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**Natural
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Conservation
Service**

**Part 654 Stream Restoration Design
National Engineering Handbook**

Chapter 8 Threshold Channel Design

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Cover photo: Threshold channels have erosion-resistant boundaries.

Advisory Note

Techniques and approaches contained in this handbook are not all-inclusive, nor universally applicable. Designing stream restorations requires appropriate training and experience, especially to identify conditions where various approaches, tools, and techniques are most applicable, as well as their limitations for design. Note also that product names are included only to show type and availability and do not constitute endorsement for their specific use.

Chapter 8 Threshold Channel Design

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654.0800 Purpose

Threshold channel design techniques are used for rigid boundary systems. In a threshold channel, movement of the channel boundary is minimal or nonexistent for stresses at or below the design flow condition. Therefore, the design approach for a threshold channel is to select a channel configuration where the stress applied during design conditions is below the allowable stress for the channel boundary. Many sources and techniques for designing stable threshold channels are available to the designer. This chapter provides an overview and description of some of the most common threshold channel design techniques. Examples have been provided to illustrate the methods.

654.0801 Introduction

A stable threshold channel has essentially rigid boundaries. The streambed is composed of very coarse material or erosion-resistant bedrock, clay soil, or grass lining. Streams where the boundary materials are remnants of processes no longer active in the stream system may be threshold streams. Examples are streambeds formed by high runoff during the recession of glaciers or dam breaks, streams armored due to degradation, and constructed channels where channel movement is unacceptable for the design flow.

A threshold channel is a channel in which movement of the channel boundary material is negligible during the design flow. The term threshold is used because the applied forces from the flow are below the threshold for movement of the boundary material. Therefore, the channel is assumed to be stable if the design stress is below the critical or recommended stress for the channel boundary. Design issues include assessing the limiting force and estimating the applied force. A requirement for a channel to be considered a threshold channel is that the sediment transport capacity must greatly exceed the inflowing sediment load so that there is no significant exchange of material between the sediment carried by the stream and the bed. Noncohesive material forming the channel boundary must be larger than what the normal range of flows can transport. For boundaries of cohesive materials, minor amounts of detached material can be transported through the system.

Threshold channels, therefore, transport no significant bed-material load. Fine sediment may pass through threshold streams as throughput. In general, this throughput sediment should not be considered part of the stream boundary for stability design purposes, even if there are intermittent small sediment deposits on the streambed at low flow.

An additional requirement for threshold channel design is to maintain a minimum velocity that is sufficient to transport the sediment load through the project reach. This sediment may consist of clays, silts, and fine sands. This is necessary to prevent aggradation in the threshold channel.

Threshold channels differ from movable bed or alluvial channels which show interaction between the incoming sediment load, flow, and channel boundary. In an alluvial channel, the bed and banks are formed from material that is transported by the stream under present flow conditions. The incoming sediment load and bed and bank material of an alluvial channel interact and exchange under design or normal flow conditions. Essentially, the configuration of a threshold channel is fixed under design conditions. An alluvial channel is free to change its shape, pattern, and planform in response to short- or long-term variations in flow and sediment. The design of alluvial channels is addressed in detail in NEH654.09.

Approaches that fall into four general categories for the design of threshold channels are addressed in this chapter. These approaches are the permissible velocity approach, allowable shear stress approach, and allowable tractive power approach. The grass-lined channel design approach, which is a specific case of either the permissible velocity or allowable shear stress approach, is also described. Table 8–1 provides general guidance for selecting the most appropriate design technique. This is a general guide, and there are certainly exceptions. For example, the allowable velocity technique, being the most historical, has been applied more broadly than indicated in table 8–1. Where there is uncertainty regarding the appropriate technique, it is recommended that the designer use several of the most appropriate techniques and look for agreement on critical design elements.

654.0802 Design discharges

Threshold channel design methods are appropriate where sediment inflow is negligible and the proposed channel boundary is to be immobile, even at high flows. Threshold channels do not have the freedom to adjust their geometry under normal flow conditions. Therefore, channel-forming discharge is not necessarily a critical factor in determining channel dimensions in a threshold channel. Design flows are traditionally based, at least in part, on programs and policy decisions.

As described in NEH654.07, the classification of a stream as alluvial or threshold may not be clear. One reach of the stream may be alluvial, while another may have the characteristics of a threshold channel. A threshold stream reach can be changed to an alluvial reach by flattening the slope to induce aggradation or increasing the slope so that the boundary material becomes mobile. At flows larger than the design flow or during extreme events, threshold channels may develop a movable boundary. It is important to evaluate channels through their entire flow range to determine how they will react to natural inflow conditions.

Design of a stream project may involve a hybrid approach. For example, project goals may require that the planform is rigid, while the cross section can vary. In this situation, a design approach might be to

Table 8–1 General guidance for selecting the most appropriate channel design technique

Technique	Significant sediment load and movable channel boundaries	Boundary material smaller than sand size	Boundary material larger than sand size	Boundary material does not act as discrete particles	No baseflow in channel. Climate can support permanent vegetation
Allowable velocity		X			
Allowable shear stress			X		
Tractive power				X	
Grass lined/tractive stress					X
Alluvial channel design techniques	X				

stabilize the grade and toe of a stream in place, and allow the upper bank to adjust naturally. Threshold channel design approaches, such as the use of riprap (NEH654.14), are also used to size stream features such as toe protection, riffles, stream barbs, and deflector dikes.

654.0803 Allowable velocity method

The allowable or permissible velocity approach is typically used with channels that are lined with grass, sand, or earth. Limiting forces for soil bioengineering and manufactured protective linings can also be expressed as permissible velocities.

To design a threshold channel using the allowable velocity method, average channel velocity is calculated for the proposed channel and compared to published allowable velocities for the boundary material. The average channel velocity in the design channel can be determined using a normal depth equation or a computer backwater model. Increased velocities at bends can be accounted for, using applicable charts and equations. Allowable velocities have been determined for a large variety of boundary materials and are provided in many texts and manuals. These tables have primarily been applied to the design of irrigation and drainage canals and were developed from data in relatively straight, uniform channels with depths less than 3 feet. It is common practice to apply allowable velocity data in meandering, nonuniform channels with depths greater than 3 feet, but such application should be done with caution. Allowable velocities can be increased or decreased to account for such irregularities as meandering alignments and increased sediment concentrations, using applicable charts. Allowable velocities are somewhat less than critical velocities so that a factor of safety is included in the values presented.

(a) Calculate average velocity

The first step in applying the allowable velocity design approach is to calculate the average velocity of the existing or proposed channel. Computing the average channel velocity requires a design discharge, cross section, planform alignment, average energy slope, and flow resistance data. If the design channel is a compound channel, it may be necessary to divide the channel into panels and calculate velocities for each panel. In channels with bends, the velocity on the outside of the bend may be significantly higher than the average velocity. Velocity can be calculated using normal depth assumptions or by a more rigorous backwater analysis if a gradually varied flow assumption is more appropriate.

A normal depth calculation is easier than a backwater analysis and can be accomplished using a flow resistance equation such as Manning's. The normal depth assumption is applicable for uniform flow conditions where energy slope, cross-sectional shape, and roughness are relatively constant in the applicable reach. In a natural channel, with a nonuniform cross section, reliability of the normal depth calculation is directly related to the reliability of the input data. Sound engineering judgment is required in the selection of a representative cross section. The cross section should be located in a uniform reach where flow is essentially parallel to the bank line with no reverse flow or eddies. This typically occurs at a crossing or riffle. Determination of the average energy slope can be difficult. If the channel cross section and roughness are relatively uniform, water surface slope can be used. Thalweg slopes and low-flow water surface slopes may not be representative of the energy slope at design flows. Slope estimates should be made over a significant length of the stream (a meander wavelength or 20 channel widths).

A computer program such as the U.S. Army Corps of Engineers (USACE) HEC–RAS can be used to perform these velocity calculations. Such programs allow the designer to account for nonuniform sections and for backwater conditions that may occur behind a bridge or at a constriction. The calculation of hydraulic parameters for both existing and proposed channels is critically important to design. A more complete treatment of the subject is provided in NEH654.06.

Minimum radius of curvature

Caution is recommended in applying this approach on channels with sharp bends. Section 16 of the National Engineering Handbook (U.S. Department of Agriculture (USDA) Soil Conservation Service (SCS) 1971) provides guidance for minimum radius of curvature for drainage ditches with very flat topography (slopes less than 0.00114). Table 8–2 provides guidance for channels in stable soil without bank protection. Conditions outside the range of table 8–2 and in erodible soils require use of the more detailed analysis provided in this chapter. The curved channel may require bank protection.

Maximum velocity in bends

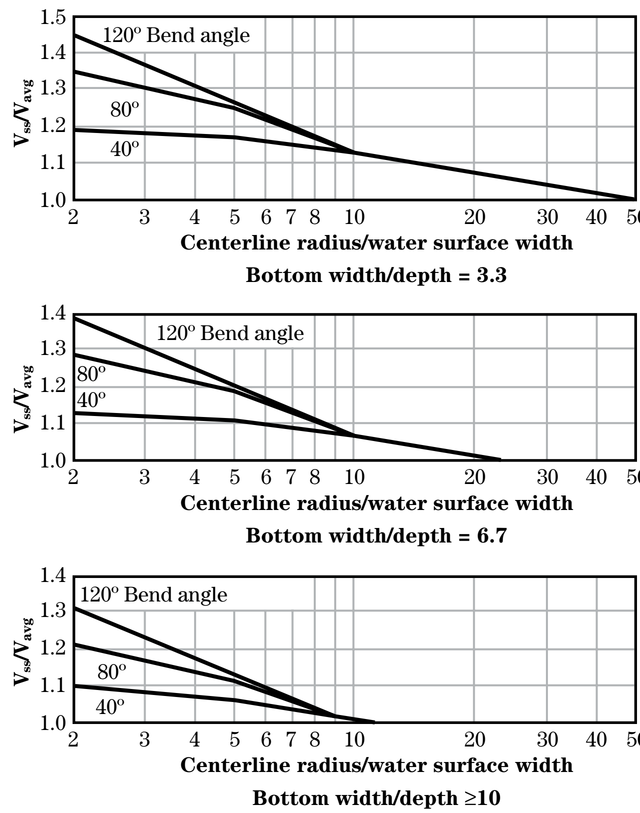
Adjustments to the calculated average channel velocity that account for flow concentration around bends is provided as part of the USACE riprap design method (USACE 1991b.) The method is based on a large body of laboratory data and has been compared to available prototype data (Maynord 1988). The method is applicable to side slopes of 1V:1.5H or flatter. The method calculates a characteristic velocity for side slopes,

Table 8–2 Suggested minimum radius of curvature in stable soils without bank protection

Type of ditch	Slope	Minimum radius of curvature (ft)	Minimum radius of curvature (m)	Approximate degree of curve (degrees)
Small ditches with maximum top width 15 ft (4.6 m)	<0.00057	300	90	19
	0.00057 to 0.00114	400	120	14
Medium-sized ditches with top width 15 to 35 ft (4.6–10.7 m)	<0.00057	500	150	11
	0.00057 to 0.00114	600	180	10
Large ditches with top width >35 ft (10.7 m)	<0.00057	600	180	10
	0.00057 to 0.00114	800	240	7

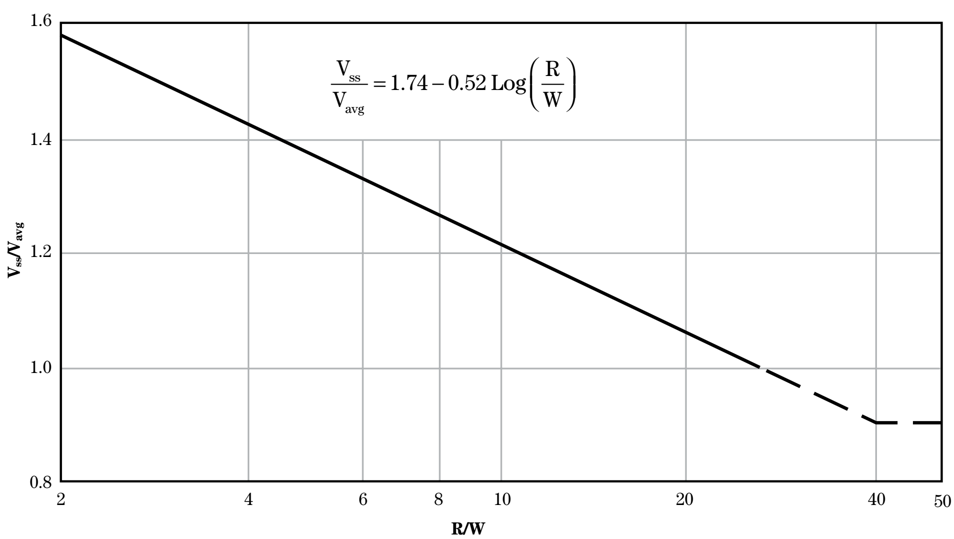
V_{ss}, which is the depth-averaged local velocity over the side slope at a point 20 percent of the slope length from the toe of the slope. This has been determined to be the part of the side slope that experiences the maximum flow velocity. The ratio V_{ss}/V_{avg}, where V_{avg} is the average channel velocity at the upstream end of the bend, has been determined to be a function of the ratio of the of centerline radius of curvature, R, and the water surface width, W. Figure 8–1 illustrates the relationship for natural channels. Figure 8–2 illustrates the relationship for trapezoidal channels. The data for trapezoidal channels shown in figure 8–2 are based on numerical model calculations described in Bernard (1993). The primary factors affecting velocity distribution in riprap lined bendways are R/W, bend angle, and aspect ratio (bottom width-to-depth). V_{avg}, R, and W should be based on main channel flow only and should not include overbank areas.

Figure 8–2 Design velocities for trapezoidal channels



Notes: V_{ss} is depth-averaged velocity at 20% of slope length up from toe, maximum value in bend. Curves based on STREMR model (Bernard 1993), V_{avg} = 6 ft/s, 1V:3H side slopes. n = 0.038, 15 ft depth

Figure 8–1 Design velocities for natural channels. Note: V_{ss} is depth-averaged velocity at 20% of slope length from toe



(b) Determine allowable velocity

The design velocity of the existing or proposed channel must be compared to the allowable velocity for the channel boundary. The allowable velocity is the greatest mean velocity that will not cause the channel boundary to erode. Since the allowable velocity is a design parameter that has a factor of safety, it is somewhat less than the critical velocity (the velocity at incipient motion of the boundary material).

The allowable velocity can be approximated from tables that relate boundary material to allowable velocity, but tabular estimates should be tempered by experience and judgment. In general, older channels have higher allowable velocities because the channel boundary typically becomes stabilized with the deposition of colloidal material in the interstices. Also, a deeper channel will typically have a higher allowable velocity than shallow channels because erosion is a function of the bottom velocity. Bottom velocities in deep channels are less than bottom velocities in shallow channels with the same mean velocity.

Fortier and Scobey (1926) presented a table of maximum permissible velocities for earthen irrigation canals with no vegetation or structural protection. Their work was compiled based on a questionnaire given to a number of experienced irrigation engineers and was recommended for use in 1926 by the Special Committee on Irrigation Research of the American Society of Civil Engineers. This compilation is presented in table 8–3.

USACE (1991b) provides allowable velocity criteria for nonscouring flood control channels in table 8–4.

Theoretical objections to use of average velocity as an erosion criterion can be overcome by using depth as a second independent variable. An example of a velocity-depth-grain size chart from the USACE (1991b) is shown in figure 8–3. This particular chart is intended to correspond to a small degree of bed movement, rather than no movement. Values given in this chart are for approximate guidance only.

