Day 6: Designing Stable Channels at Construction Sites

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Channel Stability Controls Listed in 95 US and International Guidance Manuals

Erosion and Sediment Control Tool	included in % of 95 reviewed US and international manuals
Erosion Control Blanket/Geotextiles	97
Diversion/Berm	83
Check Dam	83
Temporary Slope Drain	75
Grass Swale	71
Riprap-lined Swale	68
Lined Swale	54

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Channel Stability Controls Listed in 95 US and International Guidance Manuals (continued)

Erosion and Sediment Control Tool	included in % of 95 reviewed US and international manuals
Lined Swale	54
Temporary Stream Crossing	52
Rock Filter Dam	37
Floating Turbidity Barrier	31
Drop Structure	9
Rock Flume	3

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Massive Streambank Failure at New Outfall in a Suburban Area

WI DNR photo

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Channel Protection

- Upslope diversions
- Channel Protection
  - Channel liners
  - Check dams

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Temporary lined bypass channels at construction sites (D. Lake and J. Voorhees photos)

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Some potential solutions to stabilize streambanks.

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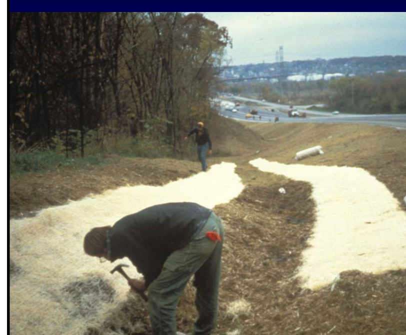
Channel Lining



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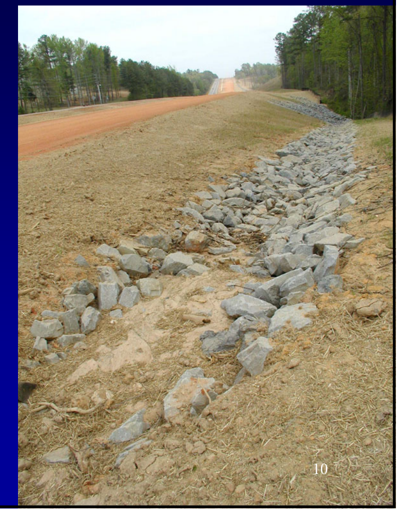

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Check Dams

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Channel Design Based on Allowable Velocity and Shear Stress

- The concepts of allowable velocity and allowable shear stress are closely linked.
- Shear stress is calculated based on water depth and channel slope.
- Velocity is affected by both slope and depth.
- Most allowable velocity charts also include slope categories for the different liner materials.
- Some allowable velocity charts also consider silt content (water carrying silt has a higher allowable velocity because its sediment carrying capacity is already reduced).

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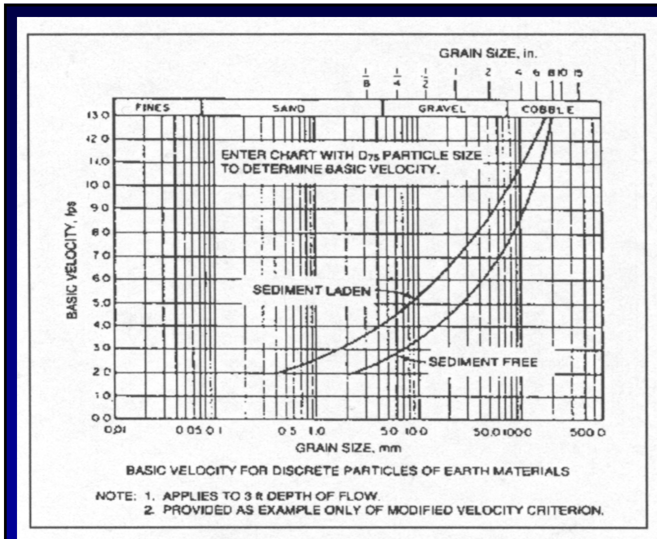
Example Allowable Velocity and Shear Stress Values

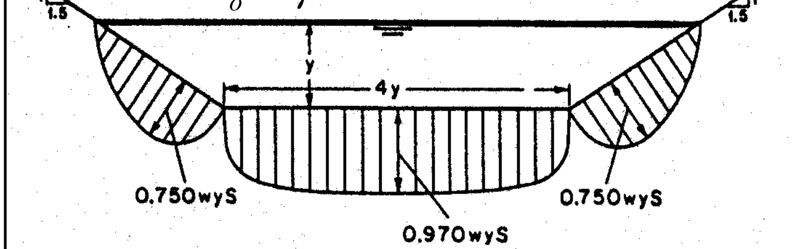
Liner Texture	Manning's roughness	Clear Water (diversions)		Silty Water (on site and downslope)	
	n	V (ft/sec)	τ_o (lb/ft^2)	V (ft/sec)	τ_o (lb/ft^2)
Fine sand	0.020	1.50	0.027	2.50	0.075
Firm loam	0.020	2.50	0.075	3.50	0.15
Fine gravel	0.020	2.50	0.075	5.00	0.32
Cobbles	0.035	5.00	0.91	5.50	1.10



