FDM 13-30-1 Channel Types and Characteristics

October 22, 2012

1.1 Channel Types

Roadside drainage channels perform the vital functions of collecting surface water runoff from the highway and carrying it to natural channels, providing snow storage and filtering sediment from runoff. They should provide the most efficient, stable, and effective disposal system for highway surface runoff, consistent with cost, importance of the road, economy of maintenance, and legal requirements. A standard drainage channel rarely provides the most satisfactory drainage for all sections of the highway, although it is the most efficient for most locations.

1.2 Roadside Ditches

Side ditches are provided in cut sections to remove runoff from cut slopes, pavement, and adjacent areas draining into the highway right-of-way. Side ditches typically are triangular in cross section and dimensioned in accordance with appropriate design standards. The depth may be varied to keep a desirable minimum longitudinal slope of 0.5 percent and to keep the runoff from the design year storm below the top of the highway subgrade (refer to FDM13-10 Attachment 1.1). The minimum depth of a ditch is 1 ft below the subgrade shoulder point to ensure positive drainage of the subgrade. Refer to FDM11-15-1 for cross section elements for rural highways and freeways.

1.3 Median Ditches

The shape, slope, bottom width, and gradient of a median may be varied as required to suit conditions. The following median geometrics are given in Chapter 11:

1. Minimum depth of low point in any depressed median shall be 1.0 foot below subgrade. The desirable median depth should be 1.5 feet. Greater depths are permissible where the median width is more than 60 feet or where dictated by inlet and discharge pipe needs.
2. Side slopes below subgrade should be 6:1 or flatter, with a desirable slope of 10:1 and 20:1 as an absolute minimum.
3. Minimum desirable longitudinal gradient shall be 0.5 percent with 0.3 percent absolute minimum. Where the roadway profile grade is less than the minimum median gradient, the median grade shall be maintained by varying the ditch bottom width, by decreasing the spacing of median drains, and/or by varying the side slopes between 20:1 to 6:1.

Median drains should be spaced so that depth of flow will not rise above the top of the subgrade and so that high erosion-causing velocities will not be reached. In any case, inlet spacing should not exceed 1,000 feet, with 800 feet as desirable maximum. Refer to standard detail drawing for Inlets Type 8, 9, 10 and 11.

1.4 Toe of Slope and Intercepting Embankments

Normally, interceptor ditches are located at the top of a cut slope or along the faces of a cut slope to intercept hillside runoff and prevent the erosion of the cut slope. Consult the region soils engineer to determine whether an interceptor ditch or embankment might cause slope failure. Because the traveling public is not exposed to these ditches safety is not an issue, they may be constructed with 2:1 side slopes, if the slopes are stable and do not erode.

FDM 13-30-5 Channel Characteristics

October 22, 2012

5.1 Introduction

Channels and road ditches are designed for the following channel characteristics: vertical alignment, horizontal alignment, roughness factors, and channel geometry. A general discussion of these channel characteristics is given in this procedure. More specific channel design criteria are covered in FDM 13-30-10.

5.2 Vertical Alignment

The vertical alignment of a new channel should be similar to the profile of the existing channel. Avoid abrupt changes in grade in the new channel. If abrupt changes in grade are designed into the channel, one of the following two effects will occur, depending upon the slope change:

1. Deposition of transported material will occur where the grade changes from steep to flat.
2. Scouring will occur when the grade changes from flat to steep.

Due to topographic features, it is normally impossible to design a channel without areas where deposition of material and/or scouring will occur. Therefore, other means of preventing these conditions from occurring must be part of the final design. Open channel scour may be reduced or prevented by using turf reinforcement mat, riprap or for extreme conditions, grouted riprap, articulated concrete block, drop structures or channel paving. In addition, in areas where vehicles are not likely to travel, vertical grade drops may be used to maintain flat ditch grades that are non-erodible.

5.3 Horizontal Alignment

Horizontal alignments for roadside drainage ditches typically follow the road alignment. Outside of the roadside alignment, the designer should construct meandering channels to reproduce preconstruction condition to imitate nature and to avoid steepening gradients. Changes to alignment should be gradual to minimize erosion. When it is necessary to construct curves that are not erosion resistant, designers should use riprap or other methods to control erosion.

5.4 Roughness Factors

The capacity of a drainage channel depends upon its shape, size, slope, and roughness. A specific channel's capacity will decrease as the roughness factor increases. Erosion potential of a channel on a steep grade may be reduced by increasing the channel roughness which decreases the flow velocity. Conversely, a specific channel's capacity will increase as its roughness decreases. Therefore, if no other options are available, the capacity of channels with flat slopes may be increased by constructing smooth channel walls and bottom that will maintain a higher velocity.

A table of roughness coefficients (n) for Manning's Equation can be found in FDM 13-25-35. With the use of this table and engineering judgment, the approximate roughness coefficients of existing channels should be determined through a field review. Any erosion or deposition of material in the existing channel(s) should be noted and recorded. These facts can be used in the design stage to compare the compatibility of new channels with the existing channels. FDM 13-30-15 and FDM 13-30-25 show the designer how to develop the Manning’s n value for a grass or riprap lined channel that is based upon the channel characteristics, lining, and flow rates.

5.5 Channel Geometry

Channels are usually constructed with a triangular or trapezoidal shape as shown in Figure 1 below. Triangular roadside ditches are typically used for WisDOT projects. Trapezoidal roadside ditches can be used when additional capacity is needed or if velocities need to be reduced. In time, triangular and trapezoidal channels naturally tend to become parabolic in shape because of siltation.

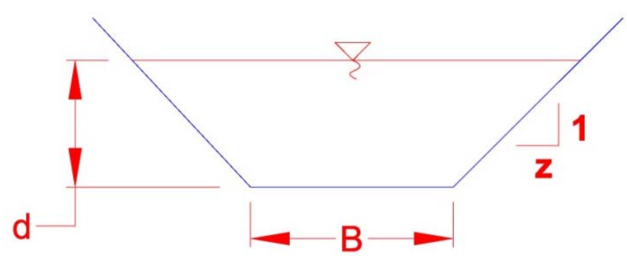

Figure 1.1 Trapezoidal Channel Cross Section

Where*:*

B = channel base (ft)

d = depth of flow (ft)

Z = side slope, Z horizontal:1 vertical

5.6 Natural Channels

For natural channel reconstruction, the designer should construct meandering channels to reproduce preconstruction conditions, to imitate nature, and to avoid steepening the channel gradients. Any change in alignment should be gradual, to minimize erosion. When it is necessary to construct curves that are not erosion resistant, the erosion may be controlled by using side slope protection, riprap and/or channel paving.

Sometimes it is necessary to connect into or change the alignment of natural channels. Changes to a natural channel should only be considered as a last resort when safety, economic, hydraulic and/or environmental issues warrant it.

A channel change is any alteration in the cross section, slope, alignment, and/or hydraulic capacity of a natural watercourse. Any straightening of a natural channel invariably results in a steeper channel slope and higher velocities, resulting in channel erosion. Channel changes should be designed to duplicate the natural channel's hydraulic conditions. When it is necessary to relocate a meandering channel, the relocated channel should include similar meanders to reproduce existing natural conditions. The stream thread, or channel length, should be maintained.

Regulatory agencies generally discourage alignment changes to natural channels. Typically, significant coordination will be necessary with the WDNR and US Army Corps of Engineers for any proposed changes. It is important that possible channel changes to natural channels be identified early in the design process and brought to the attention of the regulatory agencies for their input and concurrence.

FDM 13-30-10 Hydraulic Design of Open Channels *October 22, 2012*

10.1 Introduction

This procedure presents the theory, design criteria, basic equations, and design methods to hydraulically design open channels. The designer must be knowledgeable about the types of flow, channel design characteristics, and basic hydraulic equations. For additional information, see Hydraulic Design Series No. 4, Introduction to Highway Hydraulics (HDS 4).

With this background information, stable channels can be designed using rigid or flexible lining criteria and design techniques discussed in this procedure and the following three procedures. The design techniques along with example problems presented in this procedure are:

1. General flexible lining design procedure for grass and rock riprap lined channels.
2. Steep side slope protection.
3. Bend protection design.

10.2 Types of Flow

There are several classifications of the flow state in open channels that help determine the appropriate method of analysis for a given design problem.

- *Steady Flow and Unsteady Flow*

  Time is the criterion that distinguishes these two types of flows. The flow at any cross section is said to be steady if the velocity does not vary in magnitude or direction with time. Conversely, the flow is unsteady if the velocity varies with time. In most open channel flow problems, flow conditions are assumed to be steady.

- *Uniform Flow and Varied Flow*

  Space is the criterion that distinguishes these two types of flows. Flow is said to be uniform when the depth of flow and the mean velocities are the same at successive cross sections in any reach. Uniform flow only occurs in a channel with a constant cross section. Varied flow occurs in reaches with uniform or varying cross sections that are affected by other controls or its own changing shape and cause accelerated or decelerated flow conditions. Although steady, uniform flow rarely occurs in natural streams or constructed channels, it provides a check point for open channel design problems

- *Laminar Flow and Turbulent Flow*

  In laminar flow water particles move along well-defined paths, or streamlines. In turbulent flow water particles move in irregular paths that are neither smooth nor fixed; but as an average they represent the forward motion of the entire stream. In general, all practical open channel flow problems exhibit turbulent flow.

- *Critical Flow*

  Critical flow occurs in an open channel when the specific energy (sum of depth and velocity head) is a minimum for a particular discharge, which is also when the Froude number, Fr =1. As flow approaches the critical depth, or minimum specific energy, small changes in energy may cause unstable and excessive water surface undulations. Therefore, when designing channels, avoid the region of instability defined within the range $0.9 \leq Fr \leq 1.1$.

  The Froude number is defined as:

$Fr = V/(gD)^{0.5}$

Where:

V = average velocity (ft/s)

g = gravitational acceleration, 32.2 ft/s^2

D = hydraulic depth, the area divided by the channel top width (ft)

The channel slope at critical flow conditions is the critical slope. When the channel slope is flatter than the critical slope (mild slope), the flow is subcritical and depth of flow $d > d_c$ = critical depth. Conversely, when the channel slope is steeper than the critical slope (steep slope), the flow is supercritical and $d < d_c$. If the unstable flow region cannot be avoided in design, assume the least favorable type of flow (supercritical or subcritical) for the design and provide sufficient freeboard in the channel so that flow instability will not affect channel stability. For a more detailed discussion of critical flow, see Chow, 1959, Chapters 3 and 4 or HDS 4.

10.3 Uniform Flow

The flow depth or other condition of uniform flow in a channel at a known discharge is computed using the Manning's equation (equation (1)), along with prescribed conditions (e.g., channel shape, material, slope). In uniform flow, $S_f = S_w = S_0$, where:

S_f = (ft/ft) friction slope or energy gradient, which is the elevation of the total head of flow.

