Stability of Geosynthetic Lined Slopes-II

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in conjunction with

Geosynthetic Materials Association

FGI
Topics

- Stability factors
- Critical cross-section
- Critical failure surface
- Slope stability methods
- 2D v. 3D stability analyses
- MSW Shear Strength
- Summary
Stability Factors

• “Load the top and cut the toe”

• FS = Resistance/Driving

• Driving Stresses
  - Steep Slopes
  - High Slopes
  - High unit weight
  - Dynamic Loads

• Small Shear Resistance
  - Toe support
  - Weak materials or interfaces
  - Fluid pressures
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Critical Cross-Section
Critical Cross-Section
Critical Cross-Section
Three of the five critical cross-sections selected for slope stability analyses.

Selection of the most critical cross-sections for slope stability analyses based on a review of: grading plan, ....

A total of three critical slope sections were analyzed and are designated as sections A-A, B-B, and C-C.

The most critical factors of safety calculated ranged from between 1.52 and 1.87, which are considered acceptable.
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FAILURE MODES

• Translational
• Rotational
• Infinite
Translational
Translational
Rotational

- Homogeneous
- Isotropic

Waste

Weak Fine-Grained Soil
Rotational
Infinite Slope

• Liner system
• Cover system
• Homogenous
Critical Slip Surface

CALIFORNIA CODE REQUIREMENTS

SCALE: 1" = 40'

LANDFILL

FOUNDATION

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Topics

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Slope Stability Methods

- Ordinary Method of Slices (1927)
- Method of Wedges (1930)
- Bishop’s Modified Method (1955)
- Janbu’s Generalized Procedure of Slices (1957)
- Lowe and Karafiath (1960)
- Morgenstern and Price’s Method (1965)
- Spencer’s Method (1967)
J.M. Duncan (1982)

Vertical Slices

Forces on a typical slice

\[ S = \frac{C'}{F} + \frac{P' \tan \phi'}{F} \]

(Duncan, 1982)
Morgenstern & Price’s Procedure (1965)

Assumes inclinations of side forces follow some predetermined pattern:

\[ \theta = \lambda f(x) \]

Satisfies all conditions of equilibrium

3N equations
3N unknowns

- Horizontal side force resultant determined using \( f(x) \) and solve for \( \lambda \)
to determine resultant - removes N-1 unknowns
- Location of normal force on base, removes N unknowns
- \((5N-2) - (N) - (N-1) = 3N-1 \) => statically determinant
Morgenstern & Price (1965)

- Interslice Force Functions
  - Trapezoid
  - Half sine
  - Clipped sine = half sine but > zero
  - User-defined
- 3D Software
  - Half sine
  - Constant
Spencer (1967)

Simplifies M&P (1965)
• Horizontal side force resultant is determined with constant θ to determine resultant – side forces are parallel - removes N-1 unknowns
• Location of normal force on base, removes N unknowns
• (5N-2) – (N) - (N-1) = 3N-1 => statically determinant & θ less than slope angle
Accuracy of Stability Methods

- **Circular Failure Surfaces**
  - M&P, Spencer, or Bishop methods

- **Non-Circular Failure Surfaces**
  - M&P or Spencer methods

- Mechanics are well understood - FS ± 5%

- Uncertainty is Geosynthetic Shear Strength
Infinite Slope with No Water

$$FS = \frac{W \cos(\beta) \tan(\delta)}{W \sin(\beta)}$$

$$FS = \frac{\tan(\delta)}{\tan(\beta)}$$

δ = interface friction angle
β = slope angle
W = γ*h = cover weight

No buttress
No tension
Infinite Slope with Adhesion

$$FS = \frac{a + W \cos(\beta) \tan(\delta)}{W \sin(\beta)}$$

$$FS = \frac{a + \gamma h \cos(\beta) \tan(\delta)}{\gamma h \sin(\beta)}$$

a = adhesion
h = cover thickness
\(\gamma\) = cover unit weight

No buttress
No tension
Infinite Slope with Adhesion & Water

\[ FS = \frac{a + \left[ \gamma h - \frac{\gamma_w h_w}{\cos^2(\beta)} \right] \gamma h \cdot \cos(\beta) \cdot \tan(\delta)}{\gamma h \cdot \sin(\beta)} \]

- \( h_w \) = water depth on GM
- \( \gamma_w \) = water unit weight
Effect of Water and $\delta$

