

# Channel Erosion



---

# Channel Erosion

By

Pete Peterson, PE

PDHLibrary Course No 2023014  
5 PDH HOURS

---

# CHANNEL EROSION

## **GENERAL CONCEPTS**

The capacity of a drainage channel depends upon its shape, size, slope, and roughness. For a given channel, the capacity becomes greater when the grade or the depth of flow is increased. The channel capacity decreases as the channel surface becomes rougher. For example, a riprap-lined ditch has only about half the capacity of a concrete-lined ditch of the same size, shape, and slope because of the differences in channel roughness. A rough channel is sometimes an advantage on steep slopes where it is desirable to keep velocities from becoming too high.

The most efficient shape of channel is that of a semi-circle, but hydraulic efficiency is not the sole criterion. In addition to performing its hydraulic function, the drainage channel should be economical to construct and require little maintenance during the life of the roadway. Channels adjacent to a roadway should also be safe for vehicles accidentally leaving the traveled way, pleasing in appearance, and dispose of collected water without damage to the adjacent property. Most of these additional requirements for drainage channels reduce the hydraulic capacity of the channel. The best design for a particular channel is a compromise among the various requirements, sometimes with each requirement having a different influence on the design.

Channel lining materials fall into two classes: rigid or flexible channel linings. From an erosion control standpoint, the primary difference between rigid and flexible channel linings is their response to changes in channel shape (i.e. the width, depth and alignment). Flexible linings are able to adjust to some change in channel shape while rigid linings cannot. The ability to sustain some change in channel shape improves the overall integrity of the channel lining and reduces maintenance. Movement of a rigid lining at one location can result in a successive failure of the lining. Channel lining materials often experience forces such as frost heave, slumping or swelling of the underlying soils that can change the shape of the lining. These forces can displace rigid linings whereas flexible linings, if properly designed, will retain erosion-control capabilities.

Flexible linings also have several other advantages compared to rigid linings. They are generally less expensive, permit infiltration and exfiltration and can be vegetated to have a natural appearance. Flow in channels with flexible linings is similar to that found in natural small channels. More natural behavior offers better habitat opportunities for local flora and fauna. In many cases, flexible linings are designed to provide only transitional protection against erosion while vegetation establishes and becomes the permanent lining of the channel. Vegetative channel lining is also recognized as a best management practice for storm water quality design. The slower flow of a vegetated channel helps to deposit runoff contaminants (particularly suspended sediments) before they enter streams.

Flexible linings have a limited hydraulic performance range (depth, grade, velocity and discharge). The magnitude of hydraulic force they can sustain without damage

is limited by a number of factors including soil properties and roadway grading. Because of these limitations, flexible channel designs using the same lining material will vary from site to site and between regions of the country. Since the performance range for rigid channels is higher, such channels may be needed in cases where channel width is limited, but sufficient space exists for a high-capacity channel.

Riprap design procedures are for prismatic channels typically having a maximum depth of about 5 ft. However, the procedures for riprap design are not generally limited by depth.

The permissible tractive force and Manning's  $n$  values are based on the relative roughness theory, the biomechanical properties of grass (height, stiffness and density of the grass cover), and the properties of the underlying soil (particle size, density and plasticity). This method is comparable to methods used in agricultural channel design but offers more flexibility.

The performance information for manufactured channel linings is based on industry testing and design recommendations. Product testing is routinely conducted by major manufacturers using either their own hydraulic laboratories or using facilities at university labs. Industry protocols have been developed for large scale testing (ASTM D 6460) that provides a consistent test method for flexible channel lining materials.

The following are examples of lining materials in each classification.

1. Rigid Linings:

- a. Cast-in-place concrete or asphaltic concrete
- b. Stone masonry and interlocking modular block
- c. Soil cement and roller compacted concrete
- d. Partially grouted riprap

2. Flexible linings

a. Long-term

i. Vegetative (typically grass species)

ii. Cobbles

iii. Rock Riprap

iv. Wire-enclosed riprap (gabions)

v. Turf reinforcement (non-degradable)

b. Transitional

i. Bare soil

- ii. Vegetative (annual grasses)
- iii. Gravel mulch
- iv. Open-weave textile (degradable)
- v. Erosion control blankets (degradable)
- vi. Turf reinforcement (non-degradable)

c. Temporary

- i. Bare soil
- ii. Vegetative (annual grasses)
- iii. Gravel mulch
- iv. Open-weave textile (degradable)
- v. Erosion control blankets (degradable)

### **RIGID LININGS**

Rigid linings (see Figure 1) are useful in flow zones where high shear stress or non-uniform flow conditions exist, such as at transitions in channel shape or at an energy dissipation structure. They can be designed to include an impermeable membrane for channels where loss of water from seepage is undesirable. Since rigid linings are non-erodible the designer can use any channel shape that is necessary to convey the flow and provide adequate freeboard. This may be necessary where available right-of-way or easements limit the channel width.



Figure 1 – Rigid Lining

Despite the non-erodible nature of rigid linings, they are susceptible to failure from foundation instability. The major cause of failure is undermining that can occur in several ways. Inadequate erosion protection at the outfall, at the channel edges, and on bends can initiate undermining by allowing water to carry away the foundation material and leaving the channel to break apart. Rigid linings may also break up and deteriorate due to conditions such as a high water table or swelling soils that exert an uplift pressure on the lining. Once a rigid lining is locally broken and displaced upward, the lining continues to move due to dynamic uplift and drag forces. The broken lining typically forms large, flat slabs that are particularly susceptible to these forces. Freeze thaw cycles may also stress rigid channels. The repeated cycling of these forces can cause fine particles to migrate within the underlying soil causing filter layers and weep holes to clog and further increase uplift pressure on the lining.

Rigid linings are particularly vulnerable to a seasonal rise in water table that can cause a static uplift pressure on the lining. If a rigid lining is needed in such conditions, a reliable system of under drains and weep holes should be a part of the channel design. The migration of soil fines into filter layers should be evaluated to ensure that the ground water is discharged without filter clogging or collapse of the underlying soil. A related case is the build up of soil pore pressure behind the lining when the flow depth in the channel drops quickly. Use of watertight joints can help to reduce the build up of water behind the lining.

Construction of rigid linings requires specialized equipment and costly materials. As a result, the cost of rigid channel linings is typically higher than an equivalent flexible channel lining. Prefabricated linings can be a less expensive alternative if shipping distances are not excessive. Many construction projects include paving materials (concrete and asphaltic concrete) that are also used in rigid channel linings. This may provide an economy of scale when similar materials are used for both paving and channel construction.

## **FLEXIBLE LININGS**

Flexible linings can meet a variety of design objectives and serve a variety of roles in the construction of a project where prismatic channels are required for conveying stormwater runoff. Flexible channel linings are best suited to conditions of uniform flow and moderate shear stresses. Channel reaches with accelerating or decelerating flow (expansions, contractions, drops and backwater) and waves (transitions, flows near critical depth, and shorelines) will require special analysis and may not be suitable for flexible channel linings.

Several terms are used to describe the longevity of flexible linings - permanent, long-term, transitional, temporary, and short-term – to name a few. Recognizing that nothing is permanent, long-term is defined as serving the desired purpose throughout the lifetime of the drainage channel given appropriate maintenance. The other terms imply that changes must occur either in the removal of the channel or replacement of one lining type with another. However, the designer should keep in mind not only the manufacturer's claims of longevity, but also site-specific maintenance practices and climate or geographic location in selecting a lining type for a given transitional or temporary application.

## Long-term Flexible Linings

Long-term flexible linings are used where channels require protection against erosion for the service life of the channel.

### Vegetation

Vegetative linings consist of seeded or sodded grasses placed in and along the channel (Figure 2). Grasses are seeded and fertilized according to the requirements of that particular variety or mixture. Sod is laid with the longest side parallel to the flow direction and should be secured with pins or staples.



Figure 2 – Vegetated Channel/Median

Vegetation is one of the most common long-term channel linings. Many open channels capture only local runoff and so remain dry most of the time. For these conditions, upland species of vegetation (typically grass) provide a good lining. However, upland species of vegetation are not suited to sustained flow conditions or long periods of submergence. Some vegetative channels with sustained low flow and intermittent high flows are designed to provide a composite lining with riprap or concrete providing a low flow section. There are plant species that are adapted to wet low land conditions that can be used for the low flow channel in cases that warrant the additional design and construction effort.

Where vegetation provides the long-term channel lining, there is a transition period between seeding and vegetation establishment. The initial unvegetated condition of the lining is followed by a period of vegetation establishment that can take several growing seasons. The channel is vulnerable to erosion during the transition. Transitional flexible linings 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. Non-degradable linings have an expected life of several years beyond vegetation establishment, which enhances the performance of the vegetation.

### Cobble or Gravel Lining

Cobble or gravel lining consists of stone in the size range of small cobbles (2.5 to 5 inches) or gravel (1 to 3 inches), and tends to have a uniform gradation. The cobble or gravel layer is placed on engineering fabric on a prepared grade (see Figures 3 and 4). The cobble or gravel material is composed of uniformly graded, durable stone that is free of organic matter. Cobbles and gravel are typically alluvial in origin and smooth and rounded in appearance.

Cobble and gravel linings are often used when a decorative channel design is desired. These linings are composed of smooth stones that do not interlock, so they are not suitable for placement on steep grades or on channel side slopes that are steep. As with riprap and gabion linings, a filter material or a filter fabric is required between the stone and the underlying soil.



Figure 3 – Gravel Lining



Figure 4 – Cobble Lining

### Rock Riprap

Rock riprap is placed on a filter blanket or prepared slope to form a well-graded mass with a minimum of voids (see Figure 5). Rocks should be hard, durable, preferably angular in shape, and free from overburden, shale, and organic material. The rock should be durable and resistance to disintegration from chemical and physical weathering. The performance of riprap should be determined from specified field and laboratory tests.

Riprap and gabion linings can perform in the initial range of hydraulic conditions where rigid linings are used. Stones used for riprap and gabion installations preferably have an angular shape that allows stones to interlock. These linings usually require a filter material between the stone and the underlying soil to prevent soil washout. In most cases, an engineering fabric is used as the filter. Care should be taken to provide adequate permeability in the filter to prevent uplift pressures on the lining.



Figure 5 – Riprap Lining

### Wire-Enclosed Riprap

Wire-enclosed riprap (gabions) is a wire container or enclosure structure that binds units of the riprap lining together. The wire enclosure normally consists of a rectangular container made of steel wire woven in a uniform pattern and reinforced on corners and edges with heavier wire (see Figure 6). The wire is typically just steel wire although it can be galvanized or polymeric coated for increased resistance to abrasion and corrosion. The containers are filled with stone, connected together, and anchored to the channel side slope. Stones must be well graded and durable. The forms of wire-enclosed riprap vary from thin mattresses to box-like gabions. Wire-enclosed riprap is typically used when rock riprap is either not available or not large enough to be stable. Although flexible, gabion movement is restricted by the wire mesh.



**Figure 6. Wire-Enclosed Riprap**

### Turf Reinforcement

Depending on the application, materials, and method of installation, turf reinforcement may serve a transitional or long-term function. The concept of turf reinforcement is to provide a structure to the soil/vegetation matrix that will both assist in the establishment of vegetation and provide support to mature vegetation. Two types of turf reinforcement are commonly available: gravel/soil methods and turf reinforcement mats (TRMs)

Soil/gravel turf reinforcement is to mix gravel mulch into on-site soils and to seed the soil-gravel layer. The rock products industry provides a variety of uniformly graded gravels for use as mulch and soil stabilization. A gravel/soil mixture provides a non-degradable lining that is created as part of the soil preparation and is followed by seeding.

A TRM is a non-degradable Rolled Erosion Control Product (RECP) composed of UV stabilized synthetic fibers, filaments, netting and/or wire mesh processed into a three-dimensional matrix. TRMs provide sufficient thickness, strength and void space to permit soil filling and establishment of grass roots within the matrix. The mat, shown in Figure 7, is laid parallel to the direction of flow. TRM is stiffer, thicker (minimum of 0.25 in) and denser than an erosion control blanket (ECB). These material properties improve erosion resistance. The TRM is secured with staples and anchored into cutoff trenches at intervals along the channel. Two methods of seeding can be used with TRM. One choice is to seed before placement of the TRM, which allows the plant stems to grow through the mat. The second choice is to first place the TRM then cover the mat with soil and then seed. This method allows the plant roots to grow within the mat.



