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Terrace Channel Design Using the Spatially Varied Flow and Tractive Force Theories

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Formerly many terraces were designed with the channel grades increasing from the upper end to the outlet. This design resulted in a high absorption on permeable soils, but the difficulty of constructing and maintaining the channels to the low grades in the upper ends resulted in serious ponding on the less permeable soils. Later, terraces were designed which used a constant channel grade throughout the terrace length. Such terraces are more easily laid out and constructed and result in less ponding in the channels. On irregular topography, however, both the increasing-grade and the constant-grade designs result in crooked terraces and areas of uneven width between terraces which are difficult to farm with modern machinery.

Recently, efforts have been made to reduce curvature and to improve terrace alignment. To obtain maximum improvement for minimum cost, it is desirable to vary the grade in the terrace channels. However, if the grade is varied, some criteria must be used to determine the maximum permissible grade in any reach of the channel. Limiting-velocity criteria have been most commonly used, and have been applied by assuming uniform flow in a given reach of channel and using the Manning formula. Because changing grade and increasing discharge into a terrace channel result in non-uniform flow, certain inaccuracies are inherent in this method. For these reasons a new method of terrace channel design using spatially varied flow and tractive force theories has been developed.

DEFINITIONS OF TERMS

Open channel has one surface of the flow exposed to atmospheric pressure. The word "channel" as used hereafter in this bulletin shall refer to an "open channel".

Terrace channel is constructed across the slope of agricultural land to intercept runoff and convey it to a suitable stable outlet.

Grade is the slope of a channel bottom in the direction of flow. The terms "grade" and "gradient" shall be used interchangeably.

Steady flow occurs if the depth of flow at a section does not change with time or if it can be assumed to be constant during the time interval under consideration.

Uniform flow occurs if the velocity of successive fluid elements along any streamline is the same in both magnitude and direction at a given instant.

Non-uniform flow occurs if the magnitude or the direction of the velocity at a given instant changes from point to point along any streamline.

Spatially varied flow is flow having a non-uniform discharge resulting from the addition or diminution of fluid along its course.

Froude number. The "Froude number" is $F = \frac{V}{(gL)^{1/2}}$

where V = mean velocity (fps)
g = acceleration of gravity (ft/sec^2)
L = characteristic length (ft)

For a channel the "Froude number" can be written as

$$F = \left[\frac{Q^2}{gA^2D}\right]^{1/2}$$

where Q = total discharge at a section (cfs)
D = hydraulic depth (ft)
A = area of flow (ft^2)

Specific energy is the energy per unit weight of fluid at any section of the channel measured with respect to the channel bottom. For a channel of small gradient, the "specific energy" is the sum of the velocity head and the depth.

Critical depth is that depth of flow for which the specific energy is a minimum for a given discharge. The Froude number is unity at the "critical depth".

Mild grade is a channel grade that sustains flow at a depth greater than the critical depth for a given discharge. The Froude number is less than unity for a "mild grade".

Steep grade is a channel grade that sustains flow at a depth less than the critical depth for a given discharge. The Froude number is greater than unity.

Permissible tractive force is that maximum unit tractive force which when acting on a channel will not cause serious erosion of the material forming the bed.

Critical tractive force is the maximum unit tractive force that will not cause serious erosion of the material forming the bed of a test section.

Cohesive materials are those of which inter-particle forces are significant. Fine-grained soils generally exhibit "cohesive" properties.

SYMBOLS USED

A	Area of flow	ft^2
b	Bottom width of channel	ft
D	Hydraulic depth	ft
g	Acceleration of gravity	ft/sec^2
n	Manning coefficient	$ft^{1/6}$
P	Wetted perimeter	ft
q	Discharge added per unit length of channel	cfs/ft or cfs/100 ft
Q	Total discharge at a point	cfs
R	Hydraulic radius	ft
S_e	Energy gradient	ft/ft
S_o	Channel gradient ($\sin \theta$)	ft/ft
T	Tractive force	lb/ft^2 or psf
T_m	Maximum tractive force	lb/ft^2 or psf
T_p	Design tractive force	lb/ft^2 or psf
V	Mean velocity of flow	ft/sec or fps
w	Unit weight of water	lb/ft^3
x	Distance along channel bed	ft or 100 ft
y	Depth of flow	ft
z	Channel side slopes	ft/ft
θ	Angle of inclination of channel bed	

CONCEPTS USED IN CHANNEL DESIGN

Limiting Velocity.

The limiting velocity concept has long been used as a design criterion for channels. In 1786, du Buat published the first data which related velocity of flow to bed sediment movement.[10] Du Buat determined the transportation velocity for seven sizes of materials, ranging from clay to egg-sized stones. Etcheverry analyzed more recent data and compiled a table giving the maximum mean velocities safe against erosion for several materials.[12] Etcheverry's recommendations are included in Table I.

Fortier and Scobey submitted questionnaires to a number of irrigation engineers who had considerable experience. They sought to determine what these engineers thought to be the maximum permissible velocity for flow of water in channels for various materials without bed erosion.[13] They analyzed the data from the survey and made general recommendations as to maximum permissible velocities. Fortier and Scobey recognized the effect sediment had in the flowing water and also the effect produced by depth of flow. They suggested different velocities for water containing sediments than for clear water. Their recommendations for depths of flow less than three feet are included in Table II. They suggested that the maximum mean velocity might be increased by one-half foot per second for depths of flow greater than three feet.

The limiting velocity concept has also been used in Russia. In 1936, a Russian magazine published values of maximum permissible velocities above which scour would be produced in various kinds of non-cohesive and cohesive material.[24] The values for cohesive material are included in Table III.

Tractive Force.

Lane defined tractive force as the unit shearing force which is exerted on the periphery of a channel because of the motion of the water.[16] Brahms is believed to have been the first (1754) to extend the principle of balancing the tractive force with the channel resistance for uniform flow.[4] Du Buat, in 1786, expressed friction between running water and channel bed by the product of gradient and weight of water.[10] Du Boys expanded du Buat's ideas into a general equation in 1879.[9] Du Boys' expression for the tractive force on the bottom of an infinitely wide channel under conditions of uniform flow is

$$T = w\,y\,S_o \qquad (1)$$

Kramer stated that this equation is valid for laminar, as well as turbulent, and for shooting, as well as streaming, flows.[15]

Chang developed an expression for tractive force on an infinitely wide channel under conditions of non-uniform flow with continuous discharge.[5] Rouse, in a discussion of Chang's work, stated that the Chang equation was incorrect and developed an equation to replace the Chang equation.[21] Rouse's equation is

$$T = w\,y\left[\frac{v^2}{gy}\frac{dy}{dx} - \frac{dy}{dx} + S_o\right] \qquad (2)$$

TABLE I-CONVERSION OF B. A. ETCHEVERRY'S MAXIMUM ALLOWABLE VELOCITIES[12] TO VALUES OF THE PERMISSIBLE TRACTIVE FORCE[16]

Material	Maximum Allowable Velocity (fps)	Permissible Tractive Force (psf)
Very light pure sand of quicksand character	0.75 to 1.00	0.006 to 0.011
Very light loose sand	1.00 to 1.50	0.011 to 0.025
Coarse sand or light sandy soil	1.50 to 2.00	0.025 to 0.045
Average sandy soil	2.00 to 2.50	0.045 to 0.070
Sandy loam	2.50 to 2.75	0.070 to 0.084
Average loam, alluvial soil, volcanic ash	2.75 to 3.00	0.084 to 0.100
Firm loam, clay loam	3.00 to 3.75	0.100 to 0.157
Stiff clay soil, ordinary gravel soil	4.00 to 5.00	0.278 to 0.434
Coarse gravel, cobbles and shingles	5.00 to 6.00	0.627 to 0.903
Conglomerate, cemented gravel, soft slate, tough hardpan, soft sedimentary rock	6.00 to 8.00	0.627 to 1.114

TABLE II-CONVERSION OF THE FORTIER AND SCOBEY LIMITING VELOCITIES[13] TO VALUES OF THE PERMISSIBLE TRACTIVE FORCE[16]

Material	Clear Water		Water Transporting Colloidal Silts	
	Limiting Velocity (fps)	Permissible Tractive Force (psf)	Limiting Velocity (fps)	Permissible Tractive Force (psf)
Fine sand, colloidal	1.50	0.027	2.50	0.075
Sandy loam, noncolloidal	1.75	0.037	2.50	0.075
Silt loam, noncolloidal	2.00	0.048	3.00	0.11
Alluvial silts, noncolloidal	2.00	0.048	3.50	0.15
Ordinary firm loam	2.50	0.075	3.50	0.15
Volcanic ash	2.50	0.075	3.50	0.15
Stiff clay, very colloidal	3.75	0.26	5.00	0.46
Alluvial silts, colloidal	3.75	0.26	5.00	0.46
Shales and hardpans	6.00	0.67	6.00	0.67
Fine gravel	2.50	0.075	5.00	0.32
Graded loam to cobbles when noncolloidal	3.75	0.38	5.00	0.66
Graded silts to cobbles when colloidal	4.00	0.43	5.50	0.80
Coarse gravel, noncolloidal	4.00	0.30	6.00	0.67
Cobbles and shingles	5.00	0.91	5.50	1.10

In the use of the Rouse equation, it must be noted that if the channel gradient is considered as positive if downward in the direction of flow, following the conventions of hydraulic practice, then $\frac{dy}{dx}$ must be negative for accelerating flow, following the conventions of calculus. Tractive force will be a positive quantity.

Tractive Force Distribution. The United States Bureau of Reclamation made studies of the distribution of the tractive force on the bottom and sides of canals.[17] The following two methods were used (1) an analysis of the measured velocity distribution in trapezoidal channels; (2) a mathematical approach assuming a power law for velocity distribution. The results from the measured velocity distributions were rather inconclusive since the data available were not sufficiently exact nor of sufficient quantity to provide an adequate solution. However, the mathematical analysis seemed to yield more reliable and conclusive results.

The results for a rectangular channel indicated that when the bottom-width-over-depth ratio was four or greater, the maximum tractive force on the bottom would be 0.94 $w\ y\ S_0$ or greater. For steep-sided channels the tractive force on the sides of a given channel was considerably less than that on the bottom. The maximum value for a 2:1 side slope was approximately 0.78 $w\ y\ S_0$.

