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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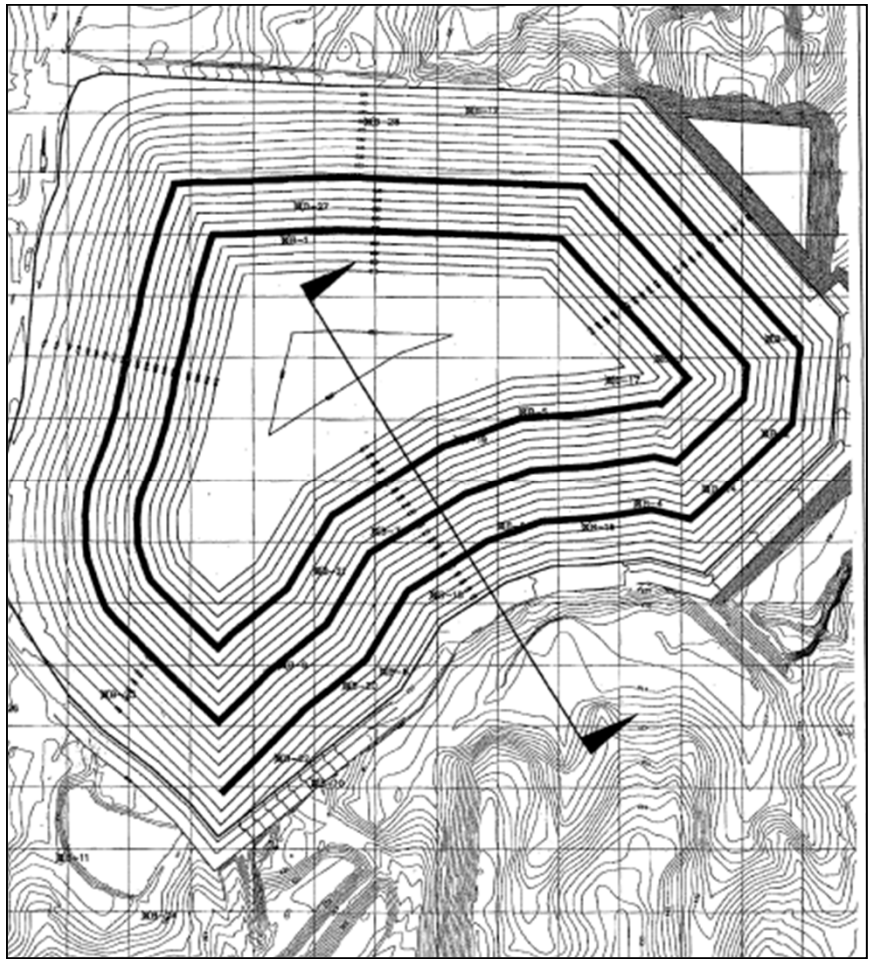
Critical Cross-Section

