

Chapter 9  
ROADSIDE CHANNELS

**SOUTH DAKOTA DRAINAGE MANUAL**

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## Chapter 9

# ROADSIDE CHANNELS

### 9.1 INTRODUCTION

Open channels are a natural or constructed conveyance for water in which:

- the water surface is exposed to the atmosphere, and
- the gravity force component in the direction of motion is the driving force.

There are various types of open channels that may be used in highway design. Artificial channels (also called “constructed” or “man-made” channels) include roadside channels, depressed median channels, culvert tailwater channels, irrigation channels and drainage ditches, which are:

- constructed channels with regular geometric cross sections, and
- unlined or lined with artificial or natural material to protect against erosion.

Stream channels are usually:

- natural channels with their size and shape determined by natural forces,
- compound in cross section with a main channel for conveying low flows and a floodplain to transport flood flows, and
- shaped in cross section and plan form by the long-term history of sediment load and water discharge that they experience.

Although the principles of open-channel flow are the same regardless of the channel type, stream channels and artificial channels (primarily roadside channels) are treated separately in this *Manual*:

- Chapter 9 applies to roadside channels and culvert tailwater channels.
- [Chapter 14 “Bridge Hydraulics”](#) discusses the assessment of stream stability for natural streams. See [Section 14.4](#).
- [Chapter 15 “Bank Protection”](#) discusses potential remedial treatments if the assessment (i.e., based on [Section 14.4](#)) of a natural stream identifies a problem.

To provide consistency within this Chapter, the symbols provided in [Figure 9.1-A](#) will be used. These symbols have been selected because of their wide use in channel hydraulics.

<b>Symbol</b>	<b>Definition</b>	<b>Units</b>
A	Cross sectional area	sq ft
B	Bottom width	ft
d	Hydraulic depth	ft
$d_c$	Critical depth of flow	ft
$D_{50}$	Median diameter of riprap, or median grain size	in
E	Specific energy	ft
Fr	Froude number	—
g	Acceleration due to gravity	ft/sec <sup>2</sup>
h	Stage (water surface height)	ft
$h_L$	Head loss	ft
K	Conveyance capacity	cfs
$k_s$	Roughness height	ft
L	Channel reach length	ft
n	Manning's roughness coefficient	—
P	Wetted perimeter	ft
Q	Discharge (flow rate)	cfs
q	Discharge per unit width	cfs
R	Hydraulic radius (A/P)	ft
$R_c$	Mean radius of the bend	ft
S	Energy gradeline slope or channel slope	ft/ft
T	Channel top width	ft
V	Velocity of flow	fps
$V_c$	Critical velocity	fps
y	Depth of flow	ft
$y_c$	Critical depth	ft
z	Elevation head	ft
z	Horizontal distance	ft
$\gamma$	Unit weight of water	pcf
$\tau_d$	Shear stress (tractive force)	psf
$\tau_p$	Permissible shear stress	psf
$\alpha$	Velocity distribution coefficient	—
$\theta$	Channel slope angle	degrees

**Figure 9.1-A — SYMBOLS AND DEFINITIONS**



## 9.2 OPEN-CHANNEL FLOW

### 9.2.1 General

The design analysis for all channels proceeds according to the basic principles of open-channel flow (see [References \(1\), \(2\) and \(3\)](#)). The basic principles of fluid mechanics — continuity, momentum and energy — can be applied to open-channel flow with the additional complication that the position of the free surface is usually one of the unknown variables. The determination of this unknown is one of the primary objectives of open-channel flow analysis. The following discussion is focused on the analysis of channels that are prismatic in shape. The regular shape can be an approximation so that a tailwater analysis can be simplified or an actual shape proposed for construction.

### 9.2.2 Definitions

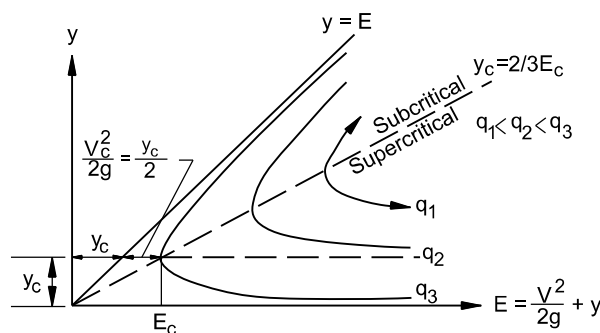
#### 9.2.2.1 Specific Energy

Specific energy,  $E$ , is defined as the energy head relative to the channel bottom. See [Figure 9.2-A](#) for a plot of the specific energy diagram. If the channel is not too steep (slope less than 10%) and the streamlines are nearly straight and parallel (so that the hydrostatic assumption holds), the specific energy becomes the sum of the depth and velocity head.

$$E = y + (V^2/2g) \tag{Equation 9.1}$$

where:

- $y$  = depth, ft
- $V$  = mean velocity, fps
- $g$  = gravitational acceleration, 32.2 ft/sec<sup>2</sup>



Source: Adopted from HDS No. 4, [Reference \(2\)](#).

**Figure 9.2-A — SPECIFIC ENERGY DIAGRAM**

### 9.2.2.2 Energy Gradeline

The total head is the specific energy head plus the elevation of the channel bottom with respect to some datum. The line joining the total head from one cross section to the next defines the energy gradeline.

### 9.2.2.3 Steady and Unsteady Flow

A steady flow is one in which the discharge passing a given cross section is constant with respect to time. The maintenance of steady flow in any reach requires that the rates of inflow and outflow be constant and equal. When the discharge varies with time, the flow is unsteady.

### 9.2.2.4 Uniform Flow and Non-Uniform Flow

A non-uniform flow is one in which the velocity and depth vary in the direction of motion, while they remain constant in uniform flow. Uniform flow can only occur in a prismatic channel, which is a channel of constant cross section, roughness and slope in the flow direction; however, non-uniform flow can occur either in a prismatic channel or in a natural channel with variable properties.

### 9.2.2.5 Gradually Varied and Rapidly Varied Flow

A non-uniform flow in which the depth and velocity change gradually enough in the flow direction that vertical accelerations can be neglected is referred to as a gradually varied flow; otherwise, it is considered to be rapidly varied.

### 9.2.2.6 Froude Number

The Froude number,  $Fr$ , represents the ratio of inertial forces to gravitational forces, is an indicator of the type of flow, and is defined by:

$$Fr = \frac{V}{(gd \cos \theta)^{0.5}} \quad (\text{Equation 9.2})$$

where:

- $V$  = mean velocity =  $Q/A$ , fps
- $g$  = acceleration of gravity, 32.2 ft/sec<sup>2</sup>
- $d$  = hydraulic depth =  $A/T$ , ft
- $A$  = cross-sectional area of flow, sq ft

- T = channel top width at the water surface, ft  
Q = total discharge, cfs  
 $\theta$  = channel slope angle, degrees

This expression for the Froude number applies to any open channel or channel subsection with uniform or gradually varied flow. For rectangular channels, the hydraulic depth is equal to the flow depth.

### 9.2.2.7 Critical Flow

Critical flow occurs when the specific energy is a minimum for a given discharge in regular channel cross sections. The depth at which the specific energy is a minimum is called critical depth. At critical depth, the Froude number has a value of one. Critical depth is also the depth of maximum discharge when the specific energy is held constant. These relationships are illustrated in [Figure 9.2-A](#). During critical flow, the velocity head is equal to half the hydraulic depth. The general expression for flow at critical depth is:

$$Q^2/g = A^3/T \quad \text{(Equation 9.3)}$$

where:

- Q = total discharge, cfs  
g = gravitational acceleration, 32.2 ft/sec<sup>2</sup>  
A = cross-sectional area of flow, sq ft  
T = channel topwidth at the water surface, ft

When flow is at critical depth, Equation 9.3 must be satisfied, no matter what the shape of the channel.