Design Values of Tractive Force. Two values of tractive force—the permissible tractive force and the critical tractive force—have been used in channel design. Chow defined the permissible tractive force as the maximum unit tractive force that would not cause serious erosion of the material forming the channel bed.[6] He also defined the critical tractive force as the maximum unit tractive force that would not cause serious erosion of the material forming the bed of a test section. According to Chow, for coarse non-cohesive material, the permissible tractive force will be higher than the critical tractive force because of the binding power of the colloidal and organic matter in the water in actual channels. However, the material in the water in actual channels may not have as great an effect for cohesive channel materials.

One method of determining permissible tractive force values is to convert permissible velocity data to tractive force values. Lane converted the Etcheverry, Fortier and Scobey, and the USSR permissible velocity data to permissible tractive force values.[16] The results are included in Tables I to III.

In 1959, Smerdon investigated the critical tractive force of cohesive soils.[23] He placed uncompacted soil in a hydraulic flume and made observations of the flow conditions when general movement of the bed material commenced. He designated the tractive force when general movement of the bed material commenced as the critical tractive force. Data from Smerdon's investigations are given in Table IV.

Examinations of Tables I to IV will show the vast range of permissible and critical tractive force values for cohesive materials obtained by different investigators.

Spatially Varied Flow With Increasing Discharge

Spatially varied flow is defined as flow having a non-uniform discharge resulting from the addition or diminution of water along the course of flow.[6] Spatially varied flow may have either increasing or decreasing discharge. Because

TABLE III-CONVERSION OF THE USSR LIMITING VELOCITIES[24] TO VALUES OF THE PERMISSIBLE TRACTIVE FORCE[16]

Principal Cohesive Material of Bed	Compactness of Bed: Loose, Voids Ratio 2.0 to 1.2		Compactness of Bed: Fairly Compact, Voids Ratio 1.2 to 0.6	
	Limiting Velocity (fps)	Permissible Tractive Force (psf)	Limiting Velocity (fps)	Permissible Tractive Force (p sf)
Sandy clays (sand content less than 50%)	1.48	0.040	2.95	0.157
Heavy clayey soils	1.31	0.031	2.79	0.141
Clays	1.15	0.024	2.62	0.124
Lean clayey soils	1.05	0.020	2.30	0.096
Sandy clays (sand content less than 50%)	4.26	0.327	5.90	0.630
Heavy clayey soils	4.10	0.305	5.58	0.563
Clays	3.94	0.281	5.41	0.530
Lean clayey soils	3.44	0.214	4.43	0.354

TABLE IV-CRITICAL TRACTIVE FORCE OF SOILS DETERMINED BY SMERDON[23]

Soil	Critical Tractive Force (psf)
Silty Loam (Marshall Surface Soil)	0.0199
Silty Loam (Knox Surface Soil)	0.0328
Silty Loam (Knox Subsoil)	0.0153
Silty Clay Loam (Menfro Surface Soil)	0.0281
Silty Clay Loam (Mexico Surface Soil)	0.0458
Clay (Mexico Subsoil)	0.0886
Silty Clay Loam (Union Surface Soil)	0.0325
Silty Loam (Weldon Surface Soil)	0.0225
(Silty Clay (Weldon Surface Soil, Serverely Eroded)	0.0241
Silty Clay Loam (Shelby Surface Soil)	0.0384
Clay (Shelby Subsoil)	0.0546

of differences in hydraulic behavior, the two types of flow are usually considered separately. Spatially varied flow is more difficult to analyze than non-uniform flow with continuous discharge.

The theory of spatially varied flow with increasing discharge has been used in several practical applications such as the design of roof gutters, road drains, wash-water troughs in filters, and lateral spillways on dams.

METHODS OF TERRACE CHANNEL DESIGN

Early terrace channel designers used a variable grade channel with the grade increasing from the upper end to the outlet end. Their purpose in using this design was to increase the infiltration of water into the soil and to reduce runoff. Experimental terraces of this design were constructed at erosion stations throughout the country. Ramser summarized the results from several of these stations and made recommendations for terrace channel gradients (1931).[19] Ramser's figures have been cited frequently by the authors of soil and water management texts. His recommendations are given in Table V.

The increasing grade design functioned well on permeable soils, but on impermeable soils ponding in the upper end of a terrace was a serious problem. The ponding problem and the desire to simplify layout caused later terrace channel designers to use a channel of constant grade which resulted in less ponding in the channel and which was easier to lay out.

On irregular topography the increasing grade and constant grade designs result in crooked terraces and odd-shaped areas between terraces which make it difficult to farm terraced land with large farm equipment. This disadvantage has led to a slow acceptance of terracing by farmers.

Recently, terrace channel designers have attempted to gain wider acceptance for terracing by improving terrace channel alignment.[2] On irregular topography, improving terrace channel alignment necessitates deviations from the commonly accepted standards of grade, depth of cut, or both. In order to obtain maximum improvement for minimum cost, it is essential that changes in grade be utilized, within the limits of safe design.

The limiting velocity concept has been applied to the problem of determining the maximum permissible gradient in any reach of a terrace channel. A maximum velocity of two feet per second has been suggested.[11] This has been applied to terrace channel design by the use of a step method assuming uniform flow in reaches of the channel. However, there are inherent inaccuracies when

TABLE V-TERRACE CHANNEL GRADIENTS RECOMMENDED BY RAMSER

Distance from Upper end of Terrace (ft)	Drop of Terrace per 100 feet of Length (in)
0 - 300	½
300 - 600	1
600 - 900	2
900 - 1200	4
1200 - 1500	6

applying this method to terrace channels in which discharge varies with distance and in which the channel gradient is not constant. For this reason, a more accurate method of terrace channel design has been developed.

A method was developed whereby the spatially varied flow and tractive force theories were used to select maximum terrace channel grades under conditions of changing grade and increasing discharge.[18]

THEORETICAL ANALYSIS

Dynamic Equation For Spatially Varied Flow

Spatially varied flow with increasing discharge may be analyzed by consideration of the momentum equation. Consider sections one and two, and the body of water between sections one and two, of Figure 1. The change in momentum between sections one and two is

$$\frac{w}{g}\left[QdV + (V + dV)\,dQ\right]$$

The component of the weight of water between sections one and two in the direction of flow is

$$w\,A\,S_o\,dx.$$

The viscous shear along the wetted perimeter is

$$F_e = w\,A\,S_e\,dx.$$

The hydrostatic pressure between sections one and two is

$$p_1 - p_2 = -\,w\,A\,dy.$$

Equating the momentum change of the body of water between sections one and two to all external forces acting on the body, the following relationship is obtained.

$$\frac{w}{g}\left[QdV + (V + dV)\,dQ\right] = -\,w\,A\,dy + w\,A\,S_o\,dx - w\,A\,S_e\,dx$$

By neglecting the product of any differentials, simplifying, substituting and rearranging, the equation may be written in the following form:

$$\frac{dy}{dx} = \frac{S_o - S_e - \dfrac{2Qq}{gA^2}}{1 - \dfrac{Q^2}{gA^2D}} \qquad (3)$$

This is the dynamic equation for spatially varied flow with increasing discharge. The equation is restricted neither as to size nor shape of channel. It should be noted that if the channel gradient is considered positive when downward in the direction of flow, following the conventions of hydraulic practice, than $\frac{dy}{dx}$ must be negative for accelerating flow, following the conventions of calculus.

The energy gradient, S_e, in equation (3) can be approximated by a uniform flow equation, such as the Manning formula,[25] if it is assumed that the rate of

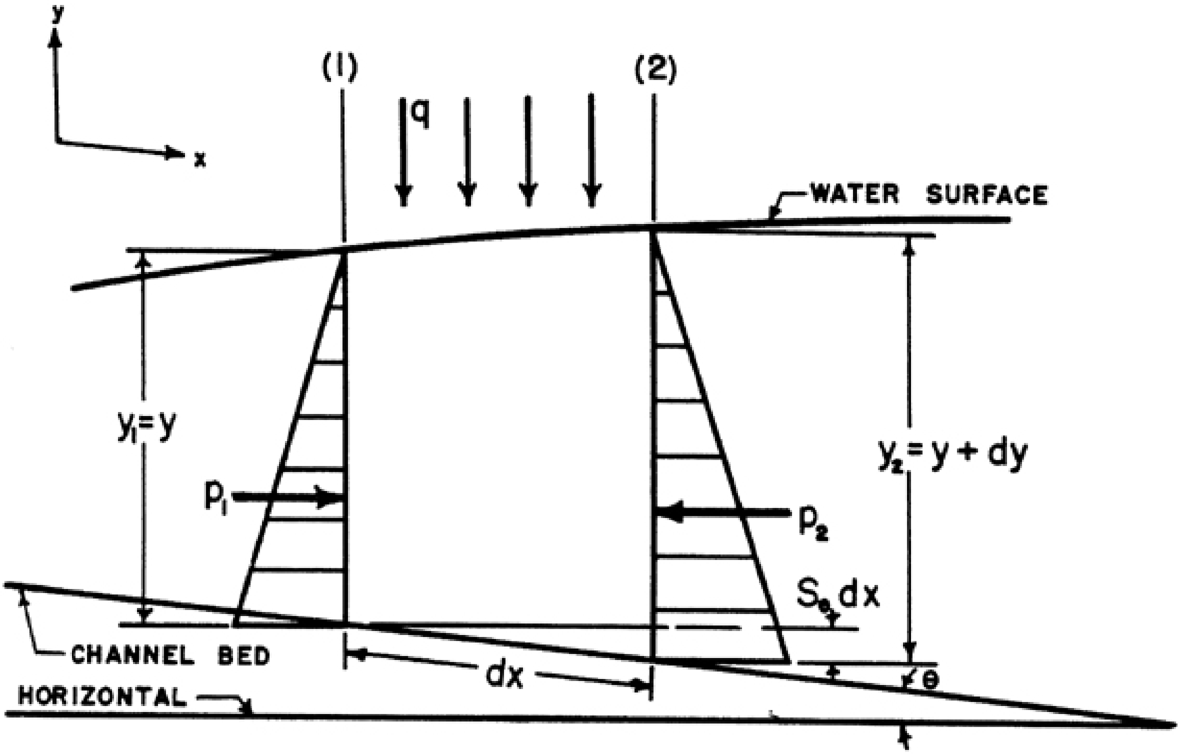

Fig. 1—Spatially varied flow diagram.

energy loss for spatially varied flow is the same as for uniform flow of the same mean velocity and depth. The equation for energy loss is

$$S_e = \frac{n^2 Q^2}{2.21 A^2 R^{4/3}} \tag{4}$$

Since the discharge for spatially varied flow is the product of the rate of inflow times the distance, qx, the equation for energy gradient may be written as

$$S_e = \frac{n^2 q^2 x^2}{2.21 A^2 R^{4/3}} \tag{5}$$

Tractive Force Under Conditions of Uniform Flow.

