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Module - 7
LECTURE - 37
Geosynthetics for steep slopes
Recap of previous lecture…..

- Introduction
- Limit equilibrium design methods for circular arc slope analysis
  - Cohesive soil \((c, \phi = 0)\)
  - Cohesion less soil \((\phi, c = 0)\)
  - \((c - \phi)\) soil
- Construction of reinforced soil slope
Example:
The resisting and driving moment of a failed slope are 1960 kN/m and 2360 kN/m respectively.
The ultimate strength of geogrid = 70 kN/m,
Reduction factor = 10,
The average moment arm = 12, and
Global factor of safety = 1.3
Calculate factor of safety without reinforcement and number of required layers of reinforcement to make the slope stable.

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Step 1: Determination of the factor of safety

\[ FS = \frac{M_R}{M_D} \]

Hence, \( FS = \frac{1960}{2360} = 0.83 \) (Not ok.)

Step 2: Allowable tensile strength of the geogrid

\[ T_{allow} = \frac{T_{ult}}{RF} \]

Hence, \( T_{allow} = \frac{70}{10} = 7 \text{ kN/m} \)
Step 3: Calculation of number of layers

\[
FS = \frac{MR + (n)(T_{allow})(Y_{avg})}{MD}
\]

\[Y_{avg} = \text{The average moment arm of reinforcement} = 12 \text{ m}\]

Given, global factor of safety = 1.3

\[1.3 = \frac{1960 + (n)(7)(12)}{2360}\]

\[n = 13.19 \approx 14\]

Take number of layer of reinforcements = 14 layers.
Example:

Height of the slope = 9 m; Slope angle = 55°; Properties of the foundation soil and the embankment are given in the figure below.
a) Calculate factor of safety without geogrid.

b) Calculate factor of safety with geogrid (Allowable tensile strength of geogrid = 54 kN/m)

c) Also calculate the factor of safety with 12 layers of geogrids at the interval of 0.75 m.

d) Determine the anchorage length behind the potential slip circle.

\[ C_i = 0.85, \quad FS = 1.5, \]
\[ \tau = \text{Mobilized shear strength} = 20 \text{ kN/m}^2, \]
\[ T_{\text{allow}} = 54 \text{ kN/m} \]
Solution:

Step 1: Determination of area

Draw the diagram in a graph paper

area of each small square = 2.25 m²

area of embankment portion (pqsrp) = 63 m²

area of foundation portion (rstur) = 59 m²

(In proper scale)
Step 2: Determination of weight of failure zone and arc length

Weight of the portion ‘pqsr’ \((W_e)\)

\[ W_e = \text{Area} \times \text{unit weight of embankment soil} \]
\[ = 63 \times 20 = 1260 \text{ kN/m} \]

Weight of the portion ‘rstu’ \((W_f)\)

\[ W_f = \text{Area} \times \text{unit weight of foundation soil} \]
\[ = 59 \times 18 = 1062 \text{ kN/m} \]

Length of the slip arc ‘pr’ \((L_e)\)

\[ L_e = \frac{2(18)\pi \left(\frac{35}{360}\right)}{2(18)\pi \left(\frac{35}{360}\right)} = 11 \text{ m} \]

Length of the slip arc ‘rt’ \((L_f)\)

\[ L_f = \frac{2(18)\pi \left(\frac{75}{360}\right)}{2(18)\pi \left(\frac{75}{360}\right)} = 23.56 \text{ m} \]
**Step 3:** Determination of factor of safety (without geogrid reinforcement)

Resisting moment ($M_R$)

\[ M_R = c_e \times L_e \times R + c_f \times L_f \times R \]

\[ = 17 \times 11 \times 18 + 22 \times 23.56 \times 18 = 12695.76 \text{ kN-m/m} \]

Divining moment ($M_D$)

\[ M_D = W_e \times x_1 + W_f \times x_2 \]

\[ = 1260 \times 10.5 + 1062 \times 0 = 13230 \text{ kN-m/m} \]

Factor of Safety ($FS$)

\[ FS = \frac{M_R}{M_D} = \frac{12695.76}{13230} = 0.96 < 1 \]

(not stable)
Step 4: Determination of factor of safety (with a single layer geogrid at the slope base)

- A single layer geogrid is placed along the surface ‘sr’ with sufficient anchorage beyond point ‘r’.

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Given,
Allowable tensile strength of the geotextile = 60 kN/m

Distance between base level ‘rs’ and centre of the slip circle (y) = 14.25m.