Figure 7 – TRM in channel

### Cabled concrete blocks

Cabled concrete blocks consist of a series of square or rectangular concrete blocks, generally about 12 inches square, tied together by steel cables, with a small space between the blocks (see Figure 8). The spaces between the blocks allow adequate room for each block to conform to the surface below the block and thereby approximately match the subsurface. The cable keeps the blocks tied to each other so while there may be some slight displacement between two blocks, the overall structure remains intact. The space between the blocks is generally filled with soil and seeded, so over time the vegetation will take over.



Figure 8 – Cabled Concrete Blocks

### **Transitional and Temporary Flexible Linings**

Transitional linings are intended and designed to facilitate establishment of the long-term flexible lining. Commonly the long-term lining would be vegetation. Temporary channel linings are used without vegetation to line channels that are part of construction site erosion control systems and other short-term channels. In some climates, rapidly growing annual grass species establish quickly enough to be used as a temporary channel lining.

Many of the transitional and temporary linings are described as degradable. Functionally, this means that the structural matrix of the lining breaks down as a result of biological processes and/or UV light exposure. In the case of organic materials, the lining

becomes a natural part of the underlying soil matrix. In the case of degradable plastics, many products lose their structural integrity and degrade to a powder that remains in the soil.

### Bare Soil

The properties of site soils are important in the design of all flexible linings because erosion of the underlying soil is one of the main performance factors in lining design. The erodibility of soil is a function of texture, plasticity and density. Bare soil alone can be a sufficient lining in climates where vegetation establishes quickly and the interim risk of soil erosion is small. Bare-soil channels may have a low risk of erosion if grades are mild, flow depths are shallow, and soils have a high permissible shear stress resistance (high plasticity cohesive soils or gravelly non-cohesive soils).

### Gravel Mulch

Gravel mulch is a non-degradable erosion control product that is composed of coarse to very coarse gravel, 0.6 to 2.5 inch. Placement of gravel is usually done immediately after seeding operations. Gravel mulch is particularly useful on windy sites or where it is desirable to augment the soil with coarse particles. Application of gravel can reduce wheel rutting on shoulders and in ditches. It can also be used to provide a transition between riprap and soil. Unlike riprap and other stone linings, gravel mulch should be placed directly on the soil surface without an underlying filter fabric. Constructing intermediate cutoff trenches that are filled with gravel enhances stability of the lining.

### Vegetation (Annual Grass)

If the construction phasing permits and the climate is suitable, annual grasses can be seeded in time to establish a transitional vegetative lining. Seed mixes typically include rapidly growing annual grasses. Soil amendments including the application of fertilizer and compost improve grass establishment. To be effective, these annual grasses need to be well established through the transition period and at a sufficient density to provide erosion control. Sodding is another rapid method of vegetation establishment for ditches. The sod needs to be staked to the ditch perimeter where flow is expected to prevent wash out.

### Open-weave Textile (OWT)

Open-weave textiles are a degradable rolled erosion control product that is composed of natural or polymer yarns woven into a matrix. OWT can be used together with straw mulch to retain soil moisture and to increase the density and thickness of the lining. OWT is more flexible, thinner and less dense compared to erosion control blankets (ECB). The OWT (Figure 9) is loosely laid in the channel parallel to the direction of flow. OWT is secured with staples and by placement of the fabric into cutoff trenches at intervals along the channel. Placement of OWT is usually done immediately after seeding operations.



Figure 9 – Open Weave Textile

### **Erosion control blanket (ECB)**

Erosion control blanket is a degradable rolled erosion control product that is composed of an even distribution of natural or polymer fibers that are mechanically, structurally or chemically bound together to form a continuous mat (Figure 10). ECB is stiffer, thicker and denser than an open-weave textile (OWT). These material properties improve erosion resistance. The ECB is placed in the channel parallel to the direction of the flow and secured with staples and by placement of the blanket into cutoff trenches. When ECBs are used and ultimately degrade, the long-term erosion protection is provided by the established vegetation.



Figure 10 – Erosion Control Blanket

## **DESIGN CONCEPTS**

The design method presented is based on the concept of maximum permissible tractive force. The method has two parts, computation of the flow conditions for a given design discharge and determination of the degree of erosion protection required. The flow conditions are a function of the channel geometry, design discharge, channel roughness, channel alignment and channel slope. The erosion protection required can be determined by computing the shear stress on the channel lining (and underlying soil, if applicable) at the design discharge and comparing that stress to the permissible value for the type of lining/soil that makes up the channel boundary.

### **Open Channel Flow**

#### **Type of Flow**

For design purposes in drainage channels (as opposed to natural streams and rivers), hydraulic conditions are usually assumed to be uniform and steady. This means that the energy slope is approximately equal to average channel slope, and that the flow rate changes gradually over time. This allows the flow conditions to be estimated using a flow resistance equation to determine the normal flow depth. Flow conditions can be either mild (subcritical) or steep (supercritical). Supercritical flow may create surface waves whose height approaches the depth of flow. For very steep channel gradients, the flow may splash and surge in a violent manner and special considerations for freeboard are required.

More technically, open-channel flow can be classified according to three general conditions:

- uniform or non-uniform flow
- steady or unsteady flow
- subcritical or supercritical flow.

In uniform flow, the depth and discharge remain constant along the channel. In steady flow, no change in discharge occurs over time. Most natural flows are unsteady and are described by runoff hydrographs. It can be assumed in most cases that the flow will vary gradually and can be described as steady, uniform flow for short periods of time.

Subcritical flow is distinguished from supercritical flow by a dimensionless number called the Froude number ( $Fr$ ), which is defined as the ratio of inertial forces to gravitational forces in the system. Subcritical flow ( $Fr < 1.0$ ) is characterized as tranquil and has deeper, slower velocity flow. In a small channel, subcritical flow can be observed when a shallow wave moves in both the upstream and downstream direction. Supercritical flow ( $Fr > 1.0$ ) is characterized as rapid and has shallow, high velocity flow. At critical and supercritical flow, a shallow wave only moves in the downstream direction.

### Normal Flow Depth

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

$$Q = (1.49/n) * A * R^{2/3} * S^{1/2} \quad \text{Equation 1}$$

Where:

Q = discharge, ft<sup>3</sup>/s

n = Manning's roughness coefficient, dimensionless

A = cross-sectional area, ft<sup>2</sup>

R = hydraulic radius, ft

S<sub>f</sub> = friction gradient, which for uniform flow conditions equals the channel bed gradient, S<sub>o</sub>, ft/ft

The depth of uniform flow is solved by trial and error by varying the depth of flow until the depth yields the estimated flow value.

### Resistance to Flow

For rigid channel lining types, Manning's roughness coefficient, n, is approximately constant. However, for very shallow flows the roughness coefficient will increase slightly. (Very shallow is defined where the height of the roughness is about one-tenth of the flow depth or more.)

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.

Tables 1 and 2 provide typical examples of n values of various lining materials. Table 1 summarizes linings for which the n value is dependent on flow depth as well as the specific properties of the material. Values for rolled erosion control products (RECPs) are presented to give a rough estimate of roughness for the three different classes of products. Although there is a wide range of RECPs available, jute net, curled wood mat, and synthetic mat are examples of open-weave textiles, erosion control blankets, and turf reinforcement mats, respectively.

Table 2 presents typical values for the stone linings: riprap, cobbles, and gravels. These are highly depth-dependent for roadside channel applications.

Table 1. Typical Roughness Coefficients for Selected Linings

| Lining Category | Lining Type                | Manning's n |         |         |
|-----------------|----------------------------|-------------|---------|---------|
|                 |                            | Maximum     | Typical | Minimum |
| Rigid           | Concrete                   | 0.015       | 0.013   | 0.011   |
|                 | Grouted Riprap             | 0.040       | 0.030   | 0.028   |
|                 | Stone Masonry              | 0.042       | 0.032   | 0.030   |
|                 | Soil Cement                | 0.025       | 0.022   | 0.020   |
|                 | Asphalt                    | 0.018       | 0.016   | 0.016   |
| Unlined         | Bare Soil                  | 0.025       | 0.020   | 0.016   |
|                 | Rock Cut (smooth, uniform) | 0.045       | 0.035   | 0.025   |
| 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   |

Table 2. Typical Roughness Coefficients for Riprap, Cobble, and Gravel Linings

| Lining Category | Lining Type                 | Manning's n for Selected Flow Depths |        |        |
|-----------------|-----------------------------|--------------------------------------|--------|--------|
|                 |                             | 0.5 ft                               | 1.6 ft | 3.3 ft |
| Gravel Mulch    | D <sub>50</sub> = 1 inch    | 0.040                                | 0.033  | 0.031  |
|                 | D <sub>50</sub> = 2 inches  | 0.056                                | 0.042  | 0.038  |
| Cobbles         | D <sub>50</sub> = 4 inches  | -                                    | 0.055  | 0.047  |
| Rock Riprap     | D <sub>50</sub> = 6 inches  | -                                    | 0.069  | 0.056  |
|                 | D <sub>50</sub> = 12 inches | -                                    | -      | 0.080  |

## Shear Stress

### Equilibrium Concepts

Most small 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. Principles of rigid boundary hydraulics can be applied to evaluate this type of system.

In a dynamic system, some change in the channel bed and/or banks is to be expected due to transport of the sediments that comprise the channel boundary. Stability in a dynamic system is attained when the incoming supply of sediment

equals the sediment transport rate. This condition, where sediment supply equals sediment transport, is referred to as dynamic equilibrium. Although some detachment and transport of bed and/or bank sediments occurs, this does not preclude attainment of a channel configuration that is basically stable. A dynamic system can be considered stable so long as the net change does not exceed acceptable levels. Because of the need for reliability, static equilibrium conditions and use of linings to achieve a stable condition is usually preferable to using dynamic equilibrium concepts in man-made channels. In natural channels, dynamic equilibrium is the preferred choice.

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): 1) the permissible velocity approach and 2) the permissible tractive force (shear stress) approach. Under the permissible velocity approach, the channel is assumed stable if the mean velocity is lower than the maximum permissible velocity. The tractive force (boundary shear stress) approach focuses on stresses developed at the interface between flowing water and materials forming the channel boundary. Permissible tractive force is the maximum unit tractive force that will not cause serious erosion of channel bed material from a level channel bed.

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

In spite of the empirical nature of permissible velocity approaches, the methodology has been employed to design numerous stable channels in the United States and throughout the world. However, considering actual physical processes occurring in open-channel flow, a more realistic model of detachment and erosion processes is based on permissible tractive force. This approach is recommended for situations where the risk of failure or the consequence of failure is relatively high.

### Applied Shear Stress

The hydrodynamic force of water flowing in a channel is known as the tractive force. The basis for stable channel design with flexible lining materials is that flow-induced tractive force should not exceed the permissible or critical shear stress of the lining materials. In a uniform flow, the tractive force is equal to the effective component of the drag force acting on the body of water, parallel to the channel bottom. The mean boundary shear stress applied to the wetted perimeter is equal to:

$$\tau_o = \gamma R S_o \quad \text{Equation 2}$$

where,

$\tau_o$  = mean boundary shear stress, lb/ft<sup>2</sup>

$\gamma$  = unit weight of water, 62.4 lb/ft<sup>3</sup>

$R$  = hydraulic radius, ft

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

Shear stress in channels is not uniformly distributed along the wetted perimeter. A typical distribution of shear stress in a prismatic channel is shown in Figure 11. 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.

