1. **REINFORCED SLOPE DESIGN REQUIREMENTS** – Except as indicated otherwise in these provisions, use Federal Highway Administration Publication No. FHWA NHI-00-043, titled “Mechanically Stabilized Earth Walls and Reinforced Soil Slopes”, as a reference document for design requirements and procedures.

Minimum factors of safety are required for both the short-term and long-term conditions, and for all failure modes.

Failure modes of reinforced slopes include:
1. Internal, where the failure plane passes through the reinforced fill;
2. External, where the failure surface passes behind and underneath the reinforced fill; and the reinforced fill foundation
3. Compound, where the failure surface passes through the reinforced fill, behind the reinforced fill, and/or the below reinforced fill foundation.

Use PASTABLE to determine slope stability for all failure modes. **When using this PCSTABLE based program, note the necessary adjustment in application of slope stability factor of safety as indicated in Chapter 6.3.d of Publication FHWA NHI-00-043, when determining the required reinforcement tensile strength.**

Design requirements outlined in these provisions require that the slope will be constructed on a stable foundation. Foundation bearing capacity for the proposed reinforced slope must be verified. If the allowable bearing capacity is insufficient for the proposed slope, then the slope must be redesigned, or the foundation treated, to remain within maximum allowable bearing pressures. Treatment and/or removal and replacement of foundation materials is an option to increase the bearing capacity of the foundation. Compute allowable bearing capacities using a minimum factor of safety of 3.0.

Foundation settlements must also be evaluated relative to their impact on:
1. the reinforced fill
2. facilities constructed within or on the reinforced fill (drainage, pavement structure, etc.)

1.1 **Establish the geometric, load, and performance requirements for design** (Figure 1.1).

1.1.(a) Geometric and load requirements.

1. Slope height, H. (ft)
2. Slope angle, $\beta$.  

1
3. External (surcharge) loads:

- Surcharge load, \( q \) (0.36 ksf)
- Temporary live load, \( \Delta q \) (if applicable)

Figure 1.1 Geometric and loading requirements for geosynthetic reinforced slope

1.1.(b) Performance requirements (see Table A).

1. External stability, \( (F_{\text{ext}}) \)

- Horizontal sliding of the reinforced mass along its base.
- External, deep-seated failures (for failure surfaces passing behind and beneath the reinforced fill).

2. Compound failure modes (\( F_{\text{com}} \) - for failure surfaces passing behind and then through and/or beneath the reinforced mass).

- Compound failure surfaces.

3. Internal stability. \( (F_{\text{int}}) \) - for failure surfaces passing entirely within the reinforced mass; does not include pullout)

- Internal failure surfaces.
**TABLE A**

Minimum Slope Stability Factors of Safety (FS<sub>min</sub>)*

<table>
<thead>
<tr>
<th>Stability Mode</th>
<th>Controlling Soil Type**</th>
<th>Slopes 1:1 and flatter</th>
<th>Slopes steeper than 1:1</th>
</tr>
</thead>
<tbody>
<tr>
<td>External (FS&lt;sub&gt;ext&lt;/sub&gt;)</td>
<td>Horizontal Sliding</td>
<td>Coarse grained</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fine grained</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>Deep</td>
<td></td>
<td>1.3</td>
</tr>
<tr>
<td>Compound (FS&lt;sub&gt;com&lt;/sub&gt;)</td>
<td></td>
<td></td>
<td>1.3</td>
</tr>
<tr>
<td>Internal (FS&lt;sub&gt;int&lt;/sub&gt;)</td>
<td></td>
<td></td>
<td>1.3</td>
</tr>
</tbody>
</table>

* Determine soil strength parameters based upon laboratory shear strength testing of actual materials to be used in reinforced slope construction (including reinforced fill, foundation material, and random material behind the reinforced fill).

** See Section 1.5(a) of these provisions

1.2 Foundation Material. All foundation information, including subsurface profile, shear strength parameters, unit weight and settlement calculations, are provided as part of the recommendations from the project Geotechnical Engineering Report. This information, and copies of lab results, shall be included in the design submission for verification.

1.3 Retained Fill. All information concerning random material, including subsurface profile, shear strength parameters, unit weight and settlement calculations if applicable, are provided as part of the recommendations from the project Geotechnical Engineering Report. This information, and copies of lab results, shall be included in the design submission for verification.