S_o = (ft/ft) slope of the channel bed.

S_w = (ft/ft) slope of the water surface.

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

Where:

Q = discharge, (ft^3/s)

n = Manning's roughness coefficient, dimensionless

A = cross-sectional area, (ft^2)

$R = A/P$ = hydraulic radius (ft)

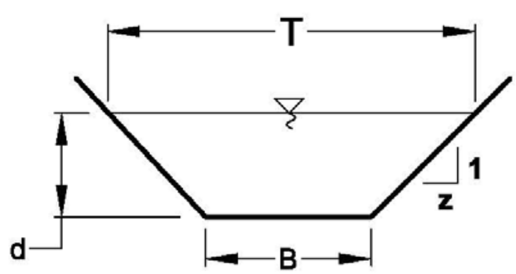

***Figure 10.1* Trapezoidal Channel Cross Section**

Manning's equation for flow in the trapezoidal channel (Figure 1) is

$$Q = \frac{1.49}{n}(Bd + Zd^2)\left(\frac{Bd + Zd^2}{B + 2d(1+Z^2)^{1/2}}\right)^{2/3} S_0^{1/2} = \frac{1.49}{n}\left(\frac{[(B+Zd)d]^{5/3}}{[B+2d(1+Z^2)^{1/2}]^{2/3}}\right)S_0^{1/2}$$

Where:

B = channel base (ft)

d = depth of flow (ft)

Z = side slope, Z horizontal:1 vertical

A = Bd + Zd^2

10.4 Manning's Roughness Coefficient

The Manning's roughness coefficient is usually considered constant, but often is not constant in shallow flow depth conditions. 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 not acceptable and consideration of the shallow flow depth should be made by using a higher n value. Similarly, the flow depth in grass channels may also be small relative to the height of the grass, so n will also vary with depth. Additional roughness guidance for both types of linings is available in FDM 13-30-15 and FDM 13-30-25, where Manning's n is varied depending upon the depth of flow.

10.5 Shear Stress

10.5.1 Equilibrium Concepts

Most highway drainage channels cannot tolerate bank instability and possible lateral migration. 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:

- essentially rigid (static)
- movable (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.

Because of the need for reliability, static equilibrium conditions and the use of linings to achieve a stable condition are 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):

- the permissible velocity approach
- the permissible tractive force (shear stress) approach.

This design procedure uses the permissible tractive force approach rather than the velocity approach, since two channels may have the same velocity with one stable and the other unstable due to different combinations of depth and slope. 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 (Chow, 1959 or HDS 4).

10.5.2 Applied Shear Stress

The hydrodynamic force on the channel boundary by water flowing in the channel is 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 uniform flow, the tractive force equals the effective component of the drag force exerted on the boundary by the water, parallel to the channel bottom (Chow, 1959). The mean boundary shear stress applied to the wetted perimeter for uniform flow is given by the following equation (2).

$$\tau_o = \gamma R S_o \tag{2}$$

Where:

τ_o = mean boundary shear stress, (lb/ft^2)

γ = unit weight of water, 62.4 lb/ft^3

R = hydraulic radius (ft)

Shear stress in channels is not uniformly distributed along the wetted perimeter (USBR, 1951; Olsen and Florey, 1952; Chow, 1959; Anderson, et al., 1970). A typical distribution of shear stress in a prismatic channel is shown in Figure 10.2. The shear stress is zero at the water surface and reaches a maximum on the centerline of the channel. The maximum for the side slopes occurs at about the lower third of the side.

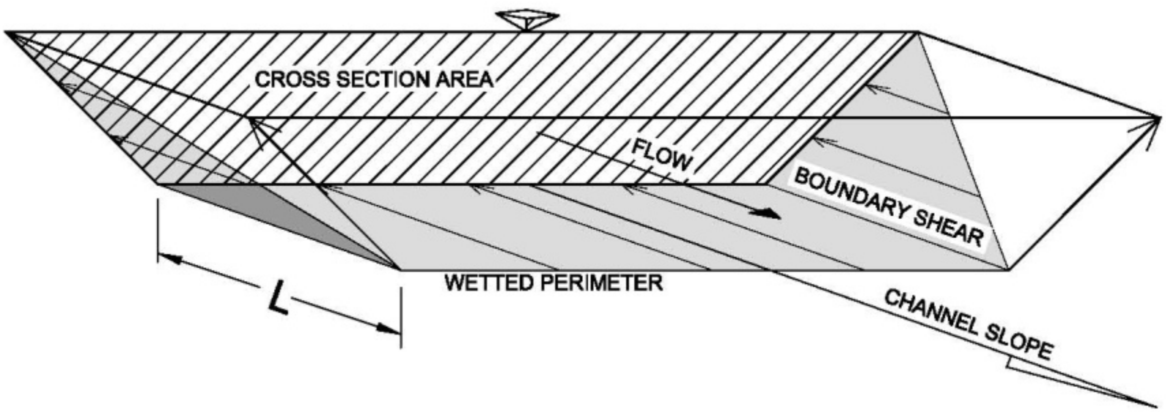

Figure 10.2 Typical Distribution of Shear Stress

The maximum shear stress on a channel bottom, τ_d, and on the channel side, τ_s, in a straight channel depends on the channel shape. To simplify the design process, the maximum channel bottom shear stress is taken as:

$$\tau_d = \gamma d S_o \tag{3}$$

Where:

τ_d = shear stress in channel at maximum depth (lb/ft^2)

d = maximum depth of flow in the channel for the design discharge (ft)

For trapezoidal channels where the ratio of bottom width to flow depth (B/d) is greater than 4, Equation 3 provides an appropriate design value for shear stress on a channel bottom. Most roadside channels are characterized by this relatively shallow flow compared to channel width. For trapezoidal channels with a B/d ratio less than 4, Equation 3 is conservative. For example, for a B/d ratio of 3, Equation 3 overestimates actual bottom shear stress by 3 to 5 percent for side slopes (Z) of 6 to 1.5, respectively. For a B/d ratio of 1, Equation 3 overestimates actual bottom shear stress by 24 to 35 percent for the same side slopes of 6 to 1.5, respectively. In general, Equation 3 overestimates in cases of relatively narrow channels with steep side slopes. In addition, the methods used to analyze riprap stability described in FDM 13-30-25 account for both side slope and bottom slope stability. For more information, see HEC-15, Chapter 2.

10.5.3 Permissible Shear Stress

Flexible linings act to reduce the shear stress on the underlying soil surface. For example, a long-term lining of vegetation in good condition can reduce the shear stress on the soil surface by over 90 percent. Transitional linings act in a similar manner as vegetative linings to reduce shear stress. Performance of these products depends on their properties: thickness, cover density, and stiffness. The erodibility of the underlying soil therefore is a key factor in the performance of flexible linings. The erodibility of soils is a function of particle size, cohesive strength and soil density. The erodibility of non-cohesive soils (defined as soils with a plasticity index of less than 10) is due mainly to particle size, while fine-grained cohesive soils are controlled mainly by cohesive strength and soil density. For most highway construction, the density of the roadway embankment is controlled by compaction rather than the natural density of the undisturbed ground. However, when the ditch is lined with topsoil, the placed density of the topsoil should be used instead of the density of the compacted embankment soil. The in-place topsoil, however, should not be overly compacted to promote vegetation establishment.

For rock linings, the permissible shear stress, τ_p, indicates the force required to initiate movement of the particles. Prior to the movement of rocks, 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 moves, the underlying soil will be exposed to the erosive force of the flow.

Permissible shear stress values for different soil types are based on the methods described in this procedure. Vegetative lining performance relates to how well the lining protects the underlying soil from shear stresses. These linings have permissible shear stresses dependent of soil types.

10.6 Design Parameters

10.6.1 Design Flow Rates

FDM 13-10 Figure 1.1, lists the design flow rate for roadside and median ditches, for flow capacity, that flow with a 25-year recurrence interval. To evaluate the erosion potential of a ditch, use a flow rate with a 10-year recurrence interval. Note that all flows through the ditch, both from the highway right-of-way and from other adjacent properties, outfalls, ditches or channels, must be included in the design flow.

If the permanent lining will be a vegetative lining with a temporary lining during the establishment period, use the 2-year recurrence interval for the temporary lining design. The temporary lining is only required for a short period of time, and if the lining is damaged, repairs are usually inexpensive. Refer to FDM 10-5-30 for a discussion on designing temporary linings.

10.6.2 Channel Cross Section Geometry

Most highway drainage channels are triangular or trapezoidal in shape with rounded corners. For design purposes, a triangular or trapezoidal representation is sufficient. Design of roadside channels should be integrated with the highway geometric and pavement design to ensure 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 increase the channel area 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. Limit the ratio of top width to depth to less than 20 (Richardson, Simons and Julien, 1990) because very wide channels have a tendency to form smaller more efficient channels within their banks. This will increase the shear stress above the planned design range, which should be avoided.

It has been demonstrated that if a riprap-lined channel has 3:1 (H:V) or flatter side slopes, there is no need to check the banks for erosion (Anderson, et al., 1970). With side slopes steeper than 3:1, 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 includes procedures for checking the potential of channel side slopes to erode.

10.6.3 Channel Slopes and Alignment

The longitudinal slope of a roadside channel is usually the same as the roadway profile and so is typically not a design variable option. If channel stability conditions are below the required performance and available linings are nearly sufficient, it may be feasible to reduce the channel slope slightly relative to the roadway profile. For channels outside the roadway right-of-way, there can be more grading design options to adjust channel slope where necessary. Channel slope is one of the major parameters in determining shear stress.

Note that the increased shear stresses created by flow around a bend may produce scour that would not occur in straight channel reaches. To prevent bend scour, it may be necessary to increase the rock riprap size or use a different lining material in the bend. Refer to the section on bend stability for more guidance.

10.6.4 Freeboard

The freeboard of a channel is the vertical distance from the water surface to the top of the channel at the 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 water surface waves or fluctuations from washing over the sides of the channel. In a permanent roadway channel 0.5 ft of freeboard above the subgrade shoulder point is the minimum freeboard height, as shown in Figure 10.3. The design channel depth should not be above the subgrade shoulder point. The minimum depth of a ditch is 1 ft below the subgrade shoulder point to ensure positive drainage of the subgrade. Steep gradient channels (supercritical flow) should have a freeboard height equal to the flow depth, which allows for large variations to occur in flow depth caused by waves, jumps, splashing, and surging. Lining materials should extend to the freeboard elevation. Freeboard requirements are shown in Table 10.1.

