CE 4780 Hurricane Engineering II

Section on
Flooding Protection:
Earth Retaining Structures and Slope Stability

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• Three weeks of classes
Methods of Slope Analysis

• Two categories of analysis
  – Slope stability
  – Slope movement

Introduction

• Slope Stability Methods
  – These methods use limit equilibrium analysis
  – They require strength information of the soils
  – They do not provide information about the magnitude of movements
  – They yield a factor of safety
  – They are usually applied in the design process
Introduction

• Slope Movement Methods
  – These methods require strain-stress information about the soil.
  – The solution is usually found using finite element solutions
  – They do not provide factor of safety (direct parameter of stability)
  – They are usually applied in the prevention of landslide, and risk emergency analysis.

Limit Equilibrium Analysis

• They are based in the upper bound theorem
• Several possible failure surfaces are considered till the least favorable is found.
• For the least favorable surface, the factor of safety is determined.
Factor of Safety

- It is defined as the ratio of the shear strength over the applied shear stress (in the local sense)
- Or the resistance forces over the driving forces (in the global sense)
- The least favorable failure surface is determined in the sense of the factor of safety.

Methodology – Infinite Slopes

- Isotropic Soils and Uniform Slopes

![Diagram showing infinite slope calculations]

- Assumed failure plane
- Shear strength $\tau = \sigma' \tan(\phi)$
- Infinite slope (and small b): $E_i = E_r; T_i = T_r$

\[
\begin{align*}
 N &= \gamma bz \cos(\beta) \\
 \sigma &= \gamma z \cos^2(\beta) \\
 S &= \gamma \beta z \sin(\beta) \\
 \tau &= \gamma z \sin(\beta) \cos(\beta)
\end{align*}
\]
Methodology – Infinite Slopes

• Isotropic Soils and Uniform Slopes (cont.)
  – Dry soil at the verge of failure:
    \[ \sum F_{\text{horizontal}} = 0 \]
    \[ S \cos(\beta) = N \sin(\beta) \Rightarrow S = \frac{N \sin(\beta)}{\cos(\beta)} = N \tan(\beta) \]
  – The maximum shear resistance is:
    \[ \tau \Delta l = \tau \frac{b}{\cos(\beta)} = N \tan(\beta) \]
    \[ S = \tau \Delta l \Rightarrow N \tan(\beta) = N \tan(\phi) \]
    \[ FS = \frac{\tan(\phi)}{\tan(i)} \]  Factor of safety

Methodology – Infinite Slopes

• Isotropic Soils and Uniform Slopes (cont.)
  – Saturated soil at the verge of failure (no water flow):
    the effective stresses and forces are reduced due to the submerged unit weight of the soil.
  – Saturated soil and flow parallel to the slope surface (helping the sliding mechanisms), max. safe slope:
    \[ \tan(\beta) = \frac{\gamma - \gamma_w \tan(\phi)}{\gamma} \]
  – The maximum shear resistance is:
    \[ FS = \frac{\gamma - \gamma_w \tan(\phi)}{\gamma_w \tan(i)} \]  Factor of safety
Methodology – Finite Slopes

- Failure approximate circular surfaces (mathematical convenience). Other surfaces: spirals.
- Crucial parameters: shear strength and pore pressure distribution
- Presence of weak layers and heterogeneities are important.

Methodology – Finite Slopes

- Problems
  - It is difficult to determine the weight and center of gravity of the sliding wedge.
  - The problem is statically indeterminate.
  - The normal effective stress along the failure surface is unknown.
  - The mobilized shear strength $\tau_m$ is unknown (it also varies along the failing surface).
  - The seepage forces are difficult to determine.
Methodology – Finite Slopes

• Typical Methods:

• Typical Methods (cont.):
Methodology – Finite Slopes

• General Concepts – Circular Failure Surfaces

\[
FS = \frac{M_{\text{resisting}}}{M_{\text{driving}}}
\]

\[
FS = \frac{\tau_{\text{max}} LR}{Wr_1 + F_{\text{external}}r_2}
\]

Repeats for other failure surfaces

Methodology – Finite Slopes

• General Concepts – Method of Slides

There are up to 13 unknown parameters (N, S, E’s, and T’s) and 3 equilibrium equations

\[\theta\]
Methodology – Finite Slopes

• Method of Slides: Bishop’s Method
  – Assumptions:
    • Circular slip surface
    • Colinear E_i and E_{i+1} and U_i and U_{i+1}
    • N_i acts on the center of the arc length

  – Summing of vertical forces:
    \[ N_i \cos(\theta_i) + S_i \sin(\theta_i) - W_i - T_i + T_{i+1} = 0 \]
    \[ N_i'\cos(\theta_i) = -S_i \sin(\theta_i) + W_i + T_i - T_{i+1} - u_i l_i \cos(\theta_i) \]

Methodology – Finite Slopes

• Method of Slides: Bishop’s Method (cont.)
  \[ r_u = \frac{u_i b_i}{W_i} \] Pore water pressure ratio
  \[ N_i'\cos(\theta_i) = W_i (1 - r_u) - S_i \sin(\theta_i) + (T_i - T_{i+1}) \]

  – Bishop’s method only considers moment equilibrium:
    \[ \sum W_i r_i - \sum S_i R = 0 \]
    \[ \sum S_i = \sum \frac{W_i r_i}{R} = \sum W_i \sin(\theta_i) \]
Methodology – Finite Slopes

• Method of Slides: Bishop’s Method (cont.)

\[
FS = \frac{\tau_r}{\tau_m} = \frac{(S_i)_m}{S_i} \quad \text{Local factor of safety}
\]

\[
FS = \frac{N_i \tan(\phi_i)}{S_i} \cdot S_i = \frac{N_i \tan(\phi_i)}{FS}
\]

\[
N_i \cos(\theta_i) = W_i (1 - r_u) - \frac{N_i \tan(\phi_i) \sin(\phi_i)}{FS} + (T_i - T_{i+1})
\]

\[
N_i = \frac{W_i (1 - r_u) + (T_i - T_{i+1})}{\cos(\phi_i) \tan(\phi_i) \sin(\phi_i) + \cos(\phi_i) \tan(\phi_i)} = m_i [W_i (1 - r_u) + (T_i - T_{i+1})]
\]

Methodology – Finite Slopes

• Method of Slides: Bishop’s Method (cont.)

\[
FS = \frac{\sum [W_i (1 - r_u) + (T_i - T_{i+1})] \tan(\phi_i) m_i}{\sum W_i \cdot \sin(\phi_i)}
\]

Disregarding the term \((T_i - T_{i+1})\) the error is less than 1 %

\[
FS = \frac{\sum W_i (1 - r_u) \tan(\phi_i) m_i}{\sum W_i \cdot \sin(\phi_i)}
\]

Water table bellow slip surface

\[
FS = \frac{\sum W_i \tan(\phi_i) m_i}{\sum W_i \cdot \sin(\phi_i)}
\]
References and Bibliography