Excerpted from: Pitt, R., S. Clark, and D. Lake. *Construction Site Erosion and Sediment Controls: Planning, Design, and Performance*. “Chapter 5: Channel and Slope Stability for Construction Site Erosion Control ” DEStech Publications. Lancaster, PA. to be published 2006.

Channel Design for Stability and the Use of Soft Channel Liners

General Channel Stability Shear Stress Relationship

The following discussion on the general shear stress relationships and channel bed movement is summarized from *Engineering and Design: Channel Stability Assessment for Flood Control Projects* (COE 1994; EM 1110-2-1418). Although this reference is specifically for large channels, many of the basic concepts are similar to what occurs at construction sites, and these are specifically addressed in the following discussion..

Massive streambank failure after new development (WI DNR photo).

Sidebar Story:

Sometimes desperate times require desperate measures. On June 21, 1972 Hurricane Agnes made its way up the east coast into the southern tier of New York and north central Pennsylvania. The ensuring flooding and economic impact was dramatic and devastating. Downtown Elmira, New York recorded a flood depth of 17 feet above street level from the Chemung River. Across the valley from Elmira on a tributary to the river called Seeley Creek, people were trying to protect their property in anyway they could.

This photo, taken in July 1973, shows a number of automobiles that were pushed over the creek bank to help prevent it from washing away. Although a gravel bar has deposited due to reduced velocity and some "windshield vegetation" has been established, the effort is not in compliance with water quality standards. Many comprehensive streambank stabilization methods can be employed that both protect against erosion and provide aquatic habitat enhancements.

Scrap Metal Stream Stabilization

Bioengineered channel slopes (IECA photo)

Geogrids being filled with sand for bank protection (IECA photo)

Allowable Velocity and Shear Stress

Allowable velocity and allowable shear stress have been used to design stable channels having minimal channel erosion. Modifications of allowable velocity or shear stress to allow for sediment transport have been proposed in a few references (see the discussion on the "regime" theory in McCuen 1998, for example).

Allowable Velocity Data

The concept of allowable velocities for various soils and materials dates from the early days of hydraulics. An example of simple velocity criteria data is given by Table 5-1 (COE undated, EM 1110-2-1601). Table 5-2 is a similar table, from U.S. Bureau of Reclamation research (Fortier and Scobey 1926, reprinted by McCuen 1998), that also shows the corresponding allowable shear stresses and Manning's roughness values.

Table 5-1. Example of Simple Allowable Velocity Objectives (From COE undated, EM 1110-2-1601)

Channel Material	Mean Channel Velocity (ft/sec)
Fine Sand	2.0
Coarse Sand	4.0
Fine Gravel	6.0
Earth	
Sandy Silt	2.0
Silt clay	3.5
Clay	6.0
Grass-lined Earth (Slopes less than 5%)	
Bermuda Grass	
Sandy Silt	6.0
Silt Clay	8.0
Kentucky Blue Grass	
Sandy Silt	5.0
Silt Clay	7.0
Poor Rock (usually sedimentary)	10.0
Soft Sandstone	8.0
Soft Shale	3.5
Good Rock (usually igneous or hard metamorphic)	20.0

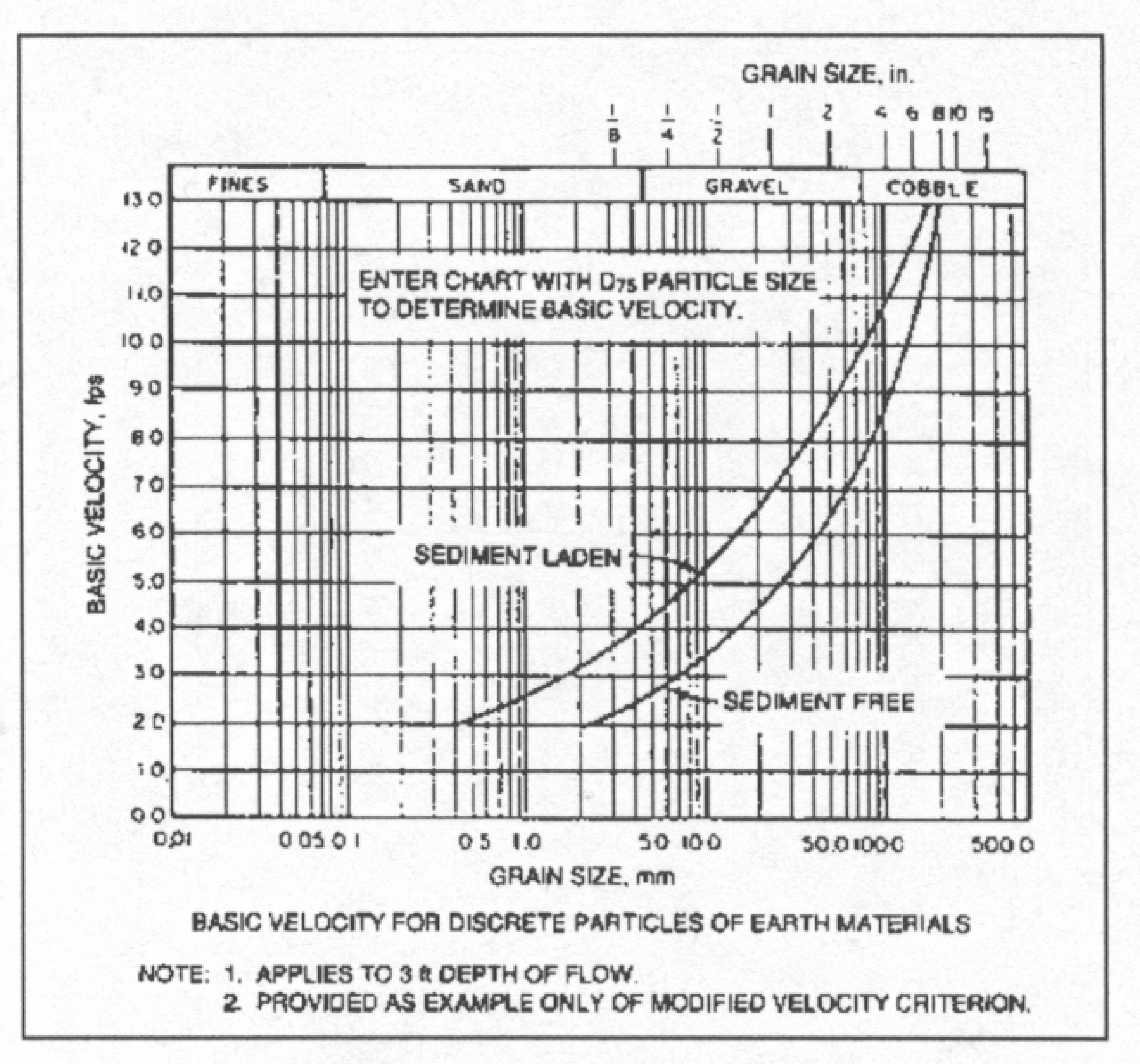
Table 5-2. Maximum Permissible Velocities and Corresponding Unit Tractive Force (Shear Stress) (U.S. Bureau of Reclamation research, Fortier and Scobey 1926)

		Clear Water (diversion structures)		Water Transporting Colloidal Silts (on site and down slope)	
Material	**n**	**V (ft/sec)**	**τ_o (lb/ft^2)**	**V (ft/sec)**	**τ_o (lb/ft^2)**
Fine sand, colloidal	0.020	1.50	0.027	2.50	0.075
Sandy loam, noncolloidal	0.020	1.75	0.037	2.50	0.075
Silt loam, noncolloidal	0.020	2.00	0.048	3.00	0.11
Alluvial silts, noncolloidal	0.020	2.00	0.048	3.50	0.15
Ordinary firm loam	0.020	2.50	0.075	3.50	0.15
Volcanic ash	0.020	2.50	0.075	3.50	0.15
Stiff clay, very colloidal	0.025	3.75	0.26	5.00	0.46
Alluvial silts, colloidal	0.025	3.75	0.26	5.00	0.46
Shales and hardpans	0.025	6.00	0.67	6.00	0.67
Fine gravel	0.020	2.50	0.075	5.00	0.32
Graded loam to cobbles when noncolloidal	0.030	3.75	0.38	5.00	0.66
Graded silts to cobbles when noncolloidal	0.030	4.00	0.43	5.50	0.80
Coarse gravel, noncolloidal	0.025	4.00	0.30	6.00	0.67
Cobbles and shingles	0.035	5.00	0.91	5.50	1.10

Note:

- an increase in velocity of 0.5 ft/sec can be added to these values when the depth of water is greater than 3 ft.
- a decrease in velocity of 0.5 ft/sec should subtracted then the water contains very coarse suspended sediments.
- for high and infrequent discharges of short duration, up to 30% increase in velocity can be added

Figure 5-1 is another guidance illustration showing SCS data (USDA 1977). This figure differentiates between "sediment-free" and "sediment-laden" flow.



BASIC VELOCITY FOR DISCRETE PARTICLES OF EARTH MATERIALS

NOTE: 1. APPLIES TO 3 ft DEPTH OF FLOW.
2. PROVIDED AS EXAMPLE ONLY OF MODIFIED VELOCITY CRITERION.

Figure 5-1. Example of allowable velocity data with provision for sediment transport (USDA 1977)

Allowable Shear Stress Data

By the 1930's, boundary shear stress (sometimes called tractive force) was generally accepted as a more appropriate erosion criterion than allowable velocity. The average boundary shear stress in uniform flow (Figure 5-3) is calculated by

$$\tau_o = \gamma RS \quad (\mathrm{lb/ft^2})$$

where:

γ = specific weight of water (62.4 $\mathrm{lbs/ft^3}$)
R = hydraulic radius (ft)
S = hydraulic slope (ft/ft)

Figure 5-2 (Chow 1959) shows a typical distribution of the shear stresses in a channel, indicating how the maximum shear stress occurs along the center of the channel for straight channel reaches having constant depths.

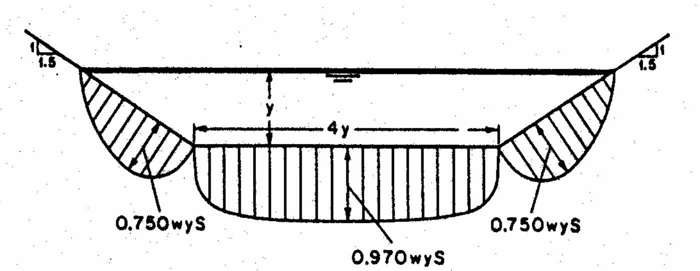


Figure 5-2. Typical shear stress distributions in a trapezoidal channel (Chow 1959).

If the maximum shear stress is desired (typical for design conditions), then the flow depth is used instead of the hydraulic radius. For sheetflow conditions, the hydraulic radius (R) is very close to the depth of flow, and the above equation is also modified, as shown in Figure 5-3, by using the depth of flow to replace the hydraulic radius.

