Hydraulic Engineering Circular No. 15

U.S. Department
of Transportation

**Federal Highway
Administration**

Publication No. FHWA-IP-87-7

April 1988

DESIGN OF ROADSIDE CHANNELS WITH FLEXIBLE LININGS

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, Virgina 22101-2296

FOREWORD

This Implementation Package provides guidance for the design of stable conveyance channels using flexible linings. The information in the manual should be of interest to State and Federal Hydraulics engineers and others responsible for stabilizing roadside channels. The manual has been adopted as HEC-15 in the Hydraulics Engineering Circular Series.

Copies of the manual are being distributed to FHWA regional and division offices and to each State highway agency for their use. Additional copies of the report can be obtained from the National Technical Information Service, 5280 Port Royal Road, Springfield, Virginia 22161.

Stanley Byington

Stanley R. Byington, Director
Office of Implementation

NOTICE

Technical Report Documentation Page

1. Report No. FHWA-IP-87-7 HEC #15	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Design of Roadside Channels with Flexible Linings		5. Report Date April 1988
		6. Performing Organization Code
7. Author(s) Dr. Y. H. Chen and Mr. G. K. Cotton		8. Performing Organization Report No.
9. Performing Organization Name and Address Simons, Li & Associates, Inc. 3555 Stanford Road P.O. Box 1816 Fort Collins, Colorado 80522		10. Work Unit No. (TRAIS) 35ZH078
		11. Contract or Grant No. DTFH61-84-C 00055
12. Sponsoring Agency Name and Address Office of Implementation, HRT-10 Federal Highway Administration 6300 Georgetown Pike McLean, Virginia 22101		13. Type of Report and Period Covered Final Report September 1984 - March 1986
		14. Sponsoring Agency Code

15. Supplementary Notes
Project Managers: John M. Kurdziel, Thomas Krylowski
Technical Assistants: Philip L. Thompson, Dennis L. Richards, J. Sterling Jones

16. Abstract

Flexible linings provide a means of stabilizing roadside channels. Flexible linings are able to conform to changes in channel shape while maintaining the overall lining integrity. Permanent flexible lining such as riprap, gravel, or vegetation reinforced with synthetic mat are suitable for hydraulic conditions similar to those requiring rigid linings. Vegetation or temporary linings are suited to hydraulic condition where uniform flow exists and shear stresses are moderate. Design procedures are given for rock riprap, wire-enclosed riprap, gravel riprap, woven paper net, jute net, fiberglass roving, curled wood mat, synthetic mat, and straw with net. Special design procedures are presented for composite channels and channels with steep gradients.

The design procedures are based on the concept of maximum permissible tractive force. Methods for determination of hydraulic resistance and permissible shear stress for individual linings are presented. Nomographs are provided for solution of uniform flow conditions in trapezoidal channels. Nomographs are also provided for determination of resistance characteristics for vegetation and permissible shear stress for soils.

17. Key Words channel lining, channel stabilization, tractive force, resistance, permissible shear stress, vegetation, riprap, jute, fiberglass roving, excelsior, synthetic mat, woven paper net	18. Distribution Statement This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	124	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

U.S. Department of Transportation
Federal Highway Administration

Memorandum

6300 Georgetown Pike
McLean, Virginia 22101-2296

Subject: Implementation Package "Design of Roadside Channels with Flexible Linings" Report No. FHWA-IP-87-7

Date: OCT 20 1988

From: Director, Office of Implementation
Director, Office of Engineering

Reply to Attn. of: HRT-10

To: Regional Federal Highway Administrators
Direct Federal Program Administrator

This manual addresses the design of stable conveyance channels using flexible linings. These linings are able to conform to changes in channel shape while maintaining the overall lining integrity. Permanent flexible linings such as riprap, gravel or vegetation reinforced with synthetic mat are suitable for hydraulic conditions similar to those requiring rigid linings. Vegetation or temporary linings are suited to hydraulic conditions where uniform flow exists and shear stresses are moderate.

Design procedures are given for rock riprap, wire-enclosed riprap, gravel riprap, woven paper net, jute net, fiberglass roving, curled wood mat, synthetic mat and straw. Special design procedures are presented for composite channels and channels with steep gradients. The design procedures are based on the concept of maximum permissible tractive force. Nomographs are provided.

Direct distribution of the report is being made to Region and Division Offices. If you have any questions concerning the report or require additional copies, please contact Mr. Thomas Krylowski at (FTS) 285-2359.

* SI is the symbol for the International System of Measurements

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (continued)

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF CHARTS

LIST OF CHARTS (continued)

LIST OF TABLES

LIST OF SYMBOLS

A = Cross-sectional area of flow prism, ft^2, m^2.

AOS = Measure of the largest effective opening in a geotextile; represents opening size for which 95 percent of fabric pores are smaller than that diameter.

B = Bottom width of trapezoidal channel, ft, m.

CG = Channel geometry.

D_{50}, D_{85} = Particle size of gradation, of which 50 percent, 85 percent, etc, of the mixture is finer by weight, ft, m.

d = Depth of flow in channel, ft, m.

d = Change in depth due to superelevation of flow in a bend, ft, m.

d_n = Depth of normal or uniform flow, ft, m.

F_d = Drag force in direction of flow.

F_l = Lift force.

Fr = Froude number, ratio of inertial forces to gravitational force in a system.

g = Gravitational acceleration, ft/sec^2, m/sec^2.

h = Average height of vegetation, ft, cm.

K_b = Ratio of maximum shear stress in bend to maximum shear stress upstream from bend.

K_c = Compound channel lining factor.

K_1 = Ratio of channel side shear to bottom shear stress.

K_2 = Tractive force ratio.

L_p = Protected length downstream from bend, ft, m.

k_s = Roughness height, ft, cm.

K_s = Tractive force ratio at bottom of channel.

MEI = Stiffness factor, $lb \cdot ft^2$, $Newton \cdot m^2$.

n = Manning's flow resistance coefficient.

P = Wetted perimeter of flow prism, ft, m.

P_ℓ = Wetted perimeter of low-flow channel, ft, m.

P.C. = Point on curve.

P.T. = Point on tangent.

Q = Discharge, flow rate, ft^3/sec, m^3/sec.

R = Hydraulic radius, A/P, ft, m.

R_c = Mean radius of channel center line, ft, m.

REG = Roughness element geometry.

S = Average channel gradient.

S_f = Energy gradient.

S_{50} = Mean of the short axis lengths of the distribution of roughness element.

SF = Safety factor.

SSF = Side slope factor.

T = Channel top width, ft, m.

V = Mean channel velocity, ft/sec, m/sec.

V_* = Shear velocity, ft/sec, m/sec.

W_s = Weight of riprap element, lb, Kg.

Y_{50} = Mean value of the distribution of the average of the long and median axes of a roughness element.

Z = Side slope; cotangent of angle measured from horizontal. $Z = \cot \phi$.

ℓ = Moment arms of riprap channel.

α = Angle of channel bed slope.

β = Angles between weight vector and the resultant in the plane of the side slope.

γ = Unit weight of water, lb/ft^3, Kg/m^3.

δ = Angle between the drag vector and resultant in the plane of the side slope.

θ = Angle of repose of coarse, noncohesive material, degrees.

η = Stability number.

η' = Stability number for side slopes.

σ = Bed material gradation.

τ = Average shear stress, lb/ft^2, Kg/m^2.

τ_b = Shear stress in a bend, lb/ft^2, Kg/m^2.

τ_d = Shear stress in channel at maximum depth, lb/ft^2, Kg/m^2.

τ_p = Permissible shear stress, lb/ft^2, Kg/m^2.

τ_s = Shear stress on sides of channel, lb/ft^2, Kg/m^2.

ϕ = Angle of side slope (bank) measured from horizontal.

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION

DESIGN OF ROADSIDE CHANNELS WITH FLEXIBLE LININGS

I. INTRODUCTION

This manual addresses the design of stable conveyance channels using flexible linings. Because the roadside channel is included within the highway right-of-way, the gradient of the channel typically parallels the grade of the highway. Hydraulic conditions in the conveyance channel can become severe even at fairly mild highway grades. As a result, these channels often require stabilization against erosion. The channel stabilization measures included in this manual are deemed flexible linings.

The primary difference between rigid and flexible channel linings from an erosion-control standpoint is their response to changing channel shape. Flexible linings are able to conform to change in channel shape while rigid linings can not. The result is that flexible linings can sustain some change in channel shape while maintaining the overall integrity of the channel lining. Rigid linings tend to fail when a portion of the lining is damaged. Damage to a lining is often from secondary forces such as frost heave or slumping. Rigid linings can be disrupted by these forces whereas flexible linings, if properly designed, will retain erosion-control capabilities.

Flexible linings also have several other advantages compared to rigid linings. They are generally less expensive, permit infiltration and exfiltration, and have a natural appearance. Hydraulically, flow conditions in channels with flexible linings generally conform to those found in natural channels, and thus provide better habitat opportunities for local flora and fauna. In some cases, flexible linings may provide only temporary protection against erosion while allowing vegetation to be established. The vegetation will then provide permanent erosion control in the channel. The presence of vegetation in a channel can also provide a buffering effect for runoff contaminants.

Flexible linings have the disadvantage of being limited in the magnitude of erosive force they can sustain without damage to either the channel or the lining. Because of this limitation, the channel geometry (both in cross section and profile) required for channel stability may not fit within the acquired right-of-way. A rigid channel can provide a much higher capacity and in some cases may be the only alternative.

Design procedures covered in this manual relate to flexible channel linings. Rigid linings are discussed only briefly so that the reader remains familiar with the full range of channel lining alternatives. The primary reference for the design of rigid channels is Hydraulic Design Series No. 3, "Design of Roadside Drainage Channels". (1) For channels which require other protection measures, the design of energy dissipators and grade-control structures can be found in Hydraulic Engineering Circular (HEC) No. 14.(2)

Riprap design procedures covered in this manual are for channels having a design discharge of 50 cfs or less. The use of the procedures in Hydraulic Engineering Circular (HEC) No. 11 is recommended for the design of riprap revetments or linings on channels and streams with design flows in excess of 50 cfs.(3)

The permissible tractive force and Manning n values provided in this manual for grass lined channels cannot be compared to values found in earlier manuals. The current values are based on research conducted at Colorado State University which takes into account the stiffness of the vegetation.

The riprap procedure for steep channels is based on an analysis of forces acting on the riprap. While this procedure is theoretically sound, the results should be used with caution and be taken as guidance. Whenever possible, the procedure should be checked against the performance of installed channels in the field. The steep slope design procedure is limited to channels having a design discharge of 50 cfs of less.

II. BACKGROUND

Considerable development and research have been done on rigid and flexible channel linings. Prior to the late 1960's, natural materials were predominantly used to stabilize channels. Typical materials included rock riprap, stone masonry, concrete, and vegetation. Since that time a wide variety of manufactured and synthetic channel linings applicable to both permanent and temporary channel stabilization have been introduced. Relatively little data on hydraulic performances of these materials are available compared to the variety of materials produced. Work is continuing on comparing hydraulic performances, material improvement, and new material development.

Lining Types

Because of the large number of channel stabilization materials currently available, it is useful to classify these materials based on their performance characteristics. Lining types are classified as rigid, such as concrete, or flexible, such as vegetation or rock riprap. Flexible linings are further classified as temporary or permanent. Lining materials are classified as follows:

Rigid Linings

- Cast-in-place concrete
- Cast-in-place asphaltic concrete
- Stone masonry
- Soil cement
- Fabric formwork systems for concrete
- Grouted riprap

Flexible Linings

Permanent

- Riprap
- Wire-enclosed riprap
- Vegetation lining
- Gravel

Temporary

- Bare soil
- Straw with net
- Curled wood mat
- Jute, paper, or synthetic net
- Synthetic mat
- Fiberglass roving

Performance Characteristics

Rigid Linings. Rigid linings (figure 1) are useful in flow zones where high shear stress or nonuniform flow conditions exist, such as at transitions in channel shape or at an energy dissipation structure. In areas where loss of water or seepage from the channel is undesirable, they provide an impermeable lining. Since rigid linings are nonerodible, the designer can use any channel shape that adequately conveys the flow and provides adequate freeboard. This may be necessary if right-of-way limitations restrict the channel size.

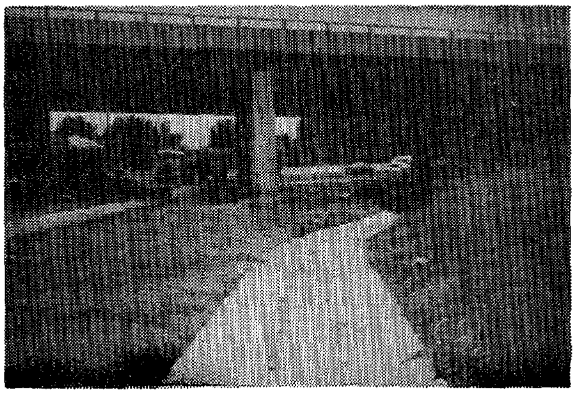


Figure 1. Rigid Concrete Channel Lining.

Despite the non-erodible nature of rigid linings, they are highly susceptible to failure from structural instability. For example, cast-in-place or masonry linings often break up and deteriorate if foundation conditions are poor. Once a rigid lining deteriorates, it is very susceptible to erosion because the large, flat, broken slabs are easily moved by channel flow.

The major causes of structural instability and failure of rigid linings are freeze-thaw, swelling, and excessive soil pore water pressures. Freeze-thaw and swelling soils exert upward forces against the lining and the cyclic nature of these conditions can eventually cause failure. Excessive soil pore pressure occurs when the flow levels in the channel drop quickly. Side slope instability can develop from excessively high pore pressures and high hydraulic gradients along the slope surface.

Construction of rigid linings requires specialized equipment and costly materials. As a result, the cost of rigid channel linings is high. Prefabricated linings can be a less expensive alternative if shipping distances are not excessive.

Flexible Linings. Riprap and vegetation are suitable linings for hydraulic conditions similar to those requiring rigid linings. Because flexible linings are permeable, they may require protection of underlying soil to prevent washout. For example, filter cloth is often used with riprap to inhibit soil piping.

Vegetative and temporary linings are suited to hydraulic conditions where uniform flow exist and shear stresses are moderate. Vegetative channel linings are not suited to sustained flow conditions or long periods of submergence. Vegetative channels with sustained low flow and intermittent high flows are often designed with a composite lining of a riprap or concrete low-flow section, (figure 2).

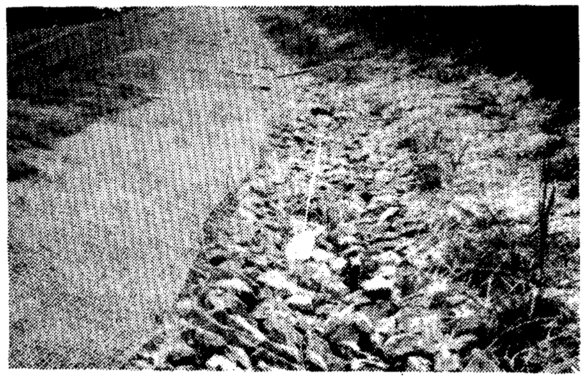


Figure 2. Composite Channel Lining
(Riprap and Jute Net).

Temporary linings provide erosion protection until vegetation is established. In most cases the lining will deteriorate over the period of one growing season, which means that successful revegetation is essential to the overall channel stabilization effort. Temporary channel linings may be used without vegetation to temporarily control erosion on construction sites.

Information on Flexible Linings

The following is a summary of materials currently available for use as flexible channel linings.

Permanent Flexible Linings

Vegetation: Vegetative linings consist of planted or sodded grasses placed in and along the drainage (figure 3). If planted, grasses are seeded and fertilized according to the requirements of that particular variety or mixture. Sod is laid parallel to the flow direction and may be secured with pins or staples.

Rock Riprap: Rock riprap is dumped in place on a filter blanket or prepared slope to form a well-graded mass with a minimum of voids (figure 4). Rocks should be hard, durable, preferably angular in shape, and free from overburden, shale, and organic material. Resistance to disintegration from channel erosion should be determined from service records or from specified field and laboratory tests.

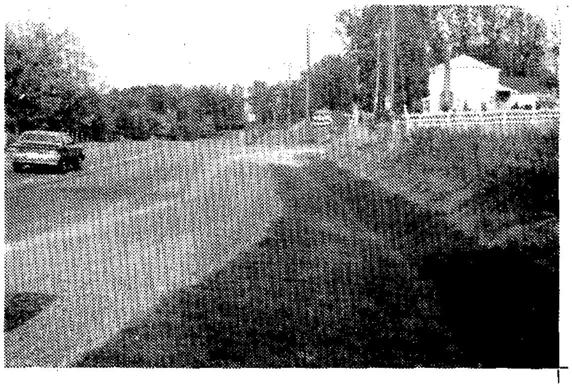


Figure 3. Vegetative Channel Lining (Class D Retardance).

Figure 4. Riprap Channel Lining.

Wire-Enclosed Riprap: Wire-enclosed riprap is manufactured from a rectangular container made of steel wire woven in a uniform pattern, and reinforced on corners and edges with heavier wire (figure 5). The containers are filled with stone, connected together, and anchored to the channel side slope. Stones must be well graded and durable. The forms of wire-enclosed riprap vary from thin mattresses to boxlike gabions. Wire-enclosed riprap is typically used when rock riprap is either not available or not large enough to be stable.

Gravel Riprap: Gravel riprap consists of coarse gravel or crushed rock placed on filter blankets or prepared slope to form a well-graded mass with a minimum of voids (figure 6). The material is composed of tough, durable, gravel-sized particles and should be free from organic matter.

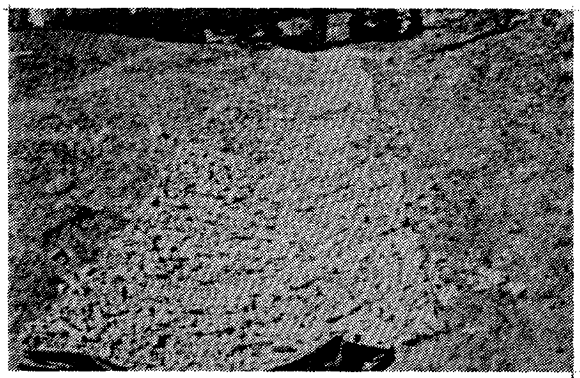


Figure 5. Wire-Enclosed Riprap.

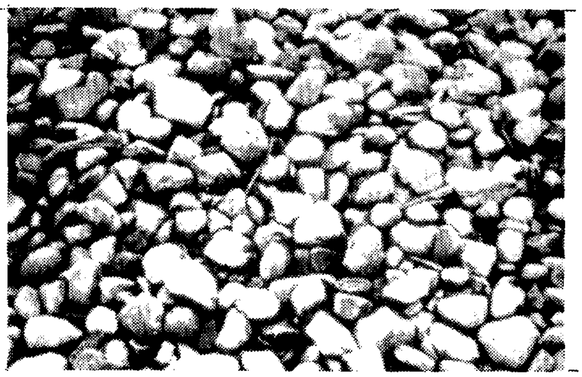


Figure 6. Gravel Channel Lining.

Temporary Flexible Linings

Woven Paper Net: Woven paper net consists of knitted plastic netting, interwoven with paper strips (figures 7 and 8). The net is applied evenly on the channel slopes with the fabric running parallel to the flow direction of the channel. The net is secured with staples and by placement of fabric into cutoff trenches at intervals along the channel. Placement of woven paper net is usually done immediately after seeding operations.

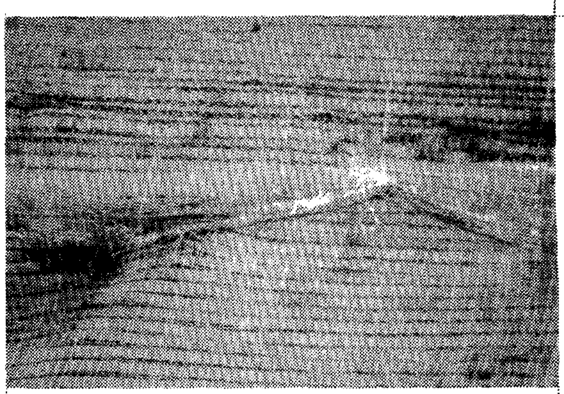


Figure 7. Woven Paper Net Channel Lining.

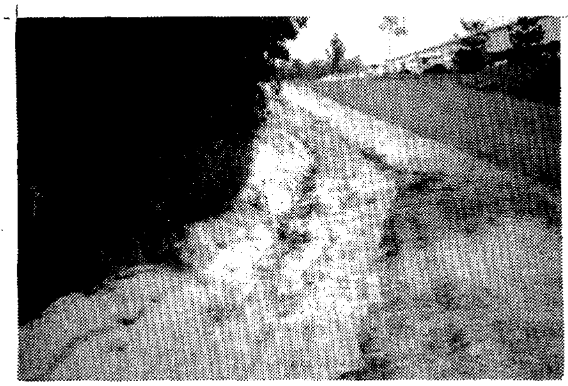


Figure 8. Installed Woven Paper Net Lining.

Jute Net: Jute net consists of jute yarn, approximately 1/4 inch (0.6 cm) in diameter, woven into a net with openings that are about 3/8 by 3/4 inch (1.0 by 2.0 cm). The jute net (figures 9 and 10) is loosely laid in the channel parallel to the direction of flow. The net is secured with staples and by placement of the fabric into cutoff trenches at intervals along the channel. Placement of jute net is usually done immediately after seeding operations.

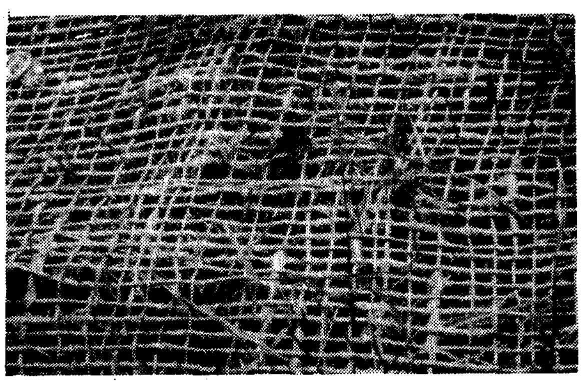


Figure 9. Jute Net Lining.

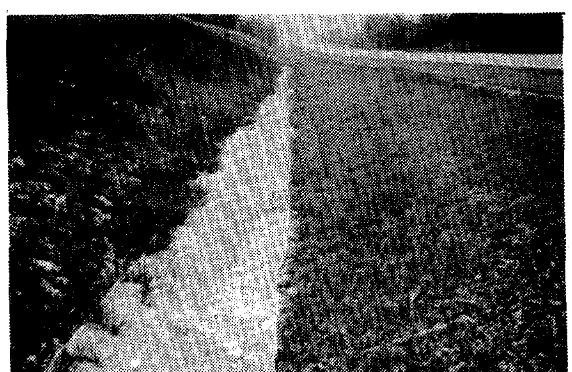


Figure 10. Installed Jute Net Channel Lining.

Fiberglass Roving: Fiberglass roving consists of continuous fibers drawn from molten glass, coated, and lightly bound together into roving. The roving is ejected by compressed air forming a random mat of continuous glass fibers. The material is spread uniformly over the channel and anchored with asphaltic materials (figures 11 and 12).

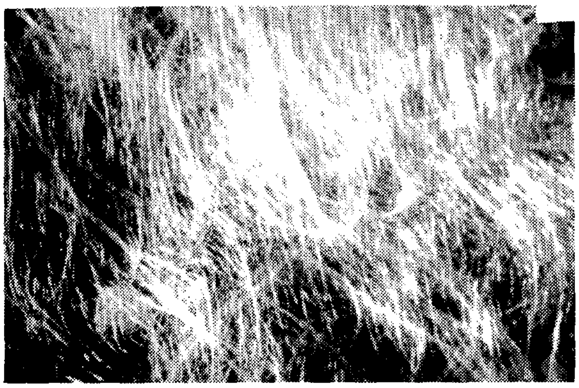


Figure 11. Fiberglass Roving Lining.

Figure 12. Installation of Fiberglass Roving Along a Roadside.

Curled Wood Mat: Curled wood mat consists of curled wood with wood fibers, 80 percent of which are 6 inches (15 cm) or longer, with a consistent thickness and an even distribution of fiber over the entire mat (figures 13 and 14). The top side of the mat is covered with a biodegradable plastic mesh. The mat is placed in the channel parallel to the direction of the flow and secured with staples and cutoff trenches.

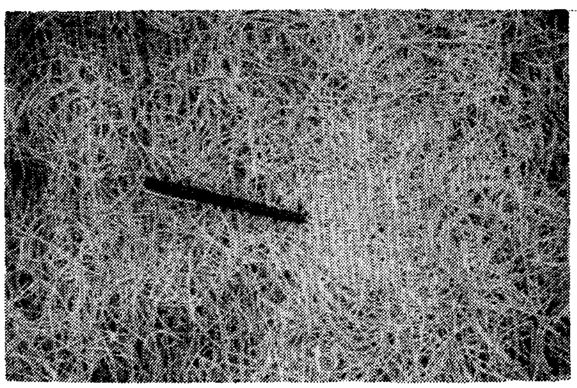


Figure 13. Curled Wood Mat Lining.

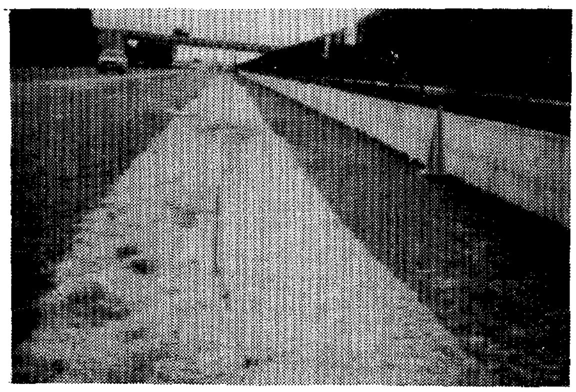


Figure 14. Installed Curled Wood Mat Channel Lining.

Synthetic Mat: Synthetic mat consists of heavy synthetic monofilaments which are fused at their intersections to form a blanket ranging in thickness from 1/4 to 3/4 inch (0.6 to 2.0 cm). The mat, shown in figures 15 and 16, is laid parallel to the direction flow. The mat is secured with staples or wooden stakes, and anchored into cutoff trenches at intervals along the channel. After the mat is in place the area is seeded through the openings in the mat and the cutoff trenches backfilled.

Figure 15. Synthetic Mat Lining.

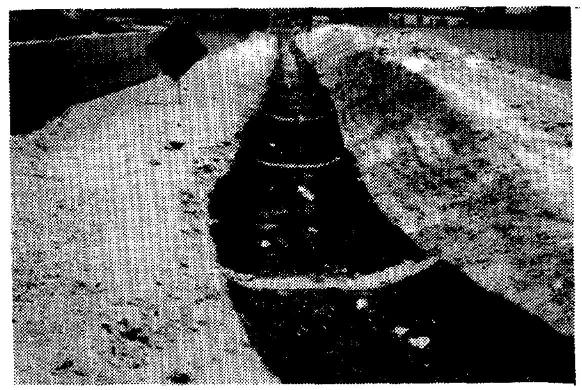


Figure 16. Installed Synthetic Mat Channel Lining.

Straw with Net: Straw with net consists of plastic material forming a net of 3/4-inch (2.0-cm) minimum square openings overlying straw mulch (figure 17). Straw is spread uniformly over the area at a rate of approximately 2.0 tons per acre (4.5 tonnes/hectare) and may be incorporated into the soil according to specifications. Plastic net is placed after mulching with straw to secure the mulch to the finished channel.

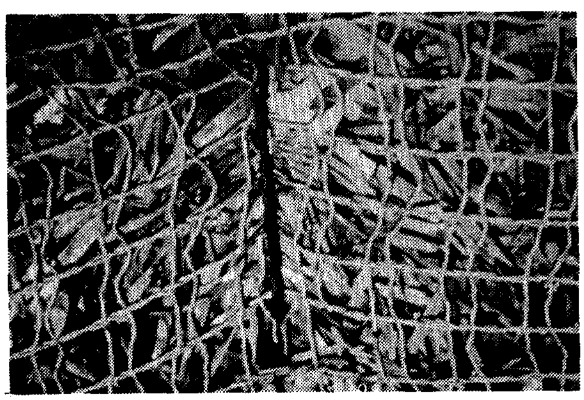


Figure 17. Straw With Net Channel Lining.

III. DESIGN CONCEPTS

The design method presented in this circular is based on the concept of maximum permissible tractive force, coupled with the hydraulic resistance of the particular lining material. The method includes two parts, computation of the flow conditions for a given design discharge and determination of the degree of erosion protection required. The flow conditions are a function of the channel geometry, design discharge, channel roughness, and channel slope. The erosion protection required can be determined by computing the shear stress on the channel at the design discharge and comparing the calculated shear stress to the permissible value for the type of channel lining used.

Open-Channel Flow Concepts

Type of Flow. Open-channel flow can be classified according to three general conditions: (1) uniform or nonuniform flow, (2) steady or unsteady flow, and (3) subcritical or supercritical flow. In uniform flow, the depth and discharge remain constant along the channel. In steady flow, no change in discharge occurs over time. Most natural flows are unsteady and are described by runoff hydrographs. It can be assumed in most cases that the flow will vary gradually and can be described as steady, uniform flow for short periods of time. Subcritical flow is distinguished from supercritical flow by a dimensionless number called the Froude number (Fr), which is defined as the ratio of inertial forces to gravitational forces in the system. Subcritical flow ($Fr < 1.0$) is characterized as tranquil and has deep, slower velocity flow. Supercritical flow ($Fr > 1.0$) is characterized as rapid and has shallow, high velocity flow.

For design purposes, uniform flow conditions are usually assumed with the energy slope approximately equal to average bed slope. This allows the flow conditions to be defined by a uniform flow equation such as Manning's equation. Supercritical flow creates surface waves that are approaching the depth of flow. For very steep channel gradients, the flow may splash and surge in a violent manner and special considerations for freeboard are required.

Resistance to Flow. Depth of uniform flow in a channel depends on the roughness of a particular lining. For practical purposes in highway drainage engineering, Manning's equation provides a reliable estimate of uniform flow conditions. With a given depth of flow, d, the mean velocity may be computed as:

$$V = \frac{1.49}{n} R^{2/3} S_f^{1/2} \qquad (1)$$

where V = average velocity in the cross section;
n = Manning's roughness coefficient;
R = hydraulic radius, equal to the cross-sectional area, A, divided by the wetted perimeter, P; and
S_f = friction slope of the channel, approximated by the average bed slope for uniform flow conditions.

The discharge in the channel is given by the continuity equation as:

$$Q = AV \qquad (2)$$

where A = flow area in the channel.

For most types of channel linings Manning's roughness coefficient, n, is approximately constant. The roughness coefficient will increase for very shallow flows where the height of the roughness features on the lining approaches the flow depth (see figure 29). For a riprap lining, the flow depth in small channels may be only a few times greater than the diameter of the mean riprap size. In this case, use of a constant n value is acceptable, but consideration of the shallow flow depth should be made by using a higher n value.

A channel lined with a good stand of vegetation cannot be described by a single n value. The resistance to flow in vegetated channels is further complicated by the fact that vegetation will bend in the flow, changing the height of the vegetation. The Soil Conservation Service (SCS) (4) developed a classification of vegetation depending on the degree of retardance. Grasses are classified into five broad categories, as shown in table 1 in chapter IV. Retardance Class A presents the highest resistance to flow and Class E presents the lowest resistance to flow. In general, taller and stiffer grass species have a higher resistance to flow, while short flexible grasses have a low-flow resistance.

Recent studies by Kouwen et al. (5,6), examined the biomechanics of vegetation and provided a more general approach for determining the Manning's n value for vegetated channels. The resulting resistance equation (see appendix B, equation 19) uses the same vegetative classification as the SCS but is more accurate for very stiff vegetation and mild channel gradients. Design charts 5 to 9 were developed from the Kouwen resistance equation.

Channel Bends. Flow around a bend in an open channel induces centrifugal forces because of the change in flow direction. (7) This results in a superelevation of the water surface. The water surface is higher at the outside of the bend than at the inside of the bend. This superelevation can be estimated by the equation:

$$\Delta d = \frac{V^2}{g}\frac{T}{R_c} = \text{superelevation of water surface} \qquad (3)$$

where V = mean velocity;
T = surface width of the channel;
g = gravitational acceleration; and
R_c = mean radius of the bend.

Flow around a channel bend imposes higher shear stress on the channel bottom and banks. The nature of the shear stress induced by a bend is discussed in more detail in the tractive force section on page 13. The increase stress requires additional design considerations within and downstream of the bend.

Freeboard. The freeboard of a channel is the vertical distance from the water surface to the top of the channel at design condition. The importance of this factor depends on the consequence of overflow of the channel bank. At a minimum the freeboard should be sufficient to prevent waves or fluctuations in water surface from overflowing the sides. In a permanent roadway channel, about one-half foot of freeboard should be adequate, and for temporary channels, no freeboard is necessary. Steep gradient channels should have a freeboard height equal to the flow depth. This allows for large variations to occur in flow depth for steep channels caused by waves, splashing and surging. Lining materials should extend to the freeboard elevation.