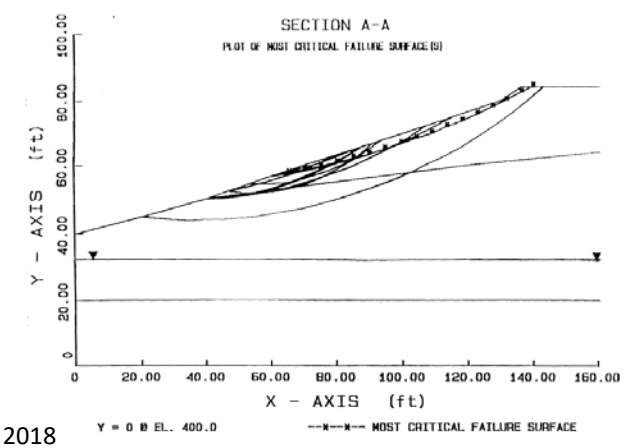


Critical Cross-Section

Critical Cross-Section

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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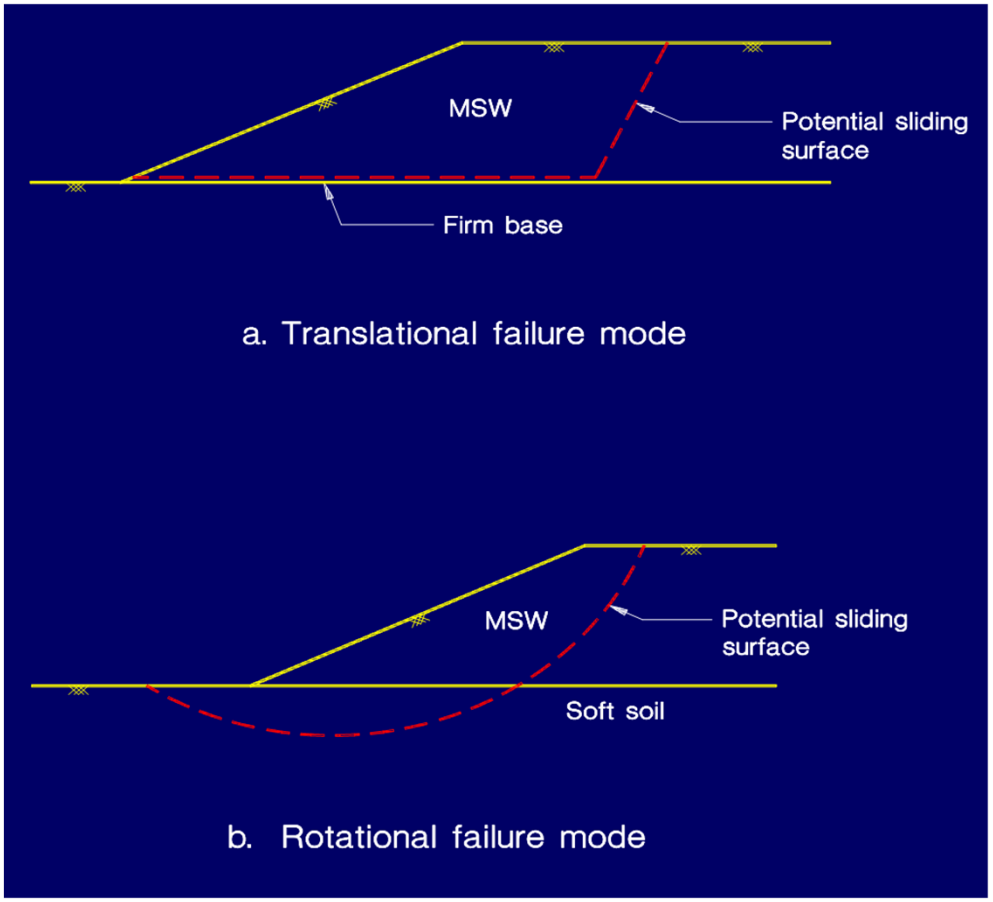
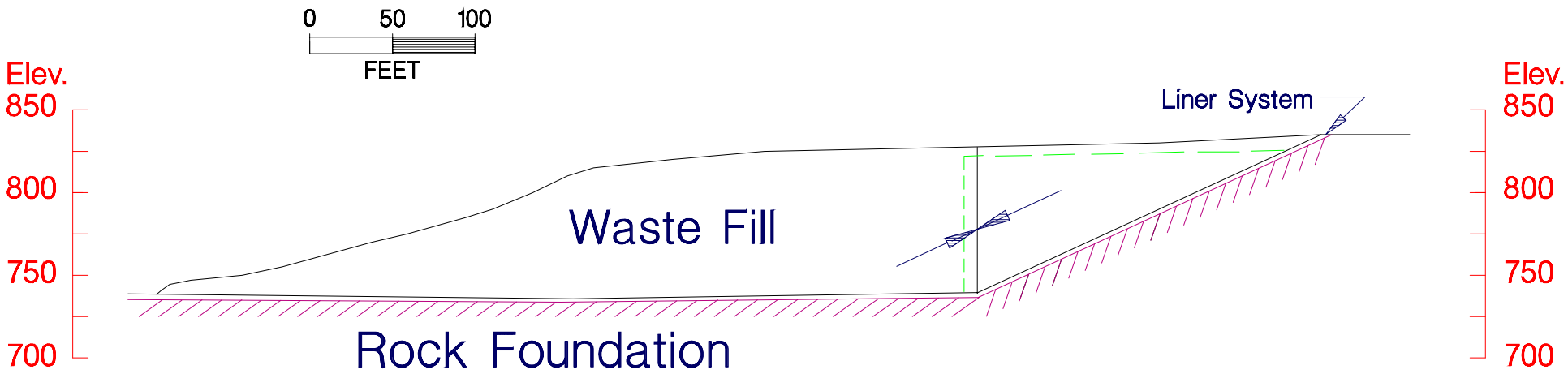
FAILURE MODES