### 9.2.2.8 Subcritical Flow

Depths greater than critical depth occur in subcritical flow, and the Froude number is less than one. In this state of flow, small water surface disturbances can travel both upstream and downstream, and the control is always located downstream.

### 9.2.2.9 Supercritical Flow

Depths less than critical depth occur in supercritical flow, and the Froude number is greater than one. Small water surface disturbances are always swept downstream in supercritical flow, and the location of the flow control is always upstream.

### 9.2.2.10 Hydraulic Jump

A hydraulic jump occurs as an abrupt transition from supercritical to subcritical flow in the flow direction. There are significant changes in depth and velocity in the jump, and energy is dissipated. For this reason, the hydraulic jump is often employed to dissipate energy at highway drainage structures.

A hydraulic jump will not occur until the ratio of the flow depth ( $y_1$ ) in the approach channel to the flow depth ( $y_2$ ) in the downstream channel reaches a specific value that depends on the channel geometry. The depth before the jump is called the initial depth ( $y_1$ ), and the depth after the jump is the sequent depth ( $y_2$ ). When a hydraulic jump is used as an energy dissipator, controls to create sufficient tailwater depth are often necessary to control the location of the jump and to ensure that a jump will occur during the desired range of discharges. If the tailwater depth is lower than the sequent depth, a drop in the channel floor must be used to ensure a jump (see [References \(2\) and \(3\)](#)). Sills can be used to control a hydraulic jump if the tailwater depth is less than the sequent depth.

### 9.2.3 Flow Classification

The classification of open-channel flow can be summarized as follows:

#### Steady Flow

- Uniform Flow
- Non-Uniform Flow
  - + Gradually Varied Flow
  - + Rapidly Varied Flow

#### Unsteady Flow

- Unsteady Uniform Flow (rare)
- Unsteady Non-Uniform Flow
  - + Gradually Varied Unsteady Flow
  - + Rapidly Varied Unsteady Flow

The steady, uniform flow case and the steady, non-uniform flow case are the most fundamental types of flow treated in highway engineering hydraulics.

### 9.2.4 Equations

The following equations are those most commonly used to analyze open channel flow.

### 9.2.4.1 Continuity Equation

The continuity equation is the statement of conservation of mass in fluid mechanics. For the special case of one-dimensional, steady flow of an incompressible fluid, it assumes the simple form:

$$Q = A_1V_1 = A_2V_2 \quad (\text{Equation 9.4})$$

where:

Q = discharge, cfs

A = cross-sectional area of flow, sq ft

V = mean cross-sectional velocity, fps (which is perpendicular to the cross section)

The subscripts 1 and 2 refer to successive cross sections along the flow path.

### 9.2.4.2 Manning's Equation

For a given depth of flow in an open channel with a steady, uniform flow, the mean velocity, V, can be computed with Manning's equation:

$$V = (1.486/n)R^{2/3}S^{1/2} \quad (\text{Equation 9.5})$$

where:

V = velocity, fps

n = Manning's roughness coefficient

R = hydraulic radius = A/P, ft

A = cross-sectional area of flow, sq ft

P = wetted perimeter, ft

S = slope of the energy gradeline, ft/ft (Note: For steady uniform flow, S = channel slope, ft/ft)

The selection of Manning's n is generally based on observation; however, considerable experience is essential in selecting appropriate n values. See [Section 9.3.3](#).

The continuity equation can be combined with Manning's equation to obtain the steady, uniform flow discharge as:

$$Q = (1.486/n)AR^{2/3}S^{1/2} \quad (\text{Equation 9.6})$$

For a given channel geometry, slope and roughness and a specified value of discharge  $Q$ ; a unique value of depth occurs in steady, uniform flow. It is called normal depth and is computed from Equation 9.6 by expressing the area and hydraulic radius in terms of depth. The resulting equation may require a trial-and-error solution. If the normal depth is greater than critical depth, the slope is classified as a mild slope. If the normal depth is less than critical depth, the slope is classified as a steep slope. Thus, uniform flow is subcritical on a mild slope and supercritical on a steep slope.

### 9.2.4.3 Energy Equation

The energy equation expresses conservation of energy in open channel flow as energy per unit weight of fluid, which has dimensions of length and is therefore called energy head. The energy head is composed of potential energy head (elevation head), pressure head and kinetic energy head (velocity head). These energy heads are scalar quantities that give the total energy head at any cross section when added. Written between an upstream open-channel cross section designated 1 and a downstream cross section designated 2 (see [Figure 9.2-B](#)), the energy equation is:

$$h_1 + (V_1^2 / 2g) = h_2 + (V_2^2 / 2g) + h_L \quad (\text{Equation 9.7})$$

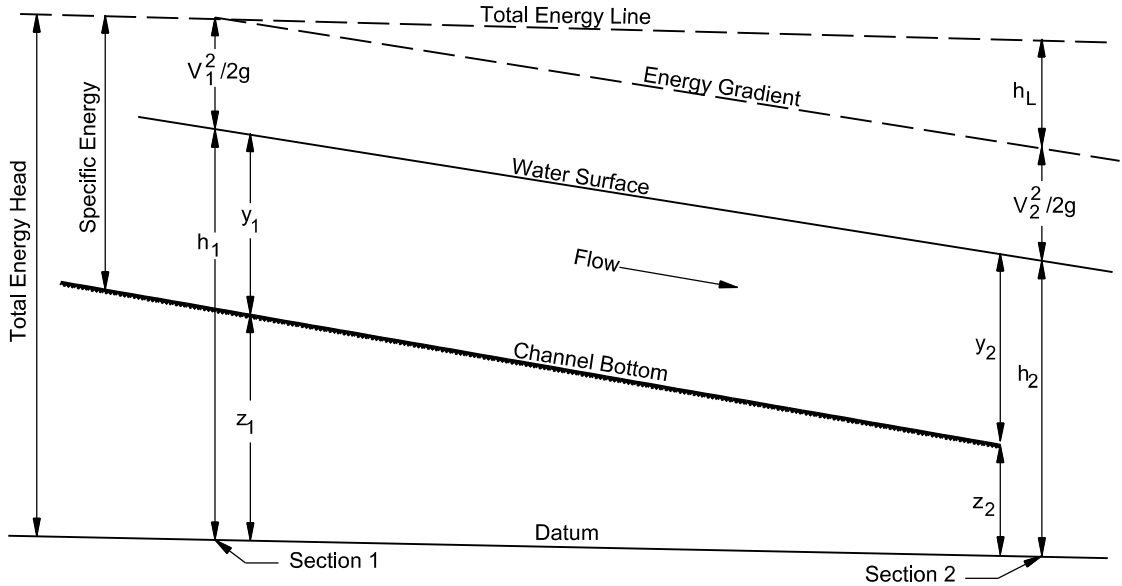
where:

$h_1, h_2$  = the upstream and downstream stages, respectively, ft

$V$  = mean velocity, fps

$h_L$  = head loss due to local cross-sectional changes (minor loss) and boundary resistance, ft

The stage,  $h$ , is the sum of the elevation head,  $z$ , at the channel bottom and the pressure head, which equals the depth of flow,  $y$ , for open-channel flow; i.e.,  $h = z + y$ . The terms in the energy equation are illustrated graphically in [Figure 9.2-B](#). The energy equation states that the total energy head at an upstream cross section is equal to the energy head at a downstream section plus the intervening energy head loss. The energy equation can only be applied between two cross sections at which the streamlines are nearly straight and parallel so that vertical accelerations can be neglected.



