportional to the rate of fall of the water, which is equal to the product of the velocity and slope.

This is a sort of overall relation, however, and silting may take place in one portion of a ditch cross section while other portions may be scouring. Because the velocity near the edge of a stream flowing in a trapezoidal section is low, in a channel carrying silt in suspension, there is a tendency to deposit at that point. This is aided by the growth of vegetation and usually a berm is formed which forms steeper sides to the section than were originally constructed. This material is quite resistant to scour, and forms more or less even in ditches where there are high velocities. This action is not ordinarily very detrimental, and is often anticipated and allowed for by computing the capacity of the channel with the slopes which it is expected the silt will cause rather than the slopes to which it is first excavated.

It is probably not feasible to entirely prevent the deposition of suspended material along the edges of channels in earth, although it may be reduced by using higher velocities. The greatest difficulties from suspended matter occur in ditches where the slopes are so slight that the energy being dissipated in the water is insufficient to prevent deposit. The remedy in these cases is to increase the velocity, or to remove the suspended material in some sort of desilting device.

CHANNELS CARRYING BED LOAD

Irrigation channels frequently carry considerable solid matter by dragging or pushing it along the bed, with either clear or silt-laden water flowing above. The amount of material depends upon the velocity near the bottom of the channel. Higher velocity is probably necessary to move the same amount of coarse material than fine material. If a channel is supplied with a heavy bed load, in order to be stable it must move this load along; otherwise the channel will fill up. This requires a high velocity along the bottom of the channel, as compared with a channel carrying clear water. For a given quality of material in the banks, the velocities which could act on the banks in the two cases would be the same. To be stable, the channel carrying bed loads should therefore have a higher velocity along the bed but the same velocity along the banks and this could only occur with a wider, shallower section. Heavily loaded channels in easily scoured material must therefore have high ratios of bed width to depth. If the banks of the loaded channel are of material which is resistant to scour, the ratio of bed width to depth can be less than in friable material without scouring the banks.

RECENT CONCEPTIONS OF FLOW NOT USED

To engineers who are familiar with the latest theories of stream mechanics and hydrodynamics, the foregoing analysis of the factors controlling stable channel shapes may seem somewhat crude, and in ignoring the drag theory of bed load movement it may appear that the writer has not taken advantage of the best available information. In making the study outlined herein, the most recent pertinent literature in stream mechanics and hydrodynamics have been studied to see what they contained which was applicable to the problem. A list of these references is included in the bibliography contained in this report. Since many engineers are not familiar with the recently developed ideas, however, and since a knowledge of them is not necessary to understand the relations developed regarding stable channel shapes, it was believed to be better to explain these relations in terms of conceptions with which all engineers are familiar, rather than to make it unnecessarily confusing to some by adding the other new ideas.

AGREEMENT OF SUGGESTED RELATIONS WITH OBSERVED DATA

The relations suggested in the foregoing paragraphs seem to agree with the observed data, as shown on Figures 1 and 2. The critical velocity shown for the Nile on Figure 1 is much less than that found by Kennedy in India and also less than that for the Imperial Valley canals. It is believed that the quantity as well as quality of silt is an important factor in these cases. The silt in both the Nile and Colorado are fine, but the Imperial canals require a much higher velocity than the canals of Egypt because the quantity of silt, especially the bed load, is much greater in the Imperial canals. The critical velocity for the canals Kennedy observed is higher than those in Egypt, probably because the particles moved on the bed were larger, and therefore required higher velocities to move them. The Imperial canals require more velocity than Kennedy's canals although the latter has coarser bed load, because the velocity required to transport the immense bed load of the fine Imperial Valley sand is greater than that necessary for the lesser quantity of coarser sand of Kennedy's canals.

A similar agreement of the relations previously discussed is found in the data on bed width-depth ratios as shown on Figure 2. In the canals of Egypt the velocities are low and therefore the velocities along the sides, although relatively high because the channels are narrow and deep, are still below those which will move the side material. The bed load is fine and small in quantity and therefore the low velocities along the bottom is sufficient to move all of it along.

The canals shown on the diagram, from India, carry medium loads of rather coarse material and therefore require rather wide sections. The Imperial Valley canals carry immense loads of fine sand, which require high velocities to transport. In order that the velocities along the sides may be low enough that the banks do not scour, the bed width-depth ratio must be high. In three of the four canals on which data is available, this relation is higher than that indicated by either Woods' or Lindley's equation. These had readily erodable sides. The fourth, which had a lower bottom width-depth ratio, had sides composed of material which had considerable resistance. The three sections with easily erodable banks gave widths considerably greater than indicated by Lacey's formula for the type of silt which they contained. It is believed that Lacey's formula was based on data from canals which carry bed loads of considerably less magnitude.

