Tractive Force Design of Vegetated Channels

Darrel M. Temple
ASSOC.
MEMBER
ASAE

ABSTRACT

A method is presented for applying tractive force concepts to the design of vegetated channels. The method is developed from previously published data on flow resistance and allowable velocities in grassed waterways. It is intended for use in its present form as a design tool, but also provides a framework in which to place refinements as the mechanics of this type of flow become more fully understood.

The protective value of vegetal channel lining is considered to be derived from two related, but distinct, interactions of the vegetation with the flow field. The first is the generation of turbulent eddies at a significant distance from the soil boundary resulting in an increase in flow resistance, and the second is a change in the structure of the turbulent eddies in immediate proximity to the boundary. The vegetation is therefore classified in terms of two indices believed to relate directly to these actions. Guidelines are provided for the selection of these indices according to type and quality of cover.

This approach eliminates the need for tabulating allowable velocities for each possible combination of channel slope, soil, and vegetal cover by considering the properties of the soil and those of the vegetation separately. An additional advantage is that the existing flow resistance curves are put in equational form as a single curve family.

INTRODUCTION

The interaction of the flow with the boundary of a vegetated open channel is only imperfectly understood. Adequate analytical expressions describing this interaction have not yet been developed. Most recent research in this area has been directed toward developing flow resistance models using artificial vegetal elements (Kouwen, 1970; Kouwen and Unny, 1973; Thompson and Roberson, 1976). Although these studies have provided valuable insight with respect to the mechanics of the flow, the resulting relations are not expressed in terms of parameters measurable in the field. Consequently, they have had little impact on design procedures.

The value of a vegetal channel lining for erosion protection is, however, widely recognized. Previous investigations, designed to evaluate the protective ability of vegetation, have established a relatively large data base from which semi-empirical design procedures may be developed. Properly devised and applied, these procedures serve as valuable design tools until adequate analytical solutions are developed. They must, however, be periodically re-examined and updated to properly reflect the current state of knowledge. This report presents an updating of vegetal channel design procedures through application of tractive force principles.

The primary advantage of the tractive force approach over the currently used allowable velocity approach is that, properly formulated, allowable tractive force is related only to the properties of the soil boundary, whereas allowable velocity is necessarily related not only to soil properties, but also to the vegetal and geometric properties of the channel. Use of tractive force, therefore, substantially simplifies the investigation and tabulation of "critical" or allowable conditions. In addition, data from laboratory soil tests or bare earth channels may be used to guide the design of vegetated channels in similar soils.

PROBLEM APPROACH

Application of tractive force concepts to vegetated channel conditions has been attempted previously without success. The reason for this is the improper selection of the tractive force parameters. Ree (1959), for example, plotted tractive force versus erosion rate and found the resulting curves to be functions of both the channel slope and the vegetation type and condition. He therefore concluded this approach offered no advantage over the use of average velocity as the primary design parameter. The tractive force parameter used, however, was the shear stress acting on the channel boundary averaged in time, computed for a wide channel by the relation:

$$\tau = \gamma DS \quad [1]$$

where

τ = the total boundary shear stress averaged in time,

γ = the unit weight of water,

D = the flow depth, and

S = the slope of the energy grade line.

There are two primary reasons why this parameter does not adequately describe conditions at the soil-water interface.

The first reason that total average shear stress is unsuitable as the primary stability parameter is that a part of this stress is transmitted to the soil through the plant root system. This part of the stress is that associated with fluid drag on the vegetal elements and would not be expected to influence channel stability, unless the stress is

Article was submitted for publication in May 1979; reviewed and approved for publication by the Soil and Water Division of ASAE in August 1979. Presented as ASAE Paper No. 79-2068.

Cooperative Research of the Science and Education Administration, U.S. Department of Agriculture, and the Oklahoma Agricultural Experiment Station.

The author is: DARREL M. TEMPLE, Research Hydraulic Engineer, Water Conservation Structures Laboratory, USDA-SEA, Stillwater, OK.

This article is reprinted from the TRANSACTIONS of the ASAE (Vol. 23, No. 4, pp. 884, 885, 886, 887, 889, 890, 1980)
Published by the American Society of Agricultural Engineers, St. Joseph, Michigan

sufficient to uproot the vegetation. Since the drag on the vegetal elements results from their interaction with the flow field, the stress associated with this drag is neither constant nor a constant proportion of the total stress. Effective application of tractive force concepts to vegetal conditions therefore requires that this component be considered separately from that transferred directly to the soil at the soil-water interface.