Stable Channel Design Concepts

Equilibrium Concepts. Stable channel design concepts focus on evaluating and defining a channel configuration that will perform within acceptable limits of stability. Methods for evaluation and definition of a stable configuration depend on whether the channel boundaries can be viewed as (1) essentially rigid (static) or (2) moveable (dynamic). In the first case, stability is achieved when the material forming the channel boundary effectively resists the erosive forces of the flow. Under such conditions the channel bed and banks are in static equilibrium, remaining basically unchanged during all stages of flow. Principles of rigid boundary hydraulics can be applied to evaluate this type of system.

In a dynamic system, some change in the channel bed and/or banks is to be expected if erosive forces of the flow are sufficient to detach and transport the materials comprising the channel boundary. Stability in a dynamic system is generally attained when the sediment supply rate equals the sediment-transport rate. This condition, where sediment supply equals sediment transport, is often referred to as dynamic equilibrium. Although some detachment and transport of bed and/or bank materials may occur, this does not preclude attainment of a channel configuration that is basically stable. A dynamic system can be considered stable so long as the net change does not exceed acceptable levels. For most highway drainage channels, bank instability and possible lateral migration cannot be tolerated. Consequently, development of static equilibrium conditions or utilization of linings to achieve a stable condition is usually preferable to using dynamic equilibrium concepts.

Two methods have been developed and are commonly applied to determine if a channel is stable in the sense that the boundaries are basically immobile (static equilibrium). These methods are defined as the permissible velocity approach and the permissible tractive force (shear stress) approach. Under the permissible velocity approach the channel is assumed stable if the adopted mean velocity is lower than the maximum permissible velocity. The tractive force (boundary shear stress) approach focuses on stresses developed at the interface between flowing water and materials forming the channel boundary. By Chow's definition, permissible tractive force is the maximum unit tractive force that will not cause serious erosion of channel bed material from a level channel bed.(7)

Permissible velocity procedures were first developed around the 1920's. In the 1950's, permissible tractive force procedures became recognized, based on research investigations conducted by the U.S. Bureau of Reclamation. Procedures for design of vegetated channels using the permissible velocity approach were developed by the SCS and have remained in common use.

In spite of the empirical nature of permissible velocity approaches, the methodology has been employed to design numerous stable channels in the United States and throughout the world. However, considering actual physical processes occurring in open-channel flow, a more realistic model of detachment and erosion processes is based on permissible tractive force.

Tractive Force Theory. The hydrodynamic force of water flowing in a channel is known as the tractive force. The basis for stable channel design with flexible lining materials is that flow-induced tractive force should not exceed the permissible or critical shear stress of the lining materials. In a uniform flow, the tractive force is equal to the effective component of the gravitational force acting on the body of water, parallel to the channel bottom.(7) The average tractive force on the channel, or shear stress is equal to:

$$\tau = \gamma RS \qquad (4)$$

where γ = unit weight of water;
R = hydraulic radius; and
S = average bed slope or energy slope.

The maximum shear stress, τ_d, for a straight channel occurs on the channel bed (7, 8) and is less than or equal to the shear stress at maximum depth.

$$\tau_d = \gamma dS \qquad (5)$$

where d = maximum depth of flow.

Shear stress in channels is not uniformly distributed along the wetted perimeter. (9,10) A typical distribution of shear stress in a trapezoidal channel tends toward zero at the corners with a maximum on the center line of the bed, and the maximum for the side slopes occurring about the lower third of the side as shown in figure 18. Flow around a bend creates secondary currents, which impose higher shear stresses on the channel sides and bottom compared to a straight reach (11) as shown in figure 19. At the beginning of the bend, the maximum shear stress is near the inside and moves toward the outside as the flow leaves the bend. The increased shear stress caused by a bend persists downstream of the bend, a distance, L_p. The maximum shear stress in a bend is a function of the ratio of channel curvature to bottom width, R_c/B.(12) As Rc/B decreases, that is as the bend becomes sharper, the maximum shear stress in the bend tends to increase (see chart 10). The bend shear stress, t_b, is expressed by a dimensionless factor, K_b, multiplied by the shear stress in an equivalent straight section of channel where

$$\tau_b = K_b \tau_d \qquad (6)$$

The relationship between permissible shear stress and permissible velocity for a lining can be found by substituting equation 4 into equation 1 giving:

$$V_p = \frac{0.189}{n} R^{1/6} \tau_p^{1/2} \qquad (7)$$

where τ_p = permissible shear stress.

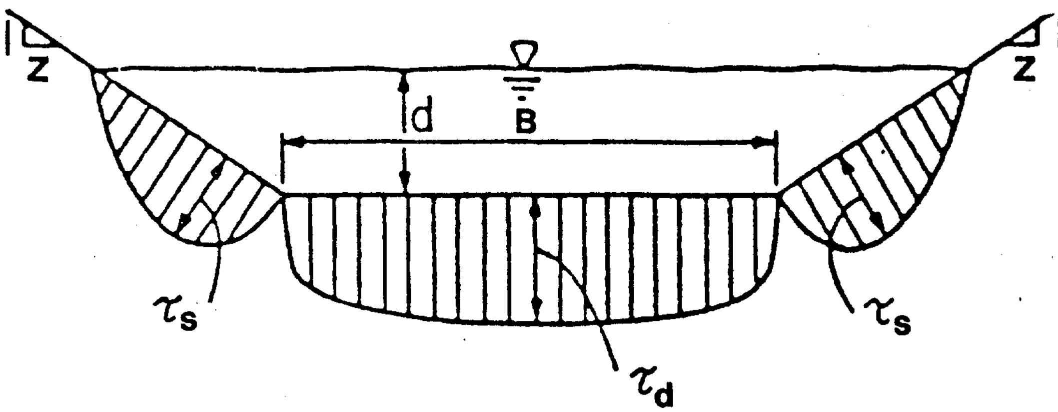


Figure 18. Typical Distribution of Shear Stress.

It can be seen from this equation that permissible velocity varies due to the hydraulic radius. However, permissible velocity is not extremely sensitive to hydraulic radius since the exponent is only 1/6. Equation 7 is useful in judging the field performance of a channel lining, because depth and velocity may be easier to measure in the field than water surface or channel gradient.

The tractive force method is a more compact approach than the permissible velocity method, because the failure criteria for a particular lining is represented by a single critical shear stress value. This critical shear stress value is applicable over a wide range of channel slopes and channel shapes. Permissible velocities, on the other hand, are a function of lining roughness, channel slope, and channel shape, and are only approximately constant over a range of these parameters. An accurate solution of the permissible velocity method therefore requires design nomographs. The simpler representation of failure for the tractive force method is a definite advantage for users who prefer to use programmable calculators and microcomputers.

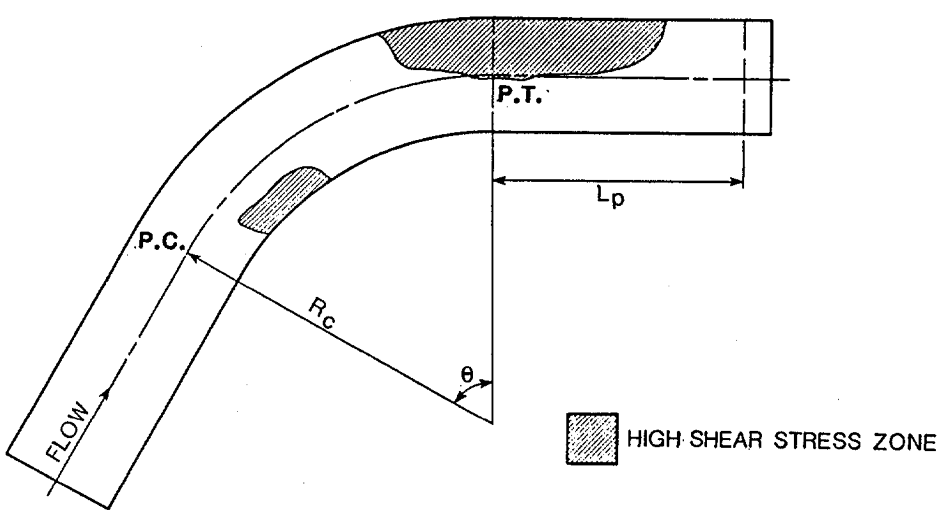


Figure 19. Shear Stress Distribution in a Channel Bend (after 11).

Design Parameters

Design Discharge Frequency. Design flow rates for permanent roadside and median drainage channel linings usually have a 5- or 10-year return period. A lower return period flow is allowable if a temporary lining is to be used, typically the mean annual storm (approximately a 2-year return period, i.e., 50 percent probability of occurrence in a year). Temporary channel linings are often used during the establishment of vegetation. The probability of damage during this relatively short time is low, and if the lining is damaged, repairs are easily made. Design procedures for determining the maximum permissible discharge in a roadway channel are given in chapter IV.

Channel Cross Section Geometry. Most highway drainage channels are trapezoidal or triangular in shape with rounded corners. For design purposes a trapezoidal or triangular representation is sufficient. Design of roadside channels should be integrated with the highway geometric and pavement design to insure proper consideration of safety and pavement drainage needs. If available channel linings are found to be inadequate for the selected channel geometry, it may be feasible to widen the channel. This can be accomplished by either increasing the bottom width or flattening the side slopes. Widening the channel will reduce the flow depth and lower the shear stress on the channel perimeter.

It has been demonstrated that if a riprap-lined channel has 3:1 or flatter side slopes, there is no need to check the banks for erosion. (8) With steeper side slopes, a combination of shear stress against the bank and the weight of the lining may cause erosion on the banks before the channel bottom is disturbed. The design method in this manual includes procedures for checking the adequacy of channels with steep side slopes.

Equations for determining cross-sectional area, wetted perimeter, and top width of channel geometries commonly used for highway drainage channels are given in appendix A.

Channel Slope. The channel bottom slope is generally dictated by the roadway profile, and therefore is usually fixed. If channel stability conditions warrant and available linings are not sufficient, it may be feasible to reduce the channel gradient slightly relative to the roadway profile. For channels outside the roadway right-of-way, the slope may be adjusted slightly.

Channel slope is one of the major parameters in determining shear stress. For a given design discharge, the shear stress in the channel with a mild or subcritical slope is smaller than a channel with supercritical slope. Roadside channels with gradients in excess of about two percent will flow in a supercritical state. Most flexible lining materials are suitable for protecting channel gradients of up to 10 percent. Riprap and wire-enclosed riprap are more suitable for protecting very steep channels with gradients in excess of 10 percent.

IV. DESIGN PROCEDURE

This section outlines the design procedure for flexible channel linings. Channels with steep gradients (slopes greater than 10%) will usually produce a tractive force in excess of the permissible shear stress for most linings presented in this chapter at relatively small discharges. Also, when riprap is used on steeper gradients, the design procedure must take into consideration the additional forces acting on the riprap. Designs involving riprap should be checked and compared to results obtained from design procedures presented in chapter V, Steep Gradient Design. The more conservative results, i.e., largest riprap size, should be used for design. Other linings presented in this chapter are applicable over a wide range of channel gradients, provided the permissible shear for the lining is not exceeded.

The basic design procedure is supplemented for riprap lined channels with side slopes steeper than 3:1. Use of side slopes steeper than 3:1 is not encouraged for flexible linings other than riprap or gabions because of the potential for erosion of the side slopes. If a combination of linings is used, the composite channel lining procedure outlined in chapter VI should be used. In cases where flexible linings discussed in this circular do not provide adequate protection, other alternatives, including rigid linings should be considered. Because of the substantial increased cost of rigid linings, and their vulnerability to failure, other alternatives such as use of additional inlets, a modified channel geometry or a flatter channel gradient are preferred.

Flexible Lining Design

The basic design procedure for flexible channel linings is quite simple. It involves only two computations and several straight forward comparisons of lining performance. The computations include a determination of the uniform flow depth in the channel, known as the normal depth, and determination of the shear stress at maximum flow depth. Designers familiar with methods for determining normal depth may use any convenient method and the Manning's roughness coefficients provided in this manual. A nomograph is also provided in this chapter for determining the normal depth in trapezoidal channels. The computation for shear stress is much simpler and can be carried out without the need of any design aids.

The basic comparison required in the design procedure is that of permissible to computed shear stress for a lining. A table and two figures are provided that give permissible shear stress values for a variety of lining types. If the permissible shear stress is greater than the computed shear, the lining is considered acceptable. If a lining is unacceptable, a lining with a higher permissible shear stress is selected and the calculations for normal depth and shear stress is repeated. A worksheet is provided at the end of this chapter (figure 23) for carrying out the design procedures presented in this chapter.

Channels lined with gravel or riprap on side slopes steeper than 3:1 must be designed using the steep side slope design procedure. Steep side slopes are allowable within a channel if cohesive soil conditions exist. Channels with steep slopes should not be allowed if the channel is constructed in non-cohesive soils.

Permissible Shear Stress

The permissible shear stress, τ_p, indicates the force required to initiate movement of the lining material. Prior to movement of the lining, the underlying soil is relatively protected. Therefore permissible shear stress is not significantly affected by the erodibility of the underlying soil. However, if the lining is eroded and moved, the bed material is exposed to the erosive force of the flow. The consequence of lining failure on highly erodible soils is great, since the erosion rate after failure is high compared to soils of low erodibility.

Values for permissible shear stress for linings are based on research conducted at laboratory facilities and in the field. The values presented here are judged to be conservative and appropriate for design use. Table 2 presents permissible shear stress values for manufactured, vegetative, and riprap lining types. The permissible shear stress for non-cohesive soils is a function of mean diameter of the channel material as shown in chart 1. For larger stone sizes not shown in chart 1 and rock riprap, the permissible shear stress is given by the following equation:

$$\tau_p = 4.0\ D_{50} \qquad (8)$$

where D_{50} is the mean riprap size in feet. For cohesive materials the variation in permissible shear stress is governed by many soil properties. The plasticity index of the cohesive soil provides a good guide to the permissible shear stress as shown in chart 2.

Determination of Normal Flow Depth

The condition of uniform flow in a channel at a known discharge is computed using the Manning's equation combined with the continuity equation:

$$Q = \frac{1.49}{n} AR^{2/3} S_f^{1/2} \qquad (9)$$

where Q = discharge;
n = Manning's roughness coefficient;
A = cross-sectional area;
R = hydraulic radius; and
S_f = friction gradient which, for uniform flow conditions, equals the channel bed gradient, S.

Chart 3 provides a solution to Manning's equation for trapezoidal channels. The geometric properties of a trapezoidal channel can be found using chart 4 or the equations provided in appendix A.

Manning's Roughness Coefficients for Nonvegetative Linings. Table 3 gives recommended values of the Manning's roughness coefficient for flexible channel lining materials, including riprap-type lining materials. The n values will vary with flow depth. The channel roughness will be higher for shallow flow depths and lower for large flow depths. The range of flow depths from 0.5 ft (15 cm) to 2.0 ft (60 cm) is typical of highway drainage channels and should be used in most cases.

Manning's Roughness Coefficients for Vegetative Linings. Manning's roughness coefficient for vegetative linings varies significantly depending on the amount of submergence of the vegetation and the flow force exerted on the channel bed. As a result, the Manning's n value must be determined by trial and error taking into consideration both the depth of flow and the flow force. Charts 5 to 9 show the variation in Manning's n for five classes of vegetation. These charts can be used to determine Manning's n for a wide range of flow conditions.

Determination of Shear Stress on Channel

As presented in chapter III, Tractive Force Theory (page 13), the shear stress on the channel lining at maximum depth, τ_d, is computed using the following equation:

$$\tau_d = \gamma d S \qquad (5)$$

where γ = unit weight of water (62.4 lb/ft^3);
d = flow depth, ft; and
S = channel gradient, ft/ft.

Flow around a channel bend imposes higher shear stress on the channel bottom and banks. For bends, the maximum shear stress is given by the following equation:

$$\tau_b = K_b \tau_d \qquad (6)$$

where the value of K_b can be found using chart 10. In chart 10, the radius of curvature of the channel center line, R_c, and the bottom width of the channel, B, determine the magnitude of factor K_b. The length of protection, L_p, required downstream of a bend is found using chart 11. The length of protection is a function of the roughness of the lining material in the bend (n_b) and the depth of flow.

Side Slope Stability

Channels lined with gravel or riprap on side slopes steeper than 3:1 may become unstable. As the angle of the side slopes approaches the angle of repose of the channel lining, the lining material becomes less stable. However, the shear stress on the channel side is less than the maximum shear stress occurring on the channel bed. The stability of a side slope is a function of the channel side slope and the angle of repose of the rock lining material.

When the tractive force ratio is compared to the ratio of the shear stress on the sides to the shear stress on the bottom of the channel, the rock size for the channel side slope can be determined. The angle of repose, θ, for different rock shapes and sizes is provided in chart 12. The ratio of shear stress on the sides and bottom of a trapezoidal channel, K_1, is given in chart 13 and the tractive force ratio, K_2, is given in chart 14. The required rock size (mean diameter of the gradation D_{50}) for the side slopes is found using the following equation:

$$(D_{50})_{sides} = \frac{K_1}{K_2} (D_{50})_{bottom} \qquad (10)$$

Maximum Discharge Approach

In many cases, the designer simply needs to know the maximum discharge a channel can convey given the permissible shear stress and the corresponding allowable depth. By knowing the maximum discharge that a lining can sustain, the designer can determine the maximum length of lining for a channel, based on the hydrology of the site. This information can assist the designer in an economic evaluation of lining types and can determine inlet spacing.

The procedure presented is for both vegetative linings and non-vegetative linings. Applying the procedure for vegetative linings is particularly useful, since it does not involve a trial and error solution.

Design Considerations for Riprap Lining

Two additional design considerations are required for riprap channel linings: (1) riprap gradation and thickness, and (2) use of filter material under rock riprap.

Riprap Gradation and Thickness. Riprap gradation should follow a smooth size distribution curve. Most riprap gradations will fall in the range of D_{100}/D_{50} and D_{50}/D_{20} between 3.0 to 1.5, which is acceptable. The most important criterion is a proper distribution of sizes in the gradation so that interstices formed by larger stones are filled with smaller sizes in an interlocking fashion, preventing the formation of open pockets. These gradation requirements apply regardless of the type of filter design used.

In general, riprap constructed with angular stones has the best performance. Round stones are acceptable as riprap provided they are not placed on side slopes steeper than 3:1. Flat slab-like stones should be avoided since they are easily dislodged by the flow. An approximate guide to stone shape is that neither the breadth nor thickness of a single stone is less than one-third its length.

The thickness of a riprap lining should equal the diameter of the largest rock size in the gradation. For most gradations, this will mean a thickness of from 1.5 to 3.0 times the mean riprap diameter.

Filter Design. When rock riprap is used the need for an underlying filter material must be evaluated. The filter material may be either a granular filter blanket or a engineering fabric.

For a granular filter blanket, the following criteria must be met:

$$\frac{D_{15\ filter}}{D_{85\ base}} < 5 < \frac{D_{15\ filter}}{D_{15\ base}} < 40 \qquad (11)$$

$$\frac{D_{50\ filter}}{D_{50\ base}} < 40 \qquad (12)$$

In the above relationships, "filter" refers to the overlying material and "base" refers to the underlying material. The relationships must hold between the filter blanket and base material and between the riprap and filter blanket.

The thickness of the granular filter blanket should approximate the maximum size in the filter gradation. The minimum thickness for a filter blanket should not be less than 6 inches.

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. (18)

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 U.S. No. 200 sieve, AOS < 0.6 mm (0.024 in) (greater than #30 U.S. Std. Sieve).

    b. For soil with more than 50 percent of the particles by weight passing a U.S. No. 200 sieve, AOS < 0.297 mm (0.012 in) (greater that #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 tests.

Design Procedures

The design procedure is summarized below. The procedure for flexible linings is a basic stepwise solution approach.

FLEXIBLE LINING DESIGN PROCEDURE
(see computation sheet, figure 23)

1. Select a flexible lining and determine the permissible shear stress, τ_p. (see Table 2)

2. Estimate flow depth for vegetation or flow depth range for non-vegetative linings, the channel shape, slope and design discharge(s).

3. Determine Manning's n value for estimated flow depth.

    a. For non-vegetive linings, use Table 3.
    b. For vegetation:
        (1) Calculate the hydraulic radius, R. (Use chart 4 for trapezoidal channels and Appendix A for other shapes.)
        (2) Determine n from Chart 5, 6, 7, 8, or 9.

4. Calculate the flow depth, d, in the channel. (Chart 3 for trapezoidal channels.)

5. Compare computed flow depth, d, with estimated flow depth, d_i. If d is outside the assumed range for non-vegetative linings or differs by more than 0.1 ft from d_i for vegetation, repeat steps 2 through 4.

6. Calculate the shear stress, τ_d. If $\tau_d > \tau_p$, the lining is not acceptable, repeat steps 1 through 5.

$$\tau_d = \gamma dS$$

7. For channel bends:

   a. Determine the factor for maximum shear stress on channel bends, K_b, from chart 10. This is a function of the ratio of channel curvature to bottom width, Rc/B.

   b. Calculate the shear stress in the bend, τ_b.

   $$\tau_b = K_b \tau_d \qquad (6)$$

   If $\tau_b > \tau_p$, the lining is not acceptable, repeat steps 1 through 7.

   c. Calculate length of protection, L_p, downstream of the bend from chart 11.

   d. Calculate superelevation.

   $$\Delta d = \frac{V^2 T}{g R_c} \qquad (3)$$

8. For riprap or gravel linings on steep side slopes (steeper than 3:1):

   a. Determine the angle of repose for the rock size and shape from chart 12.

   b. Determine K_1, the ratio of maximum side shear to maximum bottom shear for a trapezoidal channel from chart 13.

   c. Determine K_2, the tractive force ratio from chart 14.

   d. Calculate the required D_{50} for the side slopes.

   $$(D_{50})_{sides} = \frac{K_1}{K_2} (D_{50})_{bottom} \qquad (10)$$

9. For riprap on slopes greater than 10%, check design procedure in chapter V. Use whichever procedure results in the larger riprap size.

MAXIMUM DISCHARGE DESIGN PROCEUDRE

1. Determine the allowable depth of flow in the channel using the permissible shear stress (table 2 or charts 1 or 2). Check that this depth does not exceed the depth (including freeboard) provided in the typical roadway section.

$$d = \frac{\tau_p}{\gamma S} \qquad (13)$$

2. Determine the area and hydraulic radius corresponding to the allowable depth using chart 4.

3. For non-vegetative linings, find the correct Manning's n from table 3. For vegetative linings, enter into charts 5 to 9 for the correct vegetation class and determine the Manning's n value.

4. Solve Manning's equation (equation 9) to determine the maximum discharge for the channel.

Example Problems

Example 1:

Determine whether it is feasible to use jute net as a temporary lining.

Given: $Q = 20\ ft^3/sec$
$S = 0.005$ ft/ft
Trapezoidal channel with a bottom width of 4.0 ft and 3:1 side slopes.

Find: Depth of flow in the channel and the adequacy of the jute net lining.

Solution: (1) From table 2, the permissible shear stress is 0.45 lb/ft^2 and from table 3, the Manning's n value is 0.022 (assuming a flow depth between 0.5 to 2.0).

(2) Entering chart 3 for S = 0.005, Qn = 0.44, and B = 4,

$$d/B = 0.22$$
$$d = 0.88\ ft$$

The flow depth has remained within the range of 0.5 to 2.0 ft so that the assumed Manning's n value is correct.

(3) Using equation 5, the shear stress on the channel bed at maximum depth is,

$$\tau_d = \gamma dS = 62.4 \times 0.88 \times 0.005$$

$$= 0.27\ lb/ft^2$$

(4) Comparing the shear stress, 0.27 lb/ft^2, to the permissible shear stress, 0.45 lb/ft^2, shows that jute net is an acceptable channel lining.

Example 2:

Determine if a single application of fiberglass roving lining is an adequate lining for a median ditch.

Given: B = 2 ft
Z = 4
S = 0.05 ft/ft
Q = 10 ft^3/sec

Find: Depth of flow.

Solution: (1) From table 3, Manning's n is 0.021 assuming a flow depth in the range of 0.5 to 2.0 ft

(2) Entering chart 3 for S = 0.05, given
Qn = 0.21 and B = 2
d/B = 0.21
d = 0.42 ft

Checking the flow depth against the initial assumed range shows that the computed depth is below that range. The Manning's n for flow depth range of 0.0 to 0.5 ft is 0.028.

Enter chart 3 for S = 0.05,
Qn = 0.28 and B = 2
d/B = 0.24
d = 0.48 ft

The computed flow depth is within the assumed range.

(3) The maximum shear stress from equation 5 is,

$$\tau_d = \gamma dS = 62.4 \times 0.48 \times 0.05$$
$$= 1.5 \ lb/ft^2$$

(4) The permissible shear stress for fiberglass is 0.6 lb/ft^2. Since this is less than the maximum shear stress, the lining is not adequate.

Example 3:

A roadside ditch is lined with a good stand of uncut buffalo grass. Determine the flow depth and Manning's n for the depth at design discharge.

Given: Q = 20 ft^3/sec
S = 0.005 ft/ft
B = 4.0 ft
Z = 4

Find: (1) Manning's n value.

(2) Flow depth in the channel.

Solution: The vegetative retardance classification is found in table 1. A good stand of uncut buffalo grass is classified as retardance D.

The determination of Manning's n and flow depth for a vegetative lining may require several trials.

Trial 1

(1) Initial depth is estimated at 1.0 ft.

(2) From chart 4 for Z = 4 and d/B = 0.25,

R/d = 0.65 ft
R = 0.65

(3) Entering chart 8 given R = 0.65 and S = 0.005,

n = 0.088

(4) Entering chart 3 given S = 0.005, Qn = 1.76, B = 4, and Z = 4,

d/B = 0.40
d = 1.60 ft

(5) Since the difference between the initial and calculated depth is greater than 0.1 ft, the procedure is repeated.

Trial 2

(1) Use the calculated depth of 1.60 ft from trial 1.

(2) From chart 4 for Z = 4 and d/B = 0.40,

R/d = 0.61
R = 0.98

(3) Entering chart 8 given R = 0.98 and S = 0.005,

n = 0.066

(4) Entering chart 3 given S = 0.005, Qn = 1.32, and B = 4,

d/B = 0.36
d = 1.44

(5) Since the difference between the initial and calculated depths is 0.16 ft, which is greater than 0.1 ft, the procedure is repeated.

Trial 3

(1) Use the calculated depth of 1.44 ft from trial 2.

(2) From chart 4 for Z = 4 and d/B = 0.36,

R/d = 0.61
R = 0.88

(3) Entering chart 8 given R = 0.88 and S = 0.005,

n = 0.070

(4) Entering chart 3 given S = 0.005, Qn = 1.40, and B = 4,

d/B = 0.37
d = 1.48 ft

(5) The initial depth and the calculated depth are in agreement. The procedure is completed with the following results,

n = 0.070
d = 1.5 ft

Example 4:

Determine a temporary channel lining for a trapezoidal channel.

Given: Q = 16 ft^3/sec
S = 0.03 ft/ft
B = 4.0 ft
Z = 3

Find: Adequate temporary channel lining.

Solution:

Trial 1

(1) Jute net is selected as an initial channel lining alternative. The permissible shear stress (table 2) and Manning's n value (table 3) are,

τ_p = 0.45 lb/ft^2
n = 0.022 (assuming a depth range of 0.5 to 2.0 ft)

(2) The flow depth is determined from chart 3, given S = 0.03, Qn = 0.35, and B = 4,

d/B = 0.12
d = 0.48 ft

The flow depth is slightly below the specified range for Manning's n.

(3) The shear stress at maximum depth is found using equation 5,

τ_d = 62.4 x 0.48 x 0.03
= 0.90 lb/ft^2

(4) The computed shear stress of 0.90 lb/ft^2 is greater than the permissible shear stress of 0.45 lb/ft^2, so jute net would not be an acceptable lining.

Trial 2

(1) The next lining chosen is curled wood mat because the permissible shear stress for this lining exceeds the calculated shear stress from the first trial. Fiberglass roving was not chosen since its permissible shear stress was less than the calculated shear stress from the first trial. The permissible shear from table 2 and the Manning's n from table 3 for curled wood mat are,

τ_p = 1.55 lb/ft^2
n = 0.035 (assuming a depth range of 0.5 to 2.0 ft)

(2) The flow depth is determined from chart 3, given S = 0.030, Qn = 0.56, B = 4, and Z = 3,

d/B = 0.15
d = 0.60 ft

The flow depth is within the specified range for the Manning's n value used.

(3) The shear stress at maximum depth is found using equation 5,

τ_d = 62.4 x 0.60, 0.03
= 1.12 lb/ft^2

(4) The computed shear stress of 1.12 lb/ft^2 is less than the permissible shear stress of 1.55 lb/ft^2, so curled wood mat is an acceptable channel lining.

Use of the worksheets for this problem is illustrated in figure 21.

Example 5:

Determine an acceptable channel lining for the roadside channel in example 4 if a bend is included in the channel alignment.

Given: 45° channel bend
R_c = 20 ft

Find: (1) The channel lining required for the bend and the location of the lining.

(2) The superelevation of the water surface in the bend.

Solution:

Trial 1

(1) From the results of example 4, the shear stress of the straight reach upstream of the bend is,

τ_d = 1.12 lb/ft^2

A curled wood mat lining was used to stabilize the channel.

(2) The shear stress in the bend is given by equation 6. The value of K_b in equation 6 is found from chart 10 given $R_c/B = 5$,

$K_b = 1.6$

The bend shear stress is,

$$\tau_b = 1.6 \times 1.12$$
$$= 1.79 \text{ lb/ft}^2$$

(3) The computed shear stress in the bend is greater than the permissible shear stress for a curled wood mat channel lining (1.55 lb/ft^2). A new lining is required for the channel bend.

Trial 2

(1) Synthetic mat is chosen as a bend lining material, because it is permissible shear stress from table 2 (2.0 lb/ft^2) is greater than the computed shear stress from trial 1. The Manning's n value is 0.025 for a flow depth range from 0.5 to 2.0 ft.

(2) Entering chart 3 given S = 0.03, Qn = 0.40, and B = 4,

$$d/B = 0.13$$
$$d = 0.52 \text{ ft}$$

This depth falls within the range originally assumed for Manning's n.

(3) The shear stress from equation 5,

$$\tau_d = 62.4 \times 0.52 \times 0.03$$
$$= 0.97 \text{ lb/ft}^2$$

The bend shear stress from equation 6 is,

$$\tau_b = 1.6 \times 0.97$$
$$= 1.55 \text{ lb/ft}^2$$

(4) The calculated bend shear stress is less than the permissible shear stress for synthetic mat of 2.0 lb/ft^2. Synthetic mat therefore provides an acceptable channel bend lining.

(5) The synthetic mat will extend through the bend and a distance downstream. The downstream distance is found using chart 11, given $n_b = 0.025$, $R = 0.40$ (from chart 4 for $d/B = 0.13$ and $Z = 3$),

$L_p/R = 15.9$
$L_p = 6.4$ ft

The total length of synthetic mat lining is the sum of the length in the bend plus the length required for downstream protection. The following figure shows the required location of lining materials.

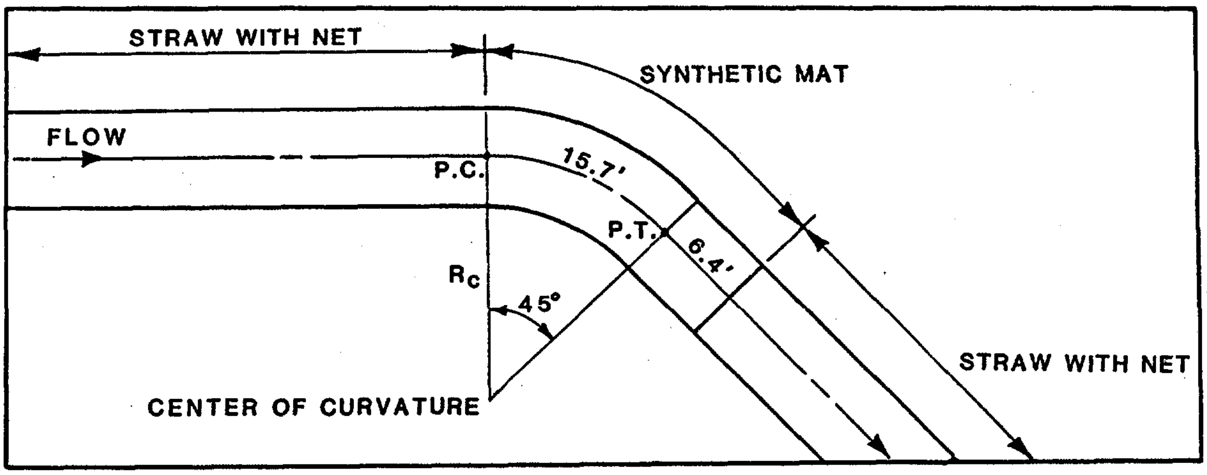


Figure 20. Location Sketch of Flexible Linings for Example 5.

