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) (1954) 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 (USDA, 1987). Grasses are classified into five broad categories, as shown in Table 4.1. 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.

Kouwen and Unny (1969) and Kouwen and Li (1981) developed a useful model of the biomechanics of vegetation in open-channel flow. This model provides a general approach for determining the roughness of vegetated channels compared to the retardance classification. The resulting resistance equation (see HEC-15 Appendix C.2) uses the same vegetation properties as the SCS retardance approach, but is more adaptable to the requirements of highway drainage channels. The design approach for grass-lined channels was developed from the Kouwen resistance equation.

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. Temple (SCS, 1954) developed a relationship between the total shear on the lining and the shear at the soil surface based on both processes.

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.

<table>
<thead>
<tr>
<th>Retardance Class</th>
<th>Cover ¹</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Weeping Love Grass</td>
<td>Excellent stand, tall, average 760 mm (30 in)</td>
</tr>
<tr>
<td></td>
<td>Yellow Bluestem Ischaemum</td>
<td>Excellent stand, tall, average 910 mm (36 in)</td>
</tr>
<tr>
<td></td>
<td>Kudzu</td>
<td>Very dense growth, uncut</td>
</tr>
<tr>
<td></td>
<td>Bermuda Grass</td>
<td>Good stand, tall, average 300 mm (12 in)</td>
</tr>
<tr>
<td></td>
<td>Native Grass Mixture (little bluestem, bluestem, blue gamma, and other long and short midwest grasses)</td>
<td>Good stand, unmowed</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Weeping lovegrass</td>
<td>Good stand, tall, average 610 mm (24 in)</td>
</tr>
<tr>
<td></td>
<td>Lespedeza sericea</td>
<td>Good stand, not woody, tall, average 480 mm (19 in)</td>
</tr>
<tr>
<td></td>
<td>Alfalfa</td>
<td>Good stand, uncut, average 280 mm (11 in)</td>
</tr>
<tr>
<td></td>
<td>Weeping lovegrass</td>
<td>Good stand, unmowed, average 330 mm (13 in)</td>
</tr>
<tr>
<td></td>
<td>Kudzu</td>
<td>Dense growth, uncut</td>
</tr>
<tr>
<td></td>
<td>Blue Gamma</td>
<td>Good stand, uncut, average 280 mm (11 in)</td>
</tr>
<tr>
<td>Covers classified have been tested in experimental channels. Covers were green and generally uniform.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 4.1 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 (product of elasticity and moment of inertia) of grass is
similar for a wide range of species (Kouwen, 1988) and is a basic property of grass linings.

Density is the number of grass stems in a given area, i.e., stems per m$^2$ (ft$^2$). A good grass lining will have about 2,000 to 4,000 stems/m$^2$ (200 to 400 stems/ft$^2$). A poor cover will have about one-third of that density and an excellent cover about five-thirds (USDA, 1987, Table 3.1). While grass density can be determined by physically counting stems, an easier direct method of estimating the density-stiffness property is provided in Appendix E of HEC-15.

For agricultural ditches, grass heights can reach 0.3 m (1.0 ft) to over 1.0 m (3.3 ft). However, near a roadway grass heights are kept much lower for safety reasons and are typically in the range of 0.075 m (0.25 ft) to 0.225 m (0.75 ft).

The density-stiffness property of grass is defined by the $C_s$ coefficient. $C_s$ can be directly measured using the Fall-Board test (Appendix E) or estimated based on the conditions of the grass cover using Table 4.2. Good cover would be the typical reference condition.

### Table 4.2. Density-stiffness Coefficient, $C_s$

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Excellent</th>
<th>Very Good</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_s$ (SI)</td>
<td>580</td>
<td>290</td>
<td>106</td>
<td>24</td>
<td>8.6</td>
</tr>
<tr>
<td>$C_s$ (CU)</td>
<td>49</td>
<td>25</td>
<td>9.0</td>
<td>2.0</td>
<td>0.73</td>
</tr>
</tbody>
</table>

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

$$C_n = \alpha \cdot C_s^{0.10} h^{0.528}$$  \hspace{1cm} (4.1)

where:

- $C_n$ = grass roughness coefficient
- $C_s$ = density-stiffness coefficient
- $h$ = stem height, m (ft)
- $\alpha$ = unit conversion constant, 0.35 (SI), 0.237 (CU)

Table 4.3 provides $C_n$ values for a range of cover and stem height conditions based on Equation 4.1. Denser cover and increased stem height result in increased channel roughness.

### Table 4.3. Grass Roughness Coefficient, $C_n$
SCS retardance values relate to a combination of grass stem-height and density. Cn 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 Cn 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 Cn = 0.20.

### Table 4.4 (SI). Grass Roughness Coefficient, Cn, for SCS Retardance Classes

<table>
<thead>
<tr>
<th>Retardance Class</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stem Height, mm</td>
<td>910</td>
<td>610</td>
<td>200</td>
<td>100</td>
<td>40</td>
</tr>
<tr>
<td>Cn</td>
<td>0.605</td>
<td>0.418</td>
<td>0.220</td>
<td>0.147</td>
<td>0.093</td>
</tr>
</tbody>
</table>

### Table 4.4 (CU). Grass Roughness Coefficient, Cn, for SCS Retardance Classes

<table>
<thead>
<tr>
<th>Retardance Class</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stem Height, in</td>
<td>36</td>
<td>24</td>
<td>8.0</td>
<td>4.0</td>
<td>1.6</td>
</tr>
<tr>
<td>Cn</td>
<td>0.605</td>
<td>0.418</td>
<td>0.220</td>
<td>0.147</td>
<td>0.093</td>
</tr>
</tbody>
</table>

### 4.2 MANNING’S ROUGHNESS

Manning’s roughness coefficient for grass linings varies depending on grass properties as reflected in the Cn 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.
\[ n = \alpha \cdot C_n \cdot \tau^{-0.4} \quad (4.2) \]

where,

| \( \tau_o \) | mean boundary shear stress, N/m\(^2\) (lb/ft\(^2\)) |
| \( \alpha \) | unit conversion constant, 1.0 (SI), 0.213 (CU) |

See Appendix C.2 for the derivation of Equation 4.2.