1.4 Required Properties of Reinforced Fill.

1.4.(a) Pub 408, Section 206.2(a)1.a and 1.b and as follows:

Gradation: 100 percent passing 2 inch sieve.

Unit Weights: Dry unit weight for compaction control and moist and saturated (where applicable) unit weights for analyses, shall be determined for the fill material.

1.4.(b) Unless provided, determine required reinforced fill shear strength parameters. Use peak shear strength parameters in analyses. Determine shear strength parameters from laboratory shear strength testing of the material to be used. Determine parameters using direct shear or consolidated-drained (CD) triaxial tests. In situations where the material to be used is not known or specified, provide a matrix of soils shear strength versus required slope reinforcement ultimate tensile strength(s) and required length(s). Provide a range of soil shear strengths consistent with local on-site or borrow materials.

1.4.(c) Chemical composition. Provide material with a pH $\geq 3$, when using polypropylene (PP) or high density polyethylene (HDPE) geosynthetics. Provide material with a pH between 3 and 9, when using polyester (PET) geosynthetics.
**1.5 Design Parameters.** As indicated in Table B.

1.5.(a) Pullout Resistance ($F_{S_{po}}$):

\[
F_{S_{min}} = 1.5 \text{ for granular fills,}
\]

and  \[
F_{S_{min}} = 2.0 \text{ for fine grained fills. (≥ 35 % passing #200 sieve)}
\]

Minimum geosynthetic embedment length ($L_e$) is seven feet (7 ft).

<table>
<thead>
<tr>
<th>Design Parameter</th>
<th>Test Method</th>
<th>Minimum Required Factor of Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Grid</td>
<td>Fabric</td>
</tr>
<tr>
<td>Pullout</td>
<td>GRI:GG5</td>
<td>GRI:GT6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5 (^b)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.0 (^c)</td>
</tr>
<tr>
<td>External Stability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Sliding</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>- Deep Seated</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>- Compound</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Internal Stability</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

\(^a\) Values indicated represent minimum requirements; higher values may be necessary to satisfy all design and construction requirements

\(^b\) Valid for granular fills (see Section 1.5.(a))

\(^c\) Valid for fine-grained fills (see Section 1.5.(a))

\(^d\) See Table A, Section 1.1(b)

**1.6 Slope Stability (Unreinforced Condition).** For each design section, determine the unreinforced stability using the slope stability computer program, PASTABLE. Use both circular arc and sliding wedge methods, considering failures through the toe and face of the slope, and deep seated failures below the toe.

Determine size of zone to be reinforced by examining the full range of potential failure surfaces. The level of geosynthetic required for stabilization will be controlled by the failure surface yielding the highest driving moment – not necessarily the lowest factor of safety. Surfaces just meeting the target factor of safety define the zone to be reinforced. Failure surfaces with safety factors less than target values specified in Table A, extending below the toe of the slope, indicate deep foundation and edge bearing capacity problems that must be addressed as part of the design.

**1.7 Internal Stability.** Assume the orientation of the geosynthetic tensile force is in the plane of the geosynthetic (i.e. horizontal).
1.7.(a) Calculate the total geosynthetic tensile force, $T_s$, necessary to obtain the required factor of safety, or resist the controlling driving moment, $M_d$, for each potential failure circle inside the geosynthetic zone as specified in Section 1.6, that extends through or below the toe of the slope (see Figure 1.2). Use the following equation:

$$T_s = (FS_r - FS_u) \times \frac{M_d}{D}$$

where:

*T $T_s$ = sum of required tensile force per unit width of geosynthetic (considering rupture and pullout) in all geosynthetic layers intersecting the failure surface, (k/ft);

$M_d$ = driving moment about the center of the failure circle, (kip-ft);

$D$ = the moment arm of $T_s$ about the center of failure circle, (assume $T_s$ acts horizontally), (ft);

$FS_r$ = target minimum slope safety factor, (dimensionless) - Section 1.1.(b);

$FS_u$ = unreinforced slope safety factor, (dimensionless).

*The largest $T_s$ calculated establishes the required design tension, $T_{max}$.

1.7.(b) Geosynthetic vertical spacing, $S_v$ (see Figure 1.2).

The maximum vertical spacing for primary geosynthetic ($S_{vp}$) is 1.5 ft. Provide an additional layer of primary reinforcement at subgrade elevation, when the subgrade elevation is greater than or equal to nine inches above the previous layer of primary reinforcement. The maximum vertical spacing for secondary geosynthetic ($S_{vs}$) is 0.5 ft.