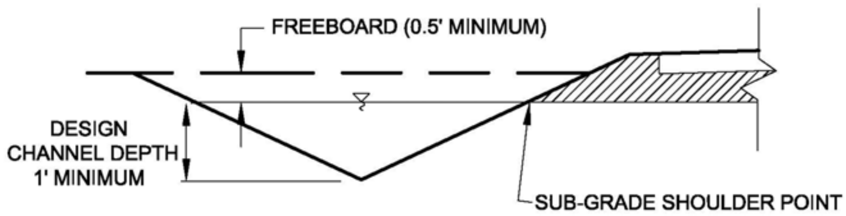

Figure 10.3 Roadside Ditch Freeboard

Table 10.1 Freeboard Requirements

Froude Number Range	Freeboard Requirement
Fr < 0.9	0.5 ft.
0.9 <= Fr <= 1.1	1.0 ft.
Fr > 1.1	Depth of flow

10.6.5 Rigid and Flexible Linings

The design of rigid linings, such as concrete channels, can be accomplished using Manning's formula to determine the required dimension of several channel shapes and chose the one that minimizes cost, maximizes constructability, and meets other roadway specifications. Since there is no erosion, there is no maximum permissible velocity. Table 10.2 outlines the advantages and disadvantages of rigid linings.

Table 10.2 Advantages and Disadvantages of Rigid Linings

Advantages	Disadvantages
Large capacity	Expensive to construct & maintain
Prevent erosion in steep channels	Unnatural appearance
May be constructed within a limited right of way	Prevent or reduce natural infiltration
Underlaying soil completely protected	Scour at downstream end
	Linings may be destroyed by undercutting, channel head cutting or hydrostatic pressure

The flexible linings covered in this discussion are temporary, vegetative, and rock riprap linings. Table 10.3 outline the advantages and disadvantages of flexible linings.

Table 10.3 Advantages and Disadvantages of Flexible Linings

Advantages	Disadvantages
Cheaper than rigid	Limited flow depth because of erosion
Self-healing	Lower capacity
Permit infiltration and exfiltration	Requires more right-of-way than rigid linings
Natural appearance	Riprap may be unavailable
Provide a filtering media for runoff contaminants	May not be able to establish vegetation
Lower velocity	

10.6.6 Composite Linings

Composite linings use two lining types in a single channel rather than one. A more shear resistant lining is used in the bottom of the channel while a less shear resistant lining protects the sides. This type of design may be desirable where the upper lining is more cost-effective and/or environmentally benign, but the lower lining is needed to resist bottom stresses.

Another important use of a composite lining is in vegetative channels that experience frequent low flows. These low flows may kill the submerged vegetation. In erodible soils, this leads to the formation of a small gully at the bottom of the channel. Gullies weaken a vegetative lining during higher flows, causing additional erosion, and can result in a safety hazard. A solution is to provide a non-vegetative low-flow channel lining such as 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.

10.7 General Design Procedures

This section outlines the general procedure for designing flexible channel linings based on the shear stress concepts presented earlier in this section. The simplest case of the straight channel is described first, followed by a discussion of variations to the straight channel including side slope stability, bends, and composite linings. Discussions of specific design approaches for grass channels and riprap channels follow this general procedure.

10.7.1 Straight Channels

The basic design procedure for flexible channel linings is quite simple. The computations include a determination of the uniform flow depth in the channel and determination of the shear stress on the channel bottom at this depth. Both concepts were discussed earlier in this section. Recall that:

$$\tau_d = \gamma d S_o$$

The basic comparison required in the design procedure is that of permissible to computed shear stress for a lining. If the permissible shear stress is greater than or equal to the computed shear stress, including consideration of a safety factor, the lining is considered acceptable. If a lining is unacceptable, a lining with a higher permissible shear stress is selected, the discharge is reduced (by diversion or retention/detention), or the channel geometry is modified. This concept is expressed as:

$$\tau_p \geq SF\,\tau_d \tag{4}$$

Where:

τ_p = permissible shear stress for the channel lining, (lb/ft^2)

The safety factor provides for a measure of uncertainty, as well as a means for the designer to reflect a lower tolerance for failure by choosing a higher safety factor. A safety factor of 1.0 is appropriate in many cases and may be considered the default. The expression for shear stress at maximum depth (Equation 3) is conservative and appropriate for design as discussed above. However, safety factors from 1.0 to 1.5 may be appropriate, subject to the designer’s discretion, where one or more of the following conditions may exist:

- critical or supercritical flows are expected
- soil types where vegetation may be uneven or slow to establish

- significant uncertainty regarding the design discharge
- consequences of failure are high

The basic procedure for flexible lining design consists of the following steps and is summarized in Figure 10.4.

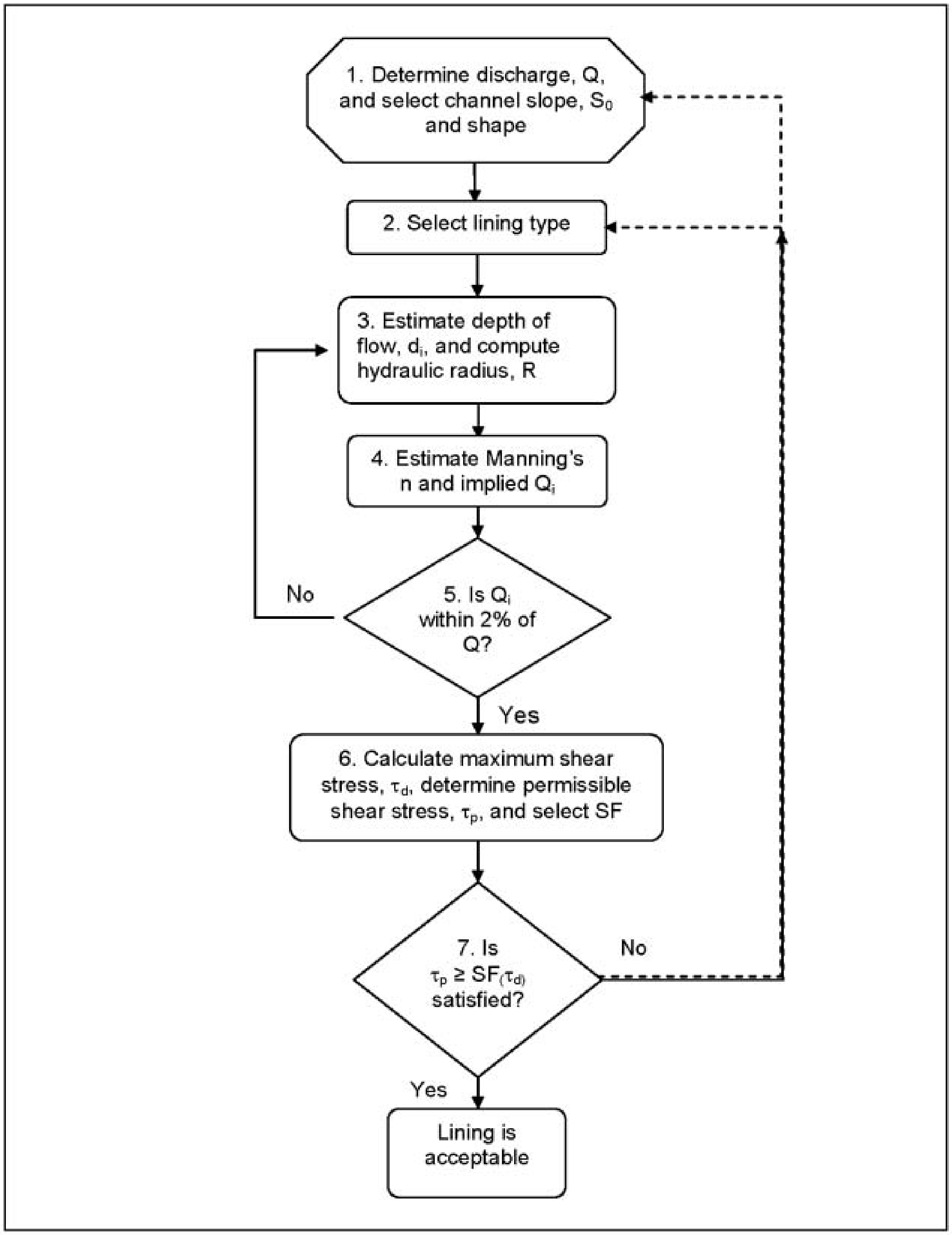

Figure 10.4 Flexible Channel Lining Design Flow Chart

Step 1. Determine a design discharge (Q) and select the channel slope (S_o) and shape.

Step 2. Select a trial lining type. Initially, determine if a long term lining is needed, and whether or not a temporary or transitional lining is required. For the latter, the trial lining type could be chosen as an erosion mat. For example, it may be determined that the bare soil is insufficient for a long-term solution, but vegetation is a good solution. For the transitional period between construction and vegetative establishment, analysis of the bare soil with an erosion control mat will determine if a temporary lining is prudent.

Step 3. Estimate the depth of flow, d_i in the channel and compute the hydraulic radius, R. The estimated depth may be based on physical limits of the channel, but this first estimate is essentially a guess. Iterations on steps 3 through 5 may be required.

Step 4. Estimate Manning's n and calculate the discharge, Q_i, with Manning's equation (using the estimated n) and flow depth values. Manning's n will vary depending upon lining type and flow depth.

Step 5. Compare Q_i with Q. If Q_i is within 2 percent of the design Q then proceed on to step 6. If not, return to step 3 and select a new estimated flow depth, d_{i+1}.

Step 6. Calculate the shear stress at maximum depth, τ_d (Equation 3), determine the permissible shear stress, τ_p ,and select an appropriate safety factor, SF. A safety factor of 1.0 is usually chosen, but may be increased as discussed earlier.

Step 7. Compare the permissible shear stress to the calculated shear stress from step 6 using Equation 3.

- If the permissible shear stress is adequate ($\tau_p \geq SF\, \tau_d$) then the lining is acceptable.

- If the permissible shear is inadequate ($\tau_p < SF\, \tau_d$), return to step 1 and modify the channel slope or shape, or return to step 2 and select an alternative lining type with greater permissible shear stress.

Once the selected lining is stable, the design process is complete. Other linings may be tested, if desired, before specifying the preferred lining.

10.7.2 Side Slope Stability

As described previously, shear stress is less on the channel sides than on the bottom. The maximum shear on the side of a channel is given by the following equation:

$$\tau_s = K_1 \tau_d \qquad (5)$$

Where:

τ_s = side shear stress on the channel, (lb/ft2)

K1 = ratio of channel side to bottom shear stress

The value K_1 depends on the size and shape of the channel. For parabolic or V-shape with rounded bottom channels there is no sharp discontinuity along the wetted perimeter and therefore it can be assumed that shear stress at any point on the side slope is related to the depth at that point using Equation 3.