(6) The superelevation of the water surface is computed from equation 3. To execute equation 3, top width and cross-sectional area must be computed, where,

$T = B + 2Zd$
$= 4 + 2 \times 3 \times 0.52$
$= 7.1$ ft

and

$A = Bd + Zd^2$
$= 4 \times 0.52 + 3 \times 0.52^2$
$= 2.89\ ft^2$

The velocity in the channel found using the continuity equation (equation 2),

$V = Q/A$
$= 16.0/2.89$
$= 5.5$ ft/sec

Solving equation 3 given V = 5.5 ft/s, T = 7.1 ft, and R_c = 20 ft,

$$\Delta d = \frac{V^2 T}{g R_c}$$

$$\Delta d = \frac{5.5^2 \times 7.1}{32.2 \times 20}$$

$$= 0.33 \text{ ft}$$

The freeboard in the channel bend should be at least 0.33 ft to accommodate the superelevation of the water surface.

Use of the worksheets for this problem is illustrated in figure 21.

Example 6:

Because of a width constraint on available right-of-way, the side slopes of a roadside ditch must be steepened to 2:1. The 2-inch gravel lining has been determined to be adequate to protect the ditch bed. Determine the gravel size, D_{50}, necessary to protect the ditch banks.

Given: Very rounded gravel
A trapezoidal channel

Z = 2
B = 3.5 ft

Flow depth, d = 0.7 ft

Find: D_{50} for side slope.

Solution: (1) From chart 12 given a D_{50} = 0.167 ft, the angle of repose θ = 36°

(2) From chart 13 given B/d = 5.0, the ratio of side shear to bottom shear, K_1 = 0.79

(3) From chart 14 given Z = 2 and θ = 36°, the tractive force ratio, K_2 = 0.65

(4) The required side slope D_{50} from equation 10 is,

$$D_{50} = \frac{0.79}{0.65}(2.0)$$

$$= 2.4 \text{ inches}$$

Example 7:

Determine the maximum allowable discharge for a median ditch lined with a good stand of Kentucky bluegrass (approximately 8 inches in height). The ditch has a depth of 3 feet from the roadway shoulder.

Given: S = 0.010 ft/ft
B = 4.0 ft
Z = 4

Worksheet for Flexible Lining Design

DESIGNER: ______________ DATE: ______________

PROJECT: Example Problems 4 & 5

STATION: ______________ TO STATION: ______________

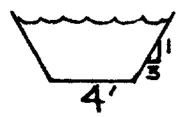
DRAINAGE AREA: ________ ACRES

DESIGN FLOW: Q ____ = ________ ft^3/sec

DESIGN FLOW FOR TEMPORARY LINING: Q 2 = 16 ft^3/sec

CHANNEL SLOPE (S) : .03 ft/ft

CHANNEL DESCRIPTION:



bend = 45°
R_c = 20′

LINING	Q	τ_p (1)	d_i (2)	R (3)	n (4)	d (5)	$\tau_d = \gamma dS$ (6)	REMARKS
Example 4								
Jute Net	16	.45	0.5-2	—	.022	.48	0.9	not acceptable
Curled Wood	16	1.55	"	—	.035	.60	1.12	OK
Example 5								
Synthetic Mat	16	2	0.5-2	—	.025	.52	.97	check bend
								$K_b = 1.6$
								$\tau_b = 1.79 < \tau_p$

OK

(1) Table 2
(2) For vegetation, estimate initial depth
For other liners, select range from table 3
(3) Vegetation only, chart 4 for trapezoidal channels
(4) For vegetation, charts 5-9
For other liners, table 3
(5) Normal deptn, chart 3 (d must be in d_i range)
(6) τ_d must be $\leq$ τ_p
(7) Check for steep side slopes and channel bends

Figure 21. Worksheet for Example Problems 4 and 5

Find: Maximum allowable discharge.

Solution: (1) From table 1, a good stand of Kentucky bluegrass is classified as retardance C. From table 2 the permissible shear stress,

$$\tau_p = 1.00 \text{ lb/ft}^2$$

Determine the allowable depth from equation 5, given $\tau_d = \tau_p$,

$$d = \tau_p/\gamma S$$

$$= \frac{1.00}{62.4 \times 0.010}$$

$$= 1.6 \text{ ft}$$

Note that the allowable depth is less than the depth of the ditch.

(2) Determine the flow area and hydraulic radius from chart 4, given $d/B = 0.40$,

$$A/Bd = 2.6$$
$$A = 16.6$$
$$R/D = 0.61$$
$$R = 0.98$$

(3) From chart 7: $n = 0.072$.

(4) Solving the Manning's equation with continuity (equation 9),

$$Q = \frac{1.49}{n} AR^{2/3}S^{1/2}$$

$$= \frac{1.49}{0.072} \times 16.6 \times 0.98^{2/3} \times 0.01^{1/2}$$

$$= 33.9 \text{ cfs}$$

Example 8:

Determine the need for a granular filter blanket.

Given: Riprap Gradation

$D_{85} = 1.3$ ft
$D_{50} = 0.66$ ft
$D_{15} = 0.33$ ft

Base Soil Gradation

$D_{85} = 1.5$ mm = 0.0049 ft
$D_{50} = 0.5$ mm = 0.0016 ft
$D_{15} = 0.167$ mm = 0.00055 ft

Find: Granular filter blanket requirement.

Solution: $\frac{D_{15} \text{ riprap}}{D_{85} \text{ base}} = \frac{0.33}{0.0049} = 67.4$ not less than 5

$\frac{D_{15} \text{ riprap}}{D_{15} \text{ base}} = \frac{0.33}{0.00055} = 600$ not less than 40

$\frac{D_{50} \text{ riprap}}{D_{50} \text{ base}} = \frac{0.66}{0.0016} = 412$ not less than 40

Since the relationships between riprap and base do not meet the recommended dimensional criteria, a filter blanket is required. First, determine the required dimensions of the filter with respect to the base material,

$\frac{D_{50} \text{ filter}}{D_{50} \text{ base}} < 40$, so $D_{50 \text{ filter}} < 40 \times 0.0016 = 0.064$ ft (20 mm)

$\frac{D_{15} \text{ filter}}{D_{15} \text{ base}} < 40$, so $D_{15 \text{ filter}} < 40 \times 0.00055 = 0.022$ ft (6.7 mm)

$\frac{D_{15} \text{ filter}}{D_{85} \text{ base}} < 5$, so $D_{15 \text{ filter}} < 5 \times 0.0049 = 0.024$ ft (7.3 mm)

$\frac{D_{15} \text{ filter}}{D_{15} \text{ base}} > 5$, so $D_{15 \text{ filter}} > 5 \times 0.00055 = 0.0028$ ft (0.83 mm)

Therefore, with respect to the base material, the filter must satisfy:

$$D_{50 \text{ filter}} < 0.064 \text{ ft}$$

$$0.0028 \text{ ft} < D_{15 \text{ filter}} < 0.22 \text{ ft}$$

Second, determine the required filter dimensions with respect to the riprap,

$\frac{D_{50} \text{ riprap}}{D_{50} \text{ filter}} < 40$, so $D_{50 \text{ filter}} > \frac{0.66}{40} = 0.016$ ft (4.9 mm)

$\frac{D_{15} \text{ riprap}}{15 \text{ filter}} < 40$, so $D_{15 \text{ filter}} > \frac{0.33}{40} = 0.0082$ ft (2.5 mm)

$$\frac{D_{15}\ \text{riprap}}{D_{85}\ \text{filter}} < 5, \text{ so } D_{85}\ \text{filter} > \frac{0.33}{5} = 0.066 \text{ ft (20 mm)}$$

$$\frac{D_{15}\ \text{riprap}}{D_{15}\ \text{filter}} > 5, \text{ so } D_{15}\ \text{filter} < \frac{0.33}{5} = 0.066 \text{ ft (20 mm)}$$

With respect to the riprap:

$$0.0082 \text{ ft} < \begin{array}{l} D_{50}\ \text{filter} > 0.016 \text{ ft} \\ D_{15}\ \text{filter} < 0.066 \text{ ft} \\ D_{85}\ \text{filter} > 0.066 \text{ ft} \end{array}$$

Combining:

$0.0082 \text{ ft} < D_{15}\ \text{filter} < 0.022 \text{ ft}$ ($2.5 \text{ mm} < D_{15}\ \text{filter} < 6.7 \text{ mm}$)
$0.016 \text{ ft} < D_{50}\ \text{filter} < 0.064 \text{ ft}$ ($4.9 \text{ mm} < D_{50}\ \text{filter} < 19.5 \text{ mm}$)
$D_{85}\ \text{filter} > 0.066 \text{ ft}$ ($D_{85}\ \text{filter} > 20.0 \text{ mm}$)

The gradation requirements for the resulting granular filter blanket specifications are illustrated in figure 22.

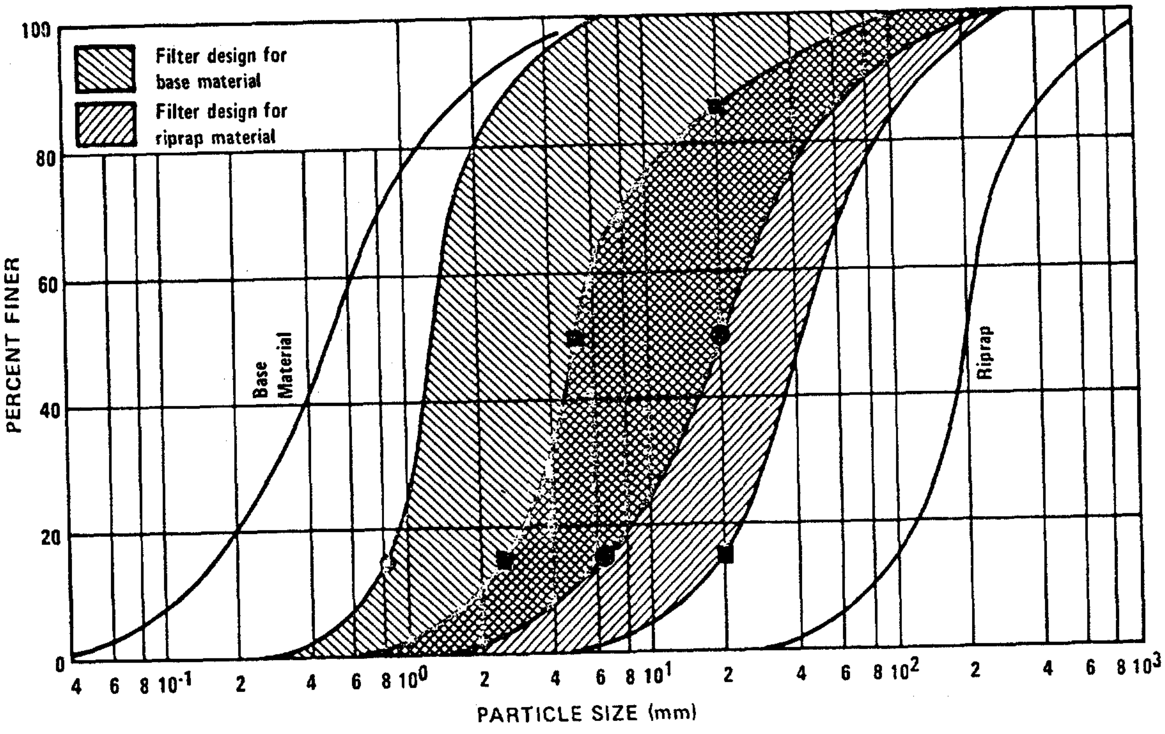


Figure 22. Gradations of Granular Filter Blanket for Example 8.

Worksheet for Flexible Lining Design

DESIGNER: ______________________ DATE: ______________________

PROJECT: ____

STATION: ______________________ TO STATION: ______________________

DRAINAGE AREA: __________ ACRES

DESIGN FLOW: Q ______ = __________ ft^3/sec

DESIGN FLOW FOR TEMPORARY LINING: Q _____ = ________ ft^3/sec

CHANNEL SLOPE (S) : _______ ft/ft

CHANNEL DESCRIPTION:

LINING	Q	τ_p (1)	d_i (2)	R (3)	n (4)	d (5)	$\tau_d=\gamma dS$ (6)	REMARKS

(1) Table 2
(2) For vegetation, estimate initial depth
For other liners, select range from table 3
(3) Vegetation only, chart 4 for trapezoidal channels
(4) For vegetation, charts 5-9
For other liners, table 3
(5) Normal depth, chart 3 (d must be in d_i range)
(6) τ_d must be $\leq$ τ_p
(7) Check for steep side slopes and channel bends

Figure 23. Worksheet for Flexible Lining Design

Table 1. Classification of Vegetal Covers as to Degree of Retardance. (4)

Retardance Class	Cover	Condition
A	Weeping lovegrass	Excellent stand, tall (average 30") (76 cm)
	Yellow bluestem Ischaemum	Excellent stand, tall (average 36") (91 cm)
B	Kudzu	Very dense growth, uncut
	Bermuda grass	Good stand, tall (average 12") (30 cm)
	Native grass mixture (little bluestem, bluestem, blue gamma, and other long and short midwest grasses).........	Good stand, unmowed
	Weeping lovegrass	Good stand, tall (average 24") (61 cm)
	Lespedeza sericea	Good stand, not woody, tall (average 19") (48 cm)
	Alfalfa	Good stand, uncut (average 11") (28 cm)
	Weeping lovegrass	Good stand, unmowed (average 13") (33 cm)
	Kudzu	Dense growth, uncut
	Blue gamma	Good stand, uncut (average 13") (28 cm)
C	Crabgrass	Fair stand, uncut (10 to 48") (25 to 120 cm)
	Bermuda grass	Good stand, mowed (average 6") (15 cm)
	Common lespedeza	Good stand, uncut (average 11") (28 cm)
	Grass-legume mixture--summer (orchard grass, redtop, Italian ryegrass, and common lespedeza)....	Good stand, uncut (6 to 8 inches) (15 to 20 cm)
	Centipedegrass.............	Very dense cover (average 6 inches) (15 cm)
	Kentucky bluegrass.........	Good stand, headed (6 to 12 inches (15 to 30 cm)
D	Bermuda grass..............	Good stand, cut to 2.5-inch height (6 cm)
	Common lespedeza	Excellent stand, uncut (average 4.5") (11 cm)
	Buffalo grass	Good stand, uncut (3 to 6 inches (8 to 15 cm)
	Grass-legume mixture--fall, spring (orchard grass, redtop, Italian ryegrass, and common lespedeza)...............	Good stand, uncut (4 to 5 inches) (10 to 13 cm)
	Lespedeza sericea	After cutting to 2-inch height (5 cm) Very good stand before cutting
E	Bermuda grass	Good stand, cut to 1.5 inch height (4 cm)
	Bermuda grass	Burned stubble

NOTE: Covers classified have been tested in experimental channels. Covers were green and generally uniform.

Table 2. Permissible Shear Stresses for Lining Materials.

Lining Category	Lining Type	Permissible Unit Shear Stress[1] (lb/ft^2)	Permissible Unit Shear Stress[1] (Kg/m^2)
Temporary*	Woven Paper Net	0.15	0.73
	Jute Net	0.45	2.20
	Fiberglass Roving:		
	Single	0.60	2.93
	Double	0.85	4.15
	Straw with Net	1.45	7.08
	Curled Wood Mat	1.55	7.57
	Synthetic Mat	2.00	9.76
Vegetative	Class A	3.70	18.06
	Class B	2.10	10.25
	Class C	1.00	4.88
	Class D	0.60	2.93
	Class E	0.35	1.71
Gravel Riprap	1-inch	0.33	1.61
	2-inch	0.67	3.22
Rock Riprap	6-inch	2.00	9.76
	12-inch	4.00	19.52
Bare Soil	Non-cohesive	See Chart 1	
	Cohesive	See Chart 2	

[1]Based on data in (5, 8, 13, 14, 15).

*Some "temporary" linings become permanent when buried.

Table 3. Manning's Roughness Coefficients.

Lining Category	Lining Type	n - value[1] Depth Ranges 0-0.5 ft (0-15 cm)	0.5-2.0 ft (15-60 cm)	>2.0 ft (> 60 cm)
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
	Fiberglass 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	1-inch (2.5-cm) D_{50}	0.044	0.033	0.030
	2-inch (5-cm) D_{50}	0.066	0.041	0.034
Rock Riprap				

Riprap n-values

D_{50}	R= 0-0.5 ft	R=0.5-2 ft	R≥2 ft
1"	Blodgett @ 0.25'	Blodgett @ 1 ft	Blodgett @ 5'
2"	*Blodgett @ 0.25'	Blodgett @ 1 ft	Blodgett @ 5'
6"	*Blodgett @ 0.5'	Blodgett @ 1 ft	Strickler @ 5'
12"	—	Blodgett @ 2 ft (0.077)	Strickler @ 5'

* $R/D_{50} \leq 1.5$ (lowest limit, out of range)

Blodgett = Ref. 19 (See App. B)

Strickler = Anderson Ref. 8.

[1]Based on data

Note: Values 1 ranges. depth.

*Some "temporar

Chart 1

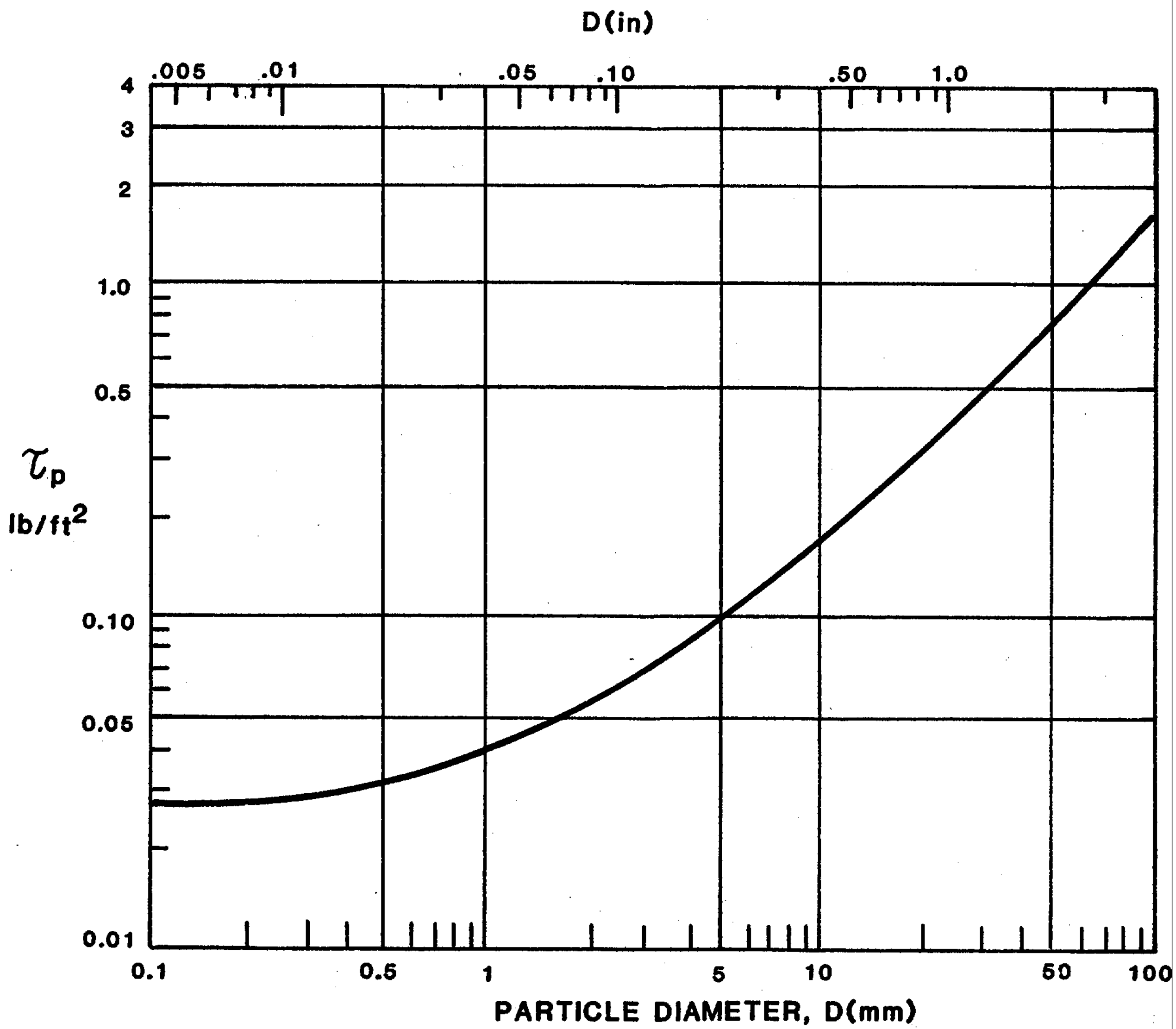


Chart 1. Permissible shear stress for non-cohesive soils. (after 15)

Chart 2

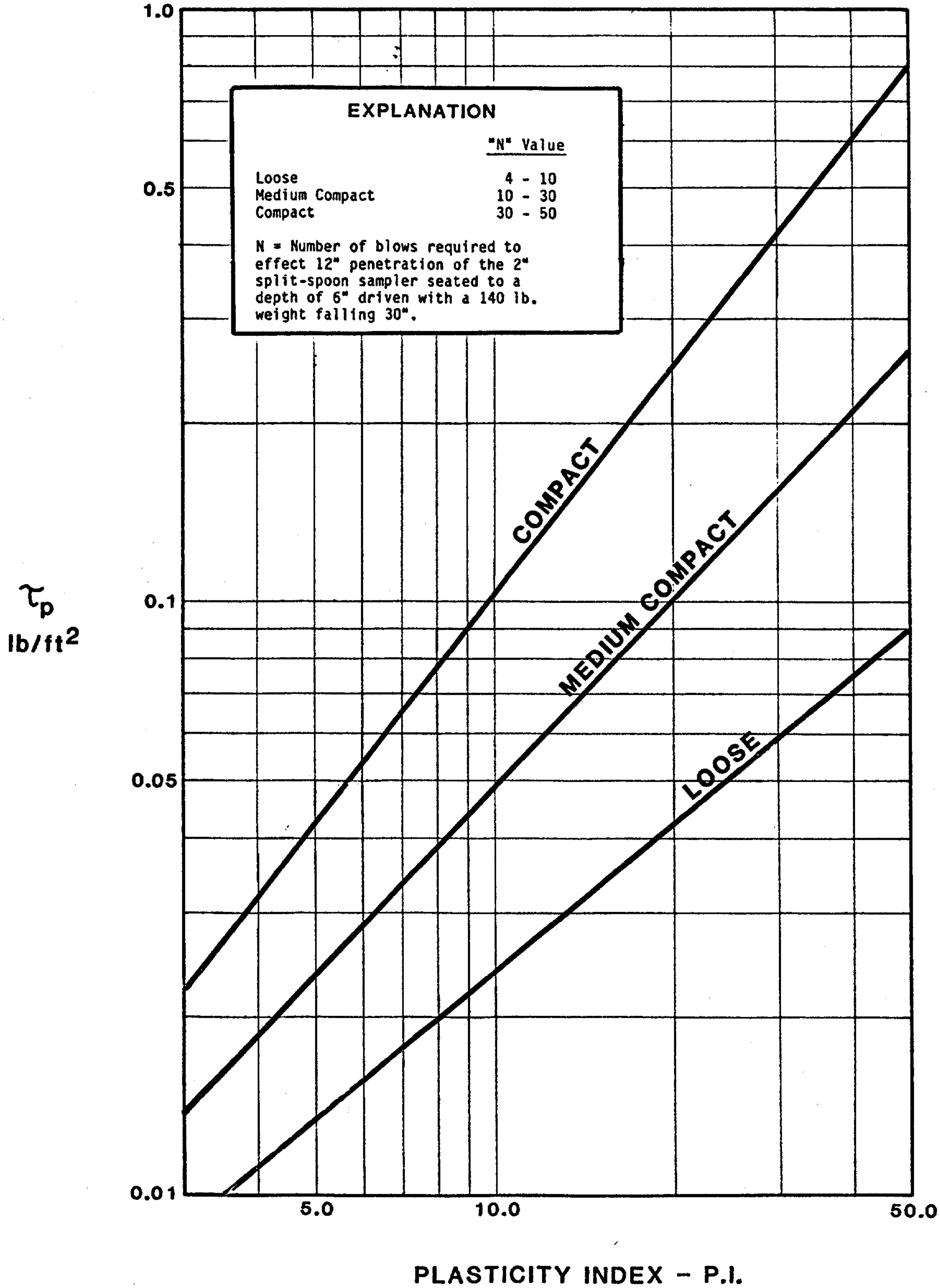


Chart 2. Permissible shear stress for cohesive soils. (after 16)

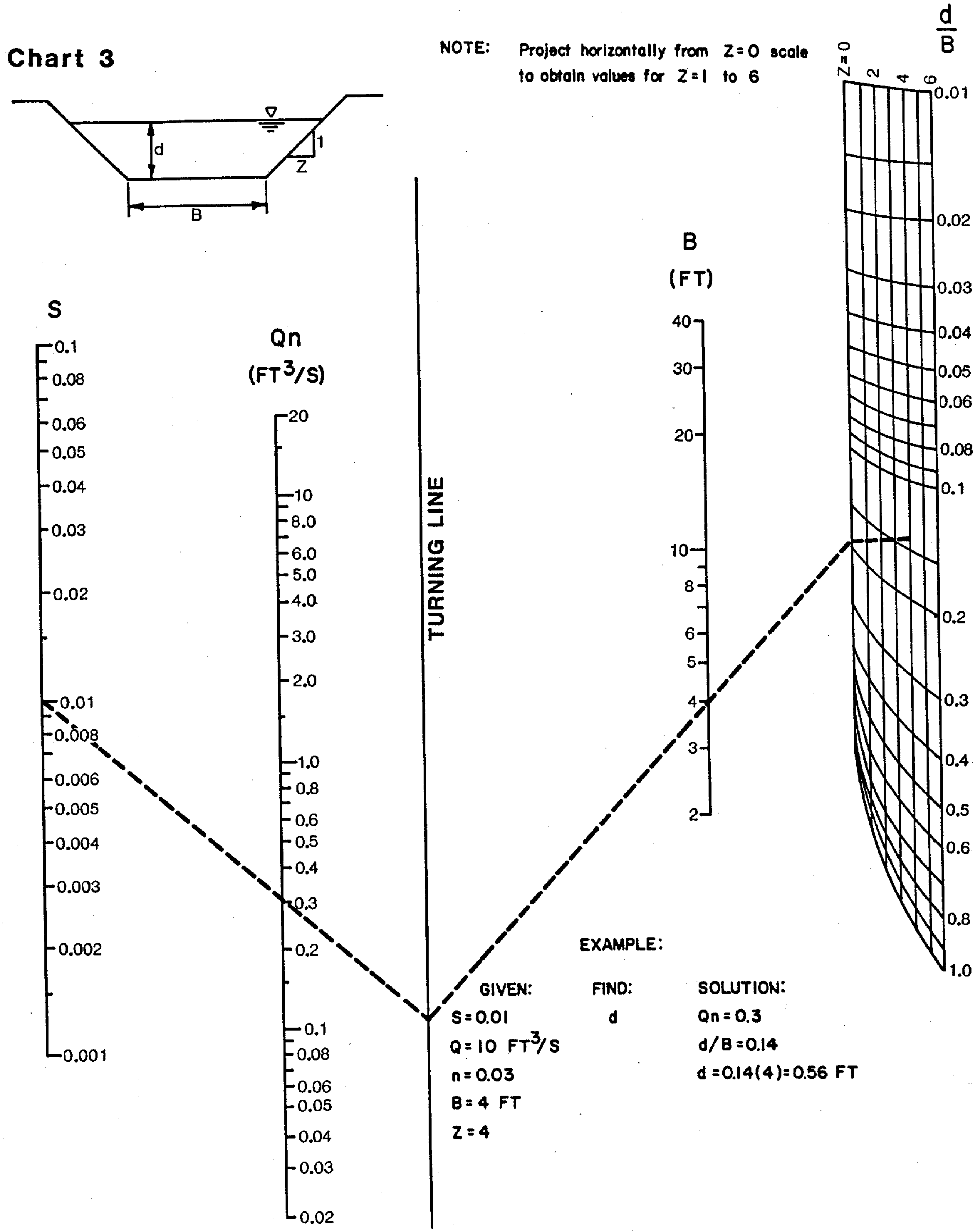


Chart 3. Solution of Manning's equation for channels of various side slopes. (after 17)

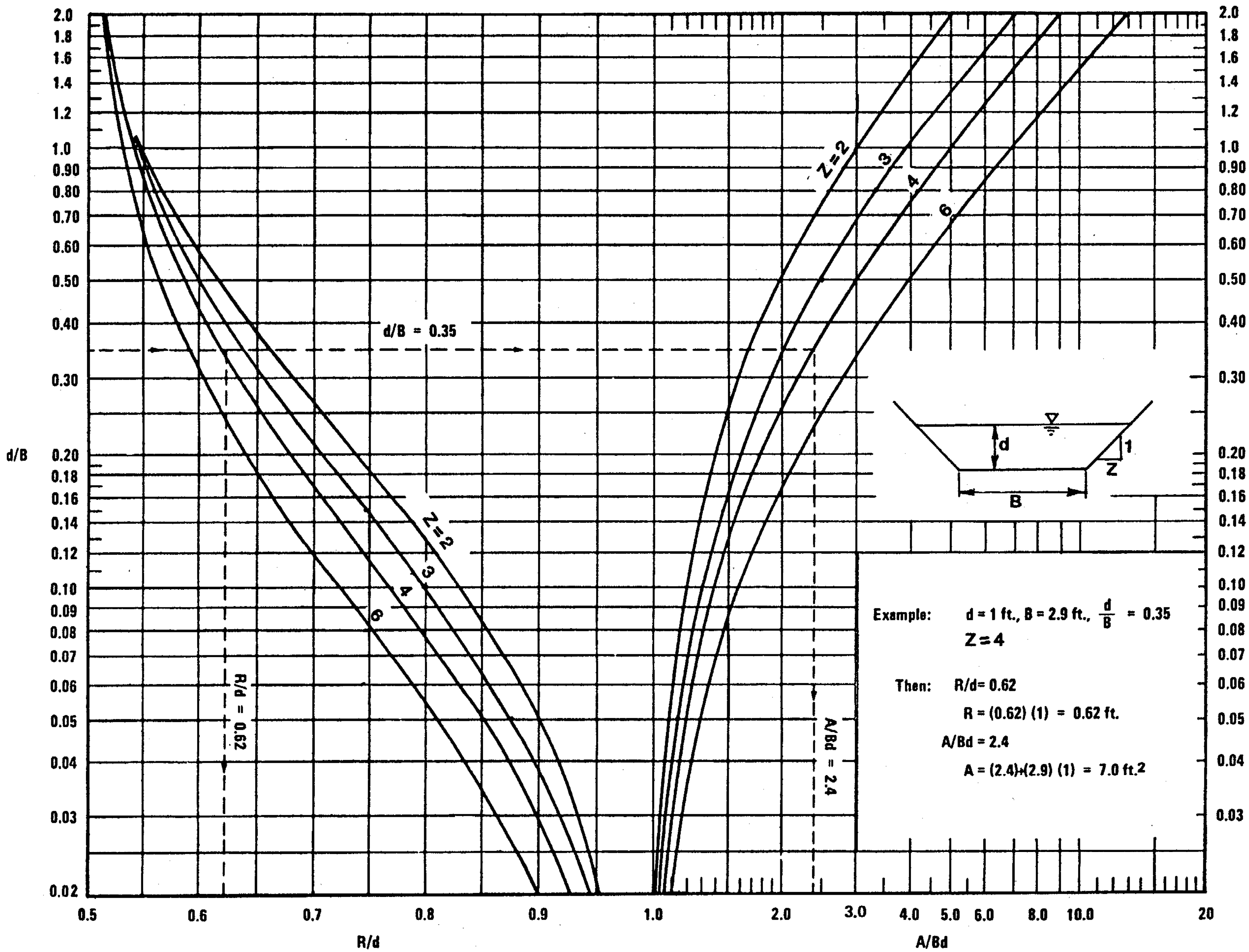


Chart 4. Geometric design chart for trapezoidal channels.