- Translational
- Rotational
- Infinite



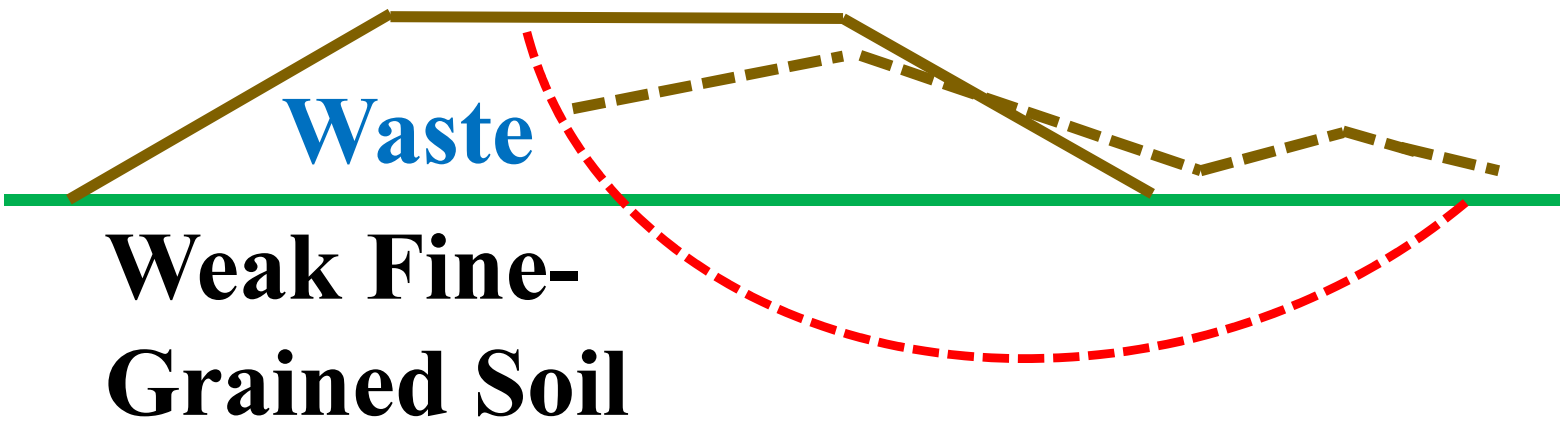
Translational



Translational

Rotational

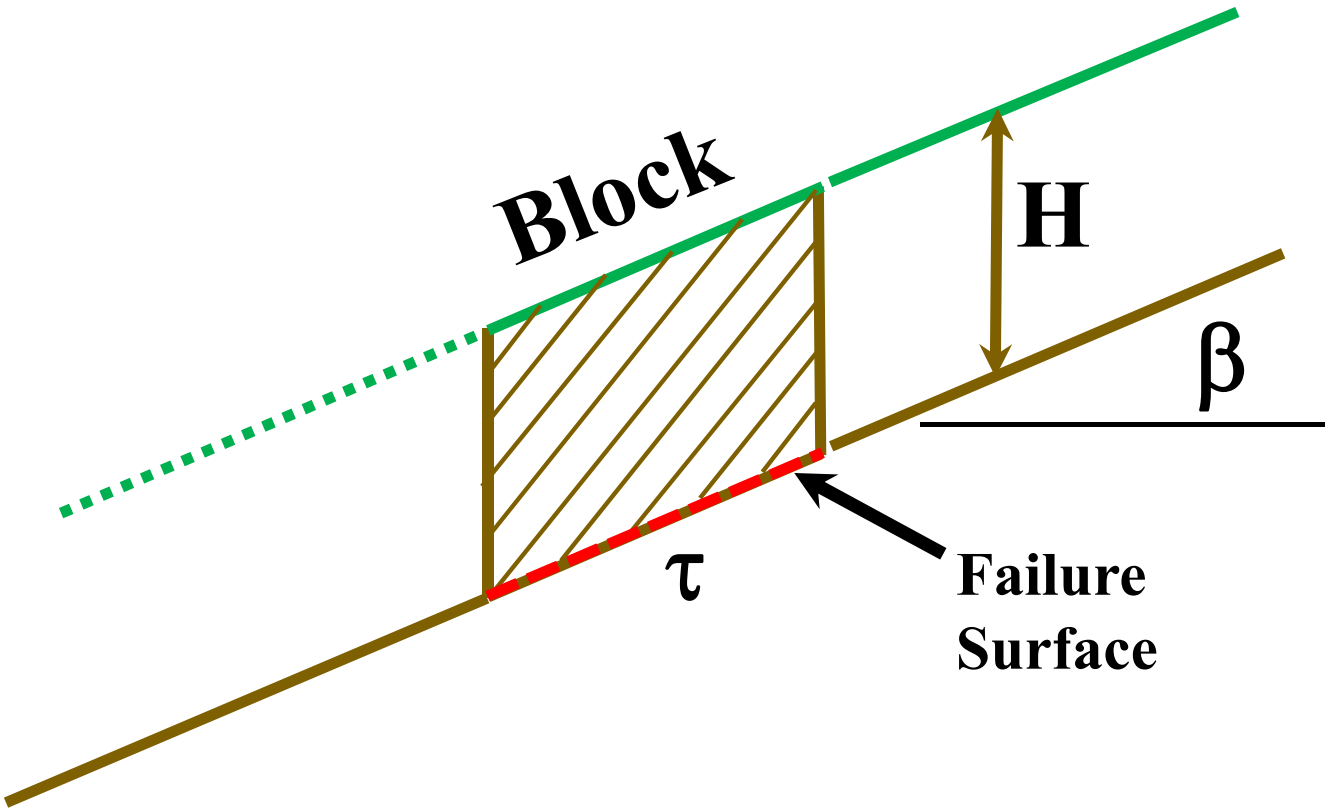
- Homogeneous
- Isotropic



Rotational

Infinite Slope

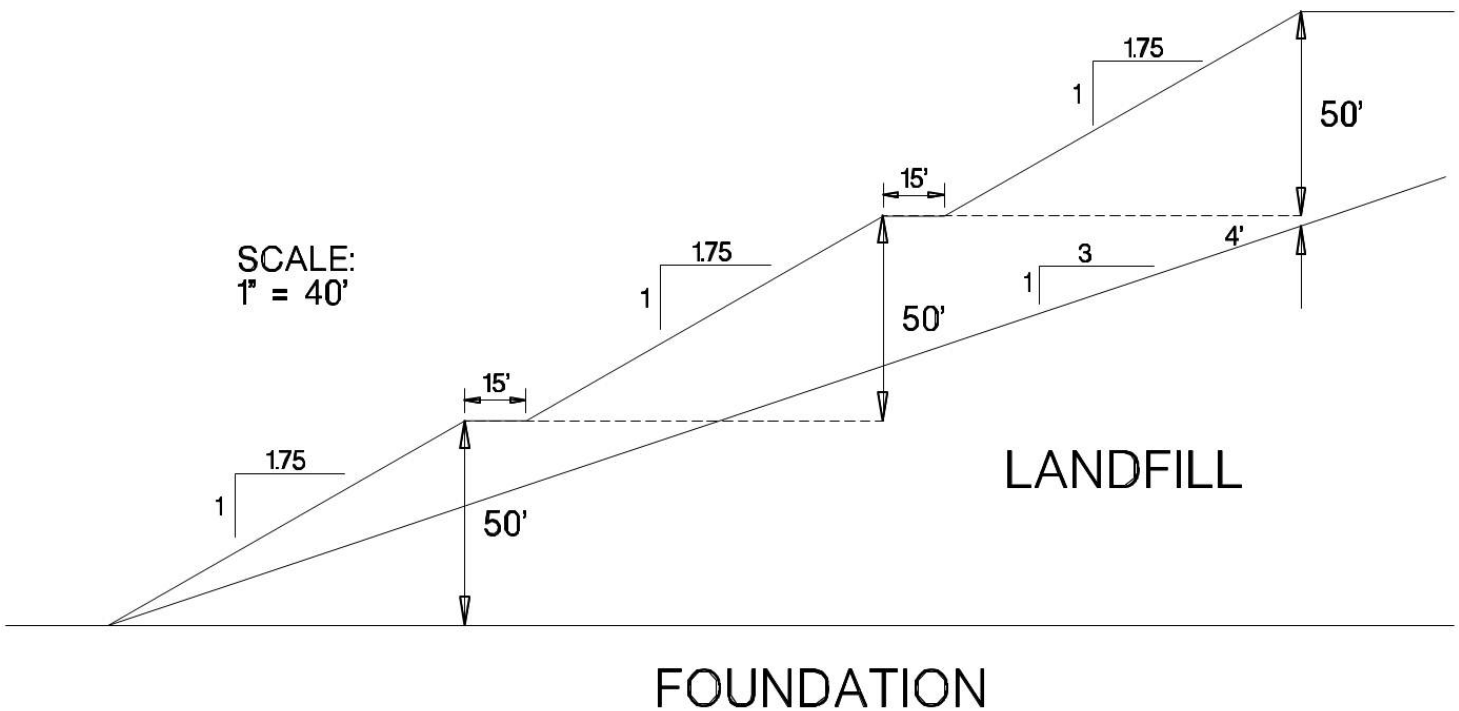
- Liner system
- Cover system
- Homogenous