For triangular and trapezoidal channels, K_1 has been developed based on the work of Anderson, et al. (1970). The following equation may be applied.

$K_1 = 0.77$	$Z \leq 1.5$	
$K_1 = 0.066Z + 0.67$	$1.5 < Z < 5$	(6)
$K_1 = 1.0$	$5 \leq Z$	

The Z value represents the ratio of horizontal to vertical dimensions, Z:1 (H:V). Use of side slopes steeper than 3:1 is not encouraged for flexible linings because of the potential for erosion of the side slopes. For riprap, the basic design procedure is supplemented for channels with side slopes steeper than 3:1 as described in FDM 13-30-25.

10.7.3 Bend Stability

As Flow around a bend creates secondary currents that impose higher shear stresses on the channel sides and bottom compared to a straight reach (Nouh and Townsend, 1979) as shown in Figure 10.6, Superelevation Height in a Channel Bend. 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.

Equation 7 gives the maximum shear stress in a bend.

$$\tau_b = K_b \tau_d \tag{7}$$

Where:

τ_b = side shear stress on the channel, (lb/ft2)

Kb = ratio of channel bend to bottom shear stress

The maximum shear stress in a bend is a function of the ratio of the radius of channel curvature to the top (water surface) width, R_C/T (Refer to Figure 10.5). As R_C/T decreases, that is as the bend becomes sharper, the maximum shear stress in the bend tends to increase. K_b can be determined from the following equation from Young, et al., (1996) adapted from Lane (1955):

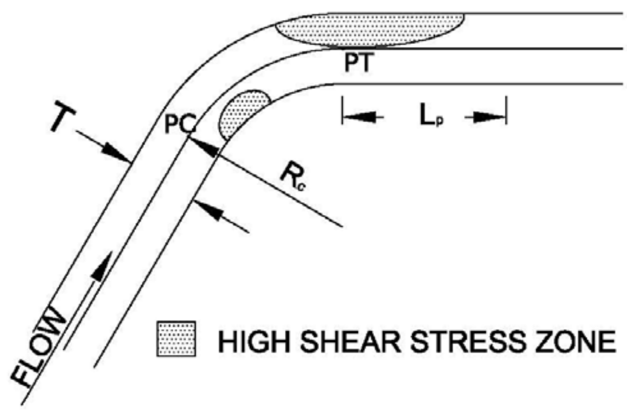

Figure 10.5 Sheer Stress Distribution in a Channel Bend (Nouh and Townsend, 1979)

Kb = 2.00	RC/T ≤ 2	
$K_b = 2.38 - 0.206\left(\frac{R_c}{T}\right) + 0.0073\left(\frac{R_c}{T}\right)^2$	2 < RC/T < 10	(8)
Kb = 1.05	RC/T ≥ 10	

Where,

R_c = radius of channel curvature of the bend to the channel centerline, (ft)

T = channel top (water surface) width, (ft)

The added stress induced by bends does not fully attenuate until some distance downstream of the bend. If added lining protection is needed to resist the bend stresses, this protection should continue downstream for a distance given by:

$$L_p = 0.60\left(\frac{R^{7/6}}{n}\right) \tag{9}$$

Where:

L_p = length of protection, (ft)

R = hydraulic radius of the straight channel, (ft)

n = Manning's roughness for lining material in the bend

A final consideration for channel design at bends is the increase in water surface elevation at the outside of the bend caused by the superelevation of the water surface. Additional freeboard is necessary in bends and can be calculated using the following equation:

$$\Delta d = \left(\frac{V^2 T}{g R_c} \right) \tag{10}$$

Where:

Δd = additional freeboard required because of superelevation, (ft)

V = average channel velocity before the bend, (ft/s)

g = acceleration due to gravity, 32.2ft/s^2

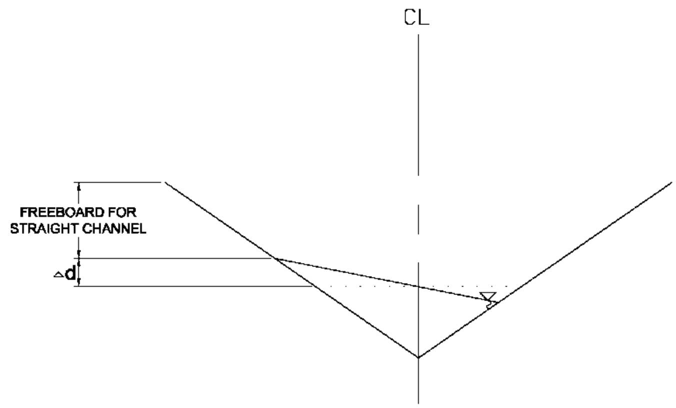

Figure 10.6 Superelevation Height in a Channel Bend

The design procedure for channel bends is summarized in the following steps:

Step 1. Determine the shear stress in the bend and check whether or not an alternative lining is needed in the bend.

Step 2. If an alternative lining is needed, select a trial lining type and compute the new hydraulic properties and bend shear stress.

Step 3. Estimate the required length of protection.

Step 4. Calculate superelevation and check freeboard in the channel.

10.7.3 Composite Linings

It is important that the bottom-lining material cover the entire channel bottom so that adequate protection is provided. To ensure that the channel bottom is completely protected, the bottom 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. To determine the 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.

The following equation is used to determine the equivalent roughness coefficient, n_e.

$$n_e = \left[\frac{P_L}{P} + \left(1 - \frac{P_L}{P}\right)\left(\frac{n_S}{n_L}\right)^{3/2} \right]^{2/3} n_L \qquad (11)$$

Where:

n_e = equivalent Manning's n value for the composite channel

P_L = low flow lining perimeter, (ft)

P = total flow perimeter, (ft)

n_s = Manning's n value for the side slope lining

n_L = Manning's n value for the low flow lining

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 transitional lining should be used adjacent to the low-flow channel to provide erosion protection until the vegetative lining is well established.

The procedure for composite lining design is based on the design procedure for straight channels with additional sub-steps to account for the two lining types. The procedure is:

Step 1. Determine design discharge and select channel slope and shape. (No change.)

Step 2. Need to select both a low flow and side slope lining.

Step 3. Estimate the depth of flow in the channel and compute the hydraulic radius. (No change.)

Step 4. After determining the Manning's n for the low flow and side slope linings, use Equation 11 to calculate the effective Manning's n.

Step 5. Compare implied discharge and design discharge. (No change.)

Step 6. Determine the shear stress at maximum depth, τ_d ,(Equation 3), and the shear stress on the channel side slope, τ_s ,(Equation 5).

Step 7. 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 than the τ_p for the respective lining, a different combination of linings should be evaluated.

10.8 References

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FDM 13-30-15 Grass Lined Channels

October 22, 2012

15.1 Introduction

Vegetation is one of the most common long-term channel linings. Most roadside channels receive highway runoff from rainfall and snowmelt events and remain dry most of the time. For these conditions, upland species of vegetation (typically grasses) provide good erosion protection and can trap sediment and related contaminants in the channel section. Thus, the vegetated liner, or “grass swale” can be used to meet the post construction total suspended solids (TSS) reduction requirements listed in Wisconsin Administrative Code TRANS 401.106. However, grasses are not suited to sustained flow conditions or long periods of submergence. Common design practice for vegetative channels with sustained low flow and intermittent high flows is to provide a composite lining with riprap, grouted riprap, articulated concrete block or concrete providing a low flow section.

Vegetative linings consist of seeded or sodded grasses placed in and along the channel. Grasses are seeded and fertilized according to the requirements of the particular WisDOT seed mix and soil type.

Between seeding and vegetation establishment, the channel is vulnerable to erosion. Erosion mats provide erosion protection during the vegetation establishment period. These linings are typically degradable and do not provide ongoing stabilization of the channel after vegetation is established. Turf reinforcement mats enhance the performance of the vegetation by permanently reinforcing the turf root structure, which increases the permissible shear stress of the channel.

The behavior of established grass in an open channel lining is complicated. Grass stems flex as flow depth and shear stress increase, which reduces the roughness height and increases velocity and flow rate. As a result, a grass-lined channel cannot be described by a single roughness coefficient.

For channels where the design shear exceeds that of vegetation alone, but where vegetation is desirable from a cost or water quality standpoint, a turf reinforcement mat may be appropriate.

Kouwen and Unny (1969) and Kouwen and Li (1981) developed a model of the biomechanics of vegetation in open-channel flow. This model provides a general approach for determining the roughness of vegetated channels based upon the retardance classification. The resulting resistance equation (refer to HEC-15, Appendix C.2) uses the same vegetation properties as the Soil Conservation Service (SCS), now known as the NRCS, retardance approach but is more adaptable to the requirements of highway drainage channels. The design approach for grass-lined channels described in this procedure was developed from the Kouwen resistance equation, as found in HEC-15 Section 4

15.2 Grass Lining Properties

Vegetative linings are classified as Retardance A, B, C, D, or E according to a certain group of grasses of given heights as defined by the SCS. The SCS Retardance Table is in HEC-15, Table 4-1. Retardance A refers to grasses of high hydraulic resistance while Retardance E refers to grasses of low hydraulic resistance. WisDOT has established typical grass heights for selected retardance classification as identified in Table 15.1.

The density, stiffness, and height of grass stems are the main biomechanical properties of grass that relate to flow resistance and erosion control. The stiffness property (product of elasticity and moment of inertia) of grass is similar for a wide range of species (Kouwen, 1988) and is a basic property of grass linings. These properties are combined to describe the cover condition of the grass.

For design purposes, good cover of a well established grass channel is the typical reference condition. Use the fair condition when you anticipate difficulty establishing or maintaining a good stand of grass. The retardance classifications for WisDOT seed mixes are listed in Table 15.1. Note that native seed mixes (mixes 70 - 80) take about three years to develop and tend to be bunched, leaving bare soil between the clumps.

Table 15.1 Typical Height and Retardance Classification of Vegetal Covers by WisDOT Seed Mix

WisDOT Highway Seed Mixture Number	Retardance Classification	Typical grass height	Cover Factor
70,70A, 75, 80	B	2 ft (24 in)	Mixed
10, 20, 30, 40, 60	C(1)	0.67 ft (8 in)	Turf

1.) Use Retardance Classification Factor D for continuously mowed conditions of 4 inches or less.

15.3 Manning's Roughness

Manning's roughness coefficient for grass linings varies with the grass roughness parameter, C_n, and the shear force, τ_o , exerted by the flow. This is because the applied shear on the grass stem causes the stem to bend, which reduces the stem height relative to the depth of flow and reducing the roughness. The Manning's n roughness coefficient is represented by:

$$n = 0.213 C_n \tau_o^{-0.4} \qquad (12)$$

Where:

C_n = grass roughness coefficient

τ_o = mean boundary shear stress, lb/ft^2

Equation (12) is derived in Appendix C.2, HEC-15.