Consider a free body of water of unit length and width within a channel of infinite width, as is shown in Figure 2. Since the free body is in equilibrium, the summation of all forces acting upon it must be zero. By balancing the forces acting on the body, an expression can be derived for the shearing force acting on the channel bed in the direction of flow.[23] This shearing force is the tractive force and the expression is

$$T = w\, y \sin \theta.$$

The gradient of the bed is defined as the sine of the angle of inclination. The above equation can be written as follows:

$$T = w\, y\, S_o \tag{1}$$

This equation is the same as the du Boys equation (1) given in a previous section. This equation is derived only from knowledge of the forces which must

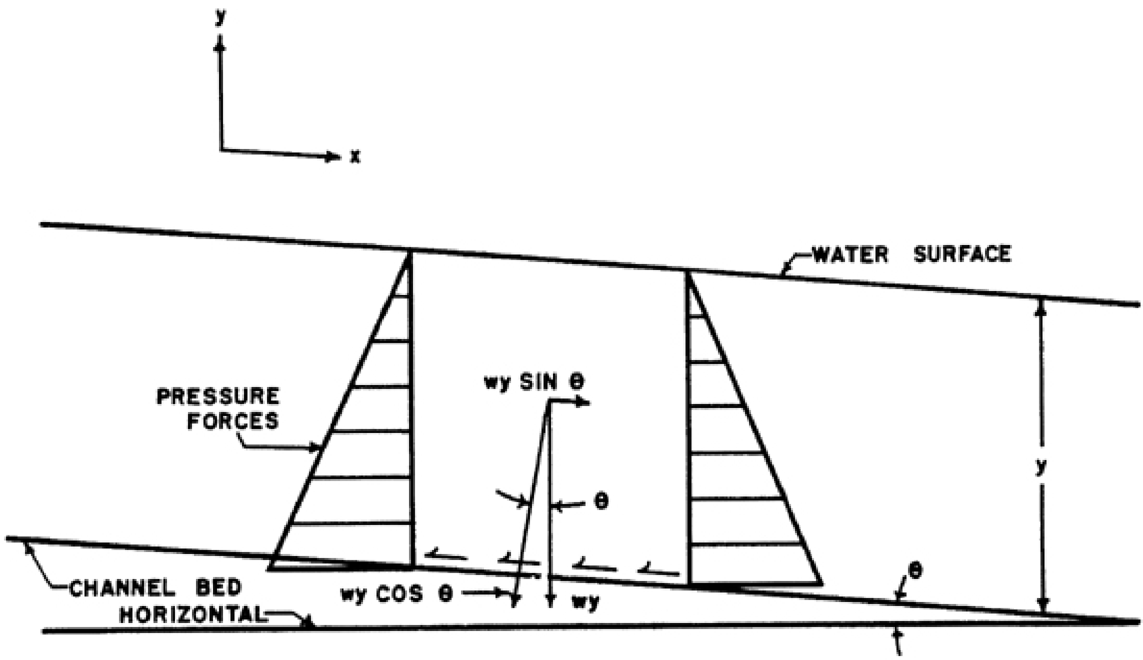

Fig. 2—Tractive force diagram.

act upon a free body of water under conditions of equilibrium and is completely independent of whether the flow occurs on mild, critical, or steep grade.

Tractive Force on Channel Bed Under Conditions of Spatially Varied Flow With Increasing Discharge.

An expression for the tractive force under conditions of spatially varied flow with increasing discharge in a channel of infinite width may be developed from equation (3) by rearranging terms.

$$S_e = S_o - \left(1 - \frac{Q^2}{gA^2D}\right)\frac{dy}{dx} - \frac{2Qq}{gA^2}$$

The term on the left is the energy gradient. Using the same assumption as was used in justifying equation (4), it follows that

$$S_e = \frac{T}{w\,y} \qquad (6)$$

and

$$T = w\,y\left[S_o - \left(1 - \frac{Q^2}{gA^2D}\right)\frac{dy}{dx} - \frac{2Qq}{gA^2}\right] \qquad (7)$$

Maximum Tractive Force on Trapezoidal Channels.

The maximum tractive force developed on the sides of a trapezoidal channel with uniform flow will be less than that on the bottom. Therefore, in channels in cohesive soils, only the bottom of a trapezoidal channel need be considered in design for uniform flow conditions. The maximum tractive force developed on the bottom of a wide trapezoidal channel under conditions of uniform flow will be slightly less than that developed on an infinitely wide channel of the same grade and depth of flow. For design purposes, an assumption of the same maximum tractive force on a trapezoidal channel as on a channel of infinite width will be conservative. If the above assumption is made for spatially varied flow, the maximum tractive force on the bottom of a trapezoidal channel can be approximated from equation (7).

PROCEDURE

Terrace channels were designed by the limiting velocity, constant grade, and increasing grade, criteria. A method was then devised whereby the spatially varied flow and tractive force theories were used in determining the maximum permissible gradient for any given reach of a given channel.

Selection of Parameters

Two 2000-foot trapezoidal channels were chosen for consideration. A channel with six-foot bottom and eight-to-one side slopes, hereafter referred to as channel A, was chosen for land of six percent or less slope. A channel with four-foot bottom and six-to-one side slopes was chosen for land of greater than 6 percent slope. These channel shapes were chosen for their economics of construction and their adaptability to mechanized farming. They are quite typical of shapes commonly recommended for terrace channel construction.[1]

A Manning coefficient of three hundredths was used in this study except where otherwise noted. This value is representative of a cultivated channel in a condition most susceptible to erosion, which limits the maximum permissible grade.[8, 25] A Manning coefficient of five hundredths was used in the two cases in which it was desired to determine the maximum depth of flow. This value is representative of a channel with considerable vegetation.[8, 25]

Design values of tractive force were chosen by examination of Tables I to IV for tractive force values for cohesive soils. A range of one tenth pounds per square foot to two tenths psf was chosen and divided into twenty-five thousandths psf intervals.

A range of expected values of inflow into the chosen channels was determined by the use of Yarnell's data on rainfall frequency and intensity[26] and a revised terrace spacing as developed by Beasley.[3] The range of inflow was determined for an area of the Middlewest including Missouri, Southern Iowa, Southeastern Nebraska, Eastern Kansas, and Northern Arkansas. A thirty-minute duration, ten-year frequency rainfall was used for design. The expected rainfall of this duration and frequency for this section of the United States is approximately one and eight tenths to one and eighty-five hundredths inches. The area between terraces per one hundred-foot length was computed for two percent land slope, six percent land slope and twelve percent land slope. The inflow into each one hundred-foot length of channel was found by use of the rational formula.[20]

$$Q_i = c\ i\ a \tag{12}$$

where Q_i = design peak runoff (cfs)

c = runoff coefficient

i = design rainfall intensity (iph)

a = watershed area (acre)

For design purposes it was assumed that there would be no infiltration, i.e., $c = 1$. The values of inflow used in analyzing flow in terraces on land of less than six percent slope ranged from five tenths to one and five tenths cubic feet per second per one hundred feet and for the terraces on land of greater than six percent slope ranged from five tenths to one cfs per one hundred feet. Each of these ranges of inflow was divided into twenty-five hundredths cfs intervals for consideration.

Limiting Velocity Design by Step Routing

The maximum rates of inflow were routed in each channel at a limiting velocity of two fps using a step routing method assuming uniform flow in 100 feet reaches with the total inflow into each reach entering at the upper end of the reach. The Manning formula (4) and a Manning coefficient of three hundredths were used. The maximum tractive force was found by the use of equation (1).

Constant Grade Design by Step Routing

The maximum rates of inflow were routed in channel A at a constant grade using the step method outlined in the previous section. A constant grade of three tenths percent was used. A grade of three tenths percent is commonly used in the layout of conventional terraces throughout Missouri. The maximum tractive force on each one hundred feet length was found by the use of equation (1).

Constant Grade Design by Spatially Varied Flow

The maximum rates of inflow were routed in channel A at a constant grade of three tenths percent by use of the spatially varied flow equation (3), where the energy gradient was approximated by the expression in equation (5). A Manning coefficient of three hundredths was used. The spatially varied flow equation is a rather complicated first-order differential equation and can be solved most readily by the approximation methods of numerical analysis. Either the Milne or Runge-Kutta method is applicable to this problem.[14] However, the Runge-Kutta is faster and Runge-Kutta programs have been written for the electronic digital computer. The Runge-Kutta method as applied to the spatially varied flow equation requires that the depth of flow be known at only one point in the channel. It was assumed that the channel would be constructed on a mild grade and that the depth at the lower end would be equal to the normal depth.

The computations were started from the lower end of the channel. The flow profile was projected up the channel by ten foot increments of length through the use of equations (3) and (5). The maximum tractive force on the bottom of the channel was found at each increment of length by rearranging equation (6) into the following form:

$$T = w\, y\, S_e \tag{8}$$

The problem was programmed for an electronic digital computer.

This program was then utilized to determine the maximum depth of flow that would occur if a minimum grade of two tenths percent was used throughout the length of channel A. A value of inflow of one cfs per hundred feet and a Manning coefficient of five hundredths were used.

Increasing Grade Design by the Spatially Varied Flow Theory

The computer program developed to route flow at constant grade was used to route flow in channel A in which the grade increased from the upper to the outlet end. The grades chosen were those given in the University of Missouri Agricultural Experiment Station Bulletin 507 (1947)[7] The length of channel A was reduced to sixteen hundred feet to conform with the length given in the bulletin. A value of inflow of one cfs per hundred feet and a Manning coefficient of five hundredths were used.