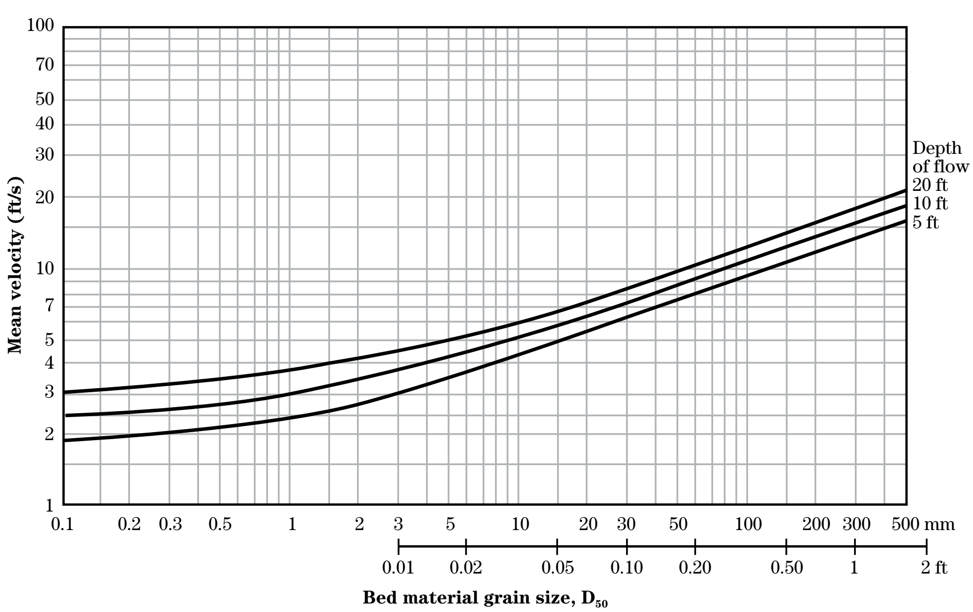
Table 8–3 Maximum permissible canal velocities

	Mean velocity, for straight canals of small slope, after aging with flow depths less than 3 ft (0.9 m)					
	Clear water, no detritus		**Water transporting colloidal silts**		**Water transporting noncolloidal silts, sands, gravels, or rock fragments**	
Original material excavated for canals	**ft/s**	**m/s**	**ft/s**	**m/s**	**ft/s**	**m/s**
Fine sand (noncolloidal)	1.5	0.46	2.5	0.76	1.5	0.46
Sandy loam (noncolloidal)	1.75	0.53	2.5	0.76	2.0	0.61
Silt loam (noncolloidal)	2.0	0.61	3.0	0.91	2.0	0.61
Alluvial silt (noncolloidal)	2.0	0.61	3.5	1.07	2.0	0.61
Ordinary firm loam	2.5	0.76	3.5	1.07	2.25	0.69
Volcanic ash	2.5	0.76	3.5	1.07	2.0	0.61
Stiff clay (very colloidal)	3.75	1.14	5.0	1.52	3.0	0.91
Alluvial silt (colloidal)	3.75	1.14	5.0	1.52	3.0	0.91
Shales and hardpans	6.0	1.83	6.0	1.83	5.0	1.52
Fine gravel	2.5	0.76	5.0	1.52	3.75	1.14
Graded, loam to cobbles (when noncolloidal)	3.75	1.14	5.0	1.52	5.0	1.52
Graded silt to cobbles (when colloidal)	4.0	1.22	5.5	1.68	5.0	1.52
Coarse gravel (noncolloidal)	4.0	1.22	6.0	1.83	6.5	1.98
Cobbles and shingles	5.0	1.52	5.5	1.68	6.5	1.98

Table 8–4 Allowable velocities

Channel material	Mean channel velocity (ft/s)	(m/s)
Fine sand	2.0	0.61
Coarse sand	4.0	1.22
Fine gravel	6.0	1.83
Earth		
Sandy silt	2.0	0.61
Silt clay	3.5	1.07
Clay	6.0	1.83
Grass-lined earth (slopes <5%)		
Bermudagrass		
Sandy silt	6.0	1.83
Silt clay	8.0	2.44
Kentucky bluegrass		
Sandy silt	5.0	1.52
Silt clay	7.0	2.13
Poor rock (usually sedimentary)	10.0	3.05
Soft sandstone	8.0	2.44
Soft shale	3.5	1.07
Good rock (usually igneous or hard metamorphic)	20.0	6.08

Figure 8–3 Allowable velocity-depth grain chart



(c) Soil Conservation Service allowable velocity approach

Basic allowable velocities may be determined from figure 8–4 (USDA SCS 1977). In this figure, allowable velocities are a function of sediment concentration, grain diameter for noncohesive boundary material, and plasticity index and soil characteristics for cohesive boundary material. Adjustments are given in figure 8–4 to the basic allowable velocity to account for frequency of design flow, alignment, bank slope, depth of flow, and sediment concentration for both discrete particles and cohesive soils. These design charts were compiled from the data of Fortier and Scobey (1926), Lane (1955a), and the Union of Soviet Socialist Republic (USSR) (1936). Soil materials are classified using the Unified Soil Classification System.

Procedure for application of allowable velocity method (USDA SCS 1977)

Step 1 Determine the hydraulics of the system. This includes hydrologic determinations, as well as the stage-discharge relationships for the channel considered.

Step 2 Determine the soil properties of the bed and banks of the design reach and of the channel upstream.

Step 3 Determine the concentration of the suspended sediment load entering the reach. This is best accomplished by measurements. Channels with suspended sediment concentrations less than 1,000 parts per million are considered sediment free for this analysis, in that the sediment load is not sufficient to decrease the energy of the stream flow. Sediment-free flows are, therefore, considered to have no effect on channel stability. Channels with suspended sediment concentrations greater than 20,000 parts per million are considered to be sediment laden. Sediment-laden flows are considered to enhance stream stability by filling boundary interstices with cohesive material. If a significant portion of the inflowing sediment load is bed-material load, it is likely that the channel is alluvial, and threshold design methods are not applicable.

Step 4 Check to see if the allowable velocity procedure is applicable using table 8–1.

Step 5 Determine the basic average allowable velocities for the channel from one or more of the available design guidelines (tables 8–3, 8–4, fig. 8–4 (USDA SCS 1977; Federal Interagency Stream Restoration Working Group (FISRWG) 1998)).

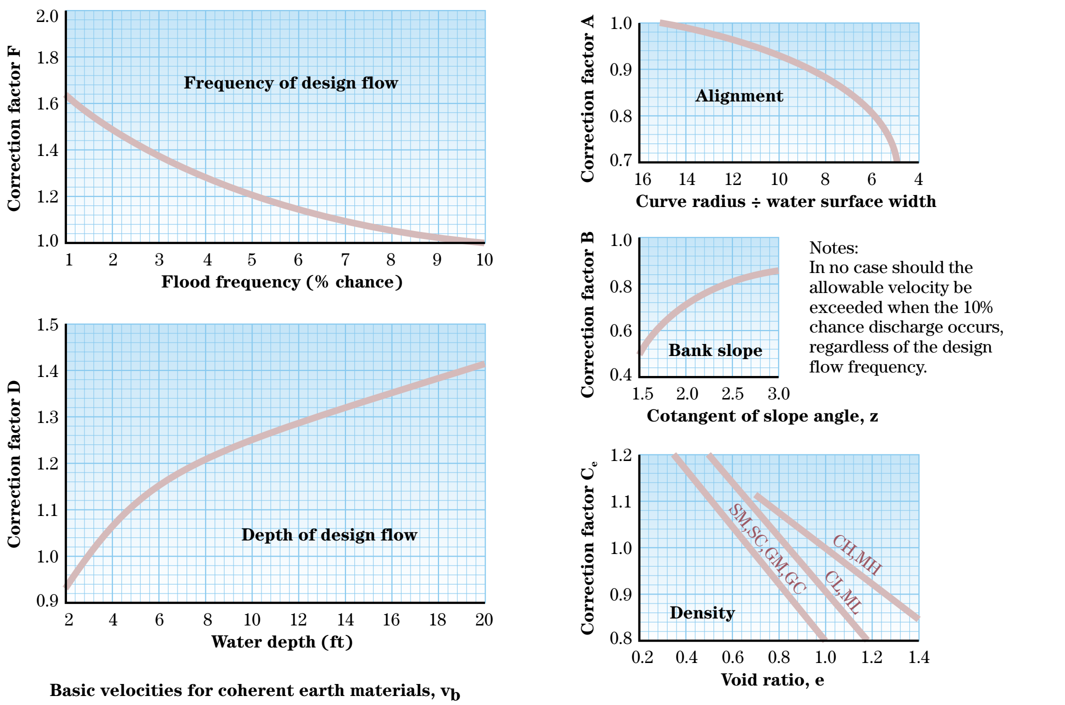
Step 6 Multiply the basic allowable velocity by the appropriate correction factors (fig. 8–4).

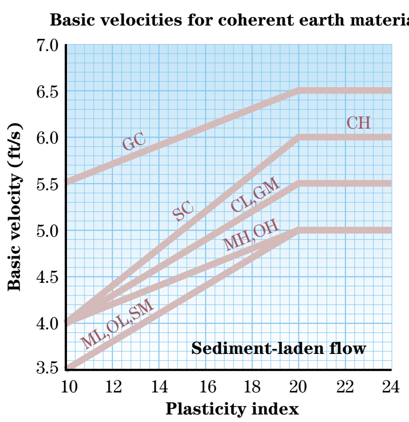
Step 7 Compare the design velocities with the allowable velocities. If the allowable velocities are greater than the design velocities, the design is satisfactory. Otherwise, three options are available:

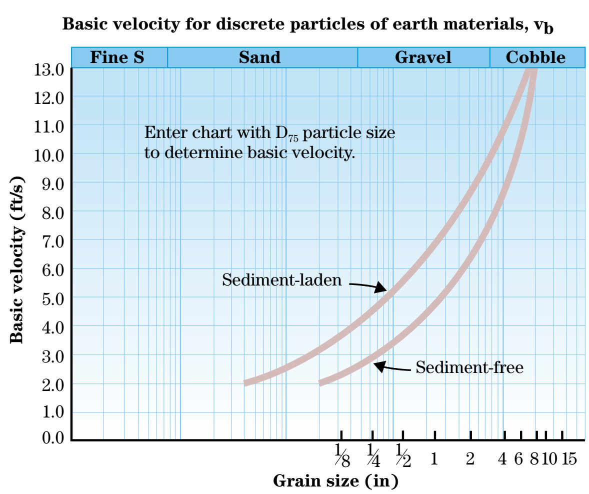
- Redesign the channel to reduce velocity.
- Provide structural measures (riprap, grade control) to prevent erosion.
- Consider a mobile boundary condition and evaluate the channel using appropriate sediment transport theory and programs.

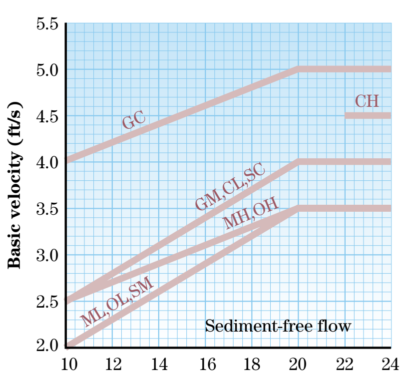
Design of Open Channels, TR–25 (USDA SCS 1977) contains several examples to guide the user through the allowable velocity approach.

Figure 8–4 Allowable velocities for unprotected earth channels









Allowable velocities for unprotected earth channels	
Channel boundary materials	Allowable velocity
Discrete particles	
Sediment-laden flow	
D_{75} >0.4mm	Basic velocity chart value x D x A x B
D_{75} <0.4mm	2.0 ft/s
Sediment-free flow	
D_{75} >0.2mm	Basic velocity chart value x D x A x B
D_{75} <0.2mm	2.0 ft/s
Coherent earth materials	
PI >10	Basic velocity chart value x D x A x F x C_e
PI <10	2.0 ft/s

Source: USDA Soil Conservation Service, 1977

654.0804 Allowable shear stress approach

The allowable shear approach (sometimes referred to as the tractive stress approach) is typically used with channels that are lined with rock, gravel, or cobbles. Limiting forces for soil bioengineering and manufactured protective linings can also be expressed as allowable shear, as well.

To design a threshold channel using the allowable shear stress approach, the average applied grain bed shear stress is compared to the allowable shear stress for the boundary material. The applied grain bed shear stress can be calculated from the hydraulic parameters determined for the design channel and the characteristics of the channel boundary material. The hydraulic parameters are calculated using the same methods as in the allowable velocity approach. For noncohesive soils, the average allowable shear stress can be calculated using a critical shear stress approach and then adding a factor of safety or by using an empirical equation with a factor of safety included. For cohesive particles, the electrochemical bonds related primarily to clay mineralogy, are the most significant sediment properties that determine allowable shear stress. Although some empirical data are available, laboratory tests to determine allowable shear stress for a specific cohesive soil are preferred.

(a) Calculate applied shear stress

The first step in applying this approach is to calculate the hydraulics of the study reach. The total average shear stress on the boundary can be approximated from equation 8–1, using any consistent units of measurement:

$$\tau_o = \gamma RS \qquad \text{(eq. 8–1)}$$

where:
τ_o = total bed shear stress (lb/ft^2 or N/m^2)
γ = specific weight of water (lb/ft^3 or N/m^3)
R = hydraulic radius (ft or m)
S = energy slope, dimensionless

In wide channels where the width is more than 10 times the depth, R is generally taken to be equal to the depth. Spatial and temporal variation may result in a higher or lower point value for shear stress. The equation approximates average bed shear stress.

The shear stress can also be expressed as a function of the velocity and the ratio of hydraulic radius and boundary roughness. Keulegan (1938) presented such a formula.

$$\tau = \frac{\rho V^2}{\left(\frac{1}{\kappa}\ln\frac{R}{k_s} + 6.25\right)^2} \qquad \text{(eq. 8–2)}$$

where:
V = depth-averaged velocity, ft/s or m/s
ρ = density of water, lb-s^2/ft^4(slugs/ft^3) or kg/m^2
κ = von Karman's constant (usually taken to be 0.4)
k_s = roughness height, ft or m

Actual shear stress values should be calculated for the banks, as well as for the bed of a trapezoidal earth channel. Maximum stresses occur near the center of the bed and at a point on the bank about a third up from the bottom. The designer should note that computer programs such as HEC–RAS may only provide average boundary shear stress in the output. For most trapezoidal sections and depths of flow, bed stress values are somewhat higher than bank stress. Figures 8–5 and 8–6 provide actual shear stress values for the bed and sides of straight trapezoidal channels in coarse grained soil materials.

Grain shear stress

The total applied bed shear stress may be divided into that acting on the grains and that acting on the bedforms. Entrainment and sediment transport are a function only of the grain shear stress; therefore, the grain shear stress is the segment of interest for threshold design. Einstein (1950) determined that the grain shear stress could best be determined by separating total bed shear stress into a grain component and a form component, which are additive. The equation for total bed shear stress is:

$$\tau_o = \tau' + \tau'' = \gamma RS \qquad \text{(eq. 8–3)}$$

where:
τ' = grain shear stress (shear resulting from size of the material on the bed)
τ'' = form shear stress (shear resulting from bed irregularities due to bedforms)

Figure 8–5 Applied maximum shear stress, τ_b, on bed of straight trapezoidal channels relative to an infinitely wide channel, τ_∞

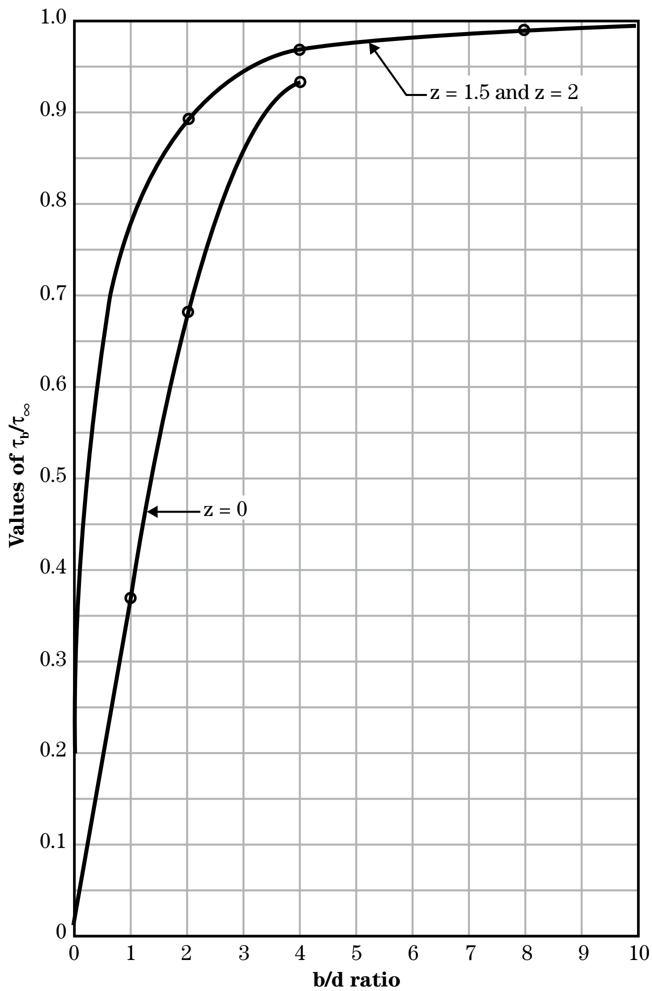
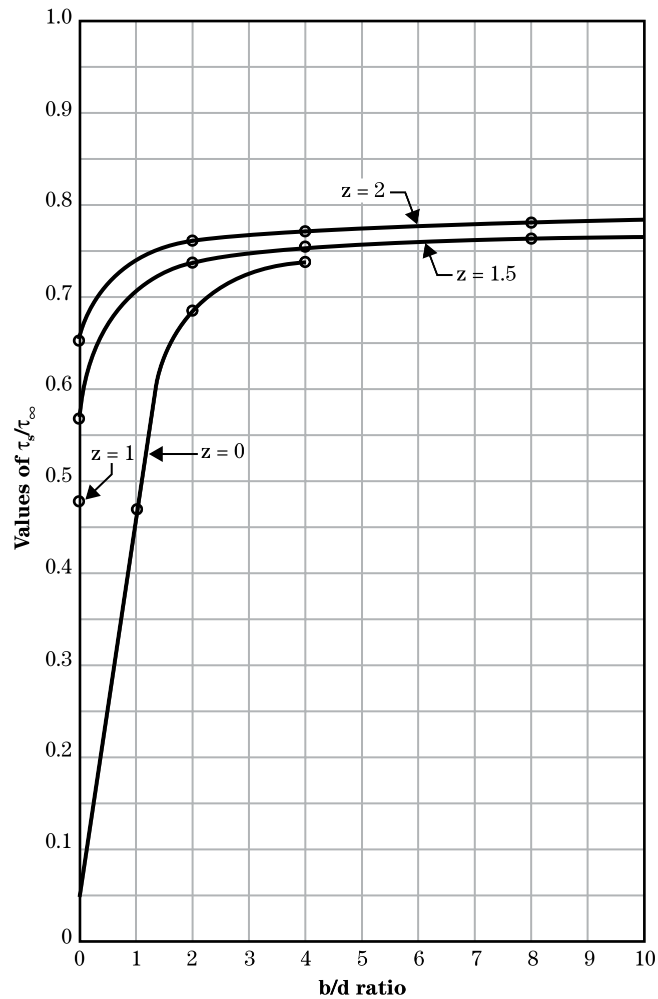