### 4.3 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.

#### 4.3.1 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. This process model (USDA, 1987) for the effective shear at the soil surface is given by the following equation.

\[ \tau_e = \tau_d \cdot (1 - C_r) \cdot (n_s/n)^2 \quad (4.3) \]

where,

| \( \tau_e \) | effective shear stress on the soil surface, N/m\(^2\) (lb/ft\(^2\)) |
| \( \tau_d \) | design shear stress, N/m\(^2\) (lb/ft\(^2\)) |
| \( C_r \) | grass cover factor |
| \( n_s \) | soil grain roughness |
| \( n \) | overall lining roughness |

Soil grain roughness is taken as 0.016 when \( D_{75} < 1.3 \text{ mm (0.05 in)} \). For larger grain soils, the soil grain roughness is given by:
\[ n_s = \alpha \cdot (D_{75})^{1/6} \quad (4.4) \]

where,

- \( n_s \) = soil grain roughness \((D_{75} < 1.3 \text{ mm (0.05 in)})\)
- \( D_{75} \) = soil size where 75\% of the material is finer, mm (in)
- \( \alpha \) = unit conversion constant, 0.015 (SI), 0.026 (CU)

Note that soil grain roughness value, \( n_s \), is less than the typical value reported in Table 2.1 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 4.3 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 4.5 provides a reasonable approach to estimating a cover factor based on (USDA, 1987, Table 3.1). 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>
<thead>
<tr>
<th>Growth Form</th>
<th>Excellent</th>
<th>Very Good</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sod</td>
<td>0.98</td>
<td>0.95</td>
<td>0.90</td>
<td>0.84</td>
<td>0.75</td>
</tr>
<tr>
<td>Bunch</td>
<td>0.55</td>
<td>0.53</td>
<td>0.50</td>
<td>0.47</td>
<td>0.41</td>
</tr>
<tr>
<td>Mixed</td>
<td>0.82</td>
<td>0.79</td>
<td>0.75</td>
<td>0.70</td>
<td>0.62</td>
</tr>
</tbody>
</table>

4.3.2 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 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.

The following sections offer detailed methods for determination of soil 
permissible shear. However, the normal variation of permissible shear stress 
for different soils is moderate, particularly for fine-grained cohesive soils. 
An approximate method is also provided for cohesive soils.

4.3.2.1 Non-cohesive Soils

The permissible soil shear stress for fine-grained, non-cohesive soils \((D_{75} < 
1.3 \text{ mm (0.05 in)})\) is relatively constant and is conservatively estimated at 1.0 
\(\text{N/m}^2 (0.02 \text{ lb/ft}^2)\). For coarse grained, non-cohesive soils \((1.3 \text{ mm (0.05 in)} < 
D_{75} < 50 \text{ mm (2 in)})\) the following equation applies.

\[
\tau_{p,\text{soil}} = \alpha \cdot D_{75}
\]  

(4.5)

where,

| \(\tau_{p,\text{soil}}\) | permissible soil shear stress, \(\text{N/m}^2 (\text{lb/ft}^2)\) |
| \(D_{75}\) | soil size where 75% of the material is finer, \(\text{mm (in)}\) |
| \(\alpha\) | unit conversion constant, 0.75 (SI), 0.4 (CU) |

4.3.2.2 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 
\((e)\). The basic formula for permissible shear on cohesive soils is the 
following.

\[
\tau_{p,\text{soil}} = (c_1 \cdot \text{PI}^2 + c_2 \cdot \text{PI} + c_3) \cdot (c_4 + c_5 \cdot e)^2 \cdot c_6
\]  

(4.6)

where,

| \(\tau_{p,\text{soil}}\) | soil permissible shear stress, \(\text{N/m}^2 (\text{lb/ft}^2)\) |
| \(\text{PI}\) | plasticity index |
| \(e\) | void ratio |
A simplified approach for estimating permissible soil shear stress based on Equation 4.6 is illustrated in Figure 4.1. 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.

Higher soil unit weight increases the permissible shear stress and lower soil unit weight decreases permissible shear stress. Figure 4.1 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 1.6 ton/m$^3$ (100 lb/ft$^3$), for silts and lean clays (ML, CL) 1.4 ton/m$^3$ (90 lb/ft$^3$) and fat clays (CH, MH) 1.3 ton/m$^3$ (80 lb/ft$^3$).