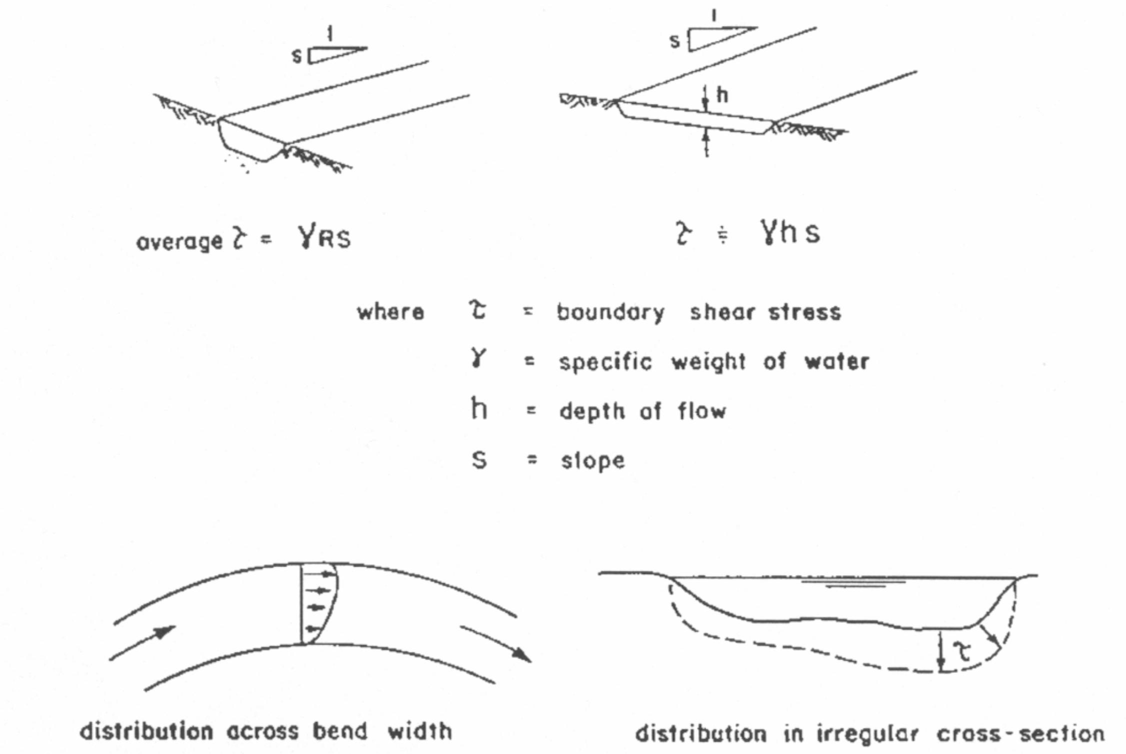


Figure 5-3. Boundary shear stress in uniform flow (COE 1994).

Flow characteristics predicting the initiation of motion of sediment in noncohesive materials are usually presented in nondimensional form in the Shield's diagram (Figure 5-4). This diagram indicates the initial movement, or scour, of noncohesive uniformly graded sediments on a flat bed. The diagram plots the Shield's number (or mobility number), which combines shear stress with grain size and relative density, against a form of the Reynolds number that uses grain size as the length variable. The ASCE *Sedimentation Manual* (1975) uses a dimensionless parameter, shown on Figure 5-4, to select the dimensionless stress value. This value is calculated as:

$$\frac{d}{\nu}\left[0.1\left(\frac{\gamma_s}{\gamma}-1\right)gd\right]^{0.5}$$

where:

d = particle diameter (meters)
g = gravitational constant (9.81 m/sec^2)
ν = kinematic viscosity (1.306 x 10^{-6} m^2/sec for 10^{o}C)
γ_s = specific gravity of the solid
γ = specific gravity of water

A series of parallel lines on Figure 5-4 represent these calculated values. The dimensionless shear stress value (τ_*) is selected where the appropriate line intersects the Shield's curve. The critical shear stress can then be calculated by:

$$\tau_c = \tau_*(\gamma_s - \gamma)d$$

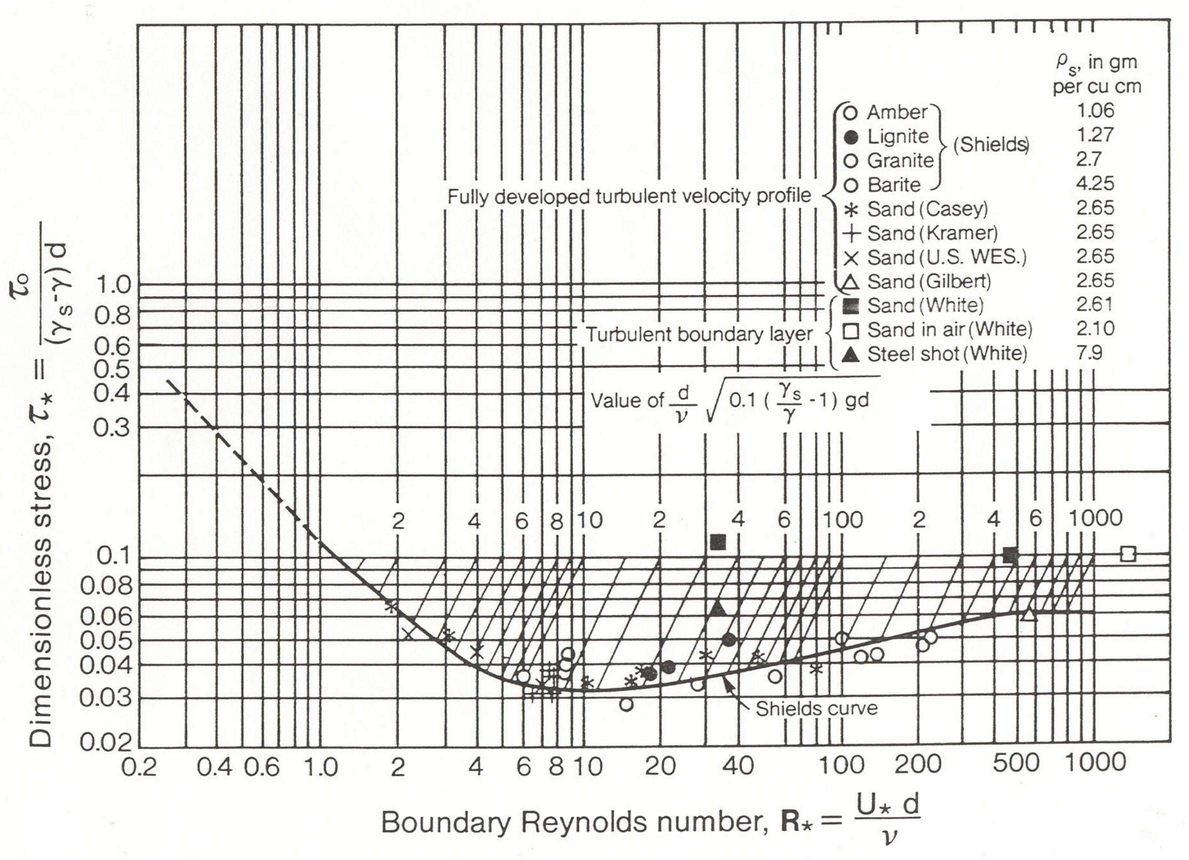


Figure 5-4. Shield's diagram for dimensionless critical shear stress (COE 1994).

The following example, presented by Chang (1988), illustrates the use of the Shield's diagram:

> "Determine the maximum depth of a wide canal for which scour of the bed material can just be prevented. The canal has rigid banks and an erodible bed; it is laid on a slope of 0.0005. The bed material has a median size of 2.5 mm and its specific gravity is 2.65. Assume a temperature of 10°C."

Therefore:

d = particle diameter (meters) = 2.5 mm = 0.0025 m
g = gravitational constant = 9.81 m/sec^2
ν = kinematic viscosity = 1.306 x 10^{-6} m^2/sec for 10°C
γ_s = specific gravity of the solid = 2.65
γ = specific gravity of water = 1

$$\frac{d}{\nu}\left[0.1\left(\frac{\gamma_s}{\gamma}-1\right)gd\right]^{0.5} = \frac{0.0025}{1.306x10^{-6}}\left[0.1\left(\frac{2.65}{1}-1\right)(9.81)(0.0025)\right]^{0.5} = 121.8$$

This line intersects the Shield's curve at $\tau_* = 0.043$. The critical shear stress is therefore:

$$\tau_c = \tau_*(\gamma_s - \gamma)d = 0.043(2.65-1)0.0025 = 1.74N/m^2$$

Using the basic shear stress formula:

$$\tau_c = \gamma DS$$

the critical depth of flow (D) is calculated to be 0.36 meters.

For sediments in the gravel size range and larger, the Shield's number for beginning of bed movement is essentially independent of the Reynolds number. For wide channels, the relationship can then be expressed as:

$$\frac{dS}{(s-1)D} = \text{constant}$$

where:

S = channel slope
s = dry relative density of sediment
D = grain size
d = depth of flow

The constant is shown as 0.06 in Figure 5-4, but it is often taken as 0.045, or even as low as 0.03 if absolutely no movement is required. For widely graded bed materials, the median grain size by weight (D_{50}) is generally taken as the representative size, although same favor a smaller percentile, such as D_{35}.

An example evaluation is given by the COE (1994) in their assessment manual. In their example, the use of the Shield's diagram is shown to likely greatly over-predict the erodibility of the channel bottom material. The expected reason they give is that the Shield's diagram assumes a flat bottom channel and the total roughness is determined by the size of the granular bottom material. The actual Manning's roughness value is likely much larger because it is largely determined by bed forms, channel irregularities, and vegetation. They recommend, as a more realistic assessment, that empirical data based on field observations be used. In the absence of local data, they present Figure

5-5 (from Chow 1959) for applications for channels in granular materials. This figure shows the permissible unit tractive force (shear stress) as a function of the average particle diameter, and the fine sediment content of the flowing water. For construction site diversion channels intercepting upland water from stable sites, the "clear" water curve is recommended. However, if the channel is on the construction site, the "high content" curve is most likely more suitable.

