APPENDIX F

GUIDELINES FOR DESIGN OF OPEN CHANNELS

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FIGURES

TABLES

APPENDIX F
GUIDELINES FOR DESIGN OF OPEN CHANNELS

F.1 Introduction

An open channel is any water conveyance route which allows a free passage of runoff, i.e. the surface is exposed to the atmosphere and hence at atmospheric pressure. Closed pipes, not flowing full, are also considered to act as open channels from a hydraulic perspective. Examples are all channels associated with roadway drainage, culverts flowing less than full and storm sewers flowing in a similar manner.

Flows along open channels can at times be simple occurrences capable of being analyzed using simple equations. A long regular-shaped channel such as a highway ditch with a constant slope and flow is a typical example. On the other hand, rather complex calculations or even modeling studies are required in other situations due to turbulence and hydraulic constrictions. The key to successfully dealing with hydraulic problems is to be able to differentiate between the situations requiring involved calculations from those that can be handled using simple approximations. In general, constant flow conditions can be easily analyzed while changing conditions of either flow or channel configuration increase the complexity of the problem.

F.2 Type of Flow

Under natural conditions, the flow rate of water flowing through any given section of a channel will vary with time. Flow variations result from changes in runoff rate due to changes in rainfall intensity, snow melt rate or ground water seepage. Similarly, variations in flow depth occur along the length of the channel. Factors accounting for these variations are inflow from the sides and changes in channel characteristics such as roughness, cross-section and bed slope.

In attempting to simplify the approach to hydraulic problems, two states of flow are defined - unsteady and steady. Unsteady flow occurs whenever there is a variation in the quantity of water flowing along the channel.

Steady flow requires the flow rate to be constant with time. Except under controlled laboratory conditions, most flows are unsteady. However, many hydraulic calculations can be simplified by assuming a steady flow state. This steady flow is taken as the maximum flow that the facility can reasonably be expected to handle without incurring excessive costs. For roadway erosion control work, the peak discharge from a 1:10 year storm is typically used when permanent structures are designed. Temporary structures require less stringent conditions for which a 1:5 year storm or even a 1:2 year storm will suffice for the less important ones.

Steady flow is further subdivided into uniform and non-uniform flow modes. With uniform flow, the depth of water and the mean velocity are constant along every section of the channel possessing such a condition. The depth is referred as the normal depth, d_n, shown in Figure F.1.

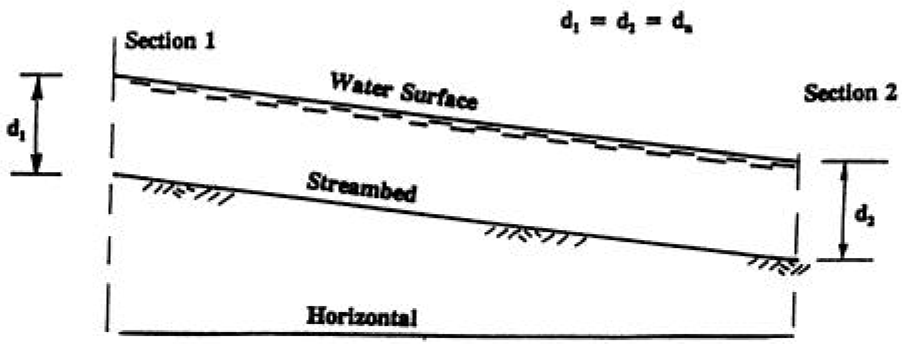


Figure F.1 Water Surface Profile of Channel with Uniform Flow

Uniform flow will occur when the following conditions are satisfied (otherwise the flow will be non-uniform).

- Channel cross-sectional area constant (including bottom width and sideslopes);
- Bed slope constant;
- Channel roughness uniform; and
- Steady flow rate.

Even with the above conditions satisfied, there will still be non-uniform flow in the transition areas at the beginning and the end of the channel section.

While uniform flow conditions are rare, the simplification leads to channel sizes and flow depths that produce realistic design cross-sections and its use is therefore justified. Further, the error incurred as a result of the simplification of the flow is often small compared to errors built into estimating procedures for the other parameters required for design such as peak discharge rate and channel roughness. An appropriate freeboard allowance to road sub grade is typically added to peak channel flow elevations to further ensure flows remain in the channel under design conditions.

F.3 Geometric Properties of Channels

The solution of uniform flow problems and other hydraulic calculations require an input of various geometric properties of the conducting channel such as bottom width, sideslopes, wetted perimeter and hydraulic radius. The properties in frequent use are defined below while Table F.1 provides formulae for the estimation of some of the properties for typical cross-sections.

Table F.1: Formulae for the Geometric Properties of Channels

Section	Area A	Wetted Perimeter P	Hydraulic Radius R	Top Width T
Trapezoid	$bd+zd^2$	$b+2d\sqrt{z^2+1}$	$\frac{bd+zd^2}{b+2d\sqrt{z^2+1}}$	$b+2zd$
Rectangle	bd	$b+2d$	$\frac{bd}{b+2d}$	b
Triangle	zd^2	$2d\sqrt{z^2+1}$	$\frac{zd}{2\sqrt{z^2+1}}$	$2zd$
Parabola	$\frac{2}{3}dT$	$T+\frac{8d^2}{3T}$	$\frac{2dT^2}{3T^2+8d^2}$	$\frac{3a}{2d}$

F.4 The Manning Equation for Uniform Steady Flow

A simple equation relating the velocity of flow under uniform conditions to the properties of a channel was developed by Robert Manning. The equation is:

$$V = (1 / n) * R^{2/3} * S^{1/2} \quad \text{...(Equation F.1)}$$

Where:
- V = velocity of flow (m/s)
- n = channel roughness (dimensionless)
- R = hydraulic radius, A/P (m)
  - A = cross-sectional area of flow (m^2)
  - P = wetted perimeter (m)
- S = channel bed slope (m/m)

All the variables on the right side of the equation are channel properties. A knowledge of them enables an estimate of the velocity of flowing water along the channel to be made under uniform flow condition. The importance of this estimation lies in the fact that the amount of water flowing along any channel can be evaluated using the cross-sectional area of flow and the estimated velocity.

F.5 MANNING ROUGHNESS COEFFICIENT, n

The only non-geometric quantity on the right side in Manning's equation is the channel roughness. This parameter is dependent on the degree of retardance a channel treatment offers to flow along it. Estimates of the parameter have been made on an empirical basis for various materials and values obtained published for design purposes. Table F.2 provides a listing of values in current use for channels with various bed materials except vegetation. Roughness values for vegetation are obtained graphically as discussed below.

Table F.2: Manning's Roughness Coefficients (n)

Lining Category	Lining Type	n - value Depth Ranges		
		0-15 cms	**15-60 cms**	**> 60 cms**
Rigid	Concrete	0.015	0.013	0.013
	Grouted riprap	0.040	0.030	0.028
	Stone masonry	0.042	0.032	0.030
	Soil cement	0.025	0.022	0.020
	Asphalt	0.018	0.016	0.016
Unlined	Bare soil	0.023	0.020	0.020
	Rock cut	0.045	0.035	0.025
Temporary*	Woven paper net	0.016	0.015	0.015
	Jute net	0.028	0.022	0.019
	Fibreglass roving	0.028	0.021	0.019
	Straw with net	0.065	0.033	0.025
	Curled wood mat	0.066	0.035	0.028
	Synthetic mat	0.036	0.025	0.021
Gravel riprap	D_{50} = 2.5 cm	0.044	0.033	0.030
	D_{50} = 5 cm	0.066	0.041	0.034
Rock riprap	D_{50} = 15 cm	0.104	0.069	0.035
	D_{50} = 30 cm	-------	0.078	0.040

Note: Values listed are representative values for the respective depth ranges. Manning's roughness coefficient, n, varies with the flow depth.
* Some "temporary" linings become permanent when buried.

Source: Chen & Cotton, 1988
N. Kouwen, et al., 1980
A.G. Anderson, et al., 1970
R.L. Cox, et al., 1971
J.C. McWhorter, et al., 1968
K.G. Thibodeaux, 1982-85

Other values for Manning's Roughness Coefficients (n) for various materials normally encountered along channels/conduits are presented in Table F.3(h).

The quantity represented by the variable, n, reflects the degree to which roughness elements on the channel wetted perimeter project into the flow. Thus channels with small projections have low roughness values and those with larger projections have higher roughness values.

For most materials, the roughness value remains virtually constant when the flow depth exceeds 600 mm. However, in erosion control work along roadways, the flow depth is almost always less than 600 mm and appropriate n values which change with depth of flow must be used in design. In the case of rock riprap, gravels and many of the manufactured ditch lining materials, the change in n values with the depth of flow is very pronounced reflecting the relatively high ratio of the roughness element sizes to the flow depth.

Vegetation adds another dimension to the roughness problem along ditches. Stems of vegetative growth, projecting into the flow in a channel, produce roughness as other materials do. But when subjected to flows of variable magnitudes the extent to which the vegetation allows the flow to go through varies with the magnitude of the flow and the type of vegetation. Thus the roughness of the ditch changes with the depth of flow through it and the type of vegetation along it.

Manning's n becomes an even more variable quantity with vegetated channels than with non-vegetated ones.

To resolve the problems associated with estimates of flow through vegetation-lined channels, the Soil Conservation Service (SCS) of the U.S. Department of Agriculture have identified five classes of vegetation, designated retardance classes A to E as shown in Tables F.3(a) and F.3(b). While Table F.3(a) shows a simplified generic classification, Table F.3(b) indicates the detailed classification proposed by the SCS. All types of vegetation are assigned a classification based on growth height and stand density, and this grouping is used to determine an appropriate roughness value.

Tests were conducted by investigators on channels lined with vegetation belonging to each of the five classes for various slopes. A set of curves were drawn up from the tests showing the variation of Manning's n with bed slope and hydraulic radius. The curves are given in Figures F.2 to F.6 from which appropriate n values can be selected for the design of channels with vegetative linings. (Please note the units for the hydraulic mean depth, R, in these figures are in feet). Generally, acceptable n values can normally range from 0.03 to 0.05 dependent on channel slope, flow depth and vegetation class.

Table F.3(a): Vegetation Retardance Classification

Vegetation Height and Density	Retardance Class
< 50 mm, good stand 50-150 mm, fair stand	E
50-150 mm, good stand 150-250 mm, fair stand	D
150-250 mm, good stand 250-600 mm, fair stand	C
250-600 mm, good stand > 600 mm, fair stand	B
> 600 mm, good stand	A

Table F.3(b): Classification of Degree of Retardance for Various Kinds of Grasses*

Retardance	Cover	Condition
A Very high	Weeping love grass	Excellent stand, tall (av. 760 mm)
	Yellow bluestem *ischaemum*	Excellent stand, tall (av. 760 mm)
	Kudzu	Very dense growth, uncut
	Bermuda grass	Good stand, tall (av. 300 mm)
	Native grass mixture (little bluestem, blue gramma and other long and short Midwest grasses)	Good stand, unmowed
B High	Weeping love grass	Good stand, tall (av. 510 mm)
	Lespedeza sericeus	Good stand, not woody, tall (av. 480 mm)
	Alfalfa	Good stand, uncut (av. 280 mm)
	Weeping love grass	Good stand, mowed (av. 330 mm)
	Kudzu	Dense growth, uncut
	Blue gramma	Good stand, uncut (av. 330 mm)
	Crab grass	Fair stand, uncut (250 - 1220 mm)
	Bermuda grass	Good stand, mowed (av. 150 mm)
	Common *lespedeza*	Good stand, uncut (av. 250 mm)
	Grass-legume mixture - summer (orchard grass)	
C Moderate	red top, Italian rye grass, and common *lespedeza*	Good stand, uncut (150 - 200 mm)
	Centipede grass	Very dense cover (av. 150 mm)
	Kentucky blue grass	Good stand, headed (150 to 300 mm)
	Bermuda grass	Good stand, cut to 64 mm height
	Common lespedeza	Excellent stand, uncut (av. 110 mm)
	Buffalo grass	Good stand, uncut (76 to 150 mm)
	Grass-legume mixture - fall (orchard grass)	
D Low	Red top, Italian rye grass, and common *lespedeza*	Good stand, uncut (100 - 130 mm) After cutting to 50 mm height
	Lespedeza sericeus	Very good stand before cutting
E Very low	Bermuda grass	Good stand, cut to 38 mm height
	Bermuda grass	Burned stubble

* Source: U.S. Soil Conservation Service, 1986
Chen & Cotton, 1988

Note:
i) Table F.3(b) is provided for design guidance only.
ii) For highway ditch use, the designer should select salt tolerant grass-types that are not attractive to animal grazing.
iii) Designer should consult local expertise on appropriate grass seed for the locality (possible expertise can reside with: local seed supplier; Alberta Forestry; Alberta Environment; local municipalities; professional agrologist).

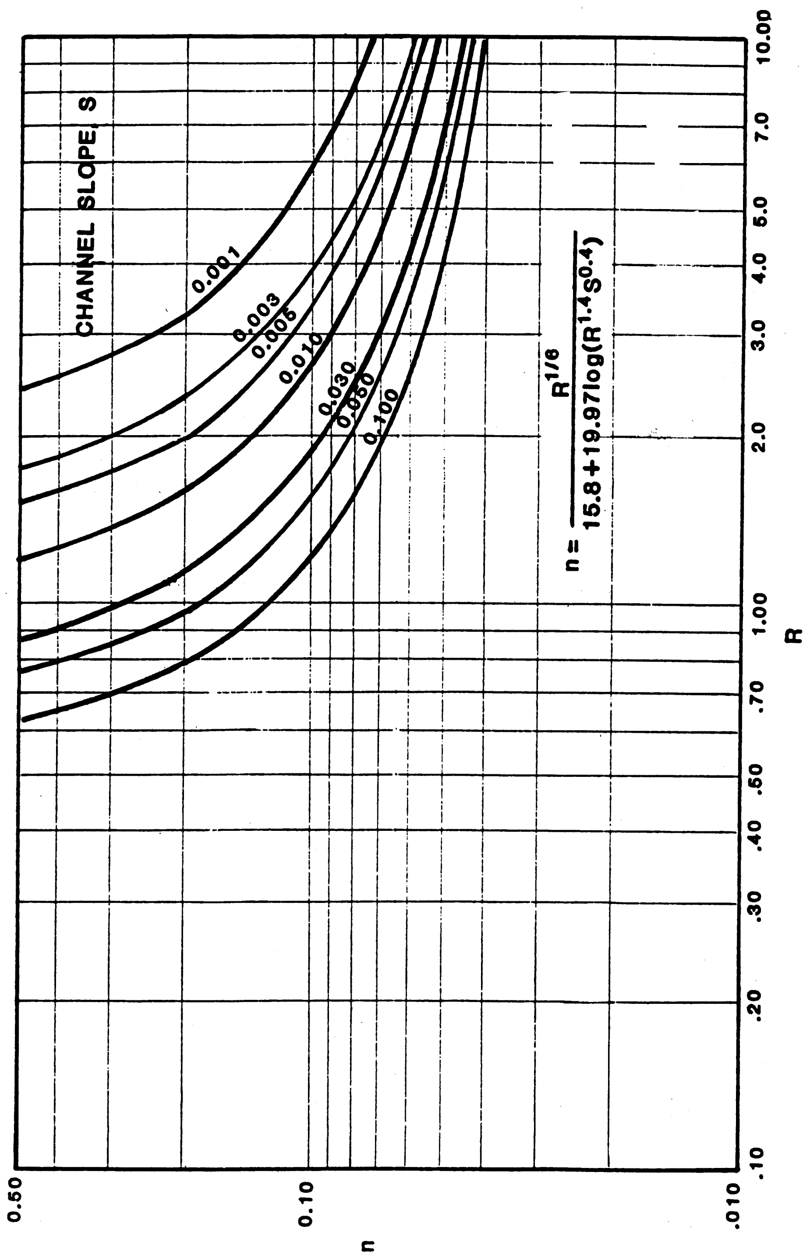


Figure F.2 Manning's n for Class A Vegetation
(Note: hydraulic depth (R) in feet)