Infinite

Critical Slip Surface

CALIFORNIA CODE REQUIREMENTS



Topics

- Stability factors
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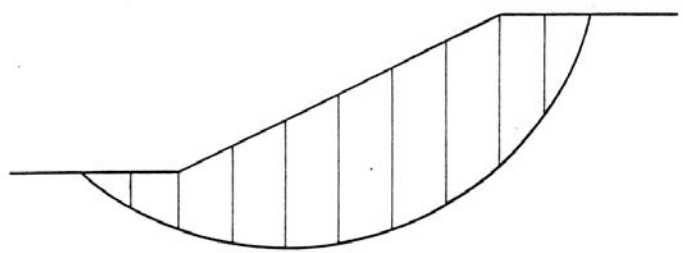
Slope Stability Methods

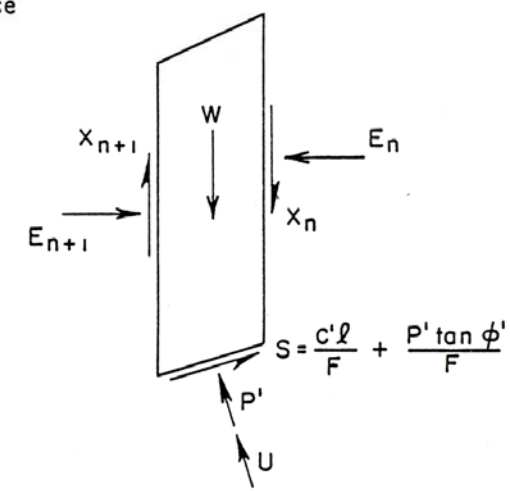
- Ordinary Method of Slices (1927)
- Method of Wedges (1930)
- Bishop's Modified Method (1955)
- Janbu's Generalized Procedure of Slices (1957)
- Lowe and Karafiath (1960)
- Morgenstern and Price's Method (1965)
- Spencer's Method (1967)

Vertical Slices

J.M. Duncan
(1982)



Forces on a typical slice



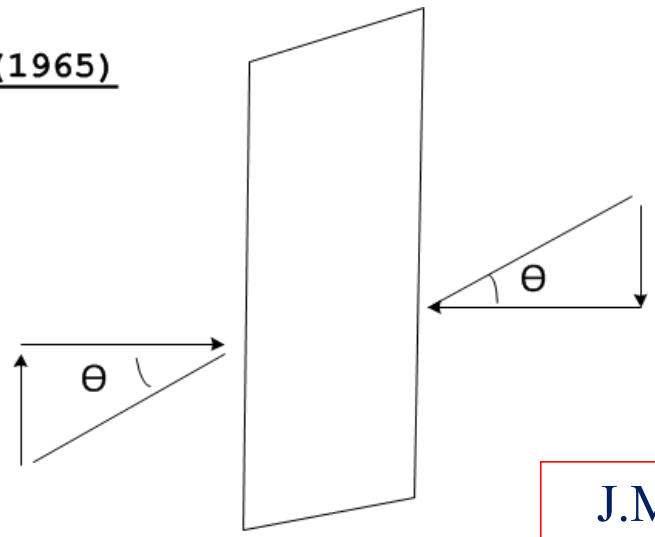
(Duncan, 1982)

Morgenstern & Price (1965)

Morgenstern & Price's Procedure (1965)

Assumes inclinations of side forces follow some predetermined pattern:

$$\theta = \lambda f(x)$$



J.M. Duncan (1982)

Satisfies all conditions of equilbrium

3N equations 3N unknowns

- Horizontal side force resultant determined using f(x) and solve for λ 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

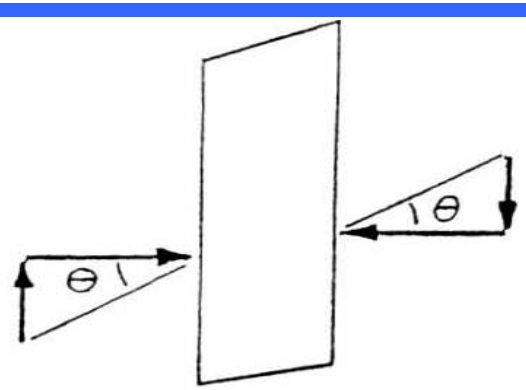
Morgenstern & Price (1965)

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

Spencer (1967)

Spencer's Procedure

Assumes resultant side force inclination (θ) is same for every slice



J.M. Duncan (1982)