Figure 8–6 Applied maximum shear stress, τ_s, on sides of trapezoidal channels relative to an infinitely wide channel, τ_∞



Note:
b = bottom width
d = depth
z = side slope, zH:1V
τ_∞ = shear stress on a straight, infinitely wide channel
τ_b = applied shear stress on a channel bed
τ_s = applied shear stress on the side of a channel

Einstein also suggested that the hydraulic radius could be divided into grain and form components that are additive. The equations for grain and form shear stress then become:

$$\tau' = \gamma R'S \qquad \text{(eq. 8–4)}$$

$$\tau'' = \gamma R''S \qquad \text{(eq. 8–5)}$$

where:
R′ = hydraulic radii associated with the grain roughness
R″ = hydraulic radii associated with the form roughness

These hydraulic radii are conceptual parameters, useful for computational purposes and have no tangible reality. The total bed shear stress can be expressed as:

$$\tau_0 = \gamma R'S + \gamma R''S \qquad \text{(eq. 8–6)}$$

Slope and the specific weight of water are constant so that the solution is to solve for one of the *R* components. The grain shear stress can be calculated with the Limerinos equation, using any consistent units of measurements.

$$\frac{V}{U'_*} = 3.28 + 5.66\log_{10}\frac{R'}{D_{84}} \qquad \text{(eq. 8–7)}$$

$$U'_* = \sqrt{gR'S} \qquad \text{(eq. 8–8)}$$

where:
V = average velocity (ft/s or m/s)
U'_* = grain shear velocity (ft/s or m/s)
D_{84} = particle size for which 84% of the sediment mixture is finer (ft or m)
g = acceleration of gravity (ft/s² or m/s²)

Limerinos (1970) developed his equation using data from gravel-bed streams. Limerinos' hydraulic radii ranged between 1 and 6 feet; D_{84} ranged between 1.5 and 250 millimeters. This equation was confirmed for plane bed sand-bed streams by Burkham and Dawdy (1976). The equation can be solved iteratively for R′ and τ′, when average velocity, slope, and D_{84} are known.

Whenever the streambanks contribute significantly to the total channel roughness, the applied shear stress to the banks must be accounted for. This is accomplished using the sidewall correction procedure, which separates total roughness into bed and bank roughness and conceptually divides the cross-sectional area into additive components. The procedure is based on the assumption that the average velocity and energy gradient are the same in all segments of the cross section.

$$A_{total} = A_b + A_w \qquad \text{(eq. 8–9)}$$

$$A_{total} = P_bR_b + P_wR_w \qquad \text{(eq. 8–10)}$$

where:
A = cross-sectional area (ft² or m²)
P = perimeter (ft or m)

Subscripts b and w are associated with the bed and wall (or banks), respectively. Note that the hydraulic radius is not additive with this formulation, as it was with R′ and R″. Using Manning's equation, with a known average velocity, slope, and roughness coefficient, the hydraulic radius associated with the banks can be calculated:

$$\frac{V}{CME\,S^{\frac{1}{2}}} = \frac{R^{\frac{2}{3}}}{n} = \frac{R_w^{\frac{2}{3}}}{n_w} \qquad \text{(eq. 8–11)}$$

$$R_w = \left(n_w \frac{V}{CME\,S^{\frac{1}{2}}}\right)^{\frac{3}{2}} \qquad \text{(eq. 8–12)}$$

where:
CME =1.486 in English units and 1.0 in SI units

Total hydraulic radius and shear stress, considering grain, form, and bank roughness, can be expressed by equations 8–13 and 8–14:

$$R_{total} = \frac{P_b\left(R' + R''\right) + P_wR_w}{P_{total}} \qquad \text{(eq. 8–13)}$$

$$\tau_{total} = \gamma S\left(\frac{P_b\left(R' + R''\right) + P_wR_w}{P_{total}}\right) \qquad \text{(eq. 8–14)}$$

Lane's tractive force method

Lane (1952) developed an analytical design approach for calculation of the applied grain shear stress and the shear distribution in trapezoidal channels. The tractive force, or applied shear force, is the force that the water exerts on the wetted perimeter of a channel due to the motion of the water. Lane determined that in most irrigation canals, the tractive force near the middle of the channel closely approaches

$$\gamma d S_o$$

where:
γ = specific weight of water
d = depth
S_o = bed slope assuming uniform flow

He also determined that the maximum tractive force on the side slopes was approximately 0.75 $\gamma d S_o$. Lane also found that the side slopes of the channel affected the maximum allowable shear stress. He developed an adjustment factor, K, to account for the side slope effects. Detailed information on the tractive force approach is found in Design of Open Channels, TR–25 (USDA SCS 1977) and Chow (1959). A summary of the method follows.

When the boundary of the channel consists of coarse-grained discrete particles, Lane (1952) determined that the grain roughness, n_s, could be determined as a function of the D_{75} of the boundary material. Applied grain shear stress can then be calculated using Manning's equation. The D_{75} range for which Lane found this relationship to be applicable was between 0.25 inches (6.35 mm) and 5.0 inches (127 mm). This is similar to determining the grain shear stress using the Limerinos equation.

$$n_s = \frac{D_{75}^{\frac{1}{6}}}{39} \text{ with } D_{75} \text{ expressed in inches} \quad \text{(eq. 8–15)}$$

$$n_s = \frac{D_{75}^{\frac{1}{6}}}{66.9} \text{ with } D_{75} \text{ expressed in millimeters} \quad \text{(eq. 8–16)}$$

The grain roughness is combined with other roughness elements to determine the total Manning's roughness coefficient, n. The friction slope associated with grain roughness, S_t, can then be calculated using equation 8–17:

$$S_t = \left(\frac{n_s}{n}\right)^2 S_e \quad \text{(eq. 8–17)}$$

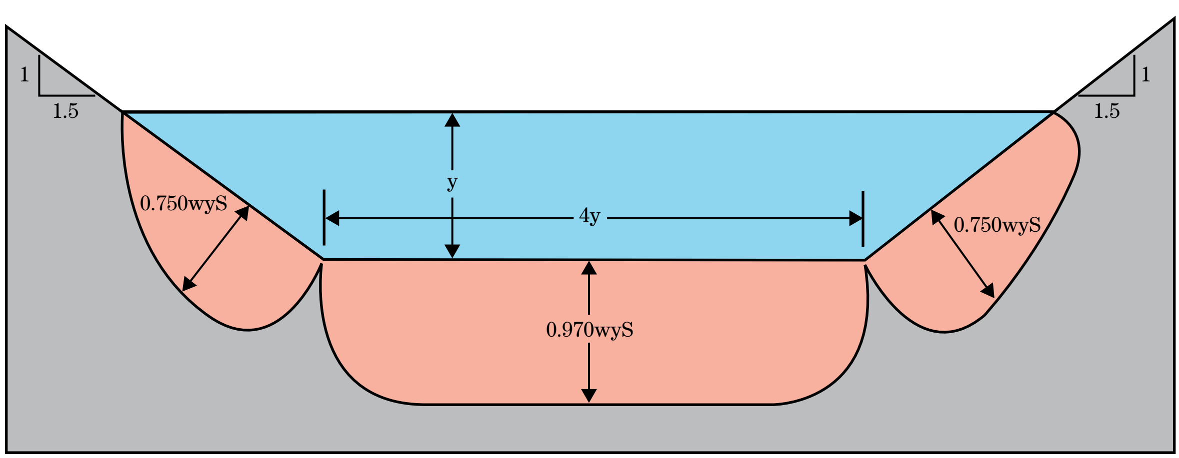
where:
S_e = total friction slope determined from Manning's equation

The applied shear stress acting on the grains in an infinitely wide channel is then calculated from equation 8–18.

$$\tau_\infty = \gamma d S_t \quad \text{(eq. 8–18)}$$

In open channels, the applied shear stresses are not distributed uniformly along the perimeter as is shown in figure 8–7 (Lane 1952). Laboratory experiments and field observations have indicated that in trapezoidal channels the stresses are very small near the water surface and corners of the channel. In straight chan-

Figure 8–7 Lateral distribution of shear stress in a trapezoidal channel



w=specific weight of water, y=depth, and S=slope nels, the maximum shear stress occurs on the bed near the center of the channel. The maximum shear stress on the banks occurs about a third the way up the bank from the bed. Figures 8–5 and 8–6 can be used to determine the shear stress distribution in a trapezoidal channel, relative to the applied shear stress in an infinitely wide channel with the same depth of flow and energy slope (USDA SCS 1977).

The magnitude of applied shear stresses is not uniform in turbulent flow. Calculations using traditional equations provide an average value of shear stress. In design, therefore, a factor of safety is typically applied to account for this fluctuation. This fluctuation may also be addressed in certain design approaches using probability methods presented later in this chapter.

Applied shear stress on curved reaches
Curved channels have higher maximum shear stresses than straight channels. Maximum stress occurs on the inside bank in the upstream portion of the curve and on the outer bank in the downstream portion of the curve. The smaller the radius of curvature, the more the stress increases along the curved reach. Maximum applied shear stress in a channel with a single curve also occurs on the inside bank in the upstream portion of the curve and near the outer bank downstream from the curve. Compounding of curves in a channel complicates the flow pattern and causes a compounding of the maximum applied shear stress. Figure 8–8 gives values of maximum applied shear stress based on judgment coupled with very limited experimental data (USDA SCS 1977). It does not show the effect of depth of flow and length of curve, and its use is only justified until more accurate information is obtained. Figure 8–9, with a similar degree of accuracy, gives the maximum applied shear stresses at various distances downstream from the curve (USDA SCS 1977). The designer should note that these adjustments are similar to rules of thumb.

(b) Calculate allowable shear stress

The applied shear stress must be compared to the allowable shear stress. Shear stress at initiation of motion can be calculated from an empirically derived relationship between dimensionless shear stress (Shields parameter), τ^*, and grain Reynolds number, R^*. The dimensionless shear stress is defined as the ratio of the critical shear stress (shear stress at the initiation of particle motion) and product of the grain diameter and the submerged specific weight of the particle. The grain Reynolds number is defined as the ratio of the product of shear velocity and grain diameter to kinematic viscosity. Shields parameter and grain Reynolds number are dimensionless and can be used with any consistent units of measurement. The relationship between τ^* and R^* represents an average curve drawn through scattered data points that were determined experimentally from flumes or rivers. Therefore, a wide range in recommended values exists for the Shields parameter, depending on how the experiment was conducted and the nature of the bed material being evaluated.

Once τ^* has been assigned, the critical shear stress for a particle having a diameter, D, is calculated from equation 8–19.

$$\tau_c = \tau^*\left(\gamma_s - \gamma\right)D \qquad \text{(eq. 8–19)}$$

where:
τ^* = Shields parameter, dimensionless
R^* = grain Reynolds number = u^*d/ν, dimensionless
τ_c = critical shear stress (lb/ft^2 or N/m^2)
γ_s = specific weight of sediment (lb/ft^3 or N/m^3)
γ = specific weight of water (lb/ft^3 or N/m^3)
D = particle diameter (ft or m)
u^* = shear velocity = $(gRS)^{1/2}$ (ft/s or m/s)
ν = kinematic viscosity of the fluid (ft^2/s or m^2/s)
g = acceleration of gravity (ft/s^2 or m/s^2)

Shields (1936) obtained his critical values for τ^* experimentally using uniform bed material and measuring sediment transport at decreasing levels of bed shear stress, and then extrapolating to zero transport. The Shields curve is shown in figure 8–10 (USACE 1995c). Shields' data suggest that τ^* varies with R^* until the grain Reynolds number exceeds 400. At larger values of R^*, τ^* is independent of R^* and is commonly taken to be 0.06. The Shields curve may be expressed as an equation, useful for computer programming and spreadsheet analysis.

$$\tau^* = 0.22\beta + 0.06\times10^{-7.7\beta} \qquad \text{(eq. 8–20)}$$

$$\beta = \left(\frac{1}{\nu}\sqrt{\left(\frac{\gamma_s - \gamma}{\gamma}\right)gD^3}\right)^{-0.6} \qquad \text{(eq. 8–21)}$$

The Shields diagram is the classic method for determining critical shear stress. However, subsequent

Figure 8–8 Applied maximum applied shear stress, τ_{bs} and τ_{sc} on bed and sides of trapezoidal channels in a curved reach

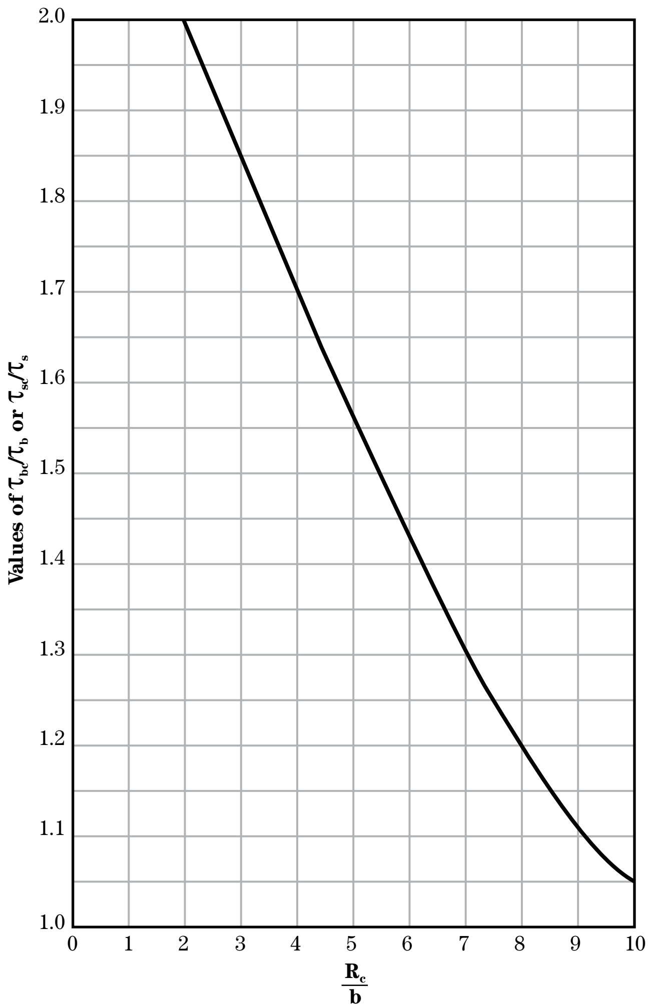
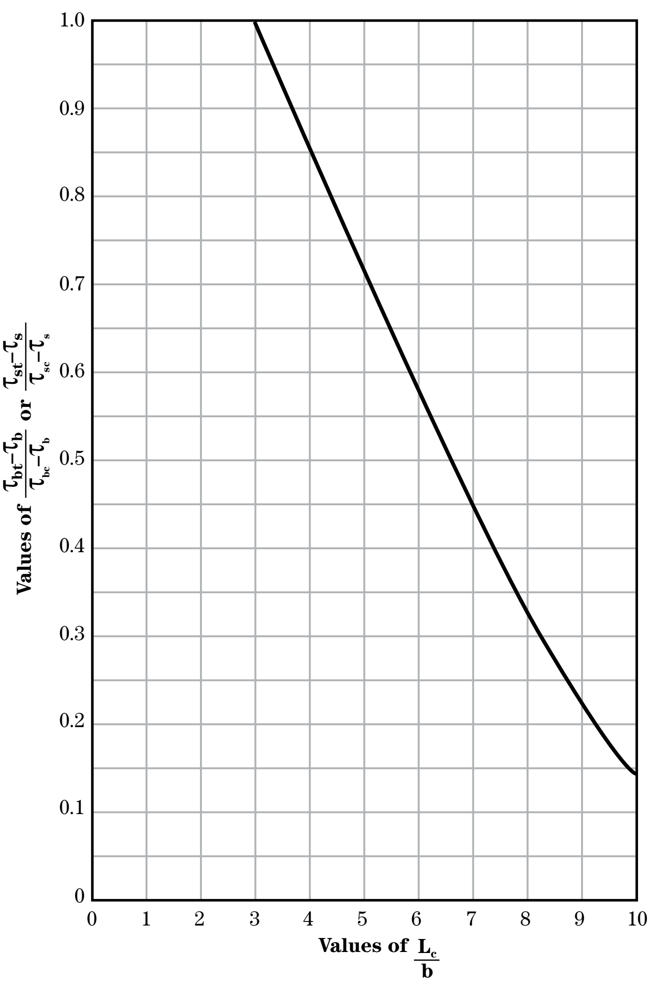


Figure 8–9 Applied maximum applied shear stress, τ_{bt} and τ_{st} on bed and sides of trapezoidal channels in straight reaches immediately downstream from curved reaches



Note:
R_c = radius of curvature
b = bottom width
d = channel depth
L_c = length of curve
τ_b = applied shear stress on a channel bed
τ_s = applied shear stress on the side of a channel
τ_{bc} = applied shear stress on channel bed in a curve
τ_{sc} = applied shear stress on channel side in a curve
τ_{bt} = applied shear stress on channel bed immediately downstream of a curve
τ_{st} = applied shear stress on channel side immediately downstream of a curve

work identified three significant problems associated with the curve itself. First, the procedure did not account for the bedforms that developed with sediment transport. Second, the critical dimensionless shear stress is based on the average sediment transport of numerous particles and does not account for the sporadic entrainment of individual particles at very low shear stresses. Thirdly, critical dimensionless shear stress for particles in a sediment mixture may be different from that for the same size particle in a uniform bed material. In general, for purposes of design of threshold channels, in which no bed movement is a requirement, the Shields curve will underestimate the critical dimensionless shear stress and is not recommended unless a factor of safety is added.