Chart 5

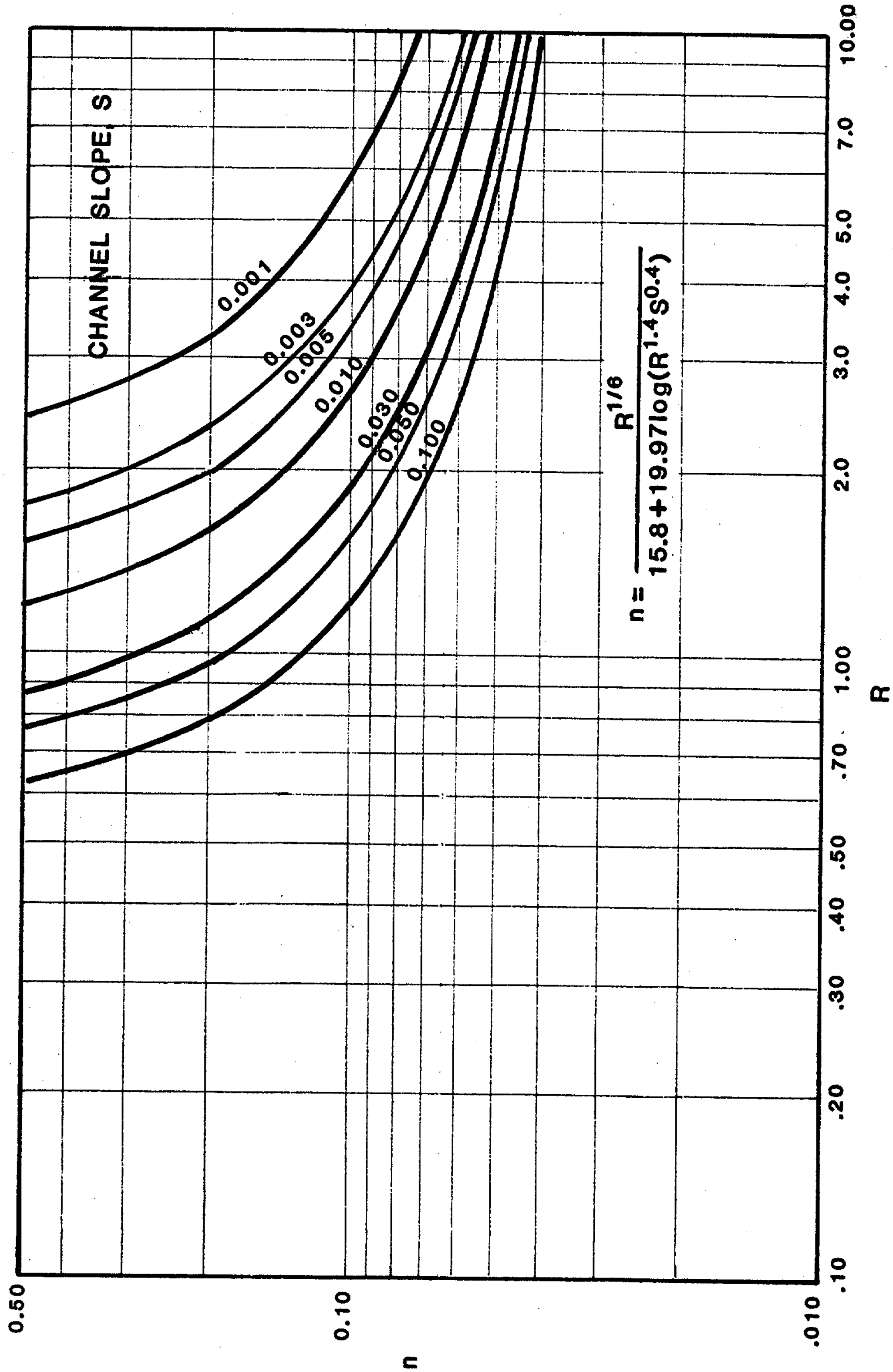


Chart 5. Manning's n versus hydraulic radius, R, for class A vegetation. (after 5)

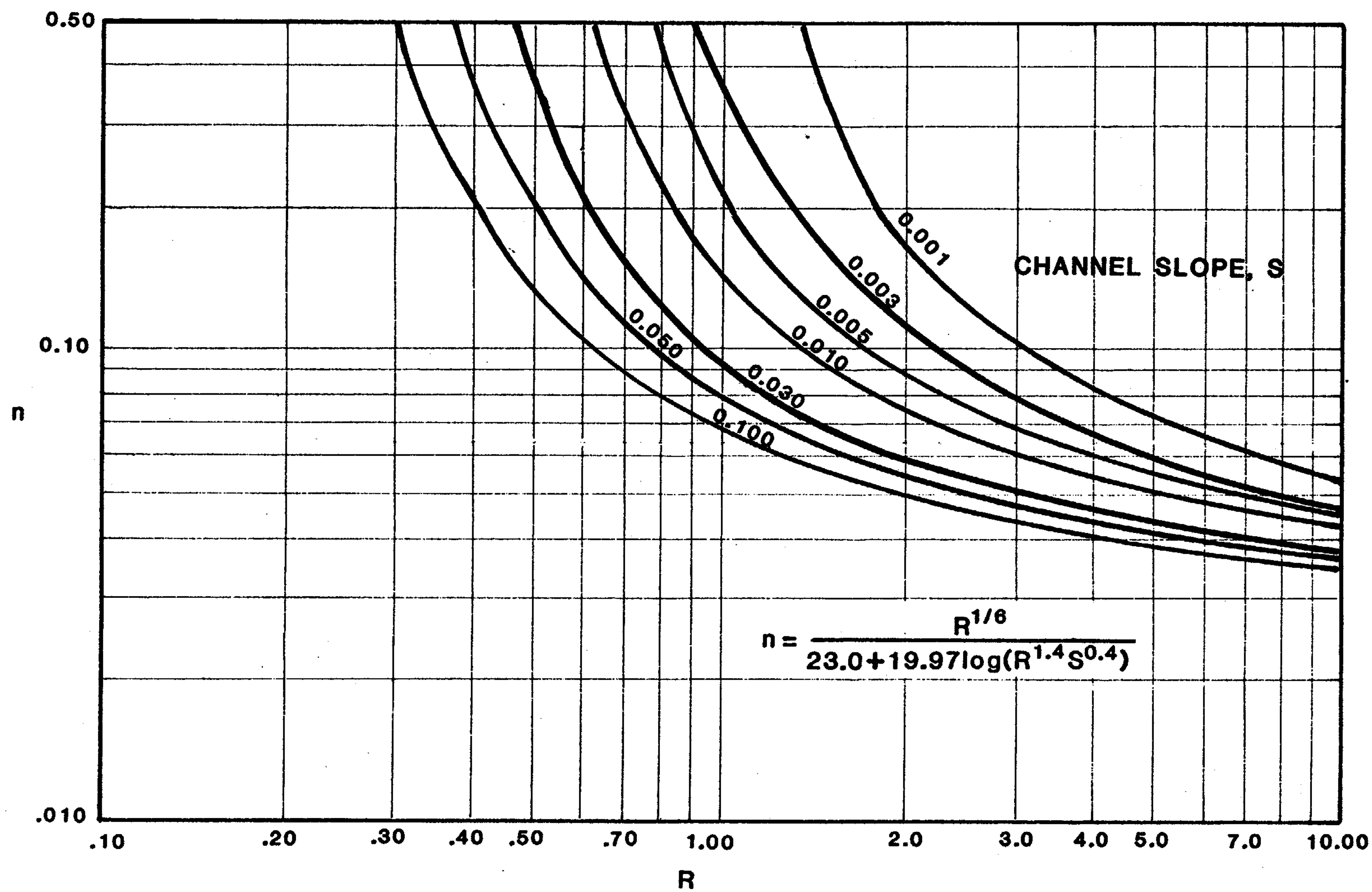


Chart 6. Manning's n versus hydraulic radius, R, for class B vegetation. (after 5)

Chart 7

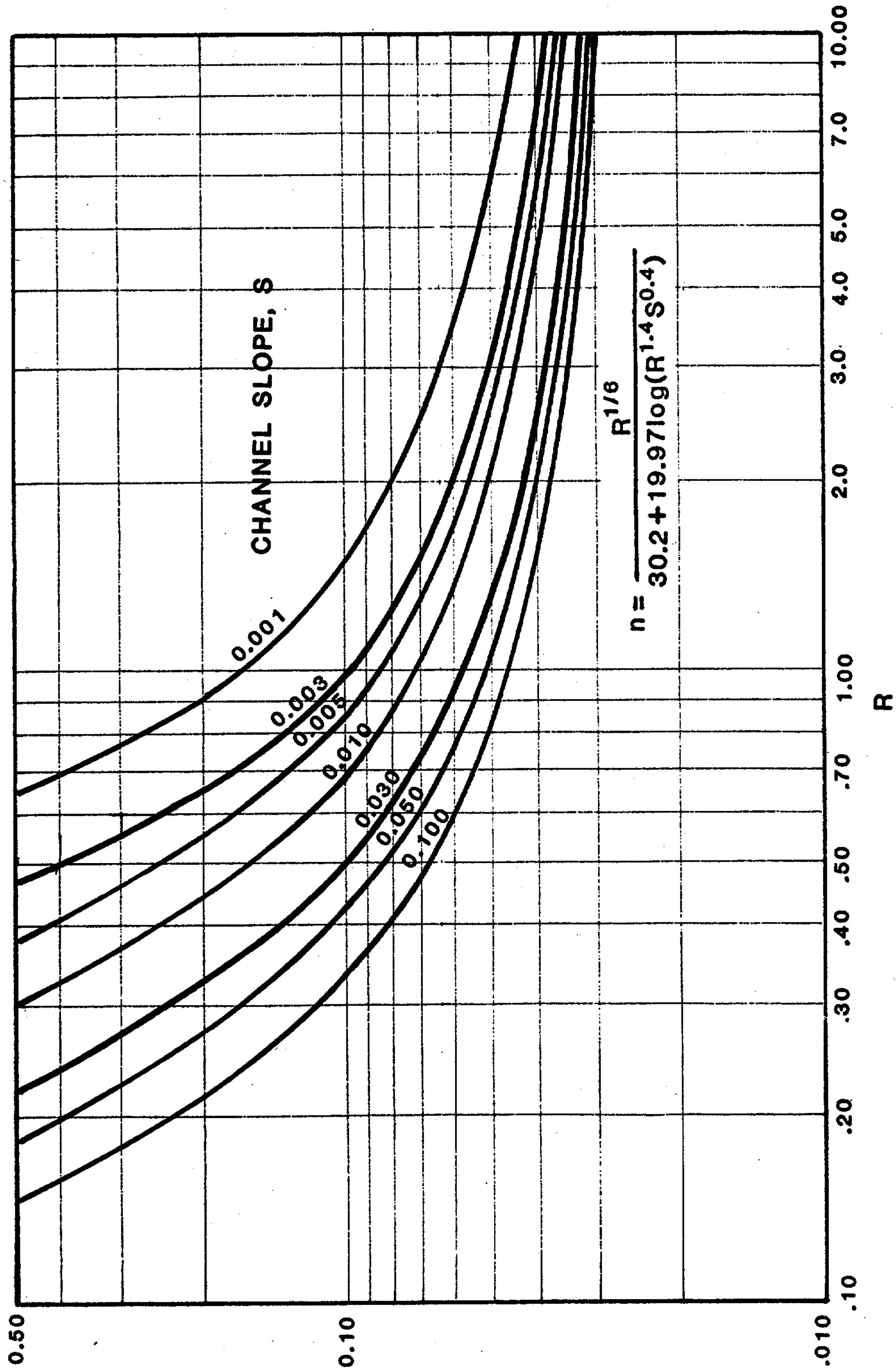


Chart 7. Manning's n versus hydraulic radius, R, for class C vegetation. (after 5)

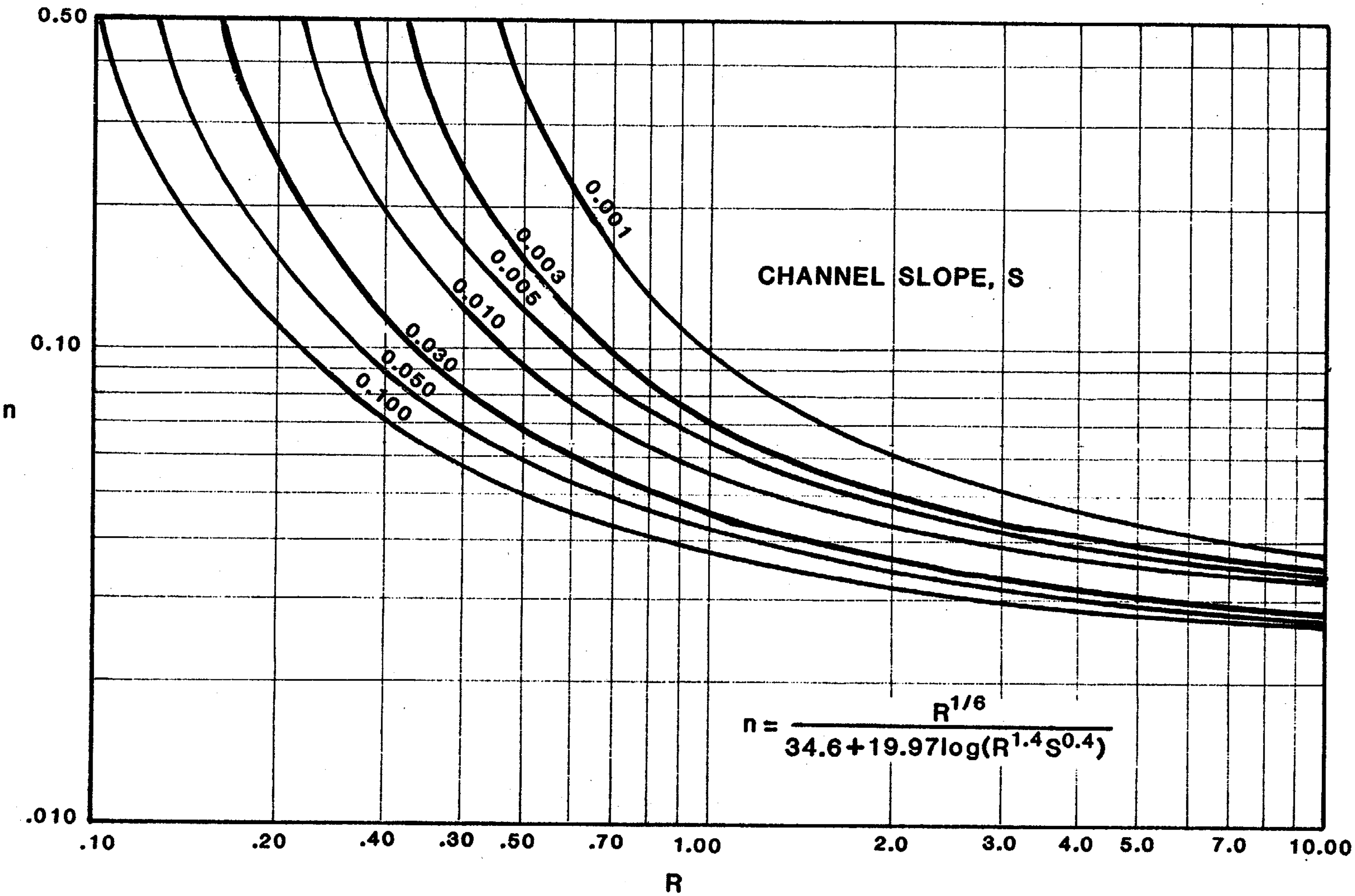


Chart 8

Chart 8. Manning's n versus hydraulic radius, R, for class D vegetation. (after 5)

Chart 9

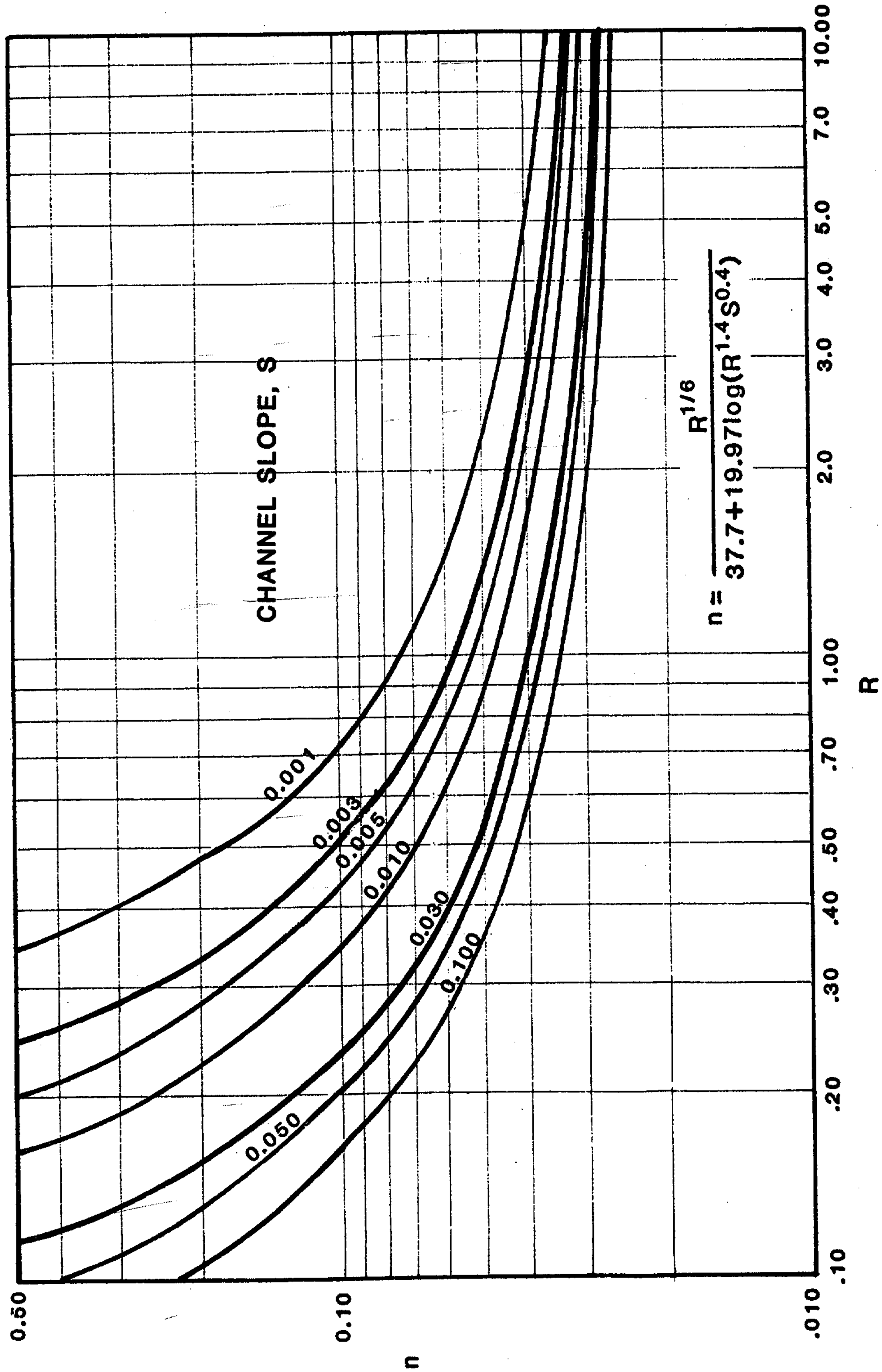


Chart 9. Manning's n versus hydraulic radius, R, for class E vegetation. (after 5)

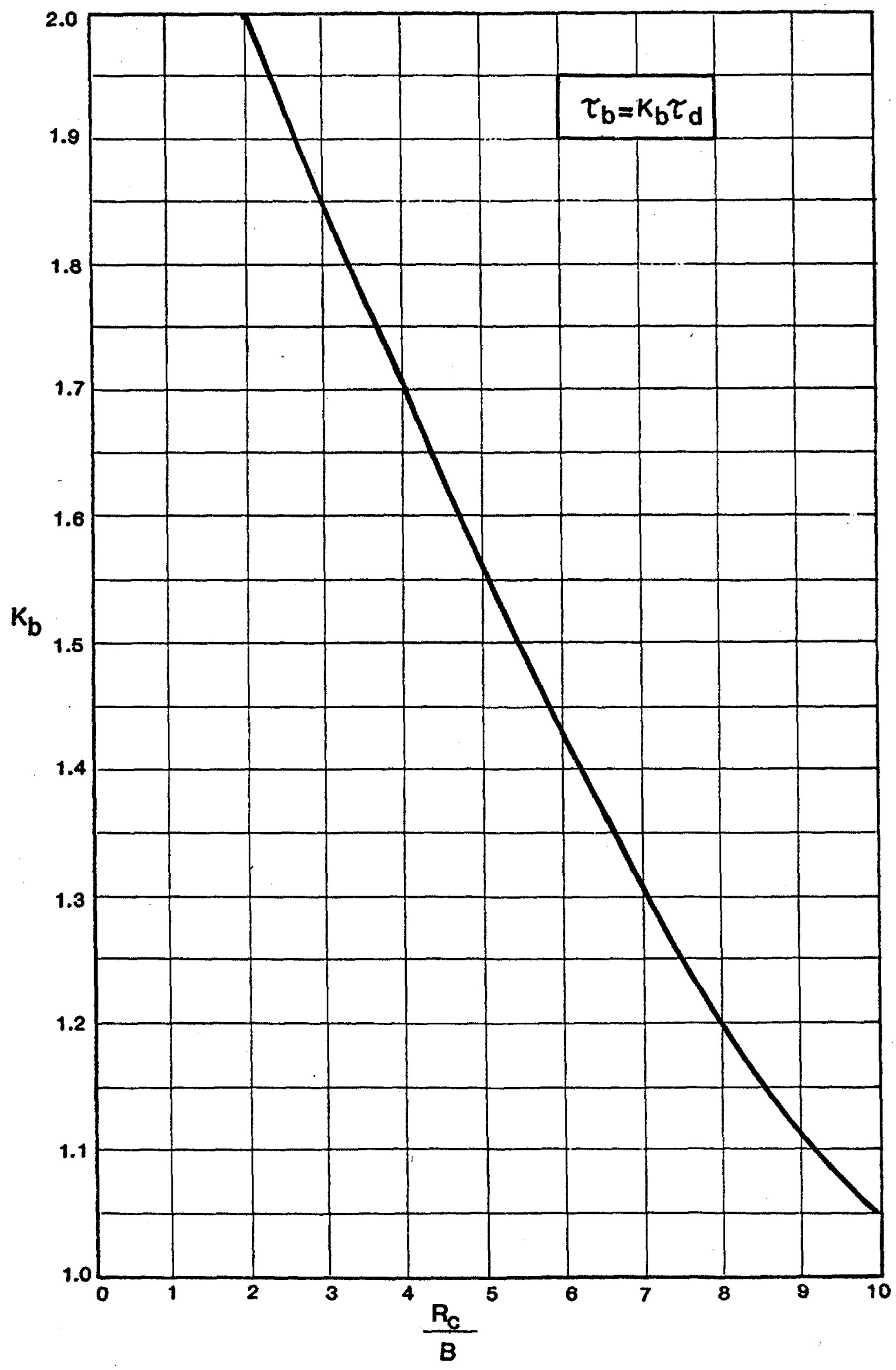


Chart 10. K_b factor for maximum shear stress on channel bends.(12)

Chart 11

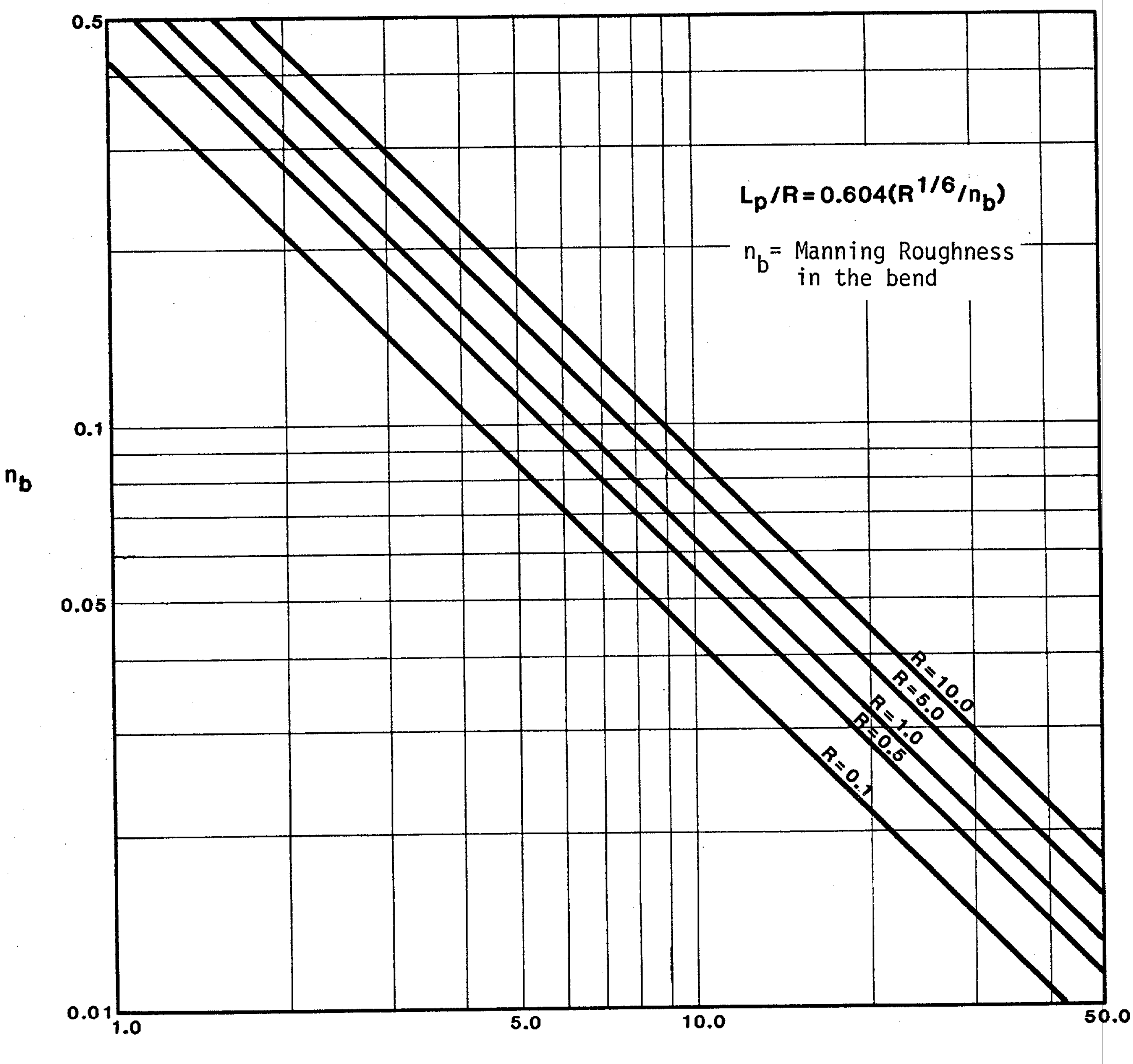


Chart 11. Protection length, Lp, downstream of channel bend. (11)

Chart 12

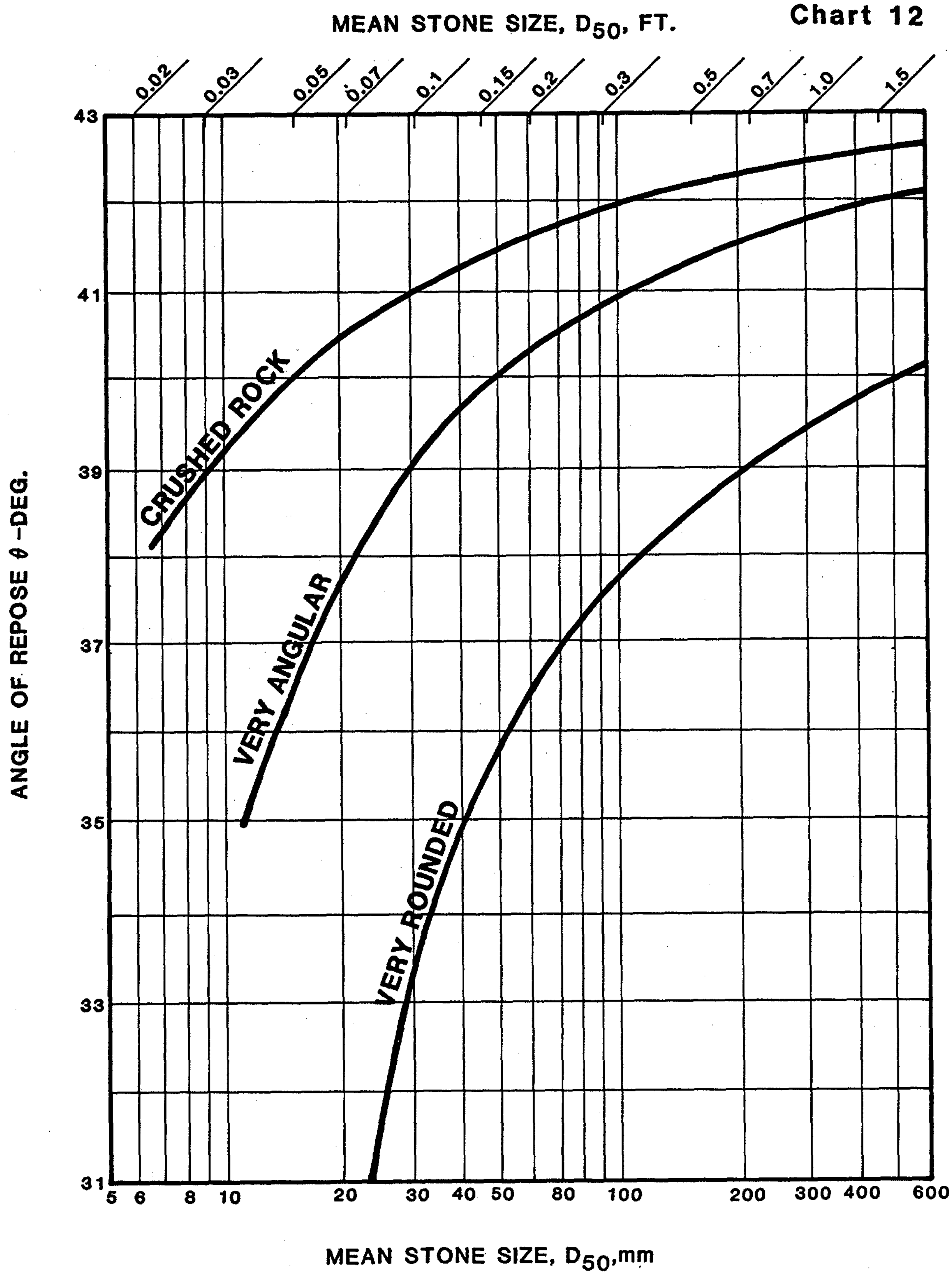


Chart 12. Angle of repose of riprap in terms of mean size and shape of stone.

Chart 13

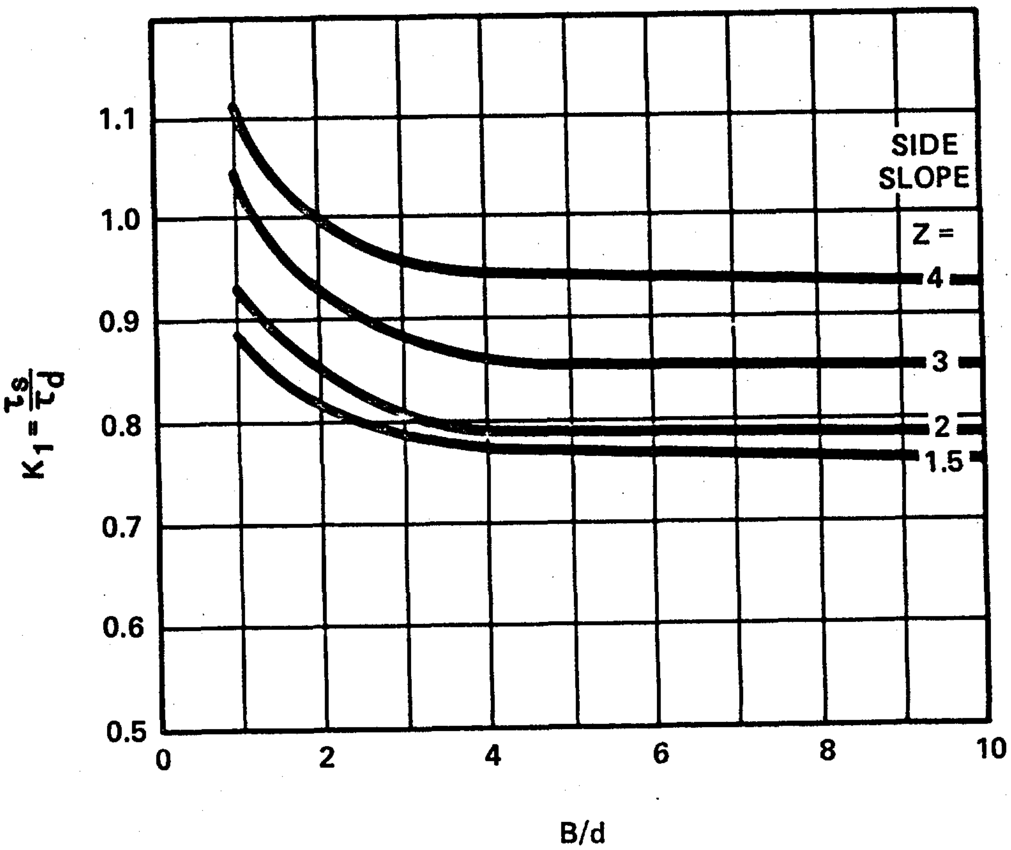


Chart 13. Channel side shear stress to bottom shear stress ratio, K_1.(8)

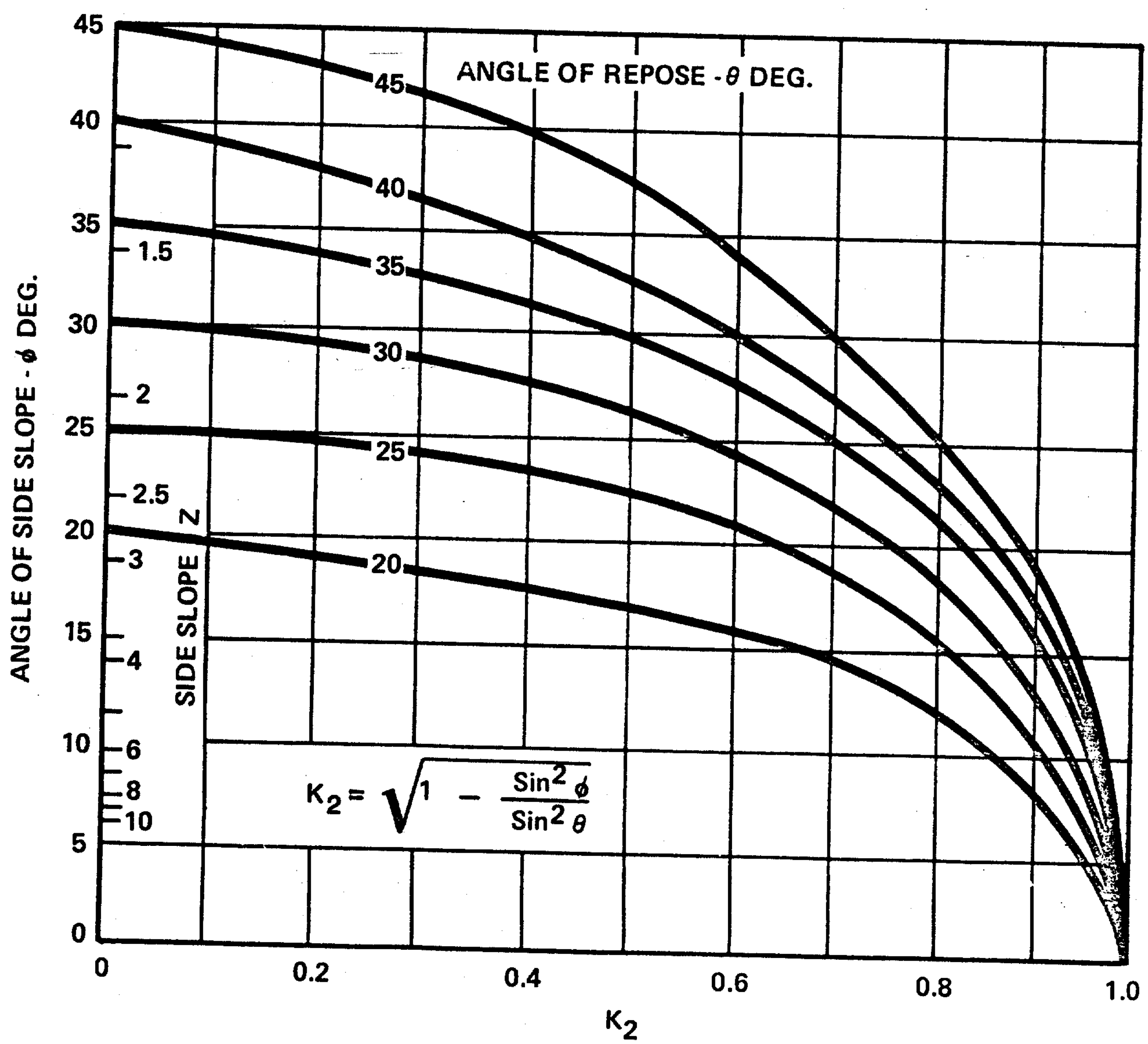


Chart 14. Tractive force ratio, K_2.(8)

V. STEEP GRADIENT CHANNEL DESIGN

Achieving channel stability on steep gradients usually requires some type of channel lining except where the channels can be constructed in durable bedrock. This section outlines the design of two types of flexible channel linings for steep gradients, riprap, and gabion mattress. Because of the additional forces acting on riprap, results obtained using the previous design procedure should be compared to the steep gradient procedures when channel gradients approach 10 percent.