Allowable velocities and sediment transport (USDA 1977)

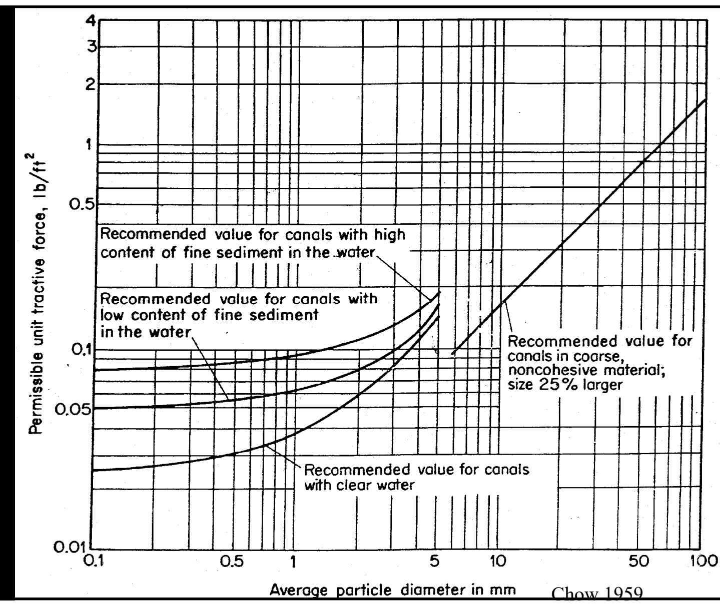
Boundary Shear Stress (tractive force):

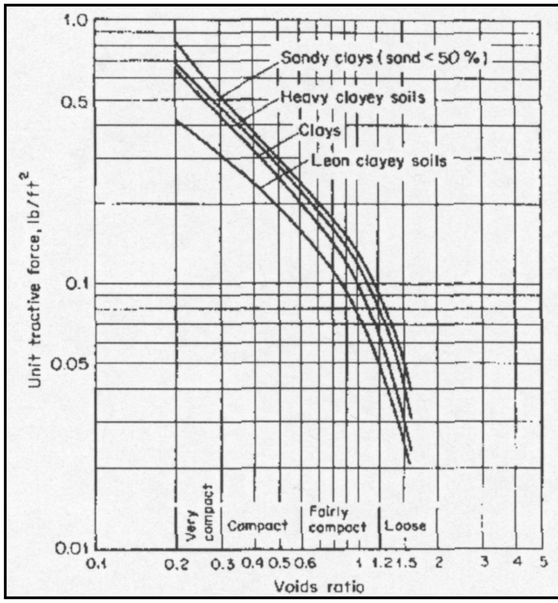
$$\tau_o = \gamma RS$$



γ = specific weight of water (62.4 lbs/ft^3)
R = hydraulic radius (flow depth is used for maximum shear stress calculations; for sheetflow conditions, the depth is equal to the hydraulic radius)
S = channel slope

Chow 1959





Example plot of allowable shear stress (unit tractive force) for cohesive materials.

COE 1994

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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.
- 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

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Example Allowable Tractive Forces

- Sheetflow: ¼ inch deep on a 10% slope:
  - (62.4 lb/ft^3)(0.021 ft)(0.10) = 0.13 lb/ft^2
  - >3.5 mm particles OK, for high slit content flow
  - >5 mm particles OK, for clear flow
  - Moderately compacted cohesive clays OK
- Sheetflow: ¼ inch deep on a 2% slope:
  - (62.4 lb/ft^3)(0.021 ft)(0.02) = 0.026 lb/ft^2
  - > 0.1 mm particles OK, for all flows
  - Ok for all loose and more compacted cohesive clays

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Example Allowable Tractive Forces (cont.)

- Channel Flow: 18 inches deep on a 5% slope:
  - (62.4 lb/ft^3)(1.5 ft)(0.05) = 4.7 lb/ft^2
  - no natural lining material safe
- Channel Flow: 18 inches deep on a 1% slope:
  - (62.4 lb/ft^3)(1.5 ft)(0.01) = 0.93 lb/ft^2
  - >70 mm noncohesive material OK

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Channel Design Steps for Maximum Permissible Velocity/Allowable Shear Stress Method

1. Estimate Manning's roughness (n), the channel slope (S), and the maximum permissible velocity (V) for the channel.
2. Calculate the hydraulic radius (R) using Manning's equation for these conditions.