Permissible Tractive Force Design by the Spatially Varied Flow Theory

A method was devised whereby the spatially varied flow equation was utilized in the design of channels for a permissible tractive force. Equations (3), (5) and (6) were considered

$$\frac{dy}{dx} = \frac{S_o - S_e - \dfrac{2Qq}{gA^2}}{1 - \dfrac{Q^2}{gA^2D}} \tag{3}$$

$$S_e = \frac{n^2\, q^2\, x^2}{2.21\, A^2\, R^{4/3}} \tag{5}$$

$$S_e = \frac{T}{w\, y} \tag{6}$$

The right-hand expressions in equations (5) and (6) were equated and rearranged to obtain the following:

$$x = \frac{1.486}{nq}\left[\frac{T}{w}\right]^{1/2} \frac{AR^{2/3}}{y^{1/2}} \tag{9}$$

The right-hand expression in equation (9) was differentiated with respect to y to obtain an expression for dx/dy.

$$\frac{dx}{dy} = \frac{1.486}{nq}\left[\frac{T}{w}\right]^{1/2} \left[-\frac{A^{5/3}}{2y^{3/2}P^{2/3}} - \frac{2A^{5/3}}{3y^{1/2}P^{5/3}}\frac{dP}{dy} + \frac{5A^{2/3}}{3y^{1/2}P^{2/3}}\frac{dA}{dy}\right] \tag{10}$$

Distance and dx/dy were obtained from equations (9) and (10) with assumed values of T and y. The corresponding channel gradient, S_o, was obtained by rearranging equation (3) into the following form:

$$S_o = \frac{T}{wy} + \left[1 - \frac{q^2x^2}{gA^3D}\right]\frac{dy}{dx} + \frac{2q^2x}{gA^2} \qquad (11)$$

The right-hand expression was written entirely in terms of constants and previously determined values.

The problem was programmed for an electronic digital computer and a printout routine was set up, whereby S_o, y, x, dy/dx, S_e, and the Froude number were obtained at each increment of depth. The Froude number indicated whether the flow was at mild or steep grade. A Froude number greater than unity indicated a steep grade, while a Froude number less than unity indicated a mild grade.

Each channel was designed by choosing a design value of tractive force and increasing the depth from zero by small increments, until the distance reached two thousand feet. Channel A was designed for the twenty-five possible combinations of design tractive force and inflow. Channel B was designed for the fifteen possible combinations of design tractive force and inflow.

DISCUSSION OF DATA AND CONCLUSIONS

Limiting Velocity by the Step Routing Method

The depth, grade and maximum tractive force data obtained by routing the maximum rates of inflow at a limiting velocity of two fps by the step routing method are presented in Table VI. The tractive force data are plotted in Figure 3. Table VI and Figure 3 show that design for limiting velocity results in increasing tractive force toward the upper end of the channel. The rate of increase is especially high in the upper five hundred feet of the channel.

Constant Grade Design

The depth, velocity, and maximum tractive force data obtained by routing the maximum rate of inflow in channel A at a constant grade of three tenths percent by the step routing method and, also, by the spatially varied flow method are presented in Table VII and Figure 4. The data show that the maximum tractive force determined by the spatially varied flow method is lower than that determined by the step routing method. The data from both methods show that constant grade design results in decreasing tractive force toward the upper end of the channel. This indicates that if a given grade is safe in the lower reaches of a channel, then the grade could be increased somewhat toward the upper end of the channel.

The depth, velocity, and maximum tractive force data obtained by routing one cfs per hundred feet in channel A at a constant grade of two tenths percent and with a Manning coefficient of five hundredths are presented in Table VIII. Since two tenths percent grade is considered to be a desirable minimum grade for most soils in Missouri, the depths of flow presented in Table VIII represent the probable maximum depths of flow upon which a terrace ridge height should be based.

TABLE VI-DATA FROM LIMITING VELOCITY STEP ROUTING METHOD
(V = 2 fps, n=0.03)

Distance From Upper End Of Channel	Channel A q = 1.5 cfs/100 ft			Channel B q = 1.0 cfs/100 ft		
x (100 ft)	y (ft)	S_o (%)	Tm (psf)	y (ft)	S_o (%)	Tm (psf)
1	0.11	3.70	0.251	0.11	3.81	0.255
2	0.20	1.83	0.226	0.19	1.93	0.233
3	0.27	1.26	0.216	0.27	1.34	0.224
4	0.34	0.99	0.211	0.33	1.05	0.218
5	0.41	0.82	0.206	0.39	0.87	0.214
6	0.46	0.70	0.204	0.45	0.76	0.211
7	0.52	0.62	0.201	0.50	0.67	0.209
8	0.57	0.56	0.199	0.55	0.61	0.207
9	0.62	0.51	0.198	0.60	0.55	0.205
10	0.67	0.47	0.196	0.64	0.51	0.203
11	0.71	0.45	0.195	0.68	0.48	0.201
12	0.75	0.42	0.194	0.72	0.44	0.199
13	0.79	0.39	0.192	0.76	0.42	0.198
14	0.83	0.37	0.191	0.80	0.40	0.197
15	0.87	0.35	0.190	0.83	0.38	0.196
16	0.91	0.34	0.189	0.87	0.36	0.195
17	0.94	0.32	0.188	0.90	0.35	0.194
18	0.98	0.31	0.188	0.94	0.33	0.194
19	1.01	0.30	0.187	0.97	0.32	0.193
20	1.05	0.29	0.186	1.00	0.31	0.193

Increasing Grade Design by the Spatially Varied Flow Theory

The depth, velocity, and tractive force data obtained by routing one cfs per hundred feet in a channel of increasing grade are presented in Table IX. The data show that, while the tractive force is rather large at the lower end of the channel, it decreases to a very small value at the upper end of the channel. The depth is less than one-half foot at the one hundred-foot station and is nearly one foot at the sixteen hundred-foot station.

Permissible Tractive Force Design by the Spatially Varied Flow Theory

The depth, velocity, and channel gradient data from the design by the spatially varied flow and tractive force theories are presented in Tables X to XVII. The reaches of channel in which the Froude number is greater than unity have been indicated. The Froude number is greater than unity in only the upper two hundred feet of the channels carrying the lower rates of inflow. As these upper reaches are on relatively steep grades, the grade could be reduced to the grade in the next reach without sacrificing practicality. For those reaches in which the Froude number is less than unity, any grade less than the computed grade would result in a maximum tractive force less than the design value, as there would be no danger of a hydraulic jump and a concentrated dissipation of energy.

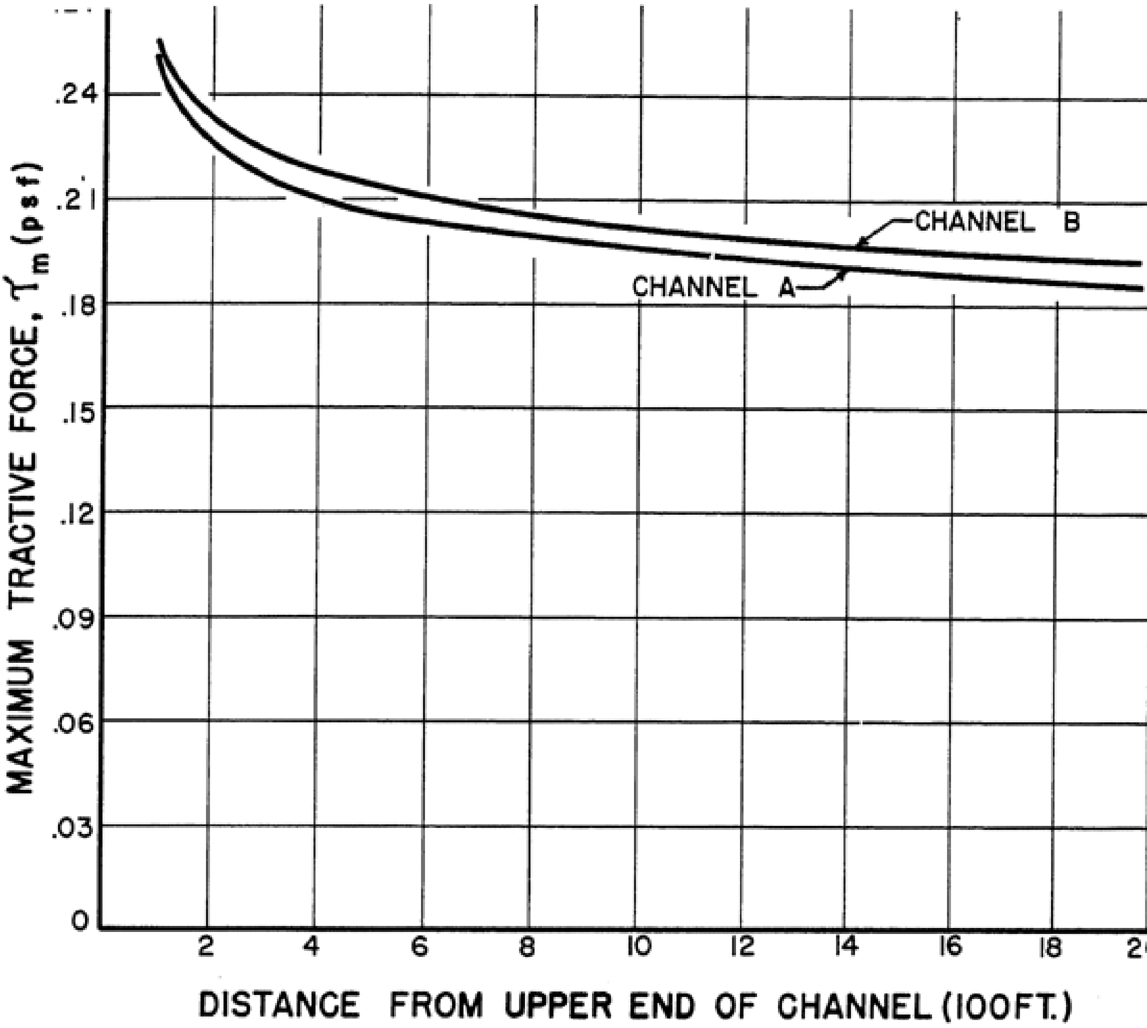

Fig. 3—Data from limiting velocity step routing method.

Tables X and XVII show that design for a permissible tractive force allows the use of higher grades toward the upper end of a terrace channel than at the lower end. Tables X to XVII show that the velocity is not constant, but decreases toward the upper end of the channel, providing further proof that design based upon the limiting velocity criteria would result in increasing tractive force toward the upper end of the channel.

The tractive force and spatially varied flow theories can thus be used to determine the maximum permissible grade in any given reach of a terrace channel on a soil for which the permissible tractive force is known.