Rigid channel linings may be a more cost-effective alternative in the case of steep slope conditions. The size of riprap and gabion linings increases quickly as discharge and channel gradient increase. The decision to select a rigid or flexible lining may be based on other site conditions, such as foundation and maintenance requirements for the steep slope channel lining.

Steep Slope Design

Riprap stability on a steep slope depends on forces acting on an individual stone making up the riprap. The primary forces include the average weight of the stones and the lift and drag forces induced by the flow on the stones. On a steep slope, the weight of a stone has a significant component in the direction of flow (see figures in appendix C). Because of this force, a stone within the riprap will tend to move in the flow direction more easily than the same size stone on a mild gradient. Hence, for a given discharge, steep slope channels require larger stones to compensate for larger forces in the flow direction and higher shear stress. The riprap design procedure is based on the factor of safety method for riprap design, using a safety factor of 1.5. A description of the factor of safety method and the assumptions made in developing the design charts is presented in appendix C.

Gabion mattress stability on a steep slope is similar to that of riprap but because the stones are bound by wire mesh, they tend to act as a single unit. Movement of stones within a gabion is negligible. This permits use of smaller stone sizes compared to those required for loose riprap. Of course the stability of gabions depend on the integrity of the wire mesh. In streams with high sediment concentrations or with rocks moving along the bed of the channel, the wire mesh may be abraded and eventually fail. Under these conditions the gabion will no longer behave as a single unit but rather as individual stones. Applications of gabion mattresses and baskets under these conditions should be avoided. A worksheet is provided at the end of this chapter (figure 25) for carrying out design procedures in this chapter.

Other Considerations for Steep Slope Design

Channel Alignment and Freeboard. Bends should be avoided on steep gradient channels. A design requiring a bend in a steep channel should be reevaluated to eliminate the bend or designed using a culvert.

Extent of riprap or gabions on a steep gradient must be sufficient to protect transition regions of the channel both above and below the steep gradient section. The transition from a steep gradient to a culvert should allow for slight movement of riprap or slumping of a gabion mattress.

Riprap or gabions should be placed flush with the invert of a culvert. The break between the steep slope and culvert entrance should equal three to five times the mean rock diameter (or mattress thickness if gabions are used). The transition from a steep gradient channel to a mild gradient channel may require an energy dissipation structure such as a plunge pool. The transition from a mild gradient to a steep gradient should be protected against local scour upstream of the transition for a distance of approximately five times the uniform depth of flow in the downstream channel. (7)

Freeboard should equal the mean depth of flow, since wave height will reach approximately twice the mean depth. This freeboard height should be used for both temporary and permanent channel installations.

Gradation, Thickness, and Filter Requirements. Riprap gradation, thickness and filter requirements are the same as those for mild slopes. It is important to note that riprap thickness is measured normal to steep channel gradients. Also, the rock gradation used in gabion mattress must be such that larger stones do not protrude outside the mattress and smaller stones are retained by the wire mesh.

Design Procedures

A stepwise guideline with complete references to charts and figures is given for steep slope riprap and steep slope gabion mattress designs.

STEEP SLOPE RIPRAP DESIGN PROCEDURE

1. For given discharge and channel slope, enter chart 15 to 18 for correct channel shape and determine the flow depth and mean riprap size. For channel widths not given in charts 15 to 18, interpolate between charts to find the correct value. For channel bottom widths in excess of 6 feet, use the more detailed design procedures in Appendix C.

2. To determine flow depth and riprap size for side slopes greater than 3:1, use the following steps:

   a. Find the flow depth using the formula:

$$d = \frac{A_3}{A_z} d_i \qquad (14a)$$

   where values of the A_3/A_z ratio are found from table 4 (the subscript refers to the side slope z-value) and d_i is the flow depth from the design charts.

   b. Find the riprap size using the formula:

$$D_{50} = \frac{d}{d_i} D_{50i} \qquad (14b)$$

   where d_i and D_{50i} are values from the design charts.

STEEP SLOPE GABION MATTRESS DESIGN

1. For given discharge and channel slope, enter chart 19 to 22 for correct channel shape and determine flow depth. For intermediate channel widths or side slopes, follow the interpolation procedures given in steep slope riprap design procedure. For channel bottom widths in excess of 6 feet, see Appendix C.

2. Determine the permissible shear stress for the gabion mattress rock fill size from Chart 23.

3. Determine the permissible shear stress for thickness of the gabion mattress from Chart 24.

4. The design permissible shear stress, τ_p, will be the larger of the two shear stress values determined in steps 2 and 3.

5. Calculate the maximum shear stress acting on the channel, τ_d.

$$\tau_d = \gamma d S \qquad (5)$$

If $\tau_d > \tau_p$, the gabion mattress analyzed is not acceptable.

Example Problems

Example 9:

Determine the mean riprap size and flow depth for a steep gradient channel.

Given: $Q = 20\ ft^3/sec$
$S = 0.15$ ft/ft
$B = 2$ ft
$Z = 3$

Find: Flow depth and mean riprap size.

Solution: Entering into chart 16, given $Q = 20\ ft^3/sec$ and $S = 0.15$ ft/ft:

$d = 0.75$ ft
$D_{50} = 0.9$ ft

Example 10:

Determine the mean riprap size and flow depth for a steep gradient channel.

Given: $Q = 30\ ft^3/sec$
$S = 0.15$ ft/ft
$B = 3.0$ ft
$Z = 3$

Find: Flow depth and mean riprap size.

Solution: (1) Enter into chart 16, for B = 2.0 given $Q = 30\ ft^3/sec$ and $S = 0.15$ ft/ft,

$d = 0.92$ ft
$D_{50} = 1.1$ ft

Enter into chart 17, for B = 4.0 given $Q = 30\ ft^3/sec$ and $S = 0.15$ ft/ft,

$d = 0.70$ ft
$D_{50} = 0.9$ ft

(2) Interpolating for a 3.0 ft bottom width gives,

$d = 0.81$ ft
$D_{50} = 1.0$ ft

Example 11:

Determine the mean riprap size and flow depth for a steep gradient channel.

Given: $Q = 20\ ft^3/sec$
$S = 0.20$ ft/ft
$B = 2.0$ ft
$Z = 4$

Find: Flow depth and mean riprap size.

Solution: (1) Enter into chart 16, given $Q = 20\ ft^3/sec$ and $S = 0.20$ ft/ft,

$d = 0.70$ ft
$D_{50} = 1.2$ ft

(2) Enter into table 4, given $d/B = 0.35$ and $Z = 4$:

$A_3/A_4 = 0.85$

Actual flow depth for 4:1 side slope,

$d = 0.85 \times 0.70$
$= 0.60$ ft

Actual riprap size for 4:1 side slope,

$D_{50} = (0.60/0.70) \times 1.2$
$= 1.0$ ft

Use of the worksheet for this problem is illustrated in figure 24.

Example 12:

Determine the flow depth and required thickness of a gabion mattress lining.

Given: $Q = 10\ ft^3/sec$
$S = 0.12\ ft/ft$
$B = 2.0\ ft$
$Z = 3$
$D_{50} = 0.5\ ft$

Find: Flow depth and gabion mattress thickness.

Solution: (1) From chart 20 given $Q = 10\ ft^3/sec$ and $S = 0.12\ ft/ft$,

$$d = 0.55\ ft$$

(2) Calculate the maximum shear stress from equation 5,

$$\tau_d = \gamma dS = 62.4 \times 0.55 \times 0.12 = 4.1\ lb/ft^2$$

(3) Permissible shear stress for rockfill size from chart 23,

$$\tau_p = 3.8\ lb/ft^2$$

Permissible shear stress for a 0.75-foot mattress thickness from chart 24,

$$\tau_p = 4.5\ lb/ft^2$$

Use $\tau_p = 4.5\ lb/ft^2$ for design.

(4) The gabion mattress 0.75-foot thick is acceptable, since

$$\tau_d = 4.1 < 4.5 = \tau_p$$

Use of the worksheet for this problem is illustrated in figure 24.

Worksheet for Steep Slope Channel Design

DESIGNER: ____________ DATE: ____________

PROJECT: Example Problems 11 & 12

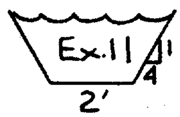
STATION: ____________ TO STATION: ____________

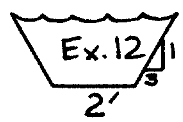
DRAINAGE AREA: ________ ACRES

DESIGN FLOW: Q ______ = 20 ft³/sec (10 for Ex. 12)

CHANNEL SLOPE (S) : 0.20 ft/ft (0.12 for Ex. 12)

CHANNEL DESCRIPTION:





RIPRAP (Example 11)

d_i (1)	D_{50i} (1)	z (2)	$A3/A_z$ (3)	d (4)	D_{50} (5)	REMARKS
0.7	1.2	4	.85	0.6	1.0	

GABION (Example 12)

Rock Fill Size	d_i (6)	z (2)	$A3/A_z$ (3)	d (4)	τ_p Rock (7)	Mattress Thickness	τ_p Mattress (8)	τ_p (9)	$\tau_d = \gamma dS$ (10)
0.5′	.55	3	1	.55	3.8	9″	4.5	4.5	4.1
									OK

(1) Charts 15-18
(2) side slope (z:1)
(3) Table 4
(4) $d = (A_3/A_z)d_i$

(5) $D_{50} = (d/d_i)D_{50i}$

(6) Charts 19-22
(7) Chart 23
(8) Chart 24
(9) τ_p = the larger of (7) or (8)
(10) τ_d must be $\leq \tau_p$

Figure 24. Worksheet for Example Problems 11 and 12

Worksheet for Steep Slope Channel Design

DESIGNER: ______________________ DATE: ______________________

PROJECT: ____

STATION: ______________________ TO STATION: ______________________

DRAINAGE AREA: __________ ACRES

DESIGN FLOW: Q ______ = __________ ft^3/sec

CHANNEL SLOPE (S) : _______ ft/ft

CHANNEL DESCRIPTION:

RIPRAP

d_i (1)	D_{50i} (1)	z (2)	$A3/A_z$ (3)	d (4)	D_{50} (5)	REMARKS

GABION

Rock Fill Size	d_i (6)	z (2)	$A3/A_z$ (3)	d (4)	τ_p Rock (7)	Mattress Thickness	τ_p Mattress (8)	τ_p (9)	$\tau_d = \gamma dS$ (10)

(1) Charts 15-18
(2) side slope (z:1)
(3) Table 4
(4) $d = (A_3/A_z)d_i$

(5) $D_{50} = (d/d_i)D_{50i}$

(6) Charts 19-22
(7) Chart 23
(8) Chart 24
(9) τ_p = the larger of (7) or (8)
(10) τ_d must be $\leq \tau_p$

Figure 25. Worksheet for Steep Slope Channel Design

Table 4. Values of A_3/A_Z for Selected Side Slopes and Depth to Bottom Width Ratios.[1]

d/B	A_3/A_Z 2:1	3:1	4:1	5:1	6:1
0.10	1.083	1.000	0.928	0.866	0.812
0.20	1.142	1.000	0.888	0.800	0.727
0.30	1.187	1.000	0.853	0.760	0.678
0.40	1.222	1.000	0.846	0.733	0.647
0.50	1.250	1.000	0.833	0.714	0.625
0.60	1.272	1.000	0.823	0.700	0.608
0.70	1.291	1.000	0.815	0.688	0.596
0.80	1.307	1.000	0.809	0.680	0.586
0.90	1.321	1.000	0.804	0.672	0.578
1.00	1.333	1.000	0.800	0.666	0.571
1.10	1.343	1.000	0.796	0.661	0.565
1.20	1.352	1.000	0.793	0.657	0.561
1.30	1.361	1.000	0.790	0.653	0.556
1.40	1.368	1.000	0.787	0.650	0.553
1.50	1.378	1.000	0.785	0.647	0.550
1.60	1.381	1.000	0.783	0.644	0.547
1.70	1.386	1.000	0.782	0.642	0.544
1.80	1.391	1.000	0.780	0.640	0.542
1.90	1.395	1.000	0.779	0.638	0.540
2.00	1.400	1.000	0.777	0.636	0.538

[1] Based on the following equation:

$$A_3/A_Z = \frac{1 + 3(d/B)}{1 + Z(d/B)}$$

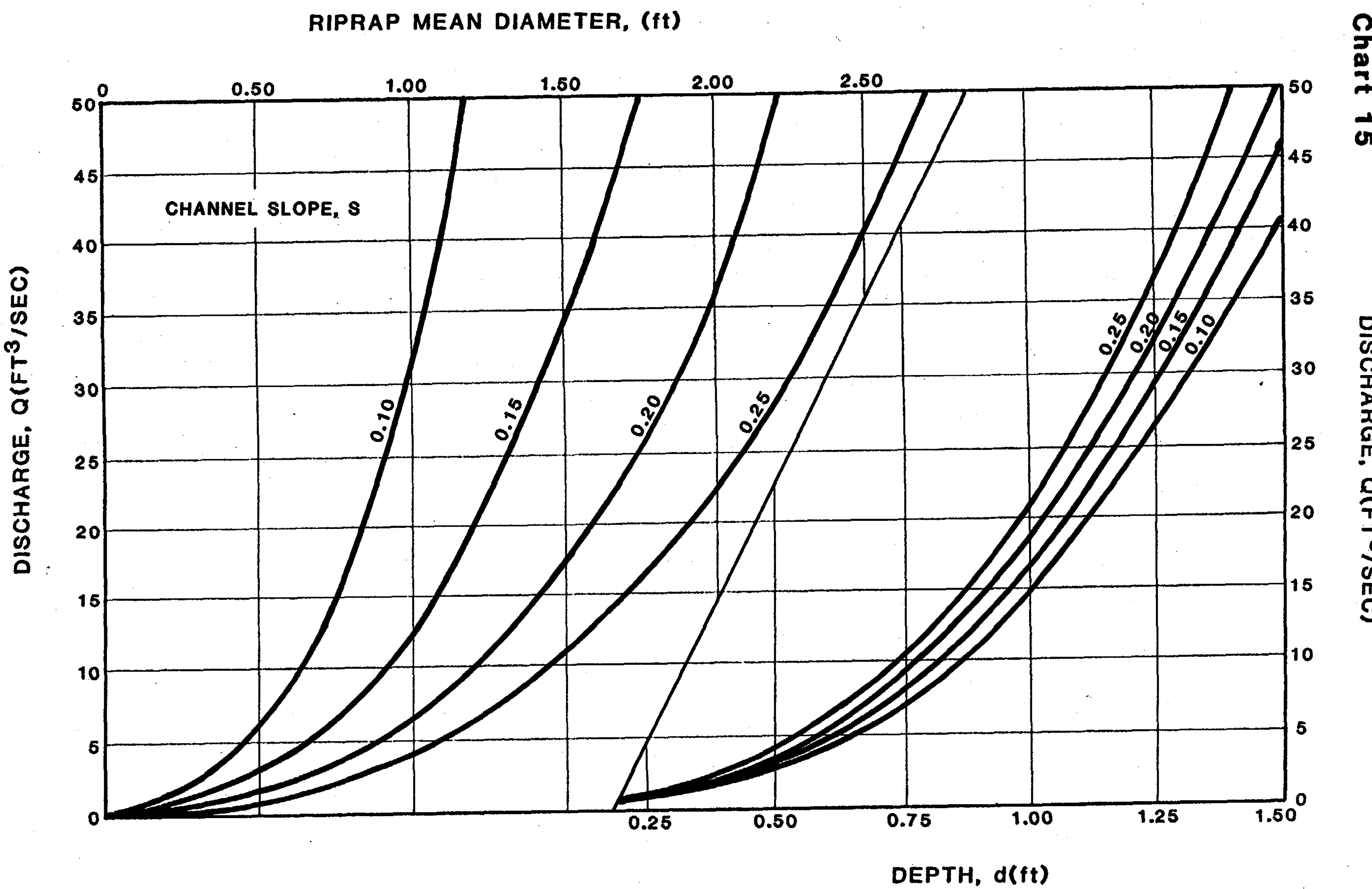


Chart 15. Steep slope riprap design, triangular channel Z = 3.

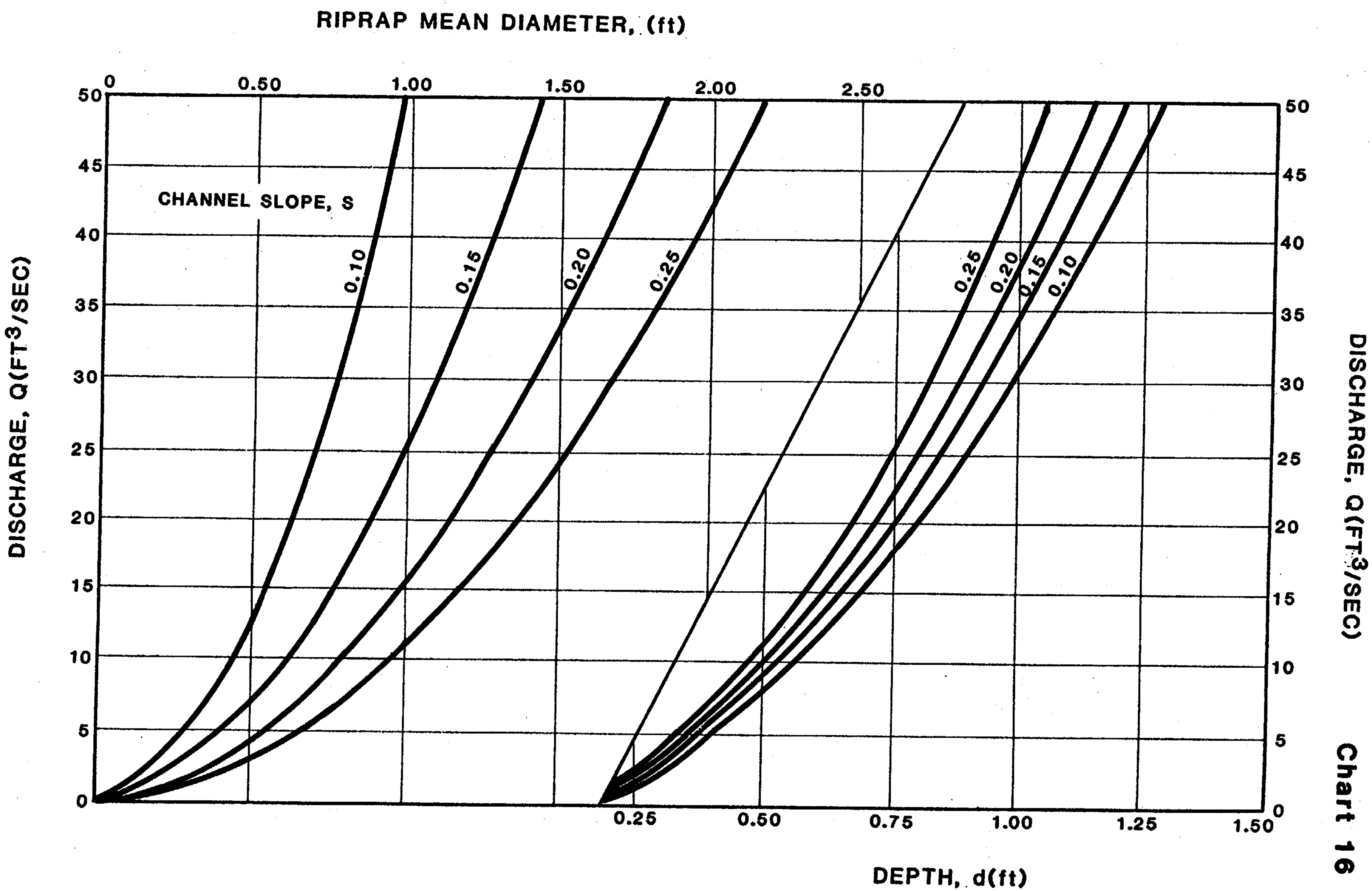


Chart 16. Steep slope riprap design, B = 2, Z = 3.

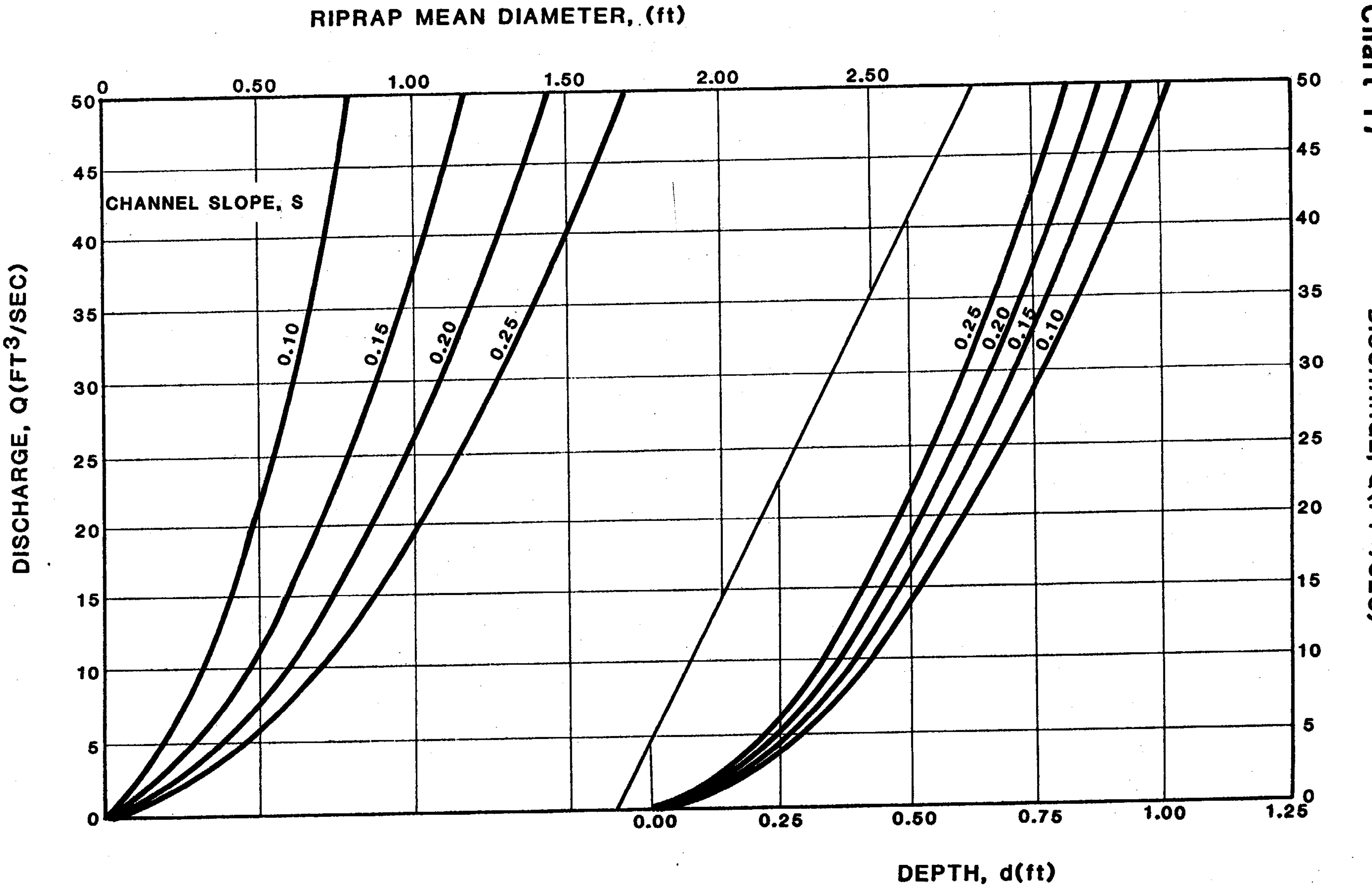


Chart 17. Steep slope riprap design, B=4, Z=3.

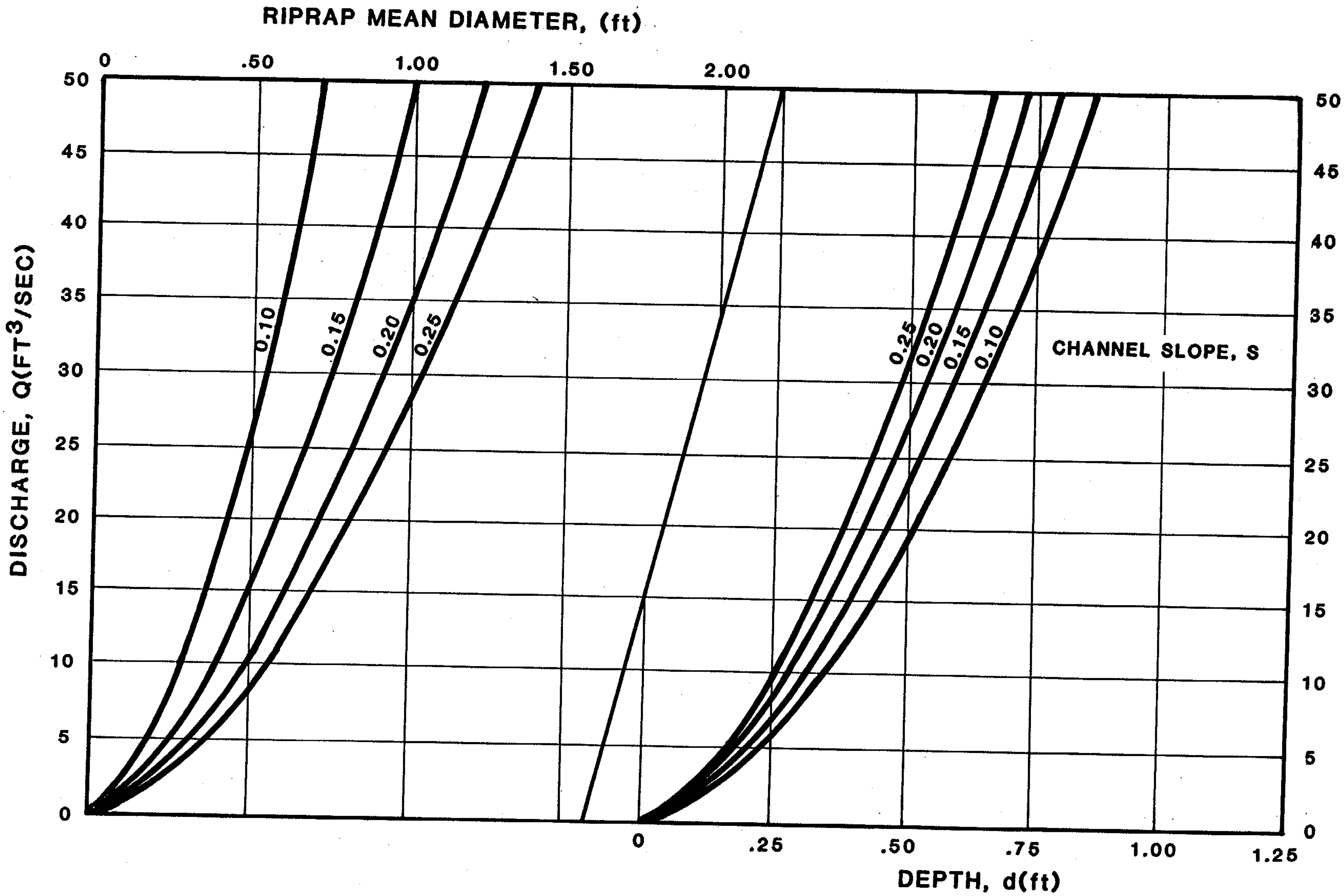


Chart 18. Steep slope riprap design, B=6, Z=3.

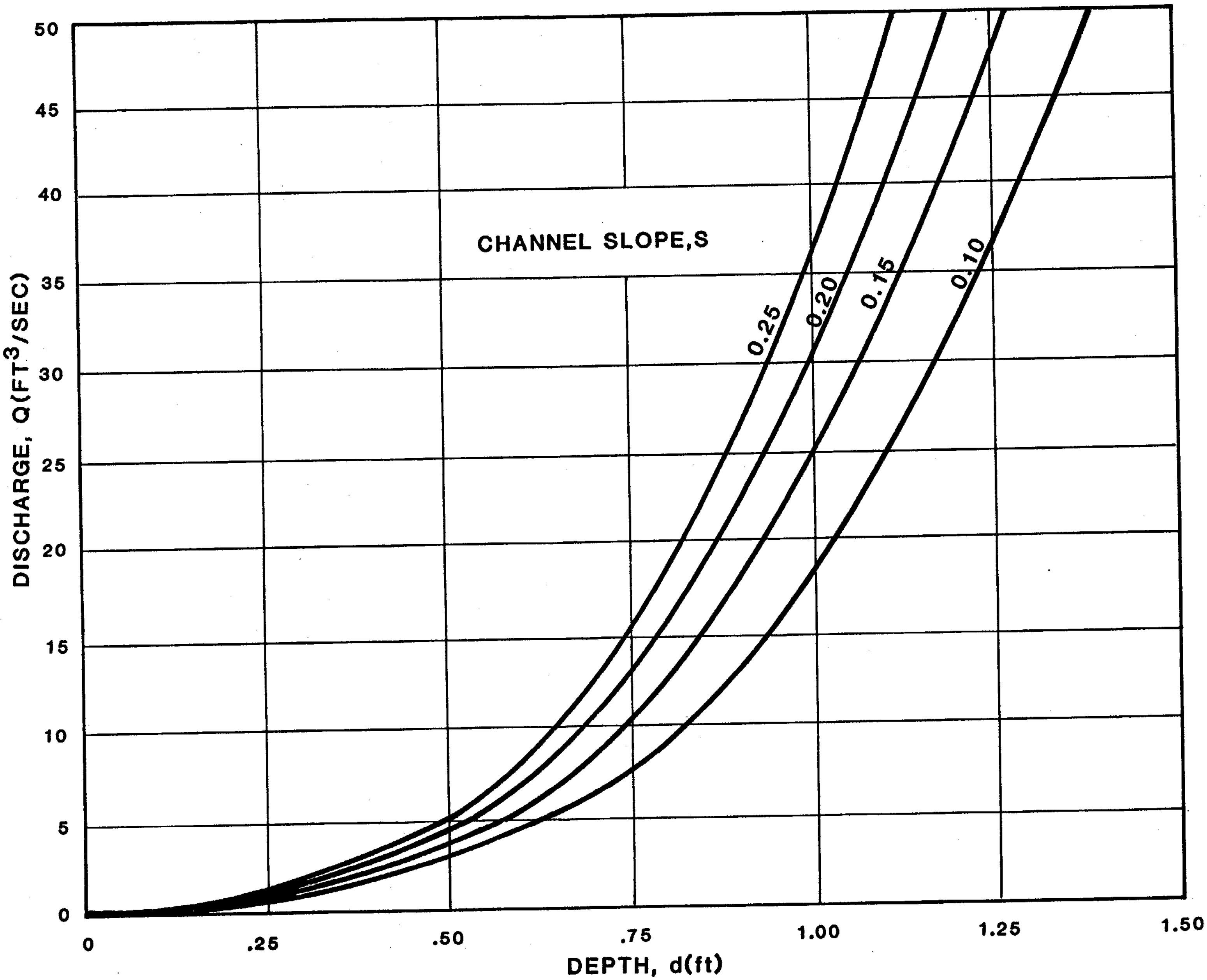


Chart 19. Steep slope gabion mattress, triangular channel, Z = 3.