The separation of shear stress into two components is not a new idea. A similar concept has been used successfully to account for the influence of bed form roughness on sediment transport characteristics of alluvial channels since it was introduced by Einstein (1950). The form roughness condition resembles the vegetated channel problem since in both cases the flow resistance and computed boundary stress are increased by form drag and dissipation of the associated turbulent eddies at a significant distance from the boundary. Thompson and Roberson (1976) also used a similar force breakdown in their development of a flow resistance function using simulated vegetal elements. Although their analysis is not expressed in terms of parameters considered suitable for real channel design purposes, their conceptual division of stresses appears sound and illustrates the intimate relationship between relative flow resistance and stress at the soil boundary.

Based on the work of these authors and following the logic discussed by Taylor and Brooks (1962), equation [1] may be rewritten as:

$$\tau = \gamma D(S' + S'') \quad [2]$$

where

S' = the energy slope associated with time average shear at the soil boundary,

S'' = the energy slope associated with drag on the vegetal elements.

The relative magnitudes of the component energy slopes may be approximated by assuming the energy loss at the soil boundary in the vegetated channel is the same as would occur in a smoothly-graded bare earth channel formed of the same soil material and having the same depth and discharge. Under this assumption, repeated application of Manning's equation yields:

$$S' = (n_s/n)^2\, S \quad [3a]$$

$$S'' = (n_v/n)^2\, S \quad [3b]$$

in which

$$n = \sqrt{n_s^{\,2} + n_v^{\,2}} \quad [3c]$$

and

n_s = Manning's resistance coefficient associated with the soil only,

n_v = Manning's resistance coefficient associated with vegetal drag (bed form roughness, if any, is included in this parameter),

n = Manning's resistance coefficient for the channel.

The form resulting from the combination of equations [2] and [3] lends itself to further analysis in terms of the existing data base, since flow resistance has been studied extensively for both bare soil and vegetated channels. These studies indicate that although n_s is relatively constant for a given soil, n for a vegetated channel depends on both the vegetal characteristics and the flow conditions. This implies a functional relationship for n_v of the form:

$$n_v = n_v(C_I, R_v) \quad [3d]$$

where

C_I = an empirical parameter describing vegetal conditions in the flow field,

R_v = a parameter describing the flow conditions.

The second reason for the unsuitability of the total average shear stress as the primary stability parameter is the influence of the vegetation on the relationship between the time average stress and the instantaneous stress at a point on the soil boundary. Whereas the influence of the vegetation on the average shear is associated primarily with the generation of turbulent eddies, its influence on the deviation of the instantaneous shear from the average is associated with the breakup or dissipation of these eddies by the vegetal elements prior to their impact on the soil surface. This dissipating action would tend to increase channel stability by decreasing the maximum stress on the soil. Turbulent eddy dissipation is seen as being primarily a function of the vegetal density and uniformity and would be expected to reduce the maximum energy associated with any single turbulent eddy reaching the soil-water interface whether the turbulence originates at the soil boundary or is associated with vegetal drag. Dissipation of turbulence generated at the soil-water interface, however, will depend almost entirely on conditions in the immediate vicinity of the soil boundary. Dissipation of turbulence associated with vegetal drag will depend both on conditions near the boundary and on the more general properties of the vegetation.

Inclusion of these concepts in equation [2], with the bare earth channel again used as the reference condition, results in an anticipated functional form for the relation describing effective shear stress at the soil-water interface as:

$$\tau_e = \gamma D([1.0 - f(C_F)]\, S' + g(C_F, C_I)\, S'') \quad [4]$$

with

$$0.0 \leq f(C_F) \leq 1.0$$

$$0.0 \leq g(C_F, C_I)$$

where

τ_e = the effective shear stress at the soil-water interface,

C_F = an empirical parameter describing the potential of the vegetal cover to dissipate turbulent eddies in the immediate vicinity of the boundary,

$f(C_F)$ = a function describing the vegetal influence on turbulence generated at the soil boundary,

$g(C_F, C_I)$ = a function describing the vegetal influence on turbulence generated in the flow field by vegetal drag.