Resisting moment \((M_R)\)
\[
= c_e \times L_e \times R + c_f \times L_f \times R + T_{\text{allow}} \times y
\]
\[
= 17 \times 11 \times 18 + 22 \times 23.56 \times 18 + 60 \times 14.25
\]
\[
= 13550.76 \text{ kN-m/m}
\]

Divining moment \((M_D)\) = 13230 kN-m/m (calculated)

\[
\text{FS} = \frac{\text{Resisting moment } (M_R)}{\text{Driving moment } (M_D)} = \frac{13550.76}{13230} = 1.02
\]

(not acceptable)

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Step 5: Determine factor of safety with twelve layers of geogrids placed at 0.75 m interval from the foundation.

Allowable tensile strength of the geotextile = 60 kN/m

Distance between base level ‘rs’ and centre of the slip circle (y) = 14.25m.

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Resisting moment \((M_R)\)
\[
M_R = c_e \times L_e \times R + c_f \times L_f \times R + \sum(T_{allow} \times y)
\]
\[
= 17 \times 11 \times 18 + 22 \times 23.56 \times 18 + 60 \times (14.25 + 13.5 + 12.75
+ 12 + 11.25 + 10.5 + 9.75 + 9 + 8.25 + 7.5 + 6.75 + 6)
\]
\[
= 17 \times 11 \times 18 + 22 \times 23.56 \times 18 + 60 \times 121.5
\]
\[
= 19885.76 \text{ kN-m/m}
\]

Divining moment \((M_D)\) = 13230 \text{ kN-m/m (calculated)}

\[
FS = \frac{\text{Resisting moment } (M_R)}{\text{Driving moment } (M_D)} = \frac{19985.76}{13230} = 1.51 \quad \text{(acceptable)}
\]

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Step 6: Determine anchorage length behind the potential slip circle ($L_{em}$)

\[ 2 \times \tau \times L_{em} \times C_i = T_{all} \times F.S. \]

\[ L_{em} = \frac{60 \times 1.5}{2 \times 20 \times 0.85} = 2.65 \text{ m} \]

$C_i = 0.85$, $FS = 1.5$, $\tau = 20 \text{ kN/m}^2$, $T_{allow} = 60 \text{ kN/m}$

Required anchorage length = 2.65 m.

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SCHEMERTMANN’S SIMPLE SLIDING WEDGE METHOD (1987)

Example: A soil embankment of 12 m height has to be constructed at a 50° slope angle. The fill is granular (fine gravel). Geogrid reinforcements can be used as horizontal reinforcement layers.

Surcharge = 34 kN/m²,

\( \gamma = 17 \text{ kN/m}^3, \phi' = 40^\circ, \)

\( c = 0 \text{ kN/m}^2, r_u = 0 \)

Overall safety factor = 2.

\( r_u = \text{pore water pressure ratio} \)

Determine number, spacing and length of geogrid layers.

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Step 1: Determination of design angle of internal fiction ($\phi'$)

\[
\tan \phi'_f = \frac{\tan \phi'}{\nu_m}
\]
\[
\tan \phi'_f = \frac{\tan 40^\circ}{1.45}
\]

$\phi' = 30^\circ$

$\phi' = \text{design angle of internal friction of granular soil,}

\phi'_f = \text{factored angle of internal friction of granular soil}

\nu_m = \text{suggested partial factor of safety for fine gravel}

Partial factor of safety (Source: Tenser, 1986)

<table>
<thead>
<tr>
<th>Basic soil type</th>
<th>Particle size (mm)</th>
<th>$\nu_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coarse</td>
<td>60-20</td>
<td>1.5-1.6</td>
</tr>
<tr>
<td>Medium</td>
<td>20-6</td>
<td>1.3-1.5</td>
</tr>
<tr>
<td>Fine</td>
<td>6-2</td>
<td>1.3-1.5</td>
</tr>
<tr>
<td>Sands</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coarse</td>
<td>2-0.6</td>
<td>1.25-1.4</td>
</tr>
<tr>
<td>Medium</td>
<td>0.60-0.2</td>
<td>1.1-1.25</td>
</tr>
<tr>
<td>Fine</td>
<td>0.20-0.06</td>
<td>1.1-1.25</td>
</tr>
<tr>
<td>Silts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coarse</td>
<td>0.06-0.02</td>
<td>Not normally used in construction</td>
</tr>
<tr>
<td>Medium</td>
<td>0.02-0.006</td>
<td></td>
</tr>
<tr>
<td>Fine</td>
<td>0.006-0.002</td>
<td></td>
</tr>
<tr>
<td>Clays</td>
<td></td>
<td>1.1-1.3</td>
</tr>
<tr>
<td>Pulverized Fuel ash</td>
<td></td>
<td>1.1-1.25</td>
</tr>
</tbody>
</table>
Step 2: Determination of horizontal reinforcement force coefficient (K)