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

Some typical values for Manning's n for open channels (Chow 1959)

- 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

Channel Design Steps for Maximum Permissible Velocity/Allowable Shear Stress Method (cont.)

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

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

4. Calculate the corresponding wetted perimeter (P):

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

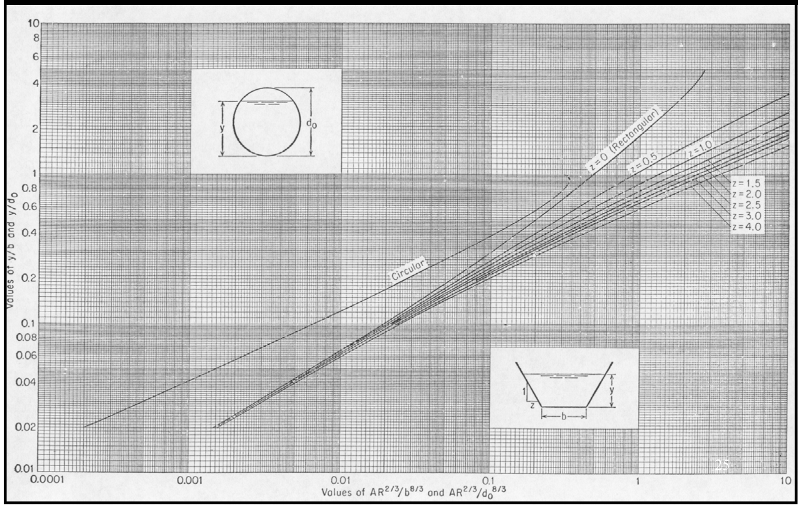
Channel Design Steps for Maximum Permissible Velocity/Allowable Shear Stress Method (cont.)

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

5b. Chow's nomograph can be used to significantly shorted the calculation effort by using the following form of Manning's equation:

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

Chow's (1959) nomograph to determine normal depth for different channel geometries and flows:



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Example Design of Stable Channel

- Noncolloidal alluvial silts channel lining, water transporting colloidal silts:
  - Manning's roughness (n) = 0.020
  - Maximum permissible velocity (V) = 3.5 ft/sec
  - Allowable shear stress is 0.15 lb/ft^2
- The previously calculated peak discharge (Q) = 13 ft^3/sec
- The channel slope (S) = 1%, or 0.01

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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:

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

Therefore, AR$^{2/3}$ = (3.7)(0.32)$^{2/3}$ = 1.7
and the wetter perimeter = A/R = 3.7/0.32 = 12 ft

There are many channel options available,

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Channel options that meet allowable velocity criterion:

Side slope z	Bottom width b	AR$^{2/3}$/b$^{8/3}$	y/b	Normal depth y	Max shear stress	Safety factor for shear
4	15	0.0012	0.017	0.26 ft	0.16	0.94
4	25	0.00032	0.008	0.20	0.12	1.25
1	25	0.00032	0.008	0.20	0.12	1.25
0.5	15	0.0012	0.017	0.26	0.16	0.94
0.5	25	0.00032	0.008	0.20	0.12	1.25

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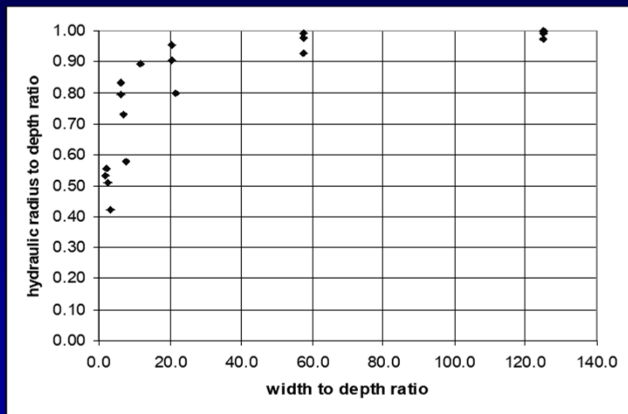
Relationship of hydraulic radius to normal depth for different channel width to depth conditions



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- As the channel becomes wide, the side slope has little effect on the normal depth and therefore on the shear stress.
- Even though all these channels meet the permissible channel velocity, only those approaching 25 feet wide also meet the allowable shear stress.
- Since the allowable shear stress is 0.15 lb/ft^2, the normal depth must be less than 0.24 ft (about 3 inches), requiring a relatively wide channel.
- Current practice is to design channel liners based on shear stress and not on allowable velocity, as it does a better job in predicting liner stability.