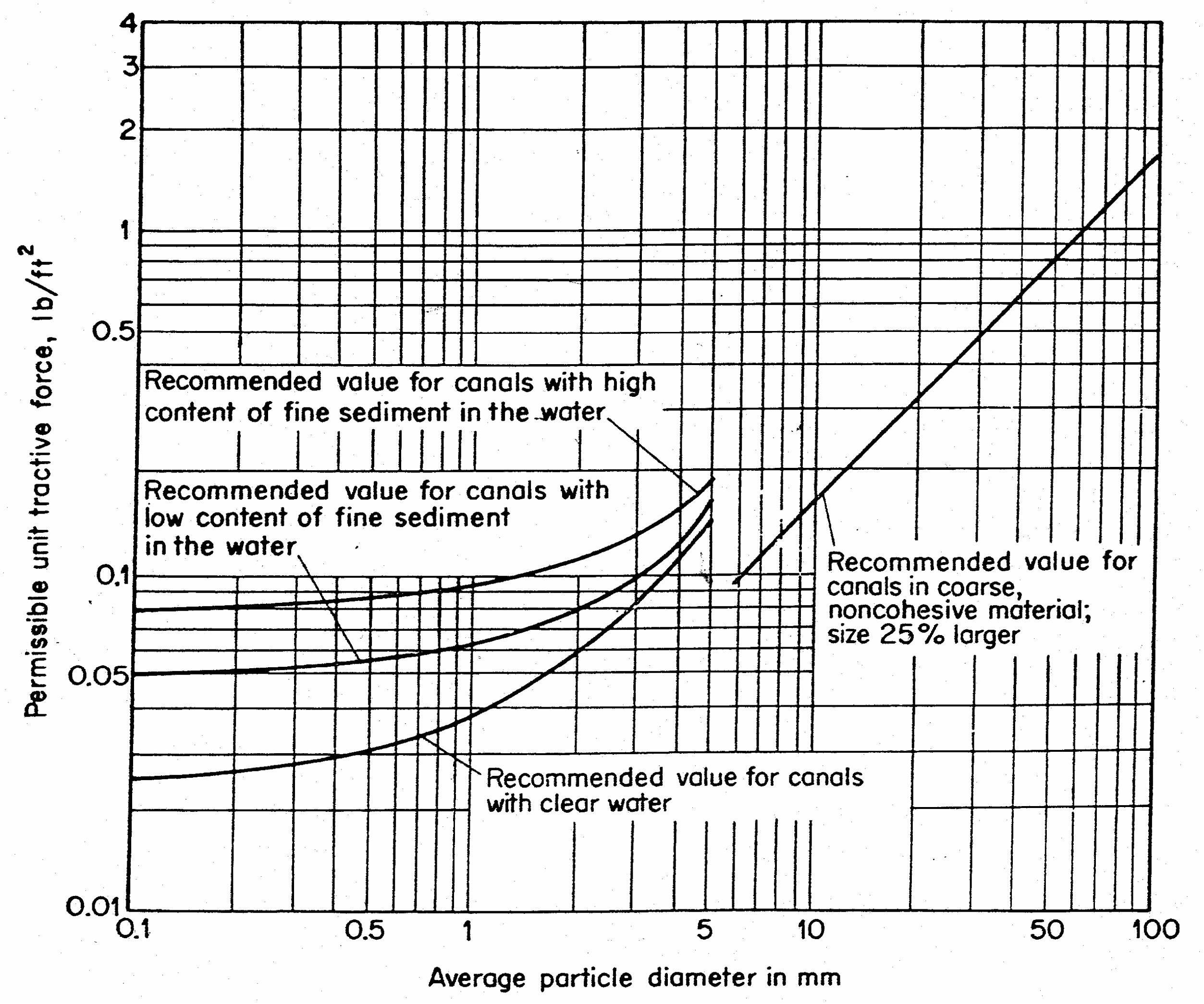


Figure 5-5. Allowable shear stresses (tractive forces) for canals in granular materials (U.S. Bureau of Reclamation, reprinted in Chow 1959).

The allowable shear stress concept has also been applied to semicohesive and noncohesive soils, but values do not correlate well with standard geotechnical parameters because the resistance to erosion is affected by such factors as water chemistry, history of exposure to flows, and weathering (Raudkivi and Tan 1984). Figure 5-6 gives an example of allowable shear stresses for a range of cohesive materials. Again, the COE recommends that local field observation or laboratory testing results be given preference.

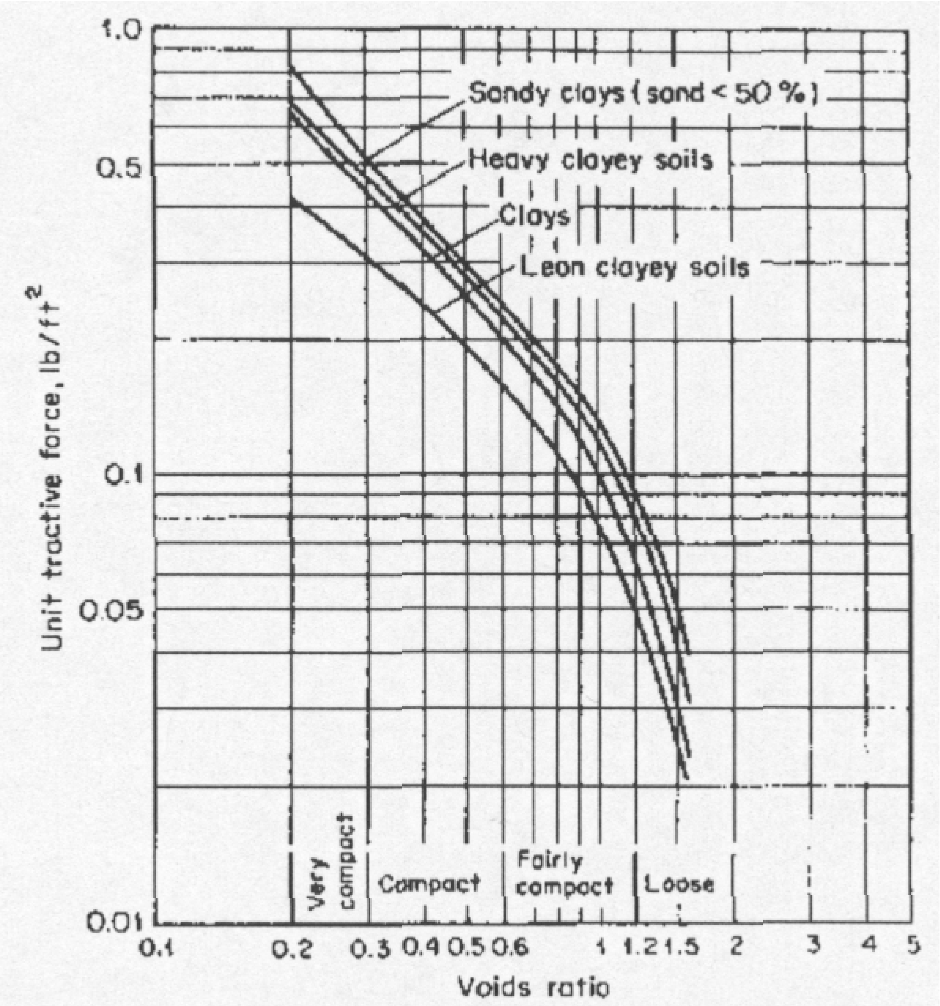


Figure 5-6. Example of allowable shear stresses (tractive forces) for cohesive materials (COE 1994).

Cautions Regarding Allowable Velocity or Shear Stress. The COE (1994) lists the following limitations of the allowable velocity and allowable shear stress approaches:

- For channels with substantial inflows of bed material, a minimum velocity or shear stress to avoid sediment deposition may be as important as a maximum value to avoid erosion. Such a value cannot be determined using allowable data for minimal erosion. [See the discussion of the "regime" theory in McCuen (1998)].

- In bends and meandering channels, bank erosion and migration may occur even if average velocities and boundary shear stresses are well below allowable values. Conversely, deposition may occur in local slack-water areas, even if average values are well above the values indicated for maximum deposition. Information on cross-sectional distributions of velocity and shear stress in bends is provided in COE (undated) (EM 1110-2-1601).

- The Shield's relationship (Figure 5-4) applies basically to uniform flow over a flat bed. In sand bed channels especially, the bed is normally covered with bed forms such as ripples or dunes, and shear stresses required for significant erosion may be much greater than indicated by the Shield's diagram. Bed forms and irregularities occur also in many channels with coarser beds. More complex approaches have been used that involve separating the total shear stress into two parts associated with the roughness of the sediment grains and of the bed forms, of which only the first part contributes to erosion. In general, however, the Shield's approach is not very useful for the design of channels in fine-grained materials.

Guidelines for Applications. The following guidelines are suggested by the COE (1994) for computations and procedures using allowable velocity and shear stress concepts:

- If cross sections and slope are reasonably uniform, computations can be based on an average section. Otherwise, divide the project length into reaches and consider values for small, medium, and large sections.

- Determine the discharge that would cause the initiation of erosion from the stage-velocity or discharge-velocity curve, and determine its frequency from a flood-frequency or flow-duration curve. This may give some indication of the potential for instability. For example, if bed movement has a return period measured in years, which is the case with some cobble or boulder channels, the potential for extensive profile instability is likely to be negligible. On the other hand, if the bed is evidently active at relatively frequent flows, response to channel modifications may be rapid and extensive.

Design Steps for Maximum Permissible Velocity/Allowable Shear Stress Method

McCuen (1998) presents the following steps when designing a stable channel using the permissible velocity/allowable shear stress method:

1) for a given channel material, estimate the Manning's roughness coefficient (n), the channel slope (S), and the maximum permissible velocity (V) (such as from Tables 5-1 or 5-2).

2) Compute the hydraulic radius (R) using Manning's equation:

$$R = \left[\frac{Vn}{1.49S^{0.5}}\right]^{1.5}$$

where:

R = hydraulic radius, ft.
V = permissible velocity, ft/sec
S = channel slope, ft/ft
n = roughness of channel lining material, dimensionless

Some typical values for Manning's n for open channels (Chow 1959) are as follows:

Very smooth surface (glass, plastic, machined metal)	0.010
Planed timber	0.011
Rough wood	0.012 – 0.015
Smooth concrete	0.012 – 0.013
Unfinished concrete	0.013 – 0.016
Brickwork	0.014
Rubble masonry	0.017
Earth channels, smooth no weeds	0.020
Firm gravel	0.020
Earth channel, with some stones and weeds	0.025
Earth channels in bad condition, winding natural streams	0.035
Mountain streams	0.040 – 0.050
Sand (flat bed), or gravel channels, d=median grain diameter, ft.	$0.034d^{1/6}$

Chow (1959) also provides an extensive list of n values, along with photographs. All engineering hydrology texts (including McCuen 1998) will also contain extensive guidance on the selection of Manning's n values.

3) Calculate the required cross-sectional area, using the continuity equation and the previously design storm peak flow rate (Q) (from Chapter 4):

$$A = \frac{Q}{V}$$

where:

A = cross-sectional area of channel (wetted portion), ft^2
Q = peak discharge for design storm being considered, ft^3/sec
V = permissible velocity, ft/sec

4) Calculate the corresponding wetter perimeter (P):

$$P = \frac{A}{R}$$

where:

P = wetted perimeter, ft
A = cross-sectional area of channel (wetted portion), ft^2
R = hydraulic radius, ft.

5) Calculate an appropriate channel base width (b) and depth (y) corresponding to a specific channel geometry (usually a trapezoid channel, having a side slope of z:1 side slopes).

Figure 5-8 (Chow 1959) can be used to significantly shorten the calculation effort for the design of channels, by skipping step 4 above and more effectively completing step 5. This figure is used to calculate the normal depth (y) of a channel based on the channel side slopes and known flow and channel characteristics, using the Manning's equation in the following form:

$$AR^{\frac{2}{3}} = \frac{nQ}{1.49S^{0.5}}$$

Initial channel characteristics that must be know include: z (the side slope), and b (the channel bottom width, assuming a trapezoid). It is easy to examine several different channel options (z and b) by calculating the normal depth (y) for a given peak discharge rate, channel slope, and roughness. The most practical channel can then be selected from the alternatives.

