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PRINCIPLES OF DESIGN OF STABLE CHANNELS IN ERODIBLE MATERIAL

By E. W. Lane

Introduction

The practice of conducting water through channels excavated in the earth extends back beyond the dawn of recorded history. In China there are canal systems which have been in continuous operation for 2,000 years. It is only recently, however, that science has developed to the point where the fundamental physical principles involved in such canals have been studied, with a view to improving their action, and securing channels which would give a maximum of service with a minimum of expenditure. The problem, however, has proved to be a difficult one, and the development of the principles involved is far from completion.

To secure the best possible design of canals, a great many factors have to be considered. One group of these factors has to do with the quantity of water which will flow in the canal, and includes such factors as slope, cross sectional area, hydraulic radius, and roughness. If the canals pass through erodible material, or the water used carries sediment, another group of factors is included which involves freedom of the canals from scouring or sloughing of the banks or bed or from filling up with sediment. This may be called the stability of the cross section. There are also a great number of practical considerations, three of which are the ease of construction, the economy of cleaning, and freedom from weeds. To secure the best possible design all of these factors must be considered and, in some cases, balanced against each other to obtain the combination of factors which will give a maximum of advantage and a minimum of disadvantage. Until it is possible to analyze all of these factors, in order that they may be satisfactorily balanced against each other, a complete method of design of canals will not be possible.

The fundamental principles involved in the flow factors have been worked out to a sufficiently satisfactory state for most design purposes, although some progress along this line is still possible. The practical aspects mentioned above are known to those experienced in canal design, but no satisfactory analysis has been developed for the design of canals from the standpoint of stability. It is with these stability factors that this memorandum deals. Considerable progress has been made in the analysis of canal side slopes from the

* Page 8 and Figures 3 and 4 revised Octobe 3, 1950

standpoint of sliding or sloughing, by the specialists in soil mechanics, and reasonable satisfactory analysis of this part of the problem has been developed. This memorandum will, therefore, be confined to the development of the principles of design of canals from the standpoint of freedom of the banks and bed of the canal from scour from excessive velocities of the water, and from the filling of the canals by deposits of sediment brought into the canal by the water.

History of the Stable Channel Problem

The science of the design of stable channels in erodible material has been largely developed in India, where the world's largest development of modern irrigation has taken place. As a result of the difficulties with canals in that country, R. G. Kennedy, in two publications [1/] [2/] presented a method of designing canals for freedom from scour or from filling with sediment, which greatly improved the designs which were being made. This was followed by numerous other papers, the most important of which were a paper by E. S. Lindley [3/] and a series by Gerald Lacey [4/] [5/] [6/] [7/] which latter cover the gradual development of an approach to the analysis of the stable channel problem, which has proved to be of great value in designing canals in India.

Additional studies, based largely on Indian experience, are those of Inglis [8/] [9/] and Blench [10/]. The experience in Egypt, which differs considerably from that in India has been given by Molesworth and Yenidunia [11/].

In connection with the design of the All-American Canal on the Lower Colorado River, it was found that the Lacey relations did not work out when applied to the fine sediments of this region, and after a thorough study of the literature of the field, a statement of the general principles of stable channel design was developed [12/] which approached the problem from a somewhat different angle than that generally used in India. The acceleration of construction of the All-American Canal project prevented the developing of these principles into quantitative relations which could be used in design. The formulation of an immense program of earth canals by the Bureau of Reclamation has reawakened interest in this subject, and considerable thought has been given to extending the knowledge of the principles involved and the formulation of a general program of studies designed to secure the quantitative data necessary to expand these principles into formulae tables, and diagrams, suitable for the design of stable channels under a wide range of conditions. The following report gives the general principles of stable channel design, as far as they have been developed by this study at the present time. It also includes a statement of the

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1/ Refer to bibliography at end of this report.

data and studies needed to develop quantitative design procedures from these principles and a brief outline of the program proposed to secure this data and carry out these studies.

Principles of Design of Stable Channels in Erodible Material

The most important principles for the design of stable channels in erodible material, as developed by the angle of approach used in the All-American Canal studies, were presented in the paper reporting the results of those studies[12/]. Fundamentally, they are really very simple and can be explained in a relatively few words. To be stable, a canal in erodible material must not scour on the sides or bottom, and deposits of sediment must not take place in it. In order that the bottom or sides may not scour, it is necessary that the velocities at all points on the wetted perimeter be kept down to values low enough so that the material composing the banks and bed are not moved. In order that sediment deposits may not take place in the canal, it is necessary that the flow conditions in the canal be such that the sediment introduced into it at the upper end be carried on through the canal and out at its lower end. These principles, therefore, involve:

1. The distribution of velocities around the perimeter of channels of various cross sections.

2. The velocities necessary to move particles on the perimeter of the canal.

3. The laws of transportation of sediment in a channel.

Unfortunately, in the past, the stable channel problem has not been approached from this standpoint, and therefore very little data on these three points have been collected.

