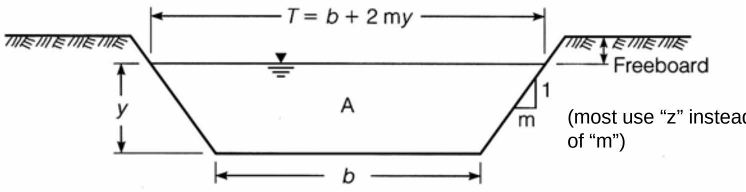
M6c: Design of Stable Open Channels

- Adequate conveyance capacity
- Stable channel
- Provide aquatic life habitat
- These objectives must be met considering future conditions, reasonable cost, minimal land consumption, and safety.

Trapezoidal Section (Figure 4.30)



(most use “z” instead of “m”)

$$A = by + zy^2$$

$$P = b + 2y\sqrt{1+z^2}$$

Channel Freeboard:

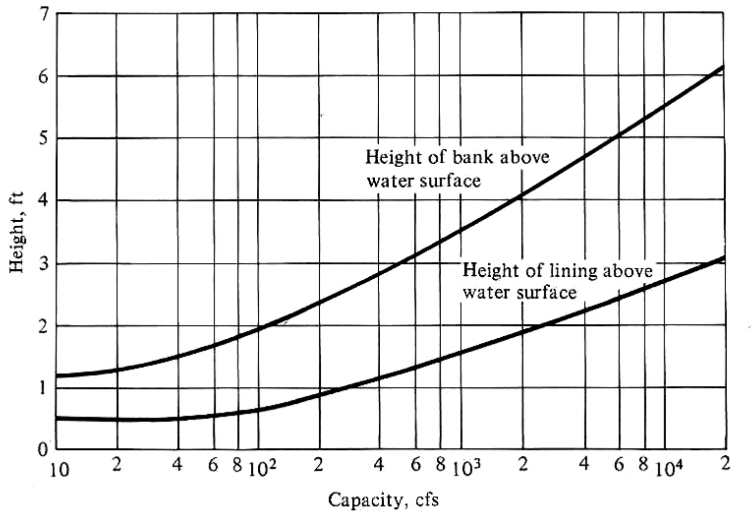
$$F = 0.55\sqrt{Cy}$$

C = 1.5 (for 0.6 m^3/sec)
to
2.5 (≥ 85 m^3/sec)

Minimum freeboard of 30 cm (1 ft)

Need to increase F in channel bends due to superelevation of water surface

Recommended freeboard and height of lining (Figure 7-6, Prasuhn 1987), from U.S. Bureau of Reclamation

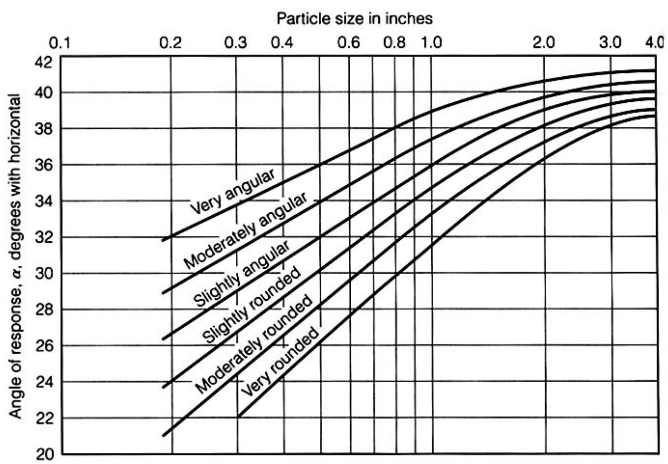


Recommended Side Slopes in Various Types of Materials (Table 3.16, Chin 2006)

Material	Side slope (H:V)
Rock	Nearly vertical
Muck and peat soils	$\frac{1}{4}$:1
Stiff clay or earth with concrete lining	$\frac{1}{2}$:1 to 1:1
Earth with stone lining or earth for large channels	1:1
Firm clay or earth for small ditches	$1\frac{1}{2}$:1
Loose, sandy earth	2:1
Sandy loam or porous clay	3:1

Source: Chow (1959).