Adjustment for bedforms

Gessler (1971) determined that Shields did not separate grain shear stress from bedform shear stress in his experimental flume data analysis. Bedforms developed with sediment transport for the fine-grained bed material in some of Shields flume data. Since a portion of the total applied shear stress is required to overcome the bedform roughness, the calculated dimensionless shear stress would be too high for a natural bed with no bedforms. Gessler reanalyzed Shields' data so that the critical Shields parameter represented only the grain shear stress (fig. 8–11). This curve is more appropriate for determining critical shear stress in plane bed streams with relatively uniform bed gradations. With fully turbulent flow (R* >400), typical of gravel-bed streams, τ* is commonly taken to be 0.047 using Gessler's curve.

Figure 8–11 Gessler's reformulation of Shields diagram. τ is critical grain shear stress and k is grain diameter.

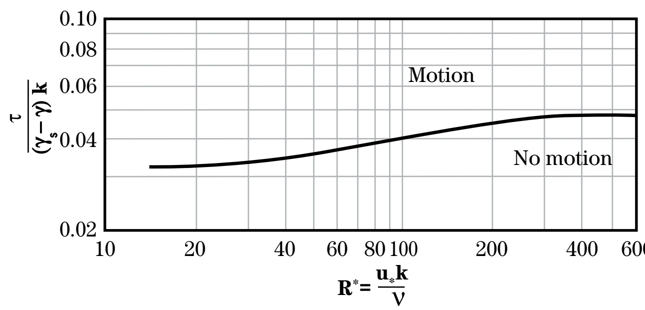
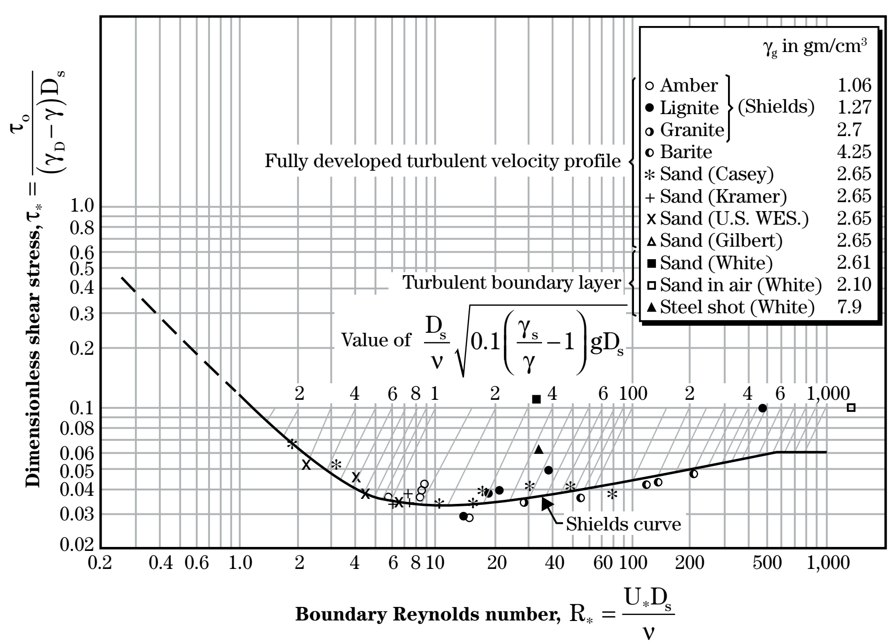


Figure 8–10 Shields curve



Adjustment for mixtures

Natural streambeds seldom have uniform bed gradations. The critical bed shear stress equation must be modified for mixtures. There are two approaches: one is to select a τ* that is characteristic of mixtures; the other is to select a percent finer grain size that is characteristic of initiation of motion. Meyer-Peter and Muller (1948) and Gessler (1971) determined that when R* >400, the critical Shields parameter for sediment mixtures was about 0.047 when median grain size was used. Neill (1968) determined from his data that in gravel mixtures, most particles became mobile when τ* was 0.030, when median grain size was used for D. Andrews (1983) found a slight difference in τ* for different grain sizes in a mixture, and presented the equation 8–22:

$$\tau_i^* = 0.0834\left(\frac{D_i}{D_{50}}\right)^{-0.872} \quad \text{(eq. 8–22)}$$

where:

subscript, i =Shields parameter and grain size for size class i

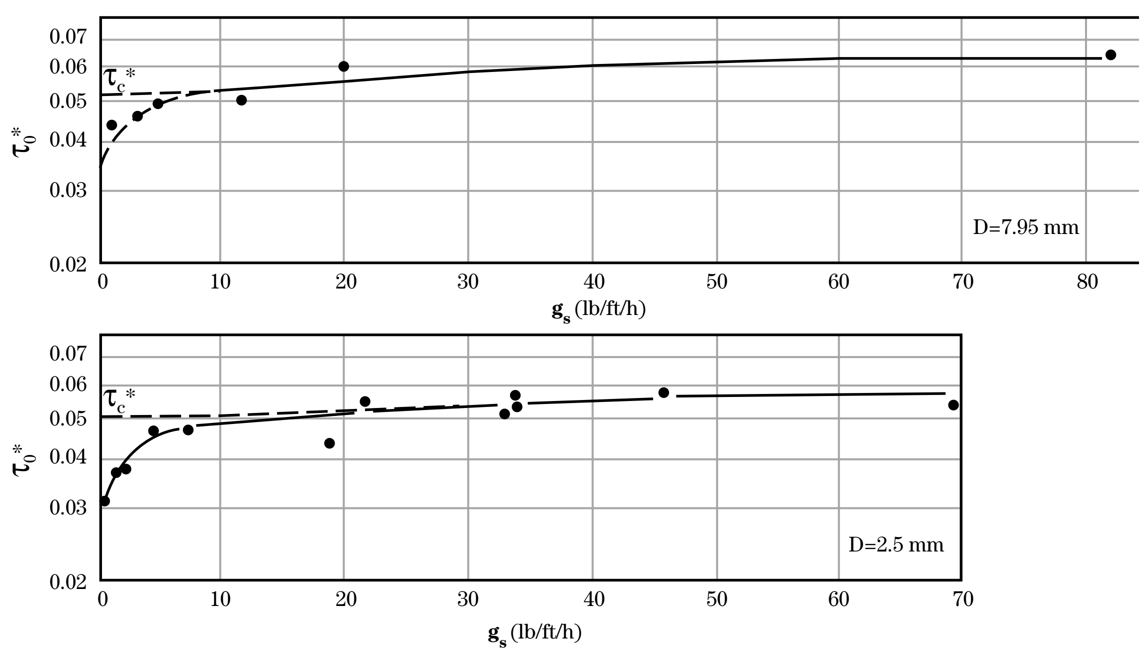
D_{50} =median diameter of the subsurface material

The minimum value for τ* was found to be 0.020. According to Andrews, the critical shear stress for individual particles has a very small range; therefore, the entire bed becomes mobilized at nearly the same shear stress. However, Wilcock (1998) and Wilcock and McArdell (1993) have demonstrated that this near-equal mobility result applies only to unimodal sediments with a small to modest standard deviation. In coarse beds with a wide range of sizes (especially mixtures of sand and gravel), the fines may begin to move at flows much smaller than the coarse grains.

Gessler's concept for particle stability

Critical shear stress is difficult to define because entrainment is sporadic at low shear stresses caused by bursts of turbulence. Due to the difficulty in defining initiation of motion in a flume, the Shields curve was developed by extrapolating measured sediment transport rates back to zero. Unfortunately, the relationship between the Shields parameter and sediment transport is not linear at low shear stresses. This phenomenon was demonstrated by Paintal (1971) (fig. 8–12). Note that the extrapolated critical dimensionless shear stress was about 0.05, but the actual critical dimensionless shear stress was 0.03.

Figure 8–12 Variation in Shields parameter with decreasing sediment load



Gessler (1971) developed a probability approach to the initiation of motion for sediment mixtures. He reasoned that due to the random orientation of grains and the random strength of turbulence on the bed, for a given set of hydraulic conditions, part of the grains of a given size will move, while others of the same size may remain in place. Gessler assumed that the critical Shields parameter represents an average condition, where about half the grains of a uniform material will remain stable and half will move. It follows then that when the critical shear stress was equal to the bed shear stress, there was a 50 percent chance for a given particle to move. Using experimental flume data, he developed a probability function, p, dependent on τ_c/τ where τ_c varied with bed size class (fig. 8–13). He determined that the probability function had a normal distribution, and that the standard deviation (slope of the probability curve) was a function primarily of turbulence intensity, and equal to 0.057. Gessler found the effect of grain-size orientation to be negligible. The standard deviation also accounts for hiding effects; that is, no attempt was made to separate hiding from the overall process. Gessler's analysis demonstrates that there can be entrainment of particles, even when the applied shear stress is less than the critical shear stress; and that not all particles of a given size class on the bed will necessarily be entrained, until the applied shear stress exceeds the critical shear stress by a factor of 2. The design implications of this work are:

- If near-complete immobility is desired in the project design, the Shields parameter used to determine critical shear stress should be on the order of half the typically assigned value.
- To assure complete mobility of the bed (fully alluvial conditions), the applied grain shear stress should be twice the critical shear stress.

The inherent dangers of using 50 percent or 200 percent of critical shear stress are that the channel could aggrade or incise.

Gessler used the probability approach to determine if the bed surface layer of a channel was stable (immobile). He suggested that the mean value of the probabilities for the bed surface to stay in place should be a good indicator of stability:

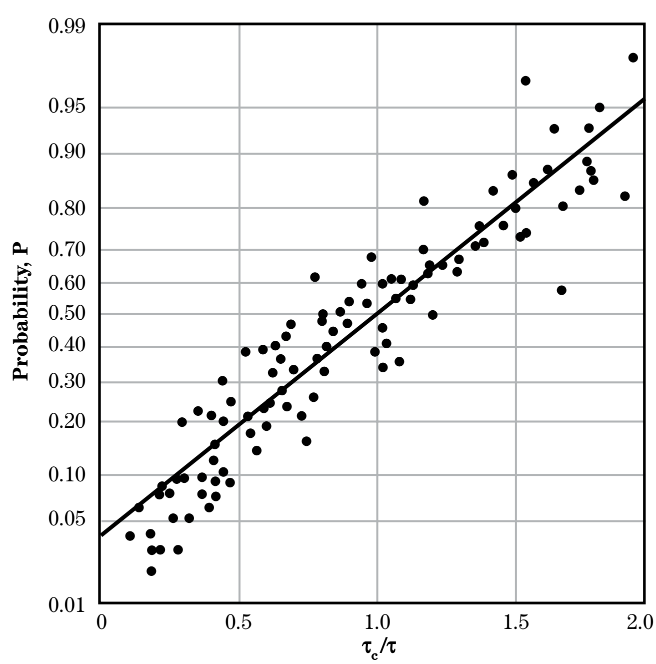
$$\bar{P} = \frac{\int_{i_{min}}^{i_{max}} P^2 f_i D_i}{\int_{i_{min}}^{i_{max}} P f_i D_i} \qquad \text{(eq. 8–23)}$$

where:
$\bar{P}$ = probability function for the mixture (depends on the frequency of all grain sizes in the underlying material)
f_i = fraction of grain size i

If the gradation of the channel bed is known, τ_c for each size class is determined from figure 8–11, and P for each size class is determined from figure 8–13. $\bar{P}$ can then be calculated from equation 8–23. Gessler suggested that when $\bar{P}$ was less than 0.65, the bed was unstable.

The probability concept was presented in an empirical fashion by Buffington and Montgomery (1997). They analyzed critical shear stress data from many investigators and suggested ranges for the critical Shields parameter. For visually base data, where initiation of motion was determined by investigator observation, Buffington and Montgomery suggested a range for τ^* between 0.073 and 0.030 for fully rough, turbulent flow ($R^* >400$). They concluded that less emphasis should be placed on choosing a universal value for τ^*, while more emphasis should be placed on choosing defendable values for particular applications. Buffington and Montgomery also provided the compiled data

Figure 8–13 Probability of grains to stay on the bed



from many investigators, including data from natural streams.

Lane's method for coarse grained soils

Lane (1955a) concentrated on the force exerted over a given surface area of the channel, rather than the force exerted on a single particle, as in the Shields parameter and Gessler approaches. He also built in a factor of safety to the critical shear stress, so that his equation more appropriately can be called an allowable shear stress equation. This factor of safety accounts for the shear stress fluctuations in turbulent flow.

For boundaries with coarse-grained discrete soil particles, where the D_{75} is between 0.25 and 5.00 inches (6.35 and 127 mm), the allowable shear stress on the channel bottom, τ_{ab}, can be approximated using equation 8–24 proposed by Lane.

$$\tau_{ab} = 0.4\,D_{75} \qquad \text{(eq. 8–24)}$$

where:

D_{75} = particle size for which 75% of the sediment is smaller (in)

τ_{ab} = allowable shear stress on channel bottom (lb/ft^2)

The allowable shear stress for the channel sides, τ_{as}, is less than that of the same material in the bed of the channel because the gravity force aids the applied shear stress in moving the materials. For channel sides composed of soil particles behaving as discrete single grain materials, considering the effect of the side slope, z, and the angle of repose, ϕ, with the horizontal, the allowable shear stress is:

$$\tau_{as} = 0.4K\,D_{75} \qquad \text{(eq. 8–25)}$$

where:

$$K = \sqrt{\frac{z^2 - \cot^2\phi}{1+z^2}} \qquad \text{(eq. 8–26)}$$

The angle of repose for various degrees of particle angularity can be determined from figure 8–14 (Lane 1952). When the unit weight, γ_s, of the boundary material greater than D_{75} is significantly different from 160 pounds per cubic foot, the allowable shear stresses, τ_{ab} and τ_{as}, should be multiplied by the factor T.

$$T = \frac{\gamma_s - \gamma}{97.8} \qquad \text{(eq. 8–27)}$$

where:
units of γ are in lb/ft^3

Figure 8–15 (from TR–25) provides adjustment values for allowable bank stress in trapezoidal channels, based on angle of repose and side slope steepness. The allowable stress for the channel sides is thought to be less than that of the same material in the bed because the gravity force adds to the stress in moving the materials.

Lane's method for fine-grained soils

Allowable shear stress in fine-grained soils (D_{75} <6.3 mm) can be determined from figure 8–16 (Lane 1955a). The curves relate the median grain size of the soils to the allowable shear stress. The curve labeled as high sediment content is to be used when the stream under consideration carries a load of 20,000 parts per million by weight or more of fine suspended sediment. The curve labeled low sediment content is to be used for streams carrying up to 2,000 parts per million by weight of fine suspended sediment. The curve labeled clear water is for flows with less than 1,000 parts per million.