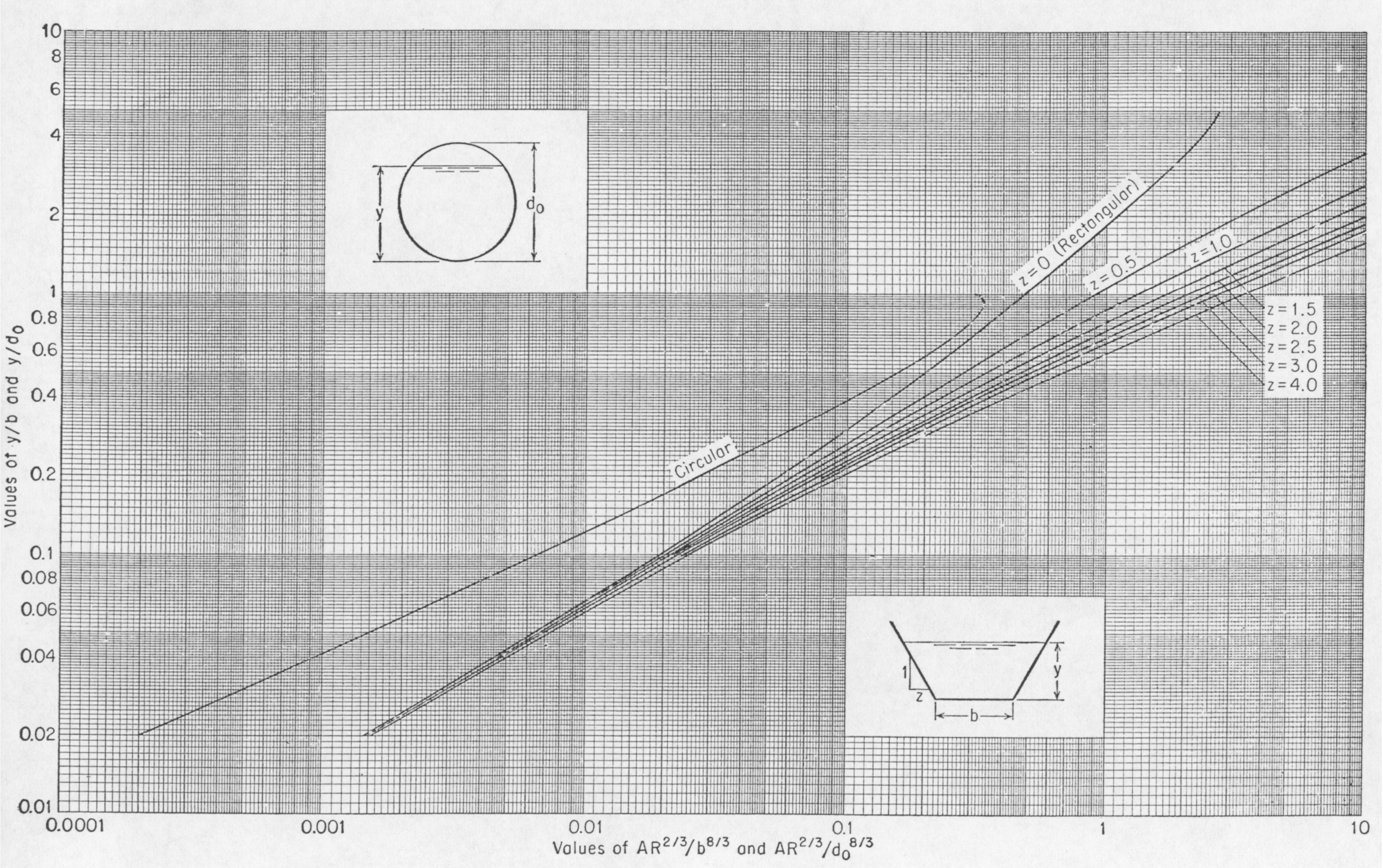


Figure 5-8. Chow (1959) curves for determining normal depth for various channel geometries.

As an example, assume the following conditions:

Noncolloidal alluvial silts, water transporting colloidal silts:
Manning's roughness coefficient (n) = 0.020
maximum permissible velocity (V) = 3.5 ft/sec
(the allowable shear stress is 0.15 lb/ft^2)

The previously calculated peak discharge (Q) = 13 ft^3/sec

Channel slope = 1%, or 0.01 ft/ft

Therefore:

The hydraulic radius (R) using Manning's equation:

$$R = \left[\frac{Vn}{1.49S^{0.5}}\right]^{1.5} = \left[\frac{3.5(0.020)}{1.49(0.01)^{0.5}}\right]^{1.5} = 0.32 ft.$$

The required cross-sectional area, using the continuity equation and the design storm peak flow rate (Q):

$$A = \frac{Q}{V} = \frac{13}{3.5} = 3.7 ft^2$$

Therefore, $AR^{2/3} = (3.7)(0.32)^{2/3} = 1.7$, and the wetted perimeter is A/R = 3.7/0.32 = 12 ft. Table 5-3 shows the calculated normal depth (y) for different channel options that all meet the allowable velocity criteria. Also shown on this table is the calculated maximum shear stress:

γyS= (62.4 lb/ft^3) (y ft) 0.01 ft/ft) = 0.62d

since the allowable shear stress is 0.15 lb/ft^2, the normal depth must be less than 0.24 ft (only about 3 inches). This will require a relatively wide channel.

As the channel becomes wider, the side slopes have little effect on the normal depth and the calculated maximum shear stress, as expected. The safety factors are the ratios of the allowable shear stress (0.15 lb/ft^2) divided by the calculated maximum shear stress. None of these channels can satisfy the allowable shear stress with this natural material, unless the channel is wide. A minimum channel width between 15 and 25 ft would result in a stable channel. However, a channel liner can be used to reinforce the channel, resulting in a larger allowable shear stress, enabling a narrower channel.

Table 5-3. Alternative Channel Geometries Meeting Maximum Permissible Velocity Criterion

Side slope (z)	Bottom width (b), ft	$b^{8/3}$	$AR^{2/3}/b^{8/3}$	y/b	Normal depth (y), ft	Maximum shear stress (τ), lb/ft^2	Safety factor (allowable shear stress/ max. shear stress)
4	2	6.4	0.27	0.32	0.62	0.38	0.39
4	4	41	0.041	0.13	0.52	0.32	0.47
4	8	260	0.0066	0.046	0.37	0.23	0.65
4	15	1400	0.0012*	0.017	0.26	0.16	0.94
4	25	5300	0.00032*	0.008	0.20	0.12	**1.25**
2	2	6.4	0.27	0.38	0.76	0.47	0.32
2	4	41	0.041	0.14	0.56	0.35	0.43
2	8	260	0.0066	0.049	0.39	0.24	0.63
2	15	1400	0.0012*	0.017	0.26	0.16	0.94
2	25	5300	0.00032*	0.008	0.20	0.12	**1.25**
1	2	6.4	0.27	0.44	0.88	0.55	0.27
1	4	41	0.041	0.16	0.64	0.40	0.38
1	8	260	0.0066	0.049	0.39	0.24	0.63
1	15	1400	0.0012*	0.017	0.26	0.16	0.94
1	25	5300	0.00032*	0.008	0.20	0.12	**1.25**
0.5	2	6.4	0.27	0.50	1.0	0.62	0.24
0.5	4	41	0.041	0.16	0.64	0.40	0.38
0.5	8	260	0.0066	0.049	0.69	0.24	0.63
0.5	15	1400	0.0012*	0.017	0.26	0.16	0.94
0.5	25	5300	0.00032*	0.008	0.20	0.12	**1.25**

* estimated, as these values are under range from the plotted curves.

A more direct approach is to use Figure 5-8 in reverse order. As shown above, the maximum depth (0.24 ft) can be calculated based on the maximum allowable shear stress and the channel slope. With the known value for $AR^{2/3}$ (1.7), Table 5-4 is used to calculate the required maximum side slope for different channel bottom widths (b). All of these options will meet both the allowable velocity and shear stress criteria.

Table 5-4. Example Calculations for Required Side Slopes for Different Bottom Widths, Meeting Allowable Velocity and Maximum Shear Stress Criteria

b (ft)	y/b	$AR^{2/3}/b^{8/3}$	Required side slope (z), or longer
8	0.030	0.0066	>4
10	0.024	0.0036	>4
15	0.016	0.0012*	5 (?)
20	0.012	0.00057*	any (0.5 to 4)

* estimated, as these values are under range from the plotted curves.

For this example, side slopes of about 5:1 and with a bottom width of 15 ft may be stable, or "any" side slope may be suitable for bottom widths of 20 ft, or wider. This example has shown that it may not be possible to design a stable channel only based on allowable maximum velocity. It is a good idea to also calculate the maximum shear stress, based on the normal depth. Without a channel liner, most stable channels in soils will need to be relatively wide. Because of the increased use of land needed for wide channels, it is usually necessary to consider channel liners, either grass-lined, or re-enforced with netting mats, as described in the following sections.

Design of Grass-Lined Channels

According to Temple, *et al.* (1987) in *Stability Design of Grass-Lined Open Channels*, USDA Agricultural Handbook # 667, it is assumed that grass channel linings are used to protect an erodible soil boundary. The following discussion is summarized from this reference. The stability limits of concern are those related to the prevention of channel degradation. Since significant bed load transport, along with its associated detachment and redeposition, is not possible with the maintenance of a quality grass cover, further design considerations may be needed to limit particle or aggregate detachment processes. This limitation results in the logical dominant parameter being the boundary stress effective in generating a tractive force on detachable particles or aggregates.

For the soils most often encountered in grass-lined channel design, particle detachment begins at levels of total stress low enough to be withstood by the vegetation without significant damage to the plants themselves. However, when this occurs, the vegetation is undercut and the weaker vegetation is removed. This removal decreases the density and uniformity of the cover, which in turn leads to greater stresses at the soil-water interface, resulting in an increased erosion rate. Supercritical flow causes a more severe problem by the tendency for slight boundary or cover discontinuities to cause flow and stress concentrations to develop during these flow conditions.

For very erosion-resistant soils, the plants may sustain damage before the effective stress at the soil-water interface becomes large enough to detach soil particles or aggregates. Although the limiting condition in this case is the stress on the plants, failure progresses in a similar manner: damage to the plant cover results in an increase in effective stress on the soil boundary until conditions critical to erosion are exceeded. The ensuing erosion further weakens the cover, and unraveling occurs.

The potential for rapid unraveling of a channel lining once a weak point has developed, combined with the variability of vegetative covers, requires conservative design criteria. Very dense and uniform covers may withstand stresses substantially larger than those specified for short periods without significant damage. Reducing of the stability limits is not advised, however, unless a high level of maintenance guarantees that an unusually dense and uniform cover will always exist. Also, unusually poor maintenance practices or nonuniform boundary conditions should be reflected in the design.

Because the failure most often observed in the field and in the laboratory has resulted from the weakening of the vegetal lining by removal of soil through the lining, few data exist related to the maximum stresses that plants rooted in highly erosion-resistant materials may withstand. Observations of cover damage under high stress conditions, however, indicate that this type of failure may become dominant when the vegetation is established on highly erosion-resistant soils. These observations also indicate that when plant failure occurs, it is a complex process involving removing young and weak plants, shredding and tearing of leaves, and fatigue weakening of stems. The use of an approximate design approach is considered appropriate for most practical applications.

Species Selection for Grass-Lined Channels

This following discussion is summarized from Temple, *et al.* (1987). This is a general discussion and does not provide site-specific guidance for different climatic regions. However, it does describe the general problems associated with establishing plants in a channel environment. Local guidance (such as from local USDA or University Extension services) needs to be sought for specific recommendations for a specific location.

The selection of grass species for use in channels is based on site-specific factors: (1) soil texture, (2) depth of underlying material, (3) management requirements of vegetation, (4) climate, (5) slope, and (6) type of structure or engineering design. Expected flow rate, availability of seed, ease of stand establishment (germination and seedling growth habit), species or vegetative growth habit, plant cover (aerial parts, height, and mulch), and persistence of established species, are other factors that must be considered in selecting the appropriate grass to meet conditions critical to channel stability.