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Channel Design using Reinforced Liners

- If a channel will have intermittent flows, it is common to use vegetated liners to increase channel stability.
- If channel will have perennial flows, then structural liners must be used.
- Reinforced turf mat liner design should examine three phases:
  - Original channel in unvegetated condition
  - Channel in partially vegetated condition
  - Channel in permanent condition with established vegetation

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Sod placed along a drainage bottom, with grass seed along the edges

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Seeding along median strip swale of highway project

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Temporary Vegetation Plantings

- 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.*).

Bermudagrass is most widely used permanent grass in the sourthern US (for permanent plantings)

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- Channel matting failure is based on soil loss (usually maximum of 0.5 inch; greater amounts hinder the establishment of vegetation.
- Basic shear stress formula can be modified to predict the shear stress applied to the soil beneath a channel mat:

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

τe = effective shear stress exerted on soil beneath vegetation
γ = specific weight of water (62.4 lbs/ft3)
D = the maximum flow depth in the cross section (ft)
S = hydraulic slope (ft/ft)
C_f = vegetal cover factor (this factor is 0 for an unlined channel)
ns = roughness coefficient of underlying soil
n = roughness coefficient of vegetal components

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Cover Factor (C_f) (good uniform stands)	Covers Tested	Reference stem density (M), 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

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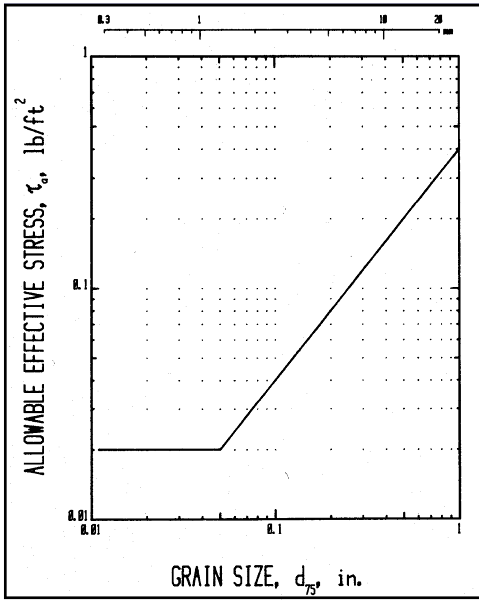

Allowable effective stress for noncohesive soils

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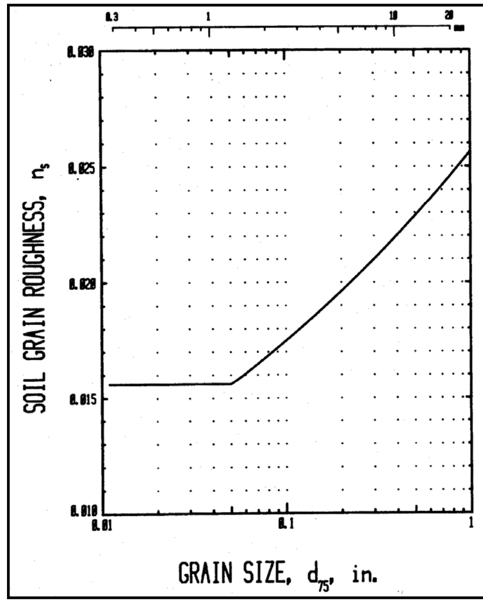

Soil grain roughness for noncohesive soils

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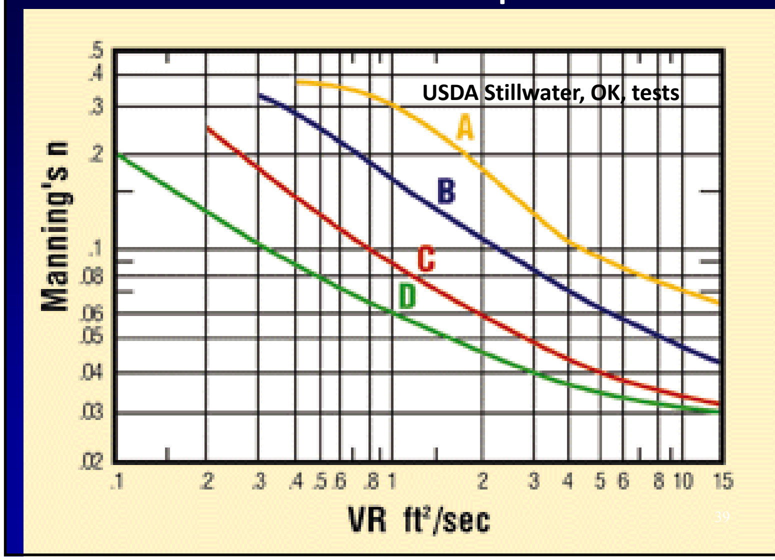
Standard VR-n curves for deep channel flows