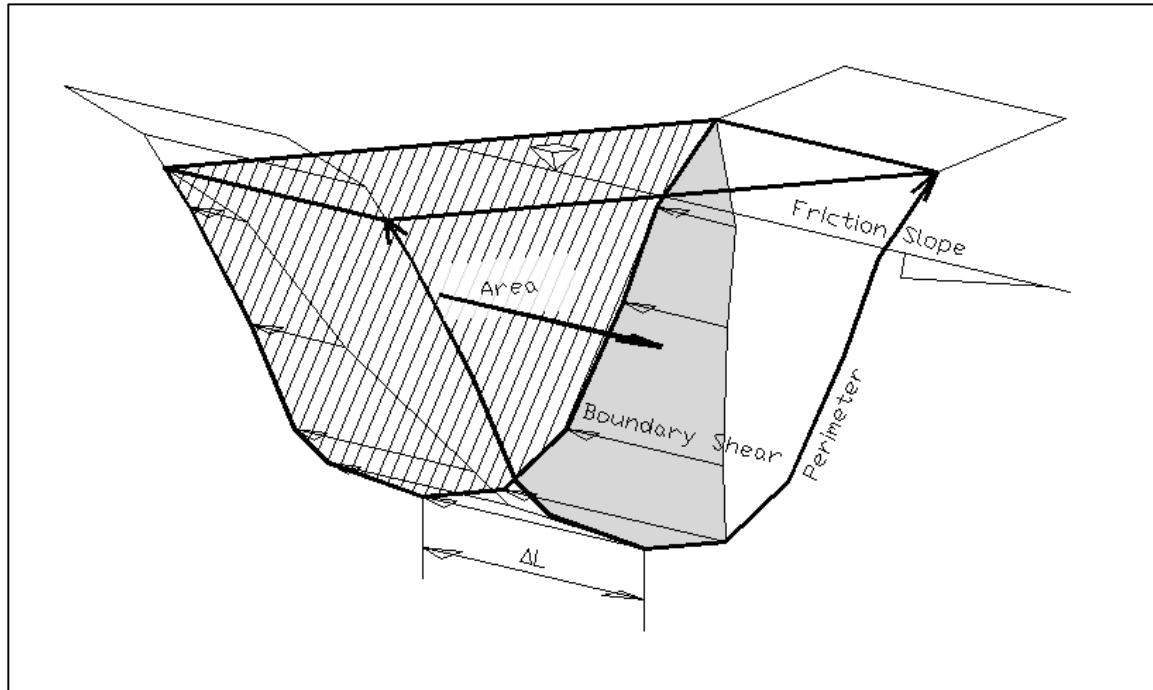


**Figure 11. Typical Distribution of Shear Stress**

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

$$\tau_d = \gamma d S_o \quad \text{Equation 3}$$

where

- $\tau_d$  = shear stress in channel at maximum depth, lb/ft<sup>2</sup>
- $d$  = 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 slope values ( $Z$ ) of 6 to 1.5, respectively. In general, Equation 3 overestimates in cases of relatively narrow channels with steep side slopes.

The relationship between permissible shear stress and permissible velocity for a lining can be found by considering the continuity equation:

$$Q = VA \quad \text{Equation 4}$$

where,

$V$  = flow velocity, ft/s

$A$  = area of flow, ft<sup>2</sup>

By substituting Equation 3 and Equation 4 into Equation 1:

$$V_p = \frac{\alpha}{n\sqrt{\gamma d}} R^{1/6} \tau_p^{1/2} \quad \text{Equation 5}$$

$V_p$  = permissible velocity, ft/s

$\tau_p$  = permissible shear stress, lb/ft<sup>2</sup>

$\alpha$  = unit conversion constant, 1.49

It can be seen from this equation that permissible velocity varies with the hydraulic radius. However, permissible velocity is not extremely sensitive to hydraulic radius since the exponent is only 1/6. Furthermore,  $n$  will change with hydraulic conditions causing an additional variation in permissible velocity.

The tractive force method has a couple of advantages compared to the permissible velocity method. First, the failure criteria for a particular lining are represented by a single permissible shear stress value that is applicable over a wide range of channel slopes and channel shapes. Second, shear stresses are easily calculated using Equation 3. Equation 3 is also useful in judging the field performance of a channel lining, because depth and gradient may be easier to measure in the field than channel velocity. The advantage of the permissible velocity approach is that most designers are familiar with velocity ranges and have a “feel” for acceptable conditions.

### 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.

For stone linings, the permissible shear stress,  $\tau_p$ , indicates the force required to initiate movement of the stone particles. Prior to movement of stones, 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.

Table 3 provides typical examples of permissible shear stress for selected lining types. Vegetative and RECP lining performance relates to how well they protect the underlying soil from shear stresses so these linings do not have permissible shear stresses independent of soil types. Permissible shear stress for gabion mattresses depends on rock size and mattress thickness.

Table 3. Typical Permissible Shear Stresses for Bare Soil and Stone Linings

| Lining Category                      | Lining type                               | Permissible Shear Stress, lb/ft <sup>2</sup> |
|--------------------------------------|-------------------------------------------|----------------------------------------------|
| Bare Soil<br>Cohesive (PI =10)       | Clayey sands                              | 0.037-0.095                                  |
|                                      | Inorganic silts                           | 0.027-0.11                                   |
|                                      | Silty sands                               | 0.024-0.072                                  |
| Bare Soil<br>Cohesive (PI ≥ 20)      | Clayey sands                              | 0.094                                        |
|                                      | Inorganic silts                           | 0.083                                        |
|                                      | Silty sands                               | 0.072                                        |
|                                      | Inorganic clays                           | 0.14                                         |
| Bare Soil<br>Non-cohesive I(PI < 10) | Finer than coarse sand $D_{75} < 0.05$ in | 0.02                                         |
|                                      | Fine gravel $D_{75} = 0.3$ in             | 0.12                                         |
|                                      | Gravel $D_{75} = 0.6$ in                  | 0.24                                         |
| Gravel Mulch                         | Coarse gravel $D_{50} = 1$ in             | 0.4                                          |
|                                      | Very coarse gravel $D_{50} = 2$ in        | 0.8                                          |
| Rock Riprap                          | $D_{50} = 6$ in                           | 2.4                                          |
|                                      | $D_{50} = 12$ in                          | 4.8                                          |

## Design Parameters

### Design Discharge Frequency

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

### Channel Cross Section Geometry

Most roadway drainage channels are trapezoidal or triangular in shape with rounded corners. For design purposes, a trapezoidal or triangular representation is sufficient. Design of roadside channels should be integrated with the geometric design and pavement design to insure proper consideration of safety and pavement drainage needs.

If available channel linings are found to be inadequate for the selected channel geometry, it may be feasible to widen the channel. Either increasing the bottom width or flattening the side slopes can accomplish this. Widening the channel will reduce the flow depth and lower the shear stress on the channel perimeter. The width of channels is limited however to the ratio of top width to depth less than about 20. Very wide channels have a tendency to form smaller more efficient channels within their banks, which increase shear stress above planned design range.

Generally if a riprap-lined channel has 3:1 (H:V) or flatter side slopes, there is no need to check the banks for erosion. 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.

### Channel Slope

The slope of a roadside channel is usually the same as the roadway profile and so is not a design 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. For a given design discharge, the shear stress in the channel with a mild or subcritical slope is smaller than a channel with a supercritical slope. Roadside channels with gradients in excess of about two percent will usually flow in a supercritical state.

### 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 washing over the sides. In a permanent roadway channel, about 0.5 ft of freeboard should be adequate, and for transitional channels, zero freeboard may be acceptable. Steep gradient channels should have a freeboard height equal to the flow depth. This allows for large variations to occur in flow depth for steep channels caused by waves, splashing and surging. Lining materials should extend to the freeboard elevation.

## **GENERAL DESIGN PROCEDURE**

The simplest case of the straight channel is described first. Subsequent sections consider variations to the straight channel including side slope stability, composite linings, and bends. The final two sections address additional considerations for channels with a steep longitudinal slope and determination of a maximum discharge for a given channel. This section is intended to apply to all flexible linings. Subsequent sections provide more detailed guidance on specific flexible lining types.

## 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, known as the normal depth, and determination of the shear stress on the channel bottom at this depth. The maximum shear stress is given by:

$$\tau_d = \gamma d S_o \quad \text{Equation 3}$$

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:

$$\tau_p \geq SF \tau_d \quad \text{Equation 6}$$

where:

$\tau_p$  = permissible shear stress for the channel lining, lb/ft<sup>2</sup>

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

$\tau_d$  = shear stress in channel at maximum depth, lb/ft<sup>2</sup>

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 is conservative and appropriate for design. 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
- climatic regions 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 12. An alternative process for determining an allowable discharge given slope and shape is presented later.

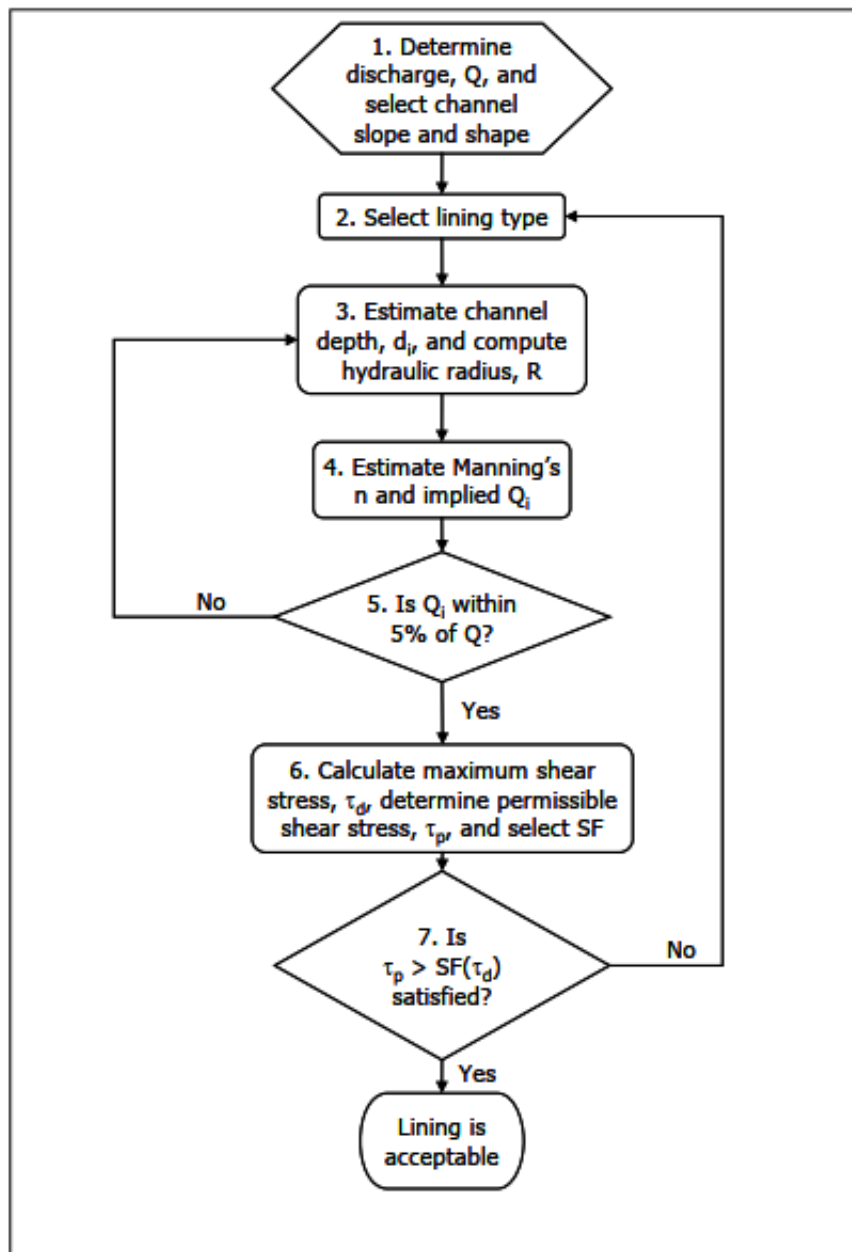


Figure 12 – Flexible Channel Lining Design Flow Chart

Step 1. Determine a design discharge and select the channel slope and channel shape.

Step 2. Select a trial lining type. Initially, the designer may need to determine if a long- term lining is needed and whether or not a temporary or transitional lining is required. For determining the latter, the trial lining type could be chosen as the native material (unlined), typically bare soil. 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 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 the discharge implied by the estimated  $n$  and flow depth values. See Tables 1 and 2 for Manning's  $n$  values. Calculate the discharge,  $Q_i$ .

Step 5. Compare  $Q_i$  with  $Q$ . If  $Q_i$  is within 5 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,  $\tau_d$  (Equation 3), determine the permissible shear stress,  $\tau_p$ , and select an appropriate safety factor.

Permissible

shear stress is determined based on guidance described in later sections of this course, as applicable to the chosen lining, or Table 3. 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 6. If the permissible shear stress is adequate then the lining is acceptable. If the permissible shear is inadequate, then return to step 2 and select an alternative lining type with greater permissible shear stress. As an alternative, a different channel shape may be selected that results in a lower depth of flow.