For $\beta = 50^0$ and $\phi_f' = 30^0$,

$K = 0.12$

(After Schmertmann et al., 1987)

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Step 3: Calculation of the maximum required cumulative tensile force ($T_{\text{max}}$)

$$T_{\text{max}} = 0.5 \times K \times \gamma \times H^2$$

$K = 0.12$, $\gamma = 17$ kN/m$^3$

Modified height of slope including surcharge,

$$H' = H + \frac{W_s}{\gamma}$$

$$H' = 12 + \frac{34}{17} = 14 \text{ m}$$

$H = \text{height of slope} = 12 \text{ m}$
$W_s = \text{weight of surcharge} = 34 \text{ kPa}$

$$T_{\text{max}} = 0.5 \times 0.12 \times 17 \times 14^2 = 200 \text{ kN/m}$$
Step 4: Distribution of maximum required cumulative tensile strength in different zones ($T_{\text{zone}}$)

As height of slope = 12 m > 6 m, the slope is divided in three zones.

**Zone-1 Bottom zone ($T_{\text{bottom}}$)**

$$T_{\text{bottom}} = \frac{1}{2} \times T_{\text{max}}$$

$$T_{\text{bottom}} = \frac{1}{2} \times 200 = 100 \text{kN/m}$$

**Zone-2 Middle zone ($T_{\text{middle}}$)**

$$T_{\text{middle}} = \frac{1}{3} \times T_{\text{max}} = \frac{1}{3} \times 200 = 66.67 \text{kN/m}$$

**Zone-3 Top zone ($T_{\text{top}}$)**

$$T_{\text{top}} = \frac{1}{6} \times T_{\text{max}} = \frac{1}{6} \times 200 = 33.33 \text{kN/m}$$

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Step 5: Determination of long term design strength, number of reinforcement layers and spacing for each zone

**Zone-1 Bottom zone**

Selecting geogrid of ultimate tensile strength \( (T_{\text{ult}}) = 50 \text{kN/m}; \)

- **Long term design strength of geogrid in zone-1,**
  \[
  \text{LTDS} = \frac{T_{\text{ult}}}{\text{Overall factor of safety}} = \frac{50}{2} = 25 \text{ kN/m}
  \]

- **Number of geogrid layers for zone-1 \( (N_{\text{bottom}}) \)**
  \[
  = \frac{(T_{\text{max}} \text{ of zone-1})}{\text{LTDS}} = \frac{100}{25} = 4
  \]

- **Spacing of geogrid layers \( (S_v)_{\text{bottom}} \)**
  \[
  (S_v)_{\text{zone}} = \frac{H_{\text{zone}}}{N_{\text{zone}}} = \frac{H}{3}
  \]
  \[
  (S_v)_{\text{bottom}} = \frac{12/3}{4} = 1
  \]
Zone-2 Middle zone

Selecting geogrid of ultimate tensile strength = 40 kN/m

- Long term design strength (LTDS) of geogrid in zone-2
  \[ = \frac{40}{2} = 20 \text{ kN/m} \]

- Number of geogrid layers in zone-2
  \[ = \frac{T_{\text{max}} \text{ of zone-2}}{\text{LTDS in zone2}} \]
  \[ = \frac{66.67}{20} = 3.33 \approx 4 \]

- Spacing of geogrid layers \((S_v)_{\text{middle}}\)
  \[ (S_v)_{\text{middle}} = \frac{12}{3} = 4 = 1 \]

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Zone-3 Top zone

Selecting geogrid of ultimate tensile strength = 30 kN/m

- Long term design strength (LTDS) of geogrid in zone-3
  \[ \text{LTDS in zone-3} = \frac{30}{2} = 15 \text{ kN/m} \]

- Number of geogrid layers in zone-3
  \[ \text{Number of layers} = \frac{T_{\text{max of zone-3}}}{\text{LTDS in zone3}} \]
  \[ = \frac{33.33}{15} = 2.22 \approx 3 \]