Soil and climate of a particular area determine the best adapted grass species for erosion control in lined channels:

1) Sandy soils take water rapidly, but do not retain moisture as long as finer textured soils.
2) Moisture is more readily caught, stored, and returned to plants grown on sandy soils.
3) Fine-textured soils are more slowly permeable than sandy soils and are characterized by (a) greater runoff, yet are less erodible; (b) less total storage capacity because of well-developed B horizons; and (c) lower yield of water to plants due to the higher colloidal fraction.

Channel construction should be scheduled to allow establishment of the grass stand before subjecting the channel to excessive flows. (Note: the use of modern channel lining systems, as discussed below, help alleviate this problem.)

Establishing permanent covers must be tailored for each location because channel stability is a site-specific problem until vegetation is well established. Establishment involves liming and fertilizing, seed bed preparation, appropriate planting dates, seeding rates, mulching, and plant-soil relationships. These activities must be properly planned, with strict attention to rainfall patterns. Often the channel is completed too late to establish permanent grasses that grow best during the optimum planting and establishment season. (Again, the use of available lining mats and vegetation systems help reduce these problems.)

Selecting Plant Materials for Establishing Temporary Channel Covers

Based on flow tests on sandy clay channels, wheat (*Triticum aestivum L.*) is recommended for winter and sudangrass [*Sorghum sudanensis* (Piper) *Hitchc.*] for late-summer temporary covers. These temporary covers have been shown to increase the permissible discharge rate to five times that of an unprotected channel. Other annual and short-lived perennials used for temporary seedings include:

- barley (*Hordeum vulgare L.*), noted for its early fall growth;
- oats (*Avena) sativa L.*), in areas of mild winters;
- mixtures of wheat, oats, barley, and rye (*Secale cereale L.*);
- field bromegrass (*Bromus spp.*); and
- ryegrasses (*Lolium spp.*).

Summer annuals, for example, German and foxtail millets (*Setaria spp.*), pearl millet [*Pennisetum americanurn (L.) Leeke*], and certain cultivated sorghums other than sudangrass, may also be useful for temporary mid- to late-summer covers. Since millets do not continue to grow as aggressively as sorghums after mowing, they may leave a more desirable, uniformly thin mulch for the permanent seeding. Temporary seedings involve minimal cultural treatment, short-lived but quick germinating species, and little or no maintenance. The temporary covers should be close-drilled stands and not be allowed to go to seed. The protective cover should provide stalks, roots, and litter into which grass seeds can be drilled the following spring or fall.

Selecting Plant Materials for Establishing Permanent Covers

Many grasses can be used for permanent vegetal channel linings. The most preferred warm- and cool-season grasses for channels are the tight-sod-forming grasses; bermudagrass [*Cyodon dactylon var dactylon (L.) Pers.*], bahiagrass (*Paspalum notatum Fluggle*), buffalograss [*Buchloe dactyloides (Nutt.) Enge1m.*], intermediate wheatgrass [*Agropyron intermedium (Host) Beauv.*], Kentucky bluegrass (*Poa ratensis L.*), reed canarygrass (*Phalaris arundinacea L.*), smooth bromegrass, (*Bromus inermis Leyss.*), vine mesquitegrass (*Panicum obtusum H.B.K.*), and Western wheatgrass (*Agropyron Smithii Rydb.*). These grasses are among the most widely used species and grow well on a variety of soils.

To understand the relation between different grasses and grass mixtures to grass-lined channel use, one must consider growth characteristics and grass-climate compatibilities in the different geographic areas of the United States. A grass mixture should include species adapted to the full range of soil moisture conditions on the channel side slopes. The local NRCS and University Extension offices know the best soil-binding grass species adapted to their particular areas and associated culture information including: seeding rates, dates of seeding particular grass species, and cultural requirements for early maximum cover. The most important characteristic of the grasses selected is its ability to survive and thrive in the channel environment.

Bermudagrass is probably the most widely used grass in the South. It will grow on many soil types, but at times it may demand extra management. It forms a dense sod that persists if managed properly. When bermudagrass is used, winter-hardy varieties should be obtained. Improved varieties, such as "Coastal," "Midland," "Greenfield," "Tifton," and "Hardie," do not produce seed, and must be established by sprigging. Where winters are mild, channels can be established quickly with seed of "Arizona Common" bermudagrass. "Seed of bermudagrass," a new seed-propagated variety with greater winter hardiness than Arizona Common, should now be available commercially. Bermudagrass is not shade tolerant and should not be used in mixtures containing tall grasses. However, the inclusion of winter annual legumes such as hairy vetch (*Vicia villosa Roth.*), narrowleaf vetch [*V. sativa L. subspecies nigra (L.) Ehrh.*], and/or a summer annual such as Korean lespedeza (*Lespedeza stipulacea Maxim.*) may be beneficial to stand maintenance.

The selection of species used in channel establishment often depends on availability of seed or plant material. Chronic national seed shortages of some warm-season grasses, especially seed of native species, have often led to planting seed marginally suited to site situations. Lack of available seed of desired grass species and cultivars adapted to specific problem sites is a major constraint often delaying or frustrating seeding programs. In addition to the grass species or base mixture of grasses used for erosion control, carefully selected special-use plants may be added for a specific purpose or situation. Desirable wildlife food plants may be included in the mixture if they do not compete to the detriment of the base grasses used for erosion control. Locally adapted legumes are often added if they are compatible with the grasses and noncompetitive. Additional information on establishment and maintenance of grass-lined channels is provided in Temple, *et al*, (1987).

Hydroseeding and Mulching

Hydroseeding and mulching provide a method of planting on moderate to steep slopes, but require large amounts of water. Mulches include:

(1) Long-stem wheat straw (preferred), clean prairie hay, and so forth. Straw or hay mulches are either broadcast and "punched" in (4 to 5 inches deep) on moderate slopes with a straight disk, or broadcast along with an adhesive or tacking agent on steep slopes. About 1.0 to 1.5 tons/acre of straw is desired. Mulches conserve surface moisture and reduce summer soil surface temperatures and crusting. The disadvantages of hay and straw mulches are that they can be a source of weed seed, and too much surface mulch, regardless of the type, can cause seedling disease problems. Commercial wood fiber mulch materials are available for relatively level areas.

2) Soil retention blankets, or mats, made of various interlocking fabrics and plastic webbing can be used on moderate to steep slopes in areas with a high potential for runoff. These erosion blankets prevent seeds from being washed out by rain, and at the same time mulch and enhance germination and establishment.

Determination of Channel Design Parameters

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

Vegetation Parameters

Stability design of a grass-lined open channel by considering the effective stress imposed on the soil layer requires the determination of two vegetation 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 vegetation cover factor (C_f) which describes the degree to which the vegetation cover prevents high velocities and stresses at the soil-water interface.

Retardance Potential. The parameter describing the retardance potential of a vegetal cover is the retardance curve index, C_I. This parameter determines the limiting vegetation stress. Its relation to the measurable physical properties of the vegetal cover is given by:

$$C_I = 2.5\left(h\sqrt{M}\right)^{\frac{1}{3}}$$

where:

h is the representative stem length
M is the stem density in stems per unit area.

When consistent units are used, the relation is dimensionless. This factor is commonly used in the following equation to estimate the maximum allowable stress on the vegetation (τ_{va}, in lb/ft^2):

$$\tau_{va} = 0.75C_I$$

The stem length will usually need to be estimated directly from knowledge of the vegetation conditions at the time of anticipated maximum flow. 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.

When this equation is used to estimate the retardance potential, an estimate of the stem density is also required. The reference stem densities contained later in Table 5-5 may be used as a guide in estimating this parameter. The values of reference stem density contained in 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 will vary from year to year and season to season, establishing an upper and a lower bound for the curve index (C_I) is often more realistic than selecting a single value. When this approach is taken, the lower bound should be used in stability computations and the upper bound should be used in determining channel capacity. Such an approach will normally result in satisfactory operation for lining conditions between the specified bounds. Whatever the approach used to obtain the flow retardance potential of the lining, the values selected should represent an average for the channel reach in question, since it will be used to infer an average energy loss per unit of boundary area for any given flow.

Vegetation Cover Factor. The vegetation cover factor, $C_{f,}$ is used to describe the degree to which the vegetation cover prevents high velocities and stresses at the soil-water interface. Because the protective action described by 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 an average for the cover.

Observation of flow behavior and available data indicate that the cover factor is dominated by the density and uniformity of density in the immediate vicinity of the soil boundary. For relatively dense and uniform covers, uniformity of density is primarily dependent on the growth characteristics of the cover, which are in turn related to grass type. This relationship was used in the development of Table 5-5. This table can not obviously account for such considerations as maintenance practices or uniformity of soil fertility or moisture.

Soil Parameters
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, satisfying sediment transport restrictions. The relations presented here are taken from the SCS (1977) channel stability criteria: the desired parameters, soil grain roughness and allowable stress, are determined from basic soil parameters. Ideally, the basic parameters should be determined from tests on representative soil samples from the site.

For effective stress design, soil grain roughness is defined as that roughness associated with particles or aggregates of a size that may be independently moved by the flow at incipient channel failure. Although this parameter is expressed in terms of a flow resistance coefficient (n_s), its primary importance in design of vegetated channels is its influence on effective stress, as shown below. Its contribution to the total flow resistance of a grass-lined channel is usually negligibly small.

The allowable stress is key to the effective stress design procedure. It is defined as that stress above which an unacceptable amount of particle or aggregate detachment would occur.

Noncohesive Soil. For purposes of determining the soil grain roughness and allowable stress, noncohesive soil is divided into fine- or coarse-grained soil, according to the diameter for which 75 percent of the material is finer (d75). Ideally, the point of division for hydraulic purposes would define the point at which particle submergence in the viscous boundary layer causes pressure drag to become negligible. Strict identification of this point is impractical for channel design applications, however. For practical application in computing soil grain roughness and allowable effective stress, noncohesive soils are defined as fine- or coarse-grained, based on whether d75 is less than or greater than 0.05 in. For fine-grained soils, the soil grain roughness and allowable effective stress are constant, while for a coarse-grained soil, these parameters are a function of particle size. These required parameters for noncohesive soils are given in Figures 5-9 and 5-10, as a function of particle size.