<table>
<thead>
<tr>
<th>ASTM Soil Classification$^{(1)}$</th>
<th>Applicable Range</th>
<th>$c_1$</th>
<th>$c_2$</th>
<th>$c_3$</th>
<th>$c_4$</th>
<th>$c_5$</th>
<th>$c_6$ (SI)</th>
<th>$c_6$ (CU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GM</td>
<td>10 &lt; PI &lt; 20</td>
<td>1.07</td>
<td>14.3</td>
<td>47.7</td>
<td>1.42</td>
<td>-0.61</td>
<td>4.8×10^{-3}</td>
<td>10^{-4}</td>
</tr>
<tr>
<td></td>
<td>20 &lt; PI</td>
<td>0.076</td>
<td>1.42</td>
<td>-0.61</td>
<td></td>
<td></td>
<td>48.</td>
<td>1.0</td>
</tr>
<tr>
<td>GC</td>
<td>10 &lt; PI &lt; 20</td>
<td>0.0477</td>
<td>2.86</td>
<td>42.9</td>
<td>1.42</td>
<td>-0.61</td>
<td>4.8×10^{-2}</td>
<td>10^{-3}</td>
</tr>
<tr>
<td></td>
<td>20 &lt; PI</td>
<td>0.119</td>
<td>1.42</td>
<td>-0.61</td>
<td></td>
<td></td>
<td>48.</td>
<td>1.0</td>
</tr>
<tr>
<td>SM</td>
<td>10 &lt; PI &lt; 20</td>
<td>1.07</td>
<td>7.15</td>
<td>11.9</td>
<td>1.42</td>
<td>-0.61</td>
<td>4.8×10^{-3}</td>
<td>10^{-4}</td>
</tr>
<tr>
<td></td>
<td>20 &lt; PI</td>
<td>0.058</td>
<td>1.42</td>
<td>-0.61</td>
<td></td>
<td></td>
<td>48.</td>
<td>1.0</td>
</tr>
<tr>
<td>SC</td>
<td>10 &lt; PI &lt; 20</td>
<td>1.07</td>
<td>14.3</td>
<td>47.7</td>
<td>1.42</td>
<td>-0.61</td>
<td>4.8×10^{-3}</td>
<td>10^{-4}</td>
</tr>
<tr>
<td></td>
<td>20 &lt; PI</td>
<td>0.076</td>
<td>1.42</td>
<td>-0.61</td>
<td></td>
<td></td>
<td>48.</td>
<td>1.0</td>
</tr>
<tr>
<td>ML</td>
<td>10 &lt; PI &lt; 20</td>
<td>1.07</td>
<td>7.15</td>
<td>11.9</td>
<td>1.48</td>
<td>-0.57</td>
<td>4.8×10^{-3}</td>
<td>10^{-4}</td>
</tr>
<tr>
<td></td>
<td>20 &lt; PI</td>
<td>0.058</td>
<td>1.48</td>
<td>-0.57</td>
<td></td>
<td></td>
<td>48.</td>
<td>1.0</td>
</tr>
<tr>
<td>CL</td>
<td>10 &lt; PI &lt; 20</td>
<td>1.07</td>
<td>14.3</td>
<td>47.7</td>
<td>1.48</td>
<td>-0.57</td>
<td>4.8×10^{-3}</td>
<td>10^{-4}</td>
</tr>
<tr>
<td></td>
<td>20 &lt; PI</td>
<td>0.076</td>
<td>1.48</td>
<td>-0.57</td>
<td></td>
<td></td>
<td>48.</td>
<td>1.0</td>
</tr>
</tbody>
</table>

$^{(1)}$ Coefficients (Table 4.6)
### Table 4.1

<table>
<thead>
<tr>
<th></th>
<th>PI Range</th>
<th>( \tau_p )</th>
<th>( n )</th>
<th>( n_s )</th>
<th>( C_f )</th>
<th>( \sigma_{soil} )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MH</strong></td>
<td>10 &lt; PI &lt; 20</td>
<td>0.0477</td>
<td>1.43</td>
<td>10.7</td>
<td>-0.373</td>
<td>4.8x10^{-2}</td>
</tr>
<tr>
<td></td>
<td>20 &lt; PI</td>
<td>0.058</td>
<td>1.38</td>
<td>-0.373</td>
<td>48</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>CH</strong></td>
<td>20 &lt; PI</td>
<td>0.097</td>
<td>1.38</td>
<td>-0.373</td>
<td>48</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**Note:**

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

---

**Figure 4.1. Cohesive Soil Permissible Shear Stress**

### 4.3.3 Permissible Vegetation/Soil Shear Stress

The combined effects of the soil permissible shear stress and the effective shear stress transferred through the vegetative lining results in a permissible shear stress for the vegetative lining. Taking Equation 4.3 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 vegetative lining:

\[
\tau_p = \frac{\tau_{p,soil}}{1-C_f} \cdot \left(\frac{n}{n_s}\right)^2
\]  

(4.7)

where,

- \( \tau_p \) = permissible shear stress on the vegetative lining, N/m² (lb/ft²)
- \( \tau_{p,soil} \) = permissible soil shear stress, N/m² (lb/ft²)
Design Example: Grass Lining Design (SI)

Evaluate a grass lining for a roadside channel given the following channel shape, soil conditions, grade, and design flow. It is expected that the grass lining will be maintained in good conditions in the spring and summer months, which are the main storm seasons.

Given:

<table>
<thead>
<tr>
<th>Shape:</th>
<th>Trapezoidal, B = 0.9 m, Z = 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil:</td>
<td>Clayey sand (SC classification), PI = 16, e = 0.5</td>
</tr>
<tr>
<td>Grass:</td>
<td>Sod, height = 0.075 m</td>
</tr>
<tr>
<td>Grade:</td>
<td>3.0 percent</td>
</tr>
<tr>
<td>Flow:</td>
<td>0.5 m$^3$/s</td>
</tr>
</tbody>
</table>

Solution

The solution is accomplished using procedure given in Section 3.1 for a straight channel.

<table>
<thead>
<tr>
<th>Step 1.</th>
<th>Channel slope, shape, and discharge have been given.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 2.</td>
<td>A vegetative lining on a clayey sand soil will be evaluated.</td>
</tr>
<tr>
<td>Step 3.</td>
<td>Initial depth is estimated at 0.30 m</td>
</tr>
</tbody>
</table>

From the geometric relationship of a trapezoid (see Appendix B):

\[
A = B \cdot d + Z \cdot d^2 = 0.9 \cdot (0.3) + 3 \cdot (0.3)^2 = 0.540 \ m^2
\]

\[
P = B + 2 \cdot d \cdot \sqrt{Z^2 + 1} = 0.9 + 2 \cdot (0.3) \cdot \sqrt{3^2 + 1} = 2.80 \ m
\]

\[
R = \frac{A}{P} = \frac{(0.54)}{(2.8)} = 0.193 \ m
\]
Step 4. To estimate \( n \), the applied shear stress on the grass lining is given by Equation 2.3

\[
\tau_o = \gamma \cdot R \cdot S_o = 9810 \cdot (0.193) \cdot (0.03) = 56.8 \text{ N/m}^2
\]