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

#### Design Example: Basic Channel

Evaluate a proposed gravel mulch lining on a trapezoidal channel for stability.

Given:  $Q = 15 \text{ ft}^3/\text{s}$

$B = 1.3 \text{ ft}$

$Z = 3$

$S_o = 0.008 \text{ ft/ft}$

$D_{50} = 1 \text{ in}$

#### Solution

Step 1. Channel slope, shape and discharge have been given. Step 2. Proposed lining type is a gravel mulch with  $D_{50} = 1 \text{ in}$ .

Step 3. Assume that the depth of flow,  $d_i$  in the channel is 1.6 ft. Compute  $R$ .

$$A = Bd + Zd^2 = 1.3(1.6) + 3(1.6)^2 = 9.76 \text{ ft}^2$$

$$P = B + 2d(Z^2 + 1)^{0.5} = 1.3 + 2(1.6)(3^2 + 1)^{0.5} = 11.4 \text{ ft}$$

$$R = A/P = 9.76/11.4 = 0.856 \text{ ft}$$

Step 4. From Table 2, Manning's  $n$  equals 0.033. The discharge is calculated using Manning's equation (Equation 1):

$$Q = (1.49/n) * A * R^{2/3} * S^{1/2} = (1.49/0.033) * 9.76 * 0.856^{2/3} * 0.008^{1/2} = 35.5 \text{ ft}^3/\text{s}$$

Step 5. Since this value is more than 5 percent different from the design flow, we need to go back to step 3 to estimate a new flow depth.

Step 3 (2<sup>nd</sup> iteration). Estimate the second depth to be 1.15 ft. Interpolating in Table 2,  $n = 0.036$ .

Compute a new hydraulic radius.

$$A = Bd + Zd^2 = 1.3(1.15) + 3(1.15)^2 = 5.46 \text{ ft}^2$$

$$P = B + 2d(Z^2 + 1)^{0.5} = 1.3 + 2(1.15)(3^2 + 1)^{0.5} = 8.57 \text{ ft}$$

Step 4 (2<sup>nd</sup> iteration). Interpolating in Table 2,  $n = 0.036$ . The discharge is calculated using Manning's equation:

$$Q = (1.49/n) * A * R^{2/3} * S^{1/2} = (1.49/0.036) * 5.46 * 0.637^{2/3} * 0.008^{1/2} = 15.0 \text{ ft}^3/\text{s}$$

Step 5. (2<sup>nd</sup> iteration). Since this value is within 5 percent of the design flow, we can now proceed to step 6.

Step 6. The shear stress at maximum depth from Equation 3 is:

$$\tau_d = \gamma d S_0 = 62.4(1.15)(0.008) = 0.57 \text{ lb/ft}^2$$

From Table 3, permissible shear stress,  $\tau_p = 0.4 \text{ lb/ft}^2$ .

For this channel, a  $SF = 1.0$  is chosen.

Step 7. Compare calculated shear to permissible shear using Equation 6:

$$\tau_p \geq SF \tau_d$$

$0.40 \geq 1.0 (0.57)$  No. The lining is not stable! Go back to step 2. Select an alternative lining type with greater permissible shear stress. Try the next larger size of gravel. If the lining had been stable, the design process would be complete.

### Side Slope Stability

As noted previously, shear stress is generally reduced on the channel sides compared with the channel bottom. The maximum shear on the side of a channel is given by the following equation:

$$\tau_s = K_1 \tau_d \quad \text{Equation 7}$$

$\tau_s$  = side shear stress on the channel,  $\text{lb/ft}^2$

$K_1$  = ratio of channel side to bottom shear stress

$\tau_d$  = shear stress in channel at maximum depth,  $\text{lb/ft}^2$

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 trapezoidal and triangular channels the following values of  $K_1$  may be used.

$$\begin{aligned}
K_1 &= 0.77 && \text{for } Z \leq 1.5 \\
K_1 &= 0.66 Z + 0.067 && \text{for } 1.5 < Z < 5 \\
K_1 &= 1.0 && \text{for } Z \geq 5
\end{aligned}
\tag{Equation 8}$$

The Z value represents the horizontal dimension Z:1 (H:V). Use of side slopes steeper than 3:1 (H:V) is not encouraged for flexible linings other than riprap or gabions because of the potential for erosion of the side slopes. Steep side slopes are allowable within a channel if cohesive soil conditions exist. Channels with steep slopes should not be allowed if the channel is constructed in non-cohesive soils.

### Composite Lining Design

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 concrete or riprap. The dimensions of the low-flow channel are sufficient to carry frequent low flows but only a small portion of the design flow. The remainder of the channel is covered with vegetation. Another option for these channels is cabled-concrete blocks, which allow vegetation to grow between the blocks, but still provide the erosion-resistant bottom.

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. For determination of equivalent roughness, the channel area is divided into two parts of which the wetted perimeters and Manning's n values of the low-flow section and channel sides are known. These two areas of the channel are then assumed to have the same mean velocity. The following equation is used to determine the equivalent roughness coefficient,  $n_e$ .

$$n_e = \left[ \frac{P_L}{P} + \left( 1 - \frac{P_L}{P} \right) \left( \frac{n_s}{n_L} \right)^{\frac{3}{2}} \right]^{\frac{2}{3}} n_L
\tag{Equation 9}$$

where:

$n_e$  = effective 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 presented previously with additional sub-steps to account for the two lining types. Specifically, the modifications are:

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 9 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,  $\tau_d$  (Equation 3), and the shear stress on the channel side slope,  $\tau_s$  (Equation 7).

Step 7. Compare the shear stresses,  $\tau_d$  and  $\tau_s$ , to the permissible shear stress,  $\tau_p$ , for each of the channel linings. If  $\tau_d$  or  $\tau_s$  is greater than the  $\tau_p$  for the respective lining, a different combination of linings should be evaluated.

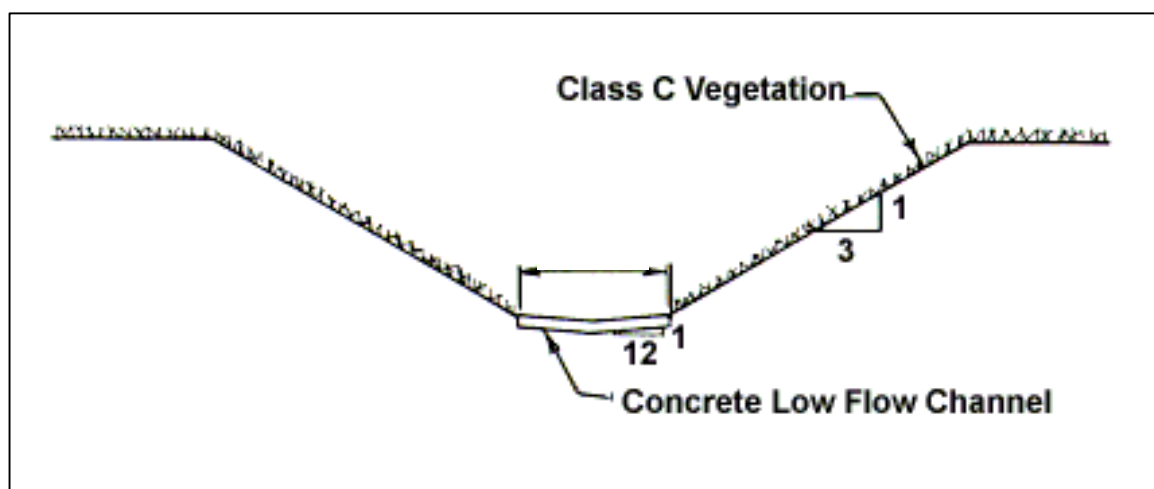


Figure 13 – Composite Lining

### Design Example: Composite Lining Design

Evaluate the channel design for the composite concrete and vegetation lining given in Figure 13.

Given:

$$\begin{aligned}Q &= 9.9 \text{ ft}^3/\text{s} \\B &= 3 \text{ ft} \quad \text{Concrete low flow channel} \\Z &= 3 \\S_o &= 0.02 \text{ ft/ft}\end{aligned}$$

Vegetation: Class C, height = 0.66 ft (mixed with good cover)

The underlying soil is a clayey sand (SC) soil with a plasticity index of 16 and a porosity of 0.5

### Solution

Step 1. Channel slope, shape and discharge have been given.

Step 2. Low flow lining is concrete. Side slope lining is Class C vegetation.

Step 3. Assume that the depth of flow,  $d_i$ , in the channel is 1.0 ft. Determine R. Assume that the concrete portion is essentially flat.

$$A = Bd + Zd^2 = 3.0(1.0) + 3(1.0)^2 = 6.00 \text{ ft}^2$$

$$P = B + 2d(Z^2 + 1)^{0.5} = 3.0 + 2(1.0)(3^2 + 1)^{0.5} = 9.32$$

$$R = A/P = 6.00/9.32 = 0.643 \text{ ft}$$

Step 4. The  $n$  value for Class C vegetation is estimated to be  $n_s = 0.043$ . For concrete, the typical  $n$  value for concrete from Table 1 is  $n_L = 0.013$ .

Effective Manning's  $n$  is calculated using Equation 9 and is 0.035.

Calculate the flow using Manning's equation:

$$Q = (1.49/n) * A * R^{2/3} * S^{1/2} = (1.49/0.035) * 6.00 * 0.643^{2/3} * 0.02^{1/2} = 26.9 \text{ ft}^3/\text{s}$$

Step 5. This flow is larger than the design flow of 9.9 ft<sup>3</sup>/s by more than 5 percent. Go back to step 3 and repeat until the assumed depth yields a flow within 5% of the design flow.

Step 6. Calculate maximum shear stress, determine permissible shear stress, and select SF.

Bottom shear stress is calculated from Equation 3:

Maximum side shear stress is calculated from Equation 7 after calculating  $K_1$ :

Step 7. Compare the maximum shear stress on the channel side slopes to the permissible shear stress on the vegetation to determine if the lining is acceptable. The concrete bottom lining is non-erodible.

## Stability In Bends

Flow around a bend creates secondary currents, which impose higher shear stresses on the channel sides and bottom compared to a straight reach as shown in Figure 14. 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.

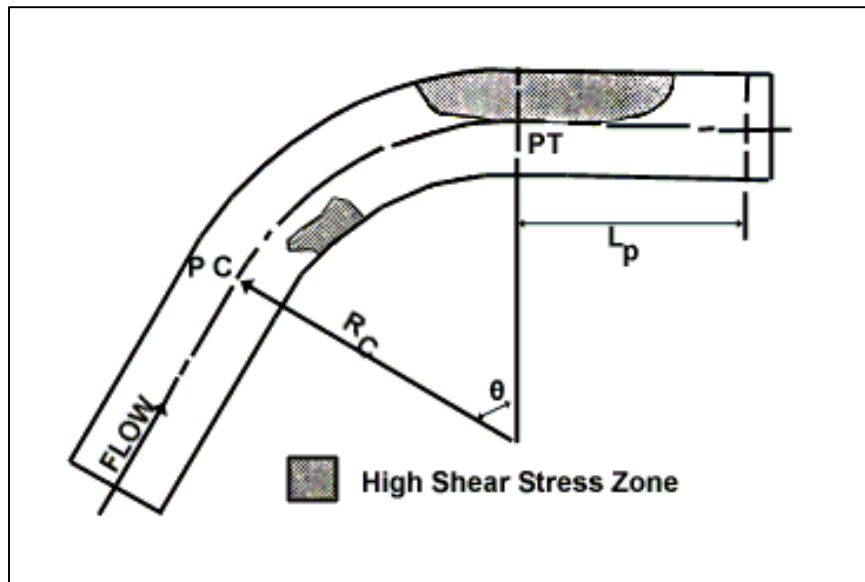


Figure 14. Shear Stress Distribution in a Channel Bend

Equation 10 gives the maximum shear stress in a bend.

$$T_b = K_b T_d \quad \text{Equation 10}$$

$T_b$  = side shear stress on the channel, lb/ft<sup>2</sup>  
 $K_b$  = ratio of channel bend to bottom shear stress  
 $T_d$  = shear stress in channel at maximum depth, lb/ft<sup>2</sup>

The maximum shear stress in a bend is a function of the ratio of channel curvature to the top (water surface) width,  $R_c/T$ . 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 Equation 11.

|                                                 |                              |
|-------------------------------------------------|------------------------------|
| $K_b = 2.00$                                    | $R_c/T \leq 2$               |
| $K_b = 2.39 - 0.206 (R_c/T) + 0.0073 (R_c/T)^2$ | $2 < R_c/T < 10$ Equation 11 |
| $K_b = 1.05$                                    | $R_c/T \geq 10$              |

Where:

$R_c$  = radius of 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 a length given by:

$$L_p = 0.60 (R^{1/6}/n)$$

where,

$L_p$  = length of protection, ft

$R$  = hydraulic radius of the channel, ft

$n$  = Manning's roughness coefficient 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. Superelevation in open channel flow does occur, but the magnitude of the increase in elevation is typically very small. Additional freeboard is necessary in bends and can be calculated use the following equation:

$$\Delta d = (V^2 * T)/(g * R_c) \quad \text{Equation 12}$$

where,

$\Delta d$  = additional freeboard required because of superelevation, ft

$V$  = average channel velocity, ft/sec

$T$  = water surface top width, ft

$g$  = acceleration due to gravity, ft/sec<sup>2</sup>

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

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

### Steep Slope Design

Intuitively, steep channel slopes may be considered a harsher environment than mild slopes for channel lining design. Furthermore, inspection of Equation 3 reveals that applied shear stress is directly proportional to channel slope. Therefore, it is appropriate to address the question of what, if any, additional consideration should be given to flexible channel lining design on steep slopes.