- $\beta = 18.4^\circ$
- $\delta = 28^\circ$
- $\delta = 25^\circ$
- $\delta = 22^\circ$
- $\delta = 20^\circ$
Drainage Above Geomembrane
Seismic Infinite Slope Analysis

\[
F = \frac{c}{(\gamma z \cos^2 \beta)} + \tan \phi [1 - (\gamma_w \cdot \frac{z - d_w}{\gamma z})] - K_s \cdot \tan \beta \cdot \tan \phi
\]

\[
K_y = \frac{c}{(\gamma z \cos^2 \beta)} + \tan \phi [1 - (\gamma_w \cdot \frac{z - d_w}{\gamma z})] - \tan \beta
\]

- Matasovic (1991)
  - \(K_s\) = seismic coefficient
  - \(K_y\) = yield coefficient
  - \(z\) = depth to failure surface
  - \(d_w\) = depth to water surface parallel to slope
Slope with Reinforcement

- **Giroud et al. (1995)**

\[ a = \text{interface adhesion} \]
\[ \delta = \text{interface friction} \]
\[ \phi = \text{cover soil friction angle} \]
\[ c = \text{cover soil cohesion} \]
\[ \beta = \text{slope angle} \]
\[ \gamma = \text{cover soil unit weight} \]
\[ h = \text{soil cover thickness} \]
\[ H = \text{vertical slope height} \]
\[ T = \text{geosynthetic tension} \]
Slope with Reinforcement

\[
FS = \frac{\tan(\delta)}{\tan(\beta)} + \frac{a}{\gamma h \sin(\beta)} + \\
\frac{h}{H} * \frac{\sin(\phi)}{\sin(2\beta) \cos(\beta + \phi)} + \\
\frac{c}{\gamma H} * \frac{\cos(\phi)}{\sin(\beta) \cos(\beta + \phi)} + \\
\frac{T}{\gamma H * h}
\]
Reinforcement Design Example

Geosynthetic Data
\( \delta = 14^\circ \)
\( a = 0 \)
NO Reinforcement (T=0)

\[
\tan \beta = \frac{\delta}{\tan a} = \frac{14^\circ}{0} = \frac{14^\circ}{1} = 14^\circ
\]

\[
\tan \theta = \tan (18.4^\circ) = 0.164
\]

\[
\tan \phi = \tan (30^\circ) = 0.588
\]

\[
\tan \phi = \tan (30^\circ) = 0.588
\]

\[
FS = \frac{\tan \delta}{\tan \beta} + \frac{a}{\gamma h \sin \beta} + \left( \frac{h}{H} \right) \frac{\sin \phi}{\sin (2 \beta) \cos (\beta + \phi)} + \left( \frac{c}{\gamma H} \right) \frac{\cos \phi}{\sin \beta \cos (\beta + \phi)} + \frac{T}{\gamma H * h}
\]

\[
FS = \frac{\tan (14^\circ)}{\tan (18.4^\circ)} + \left( \frac{3'}{100'} \right) \frac{\sin (30^\circ)}{\sin (2 * 18.4^\circ) \cos (18.4^\circ + 30^\circ)}
\]

\[
FS = 0.75 + 0.04 = 0.79
\]

FS = 0.79
Reinforcement Required for $FS \geq 1.5$

Geosynthetic Data

$\delta = 14^\circ$

$a = 0$

$T_{\text{Reqd}} = ?$

$H = 100 \text{ ft}$

$h = 3 \text{ ft}$

$\beta = 18.4^\circ$

$\gamma = 115 \text{ pcf}$, $c = 0$, $\phi = 30^\circ$

$T_{\text{Reqd}} = 24,495 \text{ lbs/ft}$

$$FS = \frac{\tan \delta}{\tan \beta} + \left(\frac{h}{H}\right) \sin \phi \sin(2\beta) \cos(\beta + \phi) + \frac{T_{\text{Reqd}}}{\gamma H \ast h} \geq 1.5$$

$$FS = \frac{\tan (14^\circ)}{\tan (18.4^\circ)} + \left(\frac{3'}{100'}\right) \sin(2 \times 18.4^\circ) \cos(18.4^\circ + 30^\circ) + \frac{T_{\text{Reqd}}}{\gamma H \ast h} \geq 1.5$$

$$FS = 0.75 + 0.04 + \frac{T_{\text{Reqd}}}{115 \text{ pcf} \times (100 \text{ ft})(3 \text{ ft})} \geq 1.5$$
Max Slope Height for FS $\geq 1.5$ & T = 7,590 lbs/ft

$$FS = \frac{\tan \delta}{\tan \beta} + \left( \frac{t}{h_{\text{reqd}}} \right) \frac{\sin \phi}{\sin(2\beta) \cos(\beta + \phi)} + \frac{T}{\gamma(h_{\text{reqd}}) t} \geq 1.5$$