Determine a Manning’s \( n \) value from Equation 4.2. From Table 4.3, \( C_n = 0.142 \)

\[
n = \alpha \cdot C_n \cdot \tau^{-0.4} = 1.0 \cdot (0.142) \cdot (56.8)^{-0.4} = 0.028
\]

The discharge is calculated using Manning’s equation (Equation 2.1): \( Q = \alpha/n \cdot A \cdot R^{2/3} \cdot S_f^{1/2} \)

\[
Q = 1/0.028 \cdot (0.540) \cdot (0.193)^{2/3} \cdot (0.03)^{1/2} = 1.12 \text{ m}^3/\text{s}
\]

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 (2nd iteration). Estimate a new depth solving Equation 2.2 or other appropriate method iteratively to find the next estimate for depth:

\[
d = 0.21 \text{ m}
\]

Revise the hydraulic radius.

\[
A = B \cdot d + Z \cdot d^2 = 0.9 \cdot (0.21) + 3 \cdot (0.21)^2 = 0.321 \text{ m}^2
\]

\[
P = B + 2 \cdot d \cdot \sqrt{Z^2 + 1} = 0.9 + 2 \cdot (0.21) \cdot \sqrt{3^2 + 1} = 2.23 \text{ m}
\]

\[
R = A/P = (0.321)/(2.23) = 0.144 \text{ m}
\]

Step 4 (2nd iteration). To estimate \( n \), the applied shear stress on the grass lining is given by Equation 2.3

\[
\tau_o = \gamma \cdot R \cdot S_o = 9810 \cdot (0.144) \cdot (0.03) = 42.4 \text{ N/m}^2
\]

Determine a Manning’s \( n \) value from Equation 4.2. From Table 4.3, \( C_n = 0.142 \)

\[
n = \alpha \cdot C_n \cdot \tau^{-0.4} = 1.0 \cdot (0.142) \cdot (42.4)^{-0.4} = 0.032
\]

The discharge is calculated using Manning’s equation (Equation 2.1): \( Q = \alpha/n \cdot A \cdot R^{2/3} \cdot S_f^{1/2} \)

\[
Q = 1/0.032 \cdot (0.321) \cdot (0.144)^{2/3} \cdot (0.03)^{1/2} = 0.48 \text{ m}^3/\text{s}
\]

Step 5 (2nd iteration). Since this value is within 5 percent of the design flow, we can proceed to step 6.
Step 6. The maximum shear on the channel bottom is:

\[ \tau_d = \gamma \cdot d \cdot S_o = 9810 \cdot (0.21) \cdot (0.03) = 61.8 \text{ N/m}^2 \]

Determine the permissible soil shear stress from Equation 4.6.

\[ \tau_{p,\text{soil}} = (c_1 \cdot PI^2 + c_2 \cdot PI + c_3) \cdot (c_4 + c_5 \cdot e)^2 \cdot c_6 = (1.07 \cdot (16)^2 + 14.3 \cdot (16) + 47.7) \cdot (1.42 - 0.61 \cdot (0.5))^2 \cdot (0.0048) = 3.28 \text{ N/m}^2 \]

Equation 4.7 gives the permissible shear stress on the vegetation. The value of \( C_r \) is found in Table 4.5.

\[ \tau_p = \frac{\tau_{p,\text{soil}}}{(1-C_r) \cdot (n/n_s)^2} = \frac{3.28}{(1 - 0.9) \cdot (0.032/0.016)^2} = 131 \text{ N/m}^2 \]

The safety factor for this channel is taken as 1.0.

Step 7. The grass lining is acceptable since the maximum shear on the vegetation is less than the permissible shear of 131 N/m².

**Design Example: Grass Lining Design (CU)**

Evaluate a grass lining for a roadside channel given the following channel shape, soil conditions, grade, and design flow. It is expected that the grass lining will be maintained in good conditions in the spring and summer months, which are the main storm seasons.

<table>
<thead>
<tr>
<th>Shape:</th>
<th>Trapezoidal, ( B = 3.0 \text{ ft}, Z = 3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil:</td>
<td>Clayey sand (SC classification), ( PI = 16, e = 0.5 )</td>
</tr>
<tr>
<td>Grass:</td>
<td>Sod, height = 0.25 ft</td>
</tr>
<tr>
<td>Grade:</td>
<td>3.0 percent</td>
</tr>
<tr>
<td>Flow:</td>
<td>17.5 ft³/s</td>
</tr>
</tbody>
</table>

**Solution**

The solution is accomplished using procedure given in Section 3.1 for a straight channel.

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

Step 2. A vegetative lining on a clayey sand soil will be evaluated.
**Step 3.** Initial depth is estimated at 1.0 ft

From the geometric relationship of a trapezoid (see Appendix B):

\[
A = B \cdot d + Z \cdot d^2 = 3.0 \cdot (1.0) + 3 \cdot (1.0)^2 = 6.00 \text{ ft}^2
\]

\[
P = B + 2 \cdot d \cdot \sqrt{Z^2 + 1} = 3.0 + 2 \cdot (1.0) \cdot \sqrt{3^2 + 1} = 9.32 \text{ ft}
\]

\[
R = \frac{A}{P} = \frac{6.00}{9.32} = 0.643 \text{ ft}
\]

**Step 4.** To estimate $n$, the applied shear stress on the grass lining is given by Equation 2.3

\[
\tau_o = \gamma \cdot R \cdot S_o = 62.4 \cdot (0.643) \cdot (0.03) = 1.20 \text{ lb/ft}^2
\]

Determine a Manning’s $n$ value from Equation 4.2. From Table 4.3, $C_n = 0.142$

\[
n = \alpha \cdot C_n \cdot \tau_o^{-0.4} = 0.213 \cdot (0.142) \cdot (1.20)^{-0.4} = 0.028
\]