First, "steep" must be defined. From a hydraulic standpoint a steep slope is one that produces a supercritical normal depth (as opposed to a mild slope). Steep may also be defined as a fixed value such as 10 percent. Neither definition is appropriate for all circumstances and a single definition is not required. Two general questions arise when considering steep slopes for channel design.

First, are the same relationships for channel roughness (Manning's  $n$ ) applicable over the entire range of slopes? For vegetative and manufactured linings the methodologies for determining roughness do apply to the full range of conditions suitable for these linings; that is, where Equation 6 is satisfied. However, for riprap and gabion mattress linings, slope may influence the approach for estimating roughness. For these linings, two roughness relationships are provided: one for relatively shallow flow ( $d_a/D_{50} < 1.5$ ) and one

for relatively moderate or deep flow ( $d_a/D_{50} > 1.5$ ). Although slope plays an important role in determining depth; discharge, channel shape, and lining  $D_{50}$  also have an influence on the appropriate selection of roughness.

The second question is whether or not a steeper slope affects the development of the permissible shear stress used in Equation 6. Again, for vegetative and manufactured linings, the answer is no and the methods discussed later apply to the full range of conditions where Equation 3 is satisfied. The same is also true for gabion linings. For riprap linings, the later section on this topic provides two alternative frameworks for evaluating permissible shear stress. One method is for slopes up to 10 percent and the other is for slopes equal to or greater than 10 percent.

Rigid channel linings may be a cost-effective alternative to flexible linings for steep slope conditions. Rigid linings could include asphalt, concrete, or durable bedrock. The decision to select a rigid or flexible lining may be based on other site conditions, such as foundation and maintenance requirements.

For flexible or rigid linings on steep slopes, bends should be avoided. A design requiring a bend in a steep channel should be reevaluated to eliminate the bend, modeled, or designed using an enclosed section.

### Maximum Discharge Approach

As the discharge increases along a channel, the shear stress may at some point reach the permissible shear for the channel lining selected indicating the need to proceed with the design of another lining for the next section of channel or provide a relief inlet or culvert to divert the flow out of the channel. The methodology for determining the length or section of channel that a selected lining will remain stable is often referred to as the maximum discharge approach. By knowing the maximum discharge that a lining can sustain, the designer can determine the maximum length of lining for a selected lining type based on the hydrology of the site. This information can assist the designer in an economic evaluation of lining types and can determine relief inlet or culvert spacing.

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

Combining Equations 3 and 6 in the following form can derive the maximum depth a channel lining can withstand:

$$d \leq \tau_p / (SF * \gamma * S_o) \quad \text{Equation 13}$$

The analysis approach is applied as follows:

Step 1. Select a candidate lining and determine its permissible shear value and an appropriate safety factor.

Step 2. Use Equation 13 to calculate the maximum depth. Check that this depth does not exceed the depth (including freeboard) provided in the typical roadway section.

Step 3. Determine the area and hydraulic radius corresponding to the allowable depth based on the channel geometry.

Step 4. Estimate the Manning's  $n$  value appropriate for the lining type and depth.

Step 5. Solve Manning's equation to determine the maximum discharge for the channel. The length of roadway and/or contributing drainage must be limited to an area generating less than or equal to this amount.

## **VEGETATIVE LINING AND BARE SOIL DESIGN**

Grass-lined channels have been widely used in roadway drainage systems for many years. They are easily constructed and maintained and work well in a variety of climates and soil conditions. Grass linings provide good erosion protection and can trap sediment and related contaminants in the channel section. Routine maintenance of grass-lined channels consists of mowing, control of weedy plants and woody vegetation, repair of damaged areas and removal of sediment deposits.

The behavior of grass in an open channel lining is complicated by the fact that grass stems bend as flow depth and shear stress increase. This reduces the roughness height and increases velocity and flow rate. For some lining materials (bare earth and rigid linings), the roughness height remains constant regardless of the velocity or depth of flow in the channel. As a result, a grass-lined channel cannot be described by a single roughness coefficient.

The Soil Conservation Service (SCS, now the Natural Resources Conservation Service) developed a widely used classification of grass channel lining that depends on the degree of retardance. In this classification, retardance is a function of the height and density of the grass cover. Grasses are classified into five broad categories, as shown in Table 4 (based on testing in experimental channels, with green and uniform cover). Retardance Class A presents the highest resistance to flow and Class E presents the lowest resistance to flow. In general, taller and denser grass species have a higher resistance to flow, while short flexible grasses have a low flow resistance.

Table 4. Retardance Classification of Vegetal Covers

| Retardance Class | Cover                                                                                                  | Condition                                                    |
|------------------|--------------------------------------------------------------------------------------------------------|--------------------------------------------------------------|
| A                | Weeping lovegrass                                                                                      | Excellent stand, tall, average 30 in                         |
|                  | Yellow Bluestem Ischaemum                                                                              | Excellent stand, tall, average 36 in                         |
| B                | Kudzu                                                                                                  | Very dense growth, uncut                                     |
|                  | Bermuda Grass                                                                                          | Good stand, tall, average 12 in                              |
|                  | Native Grass Mixture (little bluestem, bluestem, blue gamma, and other long and short Midwest grasses) | Good stand, unmowed                                          |
|                  | Weeping lovegrass                                                                                      | Good stand, tall, average 24 in                              |
|                  | Lespedeza sericea                                                                                      | Good stand, not woody, tall average 19 in                    |
|                  | Alfalfa                                                                                                | Good stand, uncut, average 11 in                             |
|                  | Weeping lovegrass                                                                                      | Good stand, unmowed, average 13 in                           |
|                  | Kudzu                                                                                                  | Dense growth, uncut                                          |
|                  | Blue Gamma                                                                                             | Good stand, uncut, average 11 in                             |
| C                | Crabgrass                                                                                              | Fair stand, uncut 10 to 48 in                                |
|                  | Bermuda grass                                                                                          | Good stand, mowed, average 6 in                              |
|                  | Common Lespedeza                                                                                       | Good stand, uncut, average 11 in                             |
|                  | Grass-Legume mixture – summer (orchard grass, redtop, Italian ryegrass and common lespedeza)           | Good stand, uncut, 6 to 8 in                                 |
|                  | Centipede grass                                                                                        | Very dense cover, average 6 in                               |
|                  | Kentucky Bluegrass                                                                                     | Good stand, headed, 6 to 12 in                               |
|                  |                                                                                                        |                                                              |
| D                | Bermuda Grass                                                                                          | Good stand, cut to 2.5 in height                             |
|                  | Common Lespedeza                                                                                       | Excellent stand, uncut, average 4 in                         |
|                  | Buffalo Grass                                                                                          | Good stand, uncut, average 3 to 6 in                         |
|                  | Grass-Legume mixture – fall, spring (orchard grass, redtop, Italian ryegrass and common lespedeza)     | Good stand, uncut, 4 to 5 in                                 |
|                  | Lespedeza sericea                                                                                      | After cutting to 2 in height. Very good stand before cutting |
|                  |                                                                                                        |                                                              |
| E                | Bermuda Grass                                                                                          | Good stand, cut to 1.5 in height                             |
|                  | Bermuda Grass                                                                                          | Burned stubble                                               |

Grass linings provide erosion control in two ways. First, the grass stems dissipate 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.

A simple field method is provided to directly measure the density-stiffness parameter of a grass cover. Grass linings for roadside ditches use a wide variety of seed mixes that meet the regional requirements of soil and climate. These seed mix designs are constantly being adapted to improve grass-lined channel performance. Maintenance practices can significantly influence density and uniformity of the grass cover. The sampling of established grasses in roadside ditch application can eliminate much of the uncertainty in lining performance and maintenance practices.

Expertise in vegetation ecology, soil classification, hydrology, and roadway maintenance is required in the design of grass-lined channels. Engineering judgment is essential in determining design parameters based on this expert input. This includes factoring in variations that are unique to a particular roadway design and its operation.

## Grass Lining Properties

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 of grass is similar for a wide range of species and is a basic property of grass linings.

Density is the number of grass stems in a given area, i.e., stems per ft<sup>2</sup>. A good grass lining will have about 200 to 400 stems/ft<sup>2</sup>. A poor cover will have about one-third of that density and an excellent cover about five-thirds.

For agricultural ditches, grass heights can reach 1.0 ft to over 3.0 ft. However, near a roadway grass heights are kept much lower for safety reasons and are typically in the range of 3 to 9 inches.

The density-stiffness property of grass is defined by the  $C_s$  coefficient.  $C_s$  can be estimated based on the conditions of the grass cover using Table 5. Good cover would be the typical reference condition.

Table 5. Density-stiffness Coefficient,  $C_s$

| Conditions |           |      |      |      |
|------------|-----------|------|------|------|
| Excellent  | Very Good | Good | Fair | Poor |
| 49         | 25        | 9    | 2    | 0.7  |

The combined effect of grass stem height and density-stiffness is defined by the grass roughness coefficient.

$$C_n = 0.237 C_s^{0.10} h^{0.528} \quad \text{Equation 14}$$

where,

$C_n$  = grass roughness coefficient

$C_s$  = density-stiffness coefficient

$h$  = stem height, ft

Table 6 provides  $C_n$  values for a range of cover and stem height conditions based on Equation

14. Denser cover and increased stem height result in increased channel roughness.

Table 6. Grass Roughness Coefficient,  $C_n$

| Stem Height, ft | Excellent | Very Good | Good  | Fair  | Poor  |
|-----------------|-----------|-----------|-------|-------|-------|
| 0.25            | 0.168     | 0.157     | 0.142 | 0.122 | 0.111 |
| 0.50            | 0.243     | 0.227     | 0.205 | 0.177 | 0.159 |
| 0.75            | 0.301     | 0.281     | 0.254 | 0.219 | 0.197 |

SCS retardance values relate to a combination of grass stem-height and density.  $C_n$  values for standard retardance classes are provided in Table 4.4. Comparing Table 4.3 and 4.4 shows that retardance classes A and B are not commonly found in roadway applications. These retardance classes represent conditions where grass can be allowed to grow much higher than would be permissible for a roadside channel, e.g., wetlands and agricultural ditches. Class E would not be typical of most roadside channel conditions unless they were in a very poor state.

The range of  $C_n$  for roadside channels is between 0.10 and 0.30 with a value of 0.20 being common to most conditions and stem heights. In an iterative design process, a good first estimate of the grass roughness coefficient would be  $C_n = 0.20$ .

Table 7. Grass Roughness Coefficient,  $C_n$  for SCS Retardance Classes

| Retardance Class | A     | B     | C     | D     | E     |
|------------------|-------|-------|-------|-------|-------|
| Stem Height, in  | 36    | 24    | 8     | 4     | 1.5   |
| $C_s$            | 33    | 7.1   | 3.9   | 2.7   | 3.8   |
| $C_n$            | 0.605 | 0.418 | 0.220 | 0.147 | 0.093 |

### Manning's Roughness

Manning's roughness coefficient for grass linings varies depending on grass properties as reflected in the  $C_n$  parameter and the shear force 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.

$$n = 0.213 C_n \tau_0^{-0.4} \quad \text{Equation 15}$$

where,

$\tau_0$  = mean boundary shear stress, lb/ft<sup>2</sup>

### 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. Determination of permissible shear stress for the lining is based on the permissible shear stress of the soil combined with the protection afforded by the vegetation, if any.