Forces Causing Scour on Canal Banks and Bed

Scour on the banks and bed of a canal take place when the particles composing the surface of the sides and bottom are acted upon by forces sufficient to cause them to move. When a particle is resting on a level bottom of a canal, the force acting to cause motion is that due to the motion of the water past the particle. If scour is to be prevented, this movement must not be rapid enough to produce forces on the particle, sufficiently large to cause it to move. If a particle is on a sloping side of a canal it is acted on, not only by the velocity of the water, but also by the force of gravity, which tends to make it roll down this slope. The force tending to cause motion in this direction is the component, in the direction of the slope, of the force of gravity acting on the particle. If the resultant of the force due to the motion of the water, and the component of the force of gravity acting on the particle, is large enough, movement of the particle will occur. Where cohesion of the particles occur, the forces acting must be sufficient to overcome this also.

For example, consider a particle on the perimeter of the cross section of a canal in noncohesive material, as shown in Figure 1. If the bottom of the canal is level, as at A, the motion will occur when the water moves past the particle with sufficient velocity to produce a force F large enough to cause it to roll longitudinally down the canal. If the particle is on the side of the canal, as at B, there will act on it a force F_2, due to the longitudinal motion of the water flowing down the canal, and the force of gravity, G, which will have a component G_2, acting in the direction of the slope of the canal bank. Motion of this particle will occur when the resultant, R, of the longitudinal force F_2, and the gravity component G_2, is sufficiently large to cause motion.

Velocity Distribution at Sides and Bed of Canal

The movement of material on the banks and bed of a canal, therefore, depends upon the steepness of the side slope and the velocity distribution near the banks and bed. The forces due to the slope of the sides is easy to analyze, but the velocity near the banks and bed is difficult to determine. The velocity conditions necessary to cause the motion of a particle lying on a canal bed are very complex, due to the variation of velocity with depth above the bed and the rapid fluctuations of velocity due to the turbulence in the flowing water. The water very near to the bed or banks moves slowly, and this velocity increases rapidly as distance from this surface increases. This change of velocity with depth is complex, even with a very smooth surface, and with a rough one, it is even more so. The situation is further complicated by the effect of the turbulence fluctuations and the inertia of the particle. In the foregoing discussion, for simplicity, these effects have been ignored. Although a complete analysis of the conditions necessary to produce motion is too complex to completely analyze with our present hydraulic knowledge, some progress in this direction can be made since variations of velocity at various points on the banks and bed of a canal can be, to some extent, analyzed.

Consider, for example, the cross section of a trapezoidal canal with a bottom width B, a depth D, and a slope of the sides of 1-1/2:1.

If the canal is large enough so that the viscous forces are negligible, (i.e. at high Reynold's numbers) as would be the case in prototype canals, the velocity distribution should be the same, when