Source: N. Kouwen, et al., 1980

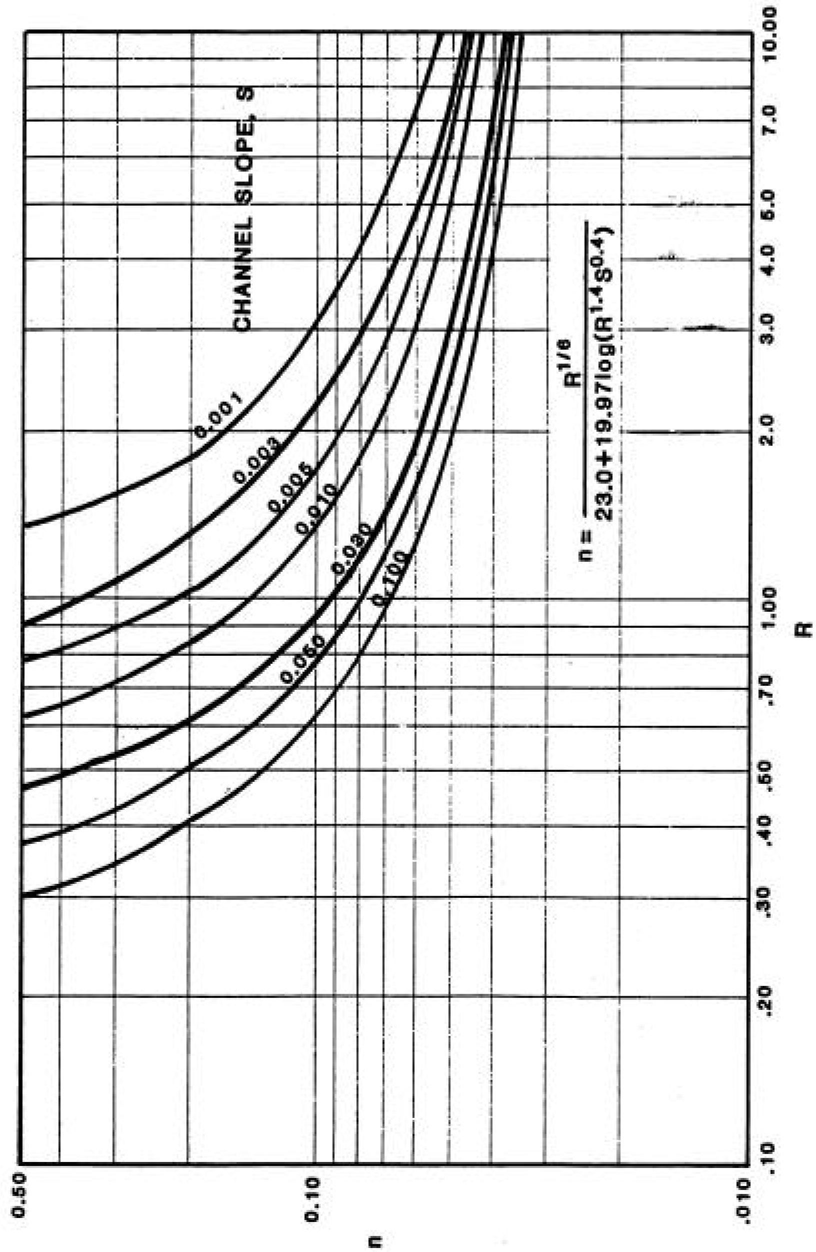


Figure F.3 Manning's n for Class B Vegetation
(Note: hydraulic depth (R) in feet)

Source: N. Kouwen, et al., 1980

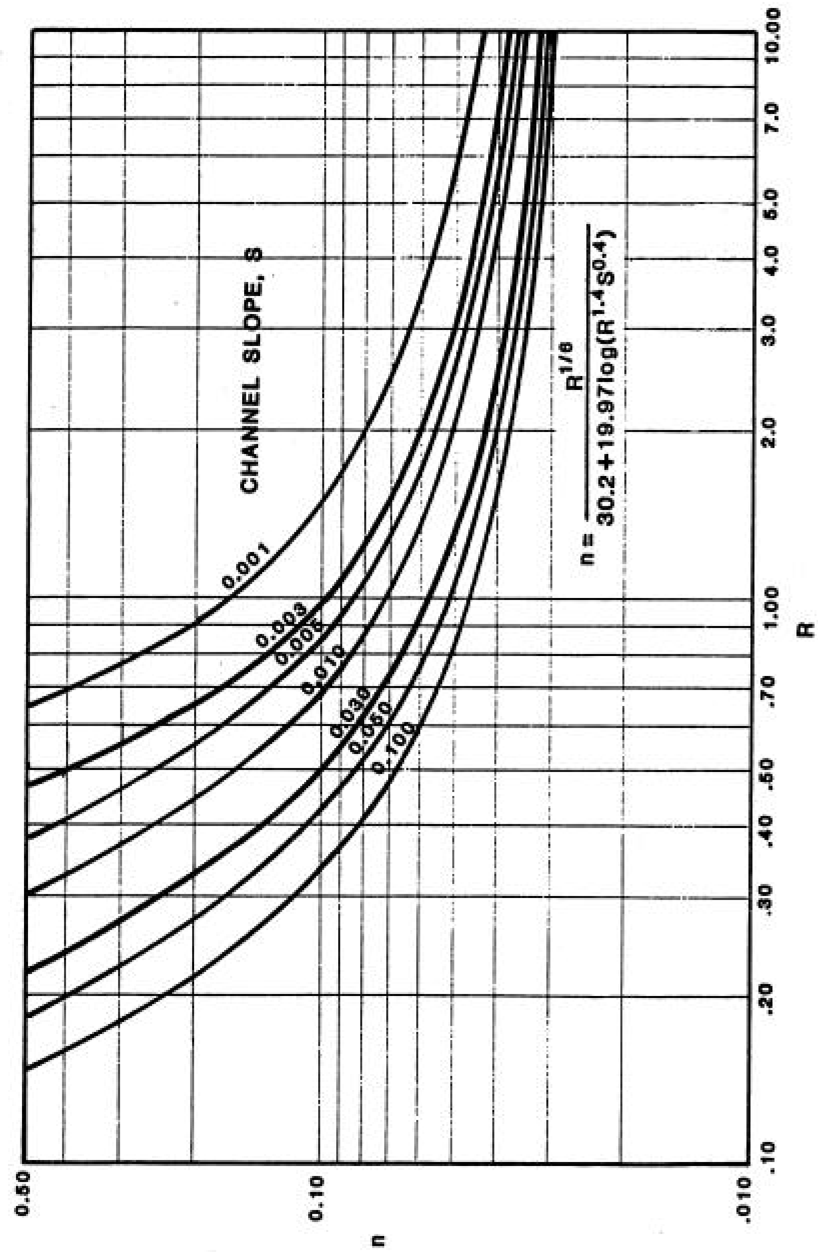


Figure F.4 Manning's n for Class C Vegetation
(Note: hydraulic depth (R) in feet)

Source: N. Kouwen, et al., 1980

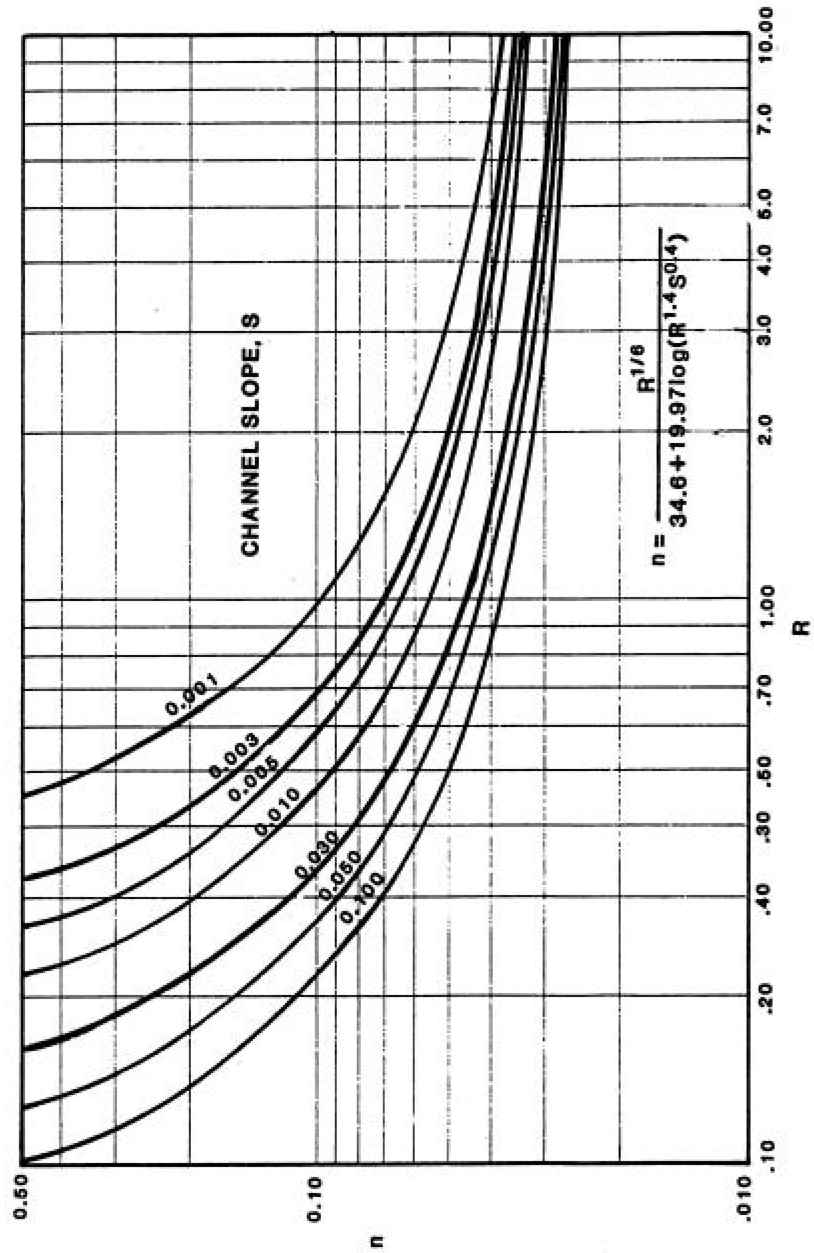


Figure F.5 Manning's n for Class D Vegetation
(Note: hydraulic depth (R) in feet)

Source: N. Kouwen, et al., 1980

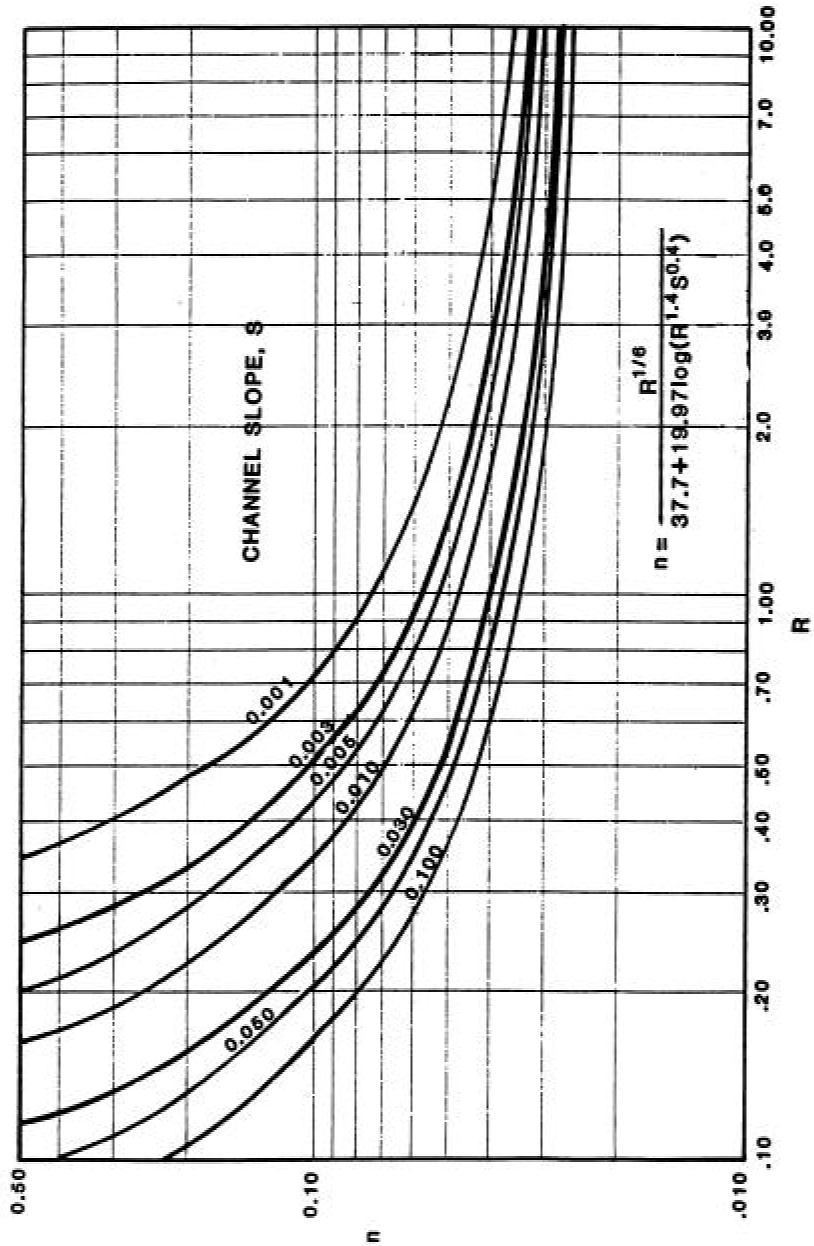


Figure F.6 Manning's n for Class E Vegetation
(Note: hydraulic depth (R) in feet)

Source: N. Kouwen, et al., 1980

F.5.1 Rolled Erosion Control Product (RECP)

Rolled Erosion Control Products (RECPs) are manufactured mulch materials used to protect disturbed soils from erosion. They are also known as erosion control blanket or mats. When properly designed and installed, RECPs reduce the erosion process and create conditions to facilitate establishing vegetation by keeping seed in place and conserving soil moisture.

RECPs are composed of organic or inorganic materials. The organic materials are subject to both photo- and biological degradation processes. Thus, they may degrade within 3 to 12 months in warm climate areas (e.g. Georgia, USA) and are considered a temporary blanket/mat. In temperate to cold areas (e.g. Alberta, Canada), the temporary blanket/mat may degrade within 10 to 36 months. The inorganic materials are less susceptible to degradation process and are considered a permanent to semi-permanent mat/blanket. Examples of RECPs are as follows:

- Straw or hay;
- Coconut or related fibers;
- Wood excelsior;
- Jute;
- Polypropylene;
- Nylon; and
- Turf Reinforcement Mat (TRM).

Product QA/QC Certification

RECPs should be specified to ensure product performance and manufacture quality control. Dependent on product type and intended performance, the product information should be provided by the product manufacturer as follows:

- Manufacturer's Certificate on:
  - Minimum Average Roll Values (MARVs) along with specified testing methods for:
    - Physical properties that include
      - Mass per unit area;
      - Thickness;
      - Tensile strength; and
      - UV Resistance.
    - Other physical properties where appropriate, such as:
      - Grab tensile strength;
      - Grab elongation;
      - Puncture strength;
      - Trapezoidal tear; and
      - Permittivity.