Source: HDS No. 4, [Reference \(2\)](#).

**Figure 9.2-B — TERMS IN THE ENERGY EQUATION**

## 9.3 HYDRAULIC ANALYSIS

### 9.3.1 General

The hydraulic analysis of a channel determines the depth and velocity at which a given discharge will flow in a channel of known geometry, roughness and slope. The depth and velocity of flow are necessary for the design or analysis of channel linings and highway drainage structures.

SDDOT may perform a hydraulic analysis for drainage applications where open-channel flow applies, including:

- roadside channels,
- culvert tailwater channels,
- existing stream channels, and
- relocated/realigned stream channels.

Two methods are commonly used in the hydraulic analysis of open channels:

- the single-section method ([Section 9.3.4](#)), or
- the step-backwater method ([Section 9.3.5](#)).

The single-section method is a simple application of Manning's equation to determine tailwater rating curves for culverts or to analyze other situations in which uniform or nearly uniform flow conditions can be assumed. The single-section method produces approximate results because it requires more judgment and assumptions than the step-backwater method. However, the single-section method is usually sufficient for a standard roadway ditch, culverts, storm drains or outfalls. Occasionally, the hydraulic designer may need to use a more detailed method of analysis than the single-section method or the computation of a water surface profile using the step-backwater method.

The step-backwater method is used to compute the complete water surface profile in a natural stream reach to evaluate the unrestricted water surface elevations for bridge hydraulic design or to analyze other gradually varied flow problems in streams. See [Section 14.5.3](#) "Bridge Waterway Opening Analysis" for more discussion on analysis options.

### 9.3.2 Cross Sections

For roadside channels, the cross section is usually determined by typical SDDOT practices. [Chapter 7 of the South Dakota Road Design Manual](#) presents the Department's typical cross section for roadside channels and depressed median channels.



Cross-sectional geometry of streams is defined by coordinates of lateral distance and ground elevation that locate individual ground points. The cross section is taken normal to the flow direction along a single, straight line where practical. Cross sections should be located to be representative of the subreach.

### 9.3.3 Manning's n Value Selection

Manning's  $n$ , the roughness coefficient, is affected by many factors, and its selection in natural channels depends heavily on engineering experience. Pictures of channels and floodplains for which the discharge has been measured and for which Manning's  $n$  has been calculated are very useful (see [References \(3\), \(4\) and \(5\)](#)) for estimating  $n$  values for tailwater channels. See [Figure 9.4-C](#) for  $n$ -values used for channel linings.

### 9.3.4 Single-Section Analysis

The single-section analysis method (slope-area method) is a solution of Manning's equation for the normal depth of flow given the discharge and cross section properties including geometry, slope and roughness. It implicitly assumes the existence of steady, uniform flow; however, uniform flow rarely exists in either artificial or natural stream channels. Nevertheless, the single-section method is often used to design roadside channels assuming uniform flow and to develop a stage-discharge rating curve in a stream channel to be used for tailwater at a culvert or storm drain outlet.

A stage-discharge curve is a graphical relationship of streamflow depth or elevation to discharge at a specific point in a channel. This relationship should cover a range of discharges up to at least the base (100-year) flood or check flood. The stage-discharge curve can be determined as follows:

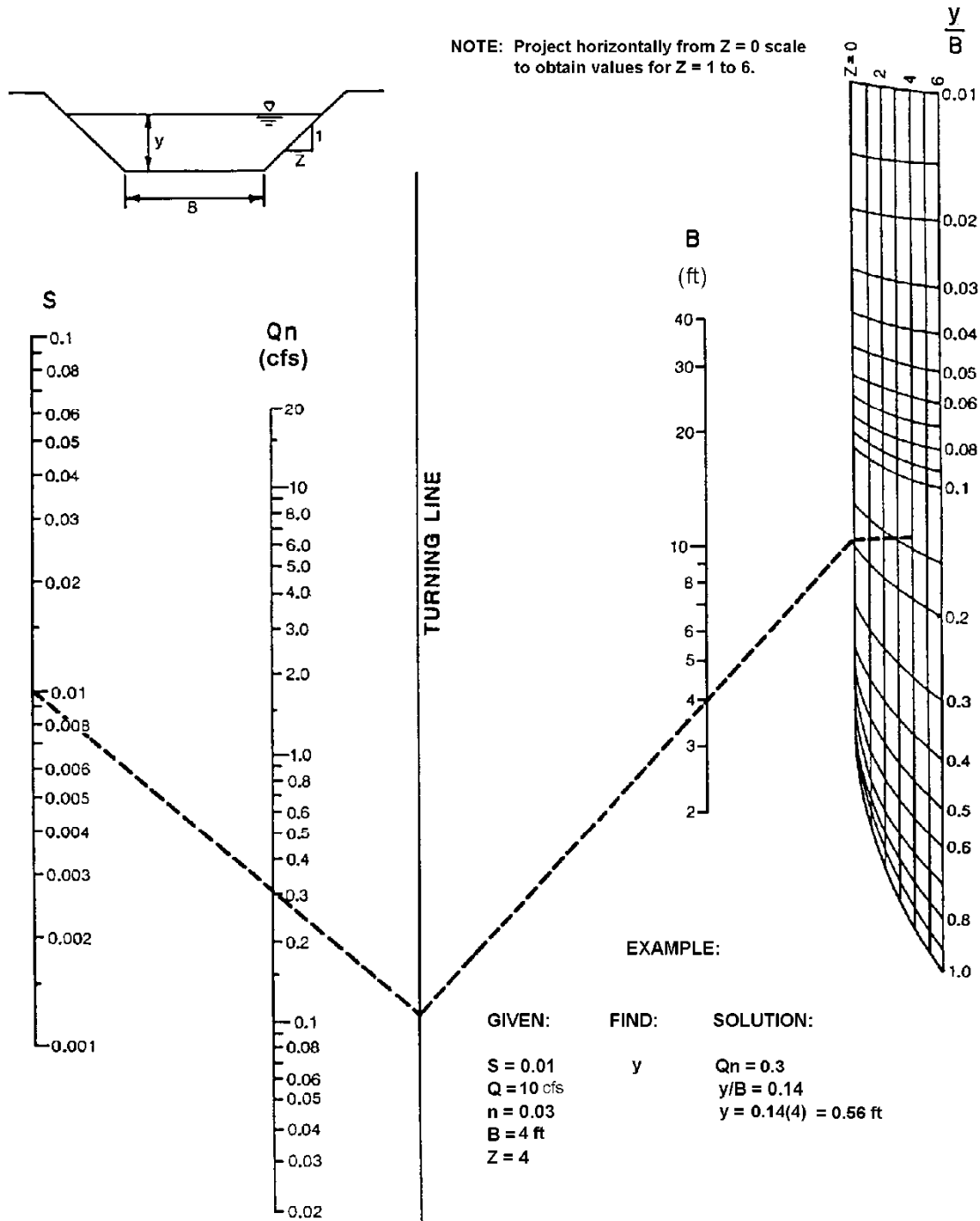
- Select the typical cross section at or near the location where the stage-discharge curve is needed.
- Subdivide the cross section and assign  $n$ -values to subsections as described in [Section 9.3.3](#).
- Estimate water-surface slope. Because uniform flow is assumed, the average slope of the channel can usually be used.
- Apply a range of incremental water surface elevations to the cross section.
- Calculate the discharge using Manning's equation for each incremental elevation. Total discharge at each elevation is the sum of the discharges from each subsection at that elevation. In determining hydraulic radius, the wetted perimeter should be measured only along the solid boundary of the cross section and not along the vertical water interface between subsections.