The discharge is calculated using Manning’s equation (Equation 2.1):

\[
Q = \frac{\alpha}{n} \cdot A \cdot R^{2/3} \cdot S_f^{1/2} = 1.49 / 0.028 \cdot (6.00) \cdot (0.643)^{2/3} \cdot (0.03)^{1/2} = 41.2 \text{ ft}^3/\text{s}
\]

**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 (2nd iteration).** Estimate a new depth solving Equation 2.2 or other appropriate method iteratively to find the next estimate for depth:

\[
d = 0.70 \text{ ft}
\]

Revise the hydraulic radius.

\[
A = B \cdot d + Z \cdot d^2 = 3.0 \cdot (0.70) + 3 \cdot (0.70)^2 = 3.57 \text{ ft}^2
\]

\[
P = B + 2 \cdot d \cdot \sqrt{Z^2 + 1} = 3.0 + 2 \cdot (0.70) \cdot \sqrt{3^2 + 1} = 7.43 \text{ ft}
\]

\[
R = \frac{A}{P} = \frac{3.57}{(7.43)} = 0.481 \text{ ft}
\]

**Step 4 (2nd iteration).** To estimate $n$, the applied shear stress on the grass lining is given by Equation 2.3

\[
\tau_o = \gamma \cdot R \cdot S_o = 62.4 \cdot (0.481) \cdot (0.03) = 0.90 \text{ lb/ft}^2
\]

Determine a Manning’s $n$ value from Equation 4.2. From Table 4.3, $C_n = 0.142$
\[ n = \alpha \cdot C_n \cdot \tau^{-0.4} = 0.213 \cdot (0.142) \cdot (0.90)^{-0.4} = 0.032 \]

The discharge is calculated using Manning’s equation (Equation 2.1):

\[ Q = \frac{\alpha \cdot A \cdot R^{2/3} \cdot S_r^{1/2}}{n} = 1.49/0.032 \cdot 3.57 \cdot (0.481)^{2/3} \cdot (0.03)^{1/2} = 17.7 \text{ ft}^3/\text{s} \]

**Step 5** (2nd iteration). Since this value is within 5 percent of the design flow, we can proceed to Step 6.

**Step 6.** The maximum shear on the channel bottom is:

\[ \tau_d = \gamma \cdot d \cdot S_o = 62.4 \cdot (0.70) \cdot (0.03) = 1.31 \text{ lb/ft}^2 \]

Determine the permissible soil shear stress from Equation 4.6.

\[ \tau_{p,\text{soil}} = (c_1 \cdot P I^2 + c_2 \cdot P I + c_3) \cdot (c_4 + c_5 \cdot e)^2 \cdot c_6 = (1.07 \cdot (16)^2 + 14.3 \cdot (16) + 47.7)(1.42 - 0.61 \cdot (0.5))^2 \cdot (0.0001) = 0.068 \text{ lb/ft}^2 \]

Equation 4.7 gives the permissible shear stress on the vegetation. The value of \( C_f \) is found in Table 4.5.

\[ \tau_p = \frac{\tau_{p,\text{soil}}}{(1-C_f) \cdot (n/n_s)^2} = 0.068/(1 - 0.9) \cdot (0.032/0.016)^2 = 2.7 \text{ lb/ft}^2 \]

The safety factor for this channel is taken as 1.0.

**Step 7.** The grass lining is acceptable since the maximum shear on the vegetation is less than the permissible shear of 2.7 lb/ft\(^2\).

### 4.4 MAXIMUM DISCHARGE APPROACH

The maximum discharge for a vegetative lining is estimated following the basic steps outlined in Section 3.6. To accomplish this, it is necessary to develop a means of estimating the applied bottom shear stress that will yield the permissible effective shear stress on the soil. Substituting Equation 4.2 into Equation 4.3 and assuming the \( \tau_o = 0.75 \cdot \tau_d \) and solving for \( \tau_d \) yields:

\[ \tau_d = \left[ \alpha \cdot \tau_e/(1-C_f) \cdot (C_n/n_s)^2 \right]^{5/9} \quad (4.8) \]

where,

\[ \alpha = \text{unit conversion constant, } 1.26 \text{ (SI), } 0.057 \text{ (CU)} \]

The assumed relationship between \( \tau_o \) and \( \tau_d \) is not constant. Therefore, once the depth associated with maximum discharge has been found, a check should be
conducted to verify the assumption.

**Design Example: Maximum Discharge for a Grass Lining (SI)**

Determine the maximum discharge for a grass-lined channel given the following shape, soil conditions, and grade.

**Given:**

<table>
<thead>
<tr>
<th>Shape:</th>
<th>Trapezoidal, B = 0.9 m, z = 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil:</td>
<td>Silty sand (SC classification), PI = 5, D_{75} = 2 mm</td>
</tr>
<tr>
<td>Grade:</td>
<td>5.0 percent</td>
</tr>
</tbody>
</table>

**Solution**

The solution is accomplished using procedure given in Section 3.6 for a maximum discharge approach.