Satisfies all conditions of equilibrium

3N equations 3N unknowns

- 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

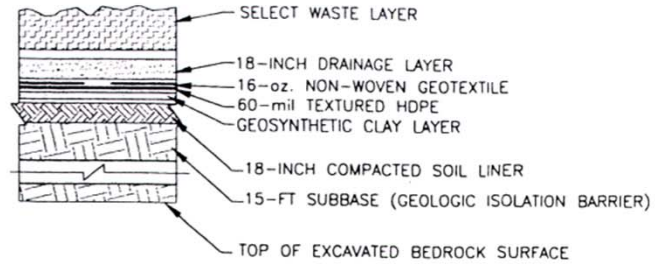
Accuracy of Stability Methods

- **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**

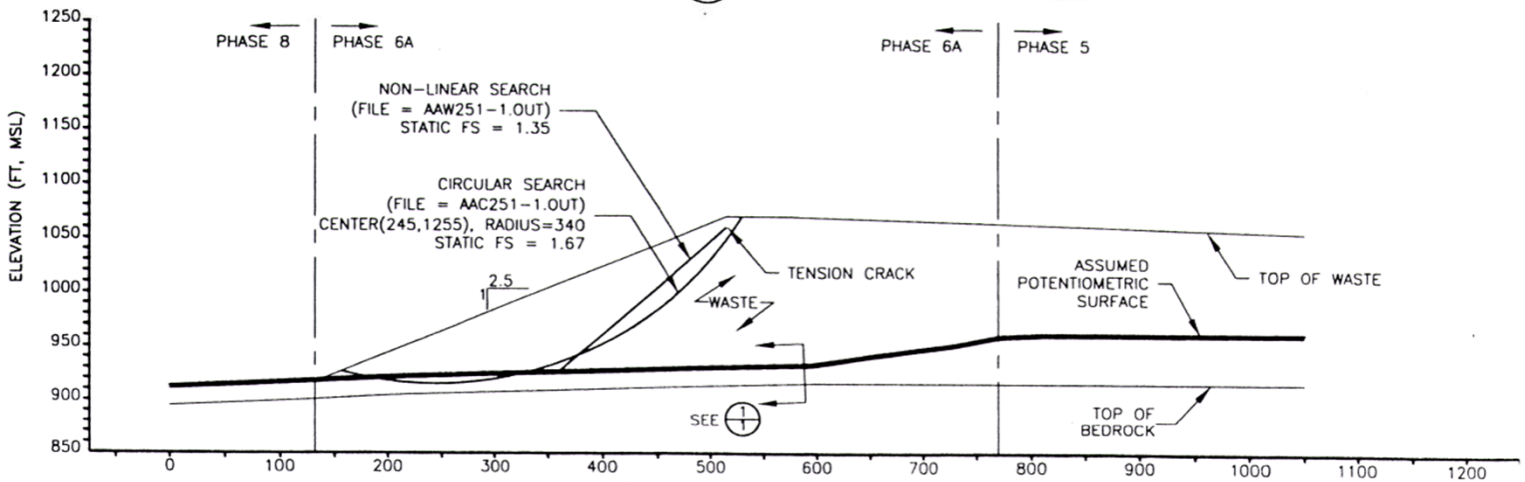
NEWMARK DEFORMATION ANALYSIS

FILE	ACCELERATION Ky	DYNAMIC FS	Ky/Kmax	DISPLACEMENT "U" (CM)
AAW251-D.OUT	0.1 0.09	0.995 1.022	0.1/0.15	1.8

"U" based on M = Richter magnitude = 6.5



1/1 PHASE 6A LINER SYSTEM SECTION
N.T.S.



CROSS SECTION STATION A-A'
SCALE: 1" = 100-FT VERTICAL AND HORIZONTAL

SOIL NUMBER	SOIL DESCRIPTION	COHESION (PSF)	FRICTION ANGLE (DEGREES)	UNIT WEIGHT (PCF)
1	BEDROCK	10000	0	140
2	SUBBASE	455	15.1	130
3	COMPACTED SOIL LINER	455	15.1	130
4	GCL vs. TEXT. HDPE (RESIDUAL)	NON-LINEAR		100
5	GCL vs. TEXT. HDPE (RESIDUAL)	NON-LINEAR		100
6	DRAINAGE LAYER (D.L.)	0	30	120
7	GEOTEXTILE/D.L. INTERFACE	0	26	100
8	SATURATED SOLID WASTE	NON-LINEAR		75

ABILITY ANALYSIS - SECTIC
CIRCULAR/WEDGE FAILURE ANALYSIS 2.5:1

DWG. BY: CWA	APPROVED BY:	SCALE:	DATE:	PROJ. NO:

Infinite Slope with No Water

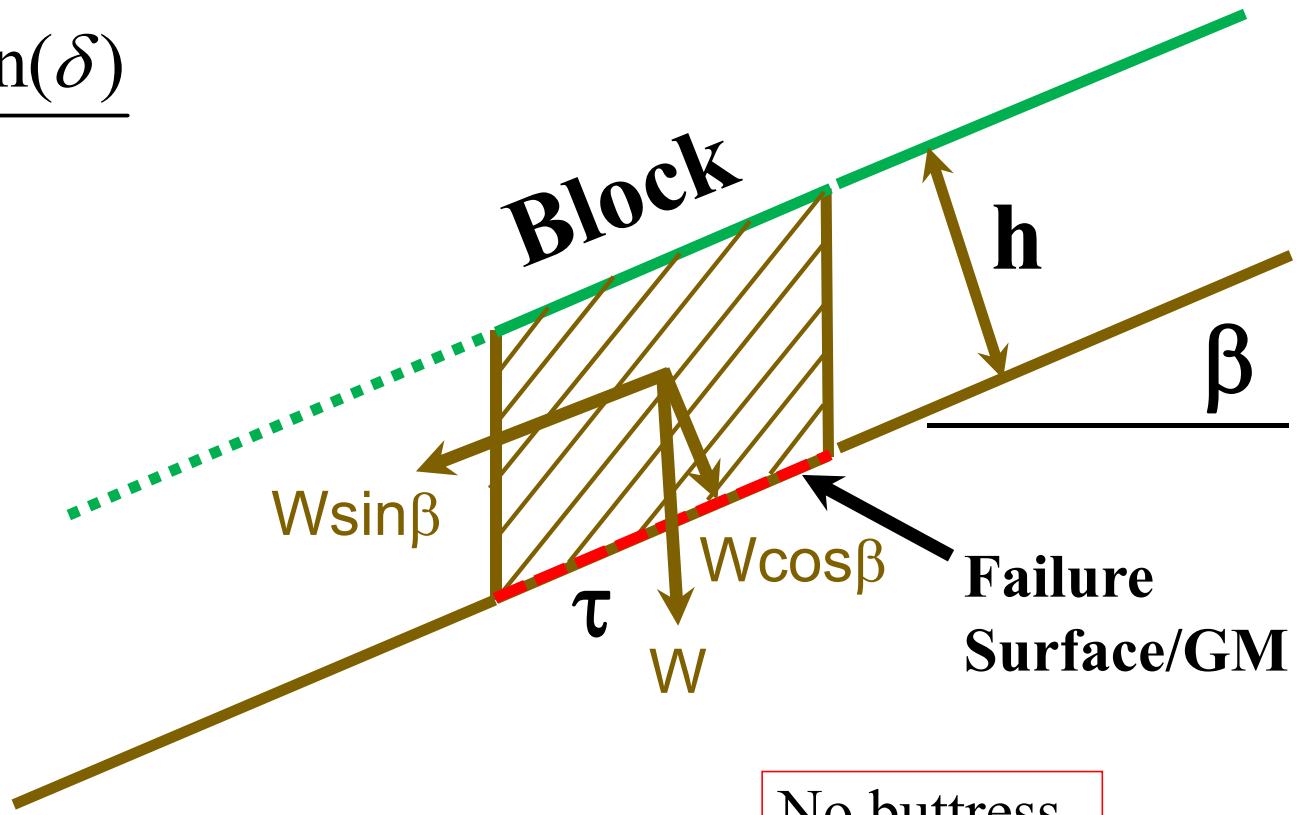
$$FS = \frac{W * \cos(\beta) * \tan(\delta)}{W * \sin(\beta)}$$