- Performance Properties, such as:
  - Tractive resistance;
  - Permissible velocity; and
  - Longevity.

The following typical values of materials (RECP and rock linings) for shear resistance and permissible value can be used for reference. RECP includes Erosion Control Mat (ECM), Turf Reinforcement Mat (TRM), Composite Turf Reinforcement Mat (C-TRM) and other products certified by the erosion matting supplier and approved by AT.

Table F.3(c): Maximum Permissible Shear – Stress Values and Velocities for Various Materials

		Performance Properties	
Materials	**Test Time (hr.)**	**Maximum Permissible Shear Stress (N/m²)**	**Maximum Permissible Velocity (m/sec.)**
Bare soil[a] (see Figure F.12) (*Table F.3d)			
Noncohesive (Dia. = 0.1 – 25 mm)	NDG	1.5 – 20	0.46-0.76*
Cohesive (P.I. = 4 – 50) (see Figure F.11) (Table F.3d)	NDG	0.5 – 38	0.52-1.13* -1.8 (hard pan)
Gravel riprap[a] (*Table F.3(d))			
D50 = 25 mm (thickness t=2D_{50})	NDG	15.8	0.76-1.13 *
D50 = 50 mm (thickness t=2D_{50})	NDG	31.6	1.13-1.22 *
Rock riprap[a] (** Table F.3(e))			
D50 = 150 mm (thickness t=1.5D_{50})	NDG	95.8	2.2 **
D50 = 300 mm (thickness t=2D_{50})	NDG	191.5	3.0 **
Gabion Mattress (ΔΔ Table F.3(f))			(V_c) – (V_l)
thickness = 0.25 m D_{50} = 120 mm	NDG	200	4.5 – 6.1 ΔΔ
thickness = 0.30 m D_{50} = 150 mm	NDG	230	5.0 – 6.4 ΔΔ
thickness = 0.50 m D_{50} = 190 mm	NDG	250	6.4 – 8.0 ΔΔ
Grass (established)[a] (Table F.3g)	NDG	16.8 – 177.2	0.8-2.4
Vegetative			
Class A Retardance	NDG	177.2	
Class B Retardance	NDG	100.6	
Class C Retardance	NDG	47.9	
Class D Retardance	NDG	28.7	
Class E Retardance	NDG	16.8	
Fiberglass roving[a] (SOP)			
Single	NDG	28.7	NDG
Double	NDG	40.7	NDG
Straw (loose) covered with net[a]	NDG	69.4	NDG

Materials	Test Time (hr.)	Performance Properties: Maximum Permissible Shear Stress (N/m²)	Performance Properties: Maximum Permissible Velocity (m/sec.)
EROSION CONTROL MAT (ECM)			
Coconut material[c]	0.5	143	3.0-4.6
Wood excelsior material[a]	NDG	74.2	NDG
Jute net[a]	NDG	21.5	NDG
Straw blanket with sewn net[c]	0.5	95.7 – 105	1.8 – 3.0
Straw/coconut blanket[c]	0.5	120	3.0
TURF REINFORCEMENT MAT (TRM)			
Bare ground conditions[a, b]	0.5	239 – 287	5.5 – 8.2
	50	95.6	2.4
Vegetation established[b]	0.5	100-380	5.5
growth period ≥ 36 mos. & growth density dependent	50	100-239	3.0
COMPOSITE TURF REINFORCEMENT MAT (C-TRM)			
Bare ground conditions,[b]	0.5	239	3.7
	50	95.6	2.1
Vegetation established[b]	0.5	382	6.1
	50	239	4.3

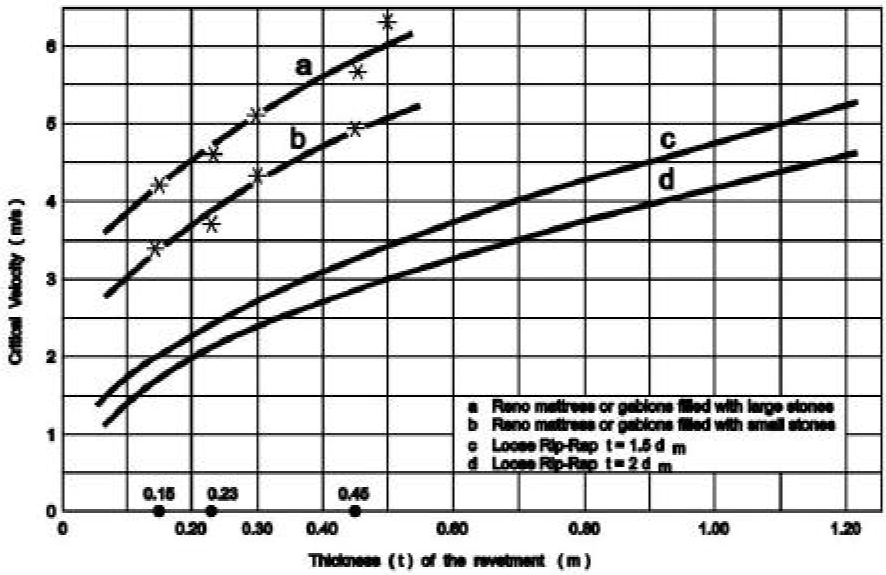
a From Chen and Cotton (1988)
b From IECA (1991, 1992, 1995)
c As reported by manufacturer

1) NDG = No data given
   SOP = Spray-on-Product (s.a. mulch)
   V_c = Critical Velocity
   V_l= Limit Velocity
2) RECP types include ECM, TRM, C-TRM
   - For use of RECP products, product certification on performance and physical properties are required from suppliers.
   - Performance of RECP will depend on Final Density of Vegetation Growth after installation and the growth period specified.
3) Relationship of shear stress not linear with flow velocity; select lining based on permissible tractive resistance.
4) Performance values given are limited to flow of 1.4 m³/sec.

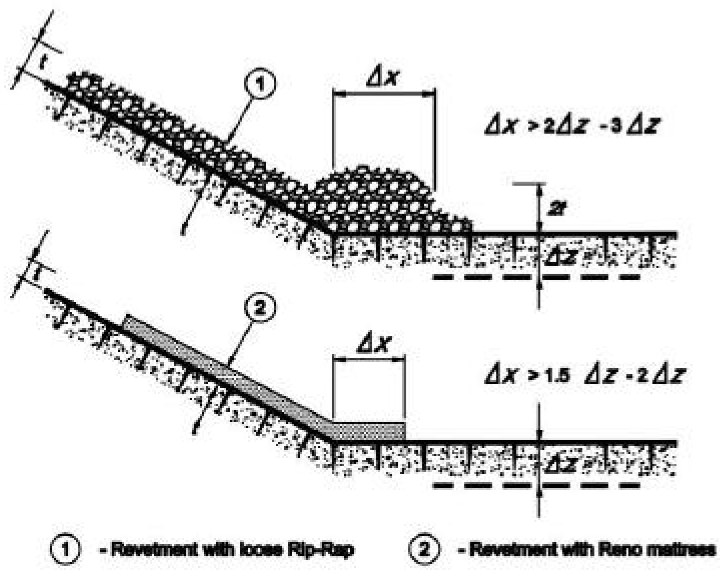
Table F.3(d): Maximum Permissible Velocities in Erodible Channels, Based on Uniform Flow in Continuously We t, Aged Channels[1]

	Maximum Permissible Velocities for -		
Material	**Clear Water**	**Water Carrying Fine Silts**	**Water Carrying Sand and Gravel**
	m/s (F.p.s.)	**m/s (F.p.s.)**	**m/s (F.p.s.)**
Fine sand (noncolloidal)	0.46 (1.5)	0.76 (2.5)	0.46 (1.5)
Sandy loam (noncolloidal)	0.52 (1.7)	0.76 (2.5)	0.61 (2.0)
Silt loam (noncolloidal)	0.61 (2.0)	0.91 (3.0)	0.61 (2.0)
Ordinary firm loam	0.76 (2.5)	1.07 (3.5)	0.67 (2.2)
Volcanic ash	0.76 (2.5)	1.07 (3.5)	0.61 (2.0)
Fine gravel	0.76 (2.5)	1.52 (5.0)	1.13 (3.7)
Stiff clay (very colloidal)	1.13 (3.7)	1.52 (5.0)	0.91 (3.0)
Graded, loam to cobbles (noncolloidal)	1.13 (3.7)	1.52 (5.0)	1.52 (5.0)
Graded, silt to cobbles (colloidal)	1.22 (4.0)	1.68 (5.5)	1.52 (5.0)
Alluvial silts (noncolloidal)	0.61 (2.0)	1.07 (3.5)	0.61 (2.0)
Alluvial silts (colloidal)	1.13 (3.7)	1.52 (5.0)	0.91 (3.0)
Coarse gravel (noncolloidal)	1.22 (4.0)	1.83 (6.0)	1.98 (6.5)
Cobbles and shingles	1.52 (5.0)	1.68 (5.5)	1.98 (6.5)
Shales and hard pans	1.83 (6.0)	1.83 (6.0)	1.52 (5.0)

[1] As recommended by Special Committee on Irrigation Research, American Society of Civil Engineers, 1926, for channel with straight alignment. For sinuous multiply allowable velocity of 0.95 for slightly sinuous, by 0.9 for moderately sinuous channels, and by 0.8 for highly sinuous channels (45, pg. 1257).



Thickness of a lining in Reno Mattress or Gabion
and in rip rap in relation to the flow velocity



Horizontal extension of lining in relation to the max erosion depth

Source: R. Agostini, et al 1988, "Flexible Gabion and Reno Mattress Structures in River and Stream Training Works", Officine Maccaferri s.p.a., Bologna, Italy, July 1988.

Table F.3(e): Gabion Reno Mattress vs. Riprap

Type	Thickness (m)	Filling Stones (mm)		* Critical velocity (m/s)	* Limit velocity (m/s)
		stone size	d_{50}		
Reno Mattress	0.15 - 0.17	70 - 100	85	3.5	4.2
		70 - 150	110	4.2	4.5
	0.23 - 0.25	70 - 100	85	3.6	5.5
		70 - 150	120	4.5	6.1
	0.30	70 - 120	100	4.2	5.5
		100 - 150	125	5.0	6.4
Gabions	0.50	100 - 200	150	5.8	7.6
		120 - 250	190	6.4	8.0

Note:

* Critical Velocity: Stone will not move and revetment in place.
* Limit Velocity: Stone start to move but mesh revetment will not deform.

Source: D.B. Simms, et al "Hydraulic test to develop design criteria for use of Reno Gabion Mattresses, Fort Collins, Colorado, USA, 1983"

Table F.3(f): Gabion Mattress Protection Thickness vs. Velocity

Table F.3(g): Maximum Permissible Velocities in Channels Lined with Uniform Stands of Grass Covers, Well Maintained[1 2]

		Maximum Permissible Velocities	
Cover	**Slope Range**	**Erosion-Resistant Soils**	**Easily Eroded Soils**
	Percent	**m/s (ft/s)**	**m/s (ft/s)**
Bermuda Grass	0 – 5 5 – 10 Over 10	2.4 (8) 2.1 (7) 1.8 (6)	1.8 (6) 1.5 (5) 1.2 (4)
Buffalo Grass Kentucky bluegrass Smooth brome Blue gramma	0 – 5 5 – 10 Over 10	2.1 (7) 1.8 (6) 1.5 (5)	1.5 (5) 1.2 (4) 0.9 (3)
Grass Mixture	0 – 5[3] 5 – 10[3]	1.5 (5) 1.2 (4)	1.2 (4) 0.9 (3)
Lespedeza sericea Weeping lovegrass Yellow bluestem Kudzu Alfalfa Crabgrass	0 – 5[4]	1.1 (3.5)	0.8 (2.5)
Common lespedeza[5] Sudangrass[5]	0 – 5[4]	1.1 (3.5)	0.8 (2.5)

1 Source: Handbook of Channel Design for Soil and Water Conservation 1954
2 Use velocities over 1.5 m/s only where good covers and proper maintenance can be obtained
3 Do not use on slopes steeper than 10 percent
4 Use on slopes steeper than 10 percent is not recommended
5 Annuals, used on mild slopes or as temporary protection until permanent covers are established.

Table F.3(h) – Additional Information on Manning's n[1] Roughness Coefficients for Other Common Channel Lining Materials (for reference and comparison only)

		Manning's n Range[2]
I	**Closed Conduits:**	
A.	Concrete pipe	0.011-0.013
B.	Corrugated metal pipe or pipe arch:	
	1. 2-2/3 by 1/2 in. corrugation (riveted pipe)[3]	0.024
	a. Plain or fully coated	0.021-0.018
	b. Paved invert (range values are for 25 and 50 percent of circumference paved):	
	(1) Flow full depth	0.021-0.018
	(2) Flow 0.8 depth	0.021-0.016
	(3) Flow 0.6 depth	0.019-0.013
	2. 3- by 1-inch corrugation	0.027
	3. 6- by 2-inch corrugation (field bolted)	0.032
C.	Vitrified clay pipe	0.012-0.014
D.	Cast-iron pipe, uncoated	0.013
E.	Steel pipe	0.009-0.011
F.	Brick	0.014-0.017
G.	Monolithic concrete:	
	1. Wood forms, rough	0.015-0.017
	2. Wood forms, smooth	0.012-0.014
	3. Steel forms	0.012-0.014
H.	Cemented rubble masonry walls:	
	1. Concrete floor and top	0.017-0.022
	2. Natural floor	0.019-0.025
I.	Laminated treated wood	0.015-0.017
J.	Vitrified clay liner plates	0.015
II	**Lined Open Channels:** [4]	
A.	Concrete, with surfaces as indicated:	
	1. Formed, no finish	0.013-0.017
	2. Trowel finish	0.012-0.014
	3. Float finish	0.013-0.015
	4. Float finish, some gravel on bottom	0.015-0.017
	5. Gunite, good section	0.016-0.019
	6. Gunite, wavy section	0.018-0.022
B.	Concrete bottom float-finished, sides as indicated:	
	1. Dressed stone in mortar	0.015-0.017
	2. Random stone in mortar	0.017-0.020
	3. Cement rubble masonry	0.020-0.025
	4. Cement rubble masonry, plastered	0.016-0.020
	5. Dry rubble (riprap)	0.020-0.030
C.	Gravel bottom, sides as indicated:	
	1. Formed concrete	0.017-0.020
	2. Random stone in mortar	0.020-0.023
	3. Dry rubble (riprap)	0.023-0.033 0.014-0.017
D.	Brick	0.013

		Manning's n Range[2]
E.	Asphalt:	
	1. Smooth	0.016
	2. Rough	0.011-0.013
F.	Wood, planed, clean	
G.	Concrete-lined excavated rock:	
	1. Good section	0.017-0.020
	2. Irregular section	0.020-0.027
III	**Unlined open channels:** [4]	
A.	Earth, uniform section:	
	1. Clean, recently completed	0.016-0.018
	2. Clean, after weathering	0.018-0.020
	3. With short grass, few weeds	0.022-0.027
	4. In gravely, soil, uniform section, clean	0.022-0.025
B.	Earth, fairly uniform section:	
	1. No vegetation	0.022-0.025
	2. Grass, some weeds	0.025-0.030
	3. Dense weeds or aquatic plants in deep channels	0.030-0.035
	4. Sides, clean, gravel bottom	0.025-0.030
	5. Sides, clean, cobble bottom	0.030-0.040
C.	Dragline excavated or dredged:	
	1. No vegetation	0.028-0.033
	2. Light brush on banks	0.035-0.050
D.	Rock:	
	1. Based on design section:	0.035
	2. Based on actual mean section	
	a. Smooth and uniform	0.035-0.040
	b. Jagged and irregular	0.040-0.045
E.	Channels not maintained, weeds and brush uncut:	
	1. Dense weeds, high as flow depth	0.08-0.12
	2. Clean bottom, brush on sides	0.05-0.08
	3. Clean bottom brush on sides, highest stage of flow	0.07-0.11
	4. Dense brush, high stage	0.10-0.14
IV	**Highway Channels and swales with maintained vegetation** [5 6] **(values shown are for velocities of 2 and 6 f.p.s.):**	
A.	Depth of flow up to 0.7 foot:	
	1. Bermuda grass, Kentucky bluegrass, buffalo grass:	
	a. Mowed to 2 inches	0.07-0.045
	b. Length 4 to 6 inches	0.09-0.05
	2. Good stand, any grass:	
	a. Length about 12 inches	0.018-0.09
	b. Length about 24 inches	0.30-0.15
	3. Fair stand, any grass:	
	a. Length about 12 inches	0.14-0.08
	b. Length about 24 inches	0.25-0.13
B.	Depth of flow 0.7-1.5 feet:	
	1. Bermuda grass, Kentucky bluegrass, buffalo grass:	
	a. Mowed to 2 inches	0.05-0.035
	b. Length 4 to 6 inches	0.06-0.04