<table>
<thead>
<tr>
<th>Step 1.</th>
<th>The candidate lining is a sod forming grass in good condition with a stem height of 0.150 m.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 2.</td>
<td>Determine the maximum depth. For a grass lining this requires several steps. First, determine the permissible soil shear stress. From Equation 4.5:</td>
</tr>
<tr>
<td></td>
<td>[ \tau_p = \alpha \cdot D_{75} = 0.75 \cdot (2) = 1.5 \text{ N/m} ]</td>
</tr>
<tr>
<td></td>
<td>To estimate the shear, we will first need to use Equation 4.1 to estimate ( C_n ) with ( C_s ) taken from Table 4.2</td>
</tr>
<tr>
<td></td>
<td>[ C_n = \alpha \cdot C_s^{0.30} \cdot h^{0.528} = 0.35 \cdot (106)^{0.30} \cdot (0.150)^{0.528} = 0.205 ]</td>
</tr>
<tr>
<td></td>
<td>Next, estimate the maximum applied shear using Equation 4.8.</td>
</tr>
<tr>
<td></td>
<td>[ \tau_d = \left[ \alpha \cdot \tau_e / (1 - C_f) \cdot (C_{a} / n_s)^2 \right]^{5/9} = \left[ 1.26 \cdot (1.5) / (1 - 0.9) \cdot (0.205 / 0.016)^2 \right]^{5/9} = 87 \text{ N/m}^2 ]</td>
</tr>
<tr>
<td></td>
<td>Maximum depth from Equation 3.10 with a safety factor of 1.0 is:</td>
</tr>
<tr>
<td></td>
<td>[ d = \tau_d / ((SF) \cdot \gamma \cdot S_o) = 87 / ((1.0) \cdot 9800 \cdot (0.05)) = 0.18 \text{ m} ]</td>
</tr>
<tr>
<td>Step 3.</td>
<td>Determine the area and hydraulic radius corresponding to the allowable depth based on the channel geometry</td>
</tr>
<tr>
<td></td>
<td>[ A = B \cdot d + Z \cdot d^2 = 0.90 \cdot (0.18) + 3 \cdot (0.18)^2 = 0.259 \text{ m}^2 ]</td>
</tr>
<tr>
<td></td>
<td>[ P = B + 2 \cdot d \cdot \sqrt{(Z^2 + 1)} = 0.9 + 2 \cdot (0.18) \cdot \sqrt{(3^2 + 1)} = 2.04 \text{ m} ]</td>
</tr>
<tr>
<td>Step</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>1.</td>
<td>The candidate lining is a sod forming grass in good condition with a stem height of 0.5 ft.</td>
</tr>
<tr>
<td>2.</td>
<td>Determine the maximum depth. For a grass lining this requires several steps. First, determine the permissible soil shear stress. From Equation 4.5:</td>
</tr>
<tr>
<td>3.</td>
<td>Solve Manning’s equation to determine the maximum discharge for the channel.</td>
</tr>
<tr>
<td>4.</td>
<td>Estimate the Manning’s n value appropriate for the lining type from Equation 4.2, but first calculate the mean boundary shear.</td>
</tr>
<tr>
<td>5.</td>
<td>Design Example: Maximum Discharge for a Grass Lining (CU)</td>
</tr>
</tbody>
</table>
To estimate the shear, we will first need to use Equation 4.1 to estimate \( C_n \) with \( C_s \) taken from Table 4.2.

\[
C_n = \alpha \cdot C_s^{0.10} \cdot h^{0.528} = 0.237 \cdot (9.0)^{0.10} \cdot (0.5)^{0.528} = 0.205
\]

Next, estimate the maximum applied shear using Equation 4.8.

\[
\tau_d = \left[ \frac{\alpha \cdot \tau_e}{(1 - C_f) \cdot (C_s/n_s)^2} \right]^{5/9} = \left[ \frac{0.57 \cdot (0.032)/(1 - 0.9) \cdot (0.205/0.016)^2}{(0.016)^2} \right]^{5/9} = 1.84 \text{ lb/ft}^2
\]

Maximum depth from Equation 3.10 with a safety factor of 1.0 is:

\[
d = \frac{\tau_d}{((SF) \cdot \gamma \cdot S_o)} = 1.84/((1.0) \cdot 62.4 \cdot (0.05) = 0.59 \text{ ft}
\]

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

\[
A = B \cdot d + Z \cdot d^2 = 3.0 \cdot (0.59) + 3 \cdot (0.59)^2 = 2.81 \text{ ft}^2
\]

\[
P = B + 2 \cdot d \cdot \sqrt{(Z^2 + 1)} = 3.0 + 2 \cdot (0.59) \cdot \sqrt{(3^2 + 1)} = 6.73 \text{ ft}
\]

\[
R = \frac{A}{P} = \frac{2.81}{6.73} = 0.42 \text{ ft}
\]

Step 4. Estimate the Manning’s \( n \) value appropriate for the lining type from Equation 4.2, but first calculate the mean boundary shear.

\[
\tau_o = \gamma \cdot R \cdot S_o = 62.4 \cdot (0.42) \cdot (0.05) = 1.31 \text{ lb/ft}^2
\]

\[
n = \alpha \cdot C_n \cdot \tau_o^{-0.4} = 0.213 \cdot (0.205) \cdot (1.31)^{-0.4} = 0.039
\]

Step 5. Solve Manning’s equation to determine the maximum discharge for the channel.

\[
Q = \frac{\alpha \cdot n \cdot A \cdot R^{2/3} \cdot S^{1/2}}{1.49/0.039 \cdot (2.81) \cdot (0.42)^{2/3} \cdot (0.05)^{1/2}} = 13.5 \text{ ft}^3/\text{s}
\]

Since Equation 4.8 used in Step 2 is an approximate equation, check the effective shear stress using Equation 4.3.

\[
\tau_e = \tau_d \cdot (1 - C_f) \cdot (n_s/n)^2 = 1.84 \cdot (1 - 0.9) \cdot (0.016/0.039^2) = 0.031 \text{ lb/ft}^2
\]

Since this value is less than, but close to \( \tau_p \) for the soil 0.032 lb/ft\(^2\), the maximum discharge is 13.5 ft\(^3\)/s.

### 4.5 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 1.76 metric ton/m³ (1.5 ton/yd³). A uniform gradation is necessary to permit germination and growth of grass plants through the gravel layer. Table 4.7 provides two typical gravel gradations for use in erosion control.