- Spacing of geogrid layers \( (S_v)_{\text{top}} \)
  \[ (S_v)_{\text{top}} = \frac{12/3}{3} = 1.3 \]
  Provide 3 layers at a spacing of 1.3 m
Step 7: Determination of length of geogrid layer at top ($L_t$) and bottom ($L_b$)

For $\beta = 50^0$ and $\phi_f' = 30^0$, 

\[
\frac{L_t}{H'} = 0.45 \quad \frac{L_b}{H'} = 0.5
\]

$H' = 14$ m (Calculated)

$L_t = 0.45 \times H' = 0.45 \times 14 = 6.3$ m

$L_b = 0.5 \times H' = 0.5 \times 14 = 7$ m

(After Schmertmann et al., 1987)
Step 8: Determination of embedment length of geogrid layer

\[ L_e = \frac{LTDS \times F.S.}{2 F^* \alpha \sigma_v'} \]

F.S. = 1.5

\[ F^* = \text{Pull-Out resistance factor (dimensionless)} \]
\[ = 0.8 \times \tan 30^\circ \text{ (for geogrid)} \]
\[ = 0.461 \]

\[ \alpha = \text{A scale effect correction factor (dimensionless)} \]
\[ = 0.8 \text{ (for geogrid)} \]

Zone-1 Bottom zone: LTDS = 25 kN/m
Zone-2 Middle zone: LTDS = 20 kN/m
Zone-3 Top zone: LTDS = 15 kN/m

\[ \sigma_v' = \text{the effective vertical stress at the soil reinforcement interface (kN/m}^2) = \gamma z + q \]

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As for example, at depth \((z) = 12 \text{ m}\),

\[ \sigma_v' = \gamma z + q = 17 \times 12 + 34 = 238 \text{ kPa} \]

\[ L_e = \frac{\text{LTDS} \times \text{F.S.}}{2 F^* \alpha \sigma_v'} = \frac{25 \times 1.5}{2 \times 0.461 \times 0.8 \times 238} = 0.214 \]

\[ L_e \geq 1 \text{ m}; \quad \text{Therefore, provided } L_e = 1 \text{ m} \]

\[ \text{FS}_{PO} = \frac{2 L_e F^* \alpha \sigma_v'}{\text{LTDS}} = \frac{2 \times 1 \times 0.461 \times 0.8 \times 238}{25} = 7.02 > 1.5 \] (OK)

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## Geosynthetics Engineering: In Theory and Practice

### Detailed calculations:

<table>
<thead>
<tr>
<th>Zone</th>
<th>Number &amp; spacing of geogrid layers</th>
<th>Depth of layers from top (z) m</th>
<th>$\sigma'_v$ kN/ m²</th>
<th>Embedment length ($L_e$) m</th>
<th>Provided Embedment length ($L_p$) m</th>
<th>$FS$ Against Pull out ($FS_{PO}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom</td>
<td>Base layer</td>
<td>12</td>
<td>238</td>
<td>0.214</td>
<td>1</td>
<td>7.02</td>
</tr>
<tr>
<td></td>
<td>4 layers @ 1 m</td>
<td>11</td>
<td>221</td>
<td>0.23</td>
<td>1</td>
<td>6.52</td>
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<td></td>
<td></td>
<td>10</td>
<td>204</td>
<td>0.25</td>
<td>1</td>
<td>6.02</td>
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<td></td>
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<td>9</td>
<td>187</td>
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<td>8</td>
<td>170</td>
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<td>Middle</td>
<td>4 layers @ 1 m</td>
<td>7</td>
<td>153</td>
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<td>5.64</td>
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<tr>
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<td>6</td>
<td>136</td>
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<td>5</td>
<td>119</td>
<td>0.34</td>
<td>1</td>
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<td>4</td>
<td>102</td>
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<td>3.76</td>
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<td>Top</td>
<td>3 layers @ 1.3 m</td>
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<td>0.36</td>
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<td>1.7</td>
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<td>1</td>
<td>3.09</td>
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<tr>
<td></td>
<td></td>
<td>0.4</td>
<td>40.8</td>
<td>0.75</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

**Note:** Provide secondary reinforcements in between the primary reinforcements.

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Details of the reinforced slope

Prof. J. N. Mandal, Department of Civil Engineering, IIT Bombay
Please let us hear from you

Any question?
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THANKS FOR LISTENING