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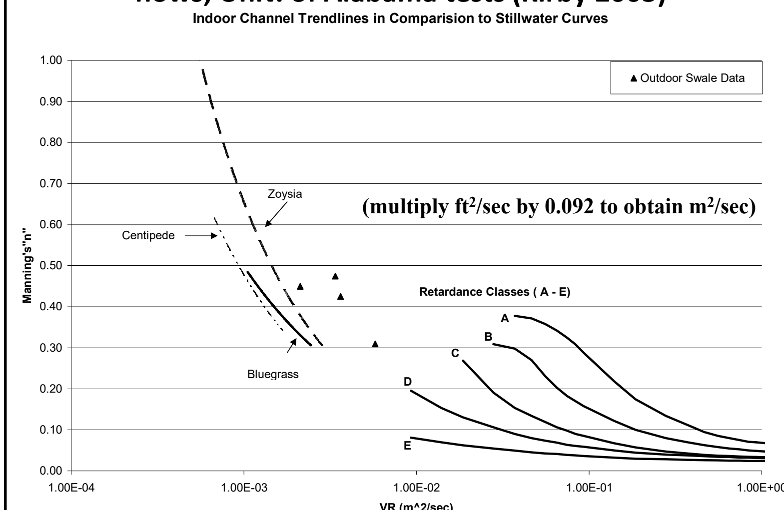
VR-n curve for different grasses, showing results for shallow flows; Univ. of Alabama tests (Kirby 2003)



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Example Problem for the Selection of Roughness Coefficient for Grass-Lined Channels

Determine the roughness value for a 10-year design storm of 70 ft^3/sec (2 m^3/sec) in a grass-lined drainage channel having a slope of 0.05 ft/ft and a 4 foot (1.2 m) bottom width and 1:1 side slopes. The grass cover is expected to be in retardance group D.

Long-term design, based on vegetated channel stability:

- **use $Q_{peak} = Q_{10year}$ = 70 ft^3/s (2 m^3/s)**
- **initially assume that $n_{vegetated}$ = 0.05**

Determine the normal depth of flow:

$$AR^{\frac{2}{3}} = \frac{nQ}{1.49S^{0.5}} = \frac{0.05(70cfs)}{1.49(0.05)^{0.5}} = 10.51$$

$AR^{2/3}/b^{8/3}$ = 10.51/40.32 = 0.26

With a 1:1 side slope trapezoidal channel, the ratio of y/b is 0.43, and the depth is 4(0.43) = 1.7 ft.

The cross-sectional area = 9.7 ft^2
The velocity = (70 ft^3/sec)/(9.7 ft^2) = 7.2 ft/sec
P = 8.8 ft
R = 9.7 ft^2/8.8 ft = 1.1 ft
VR is therefore = (7.2 ft/sec)(1.1 ft) = 7.9 ft^2/sec
From the VR-n curve, the "new" n is therefore 0.032 for retardance class D grass.

The normal depth must be re-calculated:

$$AR^{\frac{2}{3}} = \frac{nQ}{1.49S^{0.5}} = \frac{0.032(70cfs)}{1.49(0.05)^{0.5}} = 6.72$$

$AR^{2/3}/b^{8/3}$ = 6.72/40.32 = 0.17
With a 1:1 side slope trapezoidal channel, the ratio of y/b is 0.34, and the depth is 4(0.34) = 1.4 ft.

The cross-sectional area = 7.6 ft^2
The velocity = (70 ft^3/sec)/(7.6 ft^2) = 9.2 ft/sec
P = 8.0 ft
R = 7.6 ft^2/8.0 ft = 0.95 ft
VR is therefore = (9.2 ft/sec)(0.95 ft) = 8.7 ft^2/sec
From the VR-n curve, the revised value of n is still close to 0.032

The maximum shear stress (using normal depth instead of hydraulic radius) is therefore:

$$\gamma DS = (62.4\ lb/ft^3)\ (1.4\ ft)\ 0.05\ ft/ft) = 4.4\ lb/ft^2$$

This is a relatively large value for shear stress, requiring reinforcement.

Example Specifications for Erosion Control Blanket (NAG S150BN Straw, 10 month life)

RUSLE Conservation Coefficients (C)			Channel Roughness Coefficients (n)	
	Slope Gradients (S)		Flow depth (ft)	Manning's n (unvegetated)
Slope length (ft)	<3:1	3:1 to 2:1	<0.50 ft	0.055
< 20 ft	0.00014	0.039	0.50 to 2 ft	0.055 to 0.021
20 to 50	0.010	0.070	> 2 ft	0.021
>50 ft	0.020	0.100	Max. permissible shear stress: 1.85 lb/ft^2	

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Example for Matted Channel Liner

- Consider the following example:
  - Calculated max. shear stress: 2.83 lb/ft^2, requiring a NAG P300 permanent mat.
  - 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

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

The safety factor is therefore 0.08/0.053 = 1.5 and the channel lining system is expected to be stable.