		Manning's n Range[2]
	2. Good stand, any grass:	
	a. Length about 12 inches	0.12-0.07
	b. Length about 24 inches	0.20-0.10
	3. Fair stand, any grass:	
	a. Length about 12 inches	0.10-0.06
	b. Length about 24 inches	0.17-0.09
V.	**Street and expressway gutters:**	
A.	Concrete gutter, troweled finish	0.012
B.	Asphalt pavement:	
	1. Smooth texture	0.013
	2. Rough texture	0.016
C.	Concrete gutter with asphalt pavement:	
	1. Smooth	0.013
	2. Rough	0.015
D.	Concrete pavement:	
	1. Float finish	0.014
	2. Broom finish	0.016
E.	For gutters with small slope, where sediment may accumulate, increase all above values of n by	0.002
VI	**Natural stream channels:**	
A.	Minor streams[8] (surface width at flood stage less than 100 ft):	
	1. Fairly regular section:	
	a. Some grass and weeds, little or no brush	0.030-0.035
	b. Dense growth of weeds, depth of flow materially greater than weed height	0.035-0.05
	c. Some weeds, light brush on banks	0.04-0.05
	d. Some weeds, heavy brush on banks	0.05-0.07
	e. Some weeds, dense willows on banks	0.06-0.08
	f. For trees within channel, with branches submerged at high stage, increase all above values by	0.01-0.10
	2. Irregular sections, with pools, slight channel meander; increase values in 1 a-3 about	0.01-0.002
	3. Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stage:	
	a. Bottom of gravel, cobbles, and few boulders	0.04-0.05
	b. Bottom of cobbles, with large boulders	0.05-0.07
B.	Flood plains (adjacent to natural streams):	
	1. Pasture, no brush:	
	a. Short grass	0.030-0.035
	b. High grass	0.035-0.05
	2. Cultivated areas:	
	a. No crop	0.03-0.04
	b. Mature row crops	0.035-0.045
	c. Mature field crops	0.04-0.05
	3. Heavy weeds, scattered brush	0.05-0.07
	4. Light brush and trees:[9]	
	a. Winter	0.05-0.06
	b. Summer	0.06-0.08

		Manning's n Range[2]
	5. Medium to dense brush: [9]	
	a. Winter	0.07-0.11
	b. Summer	0.10-0.16
	6. Dense willows, summer, not bent over by current	0.15-0.20
	7. Cleared land with tree stumps, 100-150 per acre:	
	a. No sprouts	0.04-0.05
	b. With heavy growth of sprouts	0.06-0.08
	8. Heavy stand of timber, a few down trees, little undergrowth:	
	a. Flood depth below branches	0.10-0.12
	b. Flood depth reaches branches	0.12-0.16
	c. Major streams (surface width at flood stage more than 100 ft): Roughness coefficient is usually less than for minor streams or similar description on account of less effective resistance offered by irregular banks or vegetation on banks. Values of n may be somewhat reduced. Follow recommendation of note 7 if possible. The value of n for larger streams of most regular sections, with no boulders or brush, may be in the range of from	0.028-0.033

(see notes next page)

Source: FHWA HEC #14

Footnotes to Table F.3(h)

[1] Estimates are by Bureau of Public Roads unless otherwise noted and are for straight alignment. A small increase in value of n may be made for channel alignment other than straight.

[2] Ranges for sections 1 through 3 are for good to fair construction. For poor quality construction, use larger values of n.

[3] Friction Losses in Corrugated Metal Pipe, by M.J. Webster and L.R. Mecalf, Corps of Engineers, Department of the Army; published in Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers, Vol. 85, No. HY 9, September 1959, Paper No. 2148, pp.35-67.

[4] For important work and where accurate determination of water profiles is necessary, the designer is urged to consult the following references and to select n by comparison of the specific conditions with the channels tested: Flow of Water in Irrigation and Similar Canals, by F.C. Scobey, U.S. Department of Agriculture, Technical Bulletin No. 652, February 1939. Flow of Water in Drainage Channels, by C.E. Ramser, U.S. Department of Agriculture, Technical Bulletin No. 129, November 1929.

[5] Handbook of Channel Design for Soil and Water Conservation, prepared by the Stillwater Outdoor Hydraulic Laboratory in cooperation with the Oklahoma Agricultural Experiment Station, published by the Soil Conservation Service, U.S. Department of Agriculture, Publ. No. SCS-TP-61 March 1957, rev. June 1954.

[6] Flow of Water in Channels Protected by Vegetative Linings, by W.O. Ree and V.J. Palmer, Division of Drainage and Water Control, Research, Soil Conservation Service, U.S. Department of Agriculture, Tech. Bull. No. 967, February 1949.

[7] For calculations of stage or discharge in natural stream channels, it is recommended that the designer consult the local District Office of the Surface Water Branch of the U.S. Geological Survey, to obtain data regarding values of n applicable to streams of any specific locality. Where this procedure is not followed, the table may be used as a guide. The values of n tabulated have been derived from data reported by C.E. Ramser (see footnote 4) and from other incomplete data.

[8] The tentative values of n cited are principally derived from measurements made on fairly short but straight reaches of natural streams. Where slopes calculated from flood elevations along a considerable length of channel, involving meanders and bends, are to be used in velocity calculations by the Manning formula, the value of n must be increased to provide for the additional loss of energy caused by bends. The increase may be in the range of perhaps 3 to 15 percent.

[9] The presence of foliage on trees and brush under flood stage will materially increase the values of n. Therefore, roughness coefficients for vegetation in leaf will be larger than for bare branches. For trees in channels or on banks, and for brush on banks where submergence of branches increases with depth of flow, n will increase with rising stage.

Source: FHWA HEC #14

F.6 Channel Discharge Equation

The discharge (Q) of a channel is related to the velocity and the cross-sectional area of flow through the continuity equation:

$$Q = A*V \qquad \text{...(Equation F.2)}$$

Where: Q = discharge (m^3/s)
A = cross-sectional area of flow (m^2)
V = velocity of flow (m/s)

With uniform flow, V in above equation can be replaced by Manning's expression to arrive at the following revised continuity equation for uniform flow.

$$Q = A[(1 / n) * R^{2/3} * s^{1/2}] \qquad \text{...(Equation F.3)}$$

Knowing the geometric shape of a channel and the depth of flow, the cross-sectional area, A, and the hydraulic radius, R, can both be evaluated. Additionally, if the bed slope, s, and the channel roughness, n, are known, the entire right half of the equation can be quantified, providing an estimate for the discharge, Q.

F.7 Design Channel Dimensions

Channel design involves a reverse process to the discharge estimation procedure outlined above. The discharge is known from hydrological calculations and appropriate channel dimensions have to be determined to ensure satisfactory flow conveyance.

Inputting known values of Q, n and s into the revised continuity equation leads to a value of the quantity, $A*R^{2/3}$, which cannot be solved directly to provide flow depth and bed width estimates. Thus the design of channels using Manning's equation requires an iterative process. Briefly the procedure is as follows:

- An appropriate channel shape and bed width is chosen, taking into consideration the geometric and other requirements of the roadway;
- Evaluate channel discharge using Manning Equation (Equation F.1) based on the assumed geometric properties;
- Compare evaluated discharge with design discharge;
- Adjust original geometric parameter assumptions and recalculate channel discharge;
- Continue this procedure until congruence between calculated and design discharges occur.

This procedure is illustrated in Appendix H as design examples H.8 to H.10 and H.12. Various nomographs and computer program are available to assist in solving Manning's equation. Figure F.7 shows one such nomograph that can be used to assist in simplifying the calculations.

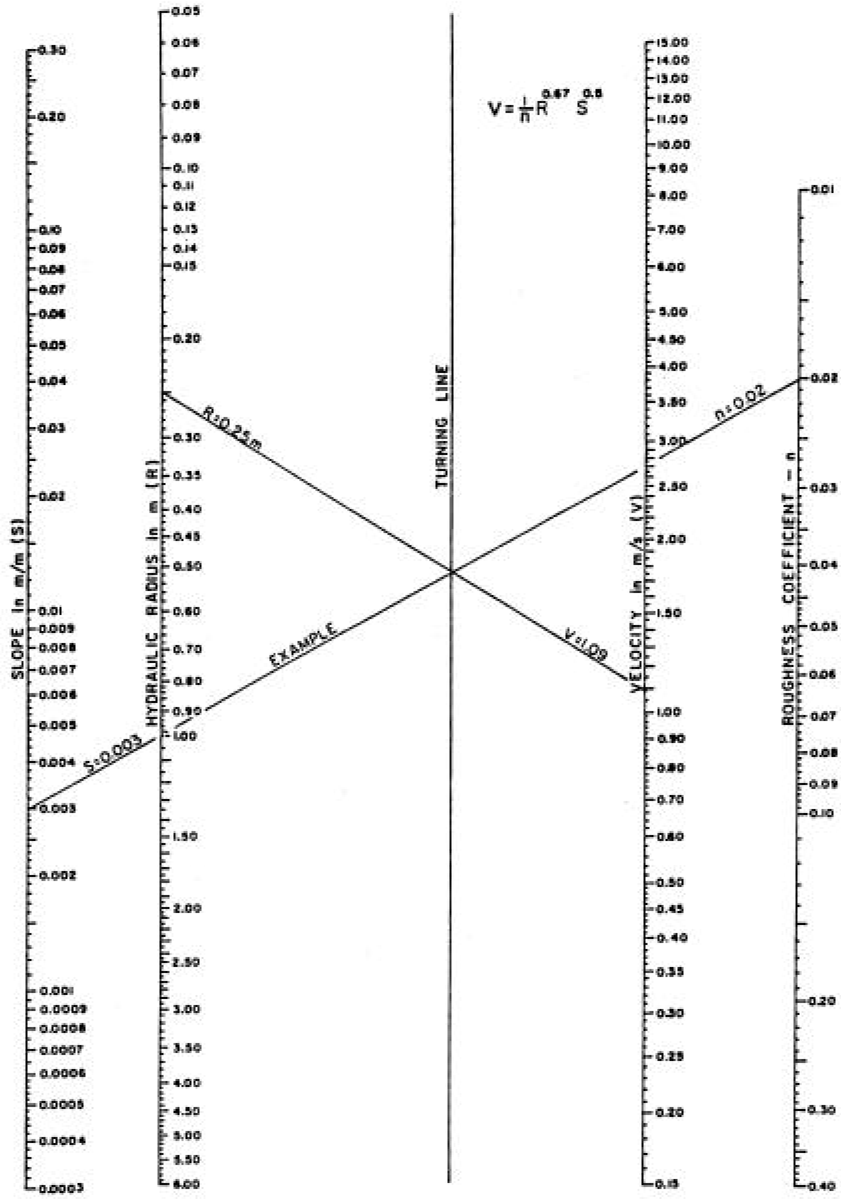


Figure F.7 Nomograph for the Solution of Manning's Equation

F.8 Approaches to Controlling Soil Erosion

There are two types of design approaches for the design of open channels depending on whether or not siltation or erosion are considerations in design. In the first approach, the material that comprises the channel and side slopes is assumed to be in dynamic equilibrium with the silt laden water of the stream. A regime state prevails with erosion and deposition occurring at the same rate over the long-term resulting in a stable channel section with no real loss or gain of material. This approach is called the Permissible Velocity Method.

Such an approach is necessary when sediment laden water is required to be handled in earthen channels as unacceptable erosion or deposition of bed material can occur. Typically this approach is applicable to drainage and irrigation systems, and river realignments.

The second approach, called the Tractive Stress Method, assumes that the material that comprises the channel boundary is capable of resisting soil class through erosion, and the channel size will be determined for carrying the design flow. Most open channels carrying clear water, including roadside ditches, are designed using this approach.

With erodible bed material such as some natural soils, the design is complete by checking the assumption of non-occurrence of erosion. If erosion is found likely to occur, the channel is redesigned using larger channel sizes, gentler bed slope if possible, or armouring along the bed and side slopes to resist any erosion.

F.9 Permissible Velocity Method

The need to check whether or not soil erosion will occur was recognized early in the design of open channels. Engineers originally approached the problem by defining limiting velocities to which a bed material can be subject to. Channel design proceeded by limiting the flow velocities along them to values lower than the permissible velocities. Alternatively, protection of the channel was provided using some form of channel lining.

Figure F.8 shows the competent mean velocities for cohesionless soils and Table F.4 shows competent mean velocities for cohesive soils. Similarly permissible velocities for channels lined with grass are shown in Table F.5. A summary table of maximum permissible velocities for various lining and vegetative protection material is also shown in Table F.3(c), (d), (e), (f) and (g).

If it is possible to design the channel to flow with a velocity less than the competent mean velocity of the native soil, soil erosion should not be a major problem. However, there may be erosion of the exposed earth due to rainfall and other weathering processes. Due to potential problems with silt that can occur, unlined channels must be regularly maintained.

The permissible velocity method was historically adopted for channel assessment. Recent developments recognized and utilized tractive stress method as currently acceptable hydraulic assessment methodology (see Section F.10).