SUMMARY

The recent interest in improving terrace channel alignment has made it advisable to reconsider the constant grade terrace channel design widely used at present. The limiting velocity concept has been applied to terrace channel design by the use of a uniform flow step routing method. However, there are inherent inaccuracies when applying this method to terrace channels in which dis-

TABLE VII-DATA FROM CONSTANT GRADE ROUTING IN CHANNEL A

(q = 1.5 cfs/100 ft, S_O = 0.3%, n = 0.03)

Distance From Upper End Of Channel	Step Method			Spatially Varied Flow Method		
x (100 ft)	y (ft)	V (fps)	Tm (psf)	y (ft)	V (fps)	Tm (psf)
1	0.22	0.88	0.041	0.26	0.70	0.026
2	0.33	1.05	0.062	0.36	0.93	0.045
3	0.41	1.18	0.077	0.44	1.07	0.059
4	0.47	1.30	0.088	0.50	1.19	0.071
5	0.53	1.39	0.099	0.56	1.28	0.082
6	0.58	1.47	0.108	0.61	1.36	0.091
7	0.62	1.54	0.116	0.65	1.43	0.100
8	0.66	1.59	0.124	0.70	1.49	0.108
9	0.70	1.65	0.132	0.74	1.54	0.115
10	0.74	1.70	0.138	0.77	1.59	0.122
11	0.78	1.73	0.146	0.81	1.64	0.129
12	0.81	1.79	0.152	0.84	1.68	0.135
13	0.84	1.83	0.157	0.87	1.72	0.141
14	0.87	1.86	0.163	0.90	1.76	0.147
15	0.90	1.89	0.168	0.93	1.80	0.153
16	0.93	1.92	0.174	0.96	1.83	0.158
17	0.96	1.96	0.179	0.98	1.87	0.163
18	0.98	1.99	0.183	1.01	1.90	0.169
19	1.00	2.02	0.188	1.03	1.94	0.175
20	1.03	2.04	0.193	1.04	2.00	0.186

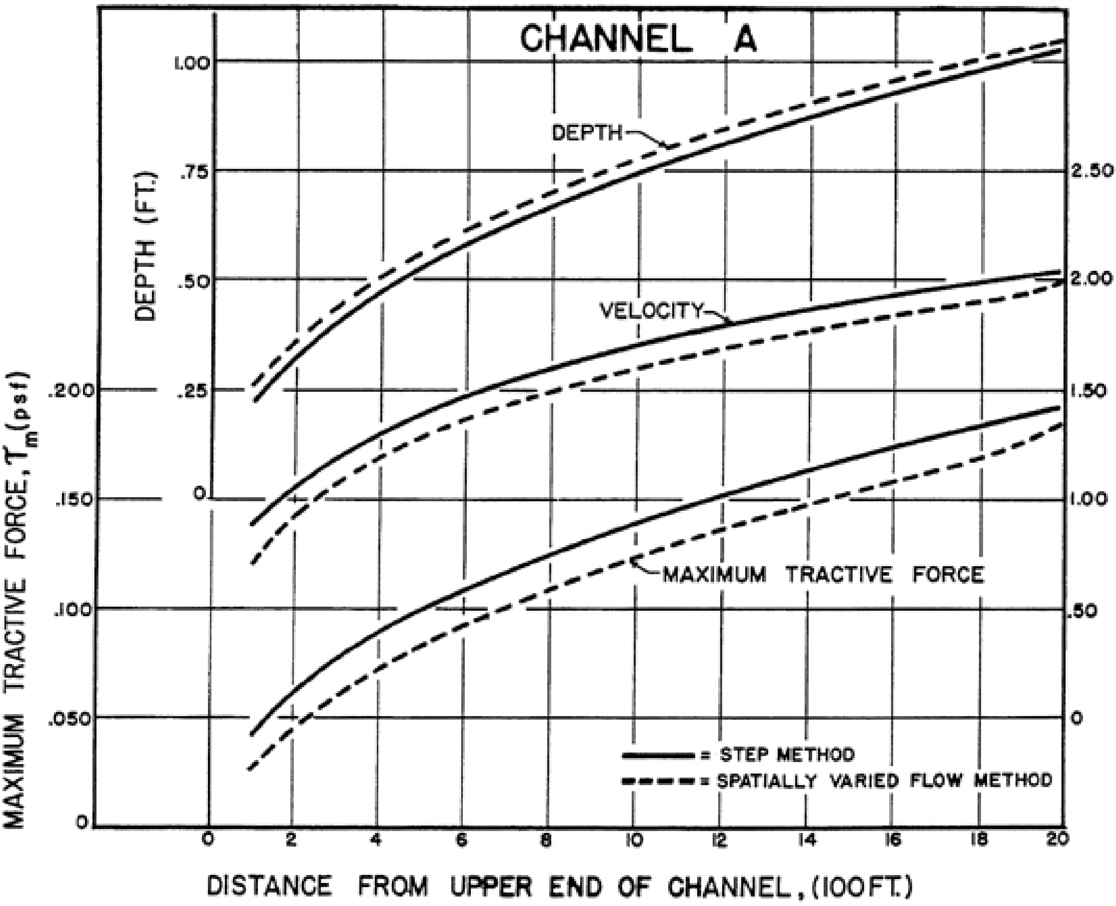

Fig. 4—Data from constant grade routing.

TABLE VIII-DATA FROM CONSTANT GRADE DESIGN BY SPATIALLY VARIED FLOW METHOD IN CHANNEL A

(q = 1.0 cfs/100 ft, S_o = 0.2%, n = 0.05)

Distance From Upper End Of Channel x (100 ft)	y (ft)	V (fps)	T_m (psf)
1	0.35	0.33	0.015
2	0.45	0.45	0.029
3	0.54	0.54	0.040
4	0.61	0.60	0.049
5	0.67	0.65	0.058
6	0.73	0.70	0.065
7	0.78	0.73	0.072
8	0.83	0.77	0.078
9	0.87	0.80	0.084
10	0.91	0.83	0.089
11	0.95	0.85	0.095
12	0.99	0.87	0.099
13	1.02	0.90	0.104
14	1.06	0.92	0.109
15	1.09	0.94	0.113
16	1.12	0.96	0.118
17	1.14	0.98	0.122
18	1.17	1.00	0.128
19	1.19	1.03	0.134
20	1.20	1.07	0.144

charge varies with distance and in which the channel gradient may not be constant. It was desired that a more correct approach be made to the problem of selecting the maximum terrace channel gradients safe against erosion in any given reach of a channel on a given soil. The spatially varied flow theory was chosen to consider the effect of changing grade and increasing discharge upon the flow profile. The tractive force theory was chosen to evaluate the erosive force of flowing water under a given flow profile. As a preliminary to development of a new method of design, terrace channels were designed by the limiting velocity and constant grade methods and the maximum tractive force on each length of the channel was determined. The manner in which maximum tractive force varied from lower to upper end of the channel for each design was noted.

A new method of design was then developed whereby the tractive force theory was used in combination with the spatially varied flow theory to select maximum terrace channel grades under conditions of changing grade and increasing discharge. Two typical terrace channels were designed for a wide range of inflow and tractive force conditions. An electronic digital computer was used to perform the computations involved in the solution of the problem.

TABLE IX-DATA FROM INCREASING GRADE DESIGN BY SPATIALLY VARIED FLOW METHOD IN CHANNEL A

(q = 1.0 cfs/100 ft, n = 0.05)

Distance from upper end of channel x (100 ft)	S_o (%)	y (ft)	V (fps)	T_m (psf)
0				
	0.13			
1		0.44	0.24	0.008
	0.13			
2		0.52	0.37	0.019
	0.13			
3		0.57	0.49	0.033
	0.17			
4		0.64	0.56	0.043
	0.17			
5		0.69	0.63	0.053
	0.17			
6		0.72	0.70	0.066
	0.20			
7		0.77	0.75	0.075
	0.20			
8		0.80	0.80	0.085
	0.20			
9		0.81	0.89	0.105
	0.25			
10		0.85	0.93	0.113
	0.25			
11		0.87	0.98	0.126
	0.25			
12		0.86	1.09	0.157
	0.33			
13		0.89	1.11	0.163
	0.33			
14		0.92	1.14	0.170
	0.33			
15		0.95	1.17	0.179
	0.33			
16		0.96	1.22	0.194

TABLE X-DESIGN FOR PERMISSIBLE TRACTIVE FORCE, CHANNEL A*

q = 1.50 cfs/100 ft, n = 0.03

	Tp = 0.100 lb/ft^2			Tp = 0.125 lb/ft^2			Tp = 0.150 lb/ft^2			Tp = 0.175 lb/ft^2			Tp = 0.200 lb/ft^2		
x (ft)	S_o (%)	y (ft)	V (fps)	S_o (%)	y (ft)	V (fps)	S_o (%)	y (ft)	V (fps)	S_o (%)	y (ft)	V (fps)	S_o (%)	y (ft)	V (fps)
1	1.20	0.16	1.31	1.57	0.14	1.44	1.99	0.13	1.58	2.43	0.13	1.70	2.89	0.12	1.80
2	0.71	0.27	1.36	0.94	0.25	1.51	1.17	0.23	1.65	1.42	0.22	1.77	1.69	0.21	1.89
3	0.55	0.36	1.38	0.70	0.34	1.54	0.87	0.31	1.68	1.05	0.30	1.81	1.25	0.28	1.93
4	0.45	0.45	1.40	0.58	0.41	1.56	0.71	0.39	1.70	0.86	0.37	1.83	1.01	0.35	1.95
5	0.39	0.52	1.41	0.50	0.48	1.57	0.61	0.45	1.72	0.73	0.43	1.85	0.86	0.41	1.97
6	0.35	0.59	1.42	0.44	0.55	1.58	0.54	0.52	1.73	0.65	0.49	1.86	0.76	0.47	1.98
7	0.32	0.65	1.43	0.40	0.61	1.59	0.48	0.57	1.74	0.58	0.54	1.87	0.69	0.52	1.99
8	0.29	0.71	1.43	0.37	0.66	1.60	0.44	0.63	1.74	0.54	0.59	1.88	0.63	0.57	2.00
9	0.27	0.77	1.44	0.34	0.72	1.60	0.42	0.68	1.75	0.50	0.64	1.89	0.58	0.61	2.01
10	0.25	0.83	1.44	0.32	0.77	1.61	0.39	0.73	1.76	0.46	0.69	1.89	0.54	0.66	2.02
11	0.24	0.88	1.45	0.30	0.82	1.61	0.37	0.77	1.76	0.43	0.73	1.90	0.51	0.70	2.03
12	0.23	0.92	1.45	0.28	0.86	1.62	0.35	0.81	1.77	0.41	0.77	1.90	0.48	0.74	2.03
13	0.22	0.97	1.46	0.27	0.91	1.62	0.33	0.86	1.77	0.39	0.82	1.91	0.46	0.78	2.04
14	0.21	1.02	1.46	0.26	0.95	1.63	0.32	0.90	1.78	0.38	0.85	1.92	0.44	0.82	2.04
15	0.20	1.06	1.47	0.25	0.99	1.63	0.30	0.94	1.78	0.36	0.89	1.92	0.42	0.86	2.05
16	0.19	1.10	1.47	0.24	1.03	1.64	0.29	0.97	1.79	0.35	0.93	1.92	0.40	0.89	2.05
17	0.18	1.14	1.47	0.23	1.07	1.64	0.28	1.01	1.79	0.33	0.96	1.93	0.39	0.93	2.06
18	0.18	1.18	1.48	0.22	1.11	1.64	0.27	1.05	1.80	0.32	1.00	1.93	0.38	0.96	2.06
19	0.17	1.22	1.48	0.21	1.14	1.65	0.26	1.08	1.80	0.31	1.03	1.94	0.36	0.99	2.07
20	0.17	1.26	1.48	0.21	1.18	1.65	0.25	1.12	1.80	0.30	1.06	1.94	0.35	1.02	2.07