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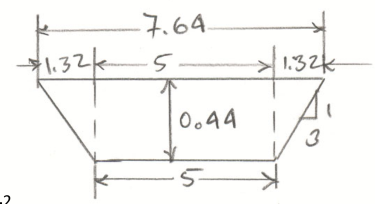
Example of a permanent channel design, with a liner:

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

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

One possible solution:



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
P = 5 + 2(3.16)(0.44) = 7.78 ft.
R = A/P = 2.78 ft2/7.78 ft. = 0.36 ft.
τ = γRS = (62.4lb/ft^3)(0.36 ft.)(0.08) = 1.8 lb/ft^2
which is relatively large (The permissible shear stress for the underlying soil is 0.08 lb/ft^2)

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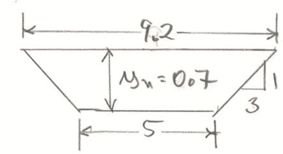
Another alternative design with a liner:



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
τ = γDS = (62.4lb/ft^3)(0.70 ft.)(0.08) = 3.49 lb/ft^2
(design case using normal depth)
V = Q/A = 29 ft^3/sec/4.97 ft^2 = 5.8 ft/sec

Permanent C350 liner, 5 ft bottom width, z=3 side slope, and phase 3 vegetation plant stage (mature)

n_s = 0.016; C_f = 0.87 phase 3
Effective shear stress on underlying soil:

$$\tau_e = \gamma DS(1-C_f)\left(\frac{n_s}{n}\right)^2 = 3.49 lb/ft^2(1-0.87)\left(\frac{0.016}{0.049}\right)^2 = 0.048 lb/ft^2$$

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

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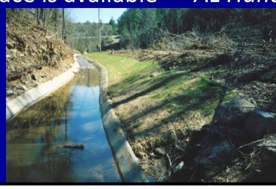
Channel Design using Concrete and Riprap Liner Materials

"A lined swale is a constructed channel with a permanent lining designed to carry concentrated runoff to a stable outlet. This practice applies where grass swales are unsuitable because of conditions such as steep channel grades, prolonged flow areas, soils that are too erodible or not suitable to support vegetation or insufficient space is available" – *AL Handbook*

Even concrete-lined channels and pipes may fail



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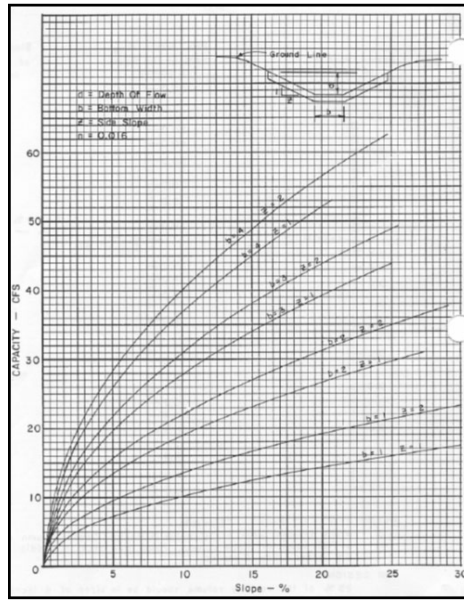

Capacity graph for concrete flumes, depth of flow = 0.50 feet

Alabama Handbook 50

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Riprap-lined Swale

"A riprap-lined swale is a natural or constructed channel with an erosion-resistant rock lining designed to carry concentrated runoff to a stable outlet. This practice applies where grass swales are unsuitable because of conditions such as steep channel grades, prolonged flow areas, soils that are too erodible or not suitable to support vegetation or insufficient space." – *Alabama Handbook*

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Stable rock sizes, for rock lined swales having gradients between 2 percent and 40 percent should be determined using the following formulas from *Design of Rock Chutes* by Robinson, Rice, and Kadavy.