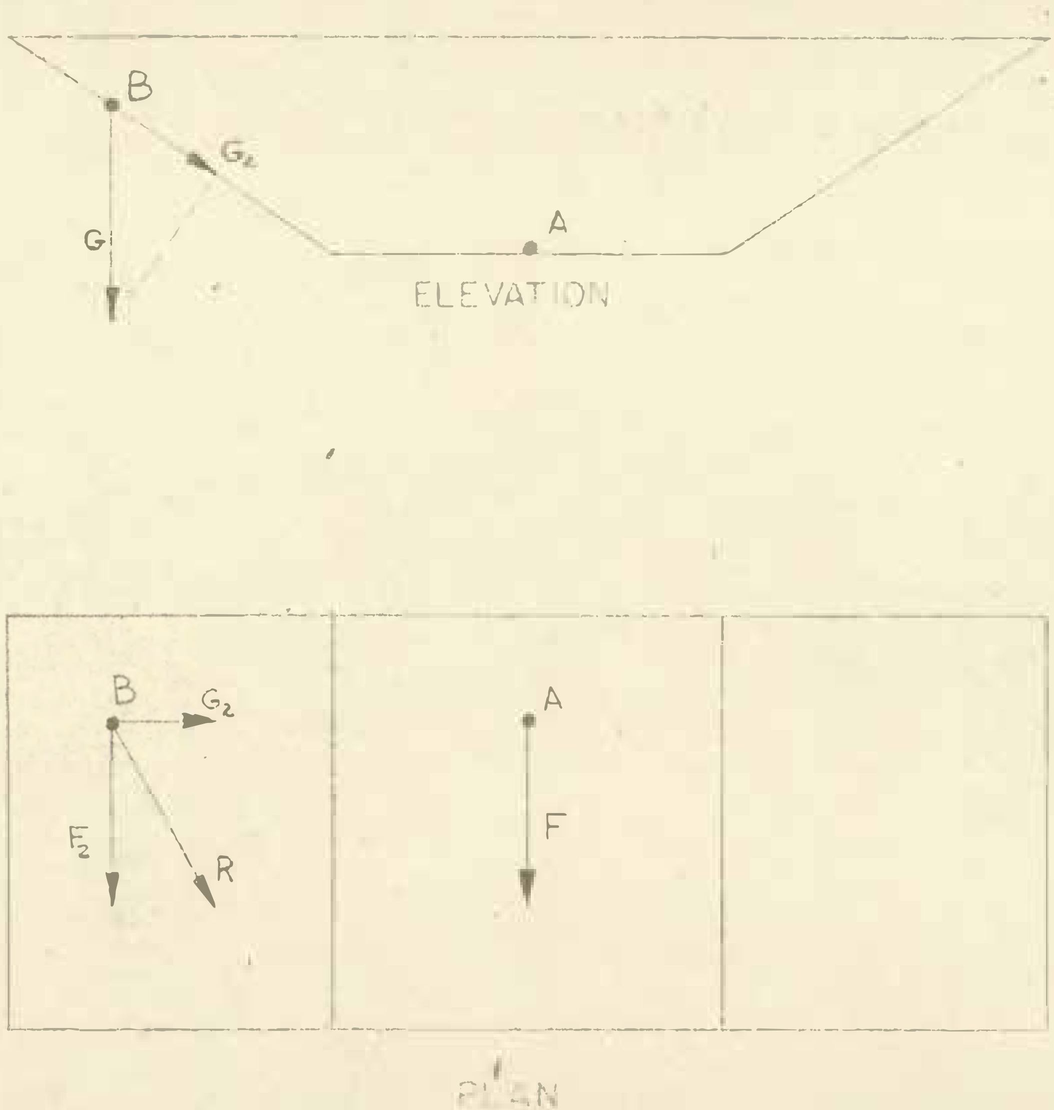

FIGURE 1

(NOT TO SCALE)

expressed in terms of the mean velocity, for all discharges.* Thus at any point in the cross section, for example, at mid-depth in the center of the channel, the velocity will always bear a fixed relation to the mean velocity of flow. Also the flow pattern should be similar or proportional for any other cross section with a similar shape. For example, in all canals having the same ratio of B to D and the same side slopes, the velocity distributions would be similar and proportional and the velocity at any point in one cross section would be similar to that in any other point in any other similar section with the corresponding position. Thus, if we can get the velocity distribution in any model canal, we would have the distribution in any canal of similar cross section.

Observations of velocity distributions in many trapezoidal channels have shown that channels with low width to depth ratios have velocities along the banks relatively higher than where the B/D values are high. Also that where the B/D values are above about 5, for the same side slopes, the velocity distribution is similar, and the velocity distribution over the center section, beginning at about 2-1/2 B/D distance out from the bottom of the side slopes, varies only with the depth.

The foregoing discussion has dealt with trapezoidal channels, but it can be applied also to other shapes of channels. The velocity distribution along the sides and bed of the channel should also be similar to that of all other channels having similar cross sections, and if we had this distribution for a canal of one cross section, we would have it for all similar canals. Unfortunately, very little data are available on the velocity distribution in channels, and it is very difficult to measure satisfactorily the velocity close to the banks and bed. Consequently, little data are available to give the velocity distribution near the bed and banks of canals of any cross section.

Shear Distribution on the Canal Bed and Banks

Since the velocity distribution would be similar for cross sections of similar shape, the distribution of the tractive force or shear at the canal bed and banks should also be similar for similar cross sections. In a great many studies of the movement of material

*Whether or not this is true for velocities above Belanger's critical value (Froude number greater than 1.0) may be controversial, but such cases rarely, if ever, enter into our problem.

by flowing water, this movement has been related to the tractive force values at the surface where the movement took place. In the study of stable channels, therefore, it is possible to approach the problem from the standpoint of tractive force distribution along the banks and bed, as well as the approach from the standpoint of velocity distribution.

As has been previously mentioned, because of the rapid change in velocity near the bed or banks of a stream, it is difficult to appraise the velocities acting on the solid particles composing these surfaces and therefore difficult to assign quantitative values to the velocities acting on these particles in a given case. Although the approach from the standpoint of tractive force is scientifically less exact, it is usually easier to get quantitative values for tractive force in a given case than it is to get quantitative values of velocity. For this reason the approach, from the standpoint of tractive force, is usually used in the analysis of problems involving the movement of coarse particles. Because of the extensive fundamental research which would be necessary before the stable channel problem could be solved quantitatively from the approach along the line of velocity, it was decided to use the tractive force approach in this analysis to get a useable solution and to perfect it later by bringing in the velocity acting on the particles, as the science of the subject developed.

The relations between the velocities acting on the particles and the corresponding tractive force or shear are explained by Kalinske[13/] and will therefore not be discussed here. Since no literature is available giving the distribution of tractive force on the banks and bed of a canal, a study has been made of available data to determine it, as far as the limited information will permit. The method used was that developed (or at least brought into the literature of this country) by J. B. Leighly[14/]. Consider the cross section of a channel through which water is flowing, as shown in Figure 2. According to the principles of tractive force, first developed by M. P. du Boys[15/], the total tractive force on the perimeter of this canal, for a unit length in the direction of flow, is equal to the component of the weight of the volume of water in this unit length of canal, in a longitudinal direction, or the force which is causing this volume of water to flow down the canal; as can be seen from the following reasoning. Assuming that there is no acceleration of this water volume, the force causing motion must be just balanced by the force exerted by the banks and bed of the canal on the volume of water. This force is the tractive force or the shear. The magnitude of this tractive force is the component of the weight of the volume of water in the direction of flow, or this weight multiplied by the slope of the energy gradient of the canal. If the flow is uniform, the energy gradient is equal to the canal slope.