* b = 6, z = 8

TABLE XI-DESIGN FOR PERMISSIBLE TRACTIVE FORCE, CHANNEL A

q = 1.25 cfs/100 ft, n = 0.03

	Tp = 0.100 lb/ft^2			Tp = 0.125 lb/ft^2			Tp = 0.150 lb/ft^2			Tp = 0.175 lb/ft^2			Tp = 0.200 lb/ft^2		
x (ft)	S_o (%)	y (ft)	V (fps)	S_o (%)	y (ft)	V (fps)	S_o (%)	y (ft)	V (fps)	S_o (%)	y (ft)	V (fps)	S_o (%)	y (ft)	V (fps)
1	1.31	0.14	1.29	1.78	0.12	1.43	2.25	0.12	1.56	2.76	0.11	1.67	3.31*	0.10	1.78
2	0.80	0.24	1.35	1.05	0.22	1.50	1.32	0.20	1.63	1.61	0.19	1.76	1.91	0.18	1.87
3	0.60	0.32	1.37	0.78	0.29	1.53	0.98	0.27	1.67	1.18	0.26	1.79	1.41	0.25	1.91
4	0.49	0.39	1.39	0.64	0.36	1.55	0.79	0.34	1.69	0.96	0.32	1.82	1.14	0.31	1.94
5	0.41	0.46	1.40	0.54	0.43	1.56	0.67	0.40	1.70	0.82	0.38	1.83	0.97	0.36	1.96
6	0.38	0.52	1.41	0.48	0.48	1.57	0.60	0.45	1.72	0.72	0.43	1.85	0.85	0.41	1.97
7	0.34	0.58	1.42	0.43	0.54	1.58	0.54	0.51	1.72	0.65	0.48	1.86	0.76	0.46	1.98
8	0.31	0.63	1.42	0.39	0.59	1.59	0.49	0.55	1.73	0.59	0.53	1.87	0.70	0.50	1.99
9	0.29	0.69	1.43	0.37	0.64	1.59	0.46	0.60	1.74	0.55	0.57	1.87	0.64	0.54	2.00
10	0.27	0.73	1.44	0.34	0.68	1.60	0.43	0.64	1.75	0.51	0.61	1.88	0.60	0.58	2.01
11	0.26	0.78	1.44	0.33	0.73	1.60	0.40	0.68	1.75	0.48	0.65	1.89	0.56	0.62	2.01
12	0.24	0.82	1.44	0.31	0.77	1.61	0.38	0.72	1.76	0.45	0.69	1.89	0.53	0.66	2.02
13	0.23	0.87	1.45	0.29	0.81	1.61	0.36	0.76	1.76	0.43	0.73	1.90	0.51	0.69	2.02
14	0.22	0.91	1.45	0.26	0.85	1.62	0.34	0.80	1.77	0.41	0.76	1.90	0.48	0.73	2.03
15	0.21	0.95	1.46	0.27	0.88	1.62	0.33	0.83	1.77	0.39	0.80	1.91	0.46	0.76	2.03
16	0.20	0.99	1.46	0.26	0.92	1.63	0.32	0.87	1.78	0.38	0.83	1.91	0.44	0.79	2.04
17	0.20	1.02	1.46	0.25	0.96	1.63	0.31	0.90	1.78	0.36	0.86	1.92	0.43	0.83	2.04
18	0.19	1.06	1.47	0.24	0.99	1.63	0.29	0.94	1.78	0.35	0.89	1.92	0.41	0.86	2.05
19	0.18	1.09	1.47	0.23	1.02	1.64	0.29	0.97	1.79	0.34	0.92	1.92	0.40	0.88	2.05
20	0.18	1.13	1.47	0.23	1.06	1.64	0.28	1.00	1.79	0.33	0.95	1.93	0.39	0.91	2.06

*Froude number greater than unity.

TABLE XII-DESIGN FOR PERMISSIBLE TRACTIVE FORCE, CHANNEL A

q = 1.00 cfs/100 ft, n = 0.03

	Tp = 0.100 lb/ft^2			Tp = 0.125 lb/ft^2			Tp = 0.150 lb/ft^2			Tp = 0.175 lb/ft^2			Tp = 0.200 lb/ft^2		
x (ft)	S_o (%)	y (ft)	V (fps)	S_o (%)	y (ft)	V (fps)	S_o (%)	y (ft)	V (fps)	S_o (%)	y (ft)	V (fps)	S_o (%)	y (ft)	V (fps)
1	1.55	0.11	1.27	2.08	0.10	1.41	2.66	0.10	1.53	3.26*	0.09	1.64	3.92*	0.09	1.74
2	0.92	0.20	1.33	1.19	0.18	1.48	1.53	0.17	1.61	1.88	0.16	1.73	2.25	0.15	1.84
3	0.68	0.27	1.36	0.89	0.25	1.51	1.12	0.23	1.65	1.38	0.22	1.76	1.64	0.21	1.89
4	0.56	0.33	1.38	0.71	0.31	1.53	0.91	0.29	1.67	1.11	0.27	1.78	1.32	0.26	1.92
5	0.48	0.39	1.39	0.62	0.36	1.53	0.78	0.34	1.69	0.94	0.32	1.82	1.12	0.31	1.94
6	0.42	0.45	1.40	0.55	0.41	1.56	0.68	0.39	1.70	0.83	0.37	1.83	0.98	0.35	1.95
7	0.38	0.50	1.41	0.49	0.46	1.57	0.61	0.43	1.71	0.74	0.41	1.84	0.88	0.39	1.96
8	0.35	0.55	1.41	0.44	0.51	1.57	0.56	0.47	1.72	0.68	0.45	1.85	0.80	0.43	1.97
9	0.32	0.59	1.42	0.41	0.55	1.58	0.52	0.52	1.73	0.62	0.49	1.86	0.74	0.47	1.98
10	0.30	0.63	1.42	0.39	0.59	1.59	0.48	0.55	1.73	0.58	0.53	1.87	0.69	0.50	1.99
11	0.28	0.67	1.43	0.36	0.63	1.59	0.45	0.59	1.74	0.55	0.56	1.87	0.64	0.54	2.00
12	0.27	0.71	1.43	0.34	0.66	1.60	0.43	0.63	1.74	0.51	0.59	1.88	0.61	0.57	2.00
13	0.26	0.75	1.44	0.33	0.70	1.60	0.41	0.66	1.75	0.49	0.63	1.88	0.58	0.60	2.01
14	0.24	0.79	1.44	0.31	0.72	1.60	0.38	0.69	1.75	0.47	0.66	1.89	0.55	0.63	2.01
15	0.23	0.82	1.44	0.30	0.77	1.61	0.37	0.72	1.76	0.44	0.69	1.89	0.52	0.66	2.02
16	0.22	0.86	1.45	0.28	0.80	1.61	0.35	0.75	1.76	0.43	0.72	1.90	0.50	0.69	2.02
17	0.22	0.89	1.45	0.28	0.83	1.62	0.34	0.78	1.76	0.41	0.75	1.90	0.48	0.72	2.03
18	0.21	0.92	1.45	0.27	0.86	1.62	0.33	0.81	1.77	0.40	0.77	1.90	0.47	0.74	2.03
19	0.20	0.96	1.46	0.26	0.89	1.62	0.32	0.84	1.77	0.38	0.80	1.91	0.45	0.77	2.04
20	0.20	0.99	1.46	0.25	0.92	1.63	0.31	0.87	1.78	0.37	0.83	1.91	0.44	0.79	2.04

*Froude number greater than unity.

TABLE XIII-DESIGN FOR PERMISSIBLE TRACTIVE FORCE, CHANNEL A

q = 0.75 cfs/100 ft, n = 0.03

x	Tp = 0.100 lb/ft^2			Tp = 0.125 lb/ft^2			Tp = 0.150 lb/ft^2			Tp = 0.175 lb/ft^2			Tp = 0.200 lb/ft^2		
(ft)	S_o (%)	y (ft)	V (fps)	S_o (%)	y (ft)	V (fps)	S_o (%)	y (ft)	V (fps)	S_o (%)	y (ft)	V (fps)	S_o (%)	y (ft)	V (fps)
1	1.91	0.09	1.24	2.75	0.08	1.37	3.30	0.08	1.49	4.09*	0.07	1.60	4.92*	0.07	1.70
2	1.11	0.16	1.31	1.48	0.14	1.45	1.89	0.13	1.58	2.33	0.13	1.70	2.79	0.12	1.80
3	0.81	0.22	1.34	1.08	0.20	1.49	1.37	0.19	1.62	1.67	0.17	1.74	2.02	0.17	1.86
4	0.66	0.27	1.36	0.87	0.25	1.51	1.10	0.23	1.65	1.35	0.22	1.77	1.62	0.21	1.89
5	0.56	0.32	1.37	0.74	0.29	1.53	0.93	0.27	1.67	1.15	0.26	1.79	1.37	0.25	1.91
6	0.49	0.36	1.38	0.65	0.34	1.54	0.82	0.31	1.68	1.00	0.30	1.81	1.19	0.28	1.93
7	0.44	0.41	1.39	0.58	0.38	1.55	0.73	0.35	1.69	0.89	0.33	1.82	1.06	0.32	1.94
8	0.41	0.45	1.40	0.53	0.41	1.56	0.67	0.39	1.70	0.81	0.36	1.83	0.96	0.35	1.95
9	0.37	0.49	1.41	0.49	0.45	1.56	0.61	0.42	1.71	0.74	0.40	1.84	0.88	0.38	1.96
10	0.35	0.52	1.41	0.45	0.48	1.57	0.57	0.45	1.72	0.69	0.43	1.85	0.82	0.41	1.97
11	0.33	0.56	1.42	0.43	0.52	1.58	0.53	0.49	1.72	0.65	0.46	1.85	0.77	0.44	1.98
12	0.31	0.59	1.42	0.40	0.55	1.58	0.50	0.52	1.73	0.61	0.49	1.86	0.73	0.47	1.98
13	0.29	0.62	1.42	0.38	0.58	1.59	0.48	0.54	1.73	0.58	0.52	1.86	0.69	0.49	1.99
14	0.28	0.65	1.43	0.36	0.61	1.59	0.45	0.57	1.74	0.55	0.54	1.87	0.65	0.52	1.99
15	0.27	0.69	1.43	0.35	0.64	1.59	0.43	0.60	1.74	0.53	0.57	1.87	0.62	0.54	2.00
16	0.26	0.71	1.43	0.33	0.66	1.60	0.42	0.63	1.74	0.50	0.59	1.88	0.60	0.57	2.00
17	0.25	0.74	1.44	0.32	0.69	1.60	0.40	0.65	1.75	0.48	0.62	1.88	0.57	0.59	2.01
18	0.24	0.77	1.44	0.31	0.71	1.60	0.38	0.68	1.75	0.47	0.64	1.89	0.55	0.61	2.01
19	0.23	0.80	1.44	0.30	0.74	1.61	0.37	0.70	1.75	0.45	0.67	1.89	0.53	0.64	2.02
20	0.22	0.82	1.44	0.29	0.77	1.61	0.36	0.72	1.76	0.44	0.69	1.89	0.51	0.66	2.02