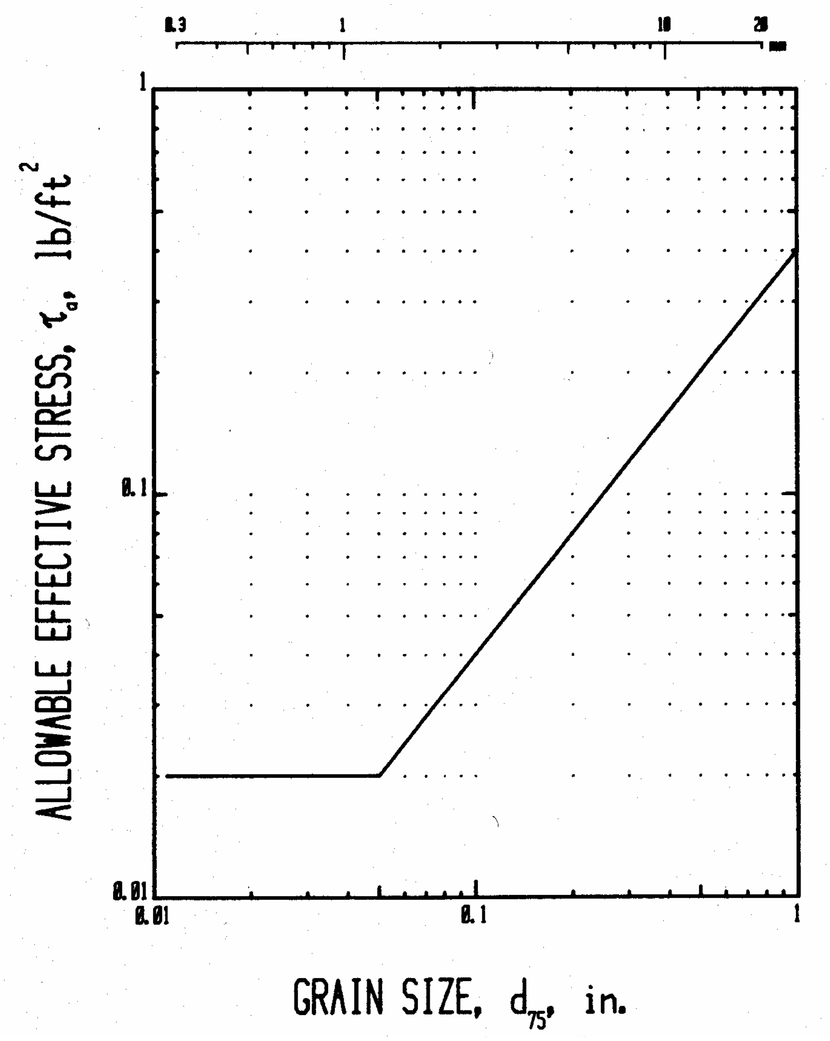


Figure 5-9. Allowable effective stress for noncohesive soils (Temple, *et al.* 1987).

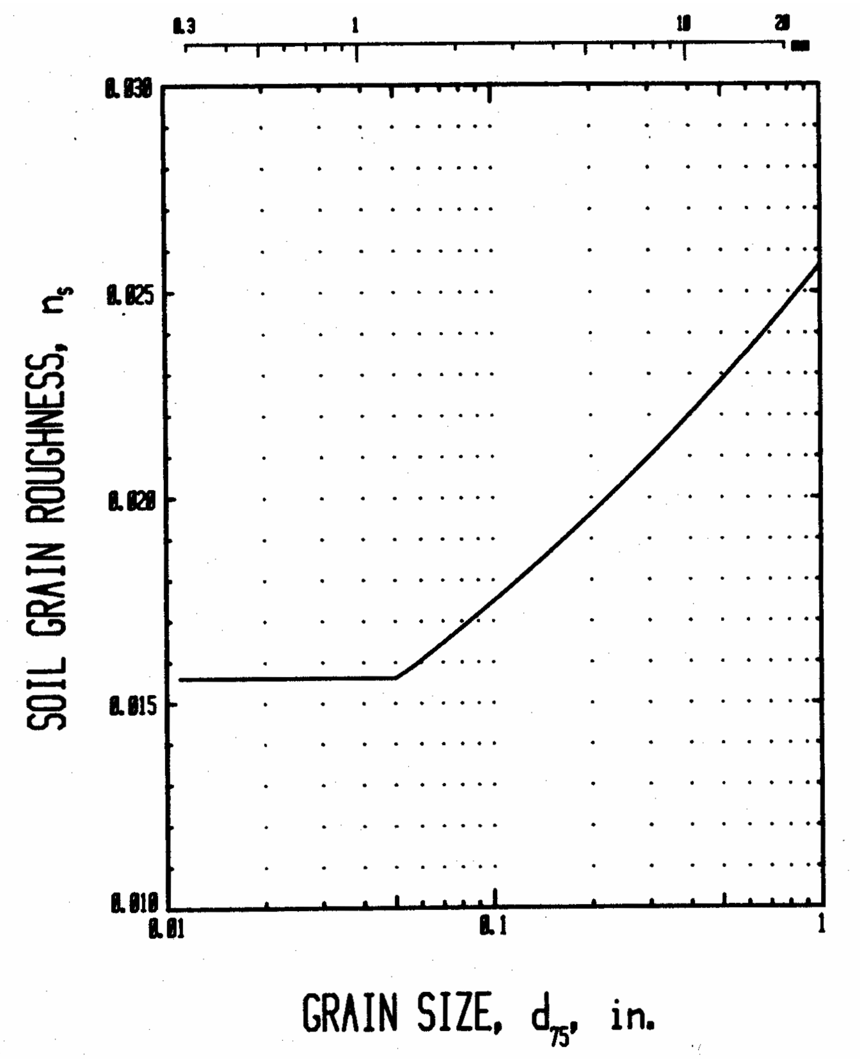


Figure 5-10. Soil grain roughness for noncohesive soils (Temple, *et al.* 1987).

Cohesive Soil. All cohesive soils are treated as fine-grained soils, having a constant soil grain roughness (about 0.0155, according to Figure 5-10). The allowable effective stresses presented here are taken directly from SCS (1977) permissible velocity design criteria. The soil properties required to determine the allowable effective stress are the soil's classification in the unified soil classification system, its plasticity index (I_w), and its void ratio (e). This calculation requires that a basic allowable effective stress (τ_{ab}) be determined from the soil classification and plasticity index. This basic value is then corrected for void ratio, according to the relation:

$$\tau_a = \tau_{ab} C_e^2$$

The basic allowable shear stress (τ_{ab}) is given in Figure 5-11, while the void ratio correction factor (C_e) is given in Figure 5-12. The soil classification information (plasticity index, I_w, and void ratio, e) are readily available for cohesive soils in standard soils references, including Temple, *et al.* (1987). See the previously presented Figure 5-6 (COE 1994) for a simplified figure for determining allowable shear stress for cohesive material for typical soils, if these detailed soil characteristics are not available.

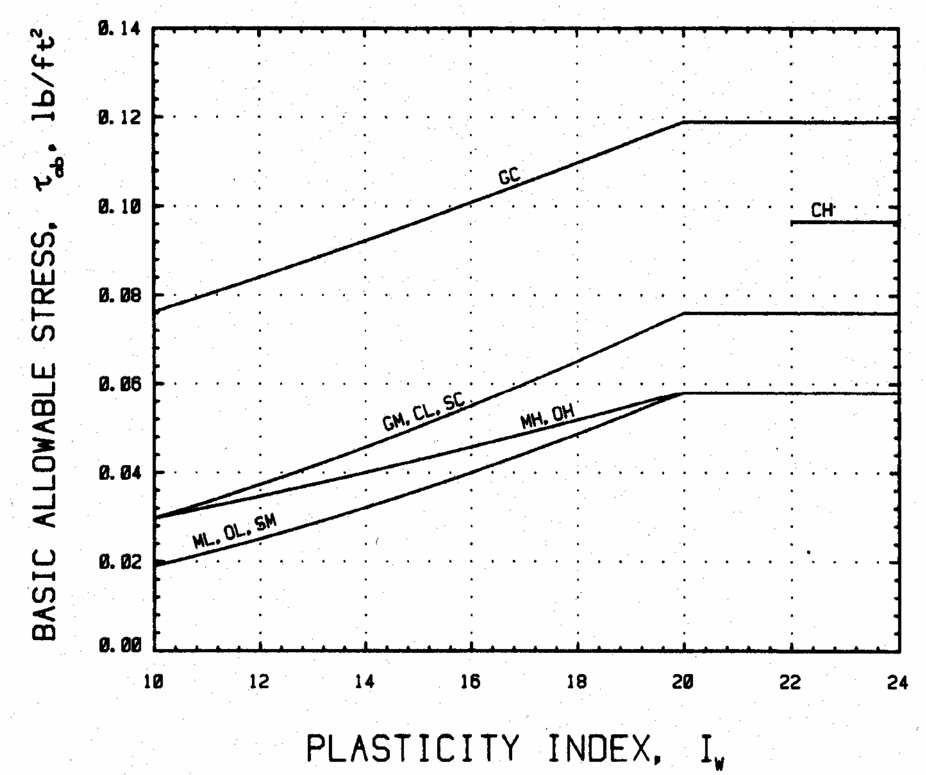


Figure 5-11. Basic allowable effective stress for cohesive soils (Temple, *et al.* 1987 and SCS 1977).

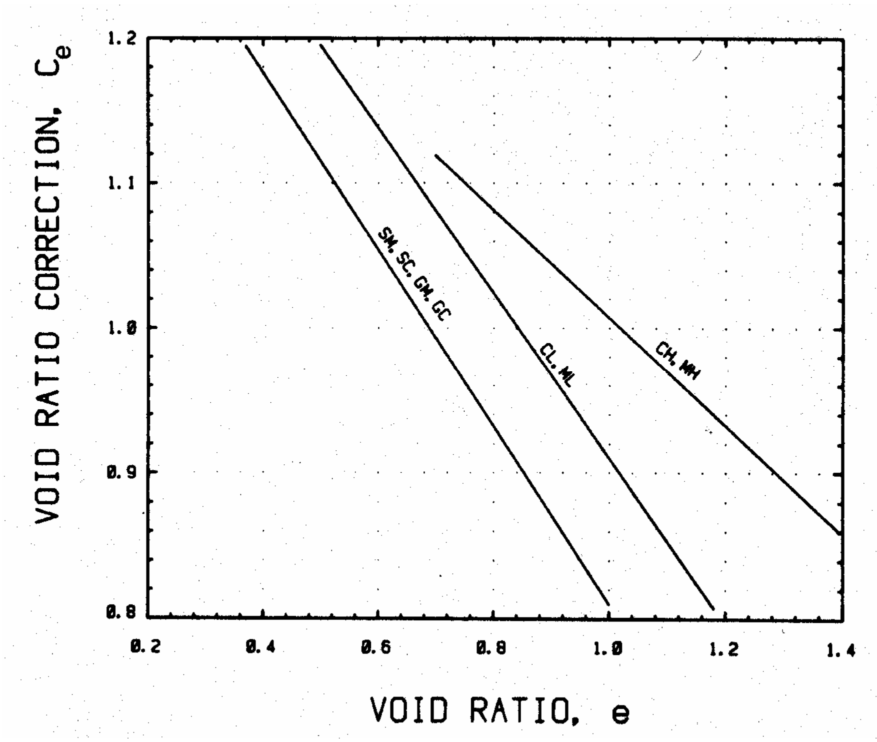


Figure 5-12. Void ratio correction factor for cohesive soils (Temple, *et al.* 1987 and SCS 1977).

General Design Procedure for Grass-Lined Channels

The design of a grass-lined open channel differs from the design of an unlined or structurally lined channel in that (1) the flow resistance is dependent on channel geometry and discharge, (2) a portion of the boundary stress is associated with drag on individual vegetation elements and is transmitted to the erodible boundary through the plant root system, and (3) the properties of the lining vary both randomly and periodically with time. Each of these differences requires special consideration in the design process. Temple, *et al*. (1987) presents detailed descriptions of the generalized step-by-step procedure for grass-lined channel design, including computer codes.

Temple, *et al.* (1987) states that numerically, stability dependent channel design may be viewed as the solution of a set of simultaneous equations relating channel geometry and flow conditions to boundary stress. The transmission of stress to the boundary via the plant root system is accounted for through a modification of the effective stress relation and an additional limit check for identification of conditions where stress on the lining rather than stress on the erodible boundary limits stability. The time variability of vegetation cover conditions is accounted for in the computational procedure through the use of different cover conditions to determine the required channel width and depth. Minimum estimated cover (minimum C_I and C_f) is assumed to determine channel width as a shape-dependent function of depth (stability). Maximum estimated cover conditions are then used to compute the required depth (capacity).