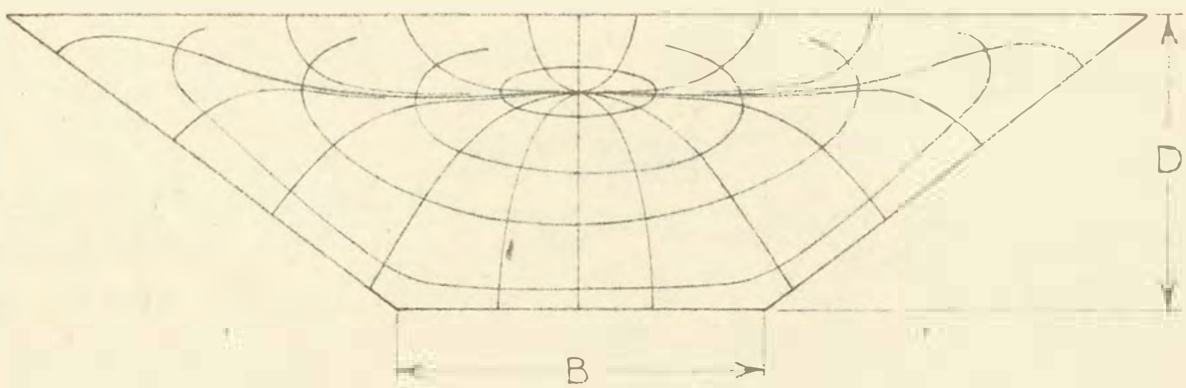

FIGURE 2
(NOT TO SCALE)

If sufficient measurements of velocity have been made at this section to show the velocity distribution by drawing the isovels (lines of equal velocity), it is also possible to divide the cross section of the flowing water up into a series of subareas by orthogonal lines starting perpendicular to the perimeter of the wetted section and running perpendicular to the isovels, ending in the point of maximum velocity. Since the lines are perpendicular to the lines of equal velocity, there is no net exchange of momentum across them and therefore no net shear. The tractive force due to the weight of the water enclosed between the lines originating from the bottom and sides of the canal is exerted on that part of the bottom or sides between the respective lines. By planimetering these partial areas, and thus determining the volumes of water involved, it is possible to compute the tractive force exerted on each of the parts of the canal perimeter and thus establish the tractive force distribution over the bottom and sides determined. The disposition of the tractive force due to the volume of water lying above the locus of maximum velocities in the verticals is a controversial matter. The lines perpendicular to the isovels in this region extend to the water surface. There is good reason to believe, however, that only a small part of the tractive force represented by the area above the locus of maximum velocities would be exerted on the air above the water surface, and that it would probably be near the truth to neglect the air drag entirely. In these studies this has been done, and the tractive forces on the bottom due to the area below the locus of maximum velocities have been increased by the ratio of the area above this locus to the area below the locus.

If sufficient information was available, it would be possible to plot diagrams such as those on Figure 3, showing the distribution of the tractive force on the bottom and sides of a large variety of shapes of trapezoidal channels. In these diagrams the magnitudes of the tractive force could be expressed in terms of percentages of the tractive force which would occur in an infinitely wide channel with a depth of Flow D equal to the depth of flow over the level bottom of the trapezoid, or to WDS where W is the unit weight of water, D the depth and S the slope of the energy gradient.

Application of Tractive Force Distribution to Canal Design

From the studies made of available data the tractive force on the sides of a trapezoidal channel has been found to vary from zero at the water surface to a maximum part way down the sides and then decrease to the bottom of the side slope. On the bottom it varies from a minimum at the bottom of the side slopes to a maximum in the center. For canals with a B/D value greater than about 5, the tractive force remains the same, at nearly 100 percent of WDS, across the bottom beginning about 2-1/2 D distance out from the sides.