- After the discharge has been calculated at several incremental elevations, a plot of stage versus discharge should be made. This plot is the stage-discharge curve, and it can be used to determine the water surface elevation corresponding to the design discharge or other discharge of interest.

Although the above procedure can be accomplished manually, software (see [Chapter 18 “Hydraulic Software”](#)) or design aids (e.g., see [Figure 9.3-A](#)) are used for trapezoidal and prismatic channels.

### **9.3.5 Step-Backwater Analysis**

Step-backwater analysis is recommended for determining unrestricted water surface profiles for roadside channels that are long, large or costly. Because the calculations involved in this analysis are tedious and repetitive, it is recommended that the hydraulic designer use software such as HEC-RAS (see [Chapter 18 “Hydraulic Software”](#)). This software can be used for calculating water surface profiles for steady, gradually varied flow in a natural or constructed channel. Both subcritical and supercritical flow profiles can be calculated.



Source: HEC 15, Reference (6).

Figure 9.3-A — NOMOGRAPH FOR NORMAL DEPTH

## 9.4 DESIGN PRACTICES AND PROCEDURES

This Section presents typical SDDOT hydraulic practices for roadside channels and outlines a hydraulic design procedure. The alignment, cross section and grade of roadside channels is usually influenced by the geometric and roadside safety design applicable to the project.

The primary function of roadside channels is to collect surface runoff from the highway and areas that drain to the right-of-way and convey the accumulated runoff to acceptable outlet points. A secondary function of a roadside channel is to drain subsurface water from the base of the roadway to prevent saturation and loss of support for the pavement or to provide a positive outlet for subsurface drainage systems such as pipe underdrains and edge drains.

### 9.4.1 SDDOT Practices

#### 9.4.1.1 Design Methodology (Channel Linings)

SDDOT uses the [1988 version of HEC 15 \(Reference \(6\)\)](#) as its basic reference to select and design linings for its roadside channels. See [Chapter 18 “Hydraulic Software.”](#) The designer should note that the riprap design procedures in HEC 15 are for constructed channels that have a uniform cross section. The flow in the channel should be either steady, uniform flow or gradually varied. The [2005 version of HEC 15 \(Reference \(7\)\)](#) may be used as an alternative if a more rigorous analysis is desired.

The HEC 15 design methodology for the evaluation of channel linings is based on shear stress. Shear stress is the tractive force caused by water flowing in the channel. A channel is unstable where the flow-induced shear stress exceeds the permissible shear stress of the channel liner material. Hydraulic conditions in a drainage channel can become erosive even at fairly mild highway grades. As a result, these channels often require stabilization against erosion.

The Office of Road Design has developed spreadsheets to compute the normal water depth, shear stress and water velocity at the required locations for the SDDOT 20-ft standard roadside ditch, flat-bottom ditch or V-ditch.

Shear stress is normally analyzed for a 10-year flood event, and the discharges should be computed using the same methods required for culvert design, which varies based on drainage area size. The designer should provide these spreadsheets or similar information to the Erosion Control Designer prior to scheduling a final design inspection to consider installing permanent erosion control measures.

### 9.4.1.2 Channel Cross Sections

Chapter 7 of the *South Dakota Road Design Manual* presents the Department's typical cross section for roadside channels and depressed median channels.

### 9.4.1.3 Channel Slope

The channel bottom longitudinal slope is generally dictated by the adjacent 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 highway right-of-way, the slope may also 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 subcritical slope is smaller than one with a supercritical slope. Roadside channels with gradients in excess of approximately 2% will flow in a supercritical state. Most flexible lining materials are suitable for protecting channel gradients up to 10%. Riprap and wire-enclosed riprap are suitable for protecting steep channels with gradients exceeding 10%.

Flat or nearly flat slopes should be avoided. If it is not possible to maintain a 0.5% grade, a paved section may be used with an absolute minimum of a 0.2% grade.

### 9.4.1.4 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 sides. In a permanent roadway channel, approximately 6 in of freeboard over the design depth should be adequate. For temporary channels, freeboard is not necessary. Steep-gradient channels (> 10%) 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. The designer should provide the elevation limits to the Erosion Control Designer at the critical locations.

### 9.4.1.5 Channel Bends

Flow around a bend in an open channel induces centrifugal forces because of the change in flow direction. 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:

$$\Delta d = \frac{V^2 T}{g R_c} = \text{superelevation of the water surface} \quad (\text{Equation 9.8})$$

where:

- V = mean velocity, fps
- T = surface width of the channel, ft
- g = gravitational acceleration, 32.2 ft/sec<sup>2</sup>
- R<sub>c</sub> = mean radius of the bend, ft

#### 9.4.1.6 Channel Linings

Designers should analyze drainage locations throughout the project with potential erosion problems to evaluate the suitability and stability of the channel lining. Examples of locations to consider are:

- existing erosion areas,
- ditches with grades steeper than 4%,
- drainage areas greater than 10 acres,
- roadway embankments that transition from a ditch cut to a fill,
- toe of fills that result in a V-ditch, and
- narrow channel sections (steep-sided V-ditches).

In addition, the designer should consider that occasionally even small concentrated flows in a channel may merit evaluation, depending on the channel grade and configuration.

The following identifies SDDOT typical practices for the selection of a channel lining type:

1. Temporary Linings:

- Crimped straw (mulch)
- Erosion control blanket
- Wood fiber mulch
- Bonded fiber matrix

2. Permanent Linings (in order of preference):

- Vegetation (Retardance Class B); see [Figure 9.4-A](#)
- Turf reinforcement mats
- Riprap
- Gabions
- Concrete liner

Retardance	Cover	Condition
A	Weeping lovegrass Yellow bluestem Ischaemum	Excellent stand, tall (average 30 in) Excellent stand, tall (average 36 in)
B	Kudzu Bermuda grass Native grass mixture: little bluestem, bluestem, blue gamma, other short- and long-stem Midwest grasses Weeping lovegrass Lasperdeza sericea Alfalfa Weeping lovegrass Kudzu Blue gamma	Very dense growth, uncut Good stand, tall (average 12 in)  Good stand, unmowed  Good stand, tall (average 24 in) Good stand, not woody, tall (average 19 in) Good stand, uncut (average 11 in) Good stand, unmowed (average 13 in) Dense growth, uncut Good stand, uncut (average 13 in)
C	Crabgrass Bermuda grass Common lespedeza Grass-legume mixture: summer (orchard grass redtop, Italian ryegrass and common lespedeza) Centipedegrass Kentucky bluegrass	Fair stand, uncut (10 in – 48 in) Good stand, mowed (average 6 in) Good stand, uncut (average 11 in)  Good stand, uncut (6 in – 8 in)  Very dense cover (average 6 in) Good stand, headed (6 in – 12 in)
D	Bermuda grass Common lespedeza Buffalo grass Grass-legume mixture: fall, spring (orchard grass redtop, Italian ryegrass and common lespedeza) Lepedeza sericea	Good stand, cut to 2½ in Excellent stand, uncut (average 4½ in) Good stand, uncut (3 in – 6 in)  Good stand, uncut (4 in – 5 in)  After cutting to 2 in (very good before cutting)
E	Bermuda grass Bermuda grass	Good stand, cut to 1½ in Burned stubble

Notes:

1. Covers classified have been tested in experimental channel. Covers were green and generally uniform. Source of table is HEC 15 (Reference (6)).
2. Most of the grasses in the Figure are not allowed by SDDOT seed mixtures. The typical vegetative grasses used in South Dakota highway ditches have a Retardance Class of B.