1.7.(c) Required geosynthetic embedment lengths. Minimum embedment length, $L_e$, is seven feet (7 ft). For cohesive soils, determine $L_e$ for both short- and long-term pullout conditions. For long-term design, use $\phi'_c$ with $c_r = 0$. For short-term evaluation, use $\phi_r$ from consolidated-undrained tests and $c_r = 0$, or run pullout tests.

1.7.(d) Length of Primary Geosynthetic. Determine minimum length of the primary geosynthetic by the maximum length of the zone specified in Section 1.6, Unreinforced Stability, and the required embedment as specified in Section 1.7.(c). Minimum length indicated shall envelope the limits of the failure zone meeting the target factor of safety, plus the required embedment length. This length shall be used as the required primary geosynthetic length, for the full height of the zone.

1.7.(e) Secondary Geosynthetic/Compaction Aid. Section 735, Class 4, Type A. Minimum length of secondary reinforcement is 7 feet.
1.8. **External Stability.** External stability of a reinforced soil mass depends on the soil mass’s ability to act as a stable block and withstand all external loads without failure. Determine external stability including the following failure possibilities: sliding, deep-seated overall instability, local bearing capacity failure at the toe, and compound failures following internal and external paths. Determine external stability for both short- and long-term conditions.

1.8.(a) Sliding resistance. Determine the sliding resistance of the reinforced mass for all zones as follows:

\[
\frac{F_{SS}}{P_a} = \frac{\text{Resisting Force}}{\text{Sliding Force}} = \frac{W \tan \phi_{sg}}{P_a}
\]

with:

- \( W = \frac{1}{2} L^2 \gamma \tan \beta \) for \( L \tan \beta \leq H \)
- \( W = (LH - H^2/(2\tan \beta)) \gamma \) for \( L \tan \beta > H \)
where:  
\[ W = \text{weight of reinforced mass in and above zone (kips)}; \]
\[ L = \text{length of bottom reinforcing layer in each zone where there is a geosynthetic length change (ft)}; \]
\[ H = \text{height of slope including zones above (ft)}; \]
\[ F_{SS} = \text{factor of safety for sliding (\( \geq 1.5 \))}; \]
\[ P_a = \text{active earth pressure including zones above (ksf)}; \]
\[ \phi_{sg} = \text{soil-geosynthetic direct shear resistance (determined in accordance with ASTM D5321 - Interface Friction Determination by Direct Shear Testing), OR geosynthetic to geosynthetic direct shear resistance where applicable} \]
\[ \beta = \text{slope angle}; \]
\[ \gamma = \text{unit weight of backfill (k/ft}^3)\];

Figure 1.3 Determination of required geosynthetic strength

1. Using PASTABLE, locate the most critical surface through the toe of the slope, and determine \( M_R \)

\[
FS_u = \frac{M_R}{M_D} = \frac{\tau_f L_f R}{(w x + q d)}
\]

where:
- \( FS_u \) = unreinforced factor of safety
- \( M_R \) = resisting moment
- \( M_D \) = driving moment
- \( \tau_f \) = shear strength of soil \( (c = 0) \)
- \( L_f \) = length of failure surface
- \( R \) = radius of slip circle (failure plain)
- \( w \) = weight of soil above failure surface
- \( x \) = moment arm for driving moment due to weight of soil \( (w) \)
- \( q \) = surcharge load (if present – uniform or concentrated)
- \( d \) = moment arm for driving moment due to surcharge load \( (q) \)
- \( y \) = moment arm for resisting moment of total required geosynthetic tensile force \( (T) \)

2. After determining the critical failure surface and corresponding factor of safety, calculate \( M_R \) as follows:

\[ M_R = FS_u (w x + q d) \]

3. Determine the total required tensile strength, \( T \)

\[
T = \frac{FS_r M_D - M_R}{y} = \frac{FS_r M_D - FS_u M_D}{y} = \frac{(FS_r - FS_u) M_D}{y}
\]

where:
- \( FS_r \) = required factor of safety

4. Required strength of geosynthetic, \( T_d \)

\[
T_d = T \times S_v / H
\]

where:
- \( S_v \) = vertical spacing of primary geosynthetic
- \( H \) = total height of reinforced slope