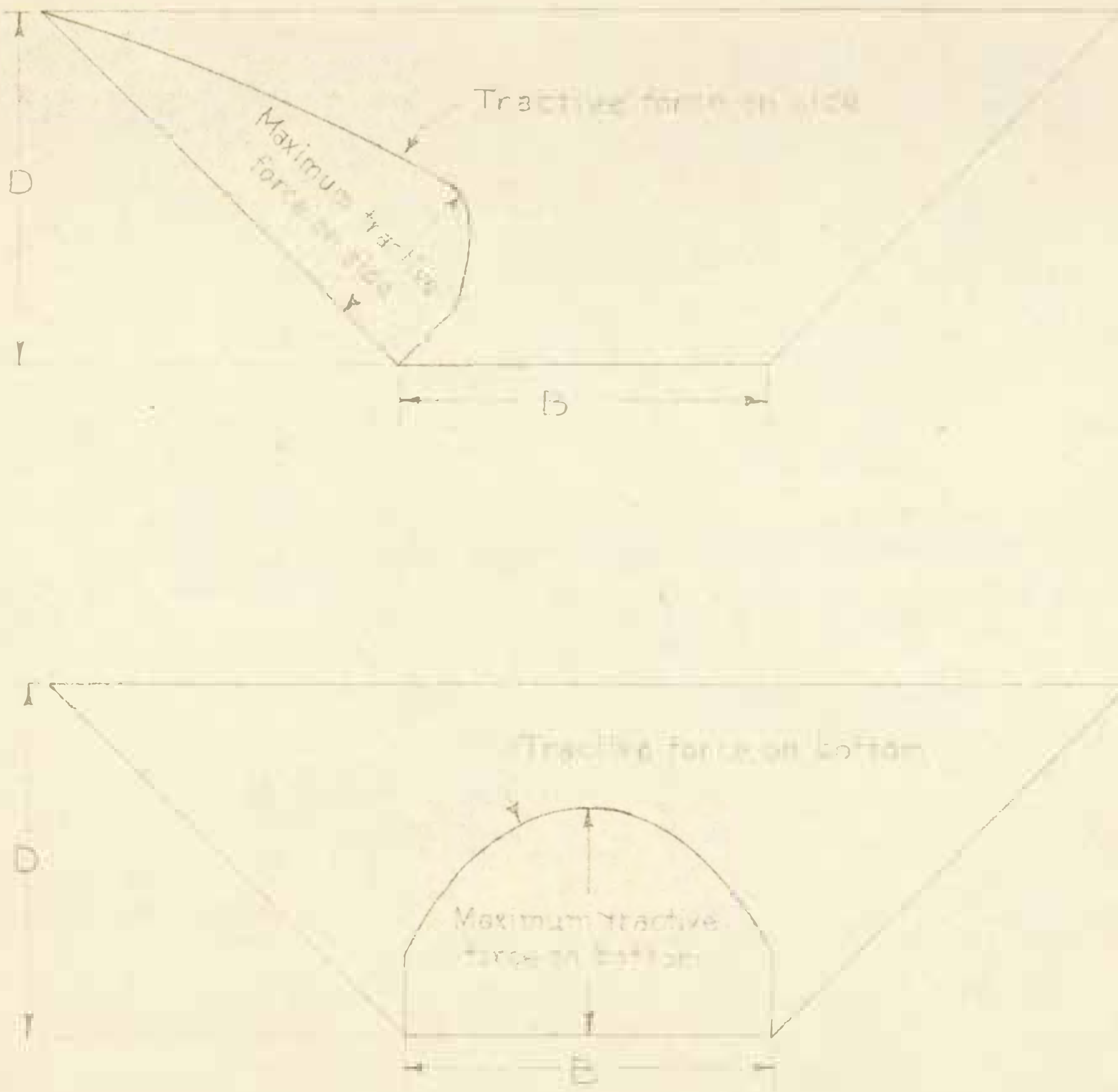

FIGURE 3
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From a large number of velocity distribution observations in trapezoidal channels, it would be possible to plot a diagram as shown in Figure 4 showing for the bottom and sides of trapezoidal channels the maximum tractive forces expressed as percentages of WDS for various side slopes and ratios B/D of channel bed width to flow depth.

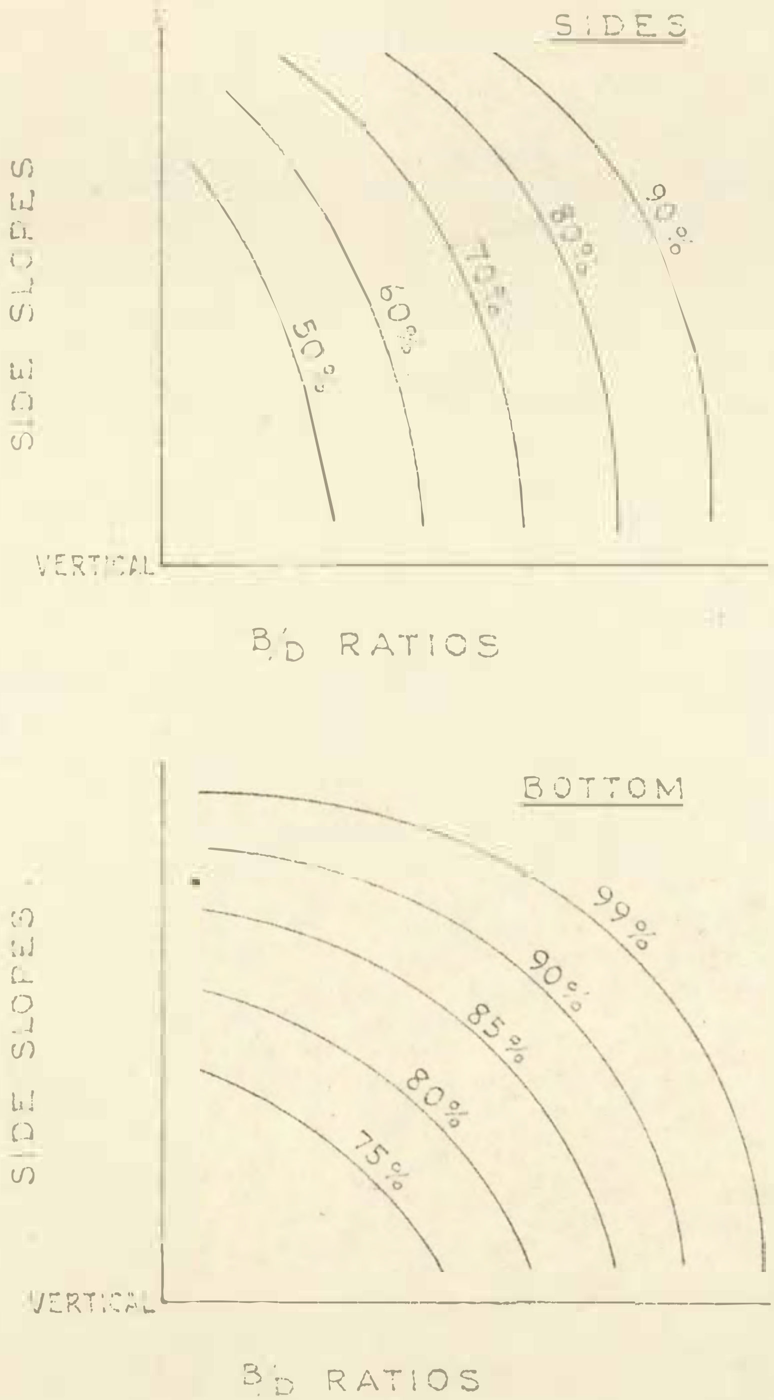
From an analysis of literature on tractive forces which will just start motion of bed particles of various sizes, it is possible to draw a curve, such as the bottom line of Figure 5, showing the critical tractive force necessary to start motion on a level surface for various sizes of particles. By combining these values with the forces due to the component of the weight of the particle down the side slope, as previously explained, it is possible to determine the critical tractive forces which will start motion on side slopes of various steepnesses.