Angles of Repose of Noncohesive Material (Figure 3.48, Chin 2006)



Type	Characteristics	Minimum *n*	Normal *n*	Maximum *n*
Cement	neat surface	0.010	0.011	0.013
	mortar	0.011	0.013	0.015
Concrete	trowel finish	0.011	0.013*	0.015
	float finish	0.013	0.015	0.016
	finished, with gravel on bottom	0.015	0.017	0.020
	unfinished	0.014	0.017	0.020
	gunite, good section	0.016	0.019	0.023
	gunite, wavy section	0.018	0.022	0.025
	on good excavated rock	0.017	0.020	—
	on irregular excavated rock	0.022	0.027	—
Concrete bottom float finished with sides of:	dressed stone in mortar	0.015	0.017	0.020
	random stone in mortar	0.017	0.020	0.024
	cement rubble masonry, plastered	0.016	0.020	0.024
	cement rubble masonry	0.020	0.025	0.030
	dry rubble or riprap	0.020	0.030	0.035
Gravel bottom with sides of:	formed concrete	0.017	0.020	0.025
	random stone in mortar	0.020	0.023	0.026
	dry rubble or riprap	0.023	0.033	0.036
Brick	glazed	0.011	0.013*	0.015
	in cement mortar	0.012	0.015*	0.018
Masonry	cemented rubble	0.017	0.025	0.030
	dry rubble	0.023	0.032	0.035
Dressed ashlar	—	0.013	0.015	0.017
Asphalt	smooth	0.013	0.013	—
Vegetal lining	—	0.030	—	0.500

Source: Chow (1959).
*Chow (1959) recommended this value for use in design.

Roughness Coefficients in Lined Open Channels (Table 4.14, Chin 2000)

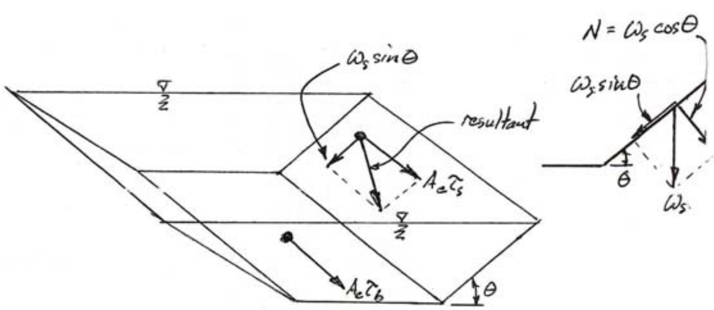
Maximum Permissible Velocity

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**

Minimum velocity should be 2 to 3 ft/sec.
Also check Froude number (≤ 0.8, to ensure subcritical flow)

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**

Method of Tractive Force



ω_s = submerged weight of particle
A_e = effective area of particle
τ_b = shear stress on channel bottom
τ_s = shear stress on channel side

Average Shear Stress on Channel Boundary (the Tractive Force):

$$\tau_o = \gamma RS$$

US customary units of lb/ft^2

where:

γ = specific weight of water (62.4 lbs/ft^3)
R = hydraulic radius (ft)
S_o = hydraulic slope (ft/ft) for uniform flow; this is substituted with S_f for non-uniform flow conditions

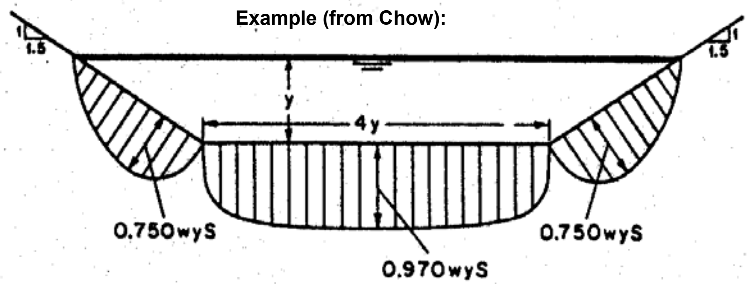
If the channel is very wide (B>>y), such as for sheetflow conditions, the hydraulic radius (R) is substituted by the flow depth:

$$\tau_o = \gamma y S_f$$

Research by the USBR has shown that the distribution of the shear stress is not uniform and that the maximum values of shear stress on the channel bottoms and side slopes are approximately:

$$\tau_b = \gamma y S_f \qquad \tau_s = 0.76 \gamma y S_f$$

Example (from Chow):



At "incipient motion," the forces causing a particle to move are just equal to those resisting motion.