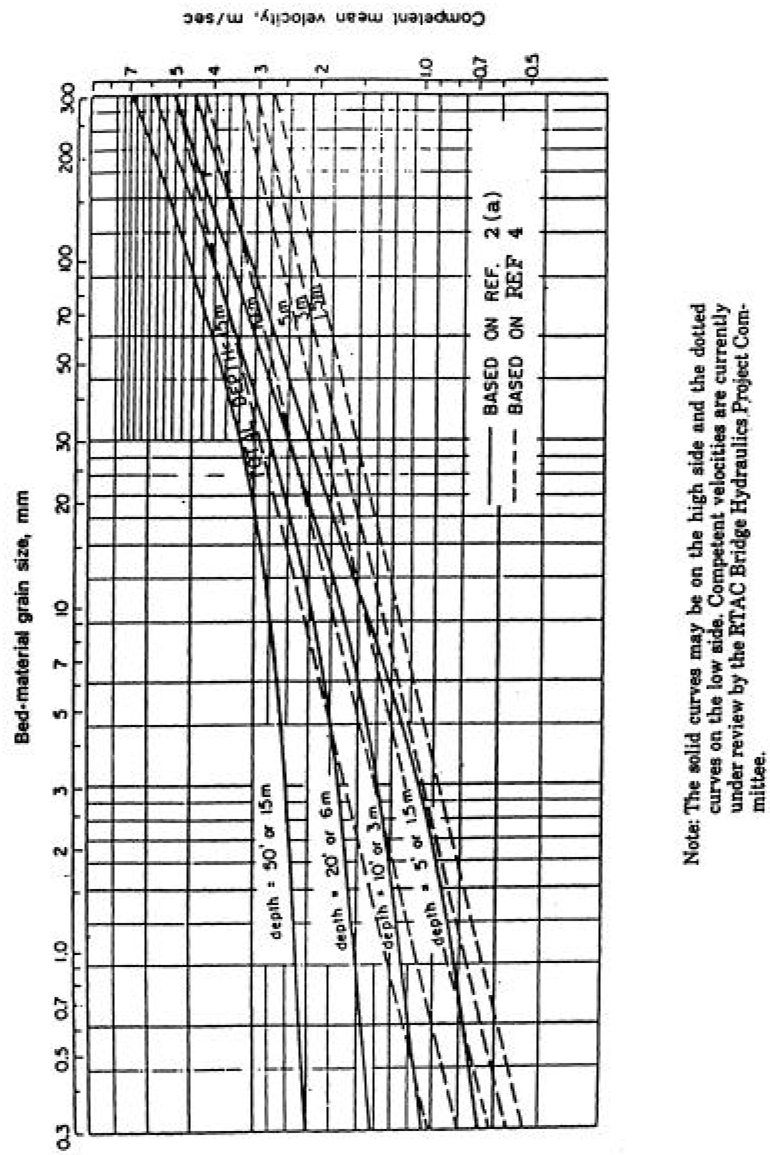


Figure F.8 Competent Mean Velocities of Cohesionless Soils

Source: RTAC Drainage Manual 1987
REF(2a) US Army HEC2 1979
REF(4) Smith AA 1974

Table F.4: Competent Mean Velocities for Cohesive Soils*

	Soil Scourability **			Remarks
Depth of Flow (m)	**High (m/s)**	**Medium (m/s)**	**Low (m/s)**	**Normal Ditch Flow for Highway**
1.0	0.5	0.9	1.6	0.3
1.5	0.6	1.0	1.8	N/A
3	0.6	1.2	2.0	N/A
6	0.7	1.3	2.3	N/A
15	0.8	1.5	2.6	N/A

Source: RTAC Drainage Manual 1987

Notes:

* Competent velocities should be based on local experience whenever possible, taking into account saturation and weathering.

** It is not considered advisable to relate the tabulated values to soil property indices because of the strong effect of saturation and weathering on the scourability of the soils. However, the following tentative relationship to consistency is offered as a rough guide.

High scourability	- very soft to soft clays
Medium scourability	- firm to stiff clays
Low scourability	- stiff to hard clays, some glacial tills

Soil consistency can be judged by the following field test applied with the soil at or near its natural water content.

Very soft:	easily penetrated several centimetres by fist
Soft:	easily penetrated several centimetres by thumb
Firm:	moderate effort required to penetrate several centimetres
Stiff:	readily indented, but penetrated only by great effort
Very Stiff:	readily indented by thumbnail
Hard:	indented with difficulty by thumbnail

Source: Chow, V.T. (1964)

Table F.5: Permissible Velocities for Channels Lined with Grass

Cover	Slope Range (%)	Permissible velocity (m/s)	
		Erosion resistant soils	Easily eroded soils
Bermuda grass	0-5	2.4	1.8
	5-10	2.1	1.5
	10	1.8	1.2
Buffalo grass, Kentucky blue grass, smooth brooms, blue grass	0-5	2.1	1.5
	5-10	1.8	1.2
	10	1.5	0.9
Grass mixture	0-5	1.5	1.2
	5-10	1.2	0.9
	Do not use on slopes steeper than 10%.		
Lespedeza Sericea, weeping love grass, *schaemum* (yellow blue-stem, kudzu, alfalfa, crabgrass)	0-5	1.1	0.8
	Do not use on slopes steeper than 5%, except for side slopes in a combination channel.		
Annuals - used on mild slopes or as Temporary protection until permanent covers are established, Sudan grass	0-5	1.1	0.8
	Use on slopes steeper than 5% is not recommended.		

Remarks:
1. The values apply to average, uniform stands of each type of cover.
2. Use velocities exceeding 1.5 m/s only where good covers and proper maintenance can be obtained.

Source: RTAC Drainage Manual 1987

F.10 TRACTIVE STRESS METHOD

In the 1950's, it was recognized that the permissible velocity approach, though successfully used in the design of open channels, does not reflect the physical phenomenon of soil erosion. It was postulated that erosion occurs as a result of the shear force exerted by water flowing over the bed and side slopes of a channel. While the velocity of flow bears a relationship to the shear force exerted, the relationship is not linear, i.e., equal increases in velocities does not produce a corresponding increase in shear force.

Attention was then focused on the development of a method for the evaluation of the applied hydraulic shear and to ensure that the bed material is capable of withstanding the applied stress. This led to the development of the Tractive Stress Theory.

The Tractive Stress Theory, as related to open channels, simply states:

applied tractive shear stress ≤ critical shear stress

Under uniform flow conditions, the applied tractive stress exerted by flowing water is given by

$$\tau = \delta * R * s \qquad \text{...(Equation F.4)}$$

Where:
- τ = Tractive stress (kPa)
- δ = Unit weight of water (kN/m^3)
- R = Hydraulic radius (m)
- s = Bed slope (m/m)

Maximum tractive stress induced by any flow occurs at the point of greatest depth or at the centre of any channel with horizontal bed is given by the equation:

$$\tau_{max} = \delta * d * s \qquad \text{...(Equation F.5)}$$

Where: d = Depth of channel (m)

The critical shear stress is a property of the material comprising the channel boundary. It is defined as the limiting hydraulic shear stress that can be applied to a material to initiate significant soil erosion or material failure in the case of ditch linings.

Natural soils possess varying critical shear stress capacity and the process of design involves evaluating this capacity and limiting the tractive stress to a value less than the capacity evaluated. Similarly, various commercially available lining materials have differing critical shear stress capacities and hence the tractive stress must be limited in a similar manner to the critical stress of the lining.

The effect of concentrated flows in channels in terms of their erosion tendency on the materials (natural soil or erosion control lining) comprising the channel bed and side slopes, is discussed in more detail in Sections F.12 to F.14.

F.11 Distribution of Tractive Stress

F.11.1 Straight Sections With Uniform Flow

In any given channel, the tractive stress is not uniform across the channel bed. Variations occur across the entire cross-section of the channel. Typically, for a trapezoidal channel, the stress variation occurs as shown in Figure F.9. Maximum values occur at the centre of the section and reduce gradually and then abruptly to zero at each corner. Along the side slopes, maximum values occur at approximately two-thirds the depth of flow with magnitudes of $0.75\tau_{max}$.

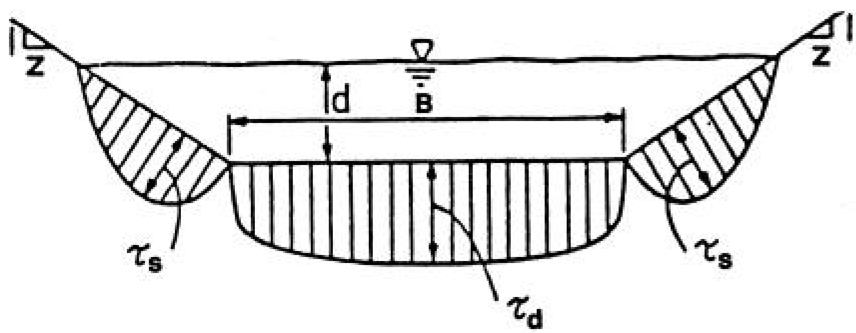


Figure F.9 Typical Shear Stress Distribution on Trapezoidal Channels

Note: ϑ_s = 0.75 * $*_w$ * ds = 0.75 * ϑ_{max}
ϑ_d = 0.97 * *w * ds = ϑ_{max}
$*_{w\,=}$ Unit Weight of Water
d = Depth of water
s = Channel gradient

Source: Chow 1959

F.11.2 Bends

The changing flow paths along a bend in a channel induce additional shear stress at the shaded locations shown in Figure F.10. Upstream of a bend, the additional shear occurs along the inside, while downstream, the greater shear moves toward the outside. Downstream, the additional shear persists for some distance beyond the bend. Protection of the channel may be required for some distance, L_p, beyond the bend as given by the equation below.

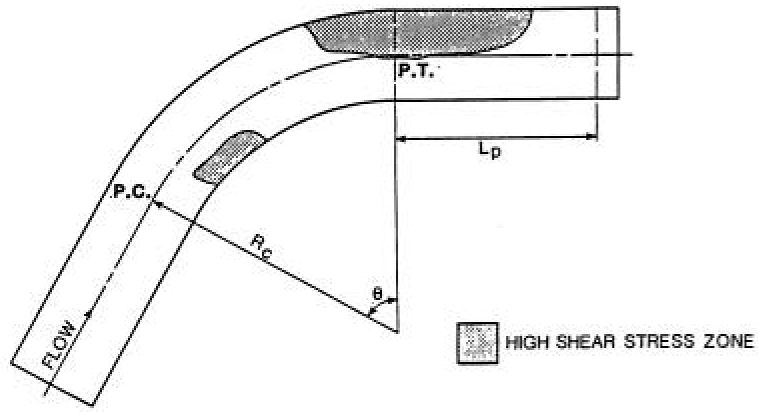


Figure F.10 High Shear Stress Zones in Bends

Source: Nouh & Townsend, 1979

$$L_p / R = (0.694 * R^{1/6}) / n_b \qquad \text{...(Equation F.6)}$$

Where: L_p = Length requiring protection
R = Hydraulic radius
n_b = Manning's roughness coefficient in bends

F.12 Resistance of Bare Soil to Erosion from Concentrated Flows

The behaviour of a soil is largely influenced by its composition. Such composition can range from completely granular material such as cobbles, gravel and sands to completely flat, plate-shaped, microscopic clayey particles. Most soils comprise a mixture of granular and clayey particles and the overall behaviour of such a soil will be dependent on the influence of each fraction comprising the soil.

Experience has found it convenient to separate naturally occurring soils into cohesive and cohesionless materials based on particle size distribution and plasticity. The convenience arises from the fact that many characteristics of a soil can be inferred from the plastic behaviour of cohesive soils and the grain size distribution of cohesionless soils. The fact is no less true of the resistance of any soil to erosion. Thus investigations into the erodibility of naturally occurring soils have been carried out by distinguishing soils as either cohesive or cohesionless materials.

F.12.1 Permissible Shear Stress

Any soil subjected to the flow of water over it experiences a shear stress along its surface which acts to dislodge soil particles. Initially, with low shear stress, the soil may be capable of resisting the flow. Thus the bed and side slopes remain stable. With increasing flow depth, there comes a time when the shear stress imposed by the flow on the channel bed is capable of dislodging soil particles into suspension. The shear stress at which this soil loss first occurs is referred to as the Critical Shear Stress and represents the maximum hydraulic shear stress to which the soil can be subjected. For design purposes, the critical shear stress is regarded as the Maximum Permissible Shear Stress.

As an extension of the concept, critical shear also occurs on manufactured channel linings. In this case, the critical shear is interpreted as either the hydraulic shear causing lining failure or rapid soil loss. Permissible shear is similarly taken as the maximum stress to which a lining can be subjected before the onset of failure.

F.12.2 Cohesive Soils

Numerous investigators have looked at the problem of cohesive soil erodibility in attempts to obtain correlations between the critical shear stress and the properties of a soil. Some of the properties identified as influencing soil erodibility are:

- Mineralogical composition
- Chemical composition of the fluid surrounding soil particles
- Sodium Absorption Ratio (SAR)
- Degree of compaction
- Plasticity

At present, no procedure exists for evaluating the critical shear stress that takes into consideration all the identified variables. Even if such a procedure existed, it would not be very valuable for design purposes as the many factors that affect soil erosion are difficult to determine. Cost would be the influencing factor.

An acceptable method using two parameters is available to evaluate the permissible shear stress of a cohesive soil. One of these parameters, the plasticity index, is routinely determined by the designer in their routine soil investigation and testing. The other parameter, compaction, as measured by the blow count, N, on the Standard Penetration Test is not as routinely evaluated. However, an estimate of the N value can be made by the feel of the sample when worked between the fingers. Alternatively, a simple hand-held soil investigation tool called a Pocket Penetrometer can be used as a more accurate determination. In theory, the penetrometer measures undrained shear strength which can be related to the blow count, N, as shown in Tables F.6 and F.7.

In the absence of any data on soil compactness, a subjective evaluation of the N parameter will be required. As a guide, the consistency of the soil can be determined in the field using simple test as given below. Then using Table F.6, an appropriate N value can be selected for use in Figure F.11 to determine the permissible tractive shear stress of the soil.

Table F.6: Field Soil Consistency Determination

Very soft	Easily penetrated several centimetres by the fist
Soft	Easily penetrated several centimetres by the thumb
Medium	Moderate effort to penetrate several centimetres by the thumb
Stiff	Readily indented by the thumb, but penetrated only with great effort
Very stiff	Readily indented by the thumb nail
Hard	Indented with difficulty by the thumb nail

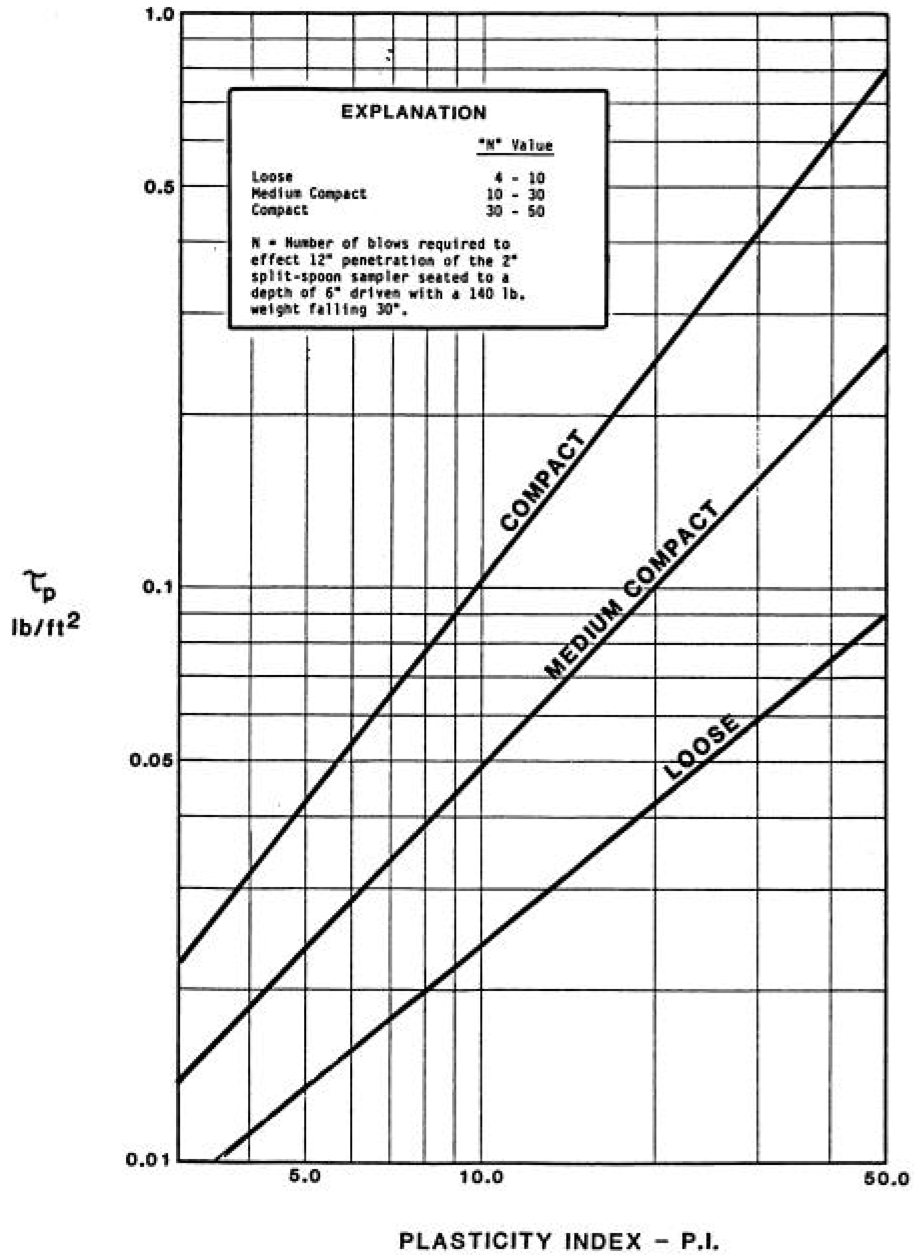


Figure F.11 Permissible Shear Stress for Cohesive Soils

Source: Smerdon & Beaseley, 1959

Note: 1 lb/ft² = 48 N/m²

Table F.7: Consistency of Cohesive Soils Related to Standard Penetration Test Value, N

Consistency	Standard Penetration Value, N
Very soft	0 - 2
Soft	2 - 4
Medium	4 - 8
Stiff	8 - 16
Very stiff	16 - 32
Hard	> 32

F.12.3 Cohesionless Soils

With cohesionless soils, the particles are relatively inert and erodibility is dependent mainly on the grain size distribution. Tests carried out on various cohesionless soil samples have shown that the permissible shear stress can be related to the mean particle size of the sample as shown in Figure F.12. Thus it is a simple matter of assessing the mean particle size from a grain size distribution curve to determine the permissible shear stress.