For swale slopes between 2% and 10%:
$d_{50} = [q\ (S)^{1.5}/4.75x10^{-3}]^{1/1.89}$

For swale slopes between 10% and 40%:
$d_{50} = [q\ (S)^{0.58}/3.93x10^{-2}]^{1/1.89}$

d_{50} = Particle size for which 50 % of the sample is finer, inch
S = Bed slope, ft/ft
q = Unit discharge, $ft^3/s/ft$ (Total discharge/Bottom width)

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Size of Riprap Stones

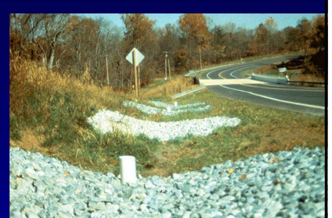
Weight (lbs)	Mean Spherical Diameter (feet)	Rectangular Shape Length Width, Height (feet)	
50	0.8	1.4	0.5
100	1.1	1.75	0.6
150	1.3	2.0	0.67
300	1.6	2.6	0.9
500	1.9	3.0	1.0
1000	2.2	3.7	1.25
1500	2.6	4.7	1.5
2000	2.75	5.4	1.8
4000	3.6	6.0	2.0
6000	4.0	6.9	2.3
8000	4.5	7.6	2.5
20000	6.1	10.0	3.3

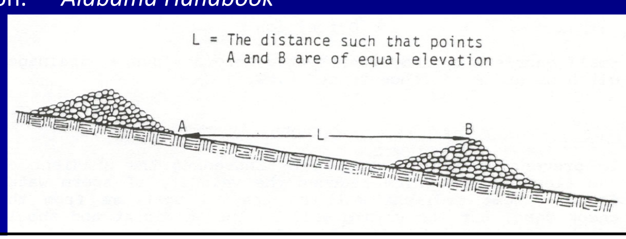
Graded Riprap

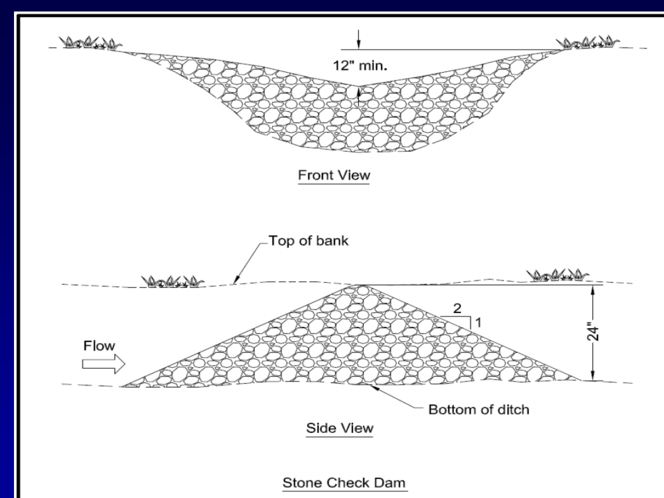
Class	Weight (lbs.)					
	d_{10}	d_{15}	d_{25}	d_{50}	d_{75}	d_{90}
1	10	-	-	50	-	100
2	10	-	-	80	-	200
3	-	25	-	200	-	500
4	-	-	50	500	1000	-
5	-	-	200	1000	-	2000

Check Dams

"Check dams are small barriers or dams constructed across a swale, drainage ditch or areas of concentrated flow. Check dams are to prevent or reduce erosion by lessening the gradient of the flow channel which reduces the velocity of storm water flows. Some sediment will be trapped upstream from the check dams, but its volume will be insignificant and should not be considered in off-site sediment reduction." – *Alabama Handbook*







Stone check dam profile and cross-section (Alabama Soil and Water Conservation Committee 2014)

Check dams at construction sites (straw bales are no longer allowed by most US regulatory agencies as an approved control)

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Effectiveness of Check Dams at Construction Sites

	number of events X locations per treatment	TSS influent (mg/L) avg	TSS effluent (mg/L) avg	% TSS reduc	Turbidity influent (NTU) avg	Turbidity effluent (NTU) avg	% Turbidity reduc
number	10	7	5	5	7	8	8
average	7.5	7,015	1,291	70	3,286	1,754	47
min	1	1,694	181	51	867	202	8
max	23	15,201	2,069	99	3,813	3,334	95
COV		0.80	0.60	0.28	0.33	0.79	0.73

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Effectiveness of Check Dams with Polymers at Construction Sites

	number of events X locations per treatment	TSS influent (mg/L) avg	TSS effluent (mg/L) avg	% TSS reduc	Turbidity influent (NTU) avg	Turbidity effluent (NTU) avg	% Turbidity reduc
number	7	4	4	4	4	7	7
average	7	6,350	522	86	2,984	631	80
min	1	1,694	82	76	867	34	42
max	27	15,201	1,028	99	3,813	2,113	99
COV		0.95	0.83	0.11	0.47	1.47	0.30