**Figure 9.4-A — CLASSIFICATION OF VEGETATION COVERS AS TO DEGREES OF RETARDANCY**

3. Special Linings. These include composite linings that have a low-flow channel with one type of lining and upper side slopes with a different lining.

#### 9.4.2 Step-by-Step Procedure

Each project is unique, but the following six basic design steps are normally applicable to the hydraulic design of roadside channels. [Section 9.5](#) presents two examples to illustrate the hydraulic design procedure. To obtain the optimum roadside channel system design, it may be necessary to make several trials with various linings before a final design is achieved:

##### *Step 1* Establish a Roadside Plan

- A. Collect available site data. See [Chapter 5 “Data Collection.”](#)
- B. Document the existing and proposed plan-profile layout including highway, culverts and bridges.
- C. Plot the locations of natural basin divides and roadside channel outlets. [Figure 9.4-B](#) presents an example of a roadside channel plan/profile.
- D. Lay out the proposed roadside channels to minimize diversion flow lengths.

##### *Step 2* Establish Cross Section Data

- A. Identify features that may restrict the cross section design:
  - right-of-way limits,
  - trees or environmentally sensitive areas,
  - utilities, and/or
  - existing drainage facilities.
- B. Provide a channel depth adequate to drain the subbase and minimize freeze-thaw effects.
- C. Choose channel side slopes based on the SDDOT design criteria, including the consideration of safety, economics, soils, aesthetics and access. See [Section 9.4.1.2](#).



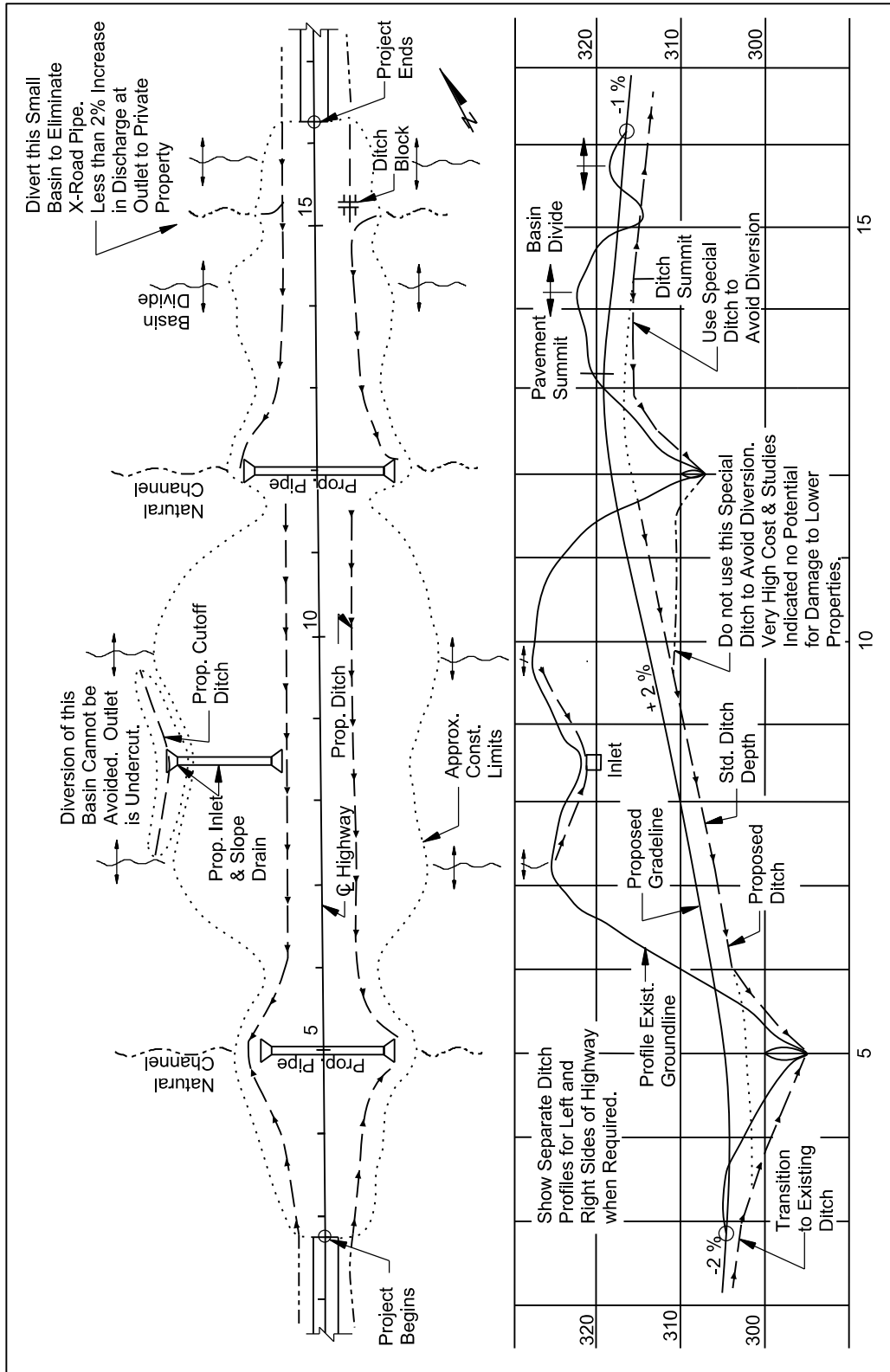


Figure 9.4-B — SAMPLE ROADSIDE CHANNEL

**Step 3** Determine Channel Grade

- A. Plot initial longitudinal grades on plan-profile layout, including inlet and outlet considerations. See [Section 9.4.1.3](#) for SDDOT practices.
- B. Consider the influence of grade on type of lining. See [Step 5](#).
- C. Where practical, avoid features that may influence or restrict grade (e.g., utility locations).
- D. Select final channel grade to minimize ponding and sediment accumulation.

**Step 4** Check Flow Capacities and Adjust as Necessary

- A. Compute the design discharge at the downstream end of a channel segment (see [Chapter 7 “Hydrology”](#)).
- B. Set preliminary values of channel size, roughness coefficient and slope.
- C. Determine maximum allowable depth of channel including freeboard. See [Section 9.4.1.4](#) for SDDOT practices.
- D. Check flow capacity using Manning’s equation and single-section analysis. For n values for the trial lining, refer to:
  - [Figure 9.4-C](#) or [9.4-D](#) for rigid, unlined, temporary, gravel and rock riprap linings, or
  - [Figure 9.4-E](#) for grass linings

The hydraulic designer may select an alternative n value with proper documentation. For example, SDDOT practice is to limit the n value for the permanent grass lining to 0.035.

- E. If capacity is inadequate, possible adjustments are as follows:
  - increase bottom width,
  - make channel side slopes flatter,
  - make channel slope steeper,
  - provide smoother channel lining, and/or
  - install drop inlets and a parallel storm drain pipe beneath the channel to supplement channel capacity.