15.4 Permissible Shear Stress

The permissible shear stress of a vegetative lining is determined both by the underlying soil properties as well as those of the vegetation. Grass linings move shear stress away from the soil surface. The remaining shear at the soil surface is termed the effective shear stress. When the effective shear stress is less than the allowable shear stress for the soil surface, then erosion of the soil surface will be controlled. Grass linings provide shear reduction in two ways. First, the grass stems absorb a portion of the shear force within the canopy before it reaches the soil surface. Second, the grass plant (both the root and stem) stabilizes the soil surface against turbulent fluctuations. Hence, the effective shear at the soil surface is a function of the design shear stress τ_d the grass cover factor C_f, the soil grain roughness n_s, and the overall lining roughness n (refer to section 4.3.1, HEC-15 for more details).

15.5 Grass Cover Factor

The grass cover factor, C_f, varies with cover density and grass growth form (turf, bunch, or mixed). Bunchgrass is the general name for perennial grass species that tend to grow in discrete tufts or clumps (i.e., bunches) and does not spread by stolons or rhizomes like turf. Turf is grass and the part of the soil beneath it held together by the roots that forms a mat. Turf grasses may also be referred to as sod (i.e. in HEC 15). Mixed is a combination of the two types, individual clumps of bunchgrasses intermixed with turf grasses. The selection of the cover factor is a matter of engineering judgment since limited data are available. Cover factors are better for turf grasses than bunch grasses. In all cases a uniform stand of grass is assumed. Non-uniform conditions include wheel ruts, animal trails and other disturbances that run parallel to the direction of the channel. Estimates of cover factor are best for good uniform stands of grass; there is more uncertainty in the estimates of fair and poor conditions. Cover factor values are provided in the WisDOT grass swale design spreadsheet.

15.6 Permissible Soil Shear Stress

Soil boundary erosion occurs when the effective shear stress exceeds the permissible soil shear stress. Permissible soil shear stress is a function of particle size, cohesive strength, and soil density. The erodibility of coarse non-cohesive soils (defined as soils with a plasticity index less than 10) is due mainly to particle size, while fine-grained cohesive soils are controlled mainly by cohesive strength and soil density.

New ditch construction includes the placement of topsoil in the channel. Salvaged topsoil is typically gathered from locations on the project and stockpiled for revegetation work. Therefore, the important physical properties of the soil can be determined during the design by sampling surface soils from the project area. Since these soils are likely to be mixed together, average physical properties are acceptable for design.

15.6.1 Non-Cohesive Soils

For non-cohesive soils, the permissible soil shear stress depends upon the particle size D_{75}, which is the particle size for which 75% of the material by weight is smaller than that size. For fine-grained, non-cohesive soils with D_{75} < 0.05 in, the permissible shear stress is relatively constant and is conservatively estimated at 0.02 lb/ft^2. For coarse-grained non-cohesive soils (0.05 in < D_{75} < 0.6 in), the permissible shear stress varies with the particle size. For more detail, refer to HEC-15 section 4.3.2.1. Non-cohesive permissible soil shear stress values are calculated in the WisDOT Grass Swale design spreadsheet. Typical values for non-cohesive soils are listed in Table 15.2

Table 15.2 Typical Particle Sizes of Native Sands at 75 Percent Passing (D_{75})

Material Description (1)	USCS Classification	D75 (in)		
		Minimum	Average	Maximum
Silty and Clayey Fine Sand with a trace to no gravel	SM, SC	0.004	0.008	0.012
Silty and Clayey Fine to Coarse Sand with a trace to little gravel	SM, SC	0.012	0.031	0.12
Silty and Clayey Fine to Coarse Sand with gravel (>20%)	SM, SC	0.08	0.24	0.51
Fine Sand with a trace to no gravel, silt, and clay	SP, SW	0.008	0.016	0.02
Fine to Coarse Sand with a trace to little gravel and a trace to no silt and clay	SP, SW	0.024	0.063	0.12
Fine to Coarse Sand with gravel (>20%) and a trace to little silt and clay	SP, SW	0.16	0.28	0.39

Notes: (1) Percentage Descriptions: Trace = 1-9%, Little = 10-19%

15.6.2 Cohesive Soils

For cohesive soils, the permissible soil shear stress depends upon the ASTM soil classification, the soil plasticity index and the void ratio of the soil. Cohesive permissible soil shear stress values are calculated in the WisDOT Grass Swale design spreadsheet based upon these variables. Typical cohesive soils are listed below; more detail is given in HEC-15, section 4.3.2.2.

- GM Silty gravels, gravel-sand silt mixtures
- GC Clayey gravels, gravel-sand-clay mixtures
- SM Silty sands, sand-silt mixtures
- SC Clayey sands, sand-clay mixtures
- ML Inorganic silts, very fine sands, rock flour, silty or clayey fine sands
- CL Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays
- MH Inorganic silts, micaceous or diatomaceous fine sands or silts, elastic silts
- CH Inorganic clays of high plasticity, fat clays

15.6.3 Combined Grass and Soil Shear Stress

The combined effects of the soil permissible shear stress and the effective shear stress transferred through the vegetative lining results in a permissible shear stress for a vegetative lining. Equation 2 is used to calculate the permissible shear stress for the vegetative lining. For more detail, go to HEC-15, section 4.3.3.

$$\tau_p = \frac{\tau_{p,soil}}{(1-C_f)}\left(\frac{n}{n_s}\right)^2 \quad (13)$$

Where:

τ_p = permissible shear stress on the vegetative lining, (lb/ft^2)

$\tau_{p,soil}$ = permissible soil shear stress, (lb/ft^2)

C_f = grass cover factor

n_s = soil grain roughness

n = overall lining roughness

15.7 Grass Lined Channel Design Example

15.7.1 Grass Lined Channel Design Using HEC-15

A grass lined channel design example using the HEC-15 method is provided as Attachment 15.1.

15.7.2 Grass Lined Channel Design Using WisDOT Spreadsheet

WisDOT has prepared a spreadsheet that incorporates all the design guidelines and equations described in HEC-15 to design grass lined channels. The spreadsheet is divided into three sections:

1. A data entry section,
2. A results section, and
3. An intermediate calculations section.

An link to the spreadsheet and an example spreadsheet is provided as Attachment 15.2. Be sure to enable the spreadsheet Macros by clicking on the security warning "options" box on the top of the spreadsheet and then highlight the "enable this content" button. A step by step example problem is provided as Attachment 15.3.

15.8 References

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LIST OF ATTACHMENTS

FDM 13-30-25 Rock Riprap Lined Channels *May 17, 2022*

25.1 Introduction

Vegetation is one of the most common long-term channel linings. Most roadside channels receive highway runoff from rainfall and snowmelt events and remain dry most of the time. For these conditions, upland species HEC-15 (FHWA, 2005) contains design methods to design rock riprap channel linings, riprap on side slopes and channel protection in bends. The methods described in HEC-15 should not be used for rapidly varied flow, which often occurs at, for example, bridge abutments. For the design of riprap around bridge structures, consult with the Bureau of Structures Hydraulic Engineer.

Riprap, cobble, and gravel linings are considered permanent flexible linings. They are described as a noncohesive layer of stone or rock with a characteristic size D_{50}. The WisDOT rock riprap sizes are found in Standard Spec 606, Rock Riprap and Standard Spec 312, Select Crushed Material. Selected design characteristics are listed in Table 25.1. Refer to the standard specification for the required size distribution of each riprap type.

***Table 25.1* Typical Particle Sizes of Native Sands at 75 Percent Passing (D_{75})**

Riprap Type	D50 (inches)	D50 (feet)	Riprap Thickness (in)	Geotextile Type
Select Crushed Material	2.2	0.18	5	Type R
Extra Light (EX-LIGHT) Riprap	6	0.5	9	Type R
Light Riprap	10	0.83	12	Type R
Medium Riprap	12.5	1.04	18	Type HR
Heavy Riprap	16	1.33	24	Type HR
Extra-Heavy Riprap	20	1.67	30	Type HR

A geotextile must be placed beneath the riprap, as described in Table 25.1, to prevent the washout of the underlying soil. The fabric should be installed per the manufacturer's specifications. The riprap should be placed to form a well-graded interlocking mass with a minimum of voids. Rocks should be hard, durable, preferably angular in shape (see additional design considerations at the end of this section), and free from overburden, shale, and organic material. The rock should be resistant to disintegration from chemical and physical weathering.

The procedures in this section are applicable to uniform prismatic channels with rock sizes within the ranges given in Table 25.1. If the channel slope is less than or equal to 20%, then the designer should use the HEC-15 rock riprap design method described in this Procedure. If the channel slope is greater than 20%, then the designer should use the NRCS Design of Rock Chutes methodology described in FDM 13-30-30. For situations not satisfying the uniform prismatic channel condition such as stream banks or lakeshores, the designer is referred to HEC-11, "Design of Riprap Revetment" (FHWA, 1989).

25.2 Analysis of Slopes Less than or Equal to 20 Percent

For channel slopes that are less than or equal to 20%, the designer should use the design methodology described in HEC-15 Chapter 6, and repeated in this Procedure. This approach uses the permissible shear stress method to determine the appropriate size riprap for a drainage channel. The process includes a procedure to determine Manning's n for the channel followed by the approach necessary to determine the permissible shear stress for the given channel and flow. If the rock size from this analysis appears excessive, use the design approach for rock chutes described in FDM 13-30-30 and select the most appropriate design for the given site conditions using engineering judgment.

For runoff from bridge decks, review SDD 8D2 and SDD 8D3.

25.3 Manning's Roughness (for Rock Riprap Lined Channels)

Manning's roughness is a key parameter needed for determining the relationships between depth, velocity, and slope in a channel. However, for gravel and riprap linings, roughness has been shown to be a function of a variety of factors including flow depth and the particle size D50, which is the particle size for which 50% of the material by weight is smaller than that size. A partial list of roughness relationships includes Blodgett (1986a), Limerinos (1970), Anderson, et al. (1970), USACE (1994), Bathurst (1985), and Jarrett (1984). For the conditions encountered in roadside and other small channels, the relationships of Blodgett and Bathurst are adopted for this procedure.

Blodgett (1986a) proposed a relationship for Manning's roughness coefficient, n, that is a function of the flow depth and the relative flow depth (da/D50) as follows:

$$n = \frac{0.262 d_a^{1/6}}{2.25 + 5.23 \log\left(\frac{d_a}{D_{50}}\right)} \qquad (14)$$

Where:

n = Manning's roughness coefficient, dimensionless

d_a = average flow depth in the channel, (ft)

D_{50} = median riprap/gravel size, (ft)

Equation 14 is applicable for the range of conditions where $1.5 \le d_a/D_{50} \le 185$. For small channel applications, relative flow depth should not exceed the upper end of this range.