When 5 millimeters <D_{50} <6.3 millimeters, use the allowable shear stress for 5 millimeters shown on the chart. When D_{50} is less than 0.1 millimeter and is still noncohesive, use the allowable shear stress for values of 0.1 millimeter.

Cohesive materials

The allowable shear stress concept has been applied to semicohesive and cohesive soils, but values do not correlate well with standard geotechnical parameters because resistance to erosion is affected by such factors as water chemistry, history of exposure to flows, and weathering. Analysis of experience with local channels and laboratory testing of local materials are generally recommended. Figure 8–17 gives an example of allowable shear stresses (tractive forces) for a range of cohesive materials, but where possible, values should be compared against the results of field observation or laboratory testing. The curves in figure 8–17 are converted from USSR (1936) permissible velocity data from straight channels with an average depth of 3 feet. The figure is reported in Chow (1959) and USACE (1991b). The basic soil textural class can be determined as a function of the percentages of clay, silt, and sand in the soil using the soil triangle in figure 8–18 (USDA SCS 1994).

Figure 8–14 Angle of repose for noncohesive material

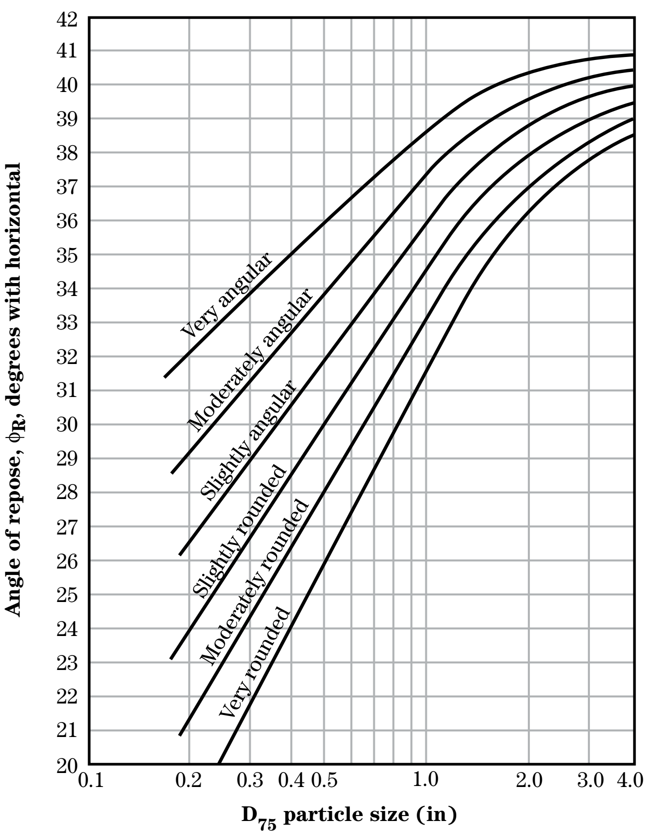


Figure 8–15 K values for allowable stress, sides of trapezoidal channels

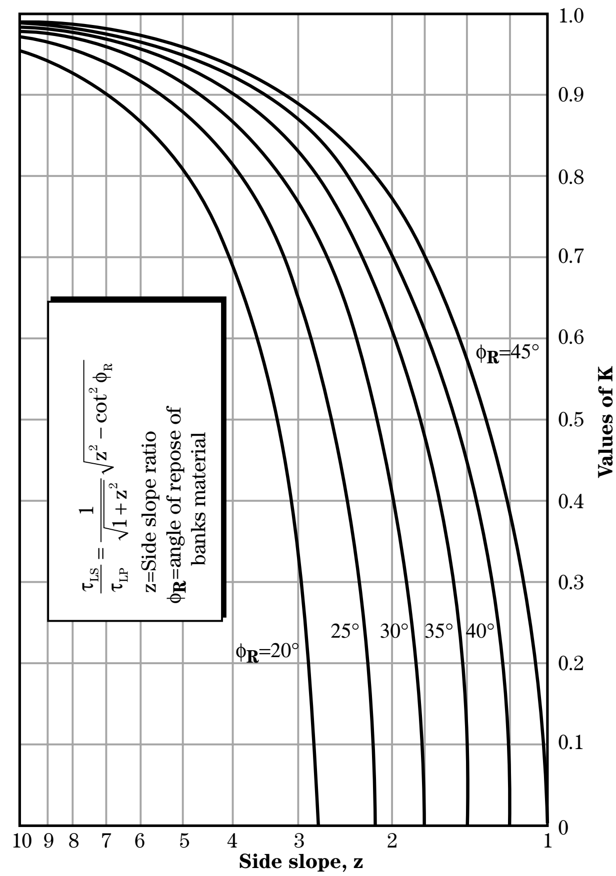


Figure 8–16 Allowable shear stress for granular material in straight trapezoidal channels

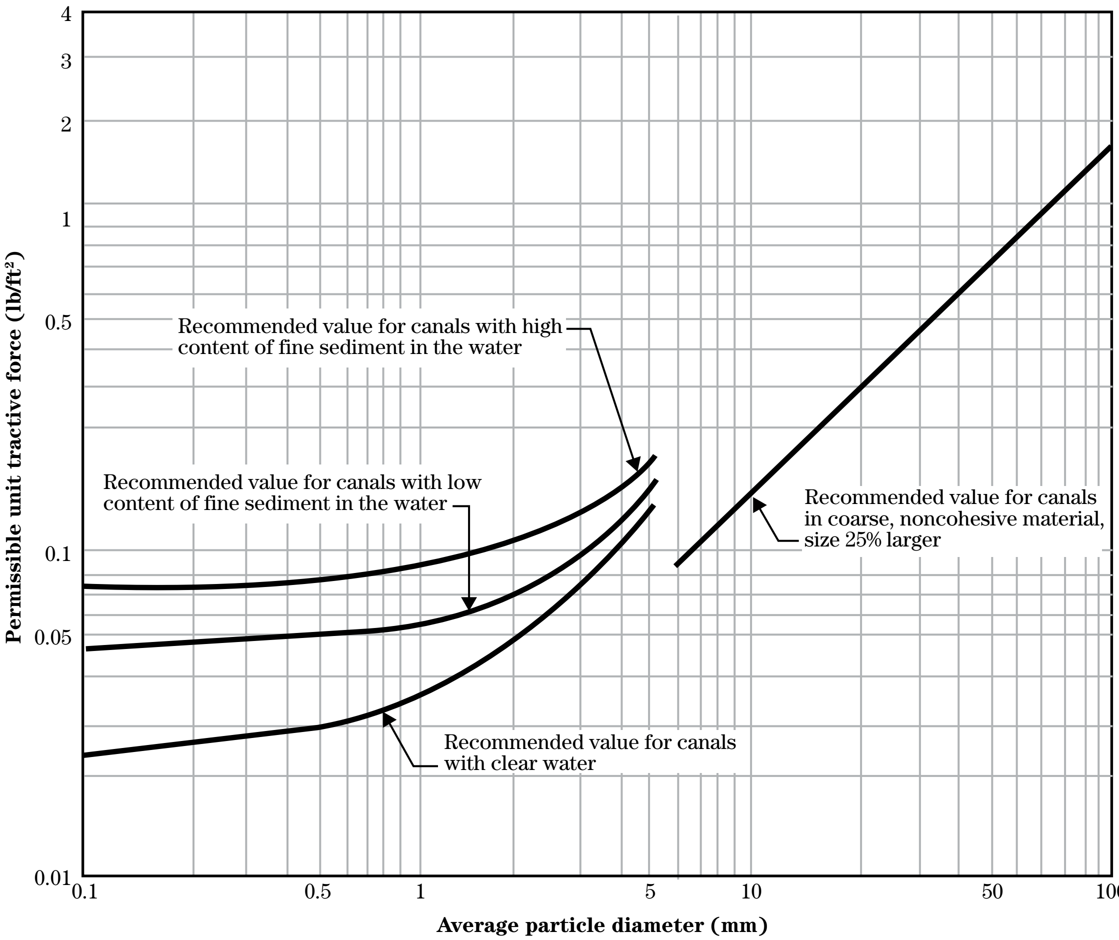


Figure 8–17 Allowable shear stress in cohesive material in straight trapezoidal channels

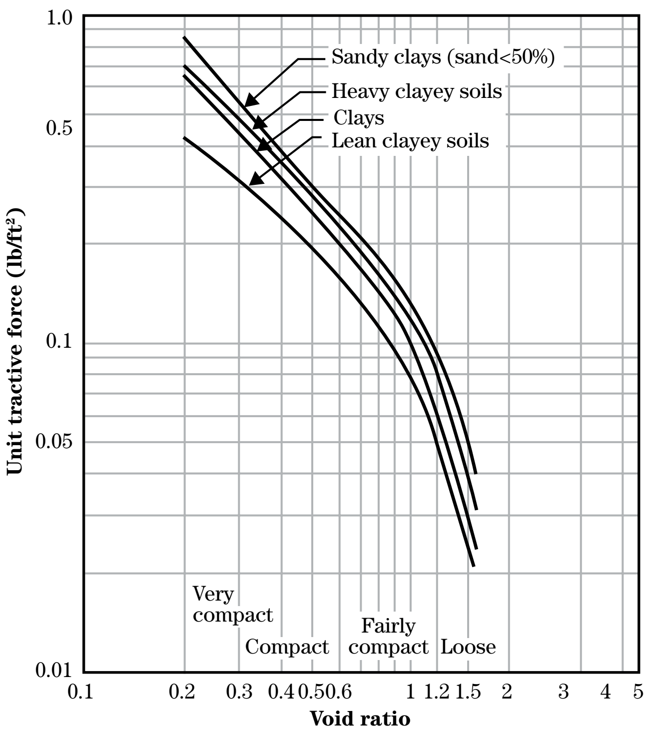
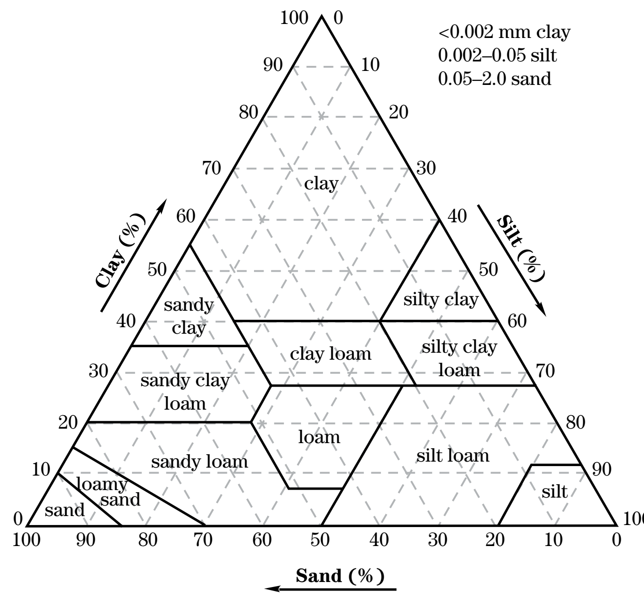


Figure 8–18 USDA textural classification chart



(c) Procedure for application of allowable shear stress method

Application of the allowable shear stress method requires first the determination of shear stress in the design channel and then comparison of the design shear stress to allowable shear stress for the boundary material. The allowable shear stress may be determined by one of three methods: Shields parameter approach, Gessler (1971) probability approach, or Lane tractive force method (Lane 1952). The characteristics of each method are summarized in table 8–5.

The use of the tractive force method to design earth channels involves the following steps modified from those found in TR–25, Design of Open Channels (USDA SCS 1977).

Step 1 Determine the hydraulics of the channel. This includes the hydrologic determinations, as well as the stage-discharge relationships for the channel being considered.

Step 2 Determine the soil properties of the bed and banks of the design reach and of the channel upstream.

Step 3 Determine the concentration of the suspended fine sediment load entering the reach. This is best accomplished by measurements. Channels with suspended fine sediment concentrations less than 1,000 parts per million are considered sediment free. Sediment-free flows are considered to have no effect on channel stability. Channels with suspended fine sediment concentrations greater than 20,000 parts per million are considered to be sediment laden. Sediment-laden flows are considered to enhance sediment stability by filling boundary interstices with cohesive material. If a significant portion of the inflowing sediment load is bed-material load, it is likely that the channel is alluvial, and threshold design methods are not applicable.

Step 4 Check to see if the allowable shear stress approach is applicable. Use table 8–1.

Step 5 Compute the applied shear stress on the boundary of the channel being studied. For noncohesive bed materials, grain shear stress can be calculated using the Limerinos equation or the Lane equation. If the Shields parameter or Gessler probability methods are used, calculate the grain shear stress using the Limerinos equation and the D_{84} of the boundary material. A factor of safety should be added to this calculated grain shear stress if the Shields parameter approach is to be used. If the tractive force method is used, calculate grain shear stress using Lane's equation with the D_{75} of the boundary material. Lane's equation already accounts for the factor of safety, so there is no need to increase the calculated applied shear stress. If the bed material is cohesive, use the total shear stress as the applied shear stress. Use (with caution) figures 8–8 and 8–9 to determine applied shear stress on the outside of bends.

Step 6 Check the ability of the soil materials forming the channel boundary to resist the computed applied shear stress. If the Shields parameter method is used, determine an appropriate Shields parameter and calculate critical shear

Table 8–5 Characteristics of methods to determine allowable shear stress

	Theoretical basis	**Bed characteristics**	**Safety factor**	**Basis for coefficients**
Shields parameter	The force on a single particle that initiates sediment motion	Noncohesive	No	Flumes and channels
Gessler probability	Probability distribution of force on a particle mixture	Noncohesive	Yes	Flume
Lane	Force on surface area	Separate equations and charts for coarse and fine-grained, noncohesive materials and cohesive material	Yes	Channels

stress. If the Gessler probability method is used, calculate critical shear stress for each size class in the mixture using figure 8–11. Then calculate the probability for each size class to stay in place, using figure 8–13. Finally, calculate the probability function for the bed mixture using Gessler's equation. For Lane's coarse-grained soils method, use Lane's equations with D_{75} to calculate allowable shear stress on the channel bottom and the channel slide slope. Lane's K factor for side slope allowable shear stress can also be adapted for use with the Shields parameter and Gessler probability methods. For Lane's method for fine-grained soils use figure 8–16 with the D_{50} and wash load sediment concentration to determine allowable shear stress. For cohesive materials, allowable shear stress should be determined by laboratory testing. Approximate values of allowable shear stress based on soil properties can be determined from figure 8–17.

Step 7 Compare the design shear stress with the allowable shear stress. If the allowable shear stress is greater than the design shear stress, the design is satisfactory. Otherwise, three options are available:

- Redesign the channel to reduce shear stress.
- Provide structural measures (riprap, grade control) to prevent erosion.
- Consider a mobile boundary condition and evaluate the channel using appropriate sediment transport theory and programs.

Step 8 Do a performance check to determine at what discharge the allowable shear stress is exceeded and the bed becomes alluvial.

(d) Limitations and cautions

For channels with substantial bed-material sediment load, aggradation of the design channel could be a problem in a channel designed using allowable velocity or allowable shear stress methods. A minimum velocity or shear stress must be determined that ensures sediment transport through the design reach, in addition to the allowable value. The minimum permissible velocity that prevents deposition is a function of the sediment concentration and the sediment transport capacity of the channel. Generally, for irrigation canal design, a mean velocity of 2 to 3 feet per second may be used safely, when the sediment load in the channel is small (Chow 1959).

In bends and meandering channels, bank erosion and migration may occur even if average velocities and shear stresses are well below allowable values.

An allowable velocity or shear stress analysis will not in itself define completely the channel design because it can be satisfied by a wide range of width, depth, and slope combinations. The design, therefore, must be supplemented by additional guidelines for slope, width, or cross-sectional shape. Usually, the slope will be predetermined within narrow limits, and practicable limits of width-to-depth ratio will be indicated by the existing channel.

The distinction between incipient motion and allowable velocity and shear stress must be remembered. Velocity and shear stress at incipient motion, when the particles on the bed begin to be entrained, are less than allowable velocity and shear stress used in design. Allowable values must include an allowance for the fluctuation of velocity and shear stress caused by turbulence. Channels should be designed using criteria that include some factor of safety beyond incipient motion.

It is important to remember that not all of the shear stress applied on the channel bottom is actually available to erode the channel bed. In sand channels especially, the bed is normally covered with bedforms, which dissipate some of the shear stress. Bedforms and irregularities also occur in many channels with coarser beds. Then it is necessary to use more complex approaches that involve separating the total applied shear stress into two or more parts, where only the shear stress associated with the roughness of the sediment grains must be less than the allowable shear stress.

Example: Allowable shear stress design

Given: A proposed flood channel has a bottom width of 8 feet, side slopes of 2H:1V, and energy slope of 0.00085. The channel will flow at a normal depth of 4 feet, a velocity of 3.2 foot per second, and a discharge of 200 cubic feet per second. The soils are slightly angular sandy gravels, with D_{75} of 0.75 inches. Manning's coefficient for the entire channel is estimated at 0.025. The channel has a curve with radius of curvature of 40 feet.