QUANTITATIVE RELATIONS

The study to determine stable shapes for the All-American Canal has not yet progressed to the point where the relations previously described can be expressed in a quantitative way. Data on existing channels are being collected, however, and the study will be continued. It is believed that the controlling principles have been determined and that by collecting data and relating it to these principles it will be possible to develop quantitative relations for the various conditions met in irrigation design.

ACKNOWLEDGMENTS

In the study leading to this report a great many articles dealing with the problem were studied and many helpful suggestions were thus secured. With these the writer has combined his own ideas. It is not always possible to say definitely which were original and which were secured from literature. In some instances ideas original to the author were afterwards found in the literature, having escaped notice on the first reading, because at that time their importance or bearing was not appreciated. The articles on the subject which have been found most useful have been incorporated in the bibliography. To the authors and discussers of those papers the writer is particularly indebted. He is also indebted to Mr. S. P. Wing, Engineer, Bureau of Reclamation, for many helpful suggestions.

SILT PROGRESS REPORT NO. 1

BIBLIOGRAPHY

No.

1. Hydraulic Diagram for Canals in Earth - R. G. Kennedy - Proc. Institute of Civil Engineers - P. 281, Vol. 119 (1895).

2. Normal Data of Design for Kennedy Channels - Dated July 28, 1917 - F. W. Woods, Chief Engineer, Irrigation Works, Punjab.

3. Regime Channels - E. S. Lindley, Executive Engineer, Punjab Irrigation Branch - Proceeding, Punjab Engineering Congress, p. 63, 1919.

4. A New Hydraulic Formula (for silting velocity - Kennedy's data) - F. W. Wood. The Engineer, p. 646, Vol. 143, June 17, 1927.

5. Instructions for Grading and Designing Irrigation Canals - Punjab Irrigation Paper No. 10 - R. G. Kennedy.

6. Hydraulic Diagrams for Channels in Earth - R. G. Kennedy - Public Works Department, India. A new edition of this was recently put out. Engineering News-Record, p. 370, Vol. 106, 1931.

7. Critical Velocity Observations - Madras Public Works Department - October 9, 1912.

8. Hydraulic Diagrams for Design of Channels in Earth by Kutter's Formula - Capt. A. Garret, R. E. - 2nd Edition, 1913 - The date and contents of the first edition is not known.

9. A New Theory of Silt and Scour - W. T. Bottomley - Engineering, p. 307, Vol. 125, March 16, 1928.

10. Irrigation Practice in Egypt - Molesworth and Yenidunia.

11. Silt Investigations - Paper No. 4 - Irrigation Projects Department of Egypt - A. B. Buckley.

12. Some Problems Connected with Rivers and the Canals in Southern India - J. M. Lacey - Proceedings of the Institute of Civil Engineers, p. 150, Vol. 216.

BIBLIOGRAPHY (Continued)

No.

13. The Influence of Silt on the Velocity of Water Flowing in Open Channels - A. B. Buckley - Proceedings of the Institute of Civil Engineers, p. 183, Vol. 216.

14. Irrigation Project of the Californias - S. L. Rothery - Proceedings of the Institute of Civil Engineers, p. 161, Vol. 216.

15. Note on Silt Investigation No. 1 - A. B. Buckley and Hughon - Cairo, 1919.

16. Influence of Silt on the Velocity of Water Flowing in Open Channels - R. B. Buckley - Engineering, p. 311, Vol. 115, 1923.

17. A Theory of Silt and Scour - W. M. Griffith - Proceedings of the Institute of Civil Engineers, Vol. 223, January 25, 1927 - Abstracted, Engineering, p. 72, Vol. 123, January 21, 1927, and p. 307, Vol. 125, March 16, 1928.

18. Stable Channels in Alluvium - Gerald Lacey - Proceedings of Institute of Civil Engineers, Vol. 225 - Engineering, pp. 179-180, Vol. 129, February 7, 1930.

Mechanics and Hydrodynamics

19. Modern Development in Study of Turbulence - L. Prandtl - Not examined - Zs. V. D. I., Bd. 77, Nr. 5, February 4, 1933.

20. The Present State of the Turbulence Problem - A. S. M. E. - Applied Mechanics, Vol. 1, No. 1.

21. Review of the Theory of Turbulent Flow and Its Relation to Sediment Transportation - M. P. O'Brien - Transactions of American Geophysical Union, April, 1933.

22. Towards a Theory of the Morphologic Significance of Turbulence in the Flow of Water in Streams - J. B. Leighly - University of California Pub. Geog., Vol. 6, No. 1, 1932.

23. Hydraulic and Sedimentary Characteristics of Rivers - L. G. Straub - Transactions of American Geophysical Union, April, 1932.