Table 4.7. Gravel Gradation Table, Percentages Passing Nominal Size Designations

<table>
<thead>
<tr>
<th>Size</th>
<th>Very Coarse (D_{75} = 45 mm (1.75 in))</th>
<th>Coarse (D_{75} = 30 mm (1.2 in))</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.0 mm (2 in)</td>
<td>90 – 100</td>
<td></td>
</tr>
<tr>
<td>37.5 mm (1.5 in)</td>
<td>35 – 70</td>
<td>90 – 100</td>
</tr>
<tr>
<td>25.0 mm (1 in)</td>
<td>0 – 15</td>
<td>35 – 70</td>
</tr>
<tr>
<td>19.0 mm (0.75 in)</td>
<td>0 – 15</td>
<td></td>
</tr>
</tbody>
</table>

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 75 to 100 mm (3 to 4 inches). The application rate of gravel to the prepared soil layer that results in a 25 percent gravel mix is calculated as follows.

\[
I_{\text{gravel}} = \alpha \cdot \left(1 - i_{\text{gravel}}\right) / 3 \cdot T_s \cdot \gamma_{\text{gravel}}
\]  

(4.9)

where,

- \(I_{\text{gravel}}\) = gravel application rate, metric ton/m³ (ton/yd³)
- \(i_{\text{gravel}}\) = fraction of gravel (equal to or larger than gravel layer size) already in the soil
- \(T_s\) = thickness of the soil surface, m (ft)
- \(\gamma_{\text{gravel}}\) = unit weight of gravel, metric ton/m³ (ton/yd³)
The gravel application rates for fine-grained soils \((i_{\text{gravel}} = 0)\) are summarized in Table 4.8. If the soil already contains some coarse gravel, then the application rate can be reduced by \(1 - i_{\text{gravel}}\).

### Table 4.8. Gravel Application Rates for Fine Grain Soils

<table>
<thead>
<tr>
<th>Soil Preparation Depth</th>
<th>Application Rate, (i_{\text{gravel}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>75 mm (3 inches)</td>
<td>0.044 ton/m² (0.041 ton/yd²)</td>
</tr>
<tr>
<td>100 mm (4 inches)</td>
<td>0.058 ton/m² (0.056 ton/yd²)</td>
</tr>
</tbody>
</table>

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.

**Design Example: Turf Reinforcement with a Gravel/Soil Mixture (SI)**

Evaluate the following proposed lining design for a vegetated channel reinforced with a coarse gravel soil amendment. The gravel will be mixed into the soil to result in 25 percent gravel. Since there is no existing gravel in the soil, an application rate of 0.058 ton/m² is recommended (100 mm soil preparation depth). See Table 4.8.

**Given:**

<table>
<thead>
<tr>
<th>Shape:</th>
<th>Trapezoidal, (B = 0.9 \text{ m}, Z = 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil:</td>
<td>Silty sand (SC classification), PI = 5, (D_{75} = 2 \text{ mm})</td>
</tr>
<tr>
<td>Grass:</td>
<td>Sod, good condition, (h = 0.150 \text{ m})</td>
</tr>
<tr>
<td>Gravel:</td>
<td>(D_{75} = 25 \text{ mm})</td>
</tr>
<tr>
<td>Grade:</td>
<td>5.0 percent</td>
</tr>
<tr>
<td>Flow:</td>
<td>1.7 m³/s</td>
</tr>
</tbody>
</table>

**Solution**

The solution is accomplished using procedure given in Section 3.1 of HEC-15 for a straight channel.
Step 1. Channel slope, shape, and discharge have been given.

Step 2. Proposed lining is a vegetated channel with a gravel soil amendment.

Step 3. Initial depth is estimated at 0.30 m

From the geometric relationship of a trapezoid (see Appendix B):

\[ A = B \cdot d + Z \cdot d^2 = 0.9 \cdot (0.3) + 3 \cdot (0.3)^2 = 0.540 \text{ m}^2 \]

\[ P = B + 2 \cdot d \cdot \sqrt{Z^2 + 1} = 0.9 + 2 \cdot (0.3) \cdot \sqrt{3^2 + 1} = 2.80 \text{ m} \]

\[ R = \frac{A}{P} = (0.540 \text{ m}^2)/(2.80 \text{ m}) = 0.193 \text{ m} \]

Step 4. To estimate n, the applied shear stress on the grass lining is given by Equation 2.3

\[ \tau_o = \gamma \cdot R \cdot S_o = 9810 \cdot (0.193) \cdot (0.05) = 94.7 \text{ N/m}^2 \]

Determine a Manning’s n value from Equation 4.2. From Table 4.3, \( C_n = 0.205 \)

\[ n = \alpha \cdot C_n \cdot \tau^{-0.4} = 1 \cdot (0.205) \cdot (94.7)^{-0.4} = 0.033 \]

The discharge is calculated using Manning’s equation (Equation 2.1):

\[ Q = \frac{\alpha}{n} \cdot A \cdot R^{2/3} \cdot S_t^{1/2} = 1/(0.033) \cdot (0.540) \cdot (0.193)^{2/3} \cdot (0.05)^{1/2} = 1.22 \text{ m}^3/\text{s} \]

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 (2nd iteration). Estimate a new depth solving Equation 2.2 or other appropriate method iteratively to find the next estimate for depth:

\[ d = 0.35 \text{ m} \]

Revise hydraulic radius.

\[ A = B \cdot d + Z \cdot d^2 = 0.9 \cdot (0.35) + 3 \cdot (0.35)^2 = 0.682 \text{ m}^2 \]

\[ P = B + 2 \cdot d \cdot \sqrt{Z^2 + 1} = 0.9 + 2 \cdot (0.35) \cdot \sqrt{3^2 + 1} = 3.11 \text{ m} \]

\[ R = \frac{A}{P} = (0.682 \text{ m}^2)/(3.11 \text{ m}) = 0.219 \text{ m} \]

Step 4 (2nd iteration). To estimate n, the applied shear stress on the grass lining is given by Equation 2.3
Design Example: Turf Reinforcement with a Gravel/Soil Mixture (CU)

Evaluate the following proposed lining design for a vegetated channel reinforced with a coarse gravel soil amendment. The gravel will be mixed into the soil to result in 25 percent gravel. Since there is no gravel in the soil, an application rate of 0.056 ton/yd² is recommended (4 inch soil preparation depth). See Table 4.8.
Given:

<table>
<thead>
<tr>
<th>Shape:</th>
<th>Trapezoidal, B = 3 ft, Z = 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil:</td>
<td>Silty sand (SC classification), PI = 5, D75 = 0.08 in</td>
</tr>
<tr>
<td>Grass:</td>
<td>Sod, good condition, h = 0.5 in</td>
</tr>
<tr>
<td>Gravel:</td>
<td>D75 = 1.0 in</td>
</tr>
<tr>
<td>Grade:</td>
<td>5.0 percent</td>
</tr>
<tr>
<td>Flow:</td>
<td>60 ft³/s</td>
</tr>
</tbody>
</table>

Solution

The solution is accomplished using procedure given in Section 3.1 of HEC-15 for a straight channel.