Since both $f(C_F)$ and $g(C_F, C_I)$ are positive functions, the signs associated with these functions in equation [4] are a direct result of using the bare channel condition as a reference. The turbulence generated at the soil boundary would also exist under reference conditions. Therefore, any damping action associated with this turbulence will tend to decrease the maximum effective tractive force on the soil. The turbulence associated with vegetal drag, however, is not present in the bare channel reference condition. Therefore, any portion of this turbulence reaching the boundary will tend to increase the maximum effective tractive force.

Equation [4] may be further simplified if consideration is limited to channels in which the vegetal cover is relatively uniform and dense. Under these conditions, $g(C_F, C_I)$ would be expected to tend to zero. That is, the turbulence generated by the vegetation at a significant distance from the soil-water interface would not significantly affect conditions at the soil boundary. With this limitation imposed, and C_F defined such that:

$$f(C_F) = C_F \quad \text{[5]}$$

Equation [4] may be rewritten as:

$$\tau_e = \gamma DS[(1.0 - C_F)(n_s/n)^2] \quad \text{[6]}$$

This form will be used throughout the remainder of this report.

The preceding discussion suggests that the properties of the vegetation may be resolved into two related, but distinct, parameters describing its potential interaction with the flow. The first (C_I) is closely related to flow resistance and is therefore substantially influenced by vegetal conditions at a significant distance from the soil boundary, whereas the second (C_F) is primarily a function of vegetal conditions in the immediate vicinity of the boundary. Although this classification is less than complete analytically, it is effective when applied to existing data and lends itself to expression in terms of variables normally available and familiar to the design engineer.

DEVELOPMENT OF DESIGN RELATIONS

Development of the conceptual model expressed by equation [6] into a usable design procedure requires its calibration using the available data base. The most extensive data available appears to be that compiled by Ree and summarized by the USDA, Soil Conservation Service (SCS) (1954) in terms of a permissible velocity design procedure. Therefore, this data summary was chosen as a base for model calibration.

Since the design relations developed are semi-empirical in nature, caution is advised when applying these relations outside of the original data base. The attempt is made to describe the most significant of these limitations as the relations are developed. For a more complete description of the data base and its tested limits of applicability, however, the reader is referred to Ree and Palmer (1949), USDA, SCS (1954), and Ree (1977).

Flow Resistance

The first step required in developing the conceptual model for practical application is identifying the flow resistance function given as equation [3d]. Ree and Palmer (1949) found that, for a given vegetal cover and condition, the flow resistance for the channels tested could be expressed as a function of the product of velocity and hydraulic radius. The vegetal covers tested were grouped into five categories based on the type of vegetation, quality of stand, and plant height, for use in the permissible velocity design procedure. A curve of Manning's n versus the product of average velocity and hydraulic radius was then fitted independently for each category.

The VR product chosen as a parameter by Ree and Palmer has the form of a Reynolds number with the fluid viscosity held constant. For convenience, this product may therefore be replaced by a dimensionless parameter defined by the relation:

$$R_v = (VR/\nu_{74}) \times 10^{-5} \quad \text{[7]}$$

in which ν_{74} is the kinematic viscosity of water at approximately 74 °F (23 °C). Since, under these conditions, the kinematic viscosity of water equals 10^{-5} ft²/s (9.3 × 10^{-7} m²/s), the numerical value of R_v is identically equal to the VR product in the English (fps) unit system. The advantage of defining the parameter in this fashion is that no change in definition is required when another unit system is used.*

In order to express Ree's data in terms of equation [3d], the SCS vegetal retardance curves were first fitted individually to various equational forms. The form that provided the best overall fit to the curves was:†

$$n_R = \exp(a_i[\ln(R_v)]^2 + b_i \ln(R_v) + c_i) \quad \text{[8a]}$$

where

n_R = computed flow resistance coefficient,
a_i, b_i, c_i = variable curve fitting coefficients.

This result suggests a curve family of the form:

$$n_R = \exp(C_I\,[a[\ln(R_v)]^2 + b\ln(R_v) + c] + d) \quad \text{[8b]}$$

where

C_I = the previously defined vegetal parameter.