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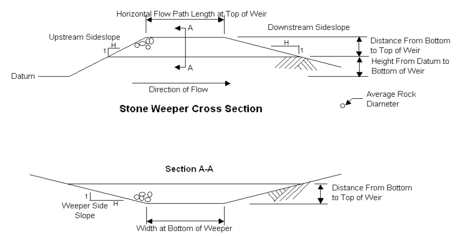
Flow Rates through Stone Check Dams

$$Q = \frac{h^{3/2} W}{\left[(L/D) + 2.5 + L^2 \right]^{0.5}}$$

Q = Outflow through the stone check dam (cfs)
h = Ponding depth behind the check dam (ft)
W = Average width of the check dam (ft), not to be confused with the horizontal flow path length through the check dam
L = Horizontal average flow path length through the check dam (ft)
D = Average rock diameter in the check dam (ft)



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Flow Rates through Stone Check Dams

h = 3 ft W = 15 ft,
L = 3 ft D = 9 inches = 0.75 ft

$$Q = \frac{h^{3/2}W}{\left[(L/D)+2.5+L^2\right]^{0.5}} = \frac{(3\,ft)^{3/2}(15\,ft)}{\left[(3\,ft/0.75\,ft)+2.5+(3\,ft)^2\right]^{0.5}} = 19.8\,ft^3/\sec$$

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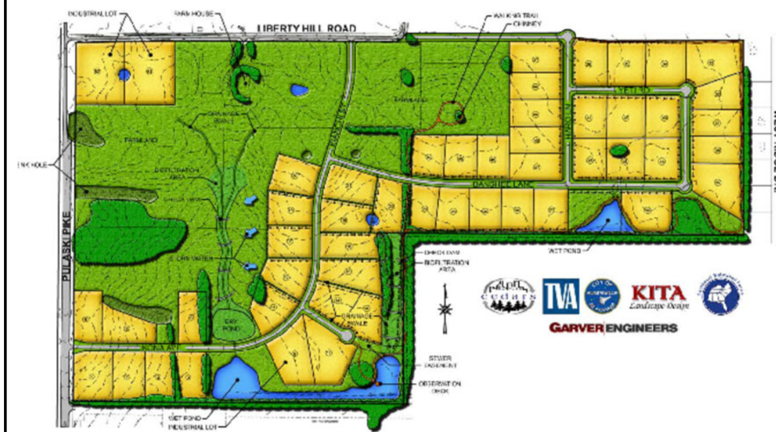
Example Design for Reinforced Grass-Lined Channels with Check Dams and Level Spreader Pads



NORTH HUNTSVILLE CONSERVATION DESIGN INDUSTRIAL PARK

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A new industrial site in Huntsville, AL, has several 2-acre individual building sites. Each of the sites will be served with a grass-lined channel that will carry site water to a larger swale system. The slopes of the channels vary from about 1 to 6.5%. The calculated peak flow from each construction site was calculated to be 16 ft^3/sec (corresponding to the Huntsville, AL, 25 yr design storm of 6.3 inches for 24 hours). A grass-lined channel is to be designed for each site. The bare seed bed is assumed to have a hydraulic roughness of about 0.016.

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The seed bed has an allowable shear stress of about 0.05 lb/ft^2. The calculated values for unprotected conditions are all much larger. Therefore, a North American Green S75 mat was selected, having an allowable shear stress of 1.55 lb/ft^2 and a life of 12 months.

Slope	Bare seed bed shear stress (lb/ft^2)	Unvegetated mat shear stress, effect on soil (lb/ft^2)	Safety factor (allowable shear stress of 0.05 lb/ft^2)	Maximum velocity with mature vegetation (ft/sec)
1%	0.14	0.012	4.2	3.1
3%	0.28	0.023	2.2	4.8
5%	0.42	0.035	1.4	5.5
6.5%	0.46	0.039	1.3	6.4

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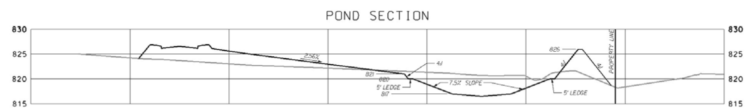
The check dams are assumed to be 2 ft high to the maximum over-topping elevation in 3 ft deep channels. In channels with 5% slopes, the check dams would have to be about 40 ft apart (or less) to ensure that the toes of the upstream check dams were at the same, or lower, elevations as the overflows of the downstream dams. Similarly, the check dams in the 6.5% sloped channels would have to be no more than 30 ft apart. Most check dam guidance requires that check dams be at least 20 ft apart to allow maintenance.



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Conclusions

- Stable channels at construction sites are critical to ensure that off-site water is safely diverted or channeled through the site.
- Stable channels are needed so they do not become significant sediment sources themselves.
- Both allowable velocity and shear stress need to be considered in the design of stable channels.

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