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

δ = interface friction angle

β = slope angle

W = γ*h = cover weight



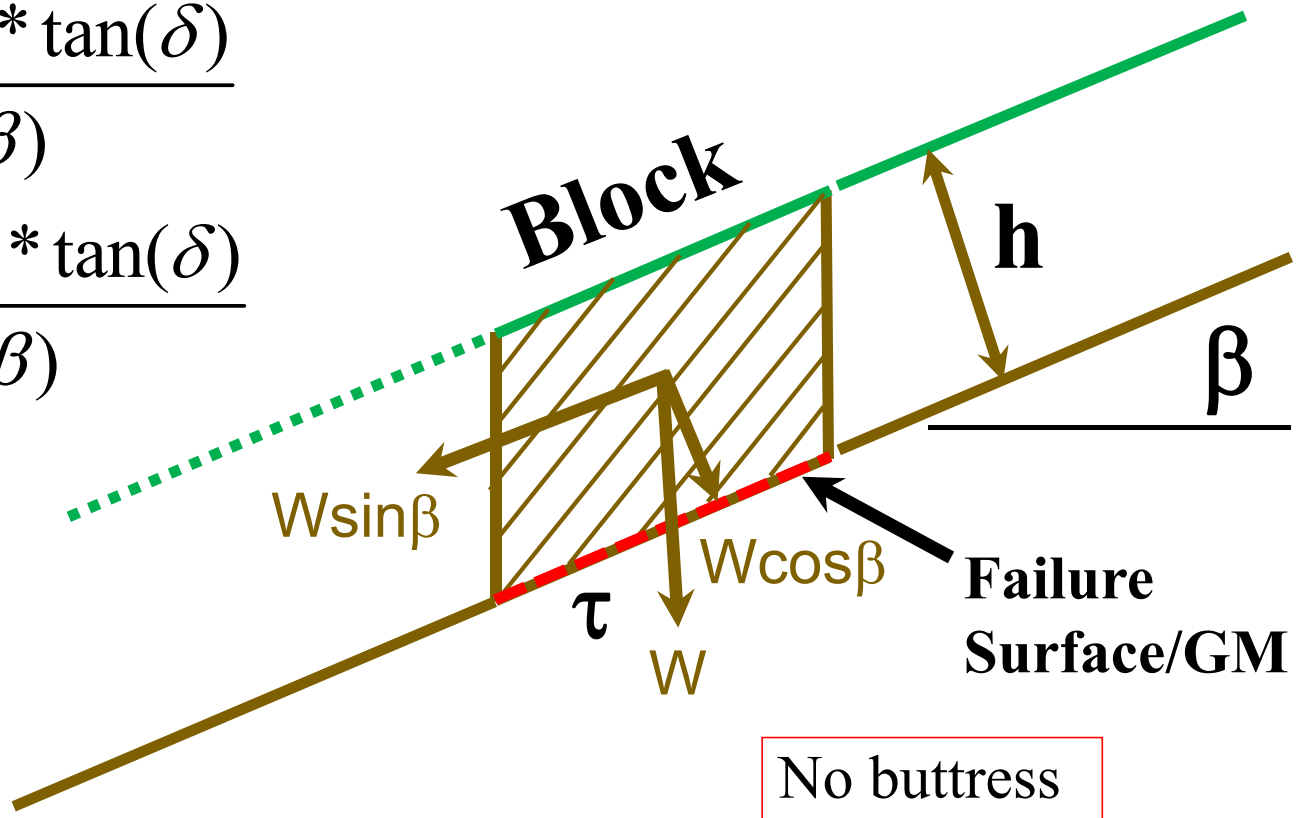
No buttress
No tension

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
γ = cover unit weight