Channel Bottom:

$$driving\ \ force = A_e \tau_b$$

$$resisting\ \ force = \omega_s \tan\alpha$$

$$\alpha = angle\ \ of\ \ repose \Rightarrow\ friction\ \ factor = \tan\alpha$$

Therefore:

$$A_e \tau_b = \omega_s \tan\alpha$$

$$\tau_b^{'} = \frac{\omega_s}{A_e}\tan\alpha \qquad \tau_b^{'} = permissible\ \ shear\ \ stress$$

Channel Side:

$$driving\ \ force = \sqrt{(A_e\ \tau_s)^2 + (\omega_s \sin\theta)^2}$$

$$where\ (\omega_s \sin\theta)^2\ \ is\ \ zero\ \ for\ \ cohesive\ \ materials$$

$$resisting\ \ force = N\tan\alpha = \omega_s \cos\theta \tan\alpha$$

Therefore:

$$\sqrt{(A_e\ \tau_s)^2 + (\omega_s \sin\theta)^2} = \omega_s \cos\theta \tan\alpha$$

$$\tau_b^{'} = \frac{\omega_s}{A_e}\cos\theta\tan\alpha\sqrt{1-\left(\frac{\tan\theta}{\tan\alpha}\right)^2} \qquad \tau_b^{'} = permissible\ \ shear\ \ stress$$

$$and = \frac{\omega_s}{A_e}\cos\theta\tan\alpha\ \ for\ \ cohesive\ \ soils$$

The "tractive force" ratio is:

$$K = \frac{\tau_s^{'}}{\tau_b^{'}} = \sqrt{1-\left(\frac{\sin\theta}{\sin\alpha}\right)^2}$$

Permissible shear stresses should be reduced for sinuous channels.

Shear stress on side usually controls design, but the bottom shear stress must also be checked.

Example Problem 3.26 from Chin (2006)

Step-by-step procedures for stable earth-lined channel design

Problem Statement:
Design a trapezoidal channel to carry 20 m^3/sec through a slightly sinuous channel on a slope of 0.0015. The channel is to be excavated in coarse alluvium with a 75-percentile diameter of 2 cm (gravel), and with the particles on the perimeter of the channel moderately rounded.

Solution (and calculation steps):

Step 1: Estimate the Manning's roughness coefficient, n. The coarse gravel n value for a uniform section is estimated to be 0.025. This can also be estimated using the following equation (d in ft, for the 75th percentile particle size):

$$n = 0.031 d^{1/6} = 0.031(0.02m)(3.281\,ft/m)^{1/6} = 0.020$$

This is close to the "table" value of 0.025. The larger, more conservative, value (0.025) will therefore be used in this design.

Step 2: Side slopes of channel. The angle of repose of the channel material can be estimated from Figure 4.31 (Chin), where the size in inches is:

$$d_{75} = 2cm = 0.8in.$$

The angle of repose, α, is therefore equal to 32° (based on moderately rounded material).

Step 3: Since the channel is slightly sinuous, the correction factor, C_s, for the maximum tractive force (as given in table 3.17, Chin) is 0.90. Correction factors for maximum tractive force (Chin 2006; Table 3.17):

Degree of sinuousness	Correction factor
Straight channels	1.00
Slightly sinuous channels	0.90
Moderately sinuous channels	0.75
Very sinuous channels	0.60

Source: Lane, E. W. "Design of Stable Channels," Transactions of the American Society of Civil Engineers, v. 120, p. 1234–79. Copyright © 1955 by ASCE. Reprinted by permission.

Step 4: The channel slope is selected to be 2:1 (H:V). The corresponding angle that the side slope makes with the horizontal, θ, is given by:

$$\theta = \tan^{-1}\left(\frac{V}{H}\right) = \tan^{-1}\left(\frac{1}{2}\right) = 26.6^\circ$$

This is less than the critical angle of repose of the material, which is 32°

Step 5: The tractive force ratio, K, (the fraction of the bottom tractive force applied to the channel side) is:

$$K = \frac{\tau_s'}{\tau_b'} = \sqrt{1-\left(\frac{\sin\theta}{\sin\alpha}\right)^2} = \sqrt{1-\frac{\sin^2 26.6^\circ}{\sin^2 32^\circ}} = 0.53$$

Step 6: The permissible tractive force on the bottom of the channel is estimated from the USBR plots (Figure 3.49, Chin) as 0.33 lb/ft², or 15.9 N/m² for a median particle size of 20 mm. Correcting this permissible force for the sinuousness leads to an allowable shear stress on the bottom of the channel of:

$$\tau_b' = C_s(15.9N/m^2) = 0.9(15.9N/m^2) = 14.3N/m^2$$

The permissible tractive force on the side of the channel is therefore:

$$\tau_s' = K\tau_b' = 0.53(14.3N/m^2) = 7.6N/m^2$$

Step 7: The normal depth of flow can be estimated by assuming that particle motion is incipient (side shear stress equal to the permissible tractive force) on the side of the channel:

$$0.76\gamma y_n S_o = 7.6N/m^2$$

Solving for y_n:

$$y_n = \frac{7.6N/m^2}{0.76\gamma S_o} = \frac{7.6N/m^2}{0.76(9790N/m^3)(0.0015)} = 0.68m$$