Cover Soil: $\gamma = 115$ pcf, $c = 0$, $\phi = 30^\circ$

$h = 3 \text{ ft}$  $\beta = 18.4^\circ$  $H = 100 \text{ ft}$

Geosynthetic Data
- $\delta = 14^\circ$
- $a = 0$
- T = 7,590 lbs/ft

$h_{\text{reqd}} \leq 34.4 \text{ ft}$
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2D v. 3D Slope Stability

- 2D analyses assume plane strain condition
- Slopes are not infinitely wide - 3D effects influence stability
Comparison of 2D & 3D Stability

- $F_{3D} \geq F_{2D}$ For Appropriate Conditions
- Difference is Caused by Shear Forces Along the Edges of the Slide Mass
- Complex Slope Conditions
  - Geometry
  - Pore-Water Pressures
  - Shear Strength
3D Slope Geometry
Effects of 3D Side Resistance

\[ W = \text{Total weight of column} \]
\[ N = \text{Normal force at the base} \]
\[ S = \text{Resisting shear force at the base} \]
\[ U = \text{Pore water pressure resultant} \]
\[ P_i \text{ and } T_i = \text{Intercolumn normal forces and horizontal shear forces in } i \text{ direction, respectively} \]
\[ \Delta P_i \text{ and } \Delta T_i = \text{Change in intercolumn normal forces and horizontal shear forces in the } i \text{ direction, respectively} \]
Effects of 3D Side Resistance

Stark and Akhtar (2011)
3D Slope Stability Software

- **CLARA 2.31** - Stark and Eid (1998)
- **3DDEM-Slope**
- **Slide³**
- **FLAC 3D**
- **PLAXIS 3D**
- **RS3**
3D Effects in Inverse-Analyses

- Translational failure
- Large MSW slope failure
- Stark et al. (2000)
- Slide mass » 1,000,000 m³
- Average slope = 21°
3D Effects in Inverse-Analyses

- Results - 3D matches laboratory shear tests

2D ANALYSIS OVERESTIMATES MOBILIZED FRICTION ANGLE BY 20-30%

Akhtar and Stark (2011)
3D Geometry

Stark and Eid (1998)
3D Geometry

Stark and Eid (1998)
Mis-Use of 3D Analyses

• 3D FS ≥ 2D FS For Appropriate Conditions
• NOT FOR MAXIMIZING SLOPES
  REQUIRED 3D FS > 1.5
  UNCERTAINTIES IN SHEAR STRENGTHS
  TOO MANY FAILURES
• NOT FOR SATISFYING REGULATIONS
Mis-Use of 3D Analyses
REQUIRED 3D FACTOR OF SAFETY

Required 3D FS = f(W/H)

Stark & Akhtar (2011)
Required 3-D Factor of Safety

• Most Conservative = 3-D FS Figure

\[ FS_{3D-Min} = FS_{2D-Min} \times \text{Ratio}_{3D/2D} \]

• Little 2-D Uncertainty so only incorporate 3D effects (Stark and Ruffing, 2017)

\[ FS_{3D-Min} = FS_{2D-Min} + \frac{FS_{3D} - FS_{2D-Min}}{FS_{2D-Min}} \]

• Least conservative 3D FS (Stark and Ruffing, 2017)

\[ FS_{3D-Min} = FS_{2D-Min} + \frac{FS_{3D} - FS_{2D-Min}}{FS_{3D}} \]
Summary of 3-D Analysis in Practice

- 3-D FS > 2-D FS for all conditions considered herein

- Inverse Analyses
  - Use 3-D for mobilized strength
  - 3D inverse strength more representative of field/laboratory testing

- Design
  - Use 2-D analysis to maintain current conservatism
  - State and federal codes should specify minimum 2-D FS of 1.5"

- Initial Estimate of 3-D FS
  - Rotational slides: 2-D weighted average
  - Translational slides:
    - Charts
    - Software
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MSW Shear Strength

Normal
- $c' = 6 \text{kPa}, \phi' = 35^\circ$ \quad $\sigma'_v < 200 \text{kPa}$
- $c' = 30 \text{kPa}, \phi' = 30^\circ$ \quad $\sigma'_v \geq 200 \text{kPa}$

Thermally Degraded
- $c' = 0 \text{kPa}, \phi' = 20^\circ$

(Stark et al. 2009)
Summary

• Morgenstern & Price (1965) - use different functions
• Uncertainty = shear strength
• 3D not to increase FS
References


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Questions, Comments, Experiences...

Discussion

Session II: Slope Stability Analyses

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