### Effective Shear Stress

Grass lining moves 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 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 dissipate 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. The effective shear at the soil surface can be calculated by Equation 16.

$$\tau_e = \tau_d (1 - C_f)(n_s/n)^2 \quad \text{Equation 16}$$

where,

$\tau_e$  = effective shear stress on the soil surface, lb/ft<sup>2</sup>

$\tau_d$  = design shear stress, lb/ft<sup>2</sup>

$C_f$  = grass cover factor

$n_s$  = soil grain roughness

$n$  = overall lining roughness

Soil grain roughness is taken as 0.016 when  $D_{75} < 0.05$  in. For larger grain soils, the soil grain roughness is given by Equation 17.

$$n_s = 0.026 (D_{75})^{1/6} \quad \text{Equation 17}$$

Note that soil grain roughness value,  $n_s$ , is less than the typical value reported in Table 1 for a bare soil channel. The total roughness value for bare soil channel includes form roughness (surface texture of the soil) in addition to the soil grain roughness. However, Equation 16 is based on soil grain roughness.

The grass cover factor,  $C_f$ , varies with cover density and grass growth form (sod or bunch). The selection of the cover factor is a matter of engineering judgment since limited data are available. Table 8 provides a reasonable approach to estimating a cover factor. Cover factors are better for sod-forming 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 and there is more uncertainty in the estimates of fair and poor conditions.

Table 8. Cover Factor Values for Uniform Stands of Grass

| Growth Form | Cover Factor, $C_f$ |           |      |      |      |
|-------------|---------------------|-----------|------|------|------|
|             | Excellent           | Very Good | Good | Fair | Poor |
| Sod         | 0.98                | 0.95      | 0.90 | 0.84 | 0.75 |
| Bunch       | 0.55                | 0.53      | 0.50 | 0.47 | 0.41 |
| Mixed       | 0.82                | 0.79      | 0.75 | 0.70 | 0.62 |

### Permissible Soil Shear Stress

Erosion of the soil boundary 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 of 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 often includes the placement of topsoil on the perimeter of the channel. 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.

### Non-cohesive Soils

The permissible soil shear stress for fine-grained, non-cohesive soils ( $D_{75} < 0.05$  in) is relatively constant and is conservatively estimated at  $0.02 \text{ lb/ft}^2$ . For coarse grained, non-cohesive soils ( $0.05 \text{ in} < D_{75} < 2 \text{ in}$ ) Equation 18 applies.

$$T_{p, \text{soil}} = 0.4 D_{75} \quad \text{Equation 18}$$

### Cohesive Soils

Cohesive soils are largely fine grained and their permissible shear stress depends on cohesive strength and soil density. Cohesive strength is associated with the plasticity index (PI), which is the difference between the liquid and plastic limits of the soil. The soil density is a function of the void ratio ( $e$ ).

A simplified approach for estimating permissible soil shear stress is illustrated in Figure 15. Fine grained soils are grouped together (GM, CL, SC, ML, SM, and MH) and coarse grained soil (GC). Clays (CH) fall between the two groups.

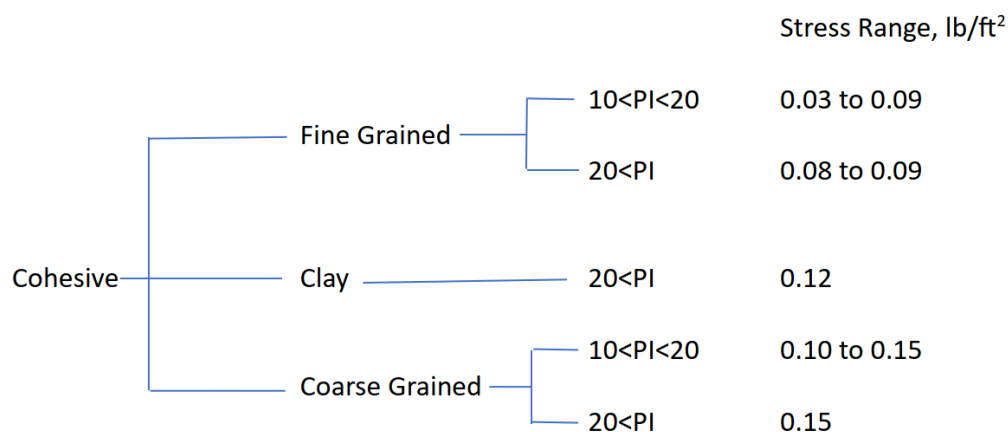


Figure 15. Cohesive Soil Permissible Shear Stress

Higher soil unit weight increases the permissible shear stress and lower soil unit weight decreases permissible shear stress. Figure 15 is applicable for soils that are within 5 percent of a typical unit weight for a soil class. For sands and gravels (SM, SC, GM, GC) typical soil unit weight is approximately  $100 \text{ lb/ft}^3$ , for silts and lean clays (ML, CL)  $90 \text{ lb/ft}^3$  and fat clays (CH, MH)  $80 \text{ lb/ft}^3$ .

### Turf Reinforcement with Gravel/Soil Mixture

The rock products industry provides a variety of uniformly graded gravels for use as mulch and soil stabilization. A gravel/soil mixture provides a non-degradable lining that is created as part of the soil preparation and is followed by seeding. The integration of gravel and soil is accomplished by mixing (by raking or disking the gravel into the soil). The gravel provides a matrix of sufficient thickness and void space to permit establishment of vegetation roots within the matrix. It provides enhanced erosion resistance during the vegetative establishment period and it provides a more resistant underlying layer than soil

once vegetation is established.

The density, size and gradation of the gravel are the main properties that relate to flow resistance and erosion control performance. Stone specific gravity should be approximately 2.6 (typical of most stone). The stone should be hard and durable to ensure transport without breakage. Placed density of uniformly graded gravel is 1.5 ton/yd<sup>3</sup>. A uniform gradation is necessary to permit germination and growth of grass plants through the gravel layer. Table 9 provides two typical gravel gradations for use in erosion control.

Table 9. Gravel Gradation Table, Percentages Passing Nominal Size Designations

| Size    | Very Coarse D <sub>75</sub> = 1.75 in | Coarse D <sub>75</sub> = 1.2 in |
|---------|---------------------------------------|---------------------------------|
| 2 in    | 90 - 100                              |                                 |
| 1.5 in  | 35 - 70                               | 90 - 100                        |
| 1.0 in  | 0 - 15                                | 35 - 70                         |
| 0.75 in |                                       | 0 - 15                          |

The application rate of gravel mixed into the soil should result in 25 percent of the mixture in the gravel size. Generally, soil preparation for a channel lining will be to a depth of 3 to 4 inches.

The gravel application rates for fine-grained soils (percentage of gravel = 0) are summarized in Table 10. If the soil already contains some coarse gravel, then the application rate can be reduced by the percentage of existing gravel.

Table 10. Gravel Application Rates for Fine Grain Soils

| Soil Preparation Depth | Application Rate of gravel |
|------------------------|----------------------------|
| 3 inches               | 0.041 ton/yd <sup>2</sup>  |
| 4 inches               | 0.056 ton/yd <sup>2</sup>  |

The effect of roadside maintenance activities, particularly mowing, on longevity of gravel/soil mixtures needs to be considered. Gravel/soil linings are unlikely to be displaced by mowing since they are heavy. They are also a particle-type lining, so loss of a few stones will not affect overall lining integrity. Therefore, a gravel/soil mix is a good turf reinforcement alternative.

## MANUFACTURED (RECP) LINING DESIGN

Manufacturers have developed a variety of rolled erosion control products (RECPs) for erosion protection of channels. These products consist of materials that are stitched or bound into a fabric. Table 11 summarizes the range of RECP linings that are available from the erosion control industry. Selection of a particular product depends on the overall performance requirements for the design. RECPs offer ease of construction in climate regions where vegetation establishes quickly.

Table 11. Manufactured (RECP) Linings

| Type                         | Description                                                                                                                                                                                                                                                                                                    |
|------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Open-Weave Textile           | A temporary degradable RECP composed of processed natural or polymer yarns woven into a matrix, used to provide erosion control and facilitate vegetation establishment. Examples: jute net, woven paper net, straw with net.                                                                                  |
| Erosion Control Blanket      | A temporary degradable RECP composed of processed natural or polymer fibers mechanically, structurally or chemically bound together to form a continuous matrix to provide erosion control and facilitate vegetation establishment. Example: curled wood                                                       |
| Turf-reinforcement Mat (TRM) | A non-degradable RECP composed of UV stabilized synthetic fibers, filaments, netting and/or wire mesh processed into a three-dimensional matrix. TRMs provide sufficient thickness, strength and void space to permit soil filling and establishment of grass roots within the matrix. Example: synthetic mat. |

## RECP Properties

The density, stiffness and thickness of light-weight manufactured linings known as rolled erosion control products (RECPs) are the main properties that relate to flow resistance and erosion control performance. There are a series of standard tests referred to as index tests that measure these physical properties. The hydraulic properties of RECP must be determined by full scale testing in laboratory flumes.

Qualitatively, denser linings prevent soil from entering into the higher-velocity flow above the liner. Linings with higher tensile strength and flexural rigidity have less deformation due to shear and uplift forces of the flow and remain in closer contact with the soil. Linings with more thickness have a larger moment of inertia, which further reduces the deformation of the lining.

Proper installation of RECPs is critical to their performance. This includes the stapling of the lining to the channel perimeter, the lapping of adjacent fabric edges and the frequency of cutoff trenches. Each manufacturer provides guidelines on installation, which should be reviewed and incorporated into installation specifications. Construction inspection should verify that all installation specifications have been met prior to acceptance.

## Manning's Roughness

There is no single  $n$  value formula for RECPs. The roughness of these linings must be determined by full-scale testing in laboratory flumes using defined testing protocols. As with vegetated linings, the  $n$  value varies significantly with the applied shear due to the displacement of the lining by shear and uplift forces.

The designer will need to obtain from the RECP manufacturer a table of  $n$  value versus applied shear. Three  $n$  values, with the corresponding applied shear values need to be provided by the manufacturer. The upper shear stress should equal or exceed the lining shear,  $\tau_l$ . The upper and lower shear stress values must equal twice and one-half of the middle value, respectively.

## Permissible Shear Stress

The permissible shear stress of an RECP lining is determined both by the underlying soil properties as well as those of the RECP. In the case of TRMs, the presence of vegetation also influences erosion resistance properties.

### Effective Shear Stress

RECPs dissipate shear stress before it reaches the soil surface. When the shear stress at the soil surface is less than the permissible shear for the soil surface, then erosion of the soil surface will be controlled. RECPs provide shear reduction primarily by providing cover for the soil surface. As the hydraulic forces on the RECP lining increase, the lining is detached from the soil, which permits a current to establish between the lining and the soil surface. Turbulent fluctuations within this current eventually erode the soil surface.

### Permissible RECP/Soil Shear Stress

The combined effects of the soil permissible shear stress and the effective shear stress transferred through the RECP lining results in a permissible shear stress for the RECP lining. Taking Equation 5.4 and substituting the permissible shear stress for the soil for the effective shear stress on the soil,  $\tau_e$ , gives the following equation for permissible shear stress for the RECP lining:

$$\tau_p = (\tau_l / 0.14)^* (\tau_{p,soil} + 0.0326) \quad \text{Equation 19}$$

where:

$\tau_p$  = permissible shear stress on the RECP lining, lb/ft<sup>2</sup>

$\tau_l$  = shear stress on the RECP that results in 0.5 in of erosion

$\tau_{p,soil}$  = permissible shear stress, lb/ft<sup>2</sup>

## Turf Reinforcement with RECPs

Turf reinforcement integrates soil, lining material and grass/stems roots within a single matrix. Since turf reinforcement is a long-term solution, the lining consists of non-degradable materials. Turf Reinforcement Mats (TRMs), a subset of RECPs, are integrated with soil, and subsequently vegetation, by either covering the mat with soil or through surface application (no soil filling) allowing the vegetation to grow up through the TRM. Stability of the TRMs is achieved through proper installation per the manufacturer's recommended methods and use of proper length and quantity of fasteners.