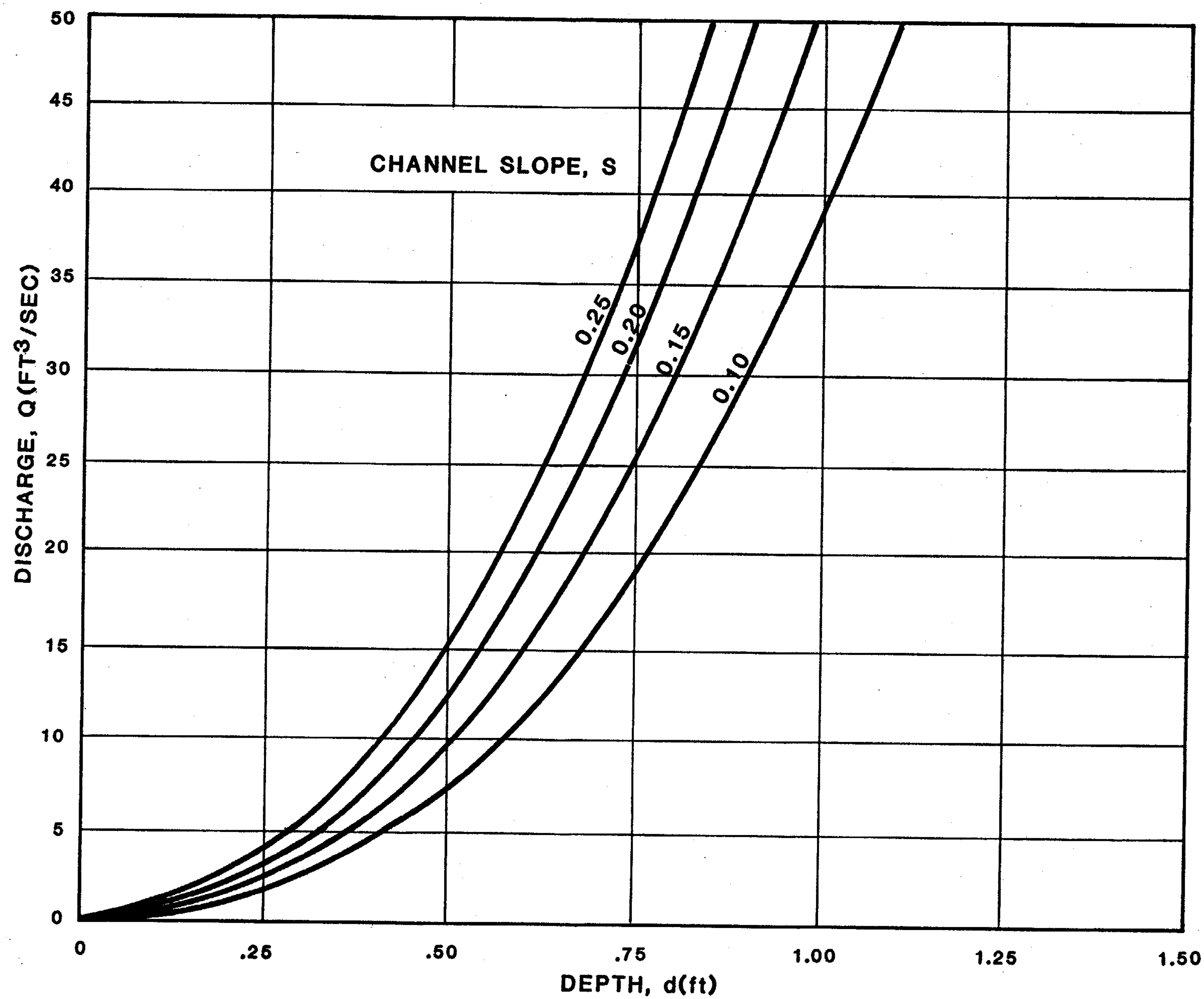


Chart 20. Steep slope gabion mattress, B= 2, Z= 3.

Chart 20

Chart 21

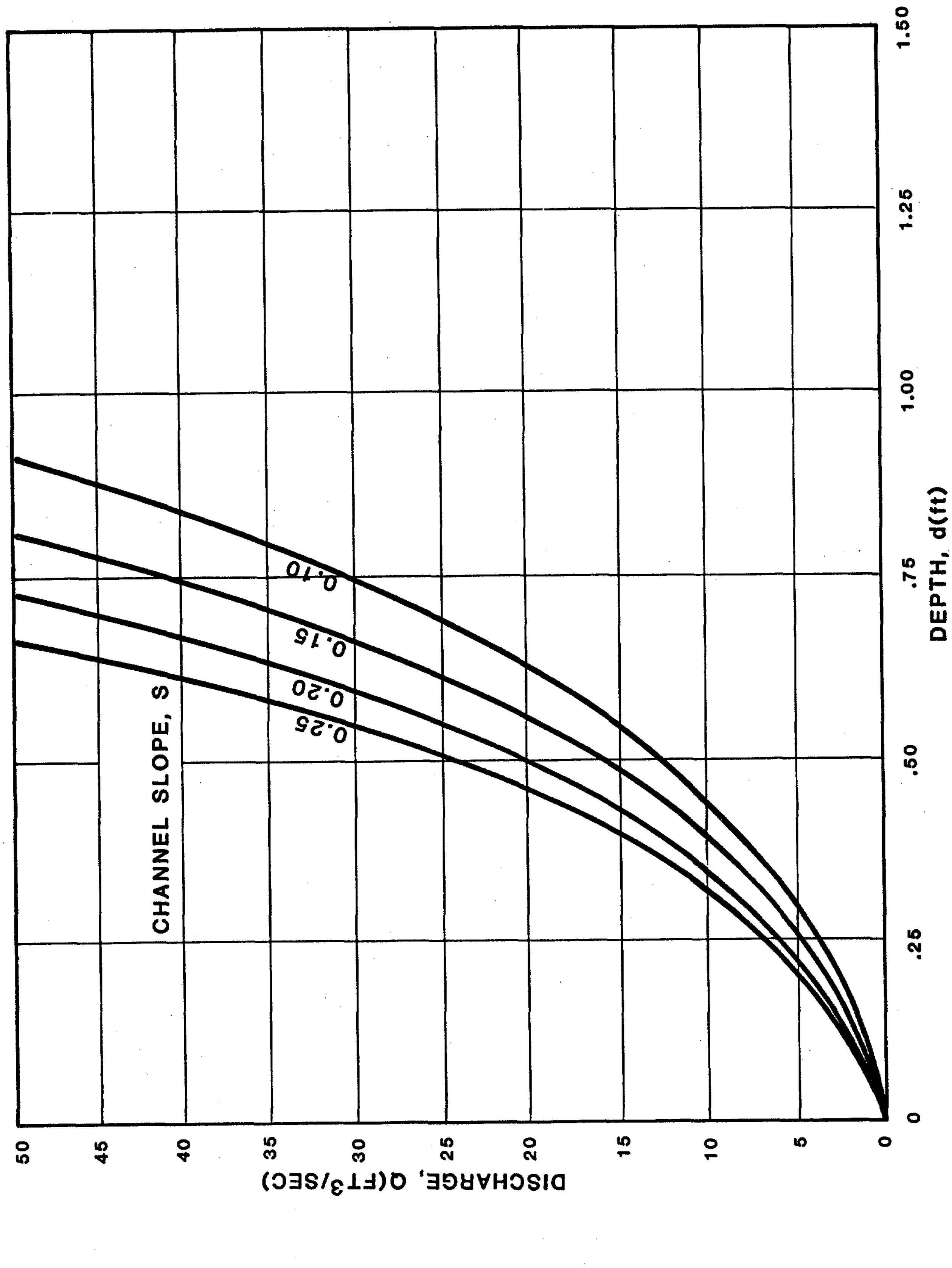


Chart 21. Steep slope gabion mattress, B = 4, Z = 3.

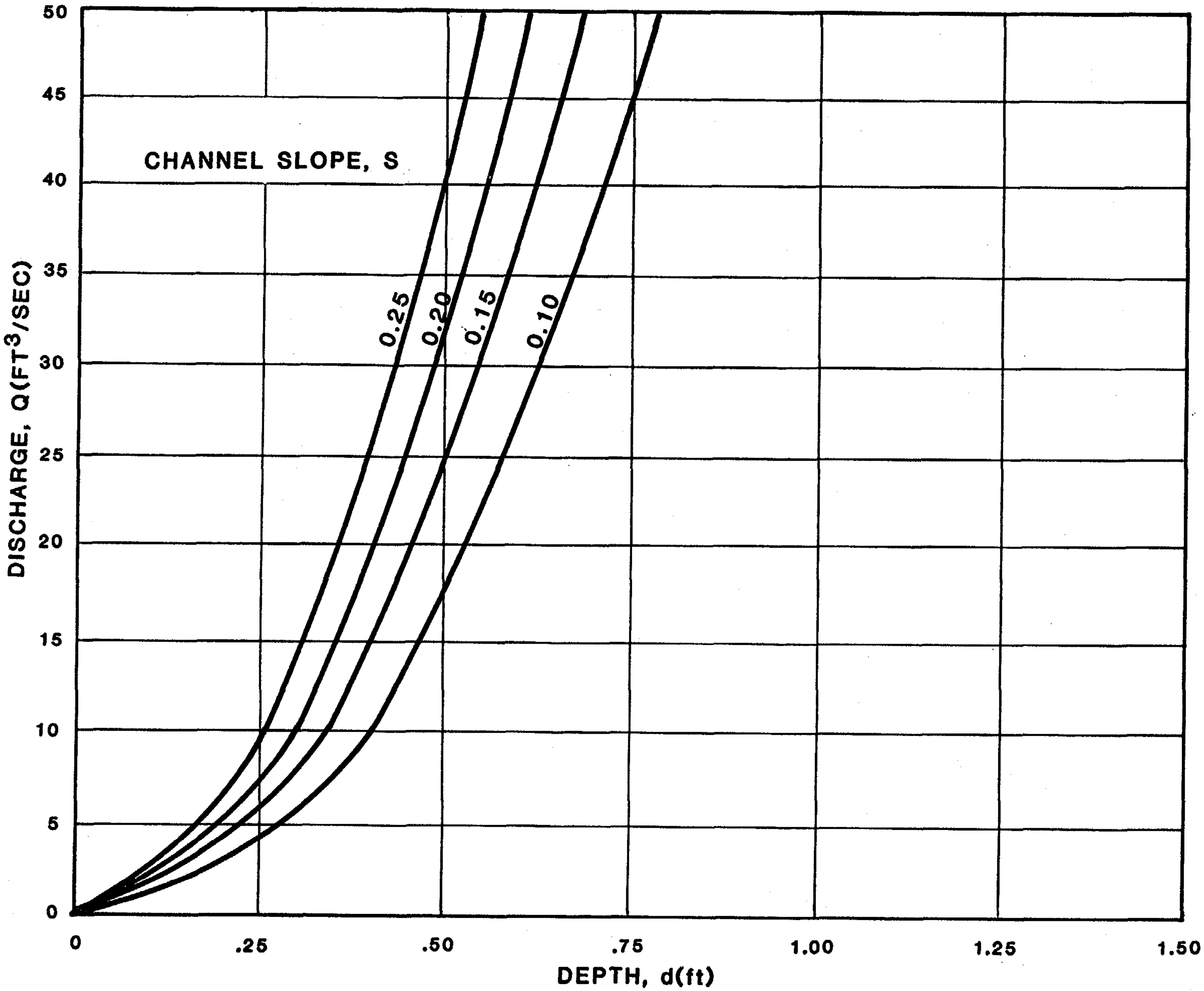


Chart 22. Steep slope gabion mattress, B = 6, Z = 3.

Chart 23

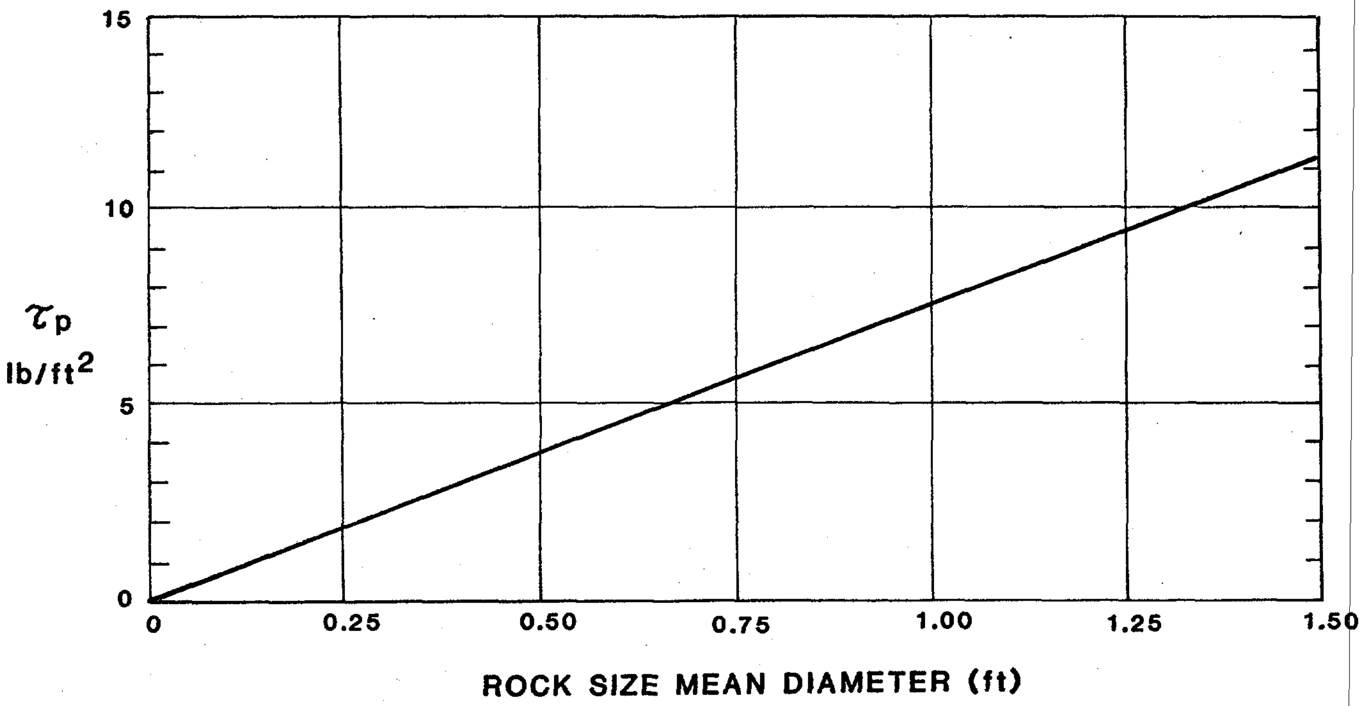


Chart 23. Permissible shear stress for gabion mattress versus rock fill size.

Chart 24

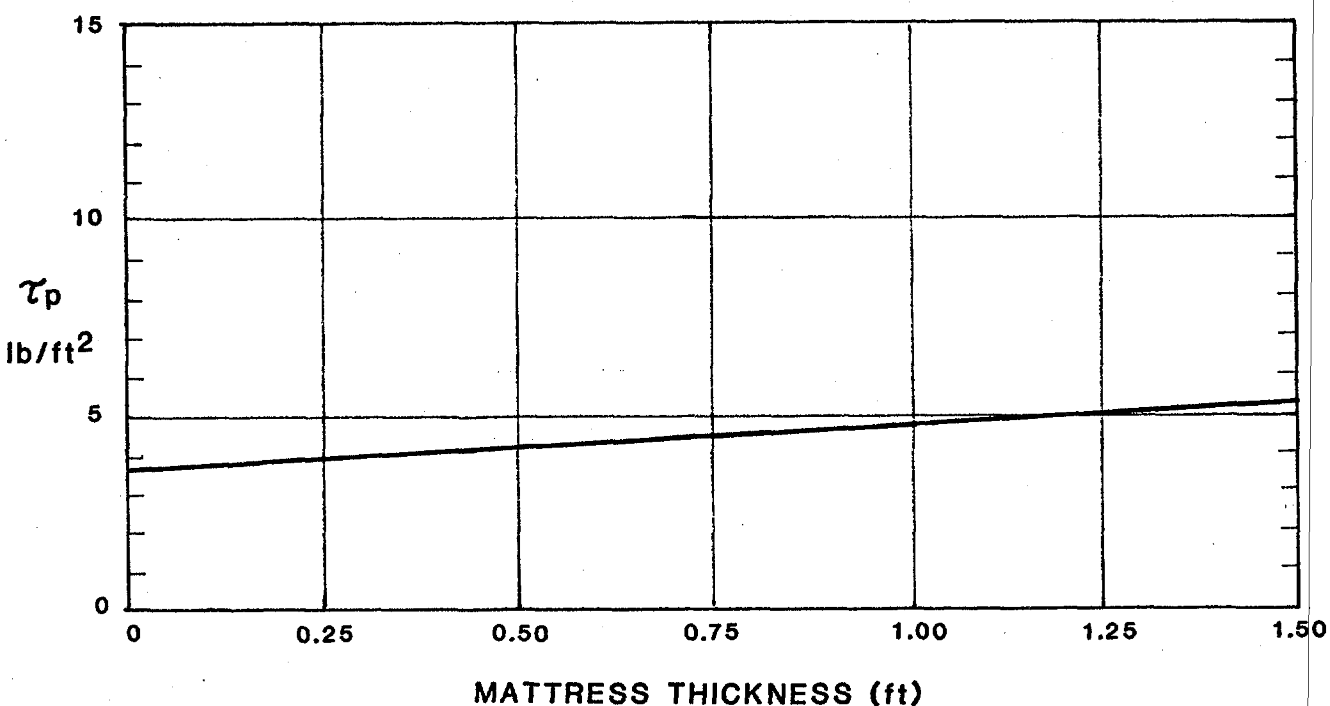


Chart 24. Permissible shear stress for gabion mattress versus mattress thickness.

VI. COMPOSITE LINING DESIGN

Composite linings protect the bed of a channel against the higher shear stress occurring in that portion of the channel. The distribution of shear stress in a trapezoidal channel section (see figure 18, chapter III) is such that the maximum shear stress on the sides of the channel is significantly less than on the channel bottom. This allows for a channel lining material to be used on the side slopes that has a lower permissible shear stress that the lining material used for the bottom of the channel. The maximum shear on the side of the channel is given by the following equation:

$$\tau_s = K_1 \tau_d \qquad (15)$$

where K_1 is a function of channel geometry and is given in chart 13 (in chapter IV) and τ_d is the shear stress at maximum depth.

It is important that the bed lining material cover the entire channel bottom so that adequate protection is provided. To guarantee that the channel bottom is completely protected, the bed lining should be extended a small distance up the side slope.

Computation of flow conditions in a composite channel requires the use of an equivalent Manning's n value for the entire perimeter of the channel. For determination of equivalent roughness, the channel area is divided into two parts of which the wetted perimeters and Manning's n values of the low-flow section and channel sides are known. These two areas of the channel are then assumed to have the same mean velocity. Chart 25 provides a means of determining the equivalent roughness coefficient, K_c, for various applications of two channel linings.

Another important use of composite linings are in vegetative lined channels that have frequent low flows. These low flows will usually kill the submerged vegetation. In erodible soils, this leads to the formation of a small gully at the bottom of the channel. Gullys weaken a vegetative lining during higher flows, causing additional erosion, and can result in a safety hazard. A solution is to provide a nonvegetative low-flow channel lining such as concrete or riprap. The dimensions of the low-flow channel are sufficient to carry frequent low flows but only a small portion of the design flow. The remainder of the channel is covered with vegetation.

Special Considerations

When two lining materials with significantly different roughness values are adjacent to each other, erosion may occur near the boundary of the two linings. Erosion of the weaker lining material may damage the lining as a whole. In the case of composite channel linings with vegetation on the banks, this problem can occur in the early stages of vegetative establishment. A temporary lining should be used adjacent to the low-flow channel to provide erosion protection until the vegetative lining is well established.

COMPOSITE LINING DESIGN PROCEDURE

The procedure for composite lining designs consists of the following steps.

1. Determine the permissible shear stress τ_p, for both lining types. (see table 2)

2. Estimate the depth of flow, d_i.

3. Determine Manning's n for each lining type. (Table 3 for nonvegetative linings and charts 5 to 9 for vegetative linings.)

4. Compute the ratio of rougher to smoother Manning's n values, n_2/n_1.

5. Determine the hydraulic radius, R, and the wetted perimeter, P, for the entire channel section (chart 4 or equations in appendix A).

6. Compute the ratio of low-flow channel wetted perimeter, P_ℓ , to total wetted perimeter, P, (P_ℓ/P).

7. Determine a compound lining factor, K_c, from chart 25. Calculate the effective Manning's *n* from,

   $$n = K_c \, n_1$$

   where n_1 = Manning's n for smoother lining.

8. Determine channel flow depth, d, using the effective Manning's *n*.

9. Compare estimated flow depth, d_i, with calculated flow depth, d. If the difference is greater than 0.1 ft, repeat steps 3 through 8.

10. Determine the shear stress at maximum depth, τ_d, and the shear stress on the channel side slopes, τ_s

    $$\tau_d = \gamma dS$$

    and

    $$\tau_s = K_1 \, \tau_d \qquad (15)$$

    where K_1 is from chart 13.

11. Compare the shear stresses, τ_d and τ_s, to the permissible shear stress, τ_p, for each of the channel linings. If τ_d or τ_s is greater the τ_p for the respective lining, a different combination of linings should be evaluated.

The design procedure is demonstrated in the following example. The worksheet at the end of this chapter (figure 28) is provided for carrying out the compound lining design procedure computations.

Example Problem

Example 13:

Determine the channel design for a composite concrete and vegetation lining.

Given: $Q = 10.0$ ft^3/sec
$S = 0.02$ ft/ft
Trapezoidal channel shape
$Z = 3$
Concrete low-flow channel, 3.0 ft wide

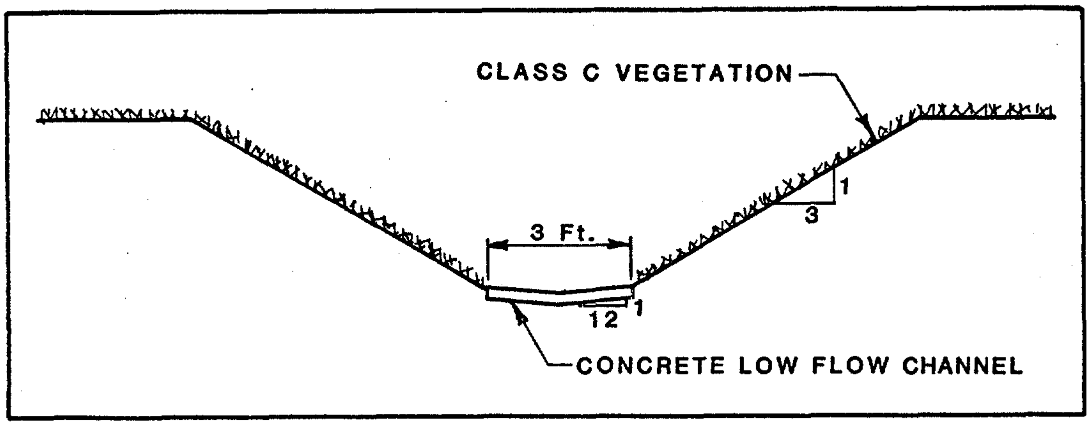


Figure 26. Compound Lining Example.

Find: (1) Effective Manning's n.
(2) Flow depth in channel.
(3) Suitability of channel lining materials.

Solution:

(1) Permissible shear stress for Class C vegetation, $\tau_p = 1.00$ lb/ft^2 and concrete is a nonerodible, rigid lining.

(2) Initial depth is estimated at 1.0 ft

(3) From chart 4, given $d/B = 0.33$

$R/d = 0.64$
$R = 0.64$ ft
$A/Bd = 2.0$
$A = 2.0 \times 3.0 \times 1.0 = 6.0$ ft^2
$P = A/R = 6.0/0.64$
$= 9.4$ ft

The concrete lining provides the low-flow channel, as given in the sketch,

$$P_\ell = 3.0$$
$$P_\ell/P = 3.0/9.4$$
$$= 0.32$$

(4) From chart 7 for Class C vegetation, $n_2 = 0.083$
From table 3 for concrete, $n_1 = 0.013$
$n_2/n_1 = 0.083/0.013$
$= 6.4$

(5) From chart 25, given $P_\ell/P = 0.32$ and $n_2/n_1 = 6.4$,
$K_c = 5.0$
$n = 5.0 \times 0.013$
$= 0.065$

(6) From chart 3 for S = 0.02, given Qn = 0.65 and B = 3,
$d/B = 0.28$
$d = 0.84$ ft

The difference between calculated depth and estimated depth is greater than 0.1 feet; therefore repeat steps 3 through 6.

(3) The revised depth of flow is 0.84 ft. From chart 4, given d/B = 0.28,

$R/d = 0.66$
$R = 0.56$
$A/Bd = 1.84$
$A = 4.64$ ft^2
$P = 4.64/0.56 = 8.3$ ft
$P_\ell/P = 3.0/8.3 = 0.36$

(4) From chart 7 for Class C vegetation, $n_2 = 0.095$.

$n_2/n_1 = 0.095/0.013$
$= 7.3$

(5) From chart 25, given $P_\ell/P = 0.36$ and $n_2/n_1 = 7.3$,
$K_c = 5.5$
$n = 5.5 \times 0.013$
$= 0.072$

(6) From chart 3 for S = 0.020, given Qn = 0.72 and B = 3,
$d/B = 0.29$
$d = 0.87$

The calculated and previous values of depth are within 0.1 feet. The results are,

$n = 0.072$
$d = 0.87$ ft

(7) The shear stress, at maximum depth from equation 5,

$$\tau_d = \gamma dS$$
$$= 62.4 \times 0.87 \times 0.02$$
$$= 1.09 \text{ lb/ft}^2$$

The maximum shear stress on the sides of the channel is determined from equation 15.

$$\tau_s = K_1 \tau_d$$

where the shear stress ratio, K_1, is determined from chart 13 given Z = 3 and B/d = 3.45, as $K_1 = 0.87$

$$\tau_s = 0.87 \times 1.09$$
$$= 0.95 \text{ lb/ft}^2$$

(8) The maximum shear stress on the channel side slopes is less than permissible, so the lining is acceptable.

Worksheet for Compound Lining Design

DESIGNER: ______________________ DATE: ______________________

PROJECT: ____

STATION: ______________________ TO STATION: ______________________

DRAINAGE AREA: __________ ACRES

DESIGN FLOW: Q ______ = __________ ft^3/sec

DESIGN FLOW FOR TEMPORARY LINING: Q _____ = ________ ft^3/sec

CHANNEL SLOPE (S) : _______ ft/ft

CHANNEL DESCRIPTION:

Lining	Type	τ_p (1)	n (2)	P_ℓ (3)
Lowflow				
Side				

d_i (4)	R (5)	$\frac{n_2}{n_1}$ (6)	P (7)	$\frac{P_\ell}{P}$	K_c (8)	n (9)	d (10)	τ_d (11)	K_1 (12)	τ_s (13)	REMARKS

(1) Table 2
(2) Non-vegetative linings, table 3
Vegetative linings, charts 5-9
(3) Lowflow channel wetted perimeter
(4) Flow depth, estimate
(5) Chart 4, trapezoidal channels
(6) Ratio of rougher to smoother n
(7) Total channel wetted perimeter
(8) Chart 25
(9) $n = K_c n_1$
(10) Chart 3, trapezoidal channels
(11) $\tau_d = \gamma ds$
τ_d must be $\leq \tau_p$ for lowflow
(12) Chart 13
(13) $\tau_s = K_1 \tau_d$
τ_s must be $\leq \tau_p$ for sides

Figure 27. Worksheet for Compound Lining Design

Worksheet for Compound Lining Design

DESIGNER: ______________________ DATE: ______________________

PROJECT: Example Problem 13

STATION: ______________________ TO STATION: ______________________

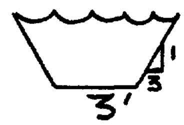
DRAINAGE AREA: __________ ACRES

DESIGN FLOW: Q _____ = 10 ft^3/sec

DESIGN FLOW FOR TEMPORARY LINING: Q _____ = _______ ft^3/sec

CHANNEL SLOPE (S) : 0.02 ft/ft

CHANNEL DESCRIPTION:



Lining	Type	τ_p (1)	n (2)	P_ℓ (3)
Lowflow	concrete	—	.013	3
Side	grass-class C	1.00	.095	for .84′
			.083	for 1.0′

d_i (4)	R (5)	$\frac{n_2}{n_1}$ (6)	P (7)	$\frac{P_\ell}{P}$	K_c (8)	n (9)	d (10)	τ_d (11)	K_1 (12)	τ_s (13)	REMARKS
1.0	.64	6.4	9.4	.32	5	.065	.84	—	—	—	$d < d_i$
.84	.56	7.3	8.3	.36	5.5	.072	.87	1.09	.87	.95	$\tau_s < \tau_p$
											ok

(1) Table 2
(2) Non-vegetative linings, table 3
Vegetative linings, charts 5-9
(3) Lowflow channel wetted perimeter
(4) Flow depth, estimate
(5) Chart 4, trapezoidal channels
(6) Ratio of rougher to smoother n
(7) Total channel wetted perimeter
(8) Chart 25
(9) $n = K_c n_1$
(10) Chart 3, trapezoidal channels
(11) $\tau_d = \gamma ds$
τ_d must be $\leq \tau_p$ for lowflow
(12) Chart 13
(13) $\tau_s = K_1 \tau_d$
τ_s must be $\leq \tau_p$ for sides

Figure 28. Worksheet for Example Problem 13

Chart 25

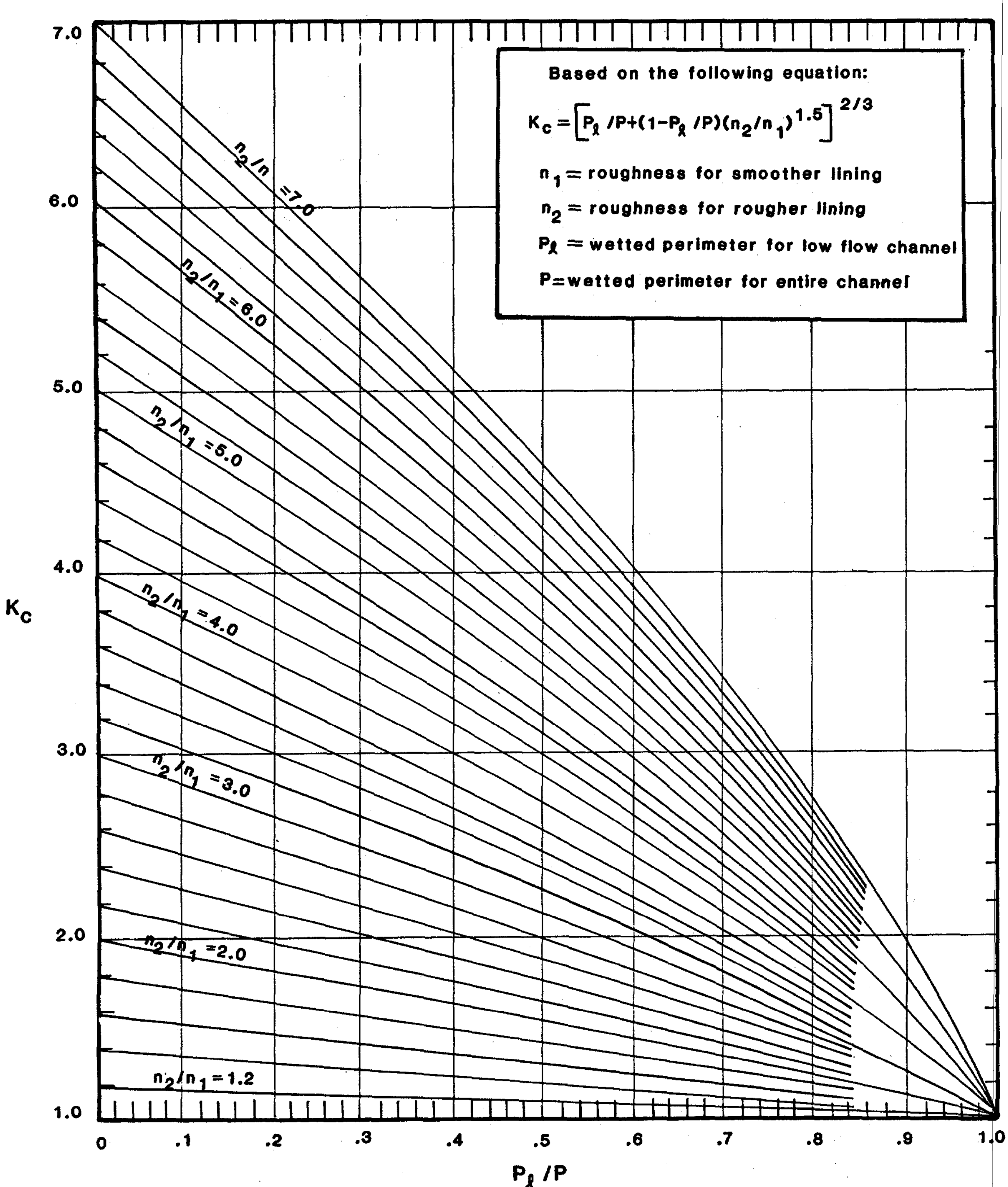
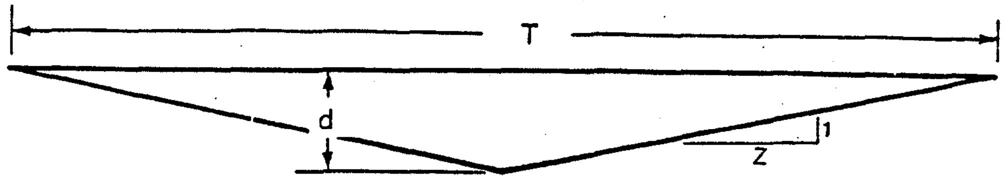


Chart 25. Roughness factor for compound channel linings.