Step 8: Determine channel bottom width using the Manning's equation:

$$Q = \frac{1}{n}AR^{2/3}S_o^{1/2} = \frac{1}{n}\frac{A^{5/3}}{p^{2/3}}S_o^{1/2}$$

Substituting gives:

$$20m^3/\sec = \frac{1}{0.025}\frac{A^{5/3}}{p^{2/3}}(0.0015)^{1/2}$$

Which simplifies to:

$$\frac{A^{5/3}}{p^{2/3}} = 12.9$$

Step 8 (continued)

$$A = [b + my_n]y_n = [b + 2(0.68m)](0.68m) = 0.68[b + 1.36]$$

$$P = b + 2y_n\sqrt{1 + m^2} = b + 2(0.68m)\sqrt{1 + 2^2} = b + 3.04$$

Substituting:

$$\frac{(b + 1.36)^{5/3}}{(b + 3.04)^{2/3}} = 24.5$$

Solving for b results in a minimum real value of 24.2 m for the bottom width of the channel.

Step 9: The actual tractive force on the channel bottom is:

$$\tau_b = \gamma y_n S_o = (9790 N/m^3)(0.68m)(0.0015) = 10 N/m^2$$

This is less than the maximum permissible tractive force on the channel bottom (14.2 N/m²), and is therefore acceptable from an tractive force aspect.

Step 10. Check for subcritical flow:
The flow area, A, is:

$$A = [b + my]y = [24.2m + (2)(0.68m)](0.68m) = 17.4m^2$$

and the average velocity in the channel, V, is given by:

$$V = \frac{Q}{A} = \frac{20m^3/\sec}{17.4m^2} = 1.1m/\sec$$

The velocity should be sufficient to prevent sedimentation (>1 m/sec) and unwanted vegetation growth.

The Froude number can be estimated by:

$$Fr = \frac{V}{\sqrt{gD}}$$

where D is the hydraulic depth:

$$D = \frac{A}{T} = \frac{A}{b + 2my} = \frac{17.4m^2}{24.2m + 2(2)(0.68m)} = 0.65m$$

Therefore, the Froude number is:

$$Fr = \frac{V}{\sqrt{gD}} = \frac{1.1m/\sec}{\sqrt{(9.81m/\sec^2)(0.65m)}} = 0.44$$

which indicates desirable subcritical flow (Fr < 1)

Step 11: Determine the required freeboard, F, in meters, for the channel

$$F = 0.55\sqrt{Cy}$$

C is 1.5 for a flow of 0.57 m^3/sec and 2.5 for a flow of 85 m^3/sec. Interpolating, the value for C for the flow of 20 m^3/sec is 1.7 and the required freeboard is:

$$F = 0.55\sqrt{Cy} = 0.55\sqrt{(1.7)(0.68m)} = 0.59m$$

The total depth of the channel to be excavated is therefore equal to the normal depth plus the freeboard: 0.68 m + 0.59 m = 1.27 m. The channel is to have a bottom width of 24.2 m and side slopes of 2:1 (H:V).

In-class problem:

Design a stable, earth-lined channel for the following conditions:

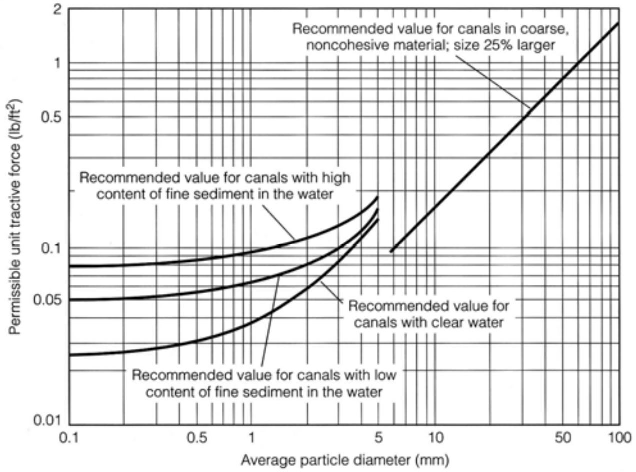
Q = 500 cfs
S_o = 0.0015

Assume rounded coarse gravel and pebbles (d75 = 1.25 in = 32 mm) and a slightly sinuous channel

Solutions:

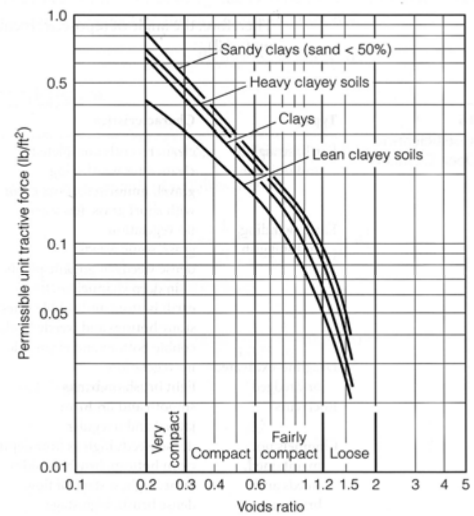
n = 0.025
C = 0.90
$\alpha = 33^o$
can use z = 2, as the side angle would be 26.2^o
K = 0.57
τ_b' = 0.45 lb/ft^2
τ_s' = 0.26 lb/ft^2
y_n = 3.6 ft
B = 23.2 ft
τ_b = 0.37 lb/ft^2, which is <0.45 lb/ft^2, therefore OK
A = 109.4 ft^2
T = 37.6 ft
V = 4.6 ft/sec
F = 0.47 therefore subcritical flow and OK

Permissible Unit Tractive Force for Channels in Noncohesive Material (Figure 3.49a, Chin 2006)



(a) Non-Cohesive Material

Permissible Unit Tractive Force in Channels in Cohesive Material (Figure 3.49b, Chin 2006)



(b) Cohesive Material

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).

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

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

where:

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

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

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

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:

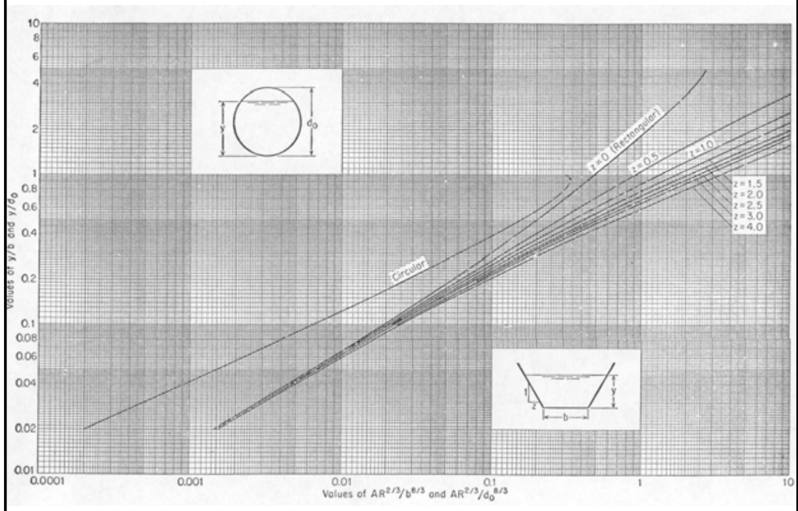
P = wetted perimeter, ft
A = cross-sectional area of channel (wetted portion), ft^2
R = hydraulic radius, ft.

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).

Chow's figure (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:

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

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.



Chow 1959

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. There are many channel options than can meet this objective. The calculated maximum shear stress is:

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.

Different flexible "solutions" to provide bank stability

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.

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.

Turf reinforcement mats (TRM) design 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.

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

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

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 therefore expected to be stable.

In-Class Problem:

Determine the normal depth in a trapezoidal channel with side slope of 1.5 to 1.0 (z = 0.667), a bottom width of 25 ft, a channel slope of 0.00088, if the discharge is 1510 ft^3/sec, and the Manning's n is 0.017. Also, calculate the shear stress for this channel condition.

Redesign this channel using a grass liner (changing the side slope to z = 2).

n_s for the soil is 0.024
n for the vegetated mat is 0.048
C_f for the vegetated mat is 0.83
The permissible shear stress for the underlying soil is 0.095 lb/ft^2

Solution to In-Class Problem

$$AR^{\frac{2}{3}} = \frac{nQ}{1.49S^{0.5}} = \frac{(0.017)(1510cfs)}{1.49(0.00088)^{0.5}} = 580.76$$

$$b^{8/3} = (25\,ft)^{8/3} = 5344$$

$$\frac{AR^{2/3}}{b^{8/3}} = \frac{580.76}{5344} = 0.109$$

$$therefore,\ for\ z = 0.667,\ \frac{y}{b} = 0.27$$

$$y = 0.27(25\,ft) = 6.75\,ft$$

Check with full Manning's equation, Q = 1478 cfs