The retardance curves were fitted to equation [8b] using a bi-level least squares curve fitting routine with an arbitrary value of 10.00 assigned to the vegetal resistance parameter, C_I, corresponding to the curve of maximum flow retardance. The resulting relation including its limits of applicability is given by:

$$n_R = \exp(0.01329\,C_I\,[\ln(R_v)]^2 - 0.09543\,C_I \ln(R_v) + 0.2971\,C_I - 4.16) \quad \text{[9]}$$

within the limits

$$n_R \leqslant (C_I + 1)/36.0$$
$$0.1 \leqslant R_v \leqslant 36.0$$
$$0.0 \leqslant C_I \leqslant 10.0$$

The maximum deviation of this relation from the SCS retardance curves is approximately 10 percent when C_I is as given in Table 1. The modified curves described by equation [9] are, therefore, well within the data scatter from which the original curves were derived.

*Temperature measurements included in the data published by Ree and Palmer (1949) indicate values only slightly below the 74 °F figure. Further analysis of this data is planned which will determine whether or not the actual viscosity should replace ν_{74} in equation [4].

†The notational form, y = exp(x), implies x = ln(y).

TABLE 1.* CLASSIFICATION OF VEGETAL COVERS AS TO DEGREE OF RETARDANCE

Note: Covers classified have been tested in experimental channels. Covers were green and generally uniform.

Retardance curve index, C_I	Retardance class	Cover	Condition
10.0	A	Weeping lovegrass	Excellent stand, tall, (average 30 in.)
		Yellow bluestem Ischaemum	Excellent stand, tall, (average 36 in.)
7.643	B	Kudzu	Very dense growth, uncut
		Bermudagrass	Good stand, tall, (average 12 in.)
		Native grass mixture (little bluestem, blue grama, and other long and short midwest grasses)	Good stand, unmowed
		Weeping lovegrass	Good stand, tall, (average 24 in.)
		Lespedeza sericea	Good stand, not woody, tall (average 19 in.)
		Alfalfa	Good stand, uncut, (average 11 in.)
		Weeping lovegrass	Good stand, mowed, (average 13 in.)
		Kudzu	Dense growth, uncut
		Blue grama	Good stand, uncut, (average 13 in.)
5.601	C	Crabgrass	Fair stand, uncut (10 to 48 in.)
		Bermudagrass	Good stand, mowed (average 6 in.)
		Common lespedeza	Good stand, uncut (average 11 in.)
		Grass-legume mixture—summer (orchard grass, redtop, Italian ryegrass, and common lespedeza)	Good stand, uncut (6 to 8 in.)
		Centipedegrass	Very dense cover (average 6 in.)
		Kentucky bluegrass	Good stand, headed (6 to 12 in.)
4.436	D	Bermudagrass	Good stand, cut to 2.5-in. height
		Common lespedeza	Excellent stand, uncut (average 4.5 in.)
		Buffalograss	Good stand, uncut (3 to 6 in.)
		Grass-legume mixture—fall, spring (orchard grass, redtop, Italian ryegrass, and common lespedeza)	Good stand, uncut (4 to 5 in.)
		Lespedeza sericea	After cutting to 2-in. height. Very good stand before cutting.
2.876	E	Bermudagrass	Good stand, cut to 1.5 in. height
		Bermudagrass	Burned stubble.

*Reproduced from USDA, SCS (1954) with a column added for curve index values.

In the context of equation [9], C_I functions as a curve index describing the location of the retardance curve within the curve family, according to the potential of the vegetation to interact with the flow field. A C_I value of zero should, therefore, represent the condition of no vegetal retardance in which the computed flow resistance is equal to flow resistance of the soil. Making this substitution into equation [9] yields a reference soil resistance value, n_s, of 0.0156. This value falls within the range observed by Ree and Palmer (1949) for a smoothly-graded bare earth channel. Substituting this value into equation [3c] and rearranging yields the relation for vegetal retardance as:

$$n_v = \sqrt{n_R^2 - (0.0156)^2} \quad \text{[10a]}$$

and, for the total flow resistance:

$$n = \sqrt{n_R^2 - (0.0156)^2 + n_s^2} \quad \text{[10b]}$$

where the variables are as previously defined. Since the present data base for vegetated channels includes only relatively fine-grained soils ($n_s \simeq 0.0156$), present application will usually be limited to conditions for which equation [10b] may be reduced to:

$$n = n_R \quad \text{[10c]}$$

This is not considered a major restriction in terms of application, however, since these are the soils most often suited to protection by vegetal lining.