Problem: Check stability using allowable shear stress approach.

Solution:

Step 1 Calculate actual stresses on bed, sides, and curve.

a. Reference stress, τ_∞

$$\tau_\infty = \gamma d S_e \left(\frac{n_t}{n}\right)^2$$

$$n_t = \frac{\left(D_{75}\right)^{\frac{1}{6}}}{39} = 0.0244$$

$$\tau_\infty = (62.4)(4)(0.00085)\left(\frac{0.0244}{0.025}\right)^2 = 0.2021 \text{ lb/ft}^2$$

b. Actual stress on channel bed, τ_b

$$\tau_b = \tau_\infty \left(\frac{\tau_b}{\tau_\infty}\right)$$

Using figure 8–5,

$$\frac{b}{d} = \frac{8}{4} = 2 \text{ and } z=2$$

$$\frac{\tau_b}{\tau_\infty} = 0.89$$

$$\tau_b = (0.2021)(0.89) = 0.1799$$

c. Actual stress on channel bed, curved reach, τ_{bc}

$$\tau_{bc} = \tau_b \left(\frac{\tau_{bc}}{\tau_b}\right)$$

Using figure 8–8:

$$\frac{R_c}{b} = \frac{40}{8} = 5$$

$$\frac{\tau_{bc}}{\tau_b} = 1.56$$

$$\tau_{bc} = (0.1799)(1.56) = 0.281 \text{ lb/ft}^2$$

d. Actual stress on channel sides, τ_s

$$\tau_s = \tau_\infty \left(\frac{\tau_s}{\tau_\infty}\right)$$

Using figure 8–6: $\frac{b}{d} = \frac{8}{4} = 2$ and z=2

$$\frac{\tau_s}{\tau_\infty} = 0.76$$

$$\tau_s = (0.2021)(0.76) = 0.154 \text{ lb/ft}^2$$

e. Actual stress on channel sides, curved reach, τ_{sc}

$$\tau_{sc} = \tau_s \left(\frac{\tau_{sc}}{\tau_s}\right)$$

$$\tau_s = (0.2021)(0.76) = 0.154 \text{ lb/ft}^2$$

Step 2 Calculate allowable stresses on beds and sides, τ_{Lb} and τ_{Ls}.

a. Allowable stress on bed, τ_{Lb}

$\tau_{Lb} = 0.4\,D_{75}$
$= (0.4)\,(0.75) = 0.3 \text{ lb/ft}^2$

b. $\tau_{Ls} = 0.4\,D_{75}K$

For K:

Use figure 8–14 and D_{75} = 0.75 in:

$\Phi_R = 34.3^\circ$ for subangular

Use figure 8–15, z = 2 and $\Phi_R = 34.3^\circ$:

K = 0.6

$\tau_{Ls} = 0.4\,(0.75)\,(0.6) = 0.18 \text{ lb/ft}^2$

Step 3 Compare actual with allowable stress for stability check.

$\tau_b = 0.1799$, $\tau_{bc} = 0.281 < \tau_{Lb} = 0.3 \text{ lb/ft}^2$ (OK)

$\tau_s = 0.154 < \tau_{Ls} = 0.18 \text{ lb/ft}^2 < \tau_{sc} = 0.24$

Therefore, for the channel to be considered to be stable, the curved reach needs a change in the hydraulics, less curvature, and/or some sort of armoring of the banks.

654.0805 Tractive power method

The tractive power method was developed by the NRCS (formally SCS) in the western United States in the 1960s to evaluate the stability of channels in cemented and partially lithified (hardened) soils. In this approach, the aggregate stability of saturated soils is assessed by use of the unconfined compression test. Field observations of several channels were evaluated against the unconfined compression strength of soil samples taken from the same channels. The results are shown in figure 8–19. Soils in channels with unconfined compression strength versus tractive power that plot above and to the left of the S-line have questionable resistance to erosion. Soils in channels with unconfined compression strength versus tractive power that plot below and to the right of the S-line can be expected to effectively resist the erosive efforts of the stream flow.

Tractive power is defined as the product of mean velocity and tractive stress. Tractive stress is calculated using the Lane method for the appropriate soil characteristics.

The use of the tractive power method to design earth channels involves the following steps modified from those found in TR–25, Design of Open Channels (USDA SCS 1977).

Step 1 Determine the hydraulics of the channel. This includes the hydrologic determinations, as well as the stage-discharge relationships for the channel being considered.

Step 2 Determine the soil properties of the bed and banks of the design reach and of the channel upstream. This includes the saturated unconfined compressive strength.

Step 3 Determine the concentration of the suspended sediment load entering the reach. This is best accomplished by measurements. Channels with suspended sediment concentrations less than 1,000 parts per million are considered sediment free. Sediment free flows are considered to have no effect on channel stability. Channels with suspended sediment concentrations greater than 20,000 parts per million are considered to be sediment laden. Sediment laden flows are considered to enhance sediment stability by filling boundary interstices with cohesive material. If a significant portion of the inflowing sediment load is bed-material load, it is likely that the channel is alluvial, and threshold design methods are not applicable.

Step 4 Check to see if the tractive power method is applicable. Use table 8–1.

Step 5 Compute the tractive power on the boundary of the channel being studied. Use velocity from step one. Calculate applied tractive force using the appropriate equation based on the boundary characteristics. For noncohesive bed materials, grain shear stress can be calculated using the Limerinos equation or Lane equation. If the bed material is cohesive, use the total shear stress as the applied shear stress. Use (with caution) figures 8–8 and 8–9 to determine applied shear stress on the outside of bends.

Step 6 Check the ability of the soil materials forming the channel boundary to resist the computed applied shear stress, using figure 8–19. If the combination of tractive power and unconfined compressive strength plots below the S-line, the design is satisfactory. Otherwise, three options are available:

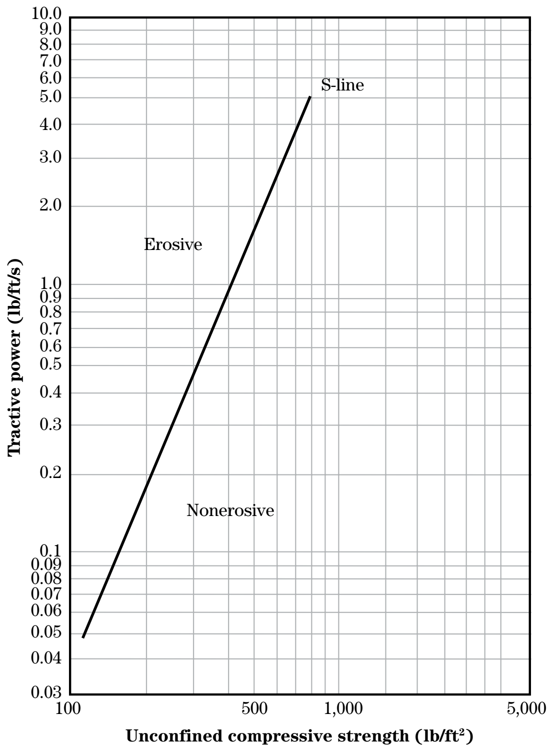
a. Redesign the channel to reduce tractive power.

b. Provide structural measures (riprap, grade control) to prevent erosion.

c. Consider a mobile boundary condition and evaluate the channel using appropriate sediment transport theory and programs.

Step 7 Do a performance check to determine at what discharge the allowable tractive power is exceeded and the bed becomes alluvial.

Figure 8–19 Unconfined strength and tractive power as related to channel stability



654.0806 Grass-lined channels

In channels where climate and soils can support permanent vegetation and baseflow does not exist, grass channel lining may be used to provide protection to erodible soil boundaries. Grass linings have been widely used to protect agricultural waterways, floodways, urban drainageways, and reservoir auxiliary spillways. The material in this section is derived from USDA Agricultural Handbook (AH) 667 (Temple et al. 1987), which has extended the concepts of SCS TP–61 (USDA SCS 1954).

(a) Allowable velocity

The method follows a similar format to the allowable or permissible velocity method described earlier. However, there are some important differences in how the allowable velocity is calculated. The allowable velocity is defined as the velocity that can be sustained for a reasonable length of time. Recommended allowable velocities for different vegetal covers, channel slopes, and soil conditions are shown in table 8–6.

Table 8–6 Allowable velocities for channels lined with grass

Cover	Slope range percent	Allowable velocity (ft/s)	
		Erosion-resistant soils	Easily eroded soils
Bermudagrass	0–5	8	6
	5–10	7	5
	>10	6	4
Buffalograss, Kentucky bluegrass, smooth brome, blue grama	0–5	7	5
	5–10	6	4
	>10	5	3
Grass mixture	0–5	5	4
	5–10	4	3
	Not recommended on slopes greater than 10%		
Lespedeza sericea, weeping lovegrass, ischaemum (yellow bluestem), kudzu, alfalfa, crabgrass	0–5	3.5	2.5
	Not recommended on slopes greater than 5%, except for side slopes in a compound channel		
Annuals—used on mild slopes or as temporary protection until permanent covers are established, common lespedeza, Sudangrass	0–5	3.5	2.5
	Not recommended for slopes greater than 5%		

Climate, soil conditions, and stability are all important factors in the selection of grass type for the channel lining. Grasses that grow in bunches, such as alfalfa, lespedeza, and kudzu, tend to concentrate flow at the bed surface. Although this characteristic may be helpful in discouraging sediment deposition, from a stability standpoint, these grasses are not suitable on steep slopes. For slopes greater than 5 percent, only fine, uniformly distributed sod-forming grasses, such as bermudagrass, Kentucky bluegrass, and smooth brome, are recommended for lining on the channel bottom. Sod-forming grasses tend to spread and may be objectionable in some cases. The upper side slope and channel berms may be planted with grasses, such as weeping lovegrass, that do not spread as easily.

Manning's roughness coefficients were also determined for the grasses tested at the USDA Agricultural Research Service (ARS) Laboratory, Stillwater, Oklahoma. Roughness was determined to be a function of the grass type, product of velocity (V), and hydraulic radius (R). Maximum VR values tested were about 20 square feet per second. These roughness values should be used to calculate the average velocity for the design channel. Average curves for five degrees of flow retardance are shown in figure 8–20 (USDA SCS 1954). Descriptions of the grasses tested and their degree of retardance are given in table 8–7.

(b) Allowable shear stress

Design criteria for grass-lined channels are provided in USDA AH 667 (Temple et al. 1987). This allowable shear stress method is based on a reanalysis of available data, largely SCS TP–61 data, and a better understanding of the interaction of the flow with a vegetated boundary. The method is still semiempirical, but it improves the separation of independent variables in the design relations. Combining this method with appropriate soil erodibility relations results in an improved design procedure that is more flexible than the allowable velocity method. The allowable shear stress design method is also consistent with current nonvegetated channel design practices.

Vegetative linings can fail with increased shear stress, either by particle detachment or failure of individual vegetal elements. For soils most often encountered in practice, particle detachment begins at levels of total

Figure 8–20 Manning's roughness coefficients for grass-lined channels

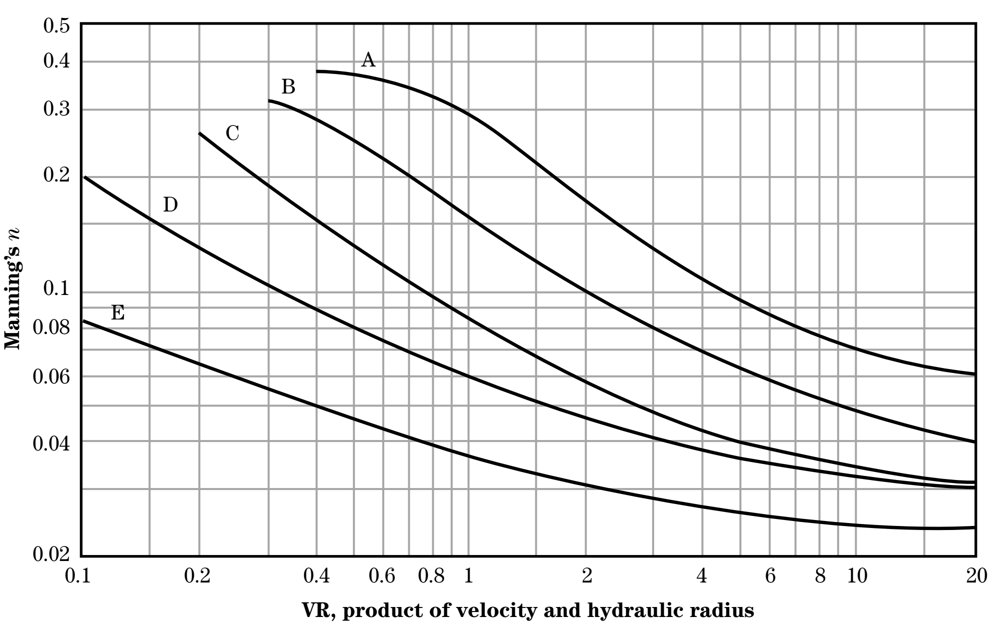


Table 8–7 Classification of degree of retardance for various kinds of grasses

Retardance	Cover	Condition
A—Very high	Weeping lovegrass	Excellent stand, tall (average 30 in)
	Yellow bluestem	Excellent stand, tall (average 36 in)
B—High	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)
C—Moderate	Crabgrass	Fair stand, uncut (10–48 in)
	Bermudagrass	Good stand, mowed (average 6 in)
	Common lespedeza	Good stand, uncut (average 11 in)
	Grass-legume mixture—summer (orchardgrass, redtop, Italian ryegrass, and common lespedeza)	Good stand, uncut (6–8 in)
	Centipede grass	Very dense cover (average 6 in)
	Kentucky bluegrass	Good stand, headed (6–12 in)
D—Low	Bermudagrass	Good stand, cut to 2.5 in
	Common lespedeza	Excellent stand, uncut, (average 4.5 in)
	Buffalo grass	Good stand, uncut (3–6 in)
	Grass-legume mixture—fall, spring (orchardgrass, redtop, Italian ryegrass, and common lespedeza)	Good stand, uncut (4–5 in)
	Lespedeza sericea	After cutting to 2 in
E—Very low	Bermudagrass	Good stand, cut to 1.5 in
	Bermudagrass	Burned stubble

shear stress low enough to be withstood by the vegetation without significant damage. When this occurs, the vegetation is undercut, and the weakest vegetation is removed. This leads to decreases in the density and uniformity of the remaining vegetative cover, which in turn leads to greater stresses at the boundary and a rapid failure of the protection. Failure progresses in much the same fashion in very resistant soils where the vegetal elements may sustain damage before the effective stress at the boundary becomes large enough to detach soil particles of aggregates. Damage to the vegetal cover in the form of removal of young and weak plants, shredding and tearing of leaves, and fatigue weakening of stems, results in an increase in effective stress on the boundary until conditions critical to erosion are exceeded. The ensuing erosion further weakens the cover and unraveling occurs. This characteristic of rapid unraveling of the channel lining once a weak point has developed, combined with the variability of vegetative covers, forces the design criteria presented in Agricultural Handbook (AH) 667 to be conservative. Therefore, a design factor of safety is built into the procedure.

The AH 667 procedure assumes that the allowable soil stress is the same for vegetated channels as for unlined channels, for which the tractive force is a suitable design parameter. For effective shear stress to be the sole stability parameter, detachment, rather than sediment transport processes must dominate stability considerations. This means that sediment deposition and sediment transport as bed-material load must be negligible.

(c) Species selection, establishment, and maintenance of grass-lined channels

The selection of grass species for use in channels for erosion control is based on site-specific factors:

- soil texture
- depth of the underlying material
- management requirements of vegetation
- climate
- slope
- type of structure or engineering design
- invasiveness of grass species and downstream impacts

Expected flow rate, availability of seed, ease of stand establishment, species or vegetative growth habit, plant cover, and persistence of established species are other factors that must be considered in selecting the appropriate grass to meet conditions critical to channel stability.

Chapter 2 of AH 667 (Temple et al. 1987) addresses the essential agronomic considerations in selecting, establishing, and maintaining grass channel linings.

(d) Determination of channel design parameters

The independent hydraulic variables governing the stability of a grass-lined open channel are the channel geometry and slope, erodibility of the soil boundary, and properties of the grass lining that relate to flow retardance potential and boundary protection.

Stability design of a grass-lined open channel using the effective stress approach requires the determination of two vegetal parameters. The first is the retardance curve index, C_I, which describes the potential of the vegetal cover to develop flow resistance. The second is the vegetal cover index, C_F, which describes the degree to which the vegetal cover prevents high velocities and stresses at the soil-water interface.