*Froude number greater than unity.

TABLE XIV-DESIGN FOR PERMISSIBLE TRACTIVE FORCE, CHANNEL A

q = 0.50 cfs/100 ft, n = 0.03

x	Tp = 0.100 lb/ft^2			Tp = 0.125 lb/ft^2			Tp = 0.150 lb/ft^2			Tp = 0.175 lb/ft^2			Tp = 0.200 lb/ft^2		
(ft)	S_o (%)	y (ft)	V (fps)	S_o (%)	y (ft)	V (fps)	S_o (%)	y (ft)	V (fps)	S_o (%)	y (ft)	V (fps)	S_o (%)	y (ft)	V (fps)
1	2.59	0.06	1.19	3.52*	0.06	1.32	4.55*	0.05	1.43	5.67*	0.05	1.53	6.85*	0.05	1.63
2	1.48	0.11	1.27	2.00	0.10	1.40	2.57	0.10	1.53	3.18	0.09	1.64	3.84*	0.09	1.74
3	1.08	0.16	1.31	1.45	0.14	1.45	1.85	0.13	1.58	2.29	0.12	1.70	2.75	0.12	1.80
4	0.86	0.20	1.33	1.16	0.18	1.48	1.48	0.17	1.61	1.82	0.16	1.73	2.19	0.15	1.84
5	0.73	0.24	1.35	0.97	0.22	1.50	1.24	0.20	1.63	1.53	0.19	1.75	1.83	0.18	1.87
6	0.64	0.27	1.36	0.85	0.25	1.51	1.08	0.23	1.65	1.33	0.22	1.77	1.59	0.21	1.89
7	0.57	0.30	1.37	0.76	0.28	1.52	0.96	0.26	1.66	1.18	0.25	1.79	1.39	0.23	1.91
8	0.52	0.33	1.38	0.69	0.31	1.53	0.87	0.29	1.67	1.07	0.27	1.80	1.28	0.26	1.92
9	0.48	0.36	1.38	0.63	0.34	1.54	0.80	0.31	1.68	0.98	0.30	1.81	1.17	0.28	1.93
10	0.44	0.39	1.39	0.59	0.36	1.55	0.74	0.34	1.69	0.91	0.32	1.82	1.08	0.31	1.94
11	0.41	0.42	1.39	0.55	0.39	1.55	0.69	0.36	1.70	0.85	0.34	1.83	1.01	0.33	1.95
12	0.39	0.45	1.40	0.52	0.41	1.56	0.65	0.39	1.70	0.80	0.37	1.83	0.95	0.35	1.95
13	0.37	0.47	1.40	0.49	0.44	1.56	0.61	0.41	1.71	0.75	0.39	1.84	0.89	0.37	1.96
14	0.35	0.50	1.41	0.46	0.46	1.57	0.58	0.43	1.71	0.71	0.41	1.84	0.85	0.39	1.96
15	0.33	0.52	1.41	0.44	0.48	1.57	0.56	0.45	1.72	0.68	0.43	1.85	0.81	0.41	1.97
16	0.32	0.55	1.41	0.42	0.51	1.57	0.53	0.47	1.72	0.65	0.45	1.85	0.77	0.43	1.97
17	0.31	0.57	1.42	0.41	0.53	1.58	0.51	0.50	1.72	0.62	0.47	1.86	0.74	0.45	1.98
18	0.30	0.59	1.42	0.39	0.55	1.58	0.49	0.52	1.73	0.60	0.49	1.86	0.71	0.47	1.98
19	0.29	0.61	1.42	0.38	0.57	1.58	0.47	0.53	1.73	0.58	0.51	1.86	0.69	0.48	1.99
20	0.28	0.63	1.42	0.36	0.59	1.59	0.46	0.55	1.73	0.56	0.52	1.87	0.66	0.50	1.99

*Froude number greater than unity.

TABLE XV-DESIGN FOR PERMISSIBLE TRACTIVE FORCE, CHANNEL B*

q = 1.00 cfs/100 ft, n = 0.03

x	Tp = 0.100 lb/ft^2			Tp = 0.125 lb/ft^2			Tp = 0.150 lb/ft^2			Tp = 0.175 lb/ft^2			Tp = 0.200 lb/ft^2		
(ft)	S_o (%)	y (ft)	V (fps)	S_o (%)	y (ft)	V (fps)	S_o (%)	y (ft)	V (fps)	S_o (%)	y (ft)	V (fps)	S_o (%)	y (ft)	V (fps)
1	1.20	0.16	1.29	1.59	0.14	1.43	1.97	0.13	1.36	2.44	0.13	1.68	2.90	0.12	1.79
2	0.73	0.27	1.34	0.95	0.25	1.43	1.18	0.23	1.63	1.43	0.22	1.75	1.68	0.21	1.87
3	0.55	0.36	1.36	0.71	0.33	1.52	0.88	0.31	1.65	1.05	0.29	1.78	1.26	0.28	1.90
4	0.46	0.44	1.38	0.58	0.41	1.53	0.72	0.38	1.67	0.87	0.36	1.80	1.02	0.34	1.92
5	0.39	0.51	1.39	0.50	0.47	1.54	0.62	0.44	1.69	0.73	0.42	1.81	0.88	0.40	1.94
6	0.35	0.58	1.40	0.45	0.54	1.55	0.55	0.50	1.70	0.66	0.48	1.83	0.77	0.46	1.95
7	0.32	0.64	1.40	0.40	0.59	1.56	0.50	0.56	1.71	0.59	0.53	1.84	0.70	0.51	1.96
8	0.29	0.70	1.41	0.37	0.65	1.57	0.46	0.61	1.71	0.54	0.58	1.85	0.64	0.55	1.97
9	0.27	0.75	1.41	0.35	0.70	1.58	0.42	0.66	1.72	0.51	0.63	1.85	0.60	0.60	1.98
10	0.26	0.80	1.42	0.32	0.75	1.58	0.40	0.70	1.73	0.47	0.67	1.86	0.55	0.64	1.98
11	0.24	0.85	1.43	0.31	0.79	1.59	0.37	0.75	1.73	0.44	0.71	1.87	0.52	0.68	1.99
12	0.23	0.90	1.43	0.29	0.84	1.59	0.35	0.79	1.74	0.42	0.75	1.87	0.49	0.72	2.00
13	0.22	0.94	1.43	0.28	0.88	1.60	0.34	0.83	1.74	0.40	0.79	1.88	0.47	0.76	2.00
14	0.21	0.98	1.44	0.26	0.92	1.60	0.32	0.87	1.75	0.38	0.83	1.88	0.45	0.80	2.01
15	0.20	1.02	1.44	0.25	0.96	1.61	0.31	0.91	1.75	0.37	0.86	1.89	0.43	0.83	2.01
16	0.19	1.07	1.45	0 24	0.99	1.61	0.30	0.94	1.76	0.35	0.90	1.89	0.41	0.86	2.02
17	0.19	1.10	1.45	0.24	1.03	1.61	0.29	0.98	1.76	0.34	0.93	1.90	0.40	0.90	2.02
18	0.18	1.14	1.45	0.23	1.07	1.62	0.28	1.01	1.76	0.33	0.97	1.90	0.38	0.93	2.03
19	0.18	1.18	1.46	0.22	1.10	1.62	0.27	1.05	1.77	0.32	1.00	1.90	0.37	0.96	2.03
20	0.17	1.21	1.46	0.21	1.14	1.62	0.26	1.08	1.77	0.31	1.03	1.91	0.36	0.99	2.03