Figures 4 and 5 are for purposes of illustration only, and should not be used for design, as they were not based on adequate data or studies for this purpose.

By means of the diagrams shown on these figures, when sufficiently perfected, the design of stable channels in coarse granular material for carrying water comparatively free of sediment, can be readily carried out. The canal cross sections can first be worked out to meet the hydraulic requirements, and this canal section can then be tested to determine its safety from scour of the banks and bed. The value of WDS can be worked out for the canal to be tested and from Figure 4 the values of maximum ratios of the tractive force acting on the sides and bed of this channel to WDS can be determined from its side slope and B/D values. If the value of WDS, when multiplied by these maximum ratio values, exceeds the safe critical tractive force values ~~for the~~ size of material in which the channel is excavated, as shown in Figure 5, for the bed and side slopes used in the section being tested, scour will take place. From the results of these tests, depending on the circumstances in each case, it will often be possible to tell whether a better cross section could be selected and the direction in which to move from the tested section to secure an improvement.

Analysis for Nontrapezoidal Channels

The foregoing discussion has been set up largely on the basis of a trapezoidal section, but the principles apply equally to canals with cross sections of any other shape. To analyze any section it is necessary to know the velocity or the shear distribution around



RATIOS OF MAXIMUM TRACTIVE FORCE TO wDS

FIGURE 4

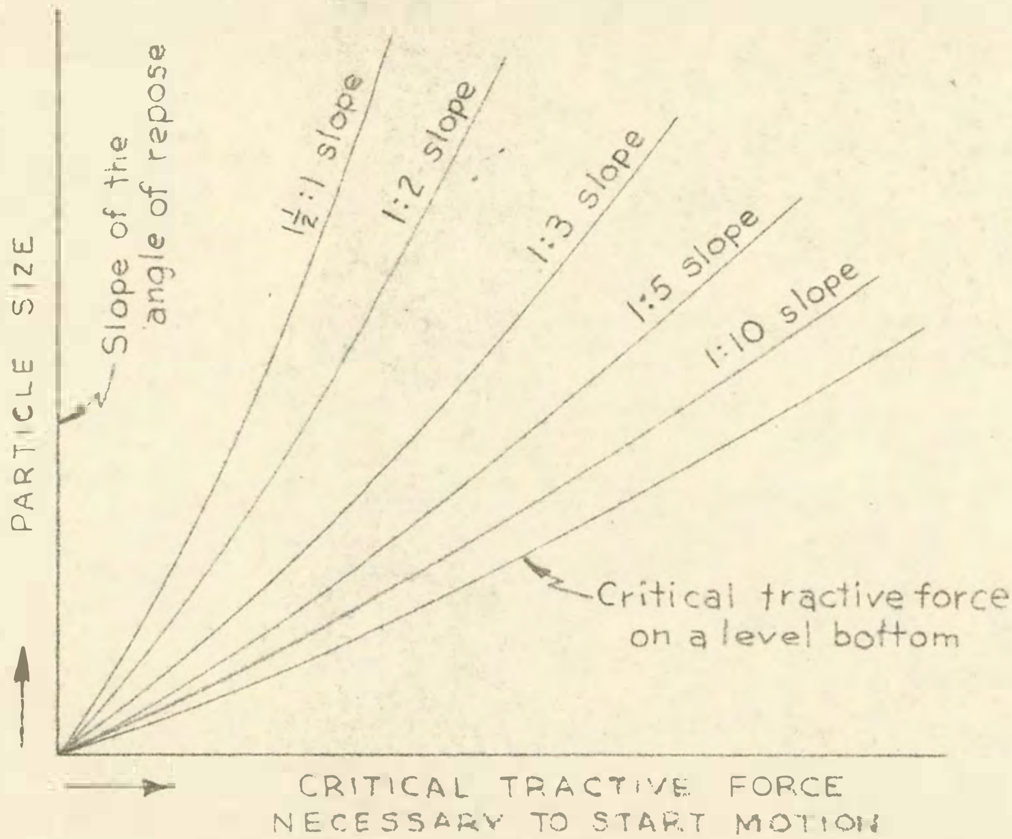


FIGURE 5
(NOT TO SCALE)

the perimeter. To determine these factors completely, it is necessary to know perfectly the laws of flowing water, which have not yet been worked out. However, it is believed that mathematical approximations and approximate analogies can be worked out which will give solutions with sufficient accuracy for practical purposes.