As grass roots/stems develop within or through the TRM matrix, the lining becomes more integrated with the vegetation and soil. In the case of TRM linings, the plant roots/stems bind the mat, which prevents the detachment of the mat from the soil surface – significantly reducing the formation of under currents between the mat and soil. Grass growth further deflects turbulence away from the soil surface, establishing a positive relationship between lining and grass growth.

Where lining material is placed on top of the seed bed, the plant stem will grow through the lining. In this type of placement, the lining material offers more initial protection for the seed bed and provides stem reinforcement of the vegetation. However, the grass stem may be less effective at securing the lining to the soil surface than the plant roots, permitting the lining to be displaced by hydraulic forces. Specific system performance is determined by the

interaction of the vegetation and the soil-filled or surface applied TRM.

When lining material remains in place for the long-term, roadside maintenance activities need to be considered, particularly mowing. Use of proper installation methods, including a sufficient quantity and size of fasteners is necessary to prevent potential problems with mowing and other vegetation maintenance equipment. Additionally, proper maintenance techniques are required to avoid damage to the installation and ensure the integrity of the system over time.

### Testing Data

Unlike other RECPs there is no broadly accepted protocol for the testing of TRMs. This places an additional burden on the designer of a TRM lining to review and understand how each manufacturer has tested its products. The following checklist can be used as minimum standard to evaluate manufacturer's testing protocols. Products that are based on a testing protocol for TRMs that do not meet these minimum elements should only be used cautiously.

Test data consisting of the following is recommended:

1. Permissible lining shear stress for a vegetated lining alone.
2. Permissible lining shear stress for a vegetated lining with turf reinforcement.
3. A plant density factor (fractional increase or decrease in plant density) that is attributable to the lining material as a fraction of the cover.

Items (1) and (2) will vary depending on the soil and vegetation used in the testing. However, this is mitigated by their use in a relative, not absolute, manner. As long as a researcher maintains consistency within a set of tests for a particular TRM, the results should be acceptable.

### Turf-Reinforcement Mat Cover Factor

A TRM modifies the cover factor for vegetated linings (Equation 16). The adjusted cover factor is determined by Equation 20.

$$C_{f,TRM} = 1 - (T_{p,VEG-test}/T_{p,TRM,-test}) * (1 - C_{f,VEG}) \quad \text{Equation 20}$$

where,

$T_{p,VEG-test}$  = permissible shear stress on the vegetative lining, lb/ft<sup>2</sup> as reported by the manufacturer's testing

$T_{p,TRM,-test}$  = permissible shear stress on the turf-reinforced vegetative lining, lb/ft<sup>2</sup> as reported by the manufacturer's testing

$C_{f,VEG}$  = grass cover factor (see Table 8)

$C_{f,TRM}$  = TRM cover factor

If the manufacturer notes that the TRM affects plant cover density, this information should be used in the selection of  $C_{f,VEG}$  from Table 8.

## RIPRAP, COBBLE, AND GRAVEL LINING DESIGN

Riprap, cobble, and gravel linings are considered permanent flexible linings. They may be described as a noncohesive layer of stone or rock with a characteristic size, typically identified as the  $D_{50}$ . The applicable sizes for the guidance in this manual range from 0.6 in gravel up to 22 in riprap. The boundary between gravel, cobble, and riprap sizes will be defined by the following ranges:

- Gravel: 0.6 - 2.5 in
- Cobble: 2.5 - 5.0 in
- Riprap: 5.0 – 22.0 in

Other differences between gravels, cobbles, and riprap may include gradation and angularity.

Gravel mulch, although considered permanent, is generally used as a supplement to aid in the establishment of vegetation. It may be considered for areas where vegetation establishment is difficult, for example, in arid-region climates. For the transition period before the establishment of the vegetation, the stability of gravel mulch should be assessed as described below.

The procedures described are applicable to uniform prismatic channels with rock sizes within the range given above.

### Manning's Roughness

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,  $D_{50}$ ,  $D_{84}$ , and friction slope,  $S_f$ .

A relationship for Manning's roughness coefficient,  $n$ , that is a function of the flow depth and the relative flow depth ( $d_a/D_{50}$ ) is shown in Equation 21.

$$n = (0.262 d_a^{1/6}) / (2.25 + 5.23 \log (d_a/D_{50})) \quad \text{Equation 21}$$

where,

$n$  = Manning's roughness coefficient, dimensionless

$d_a$  = average flow depth in the channel, ft

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

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. Iterative processes are available to estimate  $n$  values in these conditions.

## 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 presented here are judged to be conservative and appropriate for design use. Permissible shear stress is given by Equation 22:

$$\tau_p = F^* (\gamma_s - \gamma) D_{50} \quad \text{Equation 22}$$

where:

$\tau_p$  = permissible shear stress, lb/ft<sup>2</sup>  
 $F^*$  = Shield's parameter, dimensionless  
 $\gamma_s$  = specific unit weight of the stone, lb/ft<sup>3</sup>  
 $\gamma$  = specific weight of water, 62.4 lb/ft<sup>3</sup>  
 $D_{50}$  = mean riprap size, ft

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

Using Equation 6 and Equation 3:

$$\tau_p \geq SF \tau_d \quad \text{Equation 6}$$

$$\tau_d = \gamma d S_o \quad \text{Equation 3}$$

Equation 22 can be rewritten as Equation 23:

$$D_{50} \geq (SF * d * S_o) / (F^* (SG - 1)) \quad \text{Equation 23}$$

where,

$d$  = maximum channel depth, ft  
 $SG$  = specific gravity of rock, dimensionless

Changing the inequality sign to an equality gives the minimum stable riprap size for the channel bottom.

Equation 23 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. This variation is usually linked to particle Reynolds number defined by Equation 24.

$$Re = (V^* D_{50}) / \nu \quad \text{Equation 24}$$

where,

$Re$  = particle Reynolds number, dimensionless  
 $V^*$  = shear velocity, ft/sec  
 $\nu$  = kinematic viscosity (1.217 x 10<sup>-5</sup> ft<sup>2</sup>/sec at 60 degrees F)

Shear velocity is defined as:

$$V^* = (g d S)^{0.5} \quad \text{Equation 25}$$

where,

$g$  = gravitational acceleration, 32.2 ft/sec<sup>2</sup>

$d$  = maximum channel depth, ft

$S$  = channel slope, ft/ft

Higher Reynolds number correlates with a higher Shields parameter as is shown in Table 12. For many roadside channel applications, Reynolds number is less than  $4 \times 10^4$  and a Shields parameter of 0.047 should be used in Equations 22 and 23. In cases for a Reynolds number greater than  $2 \times 10^5$ , 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 12. Selection of Shields' Parameter and Safety Factor

| Reynolds Number                      | $F^*$                | SF                   |
|--------------------------------------|----------------------|----------------------|
| $\leq 4 \times 10^4$                 | 0.047                | 1.0                  |
| $4 \times 10^4 < Re < 2 \times 10^5$ | 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 also increased with Reynolds number as shown in Table 12. Depending on site-specific conditions, the safety factor may be further increased by the designer but should not be decreased to values less than those in Table 12.

Riprap stability on a steep slope depends on forces acting on an individual stone making up the riprap. The primary forces include the average weight of the stones and the lift and drag forces induced by the flow on the stones. On a steep slope, the weight of a stone has a significant component in the direction of flow. 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 23 is recommended for slopes less than 5 percent. For slopes greater than 5 percent, other methods should be considered.

## Design Procedure

### Basic Design

The riprap and gravel lining design procedure 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. In this approach, the designer begins with a design discharge and calculates an acceptable  $D_{50}$  to line the channel bottom. An alternative analytical framework is to use the maximum discharge approach. For the maximum discharge approach, the designer selects the  $D_{50}$ , and determines the maximum depth and flow permitted in the channel while maintaining a stable lining. 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. Also, determine specific weight of proposed stone.

Step 3. Estimate the depth. For the first iteration, select a channel depth,  $d_i$ . For subsequent iterations, a new depth can be estimated based on the initial estimate.

Step 4. Estimate Manning's  $n$  and the implied discharge. First, calculate the relative depth ratio,  $d_a/D_{50}$ . Use this value to calculate the Manning's  $n$ . Calculate the discharge using Manning's equation.

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

Step 6. Calculate the particle Reynolds number and determine the appropriate Shields parameter and Safety Factor values, then calculate the required  $D_{50}$ .

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,  $D_{50}$ .

### Side Slopes

The shear stress on the channel side is less than the maximum shear stress occurring on the channel bottom. However, since gravel and riprap linings are noncohesive, as the angle of the side slope approaches the angle of repose of the channel lining, the lining material becomes less stable. The stability of a side slope lining is a function of the channel side slope and the angle of repose of the rock/gravel lining material. This essentially results in a lower permissible shear stress on the side slope than on the channel bottom.

Channels lined with gravel or riprap on side slopes steeper than 3 horizontal to 1 vertical may become unstable and should be avoided where feasible.

### **Additional Considerations**

As with all lining types, the ability to deliver the expected channel protection depends on the proper installation of the lining. Additional design considerations for riprap linings include freeboard; proper specification of gradation and thickness; and use of a filter material under the riprap.

### Freeboard and Slope Changes

Freeboard is determined based on the predicted water surface elevation in a channel. For channels on mild slopes the water surface elevation for freeboard considerations may be safely taken as the normal depth elevation. For steep slopes and for slope changes, additional consideration of freeboard is required.

For steep channels, freeboard should equal the mean depth of flow, since wave height will reach approximately twice the mean depth. This freeboard height should be used for both transitional and permanent channel installations. The extent of riprap on a steep

gradient channel must be sufficient to protect transitions from mild to steep and from steep to mild sections.

The transition from a steep gradient to a culvert should allow for slight movement of riprap. The top of the riprap layer should be placed flush with the invert of a culvert while the riprap layer thickness should equal three to five times the mean rock diameter at the break between the steep slope and culvert entrance. The transition from a steep gradient channel to a mild gradient channel may require an energy dissipation structure such as a plunge pool. The transition from a mild gradient to a steep gradient should be protected against local scour upstream of the transition for a distance of approximately five times the uniform depth of flow in the downstream channel.

### Riprap Gradation, Angularity, and Thickness

Riprap gradation should follow a smooth size distribution curve. Most riprap gradations will fall in the range of  $D_{100} / D_{50}$  and  $D_{50} / D_{20}$  between 3.0 to 1.5, which is acceptable. The most important criterion is a proper distribution of sizes in the gradation so that interstices formed by larger stones are filled with smaller sizes in an interlocking fashion, preventing the formation of open pockets. These gradation requirements apply regardless of the type of filter design used. More uniformly graded stone may distribute a higher failure threshold because it contains fewer smaller stones, but at the same time will likely exhibit a more sudden failure. Increasing the safety factor is appropriate when there are questions regarding gradation.

In general, riprap constructed with angular stones has the best performance. Round stones are acceptable as riprap provided they are not placed on side slopes steeper than 3;1 (H:V). Flat slab-like stones should be avoided since they are easily dislodged by the flow. An approximate guide to stone shape is that neither the breadth nor thickness of a single stone is less than one- third its length. The safety factor should be increased if round stones are used. Permissible shear stress estimates are largely based on testing with angular rock.

The thickness of a riprap lining should equal the diameter of the largest rock size in the gradation. For most gradations, this will mean a thickness from 1.5 to 3.0 times the mean riprap diameter. It is important to note that riprap thickness is measured normal to ground surface slope.

### Riprap Filter Design

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

To determine the need for a filter and, if one is required, to select a gradation for the filter blanket, the following criteria must be met. The subscripts "upper" and "lower" refer to the riprap and soil, respectively, when evaluating filter need; the subscripts represent the riprap/filter and filter/soil comparisons when selecting a filter blanket gradation. The relationships must hold between the filter blanket and base material and between the riprap and filter blanket.

$$D_{15 \text{ upper}} / D_{85 \text{ lower}} < 5$$

$$5 < (D_{15 \text{ upper}} / D_{15 \text{ lower}}) < 40$$

$$D_{50 \text{ upper}} / D_{50 \text{ lower}} < 40$$

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

In selecting an engineering filter fabric (geotextile), four properties should be considered:

- Soil retention (piping resistance)
- Permeability
- Clogging
- Survivability

Detailed design guidance for selecting geotextiles as a riprap filter material is shown in Table 13. These guidelines should be applied in situations where problematic soil environments exist, severe environmental conditions are expected, and/or for critical installations. Problematic soils include unstable or highly erodible soils such as non-cohesive silts; gap graded soils; alternating sand/silt laminated soils; dispersive clays; and/or rock flour. Severe environmental conditions include wave action or high velocity conditions. An installation would be considered critical where loss of life or significant structural damage could be associated with failure.