- F. Provide smooth transitions at changes in channel cross section.
- G. Provide extra channel storage where needed to replace floodplain storage and/or to reduce peak discharge.

**Step 5** Determine Channel Lining/Protection Needed

*Note:* The following procedure is based on HEC 15 (1988), [Reference \(6\)](#). See [Section 9.4.1.1](#) for more discussion on the use of the 1988 and 2005 versions of HEC 15.

- A. Select a lining and determine the permissible shear stress  $\tau_p$  in psf from [Figure 9.4-F](#). See [Section 9.4.1.6](#) for typical SDDOT practices on selecting channel linings.
- B. Estimate the flow depth and choose an initial Manning's n from:
  - [Figure 9.4-C](#) or [9.4-D](#) for rigid, unlined, temporary, gravel and rock riprap linings; or
  - [Figure 9.4-E](#) for Class B grass linings; or
  - [HEC 15 \(1988\)](#) ([Reference \(6\)](#)) for Classes A, C, D and E grass linings.

The hydraulic designer may select an alternative n value with proper documentation. For example, SDDOT practice is to limit the n value for the permanent grass lining to 0.035.

- C. Calculate normal flow depth,  $y_n$  (ft), at design discharge using Manning's equation and compare with the estimated depth. If they do not agree, repeat Steps 5B and 5C.
- D. Compute maximum shear stress at normal depth as:
$$\tau_d \text{ (psf)} = 62.4y_nS, \text{ where } S = \text{channel slope, ft/ft}$$
- E. If  $\tau_d < \tau_p$ , then lining is acceptable. Otherwise consider the following options:
  - choose a more resistant lining;
  - decrease channel slope;
  - decrease slope in combination with drop structures; and/or
  - increase channel width and/or flatten side slopes.

**Step 6** Analyze Outlet Points and Downstream Effects

- A. Identify any adverse impacts (e.g., increased flooding or erosion to downstream properties) that may result from one of the following at the channel outlet:
- increase or decrease in discharge,
  - increase in velocity of flow,
  - concentration of sheet flow,
  - change in outlet water quality, or
  - diversion of flow from another watershed.
- B. Mitigate any adverse impacts identified in Step 6A. Possibilities include:
- increase capacity and/or improve lining of downstream channel;
  - install velocity-control structures (e.g., energy dissipators; see [Chapter 11](#));
  - install sedimentation/infiltration basins or control structures to provide detention of increased runoff and/or sediment (see [Chapter 13 “Storage Facilities”](#)); and/or
  - install weirs or other outlet devices to redistribute concentrated channel flow; see [HEC 22 \(Reference \(9\)\)](#).

Lining Category	Lining Type	k <sub>s</sub> (ft)	n-value <sup>1</sup>		
			Depth Ranges		
			0 – 0.5 ft	0.5 – 2.0 ft	> 2.0 ft
Rigid	Concrete		0.015	0.013	0.013
	Asphalt		0.018	0.016	0.016
	Grouted Riprap		0.040	0.030	0.028
	Stone Masonry		0.042	0.032	0.030
	Soil Cement		0.025	0.022	0.020
Unlined	Bare Soil		0.023	0.020	0.020
	Rock Cut		0.045	0.035	0.025
Temporary <sup>2</sup>	Straw with Net <sup>3</sup>	0.121	0.065	0.033	0.025
	Curled Wood Mat <sup>4</sup>	0.112	0.066	0.035	0.028
	Synthetic Mat <sup>5</sup>	0.066	0.036	0.025	0.021
Gravel <sup>6</sup>	1 in D <sub>50</sub>	0.082	0.044	0.033	0.030
	2 in D <sub>50</sub>	0.164	0.066	0.041	0.034
Rock Riprap <sup>6</sup>	6 in D <sub>50</sub>	0.5	0.104	0.069	0.035
	12 in D <sub>50</sub> (Class A)	1.0	—	0.078	0.040

<sup>1</sup> n-values are representative of the depth ranges (i.e., n varies with the flow depth)

<sup>2</sup> Some “temporary” linings become permanent when buried

<sup>3</sup> Use for SDDOT Crimped Straw (Mulch)

<sup>4</sup> Use for SDDOT Wood Fiber Mulch

<sup>5</sup> Use for SDDOT Bonded Fiber Matrix

<sup>6</sup> k<sub>s</sub> = D<sub>50</sub> for gravel and rock riprap

Source: 1988 version of HEC 15 (Reference (6)).

Lining Category	Lining Type	n-value <sup>1</sup>		
		Maximum	Typical	Minimum
Rolled Erosion Control Products (RECP)	Open-Weave Textile	0.028	0.025	0.022
	Erosion Control Blankets	0.045	0.035	0.028
	Turf Reinforcement Mat	0.036	0.030	0.024
Gabions	Wire-Enclosed Rock	Function of Rock Size		

<sup>1</sup> Typical n-value should be used for design. Actual n-value is a function of shear stress on the lining and coefficients based on all three manufacturer-supplied values. See HEC 15 (2005), Chapter 5 for RECP procedure and Chapter 7 for gabion procedure.

Source: 2005 version of HEC 15 (Reference (7)).