A first approximation has already been worked out for a channel of uniform cross section in which the granular material on the entire surface of the banks and bed is just on the point of movement. This has been developed on the assumption that the tractive force at any point is proportional to the depth at that point. This is an approximation which is probably not far from the facts in wide channels but may depart considerable from the truth for narrow ones.

The development of this solution was first undertaken by Chia-hwa Fau, whose results were published by the Chinese Society of Hydraulic Engineers in their magazine "Hydraulic Engineering," Volume 15, No. 1, page 74. This analysis has been checked and perfected by F. E. Swain and R. E. Glover of this Bureau. This gives the shape of cross section for any size of material and longitudinal slope of canal. Only one discharge would produce this condition of impending movement for a given material size and slope.

For a given size of material and longitudinal slope these assumptions produce, for one especial discharge, a cross section which starts with a side slope at the sides equal to the angle of repose of the material in which the canal is constructed, decreasing until at the centerline the bottom is level. For discharges larger than this especial discharge, the cross section is formed by adding a level section to the bottom of width just sufficient to increase the discharge from the especial discharge to the desired larger discharge. For discharges smaller than the especial discharge, the section is obtained by subtracting enough of the area equally out on both sides from the centerline of the section for the especial discharge, to reduce the especial discharge the amount necessary to produce the desired smaller discharge.

The Most Efficient Canal Section

The importance of this solution is not at first apparent, and rests in the implications of the conditions fulfilled rather than the conditions themselves. The fact that the material at all points on the bed and banks of the channel is just on the point of moving, is not of primary importance to the canal designer, but other facts which can be deduced from this condition of impending motion are very important. For example, since the material on the banks and bed at all points is just on the point of motion, if the side slopes at any point were a little steeper than this solution provides, the slightly increased component of gravity down this slightly steeper slope would increase the resultant force of this gravity component and the longitudinal force exerted by the water enough to cause the particles to move. The side slopes of the channel with a cross section as developed by this solution are therefore as steep as they can be made and still retain stability. Also the hydraulic radius of this portion of the channel is as great as is possible and maintain stability. The depth of the level bottom, where the channel is large enough to require a level bottom, is also the maximum depth which the channel can have and maintain stability.

The hydraulic radius of this section of the canal is therefore a minimum, and the hydraulic radius of the bottom and sides combined is also a minimum. Hence for a given discharge the velocity is a maximum and the cross-sectional area of the flow is a minimum.

Since the sides are as steep as possible, and the depth of the center section as great as possible, the width of the channel at the water surface is a minimum. Since the side slopes above the water surface at the angle of repose of the material, which is as steep as possible with stability, with this minimum width at the water surface, a minimum of area of excavation above the water surface results. The combination of minimum area both above and below the water surface therefore produces the channel of minimum excavation and therefore probably minimum cost.

Perfecting of Analysis for Nontrapezoidal Shapes

Because of the importance of this solution in the practical design of irrigation canals, it is very desirable that the solution be further perfected by developing an approximation for the tractive force which will be closer to the facts than the assumption that it is proportional to the depth. This latter assumption does not consider the effect of the higher velocity currents near the center of the channel dragging along the water near the sides. A study to obtain a solution taking into account these effects is now being carried on by R. E. Glover.

A study should also be made of the latest fluid mechanics research to see what light it throws on this subject. The paper by G. H. Keulegan on "Laws of Turbulent Flow in Open Channels"[16] should especially be studied.

It is also possible that the velocity and tractive force distribution might be approximated with sufficient accuracy by means of the membrane analogy. A rubber sheet stretched over an opening shaped like two channel cross sections with their water surfaces coinciding and their bottoms on opposite sides of this common line, might be used. The isovels could be traced as contours, by placing an air pressure below the membrane. This would give a distribution in which the maximum velocity was at the water surface in the center of the channel. Mr. Glover has suggested that the point of maximum velocity might be moved to the point below the surface which actual observations indicated by means of a string attached at both ends of the water surface line and shortened until the highest point in the membrane was located at the position corresponding to the point of maximum velocity.

Design of Canals for Maximum Slope

It is often desired to make canals as steep as possible, in order to reduce the height of drop structures to a minimum. Theoretically a stable canal can be made by designing the canal wide enough to reduce the depth sufficiently to produce a velocity so low that it will not scour the banks or bed. There is a practical limit; however, to the width that can be used. This depends upon how closely the canal can be constructed and maintained to the exact grade established for it. Any departure from the true grade is likely to produce greater depth of flow at certain locations than expected. These will result in greater tractive forces than planned and thus greater ability to cause scour. If scour is started it usually results in still greater depths and tractive forces, still further increasing the scour, the movement thus increasing progressively until it reaches prohibitive magnitudes.

Although some analysis of this condition is possible, it is largely a practical matter which can be determined only by experience. A search to discover actual cases of canals where excessive scour under these conditions occurred, should therefore be made and the results analyzed to the extent possible and presented to indicate the practical limits to which such canals could safely be designed.