Given equations [9] and [10], determination of flow resistance for a vegetated channel becomes a matter of rating the vegetation in terms of its potential interaction with the flow using Table 1 as a guide. The rating scale of 0 (bare channel) to 10 (maximum identified retardance potential) provides a convenient means of evaluation. It should be recognized, however, that the use of these relations in their present form implies dense uniform vegetation established on a smoothly-graded soil boundary. Therefore, curve index values approaching zero may not be realistic for field channels. Also, conditions may exist for which the curve index exceeds the presently defined upper limit of 10.

Soil Protection Parameter

The remaining unknown in equation [6] is the parameter C_F, describing the potential of the vegetal cover to dissipate turbulent eddies before they impact the soil boundary. For a dense uniform stand, this cover factor may also be evaluated using the same data base, if an estimate can be made of the allowable shear stress for the soil materials represented. Since the data reported by Ree and Palmer (1949) for bare earth channels are indeterminant with respect to allowable velocity and/or shear stress, the permissible velocity tabulation by soil type, published by Fortier and Scobey (1926), is used for this purpose.

The recommendations of Fortier and Scobey are based on answers to a questionnaire sent to a number of practicing engineers and are presented as applicable to water flowing at a depth of 3 ft or less in a straight channel. No other channel dimensions are given. To translate these recommendations into the tractive force format, the geometry of a reference channel, which will represent the

TABLE 2. ALLOWABLE EFFECTIVE TRACTIVE FORCE COMPUTED FROM PERMISSIBLE VELOCITY

Original material excavated	Permissible velocity for clear water (After Fortier and Scobey, 1926)	Allowable effective tractive force	
	ft/s	lb/ft²	Pa
Sandy loam (non-colloidal)	1.75	0.0167	0.79
Silt loam (non-colloidal)	2.00	0.0218	1.04
Alluvial silts (non-colloidal)	2.00	0.0218	1.04
Ordinary firm loam	2.50	0.0341	1.63

data base as closely as possible, must be assumed. The geometry assumed for this purpose is that of a wide channel ($R \simeq D$) flowing at a depth of 0.61 m (2.0 ft). Table 2 reproduces a portion of Fortier and Scobey's recommendations along with the corresponding effective tractive force values computed using this channel geometry. The effective tractive force values are obtained using Manning's equation and equation [6] with C_F set equal to zero‡ and n_s taken to be 0.0156.

The SCS (1954) summary of Ree's data specifies the soil only as "easily eroded" or "erosion resistant". In a previous publication, however, Ree (1952) compared allowable velocities in similar bermudagrass-lined channels on "clay loam" and "sandy loam". The allowable velocities specified were 8.0 and 5.0 ft/s respectively. Based on a comparison of these values with those in the data summary (Table 3), it is concluded that Ree's "erosion resistant" soil was probably a clay loam comparable with Fortier and Scobey's "ordinary firm loam" and his "easily eroded" soil was probably slightly more erosion resistant than a "sandy loam" soil.

The C_F values listed in Table 3 were obtained by assuming the same reference channel as before ($R \simeq D = 2.0$ ft $= 0.61$ m) but vegetated such that the curve index, C_I, equaled 5.601. Equations [6] and [9] were solved for C_F using the allowable effective tractive force values given in Table 2 for "ordinary firm loam" and the permissible velocities listed in Table 3 for "erosion resistant" soils.

The overall comparability of the results of the tractive force approach to the SCS permissible velocities is illustrated in Fig. 1. This figure was constructed by retaining the assumption of hydraulic radius equal to depth, and allowing depth to vary while holding the computed effective tractive force equal to the allowable tractive force for the soil specified. The curves shown are for a bermudagrass channel ($C_F = 0.90$) with C_I equal to 5.6. The location of the computed velocity curves for "sandy loam" and "silt loam" with respect to the permissible velocity recommendations for "easily eroded soils" tends to support the conclusions reached previously with respect to soil type.

The wide channel restriction which has been used for development up to this point may be dropped by considering the maximum effective shear stress occurring on the channel perimeter to be the significant parameter. Lane (1955) investigated shear stress distribution in trapezoidal channels using a membrane analogy and expressed his results in terms of the ratio of the maximum tractive force in the trapezoidal channel to the tractive force in a wide channel with the same depth and slope. Curves were presented expressing this ratio as a function of the width to depth ratio and side slope of the

‡Use of equation [6] in this fashion is slightly conservative since all of the stress associated with form roughness is neglected ($g(C_F, C_I) = 0$). This simplification is considered justified, however, based on the previously cited work with respect to form roughness effects on sediment transport.