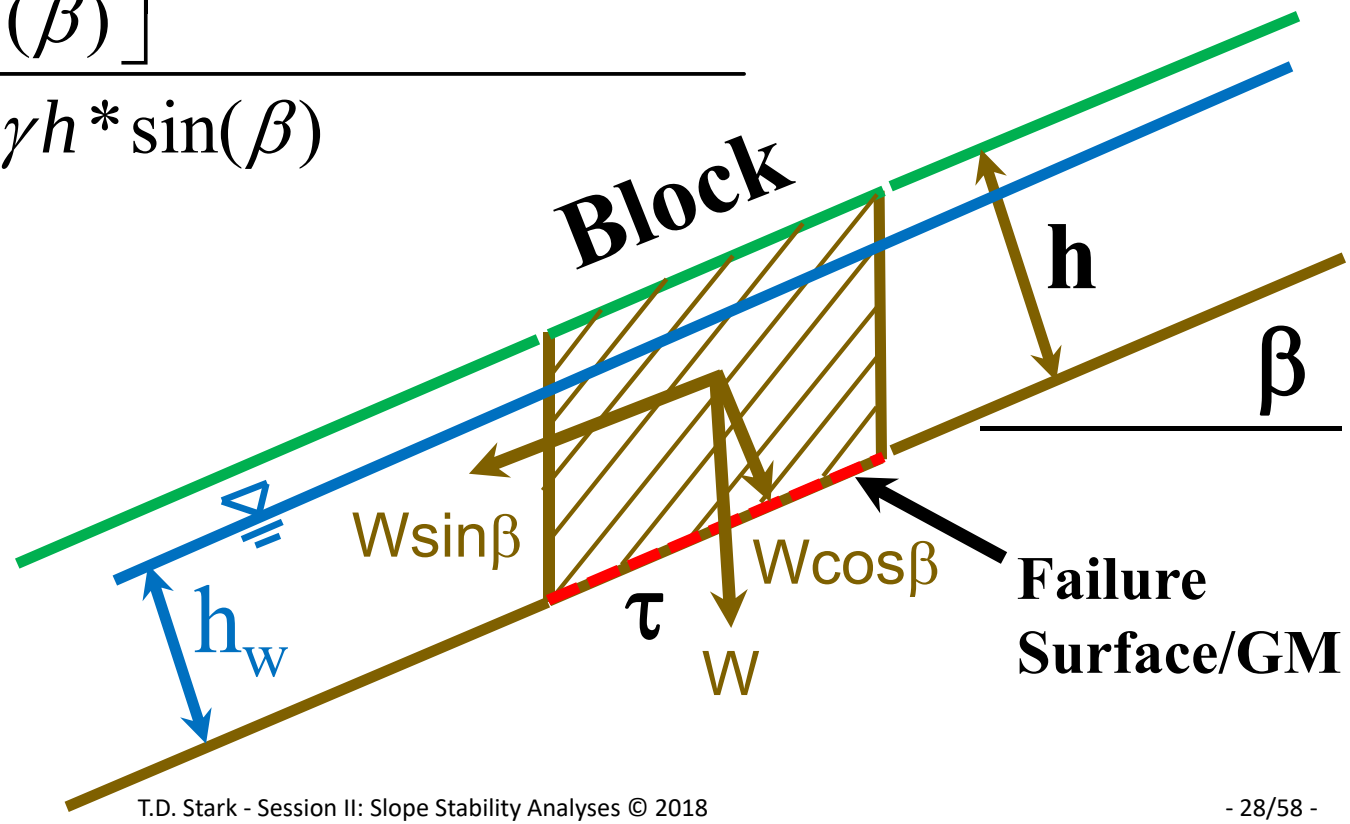
No buttress
No tension

Infinite Slope with Adhesion & Water

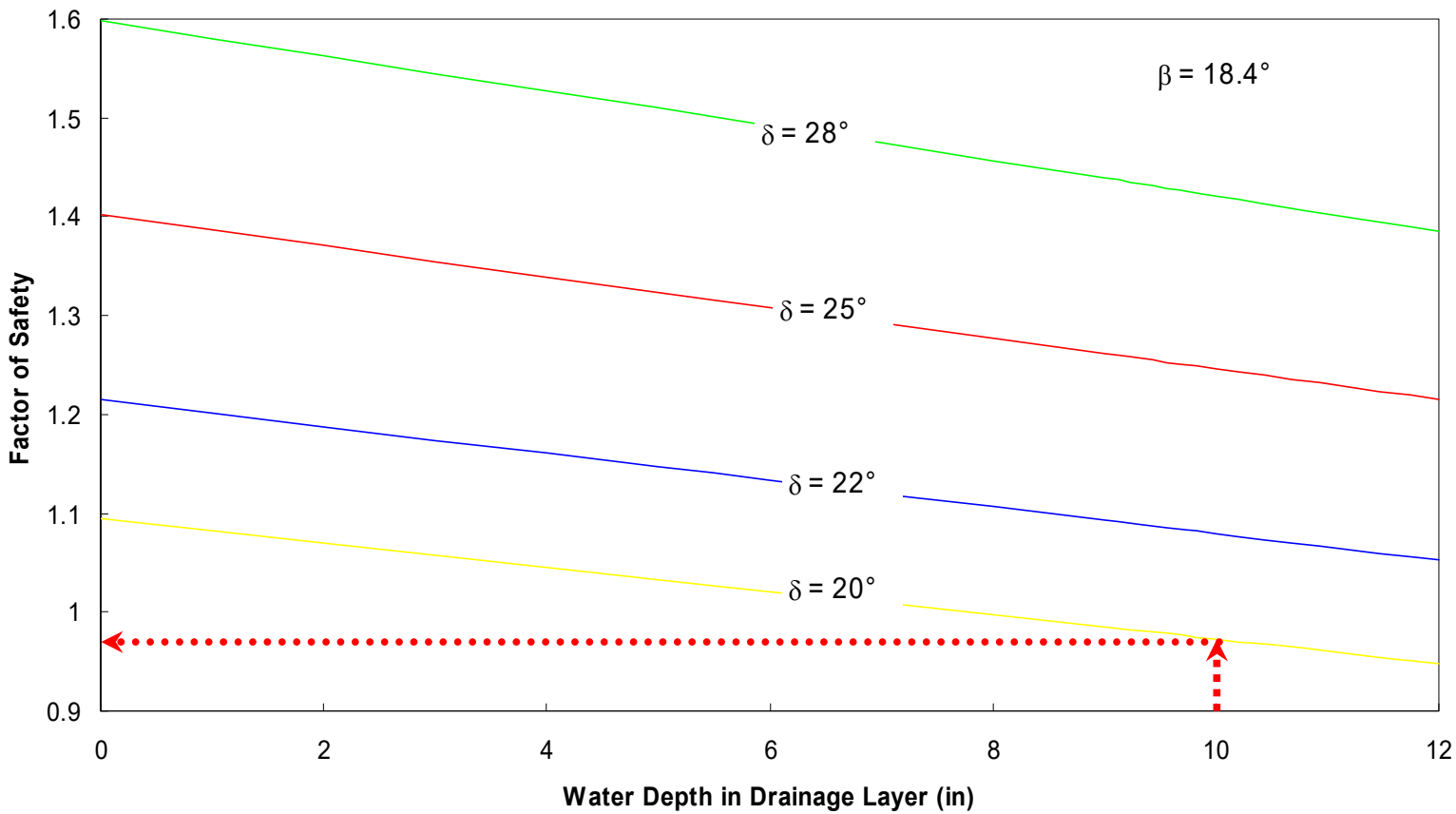
$$FS = \frac{a + \left[\gamma h - \frac{\gamma_w h_w}{\cos^2(\beta)}\right]\gamma h * \cos(\beta) * \tan(\delta)}{\gamma h * \sin(\beta)}$$