**Figure 9.4-C — TYPICAL MANNING’S ROUGHNESS COEFFICIENTS (n)**

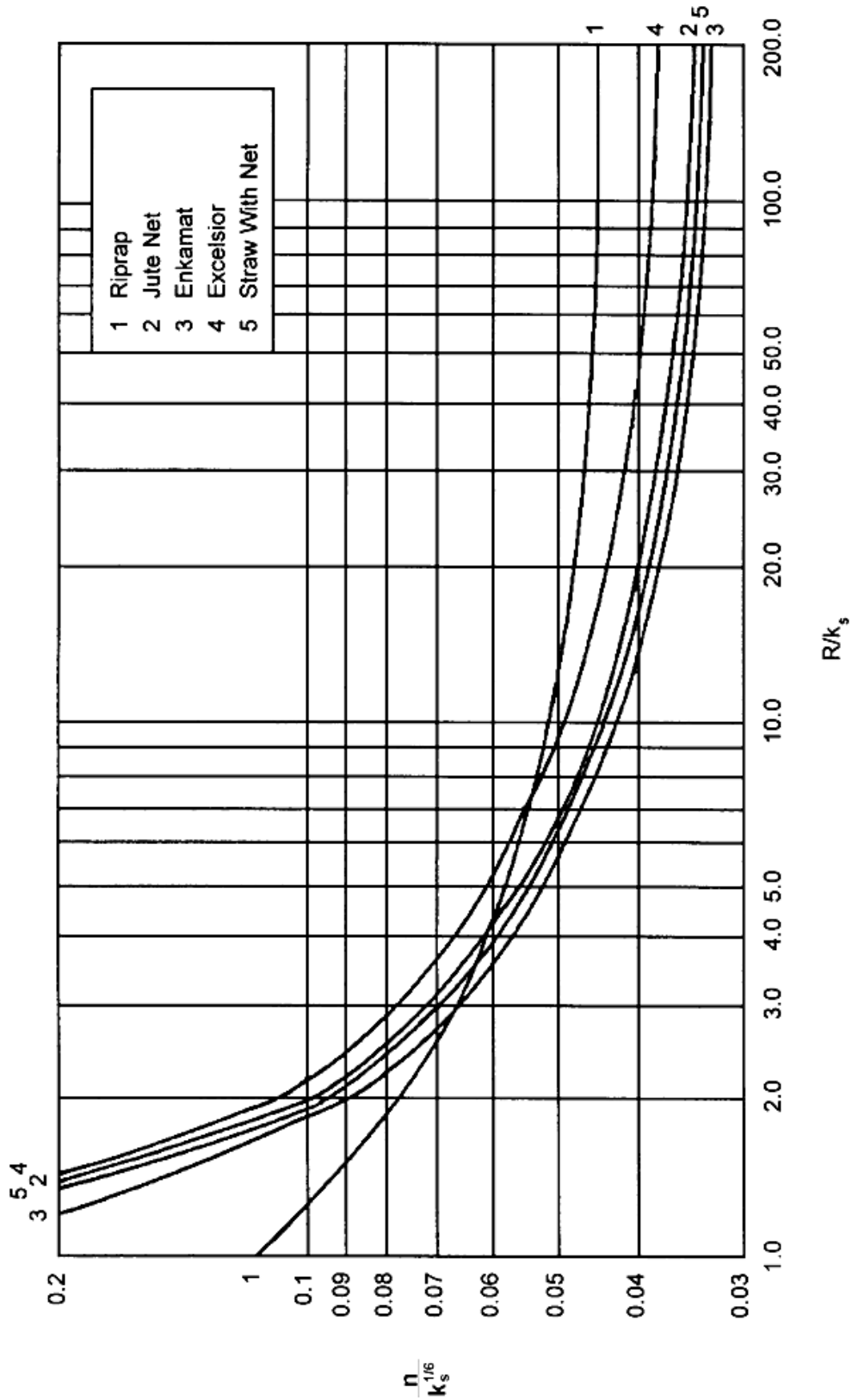


Figure 9.4-D — MANNING'S  $n$  VERSUS RELATIVE ROUGHNESS FOR SELECTED LINING TYPES (HEC 15, Reference (6))

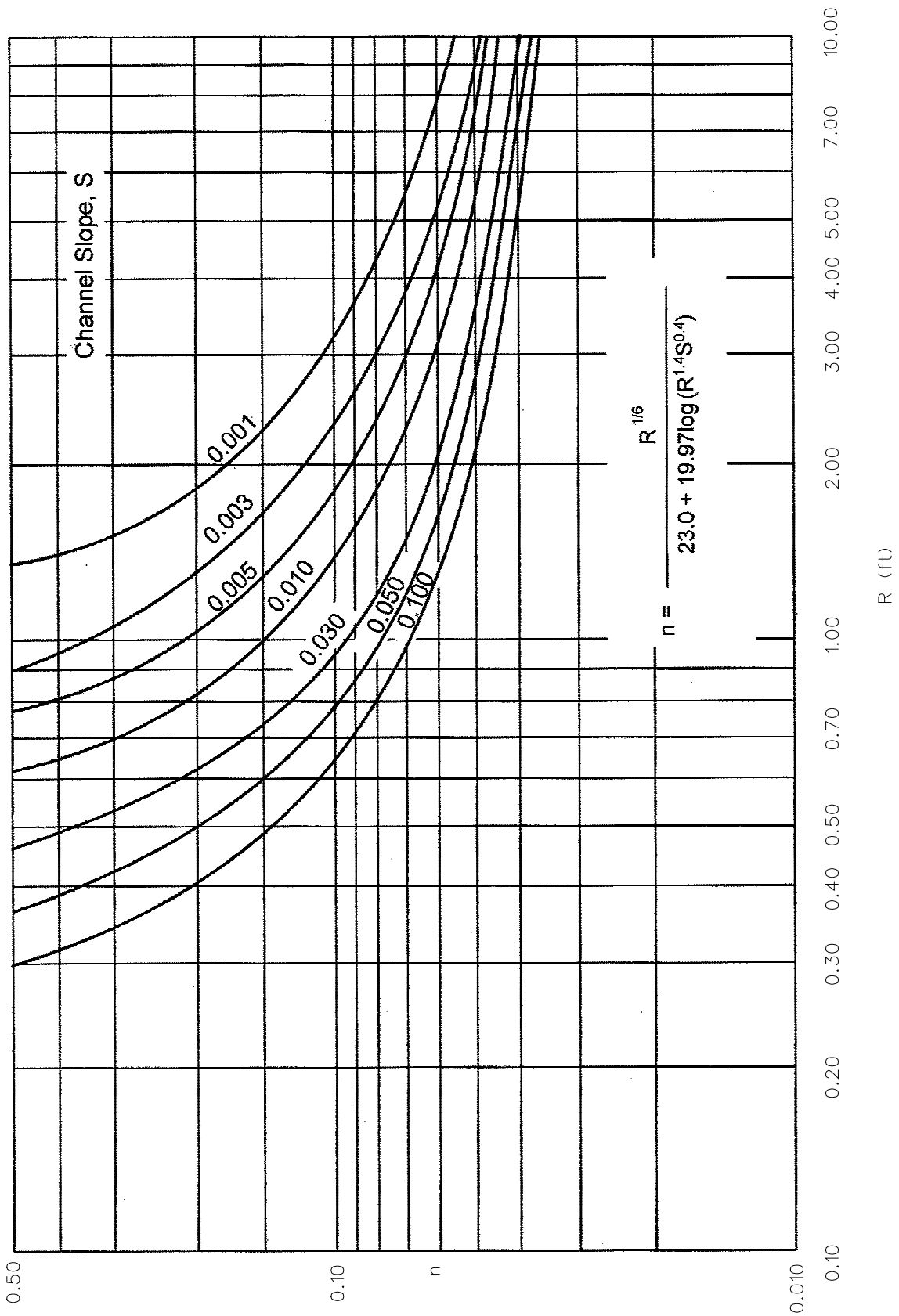


Figure 9.4-E — MANNING's n VERSUS HYDRAULIC RADIUS, R, FOR CLASS B VEGETATION (HEC 15, Reference (6))

<b>SDDOT Typical Linings</b>	<b><math>\tau_p</math> (psf)</b>
Class B Vegetation	2.10
Synthetic Mats (temporary linings)	2.00
Turf Reinforcement Mat	4.00
Rock Riprap	
D <sub>50</sub> = 6 in	2.50
D <sub>50</sub> = 12 in (Class A Riprap)	5.00
6-in to 18-in Gabions	4.00*
<b>Special Linings</b>	
Class A Vegetation	3.70
Class C Vegetation	1.00
Class D Vegetation	0.60
Class E Vegetation	0.35
Jute Net	0.45
Straw with Net	1.45
Curved Wood Mat	1.55
Gravel	
D <sub>50</sub> = 1 in	0.40
D <sub>50</sub> = 2 in	0.80
4-in Geoweb	10.00
Concrete Construction Blocks (granular filter underlayer)	> 20.00
Wedge-Shaped Blocks (with drainage slot)	> 25.00
Soil Cement (8% cement)	> 45.00

\* This value is consistent with the Equation in [Section 15.8](#).

Source: [Reference \(8\)](#).

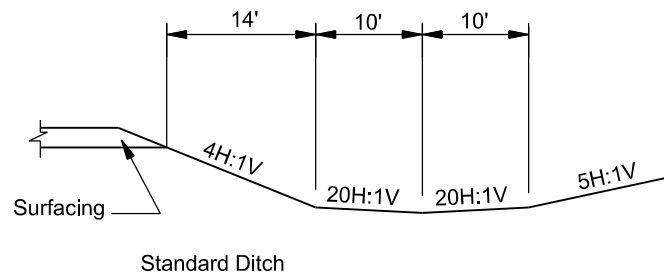
**Figure 9.4-F — PERMISSIBLE SHEAR STRESSES ( $\tau_p$ ) FOR VARIOUS PROTECTION MEASURES**



## 9.5 EXAMPLE PROBLEMS

### Example 9.5-1

Given: The SDDOT standard ditch section shown below is lined with a good stand (unmowed) of native grass mixture. The ditch gradient is 0.010 ft/ft.