In many cases, this process is a trial-and-error procedure. Chow (1959) presented many graphical aids for the design of stable grass-lined channels. His basic steps require an initial design for channel stability (based on critical stability conditions with immature vegetation offering little protection), followed by a design for channel capacity (when the vegetation is mature, offering greater flow resistance). With a seeded channel and no protective armoring from erosion control mats, the initial channel design usually results in a broad, parabolic shape, with a very shallow depth. This was necessary to increase the flow resistance by increasing the cross-sectional area. The capacity calculations resulted in additional freeboard to account for the increased flow resistance due to mature vegetation.

Currently, the use of channel lining mats protecting immature vegetation allows immediate protection of the sensitive soil boundary layer, as described in the following discussions. Also, free computer programs, such as supplied by North American Green (http://www.nagreen.com/), greatly help in the design of the most appropriate channel cross section and liner system.

Design using Vegetated Channel Liner Mats

Current practice is to design channel linings based on shear stress and not on allowable velocity. Shear stress considers the weight of the water above the lining and therefore does a better job of predicting liner stability compared to only using velocity.

If a channel will have intermittent flows, it is common to use vegetated liners to increase the channel stability. However, if the channel will have perennial (or long-term) flows, grass will not be successful and mechanical liners must be used.

According to Croke (2000), construction site channel design using turf reinforcement mats (TRM) must consider three phases: (1) the original channel in an unvegetated state to determine if the matting alone will provide the needed protection before the vegetation is established, (2) the channel in a partially vegetated state, usually at 50% plant density, and (3) the permanent channel condition with vegetation fully established and reinforced by the matting’s permanent net structure. It is also important to base the matting failure on soil loss (usually 0.5 inch of soil; greater amounts greatly hinder plant establishment) instead of physical failure of the matting material. The basic shear stress equation can be modified to predict the shear stress applied to the soil beneath a channel mat (Temple, *et al*. 1987):

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

where:

τ_e = effective shear stress exerted on soil beneath vegetation
γ = specific weight of water (62.4 lbs/ft^3)
D = the maximum flow depth in the cross section (ft)
S = hydraulic slope (ft/ft)
C_f = vegetation cover factor (this factor is 0 for an unlined channel)
n_s = roughness coefficient of underlying soil
n = roughness coefficient of vegetation

The flow depth, rather than the hydraulic radius, is used in this equation because this will result in the maximum shear stress developed, rather than the average stress (Temple, *et al.* 1987), plus the depth value is very close to the hydraulic radius for most channels, especially as sheetflow conditions are approached. The cover factor is a function of the grass and stem density, as previously described, while the roughness coefficients are standard Manning's roughness values. The permissible shear stress for a liner mat should also be available from manufacture's specifications, but it will vary for different growth phases, if vegetated. Obviously, the liner matting significantly reduces the shear stress exerted on the soil. The following tables summarize some typical values for some of these equation parameters for erosion control mats, for different products supplied by North American Green (from www.nagreen.com). Included on these tables are conservation factor, C, values used in RUSLE for slope protection, along with roughness coefficients and maximum permissible shear stress values used in channel lining analyses. Only the P300 and C350 mats shown here are permanent liners and therefore have different values for different plant growth stages.

S75 straw erosion control blanket (12 month life; 314 g/m^2 mass per unit area)

RUSLE Conservation coefficients (C):		Channel Roughness Coefficients (n)	
	Slope Gradient (S)	Flow depth	Manning's n (unvegetated)
Slope length (L)	All ≤ 3:1 slope:	≤ 0.50 ft (0.15 m)	0.055
≤ 20 ft (6 m)	0.029	0.50 – 2.00 ft	0.055 - 0.021
20 to 50 ft	0.110	≥ 2.00 ft (0.60 m)	0.021
≥ 50 ft (15 m)	0.190	Max. permissible shear stress: 1.55 lbs/ft^2 (74.4 Pa)	

S150 straw erosion control blanket (12 month life; 323 g/m^2 mass per unit area)

RUSLE Conservation coefficients (C):			Channel Roughness Coefficients (n)	
	Slope Gradient (S)		Flow depth	Manning's n (unvegetated)
Slope length (L)	≤ 3:1	3:1 to 2:1	≤ 0.50 ft (0.15 m)	0.055
≤ 20 ft (6 m)	0.004	0.106	0.50 – 2.00 ft	0.055 - 0.021
20 to 50 ft	0.062	0.118	≥ 2.00 ft (0.60 m)	0.021
≥ 50 ft (15 m)	0.120	0.180	Max. permissible shear stress: 1.75 lbs/ft^2 (84.0 Pa)	

S150BN straw erosion control blanket (10 month life; 352 g/m^2 mass per unit area)

RUSLE Conservation coefficients (C):			Channel Roughness Coefficients (n)	
	Slope Gradient (S)		Flow depth	Manning's n (unvegetated)
Slope length (L)	≤ 3:1	3:1 to 2:1	≤ 0.50 ft (0.15 m)	0.055
≤ 20 ft (6 m)	0.00014	0.039	0.50 – 2.00 ft	0.055 - 0.021
20 to 50 ft	0.010	0.070	≥ 2.00 ft (0.60 m)	0.021
≥ 50 ft (15 m)	0.020	0.100	Max. permissible shear stress: 1.85 lbs/ft^2 (88.0 Pa)	

SC150 straw erosion control blanket (24 month life; 424 g/m^2 mass per unit area)

RUSLE Conservation coefficients (C):				Channel Roughness Coefficients (n)	
	Slope Gradient (S)			Flow depth	Manning's n (unvegetated)
Slope length (L)	≤ 3:1	3:1 to 2:1	≥ 2:1	≤ 0.50 ft (0.15 m)	0.050
≤ 20 ft (6 m)	0.001	0.048	0.100	0.50 – 2.00 ft	0.050 - 0.018
20 to 50 ft	0.051	0.079	0.145	≥ 2.00 ft (0.60 m)	0.018
≥ 50 ft (15 m)	0.100	0.110	0.190	Max. permissible shear stress: 2.00 lbs/ft^2 (96.0 Pa)	

SC150BN straw erosion control blanket (18 month life; 424 g/m^2 mass per unit area)

RUSLE Conservation coefficients (C):				Channel Roughness Coefficients (n)	
	Slope Gradient (S)			Flow depth	Manning's n (unvegetated)
Slope length (L)	≤ 3:1	3:1 to 2:1	≥ 2:1	≤ 0.50 ft (0.15 m)	0.050
≤ 20 ft (6 m)	0.00009	0.029	0.063	0.50 – 2.00 ft	0.050 - 0.018
20 to 50 ft	0.005	0.055	0.092	≥ 2.00 ft (0.60 m)	0.018
≥ 50 ft (15 m)	0.010	0.080	0.120	Max. permissible shear stress: 2.10 lbs/ft^2 (100 Pa)	

C125 coconut fiber erosion control blanket (36 month life; 274 g/m^2 mass per unit area)

RUSLE Conservation coefficients (C):				Channel Roughness Coefficients (n)	
	Slope Gradient (S)			Flow depth	Manning's n (unvegetated)
Slope length (L)	≤ 3:1	3:1 to 2:1	≥ 2:1	≤ 0.50 ft (0.15 m)	0.022
≤ 20 ft (6 m)	0.001	0.029	0.082	0.50 – 2.00 ft	0.022 – 0.014
20 to 50 ft	0.036	0.060	0.096	≥ 2.00 ft (0.60 m)	0.014
≥ 50 ft (15 m)	0.070	0.090	0.110	Max. permissible shear stress: 2.25 lbs/ft^2 (108 Pa)	

C125BN coconut fiber erosion control blanket (24 month life; 360 g/m^2 mass per unit area)

RUSLE Conservation coefficients (C):				Channel Roughness Coefficients (n)	
	Slope Gradient (S)			Flow depth	Manning's n (unvegetated)
Slope length (L)	≤ 3:1	3:1 to 2:1	≥ 2:1	≤ 0.50 ft (0.15 m)	0.022
≤ 20 ft (6 m)	0.00009	0.018	0.050	0.50 – 2.00 ft	0.022 – 0.014
20 to 50 ft	0.003	0.040	0.060	≥ 2.00 ft (0.60 m)	0.014
≥ 50 ft (15 m)	0.007	0.070	0.070	Max. permissible shear stress: 2.35 lbs/ft^2 (112 Pa)	

P300 polypropylene fiber erosion control blanket (permanent use; 456 g/m^2 mass per unit area)

RUSLE Conservation coefficients (C):	Slope Gradient (S)			Channel Roughness Coefficients (n)		Maximum Permissible Shear Stress	
Slope length (L)	≤ 3:1	3:1 to 2:1	≥ 2:1	Flow depth	Manning's n (unvegetated)		
≤ 20 ft (6 m)	0.001	0.029	0.082	≤ 0.50 ft (0.15 m)	0.049 – 0.034	Unvegetated	3.00 lb/ft^2 (144 Pa)
20 to 50 ft	0.036	0.060	0.096	0.50 – 2.00 ft	0.034 – 0.020	Partially vegetated	5.50 lb/ft^2 (264 Pa)
≥ 50 ft (15 m)	0.070	0.090	0.110	≥ 2.00 ft (0.60 m)	0.020	Fully vegetated	8.00 lb/ft^2 (383 Pa)

Additional permissible shear stress information for vegetated North American Green products (permanent liners):

	Manning's roughness coefficient (n) for flow depths:			Maximum Permissible Shear Stress	
Vegetated blanket type[1]:	0 to 0.5 ft	0.5 to 2 ft	>2 ft.	Short duration (<2 hours peak flow)	Long duration (>2 hours peak flow)
C350 Phase 2	0.044	0.044	0.044	6.00 lb/ft^2 (288 Pa)	4.50 lb/ft^2 (216 Pa)
P300 Phase 2	0.044	0.044	0.044	5.50 lb/ft^2 (264 Pa)	4.00 lb/ft^2 (192 Pa)
C350 Phase 3	0.049	0.049	0.049	8.00 lb/ft^2 (384 Pa)	8.00 lb/ft^2 (384 Pa)
P300 Phase 3	0.049	0.049	0.049	8.00 lb/ft^2 (384 Pa)	8.00 lb/ft^2 (384 Pa)

[1] Phase 2 is 50% stand maturity, usually at 6 months, while Phase 3 is mature growth

Values of C_f, the grass cover factor, are given in Table 5-5 (Temple, *et al.* 1987). They recommend multiplying 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. C_f values for untested covers may be estimated by recognizing that the cover factor is dominated by density and uniformity of cover near the soil surface: the sod-forming grasses near the top of the table have higher C_f values than the bunch grasses and annuals near the bottom. For the legumes tested (alfalfa and lespedeza sericea), the effective stem count for resistance (given on the table) is approximately five times the actual stem count very close to the bed. Similar adjustment may be needed for other unusually large-stemmed, branching, and/ or woody vegetation.