TABLE 3.* EROSION PROTECTION POTENTIAL OF VEGETATION†
The values apply to average, uniform stands of each type of cover

Cover	Cover factor, C_F	Slope range‡, percent	Permissible velocity: Erosion resistant soils ($\tau_a \simeq 0.034$ lb/ft²) ft/s	Permissible velocity: Easily eroded soils ($\tau_a \simeq 0.020$ lb/ft²) ft/s
Bermudagrass	0.9	0-5	8	6
		5-10	7	5
		over 10	6	4
Buffalograss, Kentucky bluegrass, Smooth brome, Blue grama	0.87	0-5	7	5
		5-10	6	4
		over 10	5	3
Grass mixture	0.75	0-5‡	5	4
		5-10	4	3
Lespedeza sericea, Weeping lovegrass, Yellow bluestem, Kudzu, Alfalfa, Crabgrass	0.5	0-5§	3.5	2.5
Common lespedeza‖, Sudangrass‖	0.5	0-5#	3.5	2.5

*Reproduced from USDA, SCS (1954) with C_F and τ_a values added. Footnotes are as they appear on the original.
†Use velocities exceeding 5 ft/s only where good covers and proper maintenance can be obtained.
‡Do not use on slopes steeper than 10 percent except for side slopes in a combination channel.
§Do not use on slopes steeper than 5 percent except for side slopes in a combination channel.
‖Annuals—used on mild slopes or as temporary protection until permanent covers are established.
#Use on slopes steeper than 5 percent is not recommended.

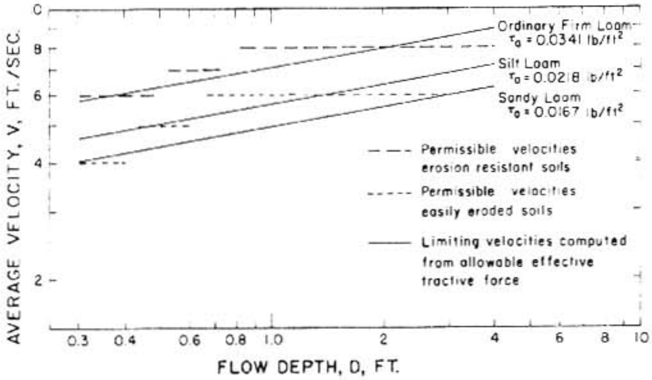

FIG. 1 Comparison of allowable tractive force to SCS's permissible velocities for a wide channel (C_I = 5.6, C_F = 0.9).

trapezoidal channel. Using this form, the relation for maximum effective tractive force becomes:

$$\tau_{e_m} = K\tau_e \qquad [11]$$

where

τ_{e_m} = the maximum effective tractive force,
K = Lane's correction coefficient,
τ_e = the effective tractive force computed by equation [6].

Lane (1955) found that for channels normally used in design, however, the value of K tended rapidly to its maximum value of 1.0. Therefore, the correction for shear on the channel bed is significant only in channels having small width-to-depth ratios. Given the potential of a vegetated channel for unraveling once erosion begins, conservative use of this correction is suggested in all cases.

APPLICATION

The relations developed to describe the vegetal effect on shear stress at the soil-water interface combined with Manning's flow equation and relations describing channel geometry are sufficient for tractive force design of vegetated channels. The relations applicable to trapezoidal channels constructed in fine-grained soil are summarized in Table 4 along with the appropriate constants discussed in the previous section. Solution of these relations proceeds in the same fashion as would be used for the conventional tractive force design problem except that Manning's resistance coefficient is now a function of flow conditions as well as boundary conditions. Use of a programmable calculator or computer for iterative solution of the relations is, therefore, desirable.

A program written in conversational basic for the IBM 370 computer was developed using the relations presented in Table 4. This program has the capability for solving the relations under four different sets of constraints. For Case A, the flow depth and effective tractive force are computed given vegetal conditions, channel geometry, and volumetric discharge. For Case B, the volumetric discharge and effective tractive force are computed given the vegetal conditions and the channel geometry including depth of flow. These two cases are therefore primarily useful in checking given channel conditions against allowable conditions. Solution of the equations for these cases is straightforward and iterative only in the determination of flow resistance.