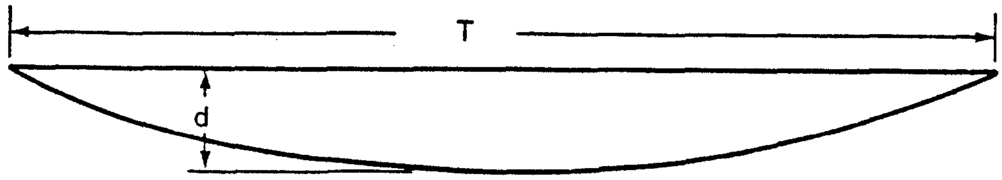
APPENDIX A

EQUATIONS FOR VARIOUS CHANNEL GEOMETRIES



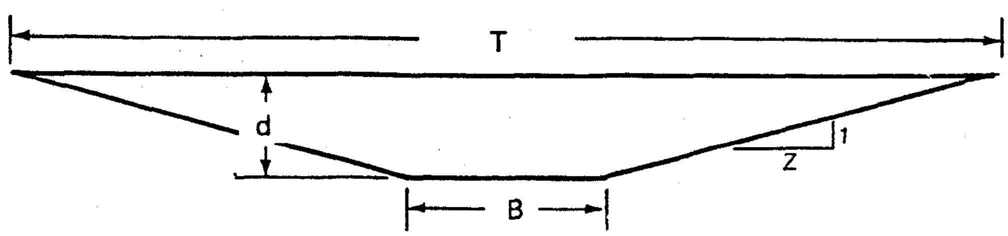
$$A = Zd^2$$
$$P = 2d\sqrt{Z^2 + 1}$$
$$T = 2dZ$$

V-SHAPE



$$A = \frac{2}{3}Td$$
$$P = \frac{1}{2}\sqrt{16d^2 + T^2} + \left(\frac{T^2}{8d}\right)\ln_e\left(\frac{4d + \sqrt{16d^2 + T^2}}{T}\right)$$
$$T = 1.5\frac{A}{d}$$

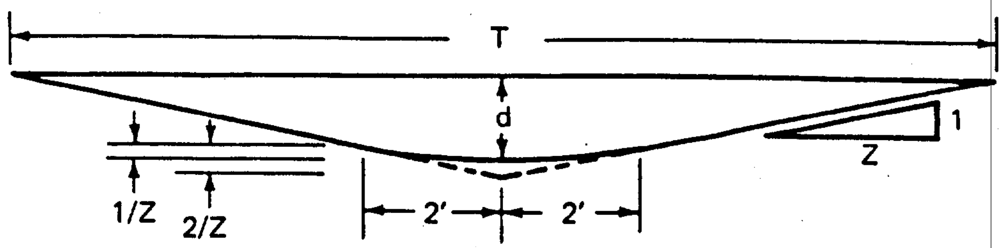
PARABOLIC



$$A = Bd + Zd^2$$
$$P = B + 2d\sqrt{Z^2 + 1}$$
$$T = B + 2dZ$$

TRAPEZOIDAL

Figure 29. Equations for Various Channel Geometries.



2 CASES

NO. 1

IF d ≤1/Z, THEN:

$$A = \frac{8}{3} d \sqrt{dZ}$$

$$P = 2Z \ln_e \left(\sqrt{\frac{d}{Z}} + \sqrt{1 + \frac{d}{Z}} \right) 2 \sqrt{d^2 + dZ}$$

$$T = 4 \sqrt{dZ}$$

NO. 2

IF d >1/Z, THEN:

$$A = \frac{8}{3} Z + 4 \left(d - \frac{1}{Z} \right) + Z \left(1 - \frac{1}{Z} \right)^2$$

$$P = 2 Z \ln_e \left(\frac{1}{Z} + \sqrt{\frac{Z^2 + 1}{Z}} \right) + 2 \sqrt{\frac{1 + Z^2}{Z}} + 2 \left(d - \frac{1}{Z} \right) \sqrt{1 + Z^2}$$

$$T = 2Z \left(d + \frac{1}{Z} \right)$$

V-SHAPE WITH ROUNDED BOTTOM

Figure 29. Equations for Various Channel Geometries (continued).

APPENDIX B

DEVELOPMENT OF DESIGN CHARTS AND PROCEDURES

Resistance Equations

Resistance to flow in open channels with flexible linings can be accurately described using the universal-velocity-distribution law. (7) The form of the resulting equation is:

$$V = V_* \left[a + b \log (R/k_s)\right] \quad (16)$$

where V = mean channel velocity;
V_* = shear velocity which is $(gRS)^{0.5}$;
a, b = empirical coefficients;
R = hydraulic radius;
k_s = roughness element height; and
g = acceleration due to gravity.

Values of k_s and the empirical coefficients, a and b, for different lining material are given in table 5. These values are based on an analysis of data collected by McWhorter et al. and Thibodeaux (14,15) for the Department of Transportation. The coefficients for riprap were developed by Blodgett and McConaughy (19) and the coefficients for vegetation are from work by Kouwen et al. (6)

Manning's equation (equation 1) and equation 16 can be combined to give Manning's roughness coefficient n in terms of the relative roughness. The resulting equation is:

$$\frac{n}{k_s^{1/6}} = \frac{(R/k_s)^{1/6}}{3.82\left[a + b \log (R/k_s)\right]} \quad (17)$$

The n value is divided by the roughness height to the one-sixth power in order to make both sides of the equation dimensionless.

Figure 29 shows the behavior of Manning's n versus relative roughness. It can be seen that for values of relative roughness less than 10, there is significant variation in the n value. Flow conditions in small to moderate sized channels will typically fall in the range of relative roughness from 10 to 100. Over this range, the n value varies about 20 percent.

The relative roughness of vegetative channel linings depends on physical characteristics of the grass as well as the shear stress exerted on the grass. With grasses, the relative roughness will vary depending on the bending of the vegetation with the degree of bending being a function of the stiffness of the

Table 5. Empirical Coefficients for Resistance Equation.

Lining Material	k_s (ft)	k_s (cm)	a	b
Woven Paper	0.004	0.12	0.73	8.00
Jute Mesh	0.038	1.16	0.74	8.04
Fiberglass Roving	0.035	1.07	0.73	8.00
Straw With Net	0.12	3.66	0.72	7.83
Curled Wood Mat	0.11	3.35	0.65	7.10
Synthetic Mat	0.065	1.98	0.96	8.13
Riprap	D_{50}		2.25	5.23
Vegetation	equation 19		0.42	5.23

Table 6. Relative Roughness Parameters for Vegetation.

Retardance Class	Average Height, h (ft)	Average Height, h (cm)	Stiffness MEI (lb © ft^2)	Stiffness MEI (Newton © m^2)
A	3.0	91	725	300
B	2.0	61	50	20
C	0.66	20	1.2	0.5
D	0.33	10	0.12	0.05
E	0.13	4	0.012	0.005

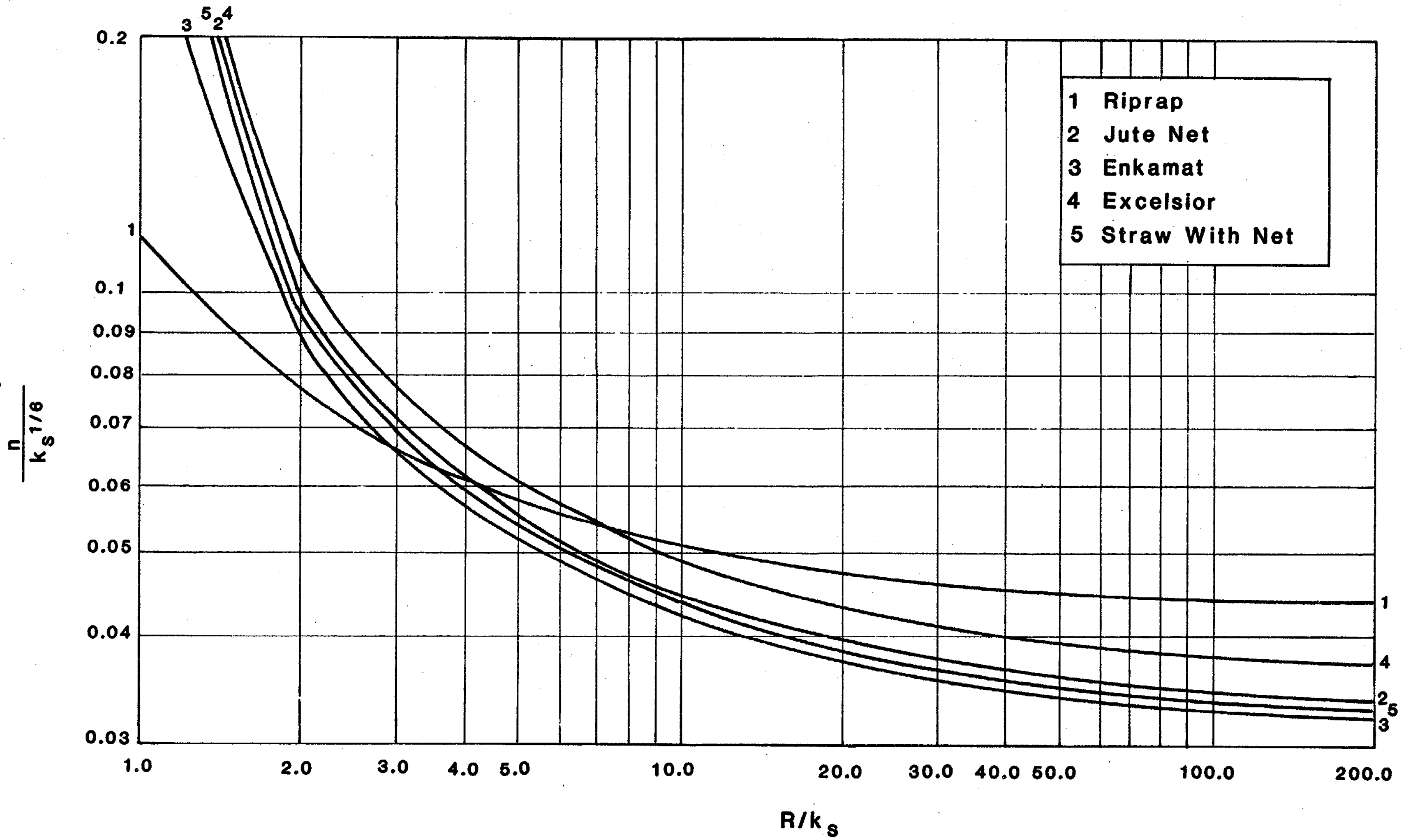


Figure 30. Manning's n Versus Relative Roughness for Selected Lining Types.

vegetation and the shear stress conditions. (6) Roughness height for vegetation is given by:

$$\frac{k_s}{h} = 0.14 \left[\left(\frac{MEI}{\tau}\right)^{1/4} / h\right]^{1.59} \qquad (18)$$

where h = average height of vegetation;
τ = ave. shear stress; and
MEI = stiffness factor.

Values of h and MEI for various classifications of vegetative roughness, known as retardance classifications, are given in table 6.

The relative roughness for grasses in classifications A through E is typically less than 10. In this range, the variation in the Manning's roughness coefficient is substantial, and it is not acceptable to use only an average value. By combining equations 17 and 18, the Manning's roughness coefficient can be described as a function of hydraulic radius and mean tractive force. The resulting equation is:

$$n = \frac{R^{1/6}}{C + 19.97 \log (R^{1.4} S^{0.4})} \qquad (19)$$

where C is $19.97 \log (44.8\ h^{0.6}\ MEI^{-0.4})$ and depends on the class of vegetation. Design charts for determining Manning's n for vegetative channel linings were developed by plotting values given by equation 19.

APPENDIX C

DEVELOPMENT OF STEEP GRADIENT DESIGN CHARTS AND PROCEDURES

General

The design of riprap for steep gradient channels presents special problems. On steep gradients, the riprap size required to stabilize the channel is often of the same order of magnitude as the depth of flow. The riprap elements often protrude from the flow, creating a very complex flow condition.

Laboratory studies and field measurements (20) of steep gradient channels have shown that additional factors need to be considered when computing hydraulic conditions and riprap stability. The development of design procedures for this manual has, therefore, been based on equations that are more general in nature and account directly for several additional forces affecting riprap stability. The Bathurst resistance equation is used to predict hydraulic conditions in steep gradient channels and the factor of safety method is used to assess riprap stability. A brief discussion of both methods is given in this appendix and the assumptions used in developing the design procedures are presented.

Bathurst Resistance Equation

Most of the flow resistance in channels with large-scale roughness is derived from the form drag of the roughness elements and the distortion of the flow as it passes around roughness elements. Consequently, a flow resistance equation for these conditions has to account for skin friction and form drag. Because of the shallow depths of flow and the large size of the roughness elements, the flow resistance will vary with relative roughness area, roughness geometry, Froude number (the ratio of inertial forces to gravitational forces), and Reynolds number (the ratio of inertial forces to viscous forces).

Bathurst's experimental work quantified these relationships in a semi-empirical fashion. The work shows that for Reynolds numbers in the range of 4×10^4 to 2×10^5, resistance is likely to fall significantly as Reynolds number increases. For Reynolds numbers in excess of 2×10^5, the Reynolds effect on resistance remains constant. When roughness elements protrude through the free surface, resistance increases significantly due to Froude number effects, i.e., standing waves, hydraulic jumps, and free-surface drag. For the channel as a whole, free-surface drag decreases as the Froude number and relative submergence increase. Once the elements are submerged, Froude number effects related to free-surface drag are small, but those related to standing waves are important.

The general dimensionless form of the Bathurst equation is:

$$\frac{V}{V_*} = \frac{1.49}{\sqrt{g}} \left(\frac{d^{1/6}}{n}\right) = f_n(Fr) \times f_n(REG) \times f_n(CG) \quad (20)$$

where $\frac{V}{V_*}$ = mean velocity divided by the shear velocity;
$V_* = (gdS)^{0.5}$;
d = mean flow depth;
g = acceleration due to gravity;
n = Manning's roughness coefficient;
Fr = Froude number;
REG = roughness element geometry; and
CG = channel geometry.

The functions of Froude number, roughness element geometry, and channel geometry are given by the following equations:

$$f_n(Fr) = \left(\frac{0.28}{b} Fr\right)^{\log (0.755/b)} \quad (21)$$

$$f_n(REG) = 13.434 \left(\frac{T}{Y_{50}}\right)^{0.492} b^{1.025(T/Y_{50})^{0.118}} \quad (22)$$

$$f_n(CG) = \left(\frac{T}{d}\right)^{-b} \quad (23)$$

where T = channel topwidth;
Y_{50} = mean value of the distribution of the average of the long and median axes of a roughness element; and
b = parameter describing the effective roughness concentration.

The parameter b describes the relationship between effective roughness concentration and relative submergence of the roughness bed. This relationship is given by:

$$b = a \left(\frac{d}{S_{50}}\right)^{c} \quad (24)$$

where S_{50} = mean of the short axis lengths of the distribution of roughness elements; and
a, c = constants varying with bed material properties.

The parameter, c, is a function of the roughness size distribution and varies with respect to the bed-material gradation, σ, where:

$$c = 0.648\, \sigma^{-0.134} \quad (25)$$

For standard riprap gradations the log standard deviation is assumed to be constant at a value of 0.182, giving a c value of 0.814.

The parameter, a, is a function of channel width and bed material size in the cross stream direction, and is defined as:

$$a^{1/c} = 1.175 \left(\frac{Y_{50}}{T}\right)^{0.557} \qquad (26)$$

In solving equation 20 for use with this manual, it is assumed that the axes of a riprap element are approximately equal for standard riprap gradations. The mean diameter, D_{50}, is therefore substituted for S_{50} and Y_{50} parameters.

Riprap Stability

The stability of riprap is determined by analyzing the forces acting on an individual riprap element and calculating the factor of safety against its movements. The forces acting on a riprap element are its weight (W_s), the drag force acting in the direction of flow (F_d), and the lift force acting to lift the particle off the bed (F_L). Figure 30 illustrates an individual element and the forces acting on it. The geometric terms required to completely describe the stability of a riprap element include:

α = angle of the channel bed slope;
β δ = angles between the two vectors: weight and drag, and their resultant in the plane of the side slope, respectively;
θ = angle of the channel side slope; and
ϕ = angle of repose for the riprap.

As the element will tend to roll rather than slide, its stability is analyzed by calculating the moments causing the particle to roll about the contact point, c, with an adjacent riprap element as shown in figure 30. The equation describing the equilibrium of the particle is:

$$\ell_2 W_s \cos\theta = \ell_1 W_s \sin\theta \cos\beta + \ell_3 F_d \cos\delta + \ell_4 F_L \qquad (27)$$

The factor of safety against movement is the ratio of moments resisting motion over the moments causing motion. This yields:

$$SF = \frac{\ell_2 W_s \cos\theta}{\ell_1 W_s \sin\theta \cos\beta + \ell_3 F_d \cos\delta + \ell_4 F_L} \qquad (28)$$

where SF = safety factor.

Evaluation of the forces and moment arms for equation 28 involves several assumptions and a complete derivation is given in Simons and Senturk.(21) The resulting set of equations are used to compute the factor of safety:

$$SF = \frac{\cos\theta \tan\phi}{\eta' \tan\phi + \sin\theta \cos\beta} \qquad (29)$$

$$b = \tan^{-1} \frac{\cos\alpha}{\frac{2 \sin\theta}{\eta \tan\phi} + \sin\alpha} \qquad (30)$$

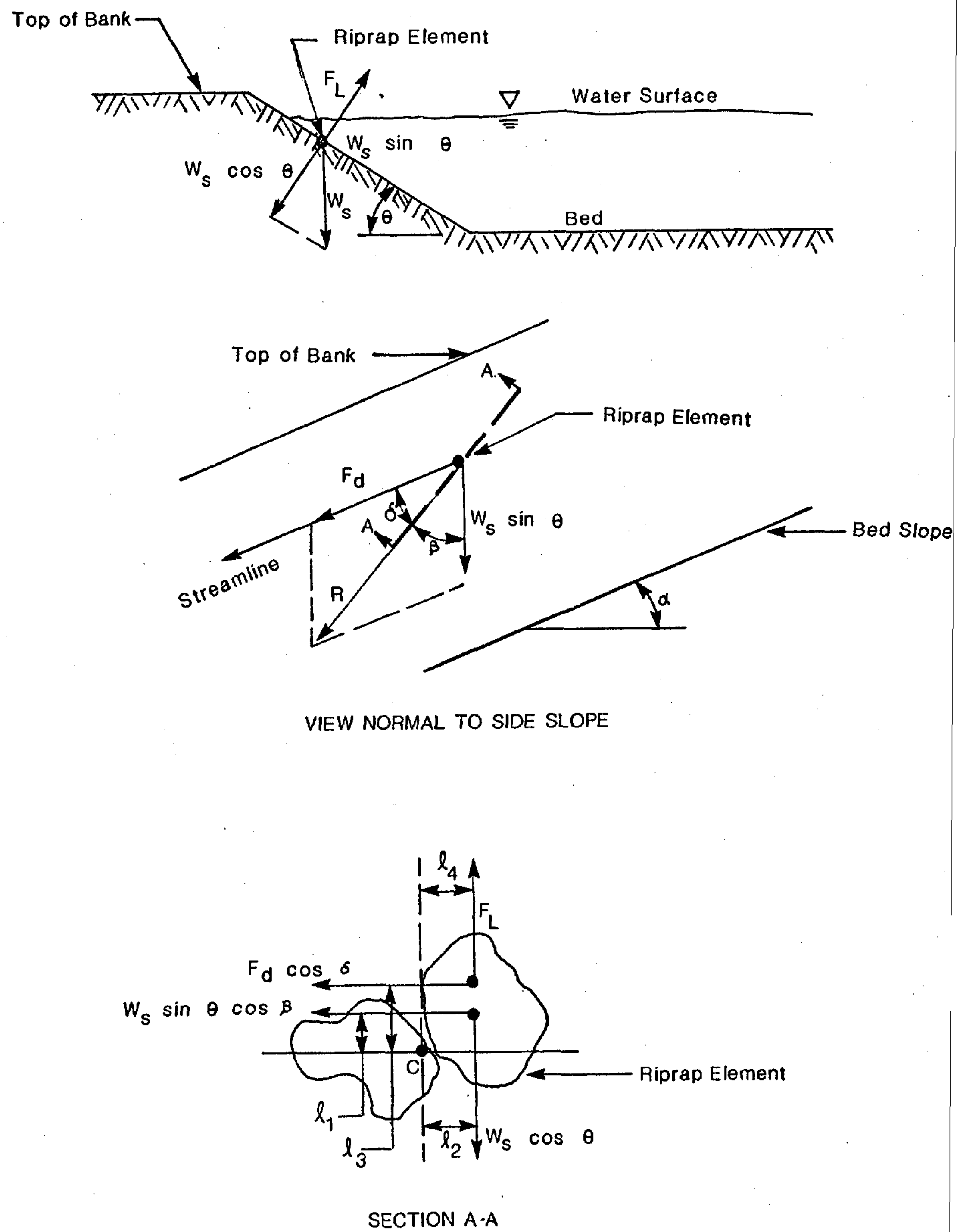


Figure 31. Hydraulic Forces Acting on a Riprap Element.

$$\eta = \frac{\tau_s}{F_* (\gamma_s - \gamma) D_{50}} \quad (31)$$

and $$\eta' = \eta \frac{1 + \sin(\alpha + \beta)}{2} \quad (32)$$

where τ_s = side slope shear stress;
F_* = dimensionless critical shear stress;
γ_s = specific weight of the rock;
γ = specific weight of water;
D_{50} = median diameter of the riprap;
η = stability number; and
η' = side slope stability number.

The side slope shear stress can be computed as:

$$\tau_s = K_1 \tau_o \quad (33)$$

K_1 can be obtained from chart 13. The angle of repose ϕ may be obtained from chart 12.

In the derivation given in Simons and Senturk (21), F_* was equal to 0.047. Recent studies (22) have shown F_* to take on much larger values for large-diameter particles in flow conditions having a high Reynolds number. Based on this work and Reynolds numbers encountered in steep gradient channels, the design procedure sets F_* equal to 0.15.

Solution Procedure

The solution procedure using the Bathurst resistance equation and factor-of-safety approach to riprap stability is outlined in the flow chart given in figure 31. A factor of safety of 1.5 is used. This value was used in developing the design charts of this manual (charts 15 through 18).

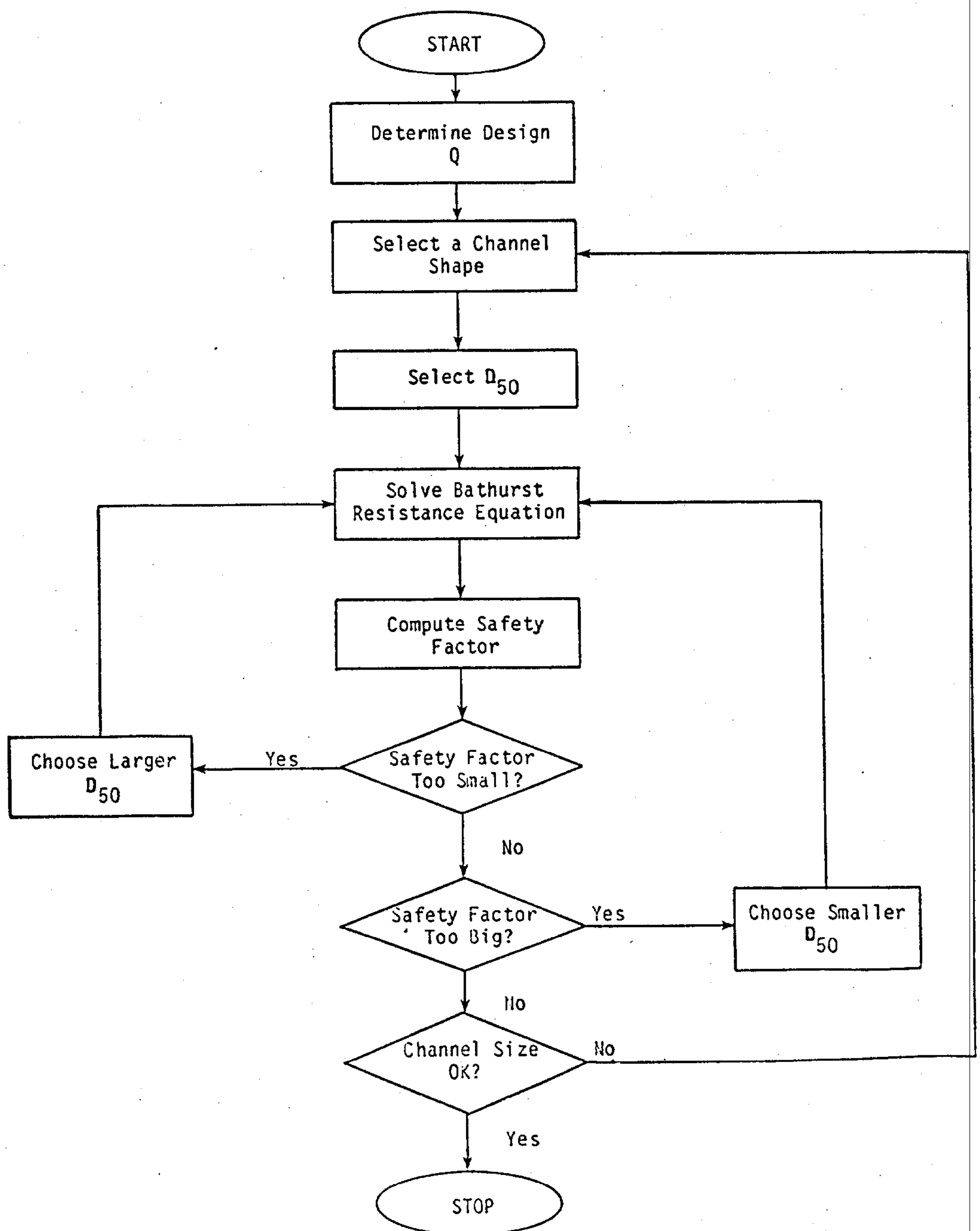


Figure 32. Steep Slope Design Procedure.

APPENDIX D

SUGGESTED GUIDE SPECIFICATIONS

The Specifications in this appendix are presented for the information of the designer, and should be modified as required for each individual design.

RIPRAP

Description

This work consists of furnishing materials and performing all work necessary to place riprap on bottoms and side slopes of channels, or as directed by the engineer.

The types of riprap included in this specification are:

a. Rock riprap. Riprap consists of stone dumped in place on a filter blanket or prepared slope to form a well graded mass with a minimum of voids.

b. Gravel channel lining. Gravel placed on filter blanket or prepared slope to form a well graded mass with a minimum of voids.

Materials

a. Rock riprap. Stone used for riprap shall be hard, durable, angular in shape; resistant to weathering and to water action; free from overburden, spoil, shale and organic material; and shall meet the gradation requirements specified. Neither breadth nor thickness of a single stone should be less than one-third its length. Rounded stone or boulders will not be accepted unless authorized by special provisions. Shale and stone with shale seams are not acceptable. The minimum weight of the stone shall be 155 pounds per cubic foot as computed by multiplying the specific gravity (bulk-saturated-surface-dry basis, AASHO Test T 85) times 62.3 pounds per cubic foot.

   The sources from which the stone will be obtained shall be selected well in advance of the time when the stone will be required in the work. The acceptability of the stone will be determined by service records and/or by suitable tests. If testing is required, suitable samples of stone shall be taken in the presence of the engineer at least 25 days in advance of the time when the placing of riprap is expected to begin. The approval of some rock fragments from a particular quarry site shall not be construed as constituting the approval of all rock fragments taken from that quarry.

   In the absence of service records, resistance to disintegration from the type of exposure to which the stone will be subjected will be determined by any or all of the following tests as stated in the special provisions:

   1. When the riprap must withstand abrasive action from material transported by the stream, the abrasion test in the Los Angeles

machine shall also be used. When the abrasion test in the Los Angeles machine (AASHO Test T 96) is used, the stone shall have a percentage loss of not more than 40 after 500 revolutions.

2. In locations subject to freezing or where the stone is exposed to salt water, the sulfate soundness test (AASHO Test T 104 for ledge rock using sodium sulfate) shall be used. Stones shall have a loss not exceeding 10 percent with the sulfate test after 5 cycles.

3. When the freezing and thawing test (AASHO Test 103 for ledge rock procedure A) is used as a guide to resistance to weathering, the stone should have a loss not exceeding 10 percent after 12 cycles of freezing and thawing.

Each load of riprap shall be reasonably well graded from the smallest to the maximum size specified. Stones smaller than the specified 10 percent size and spalls will not be permitted in an amount exceeding 10 percent by weight of each load.

Control of gradation will be by visual inspection. The contractor shall provide two samples of rock of at least 5 tons each, meeting the gradation specified. The sample at the construction site may be a part of the finished riprap covering. The other sample shall be provided at the quarry. These samples shall be used as a frequent reference for judging the gradation of the riprap supplied. Any difference of opinion between the engineer and the contractor shall be resolved by dumping and checking the gradation of two random truck loads of stone. Mechanical equipment, a sorting site, and labor needed to assist in checking gradation shall be provided by the contractor at no additional cost to the State.

b. Gravel channel lining. Gravel riprap shall consist of gravel or crushed rock of the thickness and gradations shown on project drawings. All material comprising the riprap shall be composed of tough durable particles reasonably free of thin, flat, or elongated particles and shall not contain organic matter.

Construction Requirements

a. General. Slopes to be protected by riprap shall be free of brush, trees, stumps, and other objectionable materials and be dressed to smooth surface. All soft or spongy material shall be removed to the depth shown on the plans or as directed by the engineer and replaced with approved native material. Filled areas will be compacted and a toe trench as shown on the plans shall be dug and maintained until the riprap is placed.

Protection for structured foundations shall be provided as early as the foundation construction permits. The area to be protected shall be cleared of waste materials and the surfaces to be protected prepared as shown on the plans. The type of riprap specified will be placed in accordance with these specifications as modified by the special provisions.

When shown on the plans, a filter blanket or filter fabric shall be placed on the prepared slope or area to be provided with foundation protection as specified before the stone is placed.

The contractor shall maintain the riprap until all work on the contract has been completed and accepted. Maintenance shall consist of the repair of areas where damaged by any cause.

b. Rock riprap. Stone for riprap shall be placed on the prepared slope or area in a manner which will produce a reasonably well-graded mass of stone with the minimum practicable percentage of voids. The entire mass of stone shall be placed so as to be in conformance with the lines, grades, and thicknesses shown on the plans. Riprap shall be placed to its full course thickness at one operation and in such a manner as to avoid displacing the underlying material. Placing of riprap in layers, or by dumping into chutes, or by similar methods likely to cause segregation, will not be permitted.

The larger stones shall be well distributed and the entire mass of stone shall conform to the gradation specified by the engineer. All material going into riprap protection shall be so placed and distributed so that there will be no large accumulations of either the larger or smaller sizes of stone.