For particles larger than 100 mm, τ_p, can simply be evaluated by the equation:

$$\tau_p = 6.25 \times 10^{-4} D_{50} \qquad \text{...(Equation F.7)}$$

Where: τ_p = permissible shear stress (kPa)
D_{50} = mean particle diameter (mm)

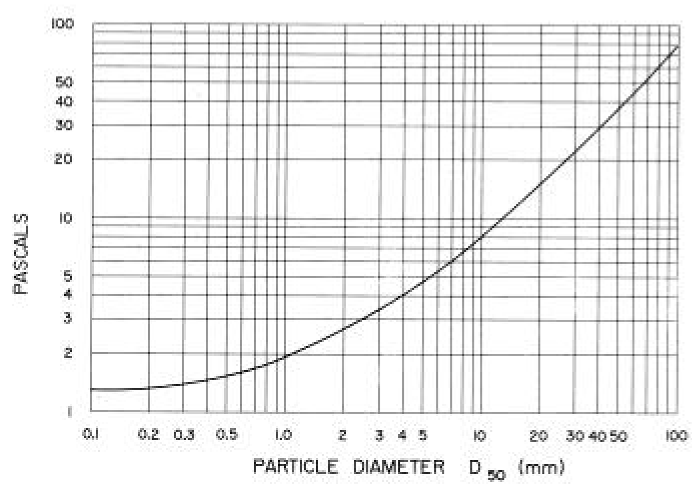


Figure F.12 Permissible Shear Stress for Cohesionless Soils

Source: Thibodeaux 1982-1985

F.13 Resistance of Vegetation to Concentrated Flow

The most widely used method for permanently controlling soil erosion, both on slopes and along ditches is the establishment of vegetation. Because of the relatively low cost, vegetation is the first and sometimes erroneously the only choice among soil erosion control practitioners.

There is however a limitation to the extent to which vegetation will be successful in controlling soil erosion along ditches. Unless the limitation is defined, many instances will occur in which vegetation will prove to be inadequate for the function intended.

The determination of the appropriateness of vegetation for soil erosion control along ditches is rather simple. It entails comparing the tractive resistance of the proposed vegetation with the shear stress exerted by the design flow. Vegetation will be adequate if the shear stress of the flow is less than the resistance of the vegetation.

There is one additional complexity in the calculation process introduced by a vegetative lining. The degree of flexibility and variations in growth height of various grasses and legumes normally used for the control of erosion vary with the different species. Further, the mowed height of the vegetation also affects roughness. As such, the roughness coefficient, n, an input into Manning's Equation is not a constant.

Choosing an appropriate roughness value was simplified by the Soil Conservation Service by defining five vegetative classes A to E. Figures F.2 and F.6 show the variation of the roughness coefficient, n, with hydraulic radius, R, and channel bed slope, s, for each classification.

F.14 Resistance of Non-Vegetative Linings to Soil Erosion

Non-vegetative ditch linings used for soil erosion control are of two types:

- Temporary; and
- Permanent.

Temporary linings are to be considered for use only at those locations at which vegetation growth in future is expected to take over the erosion control function for the long-term. Conversely, in sterile areas or those locations expected to experience larger hydraulic shear stresses than can be handled by vegetation, permanent erosion controls are required.

The approach to designing erosion control in either case is to compare the shear resistance of the lining with the tractive stress of the design flow. The lining selected should have a shear resistance greater than the flow shear stresses.
However, when the channel gradient becomes steep (say greater than 10%) and the lining selected is a weighty material (such as gravels and rock riprap), special design procedures are

required as the lining on the channel bed and more so on the side slopes provides an additional de-stabilizing force component down slope. Procedures for such design are given in Section F.18.

Other permanent linings, such as articulating blocks that rely not only on their weight but also on their inter-connection with each other for their stability, must have their design based on the recommendations of the manufacturers. These recommendations will usually be deduced from the results of hydraulic tests carried out on the linings for performance evaluation.

Many manufactured materials are currently available for soil erosion control. Most of them are bio-degradable although some permanent ones are available.

Hydraulic performance of all the manufactured linings is not available largely because some of the manufacturers have not extensively tested their products. However, a variety of tests have been independently carried out by the U.S. Department of Geological Surveys on "generic" materials to evaluate their permissible shear stresses. Design values, deduced from the tests are shown in Table F.8. A summary of permissible shear stress for commonly used lining materials is also shown in Table F.3(c).

Table F.8: Permissible Shear Stress for Some Lining Materials

	Lining Type	Permissible Shear Stress (Pa)
Temporary	Woven paper mat	7.19
	Jute	21.56
	Straw with net	69.46
	Excelsior mat	74.25
	Synthetic mat	95.80
	Spray-on-Patch (i.e. mulch)	See Table F.3(c)
Permanent	Vegetation Class A	177.23
	Vegetation Class B	100.59
	Vegetation Class C	47.90
	Vegetation Class D	28.74
	Vegetation Class E	16.77
	Gravel 25 mm dia	15.81
	Gravel 50 mm dia	32.09
	Rock riprap 150 mm dia.	95.8
	Rock riprap 300 mm dia.	191.6
	Cohesive soil	See Fig. F.11
	Cohesionless soil	See Fig. F.12
	Rolled Erosion Control Product	See Table F.3(c)
	Gabion Mattress	See Table F.3(c)

Source: Chen & Cotton, 1988

F.15 Flexible Lining Design

Flexible linings, while not always applicable, are capable of handling most of the soil erosion problems along provincial roadways. Additionally, flexible linings are more versatile than rigid linings because of their ability to accommodate minor distortions in the subgrade without leading to failure. This property, in particular, makes them the preferred choice among ditch linings.

A word of caution though should be expressed in the use of lining materials be they rigid or flexible. Linings ought not to be placed onto unstable slopes as the lining material will soon separate at one or more of the crack locations which normally appear when instability occurs on a slope. The gap so created will render the lining ineffective. In fact, the lining may aggravate the instability by conducting water from areas higher up above into the unstable mass.

The design procedure is a three step evaluation from which a decision is made at the end of each step regarding the need for the succeeding step. The three steps are given in the following paragraphs.

Step 1: Assess the capability of the in-situ soil to withstand the erosive forces of flowing water. If adequate, use seed, fertilize, harrow or mulch as required to establish vegetation. Sediment retention structures may be required to control sediment loss to areas beyond right-of-ways.

Proceed to Step 2 if in-situ soil cannot withstand erosion.

Step 2: Assess the capability of vegetation to control soil erosion. If adequate, provide temporary lining to control erosion while vegetation is being established.

Proceed to step 3 if vegetation cannot control the erosion.

Step 3: Design permanent erosion control measure (flexible or rigid), depending on local factors such as economy, ease of installation, availability of materials, maintenance costs, etc. The advantages and limitations of each lining types should be considered for situations of flow, slope, vegetation growth density, and soil type of specific soil conditions.

F.16 Rigid Lining Design

Rigid channel linings, because of cost, are only considered for erosion control when special conditions prevail that would preclude the use of other linings. Examples of such conditions are:

- Steep grade;
- Limited right-of-way;
- Appropriate flexible lining unavailable; and
- Good probability of tampering by the public (i.e. removal of riprap or other measures).

As such, the first step in the design of a rigid lining is to determine the existence of any condition that may adversely affect the performance of the lining. Conditions to look for are:

- Unstable ground;
- Ground water seepage;
- Frost susceptible soil;
- Expansive clays; and
- Hydraulic uplift conditions.

The presence of any of the above will lead to distortions in the channel lining and eventual failure if the problem is not adequately addressed at the design stage. Such conditions may require the services of a hydrotechnical or geotechnical engineer during the design and construction phase.

When non-problematic ground conditions are present, the design is completed by estimating the design discharge and providing an adequate hydraulic section using the principals of open channel hydraulics presented earlier in this section.

The design discharge for permanent installations should correspond to the estimated runoff from an event with a return period of 1:10 years. A larger design event with a return period of 1:25 years or greater may be used in situations where it is judged that a safety hazard exists and that significant disruption of traffic will be caused by a structural failure of the installation.

F.16.1 Other Requirements

Rigid lining design requires considerations of upstream and downstream scour, hydrostatic uplift of the lining, anchorage to the slope and structural cracking. For small drainage areas less than 25 ha, the above requirements can be addressed by the following "rule-of-thumb" provisions:

- Utilize virgin ground or well-compacted fill for subgrade;
- Place a 150 mm thick drainage layer under the region of the downstream outlet;
- Provide a riprap apron with 150 mm diameter rock to a thickness of 225 mm for a length of 2 m;
- Provide cutoff walls at both the upstream and downstream end of the structure. Depth of cutoff should be 0.5 m across the entire width of the transition;
- Ensure structural thickness of the lining is a minimum of 75 mm; and
- Provide adequate freeboard.

F.17 Steep Gradient Channels

Steep gradient channels, defined herein as channels having gradients in excess of 10%, are sometimes required of the conveyance of water from an elevation to another at a significantly lower level. With roadways, a typical location for such a channel is along the line of intersection where a high fill meets a valley wall. In cases of low flow conditions, a temporary lining will suffice to control any soil erosion until vegetation gets established. However, in situations of moderate flow, there will be the need for a permanent erosion control measure such as random riprap linings.

Permanent flexible linings (i.e. riprap lining) will be capable of handling most of the cases that cannot be resolved by vegetation. Rarely will a piped conduit (downdrain) or a rigid lining be required.

Materials commonly used for permanent flexible linings along steep gradients are riprap and gabions. Gabions include drop structures and mattresses. Hollow pre-cast concrete blocks which interlock may sometimes be used if economy can be achieved. Generally, pre-cast blocks tend to be more costly than riprap options.

For steep channels, drop structures are commonly used for flow control and energy dissipation. Changing the channel slope from steep to mild, by placing drop structures at intervals along the channel reach, changes a continuous steep slope into a series of gentle slopes and vertical drops.

F.17.1 Design Procedure

On steep channel bed slopes, temporary linings, which are usually of the blanket type, can be designed as outlined in Section F.15. Permanent rigid linings are to be designed according to Section F.16. In either case, there is a need to distinguish between a steep gradient and a gentle one.

With permanent flexible linings like riprap, gabion or concrete blocks, there are additional factors that must be taken into consideration when comparing the tractive stress of the design flow with the resistance of the lining. In none of the three types can a single permissible shear stress value be defined for steep gradient channels.

Physical factors to be considered are size and shape of the material comprising of the bed and side slopes and channel geometry. Other factors are material buoyancy and the weight component down slope.

With proprietary concrete block systems (in which size, shape and surface roughness vary with each type of block), a generalized channel design procedure cannot be presented. Designs incorporating these materials must be completed according to the recommendations of the manufacturer.

However, with riprap and gabions, extensive hydraulic testing and theoretical evaluations have been carried out on material gradation normally used for such purposes and design procedures were evolved which are presented below. A comparison of the relative thickness of riprap versus gabion mattress was once investigated to indicate that a smaller (2 to 3 times) thickness of gabion mattress can be utilized under identical severe hydraulic conditions. The results are shown in Table F.3(e) and F.3(f).

F.17.2 Riprap Design

Investigations into the use of riprap on steep slopes have led to rather complex equations which may not be of practical value in design. By making simplified assumptions regarding the typical gradation of riprap and by conducting hydraulic tests, charts given in Figures F.13 to F.16 have been produced from the complex formulation to simplify the design process. The charts can be used for bed slopes varying between 10 and 25% and bed width increasing from 0 to 1.5 m. Linear interpolation will be required for bed slope and bed width intermediate between the limits given on the charts. These procedures are illustrated in design examples presented in Appendix H as design examples H.10 and H.11.

Riprap used as a ditch lining on either gentle or steep grades needs to be sufficiently thick to ensure minimal loss of the underlying material. Additionally, a filter consisting of a suitably graded granular material or geosynthetic of appropriate weight is required under the riprap to prevent piping failure of the underlying material.

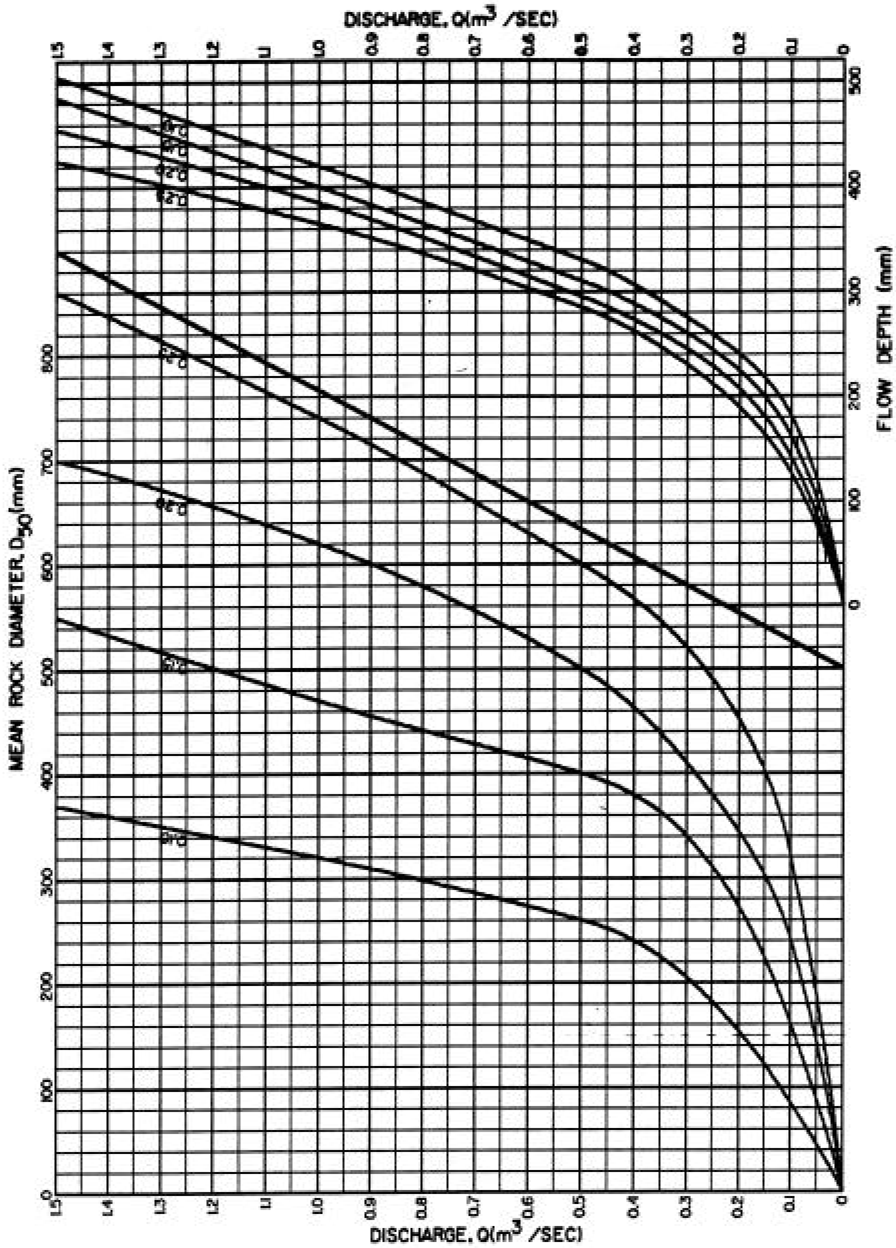


Figure F.13 Steep Slope Riprap Design
(Bed Width = 0 m, Sideslope = 3:1)