Cases C and D are more directly design oriented since the computed effective tractive force for the resulting channel is equal to a predetermined allowable value. Case C computes flow depth and channel slope corresponding to the desired tractive force given the vegetal conditions and remaining geometric parameters. Solution for this case is also straightforward. Case D computes channel width and depth given the volumetric discharge, vegetal conditions, channel slope, and bank slope. To accomplish this, the channel width corresponding to minimum excavation is first approximated using the optimizing relation given in Table 4. The effective tractive force corresponding to this geometry is then computed as for Case A and compared to the given allowable value. The channel is then widened incrementally until the computed effective tractive force is less than or equal to the allowable. Although this approach would not be satisfactory for hand calculation, computer convergence of the relations is fairly rapid.

Use of this method of design is best illustrated through an example. For this purpose, assume a channel with a capacity of 50.0 ft³/s (1.416 m³/s) is to be constructed in a silt loam soil. Further assume that a bank slope of 1:4 and a bed slope of 2.0 percent are required. Also assume the vegetation is to be a good stand of a grass-legume mixture with the maximum flow anticipated during the summer when the grass is not in the dormant state.

Solution of this problem using the computer program (showing both input and output) is presented in Fig. 2.

TABLE 4. SUMMARY OF DESIGN RELATIONS FOR TRAPEZOIDAL VEGETATED CHANNELS IN FINE-GRAINED SOILS

Hydraulic relations:	Geometric relations:	Optimizing relation:*
$V = (a_u/n)\, R^{2/3}\, S^{1/2}$	$A = D(B + ZD)$	$P = 4D\sqrt{Z^2 + 1.0} - 2ZD$
$n = \exp(C_I\,[a[\ln(R_v)]^2 + b\ln(R_v) + c] + d)$	$P = B + 2D\sqrt{Z^2 + 1.0}$	
$R_v = (VR/\nu_{74}) \times 10^{-5}$	$R = A/P$	
$\tau_e = \gamma DS(1.0 - C_F)(n_s/n)^2$		
$Q = VA$		

Constants:

a_u = 1.4859 in the English unit system; 1.0 in the SI unit system

a = 0.01329, b = − 0.09543, c = 0.2971, d = − 4.16

$\nu_{74} = 10^{-5}$ ft²/s (9.3 × 10^{-7} m²/s)
γ = 62.4 lb/ft³ (9800 N/m³)
n_s = 0.0156

See Fig. 2 for definition of variables not defined in text.
*Optimizing relation serves as a point of beginning for computations when neither channel width nor depth is specified (see Case D, Fig. 2).

```
TRACTIVE FORCE DESIGN OF VEGETATED CHANNELS

CASES FOR WHICH SOLUTIONS ARE PROGRAMMED

   CASE             GIVEN              COMPUTE
    A           CI,CF,Z,S,B,Q           D,N,T
    B           CI,CF,Z,S,B,D           Q,N,T
    C           CI,CF,Z,T,B,Q           D,N,S
    D           CI,CF,Z,S,T,Q           D,N,B

FOR WHICH CASE DO YOU WISH TO MAKE COMPUTATIONS?
(FOR A LIST OF VARIABLE DEFINITIONS, ENTER 'DEF')
?
def

      .                                      .
        . - - - - - - - - - - - - - - - - . X
        / .                             .   /
      1 /   .                         .     / D
        X-----.                     .       /
           Z    . . . . . . . . . .         X
                X------- B -------X

 CI = CHANNEL RESISTANCE CURVE INDEX
 CF = CHANNEL BED COVER FACTOR
  Z = BANK SLOPE
  S = BED  SLOPE
  B = BOTTOM WIDTH
  D = FLOW DEPTH
  Q = VOLUMETRIC DISCHARGE
  N = MANNING'S RESISTANCE COEFFICIENT
  T = 'EFFECTIVE' SOIL SHEAR STRESS

FOR WHICH CASE DO YOU WISH TO MAKE COMPUTATIONS?
(FOR A LIST OF VARIABLE DEFINITIONS, ENTER 'DEF')
?
d

IN WHICH UNIT SYSTEM DO YOU WISH TO WORK?
(ENTER 'ENGLISH' OR 'METRIC')
?
english

ENTER CI,CF,Z, AND ESTIMATED VELOCITY V
?
5.6,0.75,4.0,4.0

ENTER S,T,Q
?
0.02,0.0218,50.


                       OUTPUT

  CURVE   COVER    MANNING  AVERAGE  VOLUMETRIC  EFFECTIVE
  INDEX   FACTOR   COEFFIC. VELOCITY DISCHARGE   SOIL SHEAR
                            FT./SEC. CU.FT./SEC  LBS./SQ.FT
   5.600    0.750    0.056    3.027    50.000      0.02096

  BOTTOM   FLOW     SIDE    X-SECT.   HYDRAULIC     BED
  WIDTH    DEPTH   SLOPE     AREA      RADIUS      SLOPE
   FT.      FT.             SQ.FT.      FT.
  15.315    0.879    4.000   16.545    0.733       0.02000
```

FIG. 2 Computer solution to example design problem.