It is the intent of these specifications to produce a fairly compact riprap protection in which all sizes of material are placed in their proper proportions. Hand placing or rearranging of individual stones by mechanical equipment may be required to the extent necessary to secure the results specified.

Unless otherwise authorized by the engineer, the riprap protection shall be placed in conjunction with the construction of the embankment with only sufficient lag in construction of the riprap protection as may be necessary to allow for proper construction of the portion of the embankment protected and to prevent mixture of embankment and riprap. The contractor shall maintain the riprap protection until accepted, and any material displaced by any cause shall be replaced to the lines and grades shown on the plans at no additional cost to the State.

When riprap and filter material are dumped under water, thickness of the layers shall be increased as shown on the plans; and methods shall be used that will minimize segregation.

c. Gravel channel lining. Gravel for riprap shall be placed on the prepared slope or area.

Measurement for Payment

The quantity of riprap to be paid for, of specified thickness and extent, in place and accepted, shall be measured by the number of cubic yards as computed from surface measurements parallel to the riprap surface and thickness measured normal to the riprap surface. Riprap placed outside the specified limits will not be measured or paid for, and the contractor may be required to remove and dispose of the excess riprap without cost to the State.

Basis of Payment

Quantities shall be paid for at the contract unit price per cubic yard and shown in the bid schedule which price shall be full compensation for furnishing all material, tools, and labor; the preparation of the subgrade; the placing of the riprap; the grouting when required; and all other work incidental to finished construction in accordance with these specifications.

WIRE ENCLOSED RIPRAP

Description

This work will consist of furnishing all materials and performing all work necessary to place wire enclosed riprap on bottoms and side slopes of channels or as directed by the engineer. Wire enclosed riprap consists of mats or baskets fabricated from wire mesh, filled with stone, connected together, and anchored to the slope. Details of construction may differ depending upon the degree of exposure and the service, whether used for revetment or used as a toe protection for the other types of riprap.

Materials

Material requirements shall meet those given for riprap, except for size and gradation of stone. Stone used shall be well graded and the smallest dimension of 70 percent of stone, by weight, shall exceed the wire mesh opening. The maximum size of stone, measured normal to the slope, shall not exceed the mat or basket thickness.

Wire mesh shall be galvanized woven fencing conforming to the specifications for fence fabric, and shall be of the gage and dimensions shown on the plans. Ties and lacing wire shall be No. 9 gage galvanized unless otherwise specified.

Construction Requirements

Construction requirements shall meet those given for rock riprap. Wire enclosed segments shall be hand- or machine-formed to the dimensions shown on the plans. These units shall be placed, laced, and filled to provide a uniform, dense, protective coat over the area specified.

Perimeter edges of wire enclosed units are to be securely selvedged or bound so that the joints formed by tying the selvedges have approximately the same strength as the body of the mesh. Wire-enclosed units shall be tied to its neighbors along all contacting edges at 1-foot intervals in order to form a continuous connecting structure.

Mattresses and baskets on channel side slopes should be tied to the banks by anchor stakes driven 4 feet into tight soil (clay) and 6 feet into loose soil (sand). The anchor stakes should be located at the inside corners of mattress or basket diaphragms along an upslope (highest) wall, so that the stakes are an integral part of the mattress or basket. The exact maximum spacing of the stakes depends upon the configuration of the mattress or basket; however, the following is the minimum spacing: Stakes every 6 feet along and down the slope for slopes 2.5:1 and steeper, and every 9 feet along and down the slope for slopes flatter than 2.5:1.

Channel linings should be tied to the channel banks with wire-enclosed riprap counterforts at least every 12 feet. Counterforts should be keyed at least 12 inches into the existing banks with slope mattress or basket linings and should be keyed at least 3 feet by turning the counterfort endwise when the lining is designed to serve as a retaining wall.

Measurement for Payment

The quantity of wire-enclosed riprap of specified thickness and extent in place and accepted, shall be measured by the number of square yards obtained by measurements parallel to the riprap surface. Riprap placed outside the specified limits will not be measured or paid for, and the contractor may be required to remove and dispose of the excess riprap without cost to the State.

Basis of Payment

Quantities shall be paid for at the contract unit price per square yard and shown in the bid schedule, which price shall be full compensation for furnishing all material, tools, and labor; the preparation of the subgrade; the placing of the stone; and all other work incidental to finished construction in accordance with these specifications.

WOVEN PAPER NET

Description

This work shall consist of furnishing materials and all work necessary to install woven paper net fabric for erosion control on roadway, ditches, or slopes, or as directed by the engineer.

Materials

Materials shall consist of knitted plastic net, interwoven with paper strips. The yarn shall be of photodegradable synthetic types and the paper shall be biodegradable. Staples shall be 6 inches and 12 inches in length, and composed of high carbon iron.

Construction Requirements

Woven paper net shall be placed on the prepared slope or seedbed area which has been prepared and leveled according to various other sections in these specifications. If seeding and fertilizer are in the provisions, they should be applied immediately before laying the fabric.

Woven paper net shall be applied on slopes with the fabric running vertical from the top of the slope. In drainages, woven paper net shall be applied in the direction of the water flow. The fabric shall be secured and buried in a 4-inch trench, 1 foot back from the crown and at the bottom of the slope. Heavy gauge staples shall secure the fabric at 9-inch intervals along the edges and overlaps and at 3-foot intervals down the center of the fabric roll. Rolls shall overlap 4 inches. Woven paper net shall be draped rather than stretched across the surface.

The contractor shall maintain the fabric blanket until all work on the contract has been completed and accepted. Maintenance shall consist of the repair of areas where damaged by any cause. All damaged areas shall be repaired to reestablish the condition and grade of the soil prior to application of the covering and shall be refertilized, reseeded, and remulched as directed.

Measurement for Payment

The quantity of woven paper net, including staples, completely in place and accepted, shall be measured by the square yard of finished surface. No allowance will be made for overlap. Woven paper net placed outside the specified limits will not be measured or paid for and the contractor may be required to remove or dispose of the excess without cost to the State.

Basis of Payment

Quantities shall be paid for at the contract unit price per square yard which price shall be full compensation for furnishing all materials, tools, and labor; the preparation of the subgrade; the placing of the woven paper net; and all other work incidental to finished construction in accordance with these specifications.

JUTE NET

Description

This work consists of furnishing materials and performing all work necessary to install jute net on roadway ditches or slopes or as directed by the engineer.

Materials

Jute net shall consist of heavy mesh of a uniform open plain weave of unbleached, smolder-resistant, single jute yarn. The yarn shall be of a loosely twisted construction having an average twist of not less than 1.6 turns per inch and shall not vary in thickness by more than one-half its normal diameter. The jute net shall be furnished in approximately 90-pound rolled strips and shall meet the following requirements:

Length	approximately 75 yards
Width	48 inches ± 1 inch
	78 warp ends per width of cloth
	41 weft ends per yard
Weight	1.22 pounds per linear yard with ± 5 percent

Staples shall be 3, 6, and 12 inches in length, and composed of high carbon iron or as specified by the engineer.

Construction Requirements

The blankets shall be placed in designated locations immediately after seeding and mulching operations have been completed. The material shall be applied smoothly but loosely to the soil surface without stretching. The upslope end of each piece of jute net shall be buried in a narrow trench 6 inches deep. After the jute is buried, the trench shall be firmly tamped closed.

In cases where one roll of jute mesh ends and a second roll starts, the upslope piece should be brought over the buried end of the second roll so that there is a 12-inch overlap to form a junction slot. Where two or more widths of jute net are applied side by side, an overlap of at least 4 inches must be made.

Check slots should be made before the jute net is rolled out. A narrow trench should be dug across the slope perpendicular to the direction of flow. A piece of jute, cut the same length as the trench, is folded lengthwise. The fold is placed in the trench and the trench is tamped closed. The portion of the jute remaining above ground is unfolded and laid flat on the soil surface. Check slots will be spaced so that one check slot or junction slot occurs without each 50 feet of slope. Overlaps which run down the slope, outside edges and centers shall be stapled on 2-foot intervals. Each width of jute net will have a row of staples down the center as well as along each edge. Check slots and junction slots will be stapled across at 6-inch intervals.

For extra hard soil, use 3-inch sharp-pointed fence-type staples, composed of hardened steel.

The jute net must be spread evenly and smoothly and be in contact with the seeded area at all points. The contractor shall maintain the jute mesh until all work on the contract has been completed and accepted. Maintenance shall consist of the repair of areas where damaged by any cause. All damaged areas shall be repaired to reestablish the condition and grade of the soil prior to application of the covering and shall be refertilized, reseeded and remulched as directed.

Measurement of Payment

The quantity of jute net, including staples, completely in place and accepted, shall be measured by the square yard of finished surface. No allowance will be made for overlap. Mat placed outside the specified limits will not be measured or paid for, and the contractor may be required to remove and dispose of the excess mat without cost to the State.

Basis of Payment

Quantities shall be paid for at the contract unit price per square yard which price shall be full compensation for furnishing all materials, tools, and labor; the preparation of the subgrade; the placing of the jute net; and all other work incidental to finished construction in accordance with these specifications.

FIBERGLASS ROVING

Description

This work consists of furnishing materials and performing all work necessary to install fiberglass roving on roadway ditches or slopes, or as directed by the engineer.

Materials

a. General requirements. The material shall be formed from continuous fibers drawn from molten glass, coated with a chrome-complex sizing compound, collected into strands and lightly bound together into roving without the use of clay, starch, or like deleterious substances. The roving shall be wound into a cylindrical package approximately 1 foot high in such a manner that the roving can be continuously fed from the center of the package through an ejector driven by compressed air and expanded into a mat of glass fibers on the soil surface. The material shall contain no petroleum solvents or other agents known to be toxic to plant or animal life.

   Liquid asphaltic materials shall conform to the requirements of AASHTO M81, M82, and M141 for the designated types and grades.

b. Detailed requirements. The fiberglass roving shall conform to these detailed requirements:

Property	Limits	Test Method
Strands/Rove	56-64	End Count
Fibers/Strand	184-234	
Fiber Diameter, inch (Trade Designation-G)	0.00035-0.0004	ASTM D 578
Yd/lb of Sand	13,000-14,000	ASTM D 578
Yd/lb of Rove	210-230	ASTM D 578
Organic content, percent maximum	0.75	ASTM D 578
Package Weight, lb	30-35	ASTM D 578

Construction Requirements

The fiberglass roving shall be applied over the designated area within 24 hours after the normal seeding operations have been completed.

The fiberglass roving shall be spread uniformly over the designated area to form a random mat of continuous glass fibers at the rate of 0.25 pounds per cubic yard. This rate may be varied as directed by the engineer.

The fiberglass roving shall be anchored to the ground with the asphaltic materials applied uniformly over the glass fibers at the rate of 0.25 gallon per square yard. This rate may be varied as directed by the engineer.

The upgrade end of the lining shall be buried to a depth of 1 foot to prevent undermining. Instructions for slope and ditch protection may be stipulated by the engineer to fit the field conditions encountered.

The contractor shall maintain the roving until all work on the contract has been completed and accepted. Maintenance shall consist of the repair of areas where damaged by any cause. All damaged areas shall be repaired to reestablish the condition and grade of the soil prior to application of the covering and shall be refertilized, reseeded and remulched as directed.

Measurement for Payment

Fiberglass roving will be measured by the pound, and the quantity to be measured will be that actually used on the project. Roving placed outside the specified limits will not be paid for and the contractor may be required to remove and dispose of the excess roving without cost to the State.

Basis of Payment

Quantities shall be paid for at the contract unit price per pound and shown in the bid schedule, which price shall be full compensation for furnishing all materials, tools, and labor; the preparation of the subgrade; the placing of the roving; and all other work incidental to finished construction in accordance with these specifications.

CURLED WOOD MAT

Description

This work consists of furnishing materials and performing all work necessary to install curled wood mat on roadway ditches or slopes, or as directed by the engineer.

Materials

All materials shall meet the requirements of the following specifications. The blanket shall consist of a machine produced mat of curled wood excelsior of 80 percent, 8 inches or longer fiber length with consistent thickness and the fiber evenly distributed over the entire area of the blanket. The top side of the blanket shall be covered with a biodegradable extruded plastic mesh. The blanket shall be made smolder resistant without the use of chemical additives.

Width	48 inch ± 1 inch
Length	180 ft average
Weight per roll	78 lb + 8 lb
Weight per yd^2	0.875 lb ± 10 percent
Volume per roll	80 yd^3, average

Pins and staples shall be made of high carbon iron wire 0.162 or larger in diameter. "U" shaped staples shall have legs 8 inches long and a 1-inch crown. "T" shaped pins shall have a minimum length of 8 inches after bending. The bar of the "T" shall be at least 4 inches long with the single wire end bent downward approximately 3/4-inch.

Construction Requirements

The area to be covered shall be properly prepared, fertilized, and seeded before the blanket is placed. When the mat is unrolled, the netting shall be on top and the fibers shall be in contact with the soil. In ditches, blankets shall be unrolled in the direction of the flow of water. The end of the upstream blanket shall overlap the buried end of the downstream blanket a maximum of 8 inches and a minimum of 4 inches, forming a junction slot. This junction slot shall be stapled across at 8-inch intervals. Adjoining blankets (side by side) shall be offset 8 inches from center of ditch and overlapped a minimum of 4 inches. Use 6 staples across the start of each roll, at 4-foot intervals, alternating the center row so that the staples form an "X" pattern. A common row of staples shall be used on adjoining blankets.

The contractor shall maintain the blanket until all work on the contract has been completed and accepted. Maintenance shall consist of the repair of areas where damaged by any cause. All damaged areas shall be repaired to reestablish the condition and grade of the soil prior to application of the covering and shall be refertilized, reseeded, and remulched as directed.

Measurement for Payment

Curled wood mat, including staples, completely in place and accepted, will be measured by the square yard of finished surface. No allowance will be made for overlap. Mat placed outside the specified limits will not be measured or paid for, and the contractor may be required to remove and dispose of the excess without cost to the State.

Basis of Payment

Quantities shall be paid for at the contract unit price per square yard and shown in the bid schedule, which price shall be full compensation for furnishing all materials, tools, and labor; the preparation of the subgrade; the placing of the matting; and all other work incidental to finished construction in accordance with these specifications.

STRAW WITH NET

Description

This work consists of furnishing materials and performing all work necessary to install straw with net on roadway ditches or slopes, or as directed by the engineer.

Materials

a. Straw. Straw shall be derived from wheat, oats, or barley. The contractor shall furnish evidence that clearance has been obtained from the county agricultural commissioner, as required by law, before straw obtained from outside the county in which it is to be used is delivered to the site of the work. Straw that has been used for stable bedding shall not be used.

b. Plastic net shall be an extruded polypropylene or other approved plastic material, extruded in such a manner as to form a net of 3/4-inch minimum square openings. The net shall be furnished in rolls to meet the following characteristics:

Width	48 inch, minimum
Length	50 yard, minimum, convenient lengths
Weight	2.6 lb/1,000 ft^2, minimum

c. Pins and staples shall be made of high carbon iron wire 0.162 or larger in diameter. "U" shaped staples shall have legs 8 inches long and a 1-inch crown. "T" shaped pins shall have a minimum length of 8 inches after bending. The bar of the "T" shall be at least 4 inches long with the single wire end bent downward approximately 3/4-inch.

Construction Requirements

Plastic net shall be placed as soon as possible after mulching operations have been completed in locations designated in the plans. Net shall be used only to secure straw mulch to the finished slope or ditch.

Preparation shall include all the work required to make ready the areas for incorporating straw. Areas on which straw is to be applied shall be prepared such that the straw will be incorporated into the soil to the degree specified. Removing and disposing of rocks and debris from embankments constructed as part of the work will be considered as included in the contract price paid per ton for straw and no additional compensation will be allowed therefore.

Straw shall be uniformly spread at the rate specified in the special provisions. When weather conditions are suitable, straw may be pneumatically applied by means of equipment which will not render the straw unsuitable for incorporation into the soil.

Straw shall be incorporated into the soil with a roller equipped with straight studs, made of approximately 7/8-inch steel plate, placed approximately 8 inches apart, and staggered. The studs shall not be less than 6 inches long or more than 6 inches wide, and shall be rounded to prevent withdrawing the straw from the soil. The roller shall be of such weight as to incorporate the straw sufficiently into the soil so that the straw will not support combustion and will leave a uniform surface.

The net shall be applied smoothly but loosely on the mulched surface without stretching. The net shall be unrolled from the top to the bottom of the slope. The top edge of the net shall be buried and stapled at the top end of the slope in a narrow trench 6 inches deep. After the edge is buried and stapled, the trench shall be backfilled and tamped.

In cases where one roll of net ends and a second roll starts, the upslope piece shall be brought over the start of the second roll so that there is a 4-inch overlap.

Where two or more widths of net are applied side by side, an overlap of at least 4 inches must be made. Insert 1 staple every foot along top and bottom of edges of the net. Also, insert staples over 4 feet on each edge and down center of net so that the staples alternate between edges and center to form an "X" shape pattern.

The contractor shall maintain the straw with net until all work on the contract has been completed and accepted. Maintenance shall consist of the repair of areas where damaged by any cause. All damaged areas shall be repaired to reestablish the condition and grade of the soil prior to application of the covering and shall be refertilized, reseeded, and remulched as directed.

Measurement for Payment

Straw with net, including staples, completely in place and accepted, will be measured by the square yard of finished surface. No allowance will be made for overlap. Straw and net placed outside the specified limits will not be measured or paid for, and the contractor may be required to remove and dispose of the excess net without cost to the State.

Basis of Payment

Quantities shall be paid for at the contract unit price per square yard and shown in the bid schedule which price shall be full compensation for furnishing all materials, tools, and labor; the preparation of the subgrade; and all other work incidental to finished construction in accordance with these specifications.

SYNTHETIC MAT

Description

This work consists of furnishing materials and performing all work necessary to install nylon mat on roadway ditches or slopes, or as directed by the engineer.

Materials

Synthetic mat shall consist of three-dimensional structure of entangled nylon monofilaments, melt-bonded at their intersections, forming a stable mat of suitable weight and configuration. The mat shall be crush-resistant, pliable, resilient, water-permeable, and highly resistant to chemicals and environmental degradation. The mat shall comply with the following physical properties:

Material type	Nylon 6 plus a minimum content of 0.5 percent by weight of carbon black
Filament diameter	0.0157 inch, minimum
Weight	0.747 $\pm$ 0.075 lb/yd^2
Thickness	0.70 inch, minimum
Nominal width of roll	38 inch
Nominal length of roll	109 yard
Color	Black
Tensile properties[1]	
Strength	
Length direction	7.5 lb/inch, minimum
Width direction	4.4 lb/inch, minimum
Elongation	
Length direction	50 percent, minimum
Width direction	50 percent, minimum
Resiliency[2]	
30 minute recovery (3 cycles)	80 percent, minimum

Pins shall be 1 inch x 2 inch x 12 inch wedge-shaped wood stakes or 12 inch x 12 inch x 6 inch, 0.162-inch gauge or larger, one-piece or two-piece, ungalvanized steel "T" pins.

Construction Requirements

All surfaces to be protected shall be graded and finished so as to be stable and firm. Prepared surfaces that become crusted shall be reworked to an acceptable condition before placing the mat.

---

[1] ASTM D 1682 Strip test procedure modified to obtain filament bond strength to indicate tensile properties.

[2] Compression load cycling of 100 $16/in^2$ on 2 inch x 2 inch sample size, crosshead speed of 2 in/min.

Synthetic mat used as a ditch lining shall be applied with the length of roll laid parallel to the flow of water. Start the installation with the initial strip placed in the center of the ditch to avoid an overlap in the center of the ditch. Where more than one width is required, a longitudinal lap joint of not less than 3 inches shall be used, with the upslope width on top. All lap joints and upslope edges shall be pinned or staked at intervals of 3 feet or less.

All wood stakes shall be driven to within 2 inches of the ground surface. All steel pins shall be driven flush to the ground surface.

An anchor slot shall be placed at the upslope and downslope ends of the mat placement. At least 12 inches of the end of the mat shall be buried vertically in a slot dug in the soil. The mat shall be secured in the anchor slot by pins or stakes at intervals of 3 feet or less prior to burying. The soil shall be firmly tamped against the mat in the slot.

Successive lengths of mat shall be overlapped at least 3 feet, with the upstream length on top. Pin or stake the overlap by placing 3 pins or stakes evenly spaced across the end of each of the overlapping lengths and by placing 3 pins or stakes across the width of the center of overlap area. Check slots shall be constructed by placing a tight fold at least 8 inches vertically into the soil. Check slots shall be spaced so that a check slot occurs within each 25 feet. Pin or stake the mat in the check slot at each edge overlap and in the center of mat.

Upslope edges of mat used as ditch lining shall terminate on 6-inch wide horizontal shelves running parallel to the axis of the ditch for the full length of the ditch. Edges of the mat shall be pinned or staked at 3-foot intervals, backfilled with soil, and tamped to original slope.

After the mat has been placed, the area shall be evenly seeded as specified, allowing the seeds to drop to the grade through the openings in the mat.

The contractor shall maintain the blanket until all work on the contract has been completed and accepted. Maintenance shall consist of the repair of areas where damaged by any cause.

Measurement for Payment

Synthetic mat, including pins or stakes, complete, in place, and accepted, will be measured by the square yard of finished surface. Mat placed outside the specified limits will not be measured or paid for and the contractor may be required to remove and dispose of the excess mat without cost to the State.

Basis of Payment

Quantities shall be paid for at the contract unit price per square yard and shown in the bid schedule, which price shall be full compensation for furnishing all materials, tools, and labor; the preparation of the subgrade; placing of the mats; and all other work incidental to finished construction in accordance with these specifications.

FILTER BLANKET

Description

This work consists of furnishing materials and performing all work necessary to install filter blanket on roadway ditches or slopes, or as directed by the engineer.

Materials

The filter blanket will consist of one or more layers of gravel, crushed rock, or sand, of the thickness shown on the plans. The gradation of material in each layer of the filter blanket shall meet the requirements of the special provisions. All material comprising the filter blanket shall be composed of tough, durable particles; reasonably free from thin, flat, and elongated pieces; and shall be free from organic matter.

Construction Requirements

A filter blanket shall be placed on the prepared slope or area to the full specified thickness of each layer in one operation, using methods which will not cause segregation of particle sizes within the filter material. The surface of the finished layer should be reasonably even and free from mounds or windows. Multiple layers of filter material, when shown on the plans, shall be placed in the same manner, using methods which will not cause mixture of the material in the different layers.

The filter blanket shall be placed in accordance with various sections of these specifications requiring the use of a filter blanket or as specified by the engineer.

The contractor shall maintain the blanket until all work on the contract has been completed and accepted. Maintenance shall consist of the repair of areas where damaged by any cause.

Measurement for Payment

The quantity of filter blanket to be paid for, of specified thickness and extent, in place and accepted, shall be measured by the number of cubic yards as computed from surface measurement parallel to the riprap surface and thickness measured normal to the riprap surface. Blanket placed outside the specified limits will not be measured or paid for, and the contractor may be required to remove and dispose of the excess without cost to the State.

Basis of Payment

Quantities shall be paid for at the contract unit price per cubic yard, which price shall be full compensation for furnishing all materials, tools, and labor; the preparation of the subgrade; placing of the filter blanket; and all other work incidental to finished construction in accordance with these specifications.

ENGINEERING FABRIC

Description

This work consists of furnishing materials and performing all work necessary to install engineering fabric on roadway ditches or slopes, or as directed by the engineer.

Materials

The filter fabric shall be manufactured of polyester, nylon, or polypropylene material, or a combination thereof. The material shall not act as a wicking agent, shall be permeable, and shall conform to the following criteria:

	For Edge Drains	For Underdrains
Weight, ounces/yd^2, minimum ASTM Designation D 1910	40	4.0
Grab tensile strength (1-inch grip), lb, minimum[1]	50	90
Elongation, percent, minimum ASTM Designation, D 1682	10	30
Toughness, lb, minimum (percent elongation x grab tensile strength)	3,000	4,000

Construction Requirements

Engineering fabric shall be placed to the specified thickness in accordance with various sections of these specifications requiring the use of an engineering fabric or as specified by the engineer.

The contractor shall maintain the fabric until all work on the contract has been completed and accepted. Maintenance shall consist of the repair of areas where damaged by any cause.

Measurement for Payment

Engineering fabric to be paid for, of specified thickness and extent, in place and accepted, will be measured in square yards in accordance with the provisions in the various sections of these specifications, requiring the use of engineering fabric.

Basis of Payment

Quantities shall be paid for in accordance with the provisions in the various sections of these specifications requiring the use of engineering fabric.

[1] In each direction

GLOSSARY

ANGLE OF REPOSE. Angle of slope formed by particulate material under the critical equilibrium condition of incipient sliding.

APPARENT OPENING SIZE (AOS). Measure of the largest effective opening in an engineering fabric, as measured by the size of a glass bead where five percent or less by weight will pass through the fabric (formerly called the equivalent opening size, EOS).

COMPACTION. The closing of pore spaces among the particles of soil and rock, generally caused by running heavy equipment over the soil during construction.

DEPTH OF FLOW. Vertical distance from the bed of a channel to the water surface.

DESIGN DISCHARGE. Discharge at a specific location defined by an appropriate return period to be used for design purposes.

ENGINEERING FABRIC. Permeable textile (or filter fabric) used below riprap to prevent piping and permit natural seepage to occur.

FILTER BLANKET. One or more layers of graded noncohesive material placed below riprap to prevent soil piping and permit natural drainage.

FREEBOARD. Vertical distance from the water surface to the top of the channel at design condition.

GABION. Compartmented rectangular containers made of galvanized steel hexagonal wire mesh and filled with stone.

HYDRAULIC RADIUS. Flow area divided by wetted perimeter.

HYDRAULIC RESISTANCE. Resistance encountered by water as it moves through a channel, commonly described by Manning's n.

HYDROSTATIC PRESSURE. Pressure exerted at a depth below the water surface for flow at constant velocity or at rest.

INCIPIENT MOTION. Conditions at that point in time when any increase in factors responsible for particle movement causes motion.

LINING, COMPOSITE. Combination of lining materials in a given cross section (e.g., riprap in low-flow channel and vegetated upper banks).

LINING, FLEXIBLE. Lining material with the capacity to adjust to settlement typically constructed of a porous material that allows infiltration and exfiltration.

LINING, PERMANENT. Lining designed for long term use.

LINING, RIGID. Lining material with no capacity to adjust to settlement constructed of nonporous material with smooth finish that provides a large conveyance capacity (e.g., concrete, soil cement).

LINING, TEMPORARY. Lining designed for short term utilization, typically to assist in development of a permanent vegetative lining.

NORMAL DEPTH. Depth of a uniform channel flow.

PERMEABILITY. Property of a soil that enables water or air to move through it.

RETARDANCE CLASSIFICATION. Qualitative description of the resistance to flow offered by various types of vegetation.

RIPRAP. Broken rock, cobbles, or boulders placed on side slopes or in channels for protection against the action of water.

RIPRAP, DUMPED. Consists of stone or graded broken concrete dumped in place on a filter blanket or prepared slope to form a well-graded mass with a minimum of voids.

RIPRAP, GROUTED. Consists of riprap with all or part of the interstices filled with portland cement mortar.

RIPRAP, WIRE-ENCLOSED. Consists of wire baskets filled with stone, connected together, and anchored to the slope.

ROADWAY CHANNEL. Stabilized drainageway used to collect water from the roadway and adjacent areas and to deliver it to an inlet or main drainageway.

SHEAR STRESS. Force developed on the wetted area of the channel that acts in the direction of the flow; force per unit wetted area.

SHEAR STRESS, CHANNEL. Value of shear stress occurring in a channel section for a given set of hydraulic conditions.

SHEAR STRESS, PERMISSIBLE. Force at which the channel lining will fail.

SIDE SLOPE. Slope of the sides of a channel. It is customary to name the horizontal distance first as 1.5 to 1.0, or frequently 1-1/2:1, meaning a horizontal distance of 1.5 feet to 1-foot vertical.

SUPERELEVATION. Local increases in water surface on the outside of a bend.

TRACTIVE FORCE. Force developed due to the shear stress acting on the perimeter of a channel section which acts in the direction of flow on the channel bed. Equals the shear stress on the channel section multiplied by the wetted channel area.

UNIFORM FLOW. The flow condition where the rate of head loss due to friction is equal to bed slope of the channel (i.e., $S_f = S_o$ where S_f is the friction slope and S_o is the bed slope).

VELOCITY, MEAN. Discharge divided by the area of the water cross section.

VELOCITY, PERMISSIBLE. Mean velocity that will not cause serious erosion of the channel.

REFERENCES

(1) Federal Highway Administration, Bureau of Public Roads, "Design of Roadside Drainage Channels." Hydraulic Design Series No. 3, Hydraulics Branch, 1965.

(2) Federal Highway Administration, "Hydraulic Design of Energy Dissipators for Culverts and Channels." Hydraulic Engineering Circular No. 14, Hydraulics Branch, 1983.

(3) Federal Highway Administration, "Use of Riprap for Bank Protection." Hydraulic Engineering Circular No. 11, 1987.

(4) Soil Conservation Service, "Handbook of Channel Design for Soil and Water Conservation." SCS-TP-61, Stillwater, Oklahoma, 1954.

(5) N. Kouwen, R.M. Li, and D.B. Simons, "Velocity Measurements in a Channel Lined with Flexible Plastic Roughness Elements." Technical Report No. CER79-80-RML-DBS-11, Department of Civil Engineering, Colorado State University, Fort Collins, Colorado, 1980.

(6) N. Kouwen, T.E. Unny, and H.M. Hill, Flow Retardance in Vegetated Channel. J. Irrigation and Drainage Division, IR2, 1969, pp. 329-342.

(7) V.T. Chow, Open Channel Hydraulics (New York, McGraw-Hill Book Company, 1959).

(8) A.G. Anderson, A.A. Painta, and J.T. Davenport, "Tentative Design Procedure for Riprap Lined Channels." NCHRP Report No. 108, Highway Research Board, National Academy of Sciences, Washington, D.C., 1970.

(9) U.S. Bureau of Reclamation, Stable Channel Profiles. Lab. Report No. Hyd. 325, September 27, 1951.

(10) O.J. Olsen and Q.L. Florey, "Sedimentation Studies in Open Channels: Boundary Shear and Velocity Distribution by Membrane Analogy, Analytical and Finite-Difference Methods." Reviewed by D. McHenry and R.E. Glover, U.S. Bureau of Reclamation, Laboratory Report N. SP-34, August 5, 1952.

(11) M.A. Nouh and R.D. Townsend, "Shear Stress Distribution in Stable Channel Bends." Journal of the Hydraulics Division, ASCE, Vol. 105, No. HY10, Proc. Paper 14898, October, 1979, pp. 1233-1245.

(12) E. Lane, "Design of Stable Channels," Transactions ASCE, Vol. 120, 1955.

(13) R.L. Cox, R.C. Adams, and T.B. Lawson, "Erosion Control Study, Part II, Roadside Channels." Louisiana Department of Highways, in Cooperation with U.S. Department of Transportation, Federal Highway Administration, 1971.

(14) J.C. McWhorter, T.G. Carpenter, and R.N. Clark, "Erosion Control Criteria for Drainage Channels." Conducted for Mississippi State Highway Department in Cooperation with U.S. Department of Transportation, Federal Highway Administration, by the Agricultural and Biological Engineering Department, Agricultural Experiment Station, Mississippi State University, State College, Mississippi, 1968.

(15) K.G. Thibodeaux, "Performance of Temporary Ditch Linings." Iterim Reports 1 to 17, Prepared for Federal Highway Administration by U.S. Geological Survey, Gulf Coast Hydroscience Center and Computer Science Corporation, 1982 to 1985.

(16) E.T. Smerdon and R.P. Beaseley, "The Tractive Force Theory Applied to Stability of Open Channels in Cohesive Soils." Agricultural Experiment Station, Research Bulletin No. 715, University of Missouri, Columbia, Missouri, October 1959.

(17) B.M. Galloway, "Pavement and Geometric Design Criteria for Minimizing Hydroplaning." Texas Transportation Institute, Texas A&M University, Federal Highway Administration, Report No. FHWA-RD-30, December 1979.

(18) "Geotextile Engineering Manual, Course Text, FHWA, 1985.

(19) J.C. Blodgett and C.E. McConaughy, "Evaluation of Design Practices for Rock Riprap Protection of Channels near Highway Structures." U.S. Geological Survey, Prepared in Cooperation with the Federal Highway Administration Preliminary Draft, Sacramento, California, 1985.

(20) J.C. Bathurst, R.M. Li, and D.B. Simons, "Resistance Equation for Large-Scale Roughness." Journal of the Hydraulics Division, ASCE, Vol. 107, No. HY12, Proc. Paper 14239, December 1981, pp. 1593-1613.

(21) D.B. Simons and F. Senturk, Sediment Transport Technology (Fort Collins, Colorado: Water Resources Publications, 1977).

(22) S.Y. Wang and H.W. Shen, "Incipient Sediment Motion and Riprap Design." Journal of Hydraulics Division, ASCE, Vol. 111, No. 3, March 1985, pp. 52-538.

(23) "Hydraulic Analysis and Design of Open Channels," Highway Drainage Guidelines, Volume VI, American Association of State Highway Officials, 1982.