Table 5-5. Properties of Grass Channel Linings (Temple, *et al.* 1987)

Cover Factor (C_f) (good uniform stands)	Covers Tested	Reference stem density (stem/ft^2)
0.90	bermudagrass	500
0.90	centipedegrass	500
0.87	buffalograss	400
0.87	kentucky bluegrass	350
0.87	blue grama	350
0.75	grass mixture	200
0.50	weeping lovegrass	350
0.50	yellow bluestem	250
0.50	alfalfa	500
0.50	lespedeza sericea	300
0.50	common lespedeza	150
0.50	sudangrass	50

As an example, consider the following conditions for a mature buffalograss on a channel liner mat:

$\tau_o = \gamma DS$ = 2.83 lb/ft^2 (previously calculated), requiring a NAG P300 permanent mat, for example
n_s for the soil is 0.016
n for the vegetated mat is 0.042
C_f for the vegetated mat is 0.87

The permissible shear stress for the underlying soil is 0.08 lb/ft^2

Therefore:

$$\tau_e = 2.83(1-0.87)\left(\frac{0.016}{0.042}\right)^2 = 0.053 \text{ lb/ft}^2$$

The calculated shear stress being exerted on the soil beneath the liner mat must be less than the permissible shear stress for the soil. In this example, the safety factor is 0.08/0.053 = 1.5 and the channel lining system is expected to be stable.

An example of a permanent channel design and the selection of an appropriate reinforced liner is given below, based on the simple site example in Chapter 4, Figure 4-36 and Table 4-15. The following example is for the upslope diversion channel U2 that captures upslope runoff from 14.6 acres for diversion to an existing on-site channel. This channel is 900 ft. long and has an 8% slope. The peak discharge was calculated to be 29 ft^3/sec.

Using the Manning's equation and the VenTe Chow (1959) shortcut on channel geometry (Figure 5-8):

$$AR^{\frac{2}{3}} = \frac{nQ}{1.49S^{0.5}}$$

Where n = 0.02
Q = 29 CFS
S = 8% (0.08)

$$AR^{\frac{2}{3}} = \frac{(0.02)(29)}{1.49(0.08)^{0.5}} = 1.38$$

The following drawing illustrates the channel components for this basic analysis:

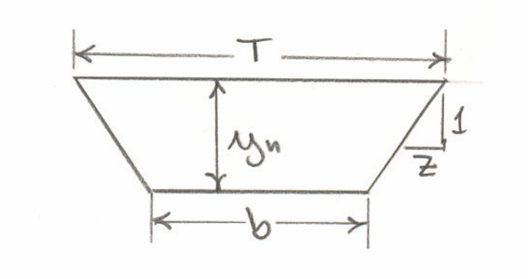
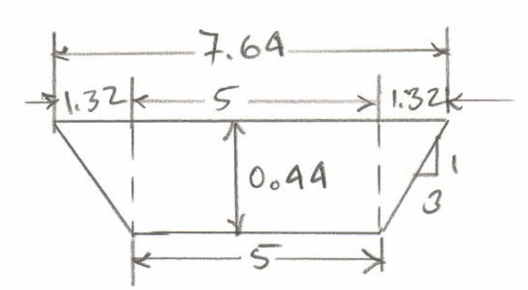


Figure 5-8 can be used to determine the normal depth (y_n) for many combinations of bottom with (b), and side slope (z). As an example, assume that the bottom width is 5 ft. and the side slope parameter, z, is 3. The calculated $AR^{2/3}$ value (1.38) needs to be divided by $b^{8/3}$ ($5^{8/3}$ = 73.14) for the shape factor used in Figure 5-8. This value is therefore: 1.38/73.14 = 0.018. For a side slope of z = 3, the figure indicates that the ratio of the depth to the bottom width (y/b) is 0.088. In this example, the bottom width was 5 ft, so the normal depth is: yn = 0.088 (5 ft.) = 0.44 ft., which is only 5.3 inches. The following shows these dimensions on the channel cross-section:



It is now possible to calculate the velocity and shear stress associated with this set of channel options:

A = [(7.64+5)/2] (0.44) = 2.78 ft^2
V = Q/A = 29 ft^3/sec/2.78 ft^2 = 10.4 ft/sec
R = A/P, and P = 5 + 2(3.16)(0.44) = 7.78 ft.; R = A/P = 2.78 ft^2/7.78 ft. = 0.36 ft.

and $\tau = \gamma RS$ = (62.4lb/ft^3)(0.36 ft.)(0.08) = 1.8 lb/ft^2

With a velocity of 10.4 ft/sec and a shear stress of 1.8 lb/ft^2, it is obvious that some type of channel reinforcement will be needed (refer to Table 5-2), or a new design option. Using Figure 5-8, plus liner information (such as listed previously), it is possible to create a simple spreadsheet with multiple cross section and liner options, as shown in Table 5-6..

Table 5-6. Optional Channel Characteristics (Q = 29 ft^3/sec and S = 8%)

		Unvegetated NAG P300, n = 0.02 (allowable shear stress = 3.0 lb/ft^2)					Channel with Reinforced Liner and Vegetation					
Bottom width (b), ft	Side slope (z)	Normal depth (y_n), ft	Top width (T), ft	Hydraulic radius (R), ft	Shear stress (τ), lb/ft^2	Velocity (V), ft/sec	Assumed NAG material and growing conditions	Manning's roughness (n)	Normal depth (y_n), ft	Shear stress (τ), lb/ft^2	Velocity (V), ft/sec	Allowable shear stress for NAG product (short and long exposures), lb/ft^2
5	3	0.44	7.6	0.36	1.8	10.4	C350 phase 3	0.049	0.7*	3.34*	5.8*	8.0/8.0
3	1	0.63	4.3	0.48	2.4	12.7	P300 phase 2	0.044	1.65	4.99	3.8	5.5/4.0
10	3	0.26	11.6	0.26	1.3	10.4	C350 phase 2	0.044	0.49	2.45	5.2	6.0/4.5
6	4	0.31	8.5	0.26	1.3	12.9	P300 phase 2	0.044	0.57	2.85	6.1	5.5/4.0
8	4	0.30	10.4	0.14	0.7	11.0	P300 phase 3	0.049	0.88	4.39	3.4	8.0/8.0
6	1.5	0.43	7.3	0.38	1.9	10.1	C350 phase 3	0.044	0.72	3.59	5.7	8.0/8.0

* example calculations:

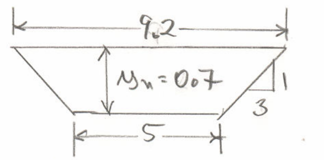
$$AR^{\frac{2}{3}} = \frac{(0.049)(29)}{1.49(0.08)^{0.5}} = 3.38$$

$b^{8/3} = 5^{8/3} = 73.1$

$AR^{2/3} / b^{8/3} = 3.38/73.1 = 0.046$

With $z = 3$, $y/b = 0.14$

Therefore $y_n = 0.14\ (5) = 0.7$ ft



$A = [(5+9.2)/2]\ (0.7) = 4.97$ ft^2

$P = 5 + 2(1.21) = 7.42$ ft

$R = A/P = 4.97/7.42 = 0.67$

$\tau = \gamma RS = (62.4\text{lb/ft}^3)(0.67\text{ ft.})(0.08) = 3.34\text{ lb/ft}^2$

$V = Q/A = 29\text{ ft}^3\text{/sec}/4.97\text{ ft}^2 = 5.8\text{ ft/sec}$

Based on these calculations, the P300 liner will be suitable. When newly placed, with no vegetation growth, the Manning's n roughness is 0.02. The calculations for this condition result in a maximum shear stress of 2.4 lb/ft^2 for the cross sections examined. This is less than the maximum allowable of 3.0 lb/ft^2. Unfortunately, the velocities are all very high, ranging from 10.1 to 12.9 ft/sec. The use of check dams is therefore highly recommended for this channel. These can range from coir logs stacked in the channel, to rock check dams. The calculations after vegetative growth shows that the P300 is also acceptable. A range of conditions were examined for phase 2 (50% stand maturity) and phase 3 (mature growth), with Manning's roughness values of 0.044 and 0.049. The smallest (and steepest side sloped) channel resulted in the highest shear stress of 4.99 lb/ft^2, less than the acceptable 5.5 lb/ft^2 for short exposures (<2 hours peak flow durations). After mature plant establishment in the channel, the maximum allowable shear stress increases to 8.0 lb/ft^2.

Design of Lined Channels having Bends

The basic shear stress formulas can be modified to account for the increased shear stress after bends in channels. Normally, the maximum shear stress is along the center part of a channel (usually the deepest area), but a hydrodynamic force is applied to the outside bend after a change in direction. Along the outside of the bend, increased water velocity and shear stress will increase the erosion potential, while sedimentation may occur along the inside of the bend where the water velocity slows. The basic shear stress formula is modified with a bend coefficient, as follows:

$$\tau_o = \gamma R S K_b$$

where:

γ = specific weight of water (62.4 lbs/ft^3)
R = hydraulic radius (ft) (can be estimated by water depth, for relatively wide channels or sheetflows)
S = hydraulic slope (ft/ft)
K_b = bend coefficient

The bend coefficient can be estimated by (Croke 2001):

$$K_b = \frac{R_c}{B}$$

where:

R_c = bend curvature (radius of the bend)
B = bottom width of the channel

These parameters are illustrated in Figure 5-13 (North American Green).

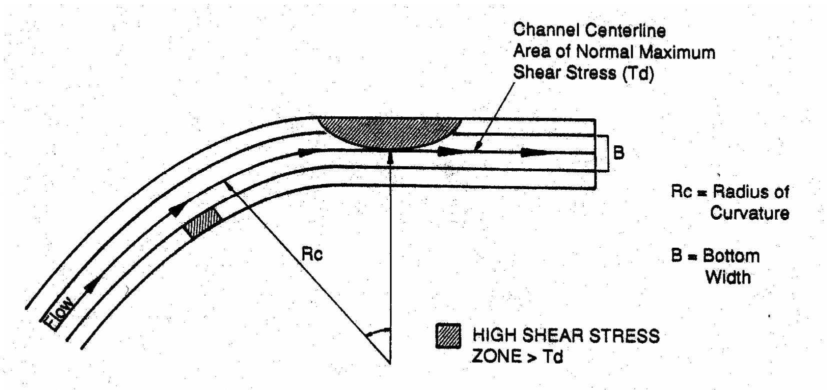


Figure 5-13. Location of increased shear stress due to channel bend (North American Green).

This formula obviously cannot be used for a V-shaped channel, where the bottom width is zero. Croke (2001) points out that this design is unlikely on construction sites due to difficulties in shaping.

The area being affected by the increased shear stress due to channel bends is usually assumed to begin immediately after the bend at the tangent to the downstream channel, as shown in Figure 5-13. The length of extra shear stress can be estimated by the following formula (after Croke 2001):

$$L_p = \frac{0.604 R^{1.17}}{n}$$

where:

L_p = length of extra protection needed due to increased shear stress on outside of bend (same units as R)
R = hydraulic radius = ratio of cross-sectional area of flow to wetted perimeter (A/P)
n = Manning's roughness coefficient for liner in the channel bend

As an example, assume the following conditions:

R = 3.0 ft
n = 0.042

then:

$$L_p = \frac{0.604(3)^{1.17}}{0.042} = 52 \text{ ft}$$

In addition to the increased shear stress being exerted along the outside bend, water elevations will also rise due to momentum. This will require an additional channel depth needing protection at outside bends.

Internet Links

US Army Corps of Engineers Channel Stability Assessment Method Report: Engineering and Design - *Channel Stability Assessment for Flood Control Projects*, 1994:
http://www.usace.army.mil/inet/usace-docs/eng-manuals/em1110-2-1418/toc.htm

USDA Agricultural Handbook 667: *Stability Design of Grass-Lined Open Channels*, 1987:
http://www.pswcrl.ars.usda.gov/ah667/ah667.htm

North America Green downloadable program for slope and channel protection:
http://www.nagreen.com/

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