For input to the program, the curve index and cover factor describing the vegetation, and the allowable effective tractive force describing the soil must be determined in addition to those parameters already specified numerically. The curve index corresponding to the described vegetation is determined from Table 1 to be approximately 5.6. The cover factor for a grass mixture is 0.75 (Table 3), and the allowable tractive force for a silt loam soil is 0.0218 lb/ft² (1.04 Pa) (Table 2). Use of these values in the design procedure results in a channel with a minimum bed width of 15 ft (4.6 m) and a flow depth of 0.88 ft (0.27 m).

Although the values for the curve index, allowable tractive force, and the cover factor for the example were taken directly from the tables, it should be emphasized that Tables 1, 2, and 3 are intended as guides to determining these values in terms of continuous scales rather than as a tabulation of discrete and exact points. For example, a decrease in grass height should be reflected by a decrease in C_I, and a decrease in the density of the stand should be reflected by a decrease in both C_I and C_F. If a knowledge of local conditions indicates a decrease or increase in allowable effective tractive force, the appropriate adjustment should be made. The values used in a specific design situation remain a judgment of the design engineer with the tables forming the best available guide to their selection. Experience, an understanding of flow behavior, and a knowledge of local conditions are still necessary ingredients to a successful design.

SUMMARY

The tractive force design procedure for vegetated channels presented in this report allows the properties of the soil and those of the vegetation to be considered separately. Tractive force values are referenced to a smoothly-graded bare earth channel allowing the same criteria to be used in designing vegetated and non-vegetated channels. The procedure has the additional advantage of being directly adaptable to programmed calculation on the calculator or computer allowing optimization to be incorporated at little additional expense.

Since the procedure is semi-empirical and calibrated on existing data, refinements and/or modifications are to be expected as the data base is enlarged and understanding of the flow phenomena improved. The author believes, however, that the tractive force approach as applied in the presented design procedure is a significant improvement over the permissible velocity procedures currently in use.

References

1 Einstein, H. A. 1950. The bed load function for sediment transport in open channel flows. USDA Tech. Bull. 1026.

2 Fortier, S. and F. C. Scobey. 1926. Permissible canal velocities. Trans. ASCE 89:940-956.

3 Kouwen, N. 1970. Flow retardance in vegetated open channels. Ph.D. Thesis, University of Waterloo.

4 Kouwen, N. and T. Unny. 1973. Flexible roughness in open channels. J. Hydr. Div., ASCE 99(HY5):713-728.

5 Lane, E. W. 1955. Design of stable channels. Trans. ASCE 120:1234-1260.

6 Ree, W. O. 1952. The use of grass in waterways. Proceedings, Sixth International Grassland Congress, State College, PA, p. 991-996.

7 Ree, W. O. 1959. Permissible velocities in vegetation lined conservation channels. Compilation Manual of Paper Prepared for the SCS-ARS Sedimentation Workshop, Oxford, MS, p. 7.1-7.9.

8 Ree, W. O. 1977. Friction factors for vegetated waterways of small slope. USDA, ARS-S-151, 56 p.

9 Ree, W. O. and V. J. Palmer. 1949. Flow of water in channels protected by vegetative linings. USDA Tech. Bull. 967.

10 Taylor, R. H., Jr. and N. H. Brooks. 1962. Discussion of 'Resistance to flow in alluvial channels' by D. B. Simons and E. V. Richardson. Trans. ASCE 127, Part I:982-992.

11 Thompson, G. T. and J. A. Roberson. 1976. A theory of flow resistance for vegetated channels. TRANSACTIONS of the ASAE 19(2):288-293.

12 USDA, Soil Cons. Service. 1947 (Revised 1954). Handbook of channel design for soil and water conservation. SCS-TP-61, 34 p.