Effect of Cohesion on Canal Cross Sections

For the design of canals in cohesive material it will be necessary to determine what velocities or tractive forces on the banks and bed various types of cohesive material will stand, and design the canals to give values which do not exceed these limits. These limits will probably have to be determined by observations on actual canals. Perhaps the resistance to scour of these materials can be related to the penetration values of the Proctor needle used in moisture determinations in earth dam construction.

In analyzing this type of channel it will probably be found that the forces of cohesion acting on a particle on the sides of a canal are so much greater than the gravity force acting on it that the latter can be safely ignored. The most efficient channels for clear water in cohesive materials will therefore probably be these where the tractive force on bottom and sides is equal.

Effect of Curvature

The analysis so far discussed has dealt with straight canals, but many canals contain numerous bends and these increase the tendency to scour. So far as is known, no quantitative study of this phase of the stable channel problem has ever been made. It should, however, be subject to analysis, which could probably best be done in a hydraulic laboratory. Tests would be made of curves with various ratios of radius of curvature to bottom width, and various central angles. The effect of spiralling the curves should also be investigated. The results from such tests could be compared with observations on actual canals.

Effects of Seepage

Seepage out of a canal produces forces tending to stabilize material on the banks and seepage into a canal has an opposite effect. Under certain conditions these actions have an effect on the susceptability of the canal to scour. An analysis of these conditions should be made and the principles involved should be developed so that they can be used in design, where they apply.

It is probable that in the case of canals carrying clear water at high velocities with bed and banks of coarse granular material, seepage effects will not be so important, since the finer portions of the surface layer will be largely washed away, the resistance of the remainder of the surface layer to percolation, as compared with deeper layers, would be small. However, in fine-grained materials and especially those where the seepage out of a canal tends to filter out fine particles from the water which forms an impervious coating over the banks and bed, the seepage forces may reach considerable magnitude and have an appreciable effect on stability. It is probable that it is this effect which causes the resistance to scour in many canals to be capable of reduction by "aging."

Secondary Currents

Under certain conditions of flow in straight channels of uniform cross section, all the water does not flow linearly in the channel, but spiral flows are set up in certain parts of the cross section. For example, in certain experiments in rectangular flumes carrying sediment spiral currents occurred which caused the sediment to form on the bottom a series of parallel ridges extending down the flume. At present, little is known about these secondary currents, and their effect is usually probably small or nonexistant. In studies of sediment transportation, however, they should be kept in mind and where present should be observed, in order that the laws governing them be developed and their importance in sediment transportation appraised.

Canals Carrying Coarse Sediments

Since a stable canal neither fills with sediment or scours, if any sediment enters such a canal at the upper end it must be carried on through the canal. The problem of preventing deposit in the canals is therefore a problem of designing the canals to transport the material brought into them.

In most cases the material which causes trouble by depositing in the canals is sand or coarser particles. Nearly all of this material moves along the bed of the canal. If the tractive force on the bed of the canal is sufficient to cause it all to move along, there will be no harmful deposits. It is therefore necessary to know the quantity and quality (size) of the sediment introduced into the canal and the tractive force necessary to carry it down the canal. The canal must then be designed to provide this tractive force on the canal bottom without producing a tractive force on the sides greater than the material of which they are composed will stand. If the quantity of sediment introduced into the canal is very large, it may not be possible to meet these conditions, and desanding devices must then be used to reduce the sediment load to be carried.

To know the tractive force necessary to carry the material down the canal, the laws governing sediment transportation must be known. Unfortunately, although considerable progress has been made and is being made in developing these laws, a satisfactory knowledge is not now available. It will, therefore, be necessary to secure a better knowledge of these laws, and the program proposed includes several studies in this field.

Canals Carrying Fine Sediments

Many canals carry a considerable quantity of fine sediments which collect along the sides of the canal and reduce the carrying capacity. This type of material is usually not so troublesome as the coarser sediments, and sometimes is beneficial, in that it tends to reduce seepage out of the canal. These side deposits are composed of particles of silt and clay sizes, and have considerable cohesion. A study should be made of the tractive force this material will stand, and it should then be possible to design canals which will prevent or limit its formation.

Data and Studies Needed to Develop Principles Quantitatively

To use the principles of stable channels in the design of hydraulic project, it will be necessary to develop them in a quantitative form. To do this a great deal of work will have to be done in the field, laboratory, library, and office.

Briefly stated, the data and studies needed fall into seven main divisions, as follows:

a. Studies of velocity and shear distribution in canals.

b. Studies of the effect of bends on velocity and shear distribution.

c. Studies of critical velocities and tractive forces in various materials.

d. Studies of the laws of sediment transportation.

e. Investigation of experience in Bureau and other canals.

f. Comparison of design procedures developed with data in literature.

g. Preparation of design formulae, tables, and diagrams.

In each of these main divisions there are a number of subdivisions, making up a list of over 20 items.

Proposed Program of Studies

To obtain the data needed to develop adequate methods of canal design, a program of office studies, laboratory investigations and field surveys and measurements has been drawn up, covering a period of about 3-1/2 years. The details of this proposed program are given in a memorandum entitled "Proposed Program of Studies to Develop Methods of Design of Stable Channels in Erodible Material," E. W. Lane, January 11, 1950. Although this is a large and expensive program, the cost of the canals which may be constructed is so great that if the program results in a saving of only one percent in the cost of the canals, it will save the cost of the studies many times over.

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