Find: Compute the maximum discharge for which this lining will be stable and the corresponding flow depth.

Solution: From [Figure 9.4-A](#), Native Grass Mixture is a retardance class of B and, from [Figure 9.4-F](#), the permissible shear stress is:

$$\tau_p = 2.1 \text{ psf}$$

The allowable depth can be determined by assuming  $\tau_p = \tau_d$ :

$$y = \tau_p / (62.4S) = 2.1 / ((62.4)(0.01)) = 3.36 \text{ ft}$$

Determine the flow area (A) and hydraulic radius (R) for  $z_1 = 4$  and  $z_2 = 5$ :

$$A_{\text{triangle}} = 5 \text{ sq ft for the first 0.5 ft}$$

$$A_{\text{trap.}} = y(b + z_1y/2 + z_2y/2) = 2.86(20 + 2(2.86) + 2.5(2.86)) = 94 \text{ sq ft}$$

$$A_{\text{total}} = 99 \text{ sq ft}$$

$$P = b + y(1 + z_1^2)^{1/2} + y(1 + z_2^2)^{1/2}$$

$$P = 20 + 2.86(1 + 16)^{1/2} + 2.86(1 + 25)^{1/2} = 20 + 11.8 + 14.6 = 46.4 \text{ ft}$$

$$R = A/P = 99/46.4 = 2.13 \text{ ft}$$

The Manning's n value from [Figure 9.4-E](#) is 0.075.

Solving for Q from Manning's equation:

$$Q = (1.486/n)AR^{2/3}S^{1/2}$$

$$Q = (1.486/0.075)(99)(2.13)^{2/3} (0.01)^{1/2} = 325 \text{ cfs}$$

Because this is a large channel and a deep depth of flow, SDDOT practice is to use an  $n = 0.035$ . Substituting this  $n$ , the channel has the following capacity:

$$Q = (1.486/0.035)(99)(2.13)^{2/3} (0.01)^{1/2} = 696 \text{ cfs}$$

*Note: This method is called the maximum discharge method and is useful for determining the stable channel capacity for a variety of different linings for comparison.*

As a check, the FHWA Hydraulic Toolbox (Channel Calculator) (see [Section 18.2.2](#)) yields 325 cfs and 697 cfs respectively when the following cross section is entered:

Station	Elevation
0	4
14	0.5
24	0
34	0.5
51.5	4

The results can also be produced using the above cross section in HY-8; see [Chapter 18 “Hydraulic Software.”](#)

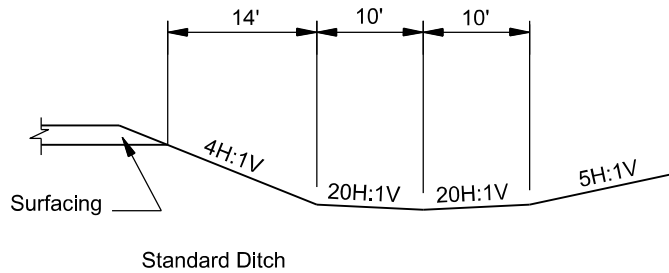
The FHWA Hydraulic Toolbox (Channel Calculator) was used to produce the data in Figure 9.5-A.

Slope (S) (ft/ft)	Maximum Depth (2.1/62.4S) (ft)	Maximum Q (cfs)
0.01	3.36	696
0.02	1.68	227
0.04	0.84	69
0.06	0.56	29
0.08	0.42	15
0.10	0.34	10

**Figure 9.5-A — MAXIMUM DEPTH AND DISCHARGE FOR CLASS B VEGETATION  
(In SDDOT Standard Channel with  $n = 0.035$ )**

**Example 9.5-2**

Given: The SDDOT standard ditch section (shown below) will be used. The ditch gradient is 0.01 ft/ft. This is the same as [Example 9.5-1](#), which established that Native Grass Mixture was acceptable for the permanent lining.



Find: Determine if the Turf Reinforcement Mat (TRM) is needed, either as a temporary or permanent lining.

Solution: The solution follows the procedure outlined in [Section 9.4.2 \(Step 5\)](#), which is based on the tractive force method:

- (1) Determine the permissible shear stress for TRM:

$$\tau_p = 4.0 \text{ psf (Figure 9.4-F)}$$

- (2) Determine  $n = 0.03$  from [Figure 9.4-C](#).
- (3) Calculate  $y$  using Manning's equation (similar to [Example 9.5-1](#)). The FHWA Hydraulic Toolbox (Channel Calculator) was used to produce [Figure 9.5-B](#).

Slope (S) (ft/ft)	Maximum Depth (4/62.4S) (ft)	Maximum Q (cfs)
0.01	> 4	NA
0.02	3.21	1043
0.04	1.60	337
0.06	1.07	172
0.08	0.80	101
0.10	0.64	64

**Figure 9.5-B — MAXIMUM DEPTH AND DISCHARGE FOR TRM  
(In SDDOT Standard Channel with  $n = 0.03$ )**

The TRM is not needed as a permanent lining on gradients less than 0.02 ft/ft if the design discharge is less than that shown in [Figure 9.5-B](#). The TRM will provide temporary protection until grass is established and will provide for a stronger permanent lining. At slopes greater than 0.02 ft/ft, TRM substantially increases capacity of the channel as a permanent lining.

## 9.6 REFERENCES

- (1) AASHTO, *Highway Drainage Guidelines (4<sup>th</sup> Edition)*, Chapter 6, “Hydraulic Analysis and Design of Open Channels,” AASHTO Technical Committee on Hydrology and Hydraulics, 2005.
- (2) Federal Highway Administration, *Introduction to Highway Hydraulics*, Hydraulic Design Series No. 4 (HDS 4), FHWA-NHI-08-090, Washington, DC, August 2008.
- (3) Chow, V.T., *Open Channel Hydraulics*, McGraw-Hill, 1970, 1959.
- (4) Arcement, G.J., Jr., and Schneider, V.R., *Guide for Selecting Manning’s Roughness Coefficients for Natural Channels and Flood Plains*, FHWA-TS-84-204, Federal Highway Administration, 1984.
- (5) Barnes, H.H., Jr., “*Roughness Characteristics of Natural Channels*,” USGS Water Supply Paper 1849, US Government Printing Office, Washington, DC, 1978.
- (6) Federal Highway Administration, *Design of Roadside Channels with Flexible Linings*, Hydraulic Engineering Circular No. 15 (HEC 15), FHWA-IP-87-7, Washington, DC, April 1988.
- (7) Federal Highway Administration, *Design of Roadside Channels with Flexible Linings*, Hydraulic Engineering Circular No. 15 (HEC 15), Third Edition, FHWA-NHI-05-114, September 2005.
- (8) Federal Highway Administration, *Hydraulic Stability of Articulated Concrete Block Revetment Systems during Overtopping Flow*, FHWA-RD-89-199, November 1989.
- (9) Federal Highway Administration, *Urban Drainage Design Manual Second Edition*, Hydraulic Engineering Circular No. 22 (HEC 22), FHWA-NHI-10-009, 2009.