The retardance curve index can be determined from the dimensionless equation (eq. 8–28) where any consistent units of measurement can be used.

$$C_I = 2.5\left(h\sqrt{M}\right)^{\frac{1}{3}} \qquad \text{(eq. 8–28)}$$

where:
h = the representative stem length
M = the stem density in stems per unit area

The stem length will usually need to be estimated directly from knowledge of the vegetal conditions at the time of anticipated maximum flow. Table 8–8 may be used as a guide for the grass species most commonly encountered (Temple et al. 1987). When two or more grasses with widely differing growth characteristics are involved, the representative stem length is determined as the root mean square of the individual stem lengths. The reference stem densities contained in table 8–9 may be used as a guide in estimating M when more direct information is unavailable. The values in

Table 8–8 Characteristics of selected grass species for use in channels and waterways

Grass species	Height at maturity	
	(ft)	(m)
Cool-season grasses		
Creeping foxtail	3–4	0.9–1.2
Crested wheatgrass	2–3	0.6–0.9
Green needlegrass	3–4	0.9–1.2
Russian wild rye	3–4	0.9–1.2
Smooth bromegrass	3–4	0.9–1.2
Tall fescue	3–4	0.9–1.2
Tall wheatgrass		1.2–1.5
Western wheatgrass	2–3	0.6–0.9
Warm-season grasses		
Bermudagrass	3/4–2	0.2–0.6
Big bluestem	4–6	1.2–1.8
Blue grama	1–2	0.3–0.6
Buffalograss	1/3–1	0.1–0.3
Green spangletop	3–4	0.9–1.2
Indiangrass	5–6	1.5–1.8
Klein grass	3–4	0.9–1.2
Little bluestem	3–4	0.9–1.2
Plains bristlegrass	1–2	0.3–0.6
Sand bluestem	5–6	1.5–1.8
Sideoats grama	2–3	0.6–0.9
Switchgrass	4–5	1.2–1.5
Vine mesquitegrass	1–2	0.3–0.6
Weeping lovegrass	3–4	0.9–1.2
Old World bluestems		
Caucasian bluestem	4–5	1.2–1.5
Ganada yellow bluestem	3–4	0.9–1.2

Table 8–9 Retardance curve index by SCS retardance class

SCS retardance class	Retardance curve index
A	10.0
B	7.64
C	5.60
D	4.44
E	2.88

this table were obtained from a review of the available qualitative descriptions and stem counts reported by researchers studying channel resistance and stability.

Since cover conditions vary from year to year and season to season, it is recommended that an upper and lower bound be determined for C_I. The lower bound should be used in stability computations, and the upper bound should be used to determine channel capacity. Some practitioners find that the use of SCS retardance class (table 8–9) is a preferable approach.

The vegetal cover index, C_F, depends primarily on the density and uniformity of density in the immediate vicinity of the soil boundary. Because this parameter is associated with the prevention of local erosion damage which may lead to channel unraveling, the cover factor should represent the weakest area in a reach, rather than the average for the cover species. Recommended values for the cover factor are presented in table 8–10. Values in this table do not account for such considerations as maintenance practices or uniformity of soil fertility or moisture. Therefore, appropriate engineering judgment should be used in its application.

Table 8–10 Properties of grass channel linings values (apply to good uniform stands of each cover)

Cover factor (C_F)	Covers tested	Reference stem density (stems/ft^2)	Reference stem density (stems/m^2)
0.90	Bermudagrass	500	5,380
	Centipede grass	500	5,380
0.87	Buffalograss	400	4,300
	Kentucky bluegrass	350	3,770
	Blue grama	350	3,770
0.75	Grass mixture	200	2,150
0.50	Weeping lovegrass	350	3,770
	Yellow bluestem	250	2,690
0.50	Alfalfa	500	5,380
	Lespedeza sericea	300	3,280
0.50	Common lespedeza	150	1,610
	Sudangrass	50	538

Multiply the stem densities given by 1/3, 2/3, 1, 4/3, and 5/3 for poor, fair, good, very good, and excellent covers, respectively. Reduce the C_F by 20% for fair stands and 50% for poor stands.

Two soil parameters are required for application of effective stress concepts to the stability design of lined or unlined channels having an erodible soil boundary: soil grain roughness, n_s, and allowable effective stress, τ_a. When the effective stress approach is used, the soil parameters are the same for both lined and unlined channels with negligible bed-material sediment transport.

Soil grain roughness is defined as the roughness associated with particles or aggregates of a size that can be independently moved by the flow at incipient channel failure. For noncohesive soils, the soil grain roughness and effective shear stress are both a function of the D_{75} grain size. When D_{75} is greater than 1.3 millimeter, the soil is considered coarse grained. When D_{75} is less than 1.3 millimeter, the soil is considered fine grained. Fine-grained roughness is considered to have a constant value of 0.0156. Fine-grained effective shear stress is taken to have a constant value of 0.02 pound per square foot. Coarse-grained shear stress and roughness are given in figures 8–21 and 8–22.

A soil grain roughness of 0.0156 is assigned to all cohesive soils. The allowable effective stresses are a function of the unified soil classification system soil type, the plasticity index, and the void ratio. The basic allowable shear stress, τ_{ab}, is determined from the plasticity index and soil classification, and then adjusted by the void ratio correction factor, C_e, using the following equation:

$$\tau_a = \tau_{ab} C_e^2 \qquad \text{(eq. 8–29)}$$

The basic allowable effective stress can be determined from figure 8–23 and the void ratio correction factor from figure 8–24. These two figures were developed directly from the allowable velocity curves in AH 667. Stress partitioning (slope partitioning) is essential to application of figures 8–21 to 8–24, with or without vegetation (Temple et al. 1987).

(e) General design procedure

Use the basic shear stress equation to determine effective shear stress on the soil beneath the vegetation. Use any consistent units of measurement.

$$\tau_e = \gamma d S \left(1 - C_F\right)\left(\frac{n_s}{n}\right)^2 \qquad \text{(eq. 8–30)}$$

where:

τ_e = effective shear stress exerted on the soil beneath vegetation (lb/ft^2 or N/m^2)
γ = specific weight of water (lb/ft^3 or N/m^3)
d = maximum depth of flow in the cross section (ft or m)
S = energy slope, dimensionless
C_F = vegetation cover factor (0 for unlined channel), dimensionless
n_s = grain roughness of underlying soil, typically taken as dimensionless
n = roughness coefficient of vegetation, typically taken as dimensionless

The flow depth is used instead of the hydraulic radius because this will result in the maximum local shear stress, rather than the average shear stress. The cover factor is a function of the grass and stem density. Roughness coefficients are standard Manning's roughness values; n_s can be determined from figure 8–22, n can be determined from the old SCS curves (fig. 8–20) or from the following equation.

$$n_R = \exp\left\{C_I\left[0.0133\left(\ln R_v\right)^2 - 0.0954\ln R_v + 0.297\right] - 4.16\right\} \qquad \text{(eq. 8–31)}$$

where:

R_v = (VR/ν) x 10^{-5} (this dimensionless term reduces to VR for practical application in English units)
V = channel velocity (ft/s or m/s)
R = hydraulic radius (ft or m)
Limited to $0.0025 C_I^{2.5} < R_v < 36$

A reference value of Manning's resistance coefficient, n_R, is applicable to vegetation established on relatively smoothly graded fine-grained soil.

If vegetated channel liner mats are used, manufacturer-supplied roughness coefficients for particular mats may be used in the equation.

Maximum allowable shear stress, τ_{va}, in pound per square foot is determined as a function of the retardance curve index, C_I. Very little information is available for vegetal performance under very high stresses and this relation is believed to be conservative.

$$\tau_{va} = 0.75 C_I \qquad \text{(eq. 8–32)}$$

Figure 8–21 Allowable shear stress for noncohesive soils

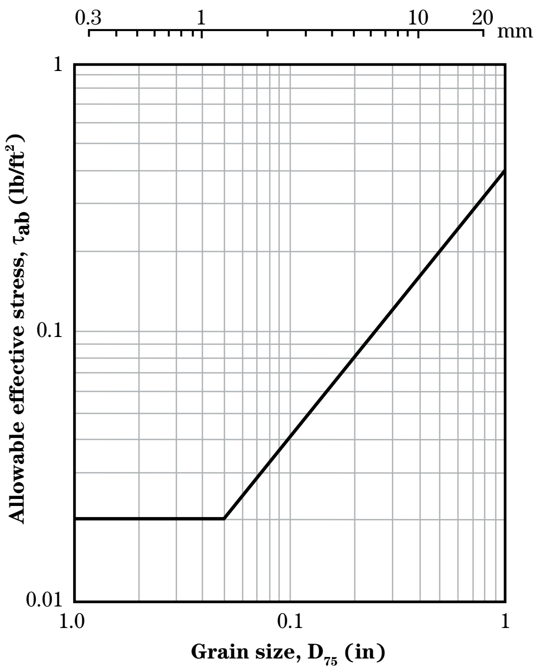


Figure 8–22 Soil grain roughness for noncohesive soils

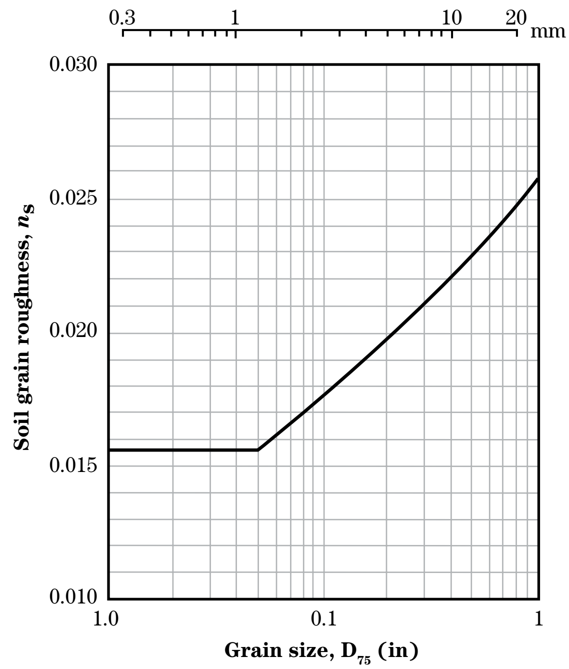


Figure 8–23 Basic allowable shear stress for cohesive soils

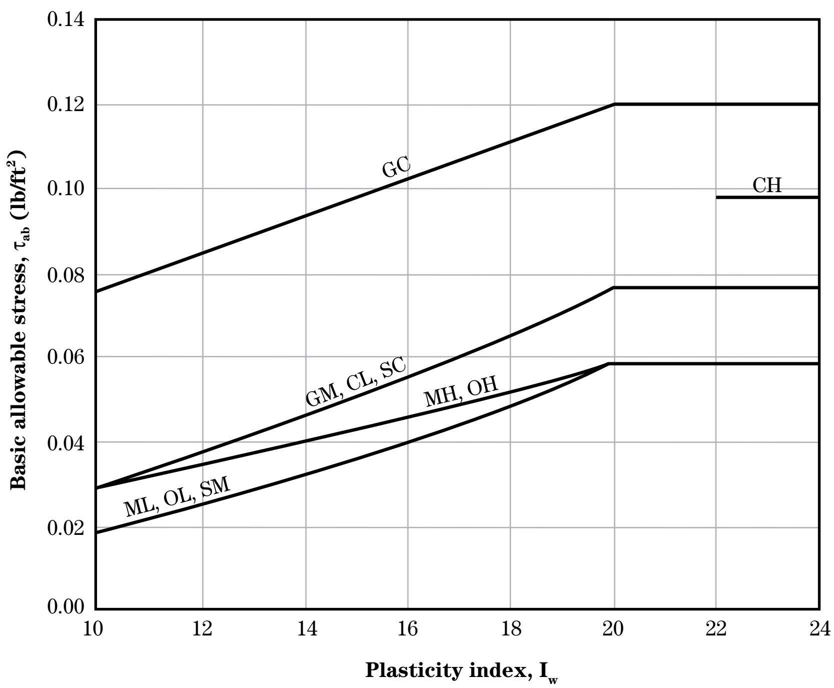
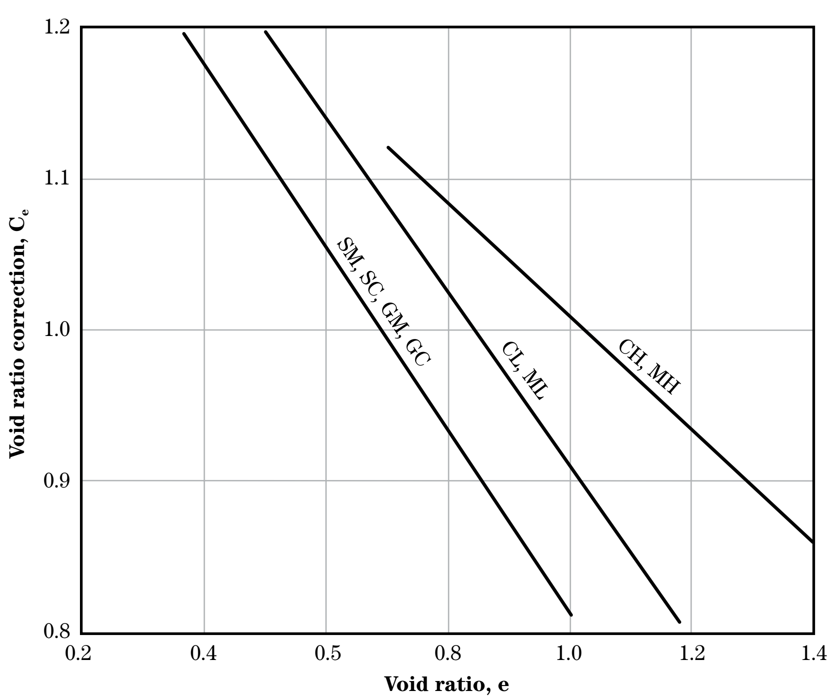


Figure 8–24 Void ratio correction factor for cohesive soils



Example problem: Threshold channel design of a grass-lined channel

Given: A vegetated floodway is to be constructed to bypass flood flows around an urban area. HEC–RAS computer program has been used to analyze the hydraulics of a preliminary design. The proposed floodway has a trapezoidal shape with bottom width of 50 feet and side slopes of 3H:1V. The floodway n value is 0.03. The floodway will have straight and curved reaches with radii of curvature equal to 300 feet. Energy slopes range from 0.00026 to 0.00060, with respective maximum flow depths of 11.0 feet and 10.5 feet.

Soils laboratory test data indicate that the floodway will be excavated into a CL soil, with plasticity index greater than 20, and void ratio of 1.2. Planned vegetation is a grass mixture of brome and Kentucky bluegrasses. Vegetation is expected to be maintained at a fair stand, equivalent to a retardance class of D.

Determine: Allowable stresses and actual stresses and compare.

Solution:

Step 1 Determine allowable stresses. Note that different references subscript the symbol for stress, τ, differently. TR–25 refers to allowable stress with the symbol, τ_L; the L stands for limiting.

a. Allowable soil stress

Basic allowable soil stress,

τ_{ab} = 0.076 lb/ft^2 (fig. 8–23; CL soil and plasticity index, I_w >20)

Void ratio correction factor, $C_e = 1.48 - 0.57e$

C_e = 0.8 (fig. 8–24; void ratio, e = 1.2)

Allowable soil stress, $\tau_a = \tau_{ab} C^2_e$

$\tau_a = 0.076\ (0.8)^2 = 0.0486$ lb/ft^2

b. Allowable vegetal stress

C_I = 4.44 (table 8–9), retardance class of D)

$\tau_{va} = 0.75\ C_I$

$\tau_{va} = 0.75\ (4.44) = 3.33$ lb/ft^2

Step 2 Determine actual stresses (straight reaches). Note that TR–25 refers to actual stress with the symbol, τ, subscripted for bed, sides.

a. Actual soil stress

$$\tau_e = \gamma dS\left(1 - C_F\right)\left(\frac{n_s}{n}\right)^2$$

For minimum slope of 0.00026 and d = 11.0 ft

γ = 62.4 lb/ft^3

n = 0.0156 (note TR–25 uses the symbol n_t)

C_F = 0.75 (0.8) = 0.6 (table 8–10; reduced 20% for fair stand of grass)

n = 0.03 (for the entire channel)

$\tau_e = (62.4)\ (11.0)\ (0.00026)\ (1 - .6)(0.0156/0.03)^2$

τ_e = 0.0193 lb/ft^2 ,which is less than the allowable soil stress of 0.0486 lb/ft^2

For maximum slope of 0.0006 and d = 10.5 ft

$\tau_e = (62.4)\ (10.5)\ (0.0006)\ (1 - 0.6)\ 0.0156/0.03)^2$

τ_e = 0.0425 lb/ft^2, which is less than the allow able soil stress of 0.0486 lb/ft^2

b. Actual vegetal stress

$$\tau_v = \left(\gamma dS_e\right) - \tau_e$$

For minimum slope,

$\tau_v = (62.4)(11.0)(0.00026) - (0.0193)$

τ_v = 0.1592 lb/ft^2

For maximum slope,

$\tau_v = (62.4)(10.5)(0.0006) - (0.0425)$

τ_v = 0.3506 lb/ft^2

which is less than the allowable vegetal stress of 3.33 pounds per square foot.