Some channels may experience conditions below the lower end of this range where protrusion of individual riprap elements into the flow field significantly changes the roughness relationship. This condition may be experienced on steep channels, but also occurs on moderate slopes. The relationship described by Bathurst (1991) addresses these conditions and can be written as follows (See HEC-15, Appendix D for the original form of the equation):

$$n = \frac{1.49 d_a^{1/6}}{\sqrt{g}\, f(Fr) f(REG) f(CG)} \qquad (15)$$

Where:

g = acceleration due to gravity, 32.2 ft/s^2

Fr = Froude number, $Q/\left(A/\sqrt{32.2 d_a}\right)$

REG = roughness element geometry (dimensionless)

CG = channel geometry (dimensionless)

Q = design flow (ft^3/s)

A = area of flow in channel (ft^2)

Equation 15 is a semi-empirical relationship applicable for the range of conditions where $0.3 < d_a/D_{50} < 8.0$. The three terms in the denominator represent functions of Froude number, roughness element geometry, and channel geometry given by the following equations:

$$f(Fr) = \left(\frac{0.28 Fr}{b}\right)^{\log(0.755/b)} \qquad (16)$$

$$f(REG) = 13.434 \left(\frac{T}{D_{50}}\right)^{0.492} b^{1.025 (T/D_{50})^{0.118}} \qquad (17)$$

$$f(CG) = \left(\frac{T}{d_a}\right)^{-b} \qquad (18)$$

Where:

T = channel top width (ft)

b = parameter describing the effective roughness concentration (dimensionless)

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

$$b = 1.14\left(\frac{D_{50}}{T}\right)^{0.453}\left(\frac{d_a}{D_{50}}\right)^{0.814} \qquad (19)$$

Equations 14 and 15 both apply in the overlapping range of $1.5 \le d_a/D_{50} \le 8$. For consistency and ease of application over the widest range of potential design situations, use the Blodgett equation (15) when $1.5 \le d_a/D_{50}$. The Bathurst equation (15) is recommended for $0.3 < d_a/D_{50} < 1.5$. As a practical problem, both methods require average depth to estimate n, while n is needed to determine average depth - setting up an iterative design process.

25.4 Permissible Shear Stress

Values for permissible shear stress for riprap and gravel linings are based on research conducted at laboratory facilities and in the field. The values developed in HEC-15 are judged to be conservative and appropriate for design use. Permissible shear stress is a function of the Shield's parameter, the specific weight of the rock and the water, and the mean riprap size. The Shields parameter is a dimensionless variable that embodies the factors that interact to initiate particle motion on a sediment bed. These factors include the Reynolds number, which is in turn a function of the shear velocity, the kinematic viscosity, and the mean riprap size. The details of these equations are described in Section 6.2 of HEC-15. Permissible shear stress is given by the following equation:

$$\tau_\rho = F^*(\gamma_s - \gamma)D_{50} \qquad (20)$$

Where:

τ_ρ = permissible shear stress (lb/ft^3)

F* = Shield's parameter (dimensionless)

γ_s = specific weight of the rock (lb/ft^3)

γ = specific weight of the water, 62.4 lb/ft^3

Typically, a specific weight of rock of 165 lb/ft^3 is used, but if the available rock is different from this value, the site-specific value should be used.

Recalling Equation 4 from FDM 13-30-10,

$$\tau_p \ge SF\,\tau_d$$

And Equation 3 from FDM 13-30-10,

$$\tau_d = \gamma d S_o$$

Equation 20 can be written in the form of a sizing equation for D_{50} as shown below:

$$D_{50} \ge \frac{SFdS_o}{F^*(SG-1)} \qquad (21)$$

Where:

d = maximum channel depth (ft)

SG = specific gravity of rock (γ_r/γ) (dimensionless)

τ_d = shear stress in channel at maximum depth (lb/ft^2)

SF = safety factor (greater than or equal to one) (dimensionless)

S_o = average bottom slope (equal to energy slope for uniform flow) (ft/ft)

Changing the inequality sign to equality gives the minimum stable riprap size for the channel bottom. Additional evaluation for the channel side slope is given in Section 6.3.2 of HEC-15.

Equation 21 is based on assumptions related to the relative importance of skin friction, form drag, and channel slope. However, skin friction and form drag have been documented to vary resulting in reports of variations in Shield's parameter by different investigators, for example Gessler (1965), Wang and Shen (1985), and Kilgore and Young (1993). This variation is usually linked to particle Reynolds number as defined below:

$$R_e = \frac{V_* D_{50}}{\upsilon} \quad (22)$$

Where:

R_e = particle Reynolds number, dimensionless

V^*= shear velocity (ft/s)

υ = kinematic viscosity, 1.217×10^{-5} ft^2/s at 60 degrees F

The shear velocity if defined as:

$$V_* = \sqrt{gdS} \quad (23)$$

Where:

g = gravitational acceleration, 32.2 ft/s^2

S = channel slope (ft/ft)

Higher Reynolds number correlates with a higher Shields parameter as is shown in Table 25.2. For many roadside channel applications, Reynolds number is less than 4×10^4 and a Shields parameter of 0.047 should be used in Equations 20 and 21. In cases for a Reynolds number greater than 2×10^5, for example, with channels on steeper slopes, a Shields parameter of 0.15 should be used. Intermediate values of Shields parameter should be interpolated based on the Reynolds number.

Table 25.2 Selection of Shield's Parameter and Safety Factor

Reynolds Number	F *	SF
$\leq 4 \times 10^4$	0.047	1.0
$4 \times 10^4 < R_e < 2 \times 10^5$	Linear interpolation	Linear interpolation
$\geq 2 \times 10^5$	0.15	1.5

Higher Reynolds numbers are associated with more turbulent flow and a greater likelihood of lining failure with variations of installation quality. Because of these conditions, it is recommended that the Safety Factor be increased with Reynolds number as shown in Table 25.2. Depending on site-specific conditions, safety factor may be further increased by the designer, but should not be decreased to values less than those in Table 25.2.

As channel slope increases, the balance of resisting, sliding, and overturning forces is altered slightly. Simons and Senturk (1977) derived a relationship that may be expressed as follows:

$$D_{50} \geq \frac{SFdS\Delta}{F^*(SG-1)} \quad (24)$$

Where:

Δ = function of channel geometry and riprap size

The parameter Δ can be defined as follows (see HEC-15, Appendix D for the derivation):

$$\Delta = \frac{K_1(1+\sin(\alpha+\beta))\tan\phi}{2(\cos\phi\tan\phi - SF\sin\theta\cos\beta)} \qquad (25)$$

Where:

K_1 = ratio of channel side to bottom shear stress

K_1 = 0.77 $\qquad$ $Z \le 1.5$

K_1 = 0.066Z + 0.67 $\qquad$ $1.5 < Z < 5$

K_1 = 1.0 $\qquad$ $5 \le Z$

Z = side slope, Z horizontal:1 vertical

α = angle of the channel bottom slope

β = angle between the weight vector and the weight/drag resultant vector in the plane of the side slope

Finally, β is defined by:

$$\beta = \tan^{-1}\left(\frac{\cos\alpha}{\frac{2\sin\theta}{\eta\tan\phi}+\sin\alpha}\right) \qquad (26)$$

Where:

The stability number is calculated using:

$$\eta = \frac{\tau_s}{F^*(\gamma_s-\gamma)D_{50}} \qquad (27)$$

Where:

τ_s = side shear stress on the channel, (lb/ft^2)

γ_s = specific weight of the rock, (lb/ft^3)

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 over the rock. On a steep slope, the weight of a stone has a significant component in the direction of flow. 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 milder gradient. As a result, for a given discharge, steep slope channels require larger stones to compensate for larger forces in the flow direction and higher shear stress.

The size of riprap linings increases quickly as discharge and channel gradient increase. Equation 24 is recommended when channel slope is greater than 10 percent and provides the riprap size for the channel bottom and sides. Equation 21 is recommended for slopes less than 5 percent. For slopes between 5 percent and 10 percent, it is recommended that both methods be applied and the larger size used for design. Values for safety factor and Shields parameter are taken from Table 25.2 for both equations.

25.5 Rock Riprap Design Procedure

This design procedure addresses the approach for selecting riprap for the bottom and sides of a channel, and for channel bends.

The riprap and gravel lining design procedure for the bottom of a straight channel is described in the following steps. It is iterative by necessity because flow depth, roughness, and shear stress are interdependent. The procedure requires the designer to specify a channel shape and slope as a starting point and is outlined in the eight-step process identified below. In this approach, the designer begins with a design discharge and calculates an acceptable D_{50} to line the channel bottom. The following steps are recommended for the standard design.

Step 1. Determine channel slope, channel shape, and design discharge.

Step 2. Select a trial (initial) D_{50}, perhaps based on available sizes for the project. Change the default specific weight if appropriate.

Step 3. Estimate the depth. For the first iteration, select a channel depth, d_i. For subsequent iterations, a new depth can be estimated from the following equation or any other appropriate method.

$$d_{i+1} = d_i \left(\frac{Q}{Q_i} \right)^{0.4} \tag{24}$$

Where:

Q_i = Flow estimate from previous iteration, (ft^3/s)

Determine the average flow depth, d_a in the channel, $d_a = A/T$

Step 4. Estimate Manning's n and the implied discharge. First, calculate the relative depth ratio, d_a/D_{50}. If d_a/D_{50} is greater than or equal to 1.5, use Equation 14 to calculate Manning's n. If d_a/D_{50} is less than 1.5, use Equation 15 to calculate Manning's n. Calculate the discharge using Manning's equation.

Step 5. If the calculated discharge is within 2 percent of the design discharge, then proceed to step 6. If not, go back to step 3 and estimate a new flow depth.

Step 6. Calculate the particle Reynolds number using Equation 22 and determine the appropriate Shields parameter and Safety Factor values from Table 2. If channel slope is less than 5 percent, calculate required D_{50} from Equation 21. If channel slope is greater than 10 percent, use Equation 24. If channel slope is between 5 and 10 percent, use both Equations 21 and 24 and take the largest value.

Step 7. If the D_{50} calculated is greater than the trial size in step 2, then the trial size is too small and unacceptable for design. Repeat procedure beginning at step 2 with new trial value of D_{50}. If the D_{50} calculated in step 6 is less than or equal to the previous trial size, then the previous trial size is acceptable. However, if the D_{50} calculated in step 6 is sufficiently smaller than the previous trial size, the designer may elect to repeat the design procedure at step 2 with a smaller, more cost effective, D_{50}.

25.6 Design Example (Using Equations): Riprap Channel (Mild Slope)

Attachment 25.1 provides an example design example solved using equations for a riprap channel that has a mild slope.