Source: Chen & Cotton, 1988

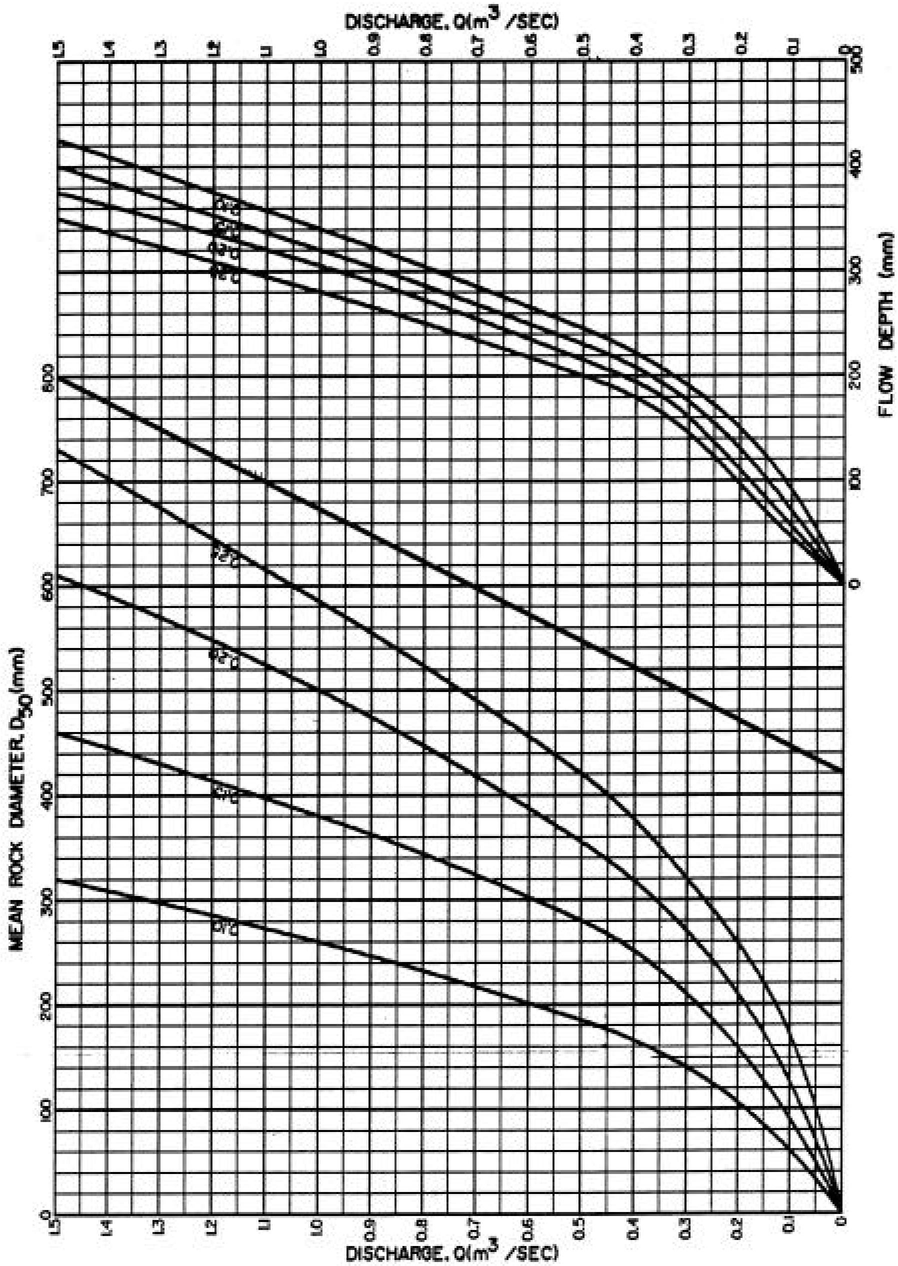


Figure F.14 Steep Slope Riprap Design
(Bed Width = 0.5 m, Sideslope = 3:1)

Source: Chen & Cotton, 1988

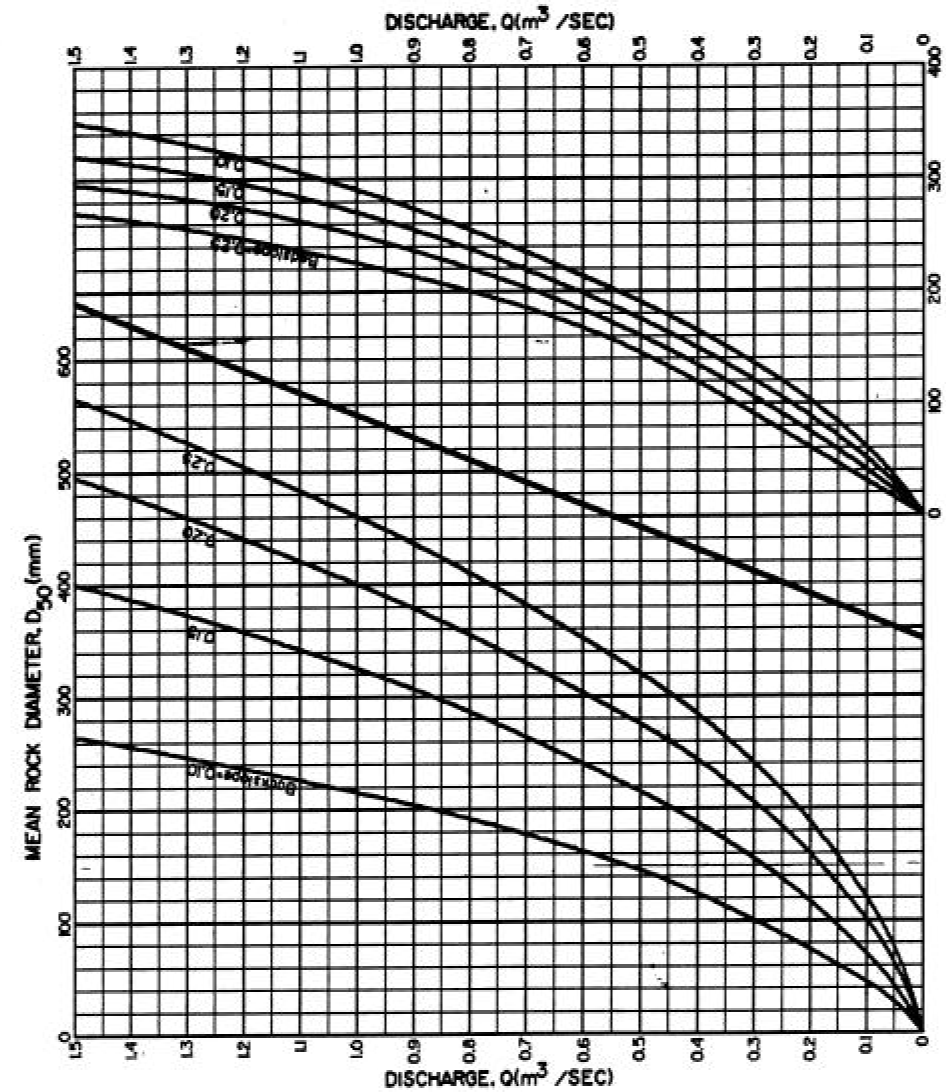


Figure F.15 Steep Slope Riprap Design
(Bed Width = 1.0 m, Sideslope = 3:1)

Source: Chen & Cotton, 1988

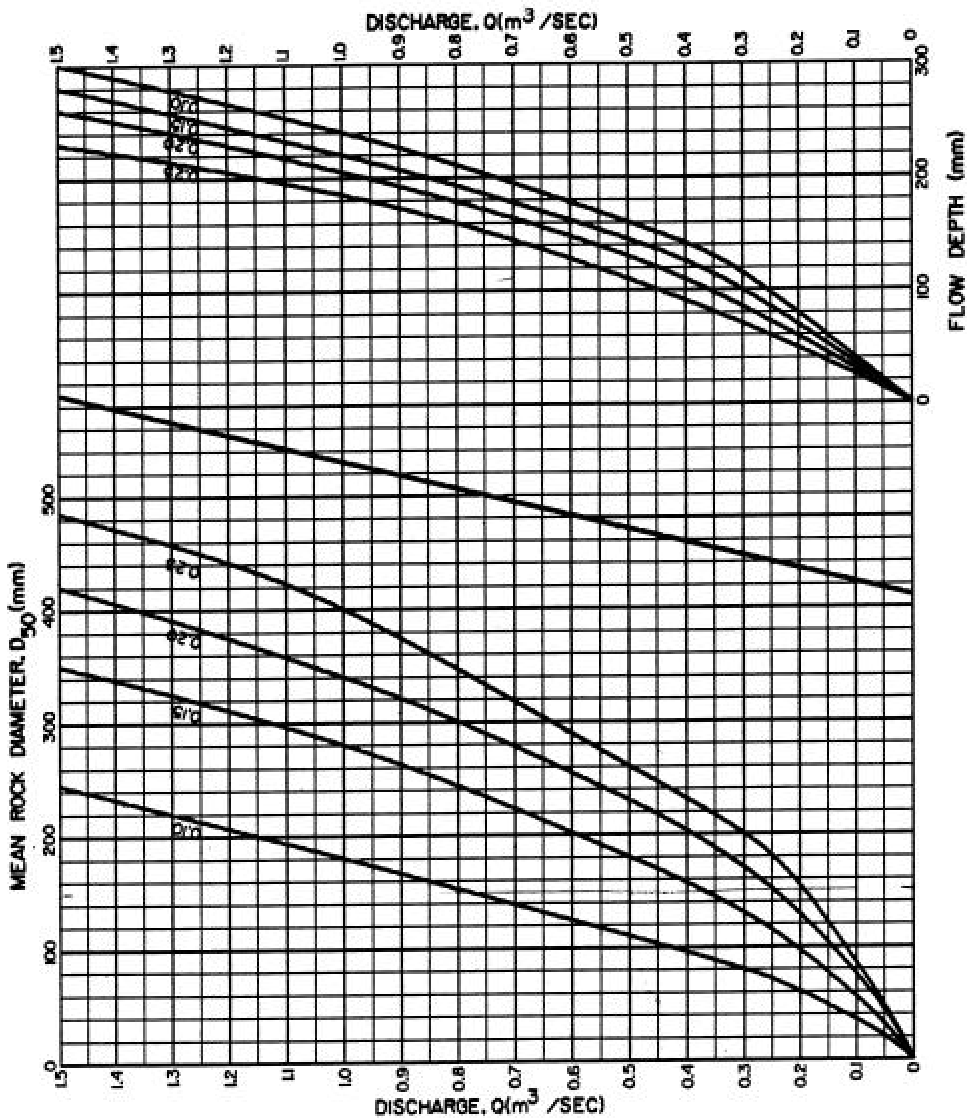


Figure F.16 Steep Slope Riprap Design
(Bed Width = 1.5 m, Sideslope = 3:1)