<table>
<thead>
<tr>
<th>Step 1.</th>
<th>Channel slope, shape, and discharge have been given.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 2.</td>
<td>Proposed lining is a vegetated channel with a gravel soil amendment.</td>
</tr>
<tr>
<td>Step 3.</td>
<td>Initial depth is estimated at 1.0 ft</td>
</tr>
</tbody>
</table>

From the geometric relationship of a trapezoid (see Appendix B):

\[
A = B \cdot d + Z \cdot d^2 = 3.0 \cdot (1.0) + 3 \cdot (1.0^2) = 6.0 \text{ ft}^2
\]

\[
P = B + 2 \cdot d \cdot \sqrt{Z^2 + 1} = 3.0 + 2 \cdot (1.0) \cdot \sqrt{3^2 + 1} = 9.32 \text{ ft}
\]

\[
R = \frac{A}{P} = \frac{(6.0 \text{ ft}^2)}{(9.32 \text{ ft})} = 0.644 \text{ ft}
\]

<table>
<thead>
<tr>
<th>Step 4.</th>
<th>To estimate n, the applied shear stress on the grass lining is given by Equation 2.3</th>
</tr>
</thead>
</table>

\[
\tau_o = \gamma \cdot R \cdot S_o = 62.4 \cdot (0.644) \cdot (0.05) = 2.01 \text{ lb/ft}^2
\]

Determine a Manning’s n value from Equation 4.2. From Table 4.3, \(C_n = 0.205\)

\[
n = \alpha \cdot C_n \cdot \tau^{-0.4} = 0.213 \cdot (0.205) \cdot (2.01)^{-0.4} = 0.033
\]

The discharge is calculated using Manning’s equation (Equation 2.1):
\[ Q = \frac{\alpha}{n} A R^{2/3} S_f^{1/2} = \frac{1.49}{0.033} \cdot (6.0) \cdot (0.644)^{2/3} \cdot (0.05)^{1/2} = 45.2 \text{ ft}^3/\text{s} \]

**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\(^{nd}\) iteration). Estimate a new depth solving Equation 2.2 or other appropriate method iteratively to find the next estimate for depth:

\[ d = 1.13 \text{ ft} \]

Revise hydraulic radius.

\[ A = B \cdot d + Z \cdot d^2 = 3.0 \cdot (1.13) + 3 \cdot (1.13)^2 = 7.22 \text{ ft}^2 \]

\[ P = B + 2 \cdot d \cdot \sqrt{(Z^2 + 1)} = 3.0 + 2 \cdot (1.13) \cdot \sqrt{(3^2 + 1)} = 10.1 \text{ ft} \]

\[ R = \frac{A}{P} = \frac{(7.22 \text{ ft}^2)}{(10.1 \text{ ft})} = 0.715 \text{ ft} \]

**Step 4** (2\(^{nd}\) iteration). To estimate \( n \), the applied shear stress on the grass lining is given by Equation 2.3

\[ \tau_o = \gamma \cdot R \cdot S_o = 62.4 \cdot (0.715) \cdot (0.05) = 2.23 \text{ lb/ft}^2 \]

Determine a Manning’s \( n \) value for the vegetation from Equation 4.2. From Table 4.3, \( C_n = 0.205 \)

\[ n = \alpha \cdot C_n \cdot \tau^{-0.4} = 1.0 \cdot (0.205) \cdot (107)^{-0.4} = 0.032 \]

The discharge is calculated using Manning’s equation (Equation 2.1):

\[ Q = \frac{\alpha}{n} A R^{2/3} S_f^{1/2} = \frac{1.49}{0.032} \cdot (7.22) \cdot (0.715)^{2/3} \cdot (0.05)^{1/2} = 60.1 \text{ m}^3/\text{s} \]

**Step 5** (2\(^{nd}\) iteration). Since this value is within 5 percent of the design flow, we can proceed to Step 6.

**Step 6.**

The maximum shear on the channel bottom is:

\[ \tau_d = \gamma \cdot d \cdot S_o = 62.4 \cdot (1.13) \cdot (0.05) = 3.53 \text{ lb/ft}^2 \]

Determine the permissible shear stress from Equation 4.4. For turf reinforcement with gravel/soil the \( D_{75} \) for the gravel is used instead of the \( D_{75} \) for the soil.

\[ \tau_{p,soil} = \alpha \cdot D_{75} = 0.4 \cdot (1.0) = 0.4 \text{ lb/ft}^2 \]
A Manning’s $n$ for the soil/gravel mixture is derived from Equation 4.4:

$$n_s = \alpha \cdot D_{75}^{1/6} = 0.026 \cdot (1.0)^{1/6} = 0.026$$

Equation 4.7 gives the permissible shear stress on the vegetation. The value of $C_r$ is found in Table 4.5.

$$\tau_p = \tau_{p,\text{soil}}/(1 - C_r) \cdot (n/n_s)^2 = 0.4/(1 - 0.9) \cdot (0.032/0.026)^2 = 6.06 \text{ lb/ft}^2$$

The safety factor for this channel is taken as 1.0.

**Step 7.** The grass lining reinforced with the gravel/soil mixture is acceptable since the permissible shear is greater than the maximum shear.