* b = 4, z = 6

TABLE XVI-DESIGN FOR PERMISSIBLE TRACTIVE FORCE, CHANNEL B

q = 0.75 cfs/100 ft, n = 0.03

x (ft)	Tp = 0.100 lb/ft² S_o (%)	y (ft)	V (fps)	Tp = 0.125 lb/ft² S_o (%)	y (ft)	V (fps)	Tp = 0.150 lb/ft² S_o (%)	y (ft)	V (fps)	Tp = 0.175 lb/ft² S_o (%)	y (ft)	V (fps)	Tp = 0.200 lb/ft² S_o (%)	y (ft)	V (fps)
1	1.14	0.12	1.27	1.92	0.11	1.41	2.44	0.11	1.53	2.99	0.10	1.64	3.58*	0.09	1.74
2	0.86	0.21	1.32	1.13	0.20	1.47	1.43	0.18	1.60	1.74	0.17	1.72	2.07	0.16	1.83
3	0.64	0.29	1.35	0.84	0.27	1.50	1.05	0.25	1.63	1.28	0.24	1.76	1.52	0.22	1.87
4	0.53	0.36	1.36	0.68	0.33	1.52	0.85	0.31	1.65	1.04	0.29	1.78	1.23	0.28	1.90
5	0.45	0.42	1.37	0.59	0.39	1.53	0.73	0.36	1.67	0.88	0.34	1.80	1.05	0.33	1.92
6	0.40	0.48	1.38	0.52	0.44	1.54	0.64	0.41	1.68	0.78	0.39	1.81	0.93	0.38	1.93
7	0.36	0.53	1.39	0.47	0.49	1.55	0.58	0.46	1.69	0.71	0.44	1.82	0.83	0.42	1.94
8	0.33	0.58	1.40	0.43	0.54	1.55	0.53	0.51	1.70	0.64	0.48	1.83	0.76	0.46	1.95
9	0.31	0.62	1.40	0.40	0.58	1.56	0.49	0.55	1.70	0.59	0.52	1.84	0.70	0.49	1.96
10	0.29	0.67	1.41	0.37	0.62	1.57	0.46	0.58	1.71	0.55	0.56	1.84	0.65	0.53	1.96
11	0.27	0.71	1.41	0.35	0.66	1.57	0.43	0.62	1.72	0.52	0.59	1.85	0.61	0.57	1.97
12	0.26	0.75	1.41	0.33	0.70	1.58	0.41	0.66	1.72	0.49	0.63	1.85	0.58	0.60	1.98
13	0.25	0.79	1.42	0.31	0.73	1.58	0.39	0.69	1.73	0.47	0.66	1.86	0.55	0.63	1.98
14	0.24	0.82	1.42	0.30	0.77	1.58	0.37	0.73	1.73	0.45	0.69	1.86	0.52	0.66	1.99
15	0.23	0.86	1.43	0.29	0.80	1.59	0.36	0.76	1.73	0.43	0.72	1.87	0.50	0.69	1.99
16	0.22	0.90	1.43	0.28	0.84	1.59	0.34	0.79	1.74	0.41	0.75	1.87	0.48	0.72	2.00
17	0.21	0.93	1.43	0.27	0.87	1.60	0.33	0.82	1.74	0.39	0.78	1.88	0.46	0.75	2.00
18	0.20	0.96	1.44	0.26	0.90	1.60	0.32	0.85	1.75	0.38	0.81	1.88	0.45	0.78	2.00
19	0.20	0.99	1.44	0.25	0.93	1.60	0.31	0.82	1.75	0.37	0.84	1.88	0.43	0.81	2.01
20	0.19	1.02	1.44	0.24	0.96	1.61	0.30	0.91	1.75	0.36	0.86	1.89	0.42	0.83	2.01

*Froude number greater than unity.

TABLE XVII-DESIGN FOR PERMISSIBLE TRACTIVE FORCE, CHANNEL B

q = 0.50 cfs/100 ft, n = 0.03

	Tp = 0.100 lb/ft^2			Tp = 0.125 lb/ft^2			Tp = 0.150 lb/ft^2			Tp = 0.175 lb/ft^2			Tp = 0.200 lb/ft^2		
x (ft)	S_o (%)	y (ft)	V (fps)	S_o (%)	y (ft)	V (fps)	S_o (%)	y (ft)	V (fps)	S_o (%)	y (ft)	V (fps)	S_o (%)	y (ft)	V (fps)
1	1.91	0.09	1.23	2.58	0.08	1.35	3.18	0.08	1.48	4.13	0.07	1.59	4.90*	0.07	1.68
2	1.11	0.16	1.29	1.49	0.15	1.44	1.90	0.13	1.56	2.34	0.13	1.68	2.80	0.12	1.79
3	0.82	0.22	1.32	1.09	0.20	1.47	1.39	0.18	1.60	1.70	0.17	1.72	2.02	0.16	1.83
4	0.67	0.27	1.34	0.89	0.25	1.49	1.12	0.23	1.63	1.37	0.22	1.75	1.63	0.21	1.86
5	0.57	0.31	1.35	0.75	0.29	1.51	0.95	0.27	1.64	1.15	0.26	1.77	1.38	0.24	1.88
6	0.50	0.36	1.36	0.66	0.33	1.52	0.83	0.31	1.66	1.01	0.29	1.78	1.20	0.27	1.90
7	0.45	0.40	1.37	0.59	0.37	1.53	0.74	0.35	1.66	0.90	0.33	1.79	1.08	0.31	1.91
8	0.41	0.44	1.38	0.54	0.41	1.53	0.68	0.38	1.67	0.82	0.36	1.80	0.98	0.34	1.92
9	0.38	0.48	1.38	0.50	0.44	1.54	0.62	0.41	1.68	0.76	0.39	1.81	0.90	0.37	1.93
10	0.35	0.51	1.39	0.46	0.47	1.54	0.58	0.44	1.69	0.70	0.42	1.82	0.84	0.40	1.94
11	0.33	0.54	1.39	0.43	0.50	1.55	0.54	0.47	1.69	0.66	0.45	1.82	0.78	0.43	1.94
12	0.31	0.58	1.40	0.41	0.53	1.55	0.51	0.50	1.70	0.62	0.48	1.83	0.74	0.46	1.95
14	0.30	0.61	1.40	0.39	0.56	1.56	0.49	0.53	1.70	0.59	0.50	1.83	0.70	0.48	1.96
14	0.29	0.64	1.40	0.37	0.59	1.56	0.46	0.56	1.71	0.56	0.53	1.84	0.67	0.51	1.96
15	0.27	0.67	1.41	0.36	0.62	1.57	0.44	0.58	1.71	0.54	0.56	1.84	0.64	0.53	1.96
16	0.26	0.69	1.41	0.34	0.65	1.57	0.42	0.61	1.71	0.51	0.58	1.85	0.61	0.55	1.97
17	0.25	0.72	1.41	0.33	0.67	1.57	0.41	0.63	1.72	0.49	0.60	1.85	0.59	0.57	1.97
18	0.24	0.75	1.41	0.32	0.70	1.58	0.39	0.66	1.72	0.47	0.63	1.85	0.56	0.60	1.98
19	0.24	0.77	1.42	0.31	0.72	1.58	0.38	0.68	1.72	0.46	0.65	1.86	0.54	0.62	1.98
20	0.23	0.80	1.42	0.30	0.74	1.58	0.37	0.71	1.73	0.45	0.67	1.86	0.53	0.64	1.98

*Froude number greater than unity.

BIBLIOGRAPHY

1. *Agricultural Conservation Program Handbook for Missouri for 1961.* United States Department of Agriculture. Columbia, Missouri, August, 1960.
2. Beasley, R. P. *A New Method of Terracing.* University of Missouri Agricultural Experiment Station, Station Bulletin 699. Columbia, Missouri, April, 1958.
3. Beasley, R. P. "Proposed Terrace Spacing." Columbia, Missouri, 1959. (Personal correspondence).
4. Brahms, A. *Anfangsgrunde der Deich-und Wasserbaukunst.* Volume 1. Aurich, Germany, 1754 and 1757.
5. Chang, Y. L. "Laboratory Investigation of Flume Traction and Transportation." *Transactions of the American Society of Civil Engineers.* Vol. 104, 1939. Pp. 1246-1313.
6. Chow, Ven Te. *Open Channel Hydraulics.* New York: McGraw-Hill Book Company, Inc., 1959.
7. Clark, M. W. and J. C. Wooley. *Terracing for Erosion Control.* University of Missouri Agricultural Experiment Station, Station Bulletin 507. Columbia, Missouri, July, 1947.
8. Cowan, Woody M. "Estimating Hydraulic Roughness Coefficients." *Agricultural Engineering.* Vol. 37, July, 1956. Pp. 473-475.
9. Du Boys, M. P. "Le Rhone et les Riveres a Lit Affouillable." *Annals des Pontes et Chaussees.* Tome XVIII, 1879.
10. Du Buat, P. L. G. *Principles d' Hydraulique.* Paris, 1786.
11. Engineering Standards for Terraces. *Soil Conservation Service.* Milwaukee, Wisconsin, July 1, 1958.
12. Etcheverry, B. A. *Irrigation Practice and Engineering.* Volume 2. New York: McGraw-Hill Book Company, Inc., 1915.
13. Fortier, S. and F. C. Scobey. "Permissible Canal Velocities." *Transactions of the American Society of Civil Engineers.* Vol. 89, 1926. Pp. 940-984.
14. Hildebrand, F. B. *Introduction to Numerical Analysis.* New York: McGraw-Hill Book Company, Inc., 1956.
15. Kramer, Hans. "Sand Mixtures and Sand Movement in Fluvial Models." *Transactions of the American Society of Civil Engineers.* Vol. 100, 1935. Pp. 798-878.
16. Lane, E. W. "Design of Stable Channels." *Transactions of the American Society of Civil Engineers.* Vol. 120, 1955. Pp. 1237-1250.
17. Lane, E. W. "Progress Report on Studies on the Design of Stable Channels by the Bureau of Reclamation." *Proceedings of the American Society of Civil Engineers.* Vol. 79, Separate Number 280, September, 1953, Pp. 1-31.
18. McCool, D. K. "A Theoretical Approach to Terrace Channel Design." Unpublished Master's Thesis. The University of Missouri, Columbia, 1961.
19. Ramser, C. E. *Farm Terracing.* United States Department of Agriculture, Farmers' Bulletin No. 1669. Washington: Government Printing Office, 1931.

20. Ramser, C. E. "Runoff From Small Agricultural Areas." *Journal of Agricultural Research.* Vol. 34, 1927. Pp. 797-823.
21. Rouse, Hunter. Discussion of "Laboratory Investigations of Flume Traction and Transportation," by Y. L. Chang. *Transactions of the American Society of Civil Engineers.* Vol. 104, 1939. Pp. 1303-1308.
22. Schoklitsch, Armin. *Hydraulic Structures.* Volume 1. New York: American Society of Mechanical Engineers, 1937.
23. Smerdon, E. T. and R. P. Beasley. *The Tractive Force Theory Applied to Stability of Open Channels in Cohesive Soils.* University of Missouri Agricultural Experiment Station, Research Bulletin 715. Columbia, Missouri, October, 1959.
24. "Standards for Permissible Non-Eroding Velocities." Bureau of the Methodology of the Hydro-Energo Plan, *Gidrotekhnicheskoye Stroitel' stvo,* Obedinennoe Naucho—Tekhnicheskoe Izdatel' stvo. Moscow, Union of Soviet Socialist Republics, May, 1936.
25. Woodward, S. M. and C. J. Posey. *Hydraulics of Steady Flow in Open Channels.* Seventh Printing. New York: John Wiley and Sons, Inc., 1958.
26. Yarnell, D. L. *Rainfall Intensity—Frequency Data.* United States Department of Agriculture, Miscellaneous Publication No. 204. Washington: Government Printing Office, 1935.