With the exception of problematic soils or high velocity conditions associated with steep channels and rundowns, geotextile filters for roadside applications may usually be selected based on the apparent opening size (AOS) of the geotextile and the soil type as shown in Table 13.

Table 13. Maximum AOS for Geotextile Filters

| Soil Type                                                            | Maximum AOS (mm) |
|----------------------------------------------------------------------|------------------|
| Non cohesive, less than 15 percent passing the 0.075 mm (#200) sieve | 0.43             |
| Non cohesive, 15 to 50 percent passing the 0.075 mm (#200) sieve     | 0.25             |
| Non cohesive, more than 50 percent passing the 0.075 mm (#200) sieve | 0.22             |
| Cohesive, plasticity index greater than 7                            | 0.30             |

## GABION LINING DESIGN

Gabions (rock filled wire containers) represent an approach for using smaller rock size than would be required by riprap. The smaller rock is enclosed in larger wire units in the form of mattresses or baskets. Gabion baskets are individual rectangular wire mesh containers filled with rock and frequently applied for grade control structures and retaining walls (see Figure 16). Gabion mattresses are also rock filled wire mesh containers. The mattresses are composed of a series of integrated cells that hold the rock allowing for a greater spatial extent in each unit. Potential roadside applications for the gabion mattress include steep channels and rundowns.



Figure 16 – Gabion Baskets (Courtesy of R.H. Moore & Associates)

The thickness of the gabion mattress may be less than the thickness of an equivalently stable riprap lining. Therefore, gabion mattresses represent a trade-off between less and smaller rock versus the costs of providing and installing the wire enclosures. Gabion mattresses are rarely cost effective on mildly sloped channels.

### **Manning's Roughness**

Roughness characteristics of gabion mattresses are governed by the size of the rock in the baskets and the wire mesh enclosing the rock. For practical purposes, the effect of the mesh can be neglected. Therefore, Manning's roughness should be determined using the  $D_{50}$  of the basket rock as applied to the relationships provided for riprap and gravel linings.

### **Permissible Shear Stress**

Values for permissible shear stress for gabion mattresses are based on research conducted at laboratory facilities and in the field. However, reports from these studies are difficult to reconcile. One study reported permissible shear stresses in the range of 3 to 4 lb/ft<sup>2</sup> while another reported values approaching 35 lb/ft<sup>2</sup>. The first study tested mattresses ranging in depth from 6 to 18 in and on slopes of up to 2 percent. Since the objective of the second study to test embankment overtopping, this study evaluated 6 inch mattresses on 25 and 33 percent slopes.

The difference in reported permissible shear stresses may be partly due to the definition of failure. In the second study, failure was noted after rocks within the basket had shifted to the downstream end of the baskets and an undulating surface was formed leaving part of the embankment exposed. Although this may be an appropriate definition for a rare embankment-overtopping event, such failure is not appropriate for the more frequently occurring roadside design event. For this reason as well as to provide for conservative guidance, the results from the first study are recommended.

Permissible shear stress for gabions may be estimated based on the size of the rock fill or based on gabion mattress thickness. Both estimates are determined and the largest value is taken as the permissible shear stress.

Equation 26 provides a relationship for permissible shear stress based on rock fill size. This shear stress exceeds that of loose riprap because of the added stability provided by the wire mesh. The equation is valid for a range of  $D_{50}$  from 0.25 to 1.5 ft.

$$\tau_p = F^* (\gamma_s - \gamma) D_{50} \quad \text{Equation 26}$$

where,

$\tau_p$  = permissible shear stress, lb/ft<sup>2</sup>

$F^*$  = Shields' parameter, dimensionless

$D_{50}$  = median stone size, ft

In the tests from the first study noted above, the Shields' parameter for use in Equation 26 was found to be equal to 0.10.

A second equation provides for permissible shear stress based on mattress thickness. It is applicable for a range of mattress thickness from 0.5 to 1.5 ft.

$$\tau_p = 0.0091 (\gamma_s - \gamma) (MT + 4.07) \quad \text{Equation 27}$$

where,

MT = gabion mattress thickness, ft

The limits on Equations 26 and 27 are based on the range of laboratory data from which they are derived. Rock sizes within mattresses typically range from 0.25 to 0.5 ft rock in the 0.5 ft thick mattresses to 0.33 to 1 ft rock in the 1.5 ft thick mattresses.

The guidance found in Table 12 is applicable to gabions. Since the Shields parameter in Equation 26 is 0.10, the appropriate corresponding safety factor is 1.25. Alternatively, the designer may compute the particle Reynolds number and, using Table 12, determine both a Shields' parameter and SF corresponding to the Reynolds number.

## Design Procedure

The design procedure for gabions is as follows. It uses the same roughness relationships developed for riprap.

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

Step 2. Select a trial (initial) mattress thickness and fill rock  $D_{50}$ , perhaps based on available sizes for the project. (Also, determine specific weight of proposed stone.)

Step 3. Estimate the depth. For the first iteration, select a channel depth,  $d_i$ . For subsequent iterations, a new depth can be estimated based on the results from the first iteration.

Step 4. Calculate the relative depth ratio,  $d_a/D_{50}$ . Calculate the discharge using Manning's equation

Step 5. If the calculated discharge is within 5 percent of the design discharge, then proceed to step 6. If not, go back to step 3.

Step 6. Calculate the permissible shear stress from Equations 26 and 27 and take the largest as the permissible shear stress.

Use Equation 3 to determine the actual shear stress on the bottom of the channel.

Select a safety factor.

Apply Equation 6 to compare the actual to permissible shear stress.

Step 7. If permissible shear is greater than computed shear, the lining is stable. If not, repeat the design process beginning at step 2.

### **Additional Considerations**

As with riprap linings, the ability to deliver the expected channel protection depends on the proper installation of the lining. Additional design considerations for gabion linings include consideration of the wire mesh; freeboard; proper specification of gradation and thickness; and use of a filter material under the gabions.

The stability of gabions depends on the integrity of the wire mesh. In streams with high sediment concentrations or with rocks moving along the bed of the channel, the wire mesh may be abraded and eventually fail. Under these conditions the gabion will no longer behave as a single unit but rather as individual stones. Applications of gabion mattresses and baskets under these conditions should be avoided.

Extent of gabions on a steep gradient (the most common roadside application for gabions) must be sufficient to protect transition regions of the channel both above and below the steep gradient section. The transition from a steep gradient to a culvert should allow for slumping of a gabion mattress. The other challenge with gabions on a steep gradient is erosion of the material below the gabion. Because the gabion has substantial openings, water will flow within the gabion, not just on top of the gabion. The flow within the gabion has the potential to erode the substrate below the gabion, resulting in failure of the entire structure.

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

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

The rock gradation used in gabions mattress must be such that larger stones do not protrude outside the mattress and the wire mesh retains smaller stones.

When gabions are used, the need for an underlying filter material must be evaluated. The filter material may be either a granular filter blanket or geotextile fabric.

# Channel Erosion - Quiz

Updated: 11/17/2023

1. Which of the following is the most hydraulically efficient channel shape?
  - a. Trapezoid
  - b. Rectangle
  - c. Semi-circle
  - d. Triangle
2. Which of the following is not considered a flexible lining?
  - a. Partially grouted riprap
  - b. Wire enclosed riprap
  - c. Gravel mulch
  - d. Erosion control blankets
3. Which of the following is a potential cause of failure of rigid linings?
  - a. Undermining due to inadequate erosion protection at the outfall
  - b. High water table exerting an uplift pressure on the lining
  - c. Swelling soils that exert an uplift pressure on the lining
  - d. All of the above
4. Which of the following vegetative types would be best for a channel with long periods of submergence?
  - a. Upland vegetation
  - b. Wetland species
  - c. Either of the above
  - d. None of the above
5. Which of the following is not desirable for rock used for riprap?
  - a. Hard
  - b. Durable
  - c. Composed of shale
  - d. Angular in shape
6. Which of the following coatings can be used to increase the resistance to abrasion and corrosion for the wire used for gabions baskets?
  - a. Galvanized
  - b. Polymeric coating
  - c. Both of the above
  - d. Wires are only made with plain steel. No coatings are available.
7. Biodegradable materials are not acceptable in which of the following types of linings?
  - a. Transitional linings
  - b. Temporary linings
  - c. Permanent linings
  - d. They are acceptable for all lining types

8. What type of filter should be placed under gravel mulch?
  - a. Filter fabric
  - b. A sand filter
  - c. Either of the above
  - d. No filter needs to be placed under gravel mulch
9. How are the fibers of an erosion control blanket bound together?
  - a. Mechanically
  - b. Structurally
  - c. Chemically
  - d. Any of the above
10. What is a typical Manning's n value for an open-weave geotextile?
  - a. 0.013
  - b. 0.025
  - c. 0.035
  - d. 0.040
11. Which of the following is an appropriate definition of stability in a dynamic system?
  - a. There is no change in the channel bed
  - b. There is no change in the channel banks
  - c. The incoming supply of sediment equals the sediment transport rate
  - d. None of the above
12. The mean boundary shear stress is a function of which of the following?
  - a. The unit weight of water
  - b. The hydraulic radius of the channel
  - c. The average bottom slope
  - d. All of the above
13. The erodibility of soil is a function of which of the following?
  - a. Particle size
  - b. Cohesive strength
  - c. Soil density
  - d. All of the above
14. What is the recommended freeboard for steep gradient channels?
  - a. Zero
  - b. 0.5 ft
  - c. Equal to the flow depth
  - d. None of the above
15. For a trapezoidal channel with side slopes of 1.5 horizontal to 1 vertical, what is ratio of side shear stress to bottom shear stress?
  - a. 1.0
  - b. 0.85
  - c. 0.77
  - d. 0.54

16. At the beginning of a bend, where is the maximum shear stress?
- Near the outside of the bend
  - At the center of the bend
  - Near the inside of the bend
  - The shear stress is uniform through the cross-section
17. Grass linings can provide which of the following advantages?
- Good erosion protection
  - Trap sediment
  - Trap related contaminants
  - All of the above
18. How does increased shear stress impact the roughness coefficient for grass linings?
- The roughness coefficient decreases with increased shear stress
  - The roughness coefficient increases with increased shear stress
  - The roughness coefficient doesn't change with increased shear stress
  - There is no correlation between shear stress and roughness
19. What is the permissible shear stress for a fine-grained, cohesive soil with a PI greater than 20?
- 0.03 to 0.09 lb/ft<sup>2</sup>
  - 0.08 to 0.09 lb/ft<sup>2</sup>
  - 0.12 lb/ft<sup>2</sup>
  - 0.10 to 0.15 lb/ft<sup>2</sup>
20. How is the shear stress of an RECP lining determined?
- By the underlying soil properties
  - By the properties of the RECP
  - Both of the above
  - None of the above
21. Riprap, cobble and gravel linings are generally considered which of the following?
- Temporary flexible linings
  - Permanent flexible linings
  - Temporary rigid linings
  - Permanent rigid linings
22. The primary forces impacting riprap stability on a steep slope include which of the following?
- Average weight of the stone
  - Lift forces induced by the flow on the stones
  - Drag forces induces by the flow on the stones
  - All of the above
23. The stability of a gravel lining on a side slope is a function of which of the following?
- Channel side slope
  - Angle of repose of the rock/gravel lining material
  - Both of the above
  - None of the above

24. How does the required rock size for a gabion basket compare to the rock size required for riprap?
- a. The rock size for a gabion is smaller
  - b. The rock size for a gabion is larger
  - c. The rock size for a gabion is the same as riprap
  - d. None of the above
25. What is the recommended freeboard height for a gabion mattress?
- a. 1 foot
  - b. 2 feet
  - c. Half the mean depth of flow
  - d. Equal to the mean depth of flow