25.7 Example Riprap Lined Design for Channel Slopes ≤ 20% Using the WisDOT Spreadsheet

Attachment 25.2 is a blank example sheet and provides a link to a working copy of a WisDOT Spreadsheet for riprap lined design channel with slope less than or equal to 20%. Be sure to enable the spreadsheet Macros by clicking on the security warning "options" box on the top of the spreadsheet and then highlight the "enable this content" button. Attachment 25.3 is a step by step example using the WisDOT spreadsheet for riprap lined channel that have a mild slope.

25.8 Additional Design Considerations

25.8.1 Water Surface Profiles, HEC RAS

In situations where it is necessary to determine the water surface profile of a channel with varying channel characteristics and flow rates, a program that analyzes gradually varied flow must be employed. One such computer program, entitled "HEC-RAS River Analysis System," was developed and first published by the U. S. Army Corps of Engineers (USACE) in 1968. The current version 4.1 (USACE, 2010) is available from the USACE web site: http://www.hec.usace.army.mil/software/hec-ras/. For further information on this subject, refer to the discussion in FDM 13-20-1 under "Water Surface Profiles, (HEC-2) and (HEC-RAS)."

25.8.2 Angular vs. Rounded Riprap

The riprap design methods described in this procedure assume that the contractor will construct riprap channels with angular riprap. If the designer does not expect that angular riprap will be available for the project and that the contractor will be using rounded riprap, then the design riprap size should be increased by 40% (Ullmann and Abt, 2000). To apply this to a channel design, for channel slopes less than or equal to 10% increase the size of the riprap to the next highest size. Refer to Attachment 25.5 for a map of those areas of the state where rounded riprap is predominantly available.

25.8.3 Inflow from the Sides

The riprap design methods Channels that intercept surface flow from the sides must incorporate into their design the following criteria:

1. The lining shall be carried to an elevation slightly below the ground level.
2. A cut-off wall must be placed at the top of the lining to prevent undermining.
3. Pipes discharging into the channel shall be flush with the channel lining.

25.8.4 Drainage

If hydrostatic pressure is foreseen behind the sidewalls of an apron endwall discharging into a channel, install both weep holes and a subsurface drainage system behind the sidewalls.

25.8.5 Bulking

At supercritical velocities, air entrainment occurs causing increases in the depth of flow (bulking effect). With concrete-lined channels, determine the normal depth of flow with a bulking condition by setting Manning's "n" equal to 0.018 instead of 0.014. For other lining types, multiply the n values calculated using the appropriate design process by 1.3.

25.9 References

1. Bathurst, J.C., 1985. "Flow Resistance Estimation in Mountain Rivers," Journal of Hydraulic Engineering, ASCE, Vol. 111, No. 4.

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

3. Blodgett, J.C., 1986. "Rock Riprap Design for Protection of Stream Channels Near Highway Structures, Volume 1 - Hydraulic Characteristics of Open Channels," USGS Water Resources Investigations Report 86-4127.

4. U.S. Department of Transportation, Federal Highway Administration, Design of Riprap Revetment, Hydraulic Engineering Circular (HEC) No. 11, Washington, D.C. March 1989, 182 pp.

5. U.S. Department of Transportation, Federal Highway Administration, Design of Roadside Channels with Flexible Linings, Hydraulic Engineering Circular #15, Washington, D.C., September 2005.

6. U.S. Army Corps of Engineers Hydraulic Engineering Center, "HEC-RAS River Analysis System Applications Guide, Version 4.0, March 2008.

7. Ullmann, Craig M. and Abt, Steven R., “Stability of Rounded Riprap in Overtopping Flow”, 2000 Joint Conference on Water Resource Engineering and Water Resouce Planning and Management, Minneapolis, MN, 2000.

LIST OF ATTACHMENTS

FDM 13-30-30 Rock Riprap Lined Chutes

May 17, 2022

30.1 Introduction

The Natural Resource Conservation Service (NRCS) has developed a design procedure for rock chute drainageways that WisDOT has modified to account for WisDOT specific riprap sizes and design requirements. A rock chute is defined as a channel with a slope that is 5:1 or steeper and that has an energy dissipation structure at the toe of the chute. This method should not be used for rapidly varied flow, which often occurs at, for example, bridge abutments.

The WisDOT rock riprap sizes are found in the Standard Spec 606, Rock Riprap and Standard Spec 312, Select Crushed Material. Design characteristics are listed in Table 30.1

Table 30.1 WisDOT Riprap Size Classifications

Riprap Type	D50 (inches)	D50 (feet)	Riprap Thickness (in) SF=1.2(1)	Riprap Thickness (in) SF=2.0 1	Geotextile Lining Type
Select Crushed Material	2.2	0.18	6	9	Type R
Extra Light (EX-LIGHT) Riprap	6	0.5	14	24	Type R
Light Riprap	10.	0.83	24	40	Type R
Medium Riprap	12.5	1.04	30	50	Type HR
Heavy Riprap	16	1.33	38	64	Type HR
Extra-Heavy Riprap	20	1.67	48	80	Type HR

Note: (1) Riprap thickness must equal 2 x D_{50} x SF, where SF is the selected factor of safety for the riprap design. This thickness requirement must be noted in the special provisions.

Riprap requires a filter material between the rock and the underlying soil to prevent soil washout. WisDOT requires a geotextile lining beneath the riprap, as described in Table 30.1, which is used as the filter. The lining should be installed per the manufacturer’s specifications. Riprap is placed on the geotextile to form a well-graded mass with a minimum of voids. Rocks should be hard, durable, preferably angular in shape, and free from overburden, shale, and organic material. The rock should be resistant to disintegration from chemical and physical weathering.

The procedures in this section are applicable to uniform prismatic channels (as would be characteristic of roadside channels) with rock sizes within the range in Table 30.1. If the channel slope is less than or equal to 10%, then the designer should use the HEC-15 rock riprap design method described in FDM 13-30-25. If the channel slope is greater than 10%, then the designer should use the NRCS Design of Rock Chutes methodology described in this procedure. For situations not satisfying the uniform prismatic channel condition such as stream banks or lakeshores, refer to HEC-11, “Design of Riprap Revetment” (FHWA, 1989).

30.2 Steep Slope Analysis

If channel slopes are greater than 10%, then the designer should use the design procedures for a rock-lined chute. This approach is based upon the paper "Design of Rock Chutes" by Robinson, Rice, and Kadavy, ASAE Vol. 41(3), pp. 621-626, 1998. The design procedure was developed by the Iowa NRCS design staff, who developed a design spreadsheet based upon the rock chute design procedures. This spreadsheet was modified by NRCS WI and by WisDOT.

The tests that were used to develop this approach focused on rock slope stability, roughness, and outlet stability. The relationship to predict rock size for the highest stable unit discharge uses rock size as a function of the discharge and channel slope. Rice et al. (1997) developed empirical relationships to predict the Manning roughness coefficient as a function of stone size and bed slope. These roughness relationships allow calculation of the flow depth in a rock chute.

Rock size for chutes shall be expressed by the D_{50} size (50 percent passing by weight). To determine the D_{50} size for slopes (S_{ch}) greater than 10% (10:1), use the following equation:

$$D_{50} = \left[\frac{q_t (S_{ch})^{0.58}}{0.0395} \right]^{1/1.89} \quad (28)$$

Where:

D_{50} = median rock size in inches

q_t = equivalent unit discharge in (ft^3/sec) per foot of channel width

S_{ch} = chute slope (ft/ft)

The roughness value of the rock lining varies according to the rock size (D_{50}) and the slope of the chute's bed S_{ch}. Manning's n is found using the following equation:

$$n = 0.047(D_{50} S_{ch})^{0.147} \quad (29)$$

Where:

n = Manning's n for given rock size and chute slope

The riprap design methods described in this procedure assume that the contractor will construct riprap channels with angular riprap. If the designer does not expect that angular riprap will be available for the project and that the contractor will be using rounded riprap, then use the safety factor to compensate for any unexpected variables in the flow, rock shape, or the n value. The minimum SF allowed on any chute is 1.2. For rounded riprap, set SF = 2.0. Refer to FDM 13-30 Attachment 25.5 for a map of those areas of the state where rounded riprap is predominantly available Use your engineering judgment to determine an appropriate safety factor for riprap that combines angular and rounded rock. The SF is used in Equation 3 to determine the D_{50}* that shall be used in the design.

$$D_{50}^* = D_{50} \times SF \quad (30)$$

Where:

D_{50}* = Minimum design rock size (in)

To use the design spreadsheet for rock chutes, enter values for the following variables, which are highlighted as blue, bold numbers in a box.

30.2.1 Input Geometry - Upstream Channel

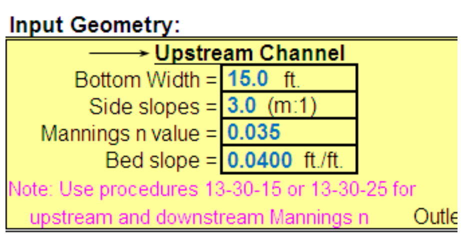

Figure 30.1 Riprap Lined Chute - Input Geometry

Bottom Width - The bottom width of the upstream channel (ft).

Side slopes - The side slope of the upstream channel (ft.Horizontal:1 ft. Vertical).

Mannings n Values - The Mannings n value of the upstream channel. Use either FDM 13-30-15 or FDM 13-30-25 to determine these values if they are not known.

Bed slope – The bed slope of the upstream channel (ft./ft.).

30.2.2 Input Geometry - Chute

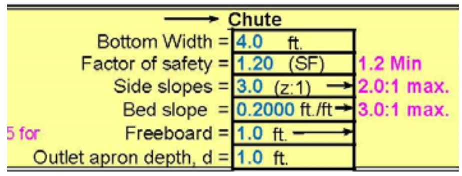

Figure 30.2 Riprap Lined Chute - Chute Input

Bottom Width - The bottom width of the upstream channel (ft).

Factor of Safety - The safety factor for the chute design, selected using engineering judgment and the guidelines described about equation (3) in this section. The minimum value is 1.2.

Side slopes - The side slope of the chute (ft.Horizontal:1 ft. Vertical). The steepest allowable side slope is 2:1.

Bed slope - The bed slope of the chute (ft./ft.). The steepest allowable side slope is 3:1, or 0.333 ft/ft.

Freeboard - The required distance from the top of the water surface in the chute and the top edge of the chute (ft).

Outlet apron depth - The distance between the bottom of the discharge apron and the downstream channel bottom (ft).