Example problem: Threshold channel design of a grass-lined channel—Continued

Step 3 Determine actual soil stress (curved reaches), τ_{ec}.

For minimum slope of 0.00026,

$$\frac{w}{r_c} = \frac{\text{water width}}{\text{radius of curvature}}$$

$$\frac{w}{r_c} = \frac{\left[(11.0)(5)(2)+50\right]}{300} = 0.533$$

$$\frac{\tau_{ec}}{\tau_e} = 2.1$$

$$\tau_{ec} = 2.1(0.0193) = 0.0405 \text{ lb/ft}^2$$

which is less than the allowable soil stress of 0.0486 lb/ft^2

For maximum slope of 0.0006,

$$\frac{w}{r_c} = \frac{\left[(10.5)(5)(2)+50\right]}{300} = 0.517$$

$$\frac{\tau_{ec}}{\tau_e} = 2.05$$

$$\tau_{ec} = 2.05(0.0425) = 0.0870 \text{ lb/ft}^2$$

which is greater than the allowable soil stress of 0.0486 pounds per square foot. The curve sections with energy slope of 0.0006 should be considered for change of planform (less curvature or flatter energy slope) or armoring.

654.0807 Allowable velocity and shear stress for channel lining materials

Allowable velocity and allowable shear stress values for a number of different channel lining materials are presented in table 8–11. Data in the table were compiled from many sources by Fischenich (2001b). Information for specific soil bioengineering practices is provided in NEH654 TS14I. Ranges of allowable velocity and shear stress, therefore, are presented in the table. For manufactured products, the designer should consult the manufacturer's guidelines to determine thresholds for a specific product.

The values in table 8–11 relate to cross-sectional averaged values. The data typically come from flumes where the flow is uniform and does not exhibit the same level of turbulence as natural channels. The recommended values are empirically derived. The designer should consider modifying tabular values based on site-specific conditions such as duration of flow, soils, temperature, debris, ice load in the stream, and plant species, as well as channel shape and planform (Hoag and Fripp 2002). To account for some of these differences, Fischenich recommends that a factor of safety of between 1.2 and 1.3 be applied to the tabular values.

The allowable limits of velocity and shear stress published by manufacturers for various products are typically developed from studies using short durations. Studies have shown that extended flow duration reduces the erosion resistance of many types of erosion control products as shown in figure 8–25. Fischenich (2001b) recommends a factor of safety be applied when flow duration exceeds a couple of hours.

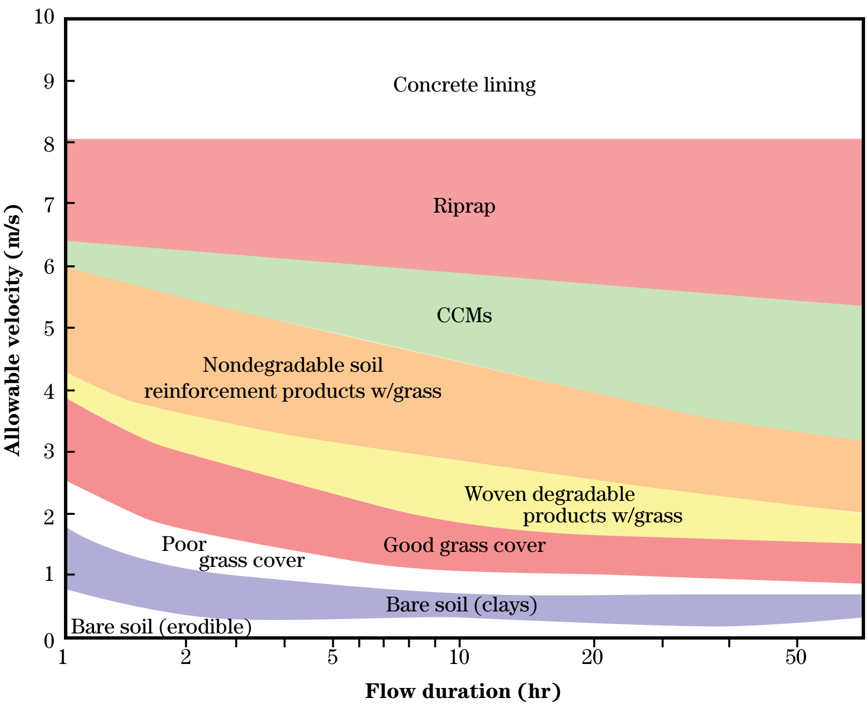
Table 8–11 Allowable velocity and shear stress for selected lining materials[1/]

Boundary category	Boundary type	Allowable velocity (ft/s)	Allowable shear stress (lb/ft^2)	Citation(s)
Temporary degradable reinforced erosion control products (RECP)	Jute net	1–2.5	0.45	B, E, F
	Straw with net	1–3	1.5–1.65	B, E, F
	Coconut fiber with net	3–4	2.25	B, F
	Fiberglass roving	2.5–7	2	B, E, F
Nondegradable RECP	Unvegetated	5–7	3	B, D, F
	Partially established	7.5–15	4–6	B, D, F
	Fully vegetated	8–21	8	C, F
Hard surface	Gabions	1–19	10	A
	Concrete	>18	12.5	E

1/ Ranges of values generally reflect multiple sources of data or different testing conditions

(Goff 1999)
(Gray and Sotir 1996)
(Julien 1995)
(Kouwen, Li, and Simons 1980)
(Norman 1975)
(TXDOT 1999)

Figure 8–25 Effect of flow duration on allowable velocities for various channel linings



*For slopes <5%

654.0808 Basic steps for threshold channel design in stream restoration projects

The following step-by-step procedure for design of natural threshold channels is from American Society of Civil Engineers (ASCE) Manual 54 (ASCE 2006). This method is applicable when width, depth, and slope are design variables; for example, slope can be varied and is not dictated by geology or other constraints. Although the procedure is presented as a series of linear steps, the actual design process is iterative, and design variables should be refined as the process proceeds from preliminary to final results. This method provides only the average channel cross-sectional dimensions. Channel variability in width and depth, and riffles and pools may be added later. Threshold methods should be used to determine the stability of the channel in areas where velocity and shear stress are increased, such as constrictions and riffles.

Step 1 Determine design bed-material gradation/channel boundary.

Determine the design bed-material gradation and the design discharge. The design discharge is the maximum flow at which channel stability is required. Channel-forming discharge theory is not generally used as the design flow for threshold channel design because the boundary of the channel will be immobile, and natural fluvial process will not be able to adjust channel dimensions.

Step 2 Determine preliminary width.

Use hydraulic geometry or regime formula (described in the NEH654.09 on alluvial channel design) with the design discharge to compute a preliminary average flow width. It is appropriate to use hydraulic geometry theory in threshold channels, even though the boundary is immobile. This is because natural flow processes will tend to form helical cells of specific widths; if the channel is too wide, ineffective flow areas will develop in the channel. If wash load is available in the stream, it may become trapped in these ineffective flow areas, and the channel will eventually narrow, even though the boundaries are immobile, and the calculated average velocity is sufficient to move the wash load.

Step 3 Estimate critical shear stress/velocity.

Using the design bed-material size gradation, estimate the critical bed stress. This may be determined using a Shields parameter approach with a factor of safety, the Gessler probability approach, or the Lane tractive force approach. If the allowable velocity approach is used, determine the allowable velocity from published tables.

Step 4 Determine flow resistance (Manning's n).

Use the bed-material size, estimated channel sinuosity, bank vegetation, and flow depth to estimate a flow resistance coefficient. The Cowan (1956) method is applicable for channels with multiple sources of roughness. If resistance due to bars and bedforms are not important, formulas such as those proposed by Limerinos (1970) or Hey (1979) may be used to compute resistance coefficients. Bathurst (1997) provides a review of flow resistance equations and their proper application.

Step 5 Calculate depth and slope.

Using the continuity equation and a uniform flow equation, compute the average depth and bed slope needed to pass the design discharge. Sinuosity may be computed by dividing the valley slope by the bed slope. Adjustment of the flow resistance coefficient for sinuosity and reiteration may be required.

Step 6 Determine planform.

Planform is a function of the sinuosity and meander wavelength. Although threshold channels are not self forming, it is appropriate to use the same techniques outlined in NEH654.09 on alluvial channels to determine planform in threshold channels.

Step 7 Assess for failure and sediment impact.

After the threshold channel design is complete, an assessment of failure should be made. This involves determination of the discharge at which the allowable velocity or shear stress would be exceeded. Confirmation should be made that the channel boundary will not become active, in which case alluvial design techniques should be examined. In addition, the possible impacts of sediment deposition should be assessed. More information on sediment impact assessments is provided in NEH654.13.

Example problem: Threshold channel design

Given:

Valley slope = 0.007 (this is the maximum possible slope)

Bed material D_{50} = 45 mm = 0.148 ft

Bed material D_{75} = 55 mm = 2.17 in

Bed material D_{84} = 60 mm = 0.197 ft

Channel side slope = 3H:1V

Specific weight of sediment = 165 lb/ft^3

Water temperature = 68 °F

Design discharge is 25-year storm = 400 ft^3/s

Problem:

Design a threshold channel to convey the design discharge.

Note: There is no unique solution with the given design constraints.

Step 1 Estimate channel width using hydraulic geometry equation (fig. 9–9, NEH654.09):

$$W = 2.03Q^{0.5}$$
$$W = 2.03(400)^{0.5}$$
$$W = 41 \text{ ft}$$

Note from figure 9–9 in NEH654.09 that widths between 22 and 74 feet are within the 90 percent single response confidence bands. If there are width constraints on the project design they may be applied here. If there are minimum depth requirements, a narrower width may be necessary. It should also be noted that the figure refers to measurements of top width. However, the difference between the top and bottom width is within the error bounds. This example will proceed with the mean width of 41 feet.

Step 2 Determine critical Shields parameter (fig. 8–10):

Initially, assume fully turbulent rough flow where grain Reynolds number >400.

$$\tau^* = 0.047$$

Step 3 Calculate critical shear stress:

$$\tau_c = \tau^*(\gamma_s - \gamma_w)D_{50}$$
$$\tau_c = (0.047)(165 \text{ lb/ft}^3 - 62.4 \text{ lb/ft}^3)(0.148 \text{ ft})$$
$$\tau_c = 0.714 \text{ lb/ft}^2$$

Step 3a. Calculate critical shear stress using the Lane equation:

$$\tau_{ab} = 0.4D_{75}$$
$$\tau_{ab} = 0.4(2.17)$$
$$\tau_{ab} = 0.868 \text{ lb/ft}^2$$

Note that the Lane equation provides a higher critical shear stress. This information will be useful in evaluating the sensitivity of the final design channel.

Step 4 Calculate depth when applied shear stress equal to critical shear stress:

$$d = \frac{\tau_c}{\gamma S}$$
$$d = \frac{(0.714 \text{ lb/ft}^2)}{(62.4 \text{ lb/ft}^2)(0.007)}$$
$$d = 1.63 \text{ ft}$$

Step 5 Calculate area and hydraulic radius for channel:

$$A = d(dz + W)$$
$$A = (1.63)[1.63(3) + 41]$$
$$A = 74.8 \text{ ft}^2$$

$$R = \frac{A}{P} = \frac{A}{\left(W + 2d\sqrt{1+z^2}\right)}$$
$$R = \frac{74.8}{\left[41 + 2(1.63)\sqrt{1+3^2}\right]}$$
$$R = 1.46 \text{ ft}$$

Example problem: Threshold channel design—Continued

Step 6 Check for fully rough flow:

$$R^* = \frac{D_{50}\sqrt{gRS}}{\upsilon}$$

$$R^* = \frac{[0.148]\left[\left(32.2\ \text{ft/s}^2\right)(1.46\ \text{ft})(.007)\right]^{0.5}}{1.082\times10^{-5}\ \text{ft}^2/\text{s}}$$

$$R^* = 7{,}850$$

R* is greater than 400, therefore, fully rough flow assumption was OK.

Step 7 Calculate Manning's roughness coefficient:

Since this is a gravel-bed stream, assume no form loss and use the Limerinos equation:

$$n = \frac{0.0926R^{\frac{1}{6}}}{1.16 + 2.03\log\frac{R}{D_{84}}}$$

$$n = \frac{(0.0926)(1.46)^{\frac{1}{6}}}{\left[1.16 + 2.03\log\left(\frac{1.46}{0.197}\right)\right]}$$

$$n = \frac{(0.0926)(1.46)^{\frac{1}{6}}}{\left[1.16 + 2.03\log\left(\frac{1.46\ \text{ft}}{0.197\ \text{ft}}\right)\right]}$$

$$n = .0337$$

Step 8 Calculate velocity and discharge:

$$V = \frac{1.49}{n}R^{\frac{2}{3}}S^{\frac{1}{2}}$$

$$V = \frac{(1.49)(1.46)^{\frac{2}{3}}(.007)^{\frac{1}{2}}}{(.0337)}$$

$$V = 4.76\ \text{ft/s}$$

$$Q = VA = (4.76\ \text{ft/s})\left(74.8\ \text{ft}^2\right)$$

$$Q = 356\ \text{ft}^3/\text{s}$$

Step 9 Modify slope until design discharge is achieved.

This iterative process can be achieved using a spreadsheet similar to the one shown in figure 8–26. The slope is decreased until the design discharge can be conveyed, without exceeding the critical shear stress. The calculated maximum slope is 0.00643. The channel planform would have a sinuosity of 1.09. The spreadsheet can also be used to evaluate the sensitivity of the solution. For example, if Gessler's criterion is applied that a stable bed should have a probability of 0.65 for the grains to stay in place, the critical shear stress is divided by 1.25 (fig. 8–13). This yields a maximum slope of 0.00473 and a sinuosity of 1.48. The solution is very sensitive to the critical shear stress. An alternative to adjusting the channel slope is to adjust the channel width between limits of the 90 percent single response confidence limits.

If movement of the bed material in this channel is a concern, select the solution where the probability of the grains on the bed to stay in place is 0.65.

Base width = 41 ft
Depth = 1.93 ft
Slope = 0.0047
Sinuosity = 1.48

As a final check, the designer should assess if the incoming sediment load can be transported through the design channel without depositing. If there is a significant incoming bed-material load, this is not a threshold channel, and alluvial channel design methods should be used. This sediment assessment is addressed in more detail in NEH654.13.

Example problem: Threshold channel design—Continued

Figure 8–26 Spreadsheet calculations for threshold channel using critical shear stress

Valley slope **0.007**
Width **41 ft**
Side slope **3**
Critical shear **0.714 lb/ft²**
D_{84} **0.197 ft**

Iteration	Slope	Sinuosity	Max depth (ft)	Area (ft²)	R (ft)	*n*	Velocity (ft/s)	Discharge (ft³/s)
1	0.007	1.00	1.63	75.0	1.46	0.0337	4.76	357
2	0.0065	1.08	1.76	81.5	1.56	0.0334	4.84	394
3	0.0064	1.09	1.79	82.9	1.58	0.0333	4.86	403
4	0.00642	1.09	1.78	82.6	1.58	0.0334	4.86	401
5	0.00643	1.09	1.78	82.5	1.58	0.0334	4.85	400

Spreadsheet calculations for threshold channel using 0.8 times critical shear stress

Critical shear **0.571 lb/ft²**

Iteration	Slope	Sinuosity	Max depth (ft)	Area (ft²)	R (ft)	*n*	Velocity (ft/s)	Discharge (ft³/s)
1	0.007	1.00	1.31	58.7	1.19	0.0347	4.04	237
2	0.005	1.40	1.83	85.1	1.62	0.0333	4.37	372
3	0.004	1.75	2.29	109.5	1.97	0.0325	4.56	500
4	0.0046	1.52	1.99	93.4	1.74	0.0330	4.44	415
5	0.0047	1.49	1.95	91.2	1.71	0.0330	4.42	403
6	0.00473	1.48	1.93	90.5	1.70	0.0331	4.42	400

654.0809 Conclusion

Channels cut through bedrock or coarse bed materials, grass-lined channels, and channels with cohesive beds may be designed using threshold methods. Typically, bed-material sediment transport is negligible in a threshold channel, although fine sediments that do not interchange with the bed (wash load) may be transported through the channel. The objective of the threshold channel design procedure is to ensure that the design hydraulic parameters are less than the allowable values for the channel boundary. To provide a factor of safety, allowable design variables are typically less than the critical values for the boundary material used. Average channel velocity and shear stress are the hydraulic parameters typically used for threshold channel design. As with any stream restoration, stabilization or creation, the application of design techniques should be done with caution. In many circumstances, several techniques should be examined. For channels designed using threshold assumptions and procedures, the designer must confirm that deposition or erosion will not change the boundary conditions and result in alluvial channel behavior.