Source: Chen & Cotton, 1988

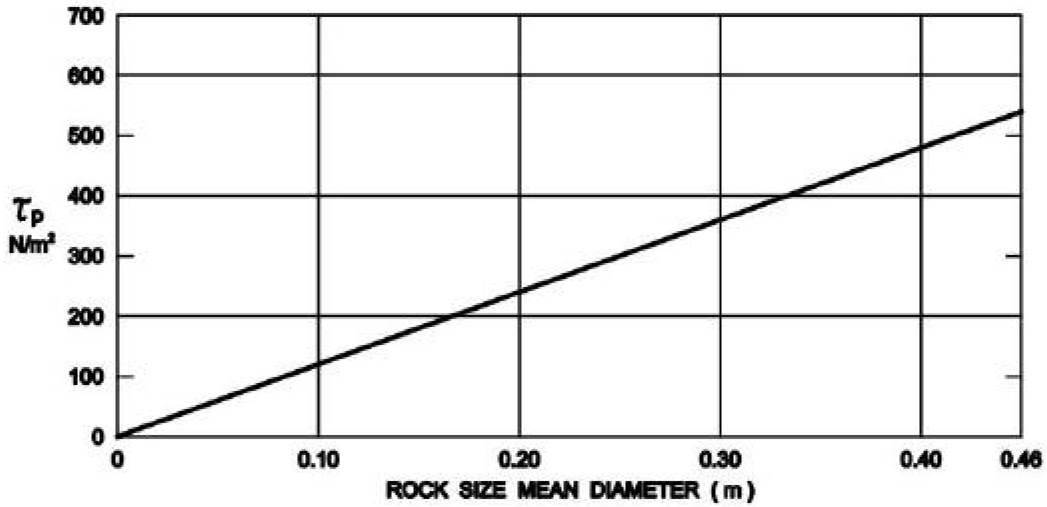


Figure F.17 Permissible Shear of Gabion Mattress vs. Rock Fill Size

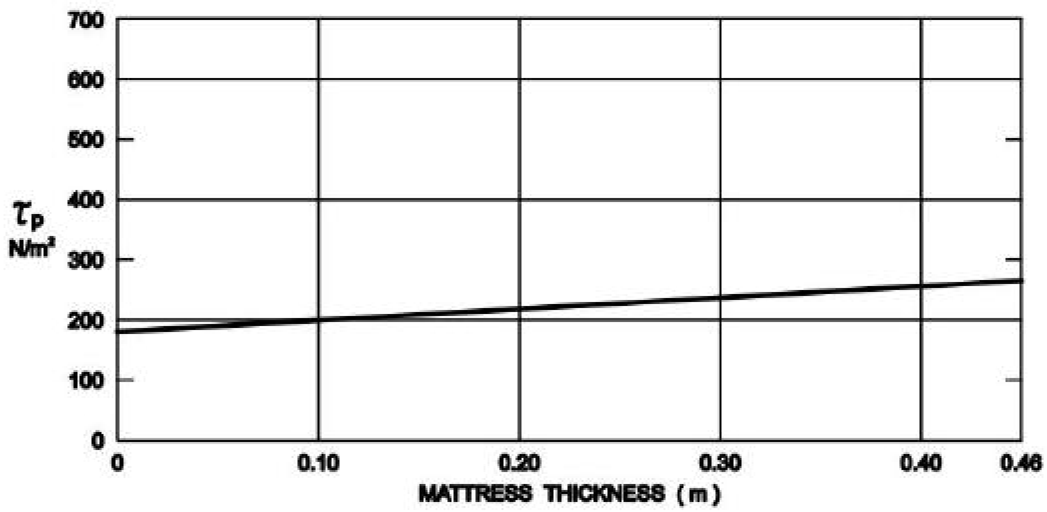


Figure F.18 Permissible Shear of Gabions vs. Mattress Thickness

Source: Chen & Cotton, 1988

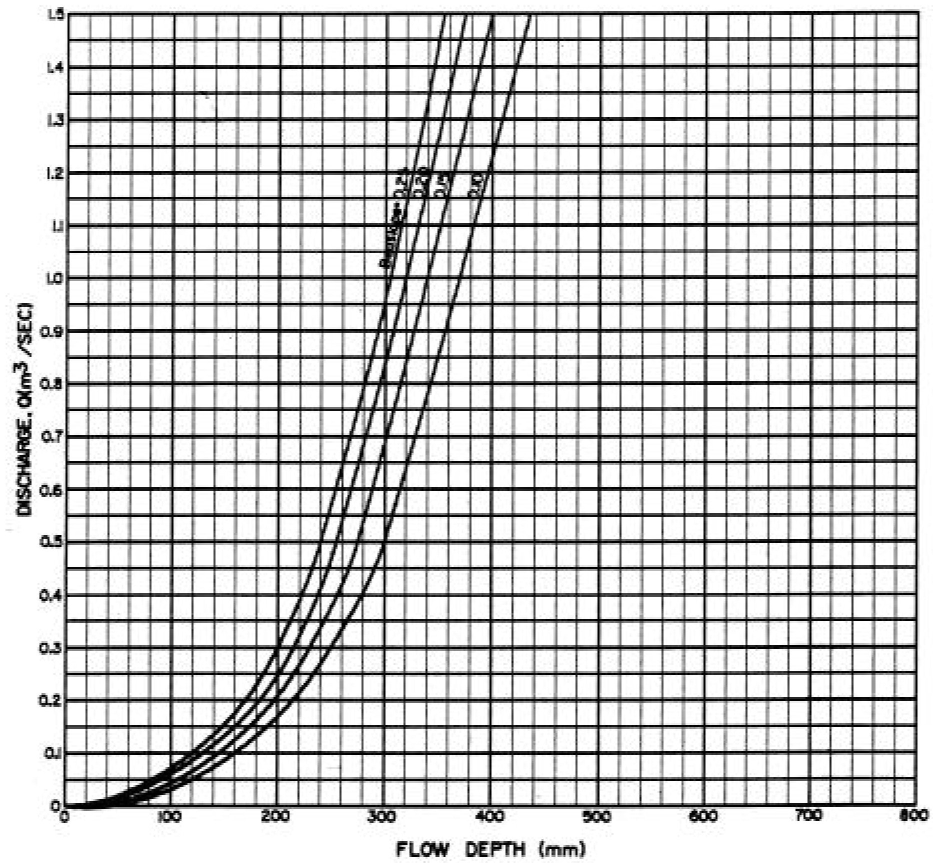


Figure F.19 Steep Slope Gabion Design
(Bed Width = 0 m, Sideslope = 3:1)

Source: Chen & Cotton, 1988

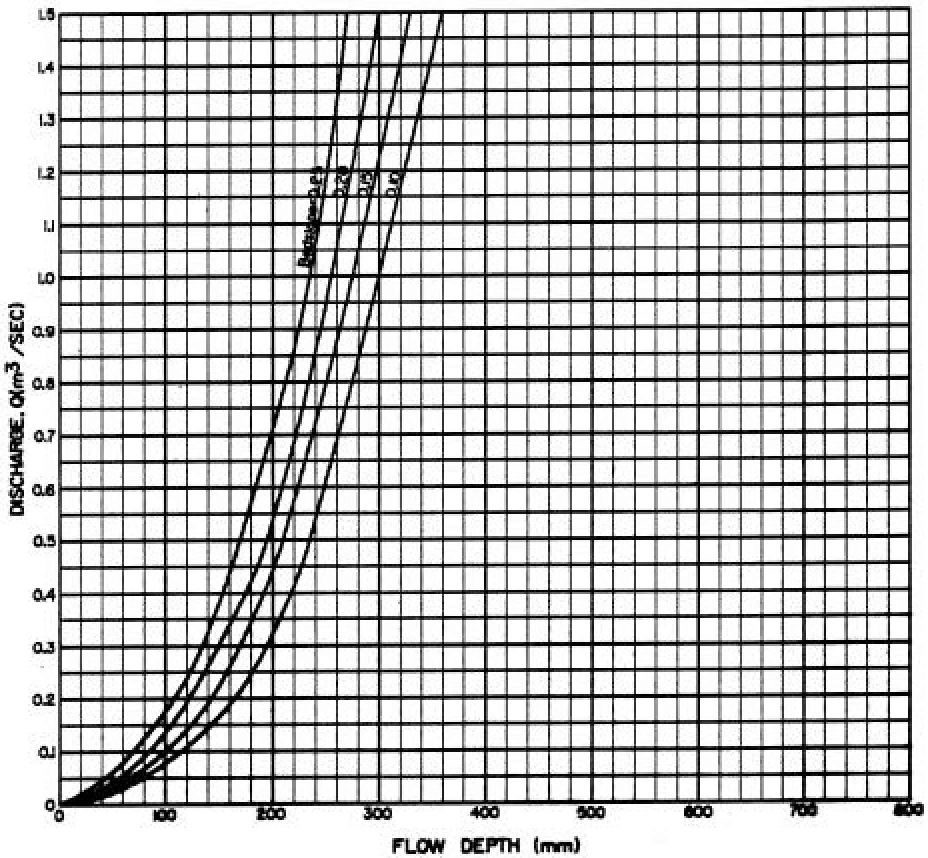


Figure F.20 Steep Slope Gabion Design
(Bed Width = 0.5 m, Sideslope = 3:1)

Source: Chen & Cotton, 1988

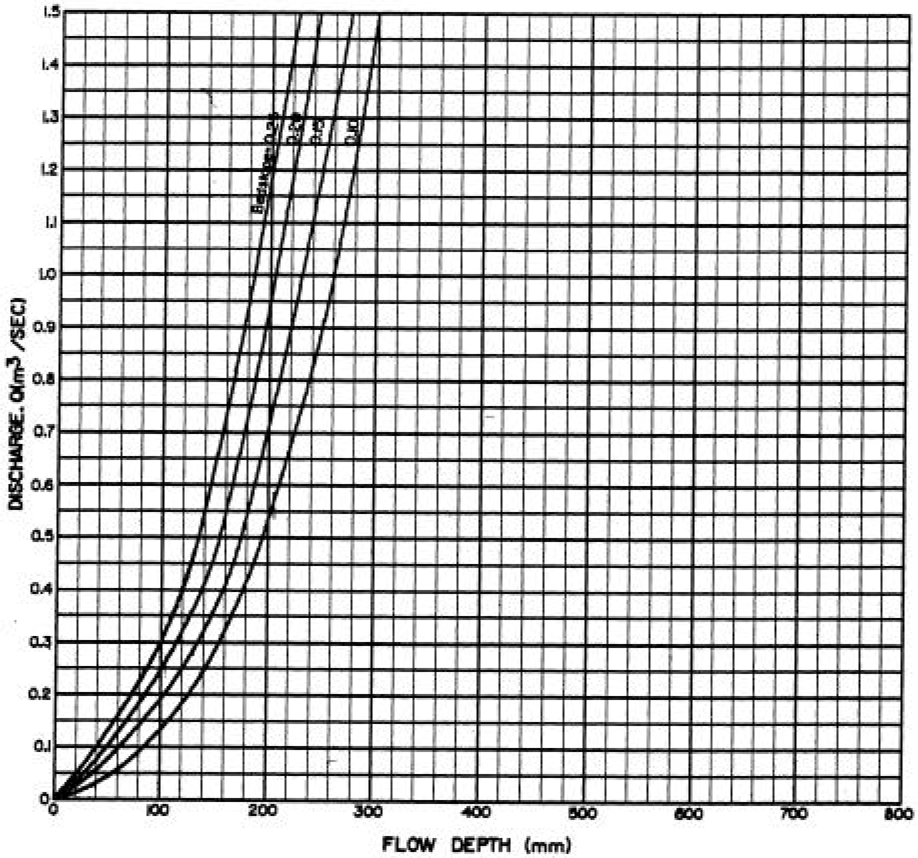


Figure F.21 Steep Slope Gabion Design
(Bed Width = 1.0 m, Sideslope = 3:1)

Source: Chen & Cotton, 1988

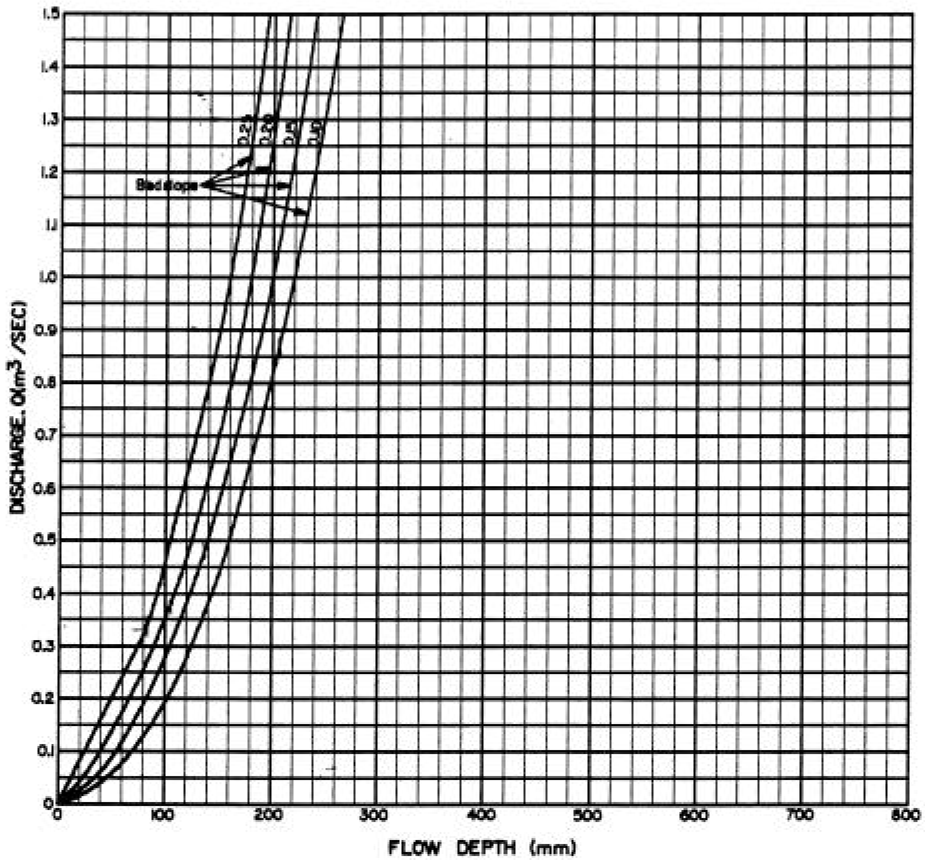


Figure F.22 Steep Slope Gabion Design
(Bed Width = 1.5 m, Sideslope = 3:1)

Source: Chen & Cotton, 1988

F.17.3 Gabion Design

Gabions are somewhat different from riprap in that the rocks are bound together by a wire mesh. Thus rocks rolling down slope are not considered to be a mode of failure. The gabion structures can accommodate higher discharges than an equivalent-sized riprap channel.

Gabions are commonly used as drop structures for flow control and energy dissipation. Changing the channel slope from steep to mild, by placing drop structures at intervals along the channel reach, changes a continuous steep slope into a series of gentle slopes and vertical drops. Instead of slowing down and transferring high erosion producing velocities into low non-erosive velocities, drop structures control the slope of the channel in such a way that the high, erosive velocities never develop. The kinetic energy or velocity gained by the water as it drops over the crest of each structure is dissipated by a specially designed apron or stilling basin which may be constructed of gabion mattress (FHWA HEC #14).

One probable failure mode though is the rearrangement of the rocks within the gabion structure through the shear action of flowing water. Another mode is the scouring of the material underneath and behind the gabions. Both failure modes must be addressed in design to ensure a functional structure. In this regard, charts given in Figures F.17 and F.18 have been prepared to guide both rock size selection and structure thickness evaluation.

The hydraulics of gabion structures has also been investigated (Chen & Cotton 1988). To assist in design, charts shown in Figures F.19 to F.22 have been prepared which relate discharge with depth of flow and bed slope. Bed widths considered are 0 to 1.5 m and bed slopes varying between 10 and 25% with side slopes fixed at 3:1.

The charts can be extended to other channels with stable side slopes by firstly designing an equivalent bed width channel with 3:1 side slopes. The flow depth in the channel to be designed is then adjusted by equating flow areas. This procedure is presented in the design example presented in Appendix H as Example H.13.

Gabions used as ditch lining on either gentle or steep grades, need to be sufficiently thick to ensure minimal loss of the underlying material. Additionally, a filter consisting of suitably graded granular material or geosynthetic of appropriate weight is required under them to prevent piping failure of the underlying material.

F.17.4 Filter Material

Traditionally, a filter layer comprised of well-graded granular material is placed between the base soil and the riprap or gabion system. The intent is to ensure sufficient permeability to allow seepage to take place out of the underlying soil while at the same time minimizing the size of the voids in the filter to prevent the underlying material from migrating into the armour layer.

In current engineering practice, the granular filter blanket is largely replaced by a geotextile filter which performs essentially the same functions. Specific requirements for each type of filter area are:

<u>Granular Filter</u>:

(1) $$\frac{D_{15}(filter)}{D_{85}(soil)} < 5 < \frac{D_{15}(filter)}{D_{15}(soil)} < 40$$ ...(Equations F.8)

(2) $$\frac{D_{50}(filter)}{D_{50}(soil)} < 40\ (U.S.\ Army\ Corps.\ of\ Engineers, 1955)$$

(3) Filter thickness ≥ 1xD_{100} (filter) or 150 mm minimum thickness, whichever is greater.

where:

D_{50} = particle size diameter (m/mm) corresponding to 50% passing by mass

<u>Geotextile Filter</u>:

In selecting an engineering filter fabric, the fabric should be able to transmit water from the soil and also have a pore structure that will hold back soil. The following properties of an engineering filter fabric are required to assure that their performance is adequate as a filter under riprap and gabion rock.

1. The fabric must be able to transmit water faster than the soil.
2. The following criteria for the apparent opening size (AOS) must be met:
   a) For soil with less than 50 percent of the particles by weight passing a 0.075 mm opening (U.S. No. 200) sieve AOS < 0.6 mm (greater than #30 U.S. Std. Sieve).
   b) For soil with more than 50 percent of the particles by weight passing a 0.075 mm opening (U.S. No. 200) sieve AOS <0.297 mm (greater than #50 U.S. Std. Sieve).

The above criteria only applies to non-severe or non-critical installations. Severe or critical installations should be designed based on permeability and gradient ratio testing.

F.17.5 Lining Thickness

The minimum thickness of gabion or riprap structures should be the size of the largest stone to be used. Obviously, an isolated large stone which is not representative of the overall material should be discarded and not taken as a measure of the structure thickness. For most rocks used for ditch lining purposes, the criterion will translate into the following:

Lining thickness = (2 to 3) x D_{50} ...(Equation F.9)

F.17.6 Gradation

Both riprap and gabion stone should be uniformly graded meeting the requirements below:

- $3 > D_{100} / D_{50} > 1.5$; and
- $3 > D_{50} / D_{20} > 1.5$. ...(Equation F.10)

The criteria will allow some smaller rock sizes in the armouring which will fill the voids between the larger rocks to form a compact layer.

A further requirement, applicable only to gabion structures, is that the largest rock should not be less than 2/3 of gabion thickness nor should the smallest rock be smaller than the mesh opening size.

F.18 Design Examples

Simple design examples using the tractive stress theory and permissible velocity theory have been worked out and are illustrated in design examples presented in Appendix H as H.8 to H.14.