30.2.3 Input Geometry - Downstream Channel

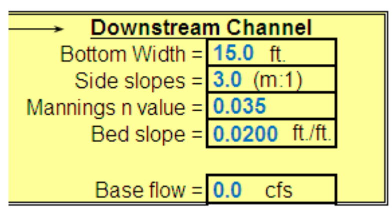

Figure 30.3 Riprap Lined Chute - Downstream Channel

Bottom Width - The bottom width of the downstream channel (ft).

Side slopes - The side slope of the downstream channel (ft.Horizontal:1 ft. Vertical).

Manning's n value - The Manning's n value of the downstream channel. Use either FDM 13-30-15 or FDM 13-30-25 to determine these values if they are not known.

Bed slope - The bed slope of the downstream channel (ft./ft.).

Base flow - The constant flow rate due to non-runoff related discharges that is added to the design flow (cfs).

30.2.4 Flow and Elevation Data

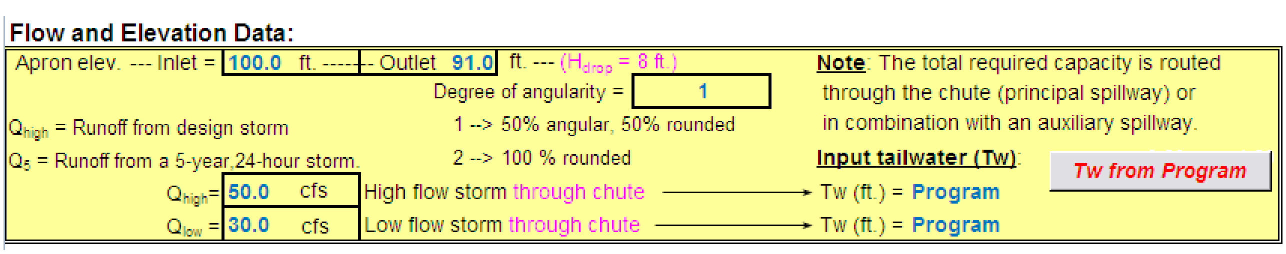

Figure 30.4 Flow and Elevation Data

Apron elevation - inlet - The inlet elevation of the chute apron (ft)

Apron elevation - outlet - The outlet elevation of the chute apron (ft). The H_{drop} value is the difference between the inlet and outlet elevations less the outlet elevation depth.

Degree of angularity - Enter a ‘1’ if the rock is at least 50% angular rock or a ‘2’ if the riprap is less than 50%

angular rock. If the rock is less than 50% angular and the safety factor is less than 1.7 a warning message will appear below the apron elevation data.

Q_{high} - The peak design storm flow value (cfs).

Q_{low} - The low flow design storm flow value (cfs), which is typically a 5-year design flow rate.

Input Tailwater - The user has the option of allowing the program to calculate the tailwater values used in the analysis or to enter specific values for the tailwater elevation. For the former option, press the 'Tw from Program' button and the word 'Program' will appear in place of a tailwater value.

30.2.5 Profile and Cross Section (Output)

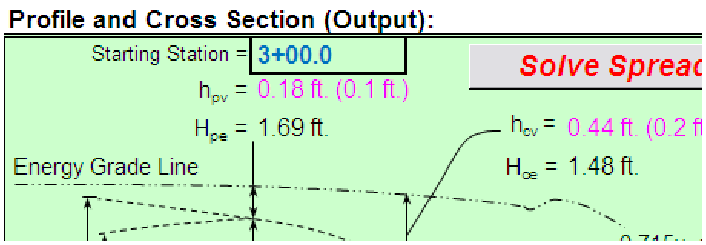

Figure 30.5 Profile and Cross Section (Output)

Starting Station - The station at the upstream edge of the rock chute inlet apron. This value is used to calculate the stationing for the Stakeout Notes listed on the Plan Sheet.

30.3 Rock Chute Design Spreadsheet

30.3.1 Spreadsheet Overview

There are five tabs included on the "Rock Chute Design Data" spreadsheet:

1. Design Data Tab (refer to example included as Attachment 30.1) - Enter the project name, designer and date as well as the upstream and downstream chute and flow data listed above. You will also initiate the calculations to determine the appropriate size riprap from this tab. Print this tab to document your work.
2. Plan Sheet Tab (refer to example included as Attachment 30.2) - Review the spreadsheet output and enter unit cost information on this tab.
3. Construction Detail Tab (refer to example included as Attachment 30.3) - This tab provides a printout of the proposed design. Print this tab to document your work.
4. Calculations Tab - This tab contains the formulas needed to calculate the appropriate riprap size for the channel or rock chute.
5. Help Tab - The variable definitions and instructions for using the spreadsheet are on this tab.

Be sure to enable the spreadsheet Macros by clicking on the security warning "options" box on the top of the spreadsheet and then highlight the "enable this content" button.

30.3.2 Spreadsheet Directions

Follow these steps to evaluate a steep slope for riprap protection:

1. Enter your project information and data on the 'Design Data' sheet. Begin with the 'Input Geometry and Flow' section, which is the major input area for setting channel geometry. All blue values and text can be entered (or changed) by the user.
2. Changing any value (with the exception of Freeboard under the inlet channel column, Outlet apron depth, d, and the Factor of safety (multiplier) under the chute column) will clear the output values in the Profile and Cross Section area.
3. Enter the Inlet and Outlet apron elevation.
4. Enter the high and low frequency storm (in cfs) flowing through the chute portion of the structure (this program does not design the auxiliary spillway).
5. Select the 'Tw from Program' button if you want the spreadsheet to calculate the tailwater for both high and low flow events, or enter your own values. If you select the 'Tw from Program' button, the

spreadsheet will enter the word "Program" in the tailwater cells indicating that the spreadsheet will calculate the tailwater.

6. Select the ‘Solve Spreadsheet’ button when finished entering data.

30.3.3 Spreadsheet Notes

Designers need to be aware of the following spreadsheet notes;

1. The program sets a limit on the steepest side slope allowed in the chute (2:1) and the steepest bed slope (3:1). Values steeper than these will blank the output area and the program cannot be solved or printed (just to the right of these cells a note will indicate “Too Steep”).
2. Enter a 1.0-foot "suggested" minimum for d, and always make sure that T_w + d is greater than or equal to z_2.
3. Select the ‘Solve Spreadsheet’ button if you change Q_{high} or Q_{low}.

The link to the spreadsheet that WisDOT has revised that incorporates all the design guidelines and equations described in Robinson, Rice and Kadavy (1998) to design steep rock lined channels is located on the top of Attachment 30.1.

30.3.4 Riprap Lined Chute Example Spreadsheets

The following example illustrates the design procedure. Enter the data into the design spreadsheet on the appropriate row. Assume the following:

Table 30.2 Riprap Lined Chute Design Example Data

Upstream Channel		**Downstream Channel**	
Bottom Width =	4.0 ft	Bottom Width =	4.0 ft
Side Slopes =	3.0	Side Slopes =	3.0
Mannings n value =	0.040	Mannings n value =	0.040
Bed Slope =	0.01	Bed Slope =	0.01 ft
Chute		Base Flow =	0 cfs
Bottom Width =	4.0 ft	**Flow and Elevation Data**	
Factor of Safety =	1.2	Apron Elevation – Inlet =	100.0 ft
Side Slopes =	3.0	Apron Elevation – Outlet =	91.0 ft
Bed Slope =	0.10	High Flow Rate =	50 cfs
Freeboard =	0.5 ft	Low Flow Rate =	30 cfs
Outlet Apron Depth =	1.0 ft	Tailwater from Program? =	YES
Degree of angularity =	1		

To evaluate the data, press the “Solve Spreadsheet” button. Refer to Attachments 30.2and 30.3for the example output. Review the critical slope information (Design Data tab, cell A41) and the High Flow Storm Information on the Design Data Tab. The design riprap gradation is listed on the Plan Sheet tab, cell A42, as is the overall design. If the channel or chute does not function adequately, you can flatten the side slopes and/or widen the channel bottom to decrease the flow depth.

Additional information is available from the ‘Help’ tab of the spreadsheet.

30.3.5 Additional Design Considerations

Water Surface Profiles, HEC-RAS: In situations where it is necessary to determine the water surface profile of a channel with varying channel characteristics and flow rates, use a program that analyzes gradually varied flow.

One such computer program, entitled "HEC-RAS River Analysis System," was developed and first published by the U. S. Army Corps of Engineers (USACE) in 1968. The current version 4.0 (USACE, 2008) is available from the USACE web site: http://www.hec.usace.army.mil/software/hec-ras/. For further information on this subject, see the discussion in FDM 13-20-1 under "Water Surface Profiles, (HEC-2) and (HEC-RAS)."

Inflow from the Sides: Channels that intercept surface flow from the sides must incorporate into their design the criteria that follow:

1. The lining shall be carried to an elevation slightly below the ground level.
2. A cut-off wall must be placed at the top of the lining to prevent undermining.
3. Pipes discharging into the channel shall be flush with the channel lining.

Drainage: If hydrostatic pressure is foreseen behind the sidewalls of an apron endwall discharging into a channel, install both weep holes and a subsurface drainage system behind the sidewalls.

Bulking: At supercritical velocities, air entrainment occurs, causing increases in the depth of flow (bulking effect). With concrete-lined channels, determine the normal depth of flow with a bulking condition by setting Manning's "n" equal to 0.018 instead of 0.014. For other lining types, multiply the n values calculated using the appropriate design process by 1.3.

30.4 References

1. Rice, C.E., K.C. Kadavy , and K.M. Robinson, “Roughness of Loose Rock Riprap on Steep Slopes”, Journal of Hydraulic Engineering, American Society of Civil Engineers, Volume 124(2), 1998.

2. Lorenz, E.EA, and K.M. Robinson, “An Excel Program to Design Rock Chutes for Grade Stabilization”, 2000 ASAE Annual International Meeting, Milwaukee, WI,, July 2000, ASAE Meeting Presentation Paper No. 002008.

3. Robinson, Rice and Kadavy, “Design of Rock Chutes”, ASAE Volume 41(3), pgs 621-626, 1998.

4. U.S. Army Corps of Engineers Hydraulic Engineering Center, "HEC-RAS River Analysis System Applications Guide, Version 4.0, March 2008.

5. U.S. Department of Transportation, Federal Highway Administration, Design of Riprap Revetment, Hydraulic Engineering Circular (HEC) No. 11, Washington, D.C. March 1989, 182 pp.

6. Ullmann, Craig M. and Abt, Steven R., “Stability of Rounded Riprap in Overtopping Flow”, 2000 Joint Conference on Water Resource Engineering and Water Resouce Planning and Management, Minneapolis, MN, 2000.

LIST OF ATTACHMENTS

Attachment 30.1	Rock Chute Design Data Spreadsheet and Design Example
Attachment 30.2	Rock Chute Design - Plan Sheet
Attachment 30.3	Rock Chute Design- Construction Detail