h_w = water depth on GM

γ_w = water unit weight



Effect of Water and δ



Drainage Above Geomembrane

Terram Geosynthetics

Seismic Infinite Slope Analysis

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

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

- 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 = interface adhesion
δ = interface friction
ϕ = cover soil friction angle
c = cover soil cohesion
β = slope angle
γ = cover soil unit weight
h = soil cover thickness
H = vertical slope height
T = geosynthetic tension

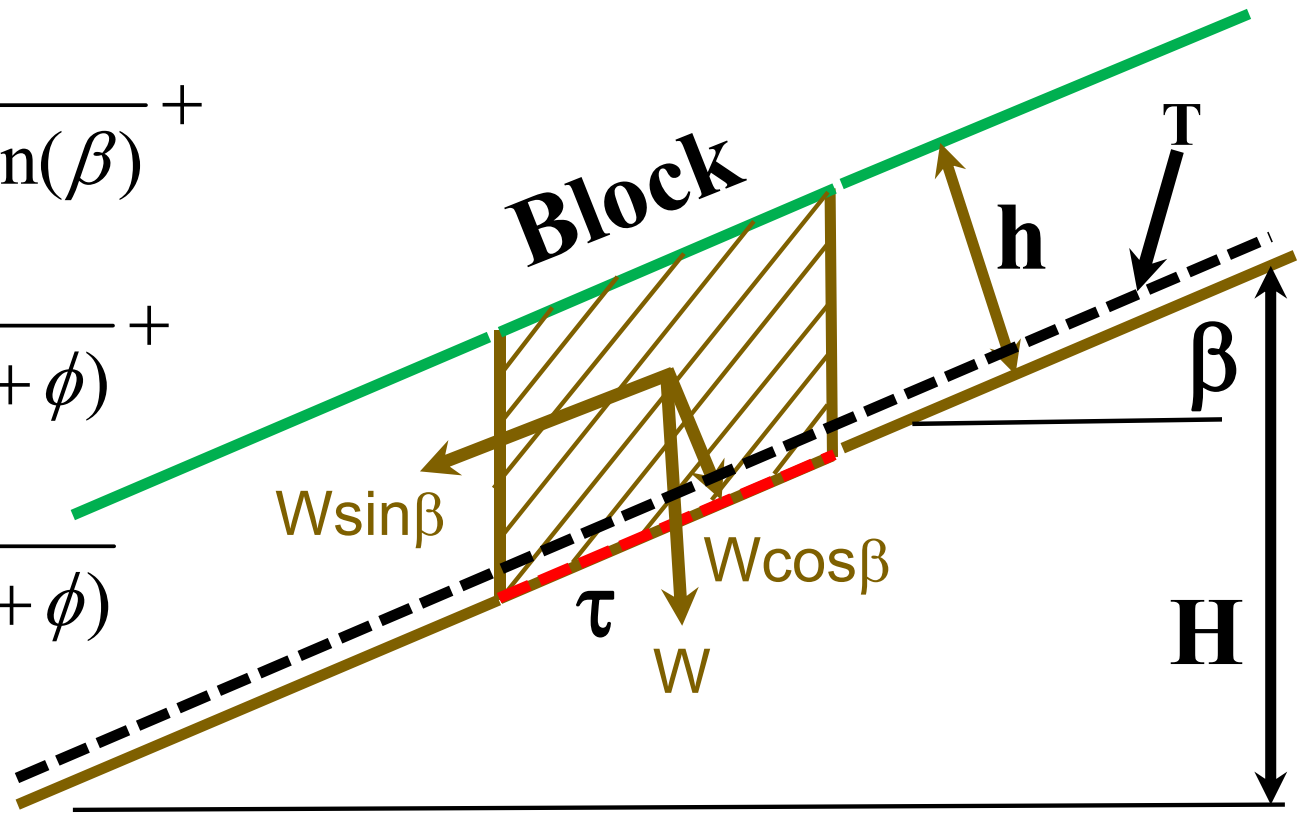
Slope with Reinforcement

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

$$+ \frac{h}{H} * \frac{\sin(\phi)}{\sin(2\beta)\cos(\beta+\phi)} +$$

$$+ \frac{c}{\gamma H} * \frac{\cos(\phi)}{\sin(\beta)\cos(\beta+\phi)}$$

$$+ \frac{T}{\gamma H * h}$$



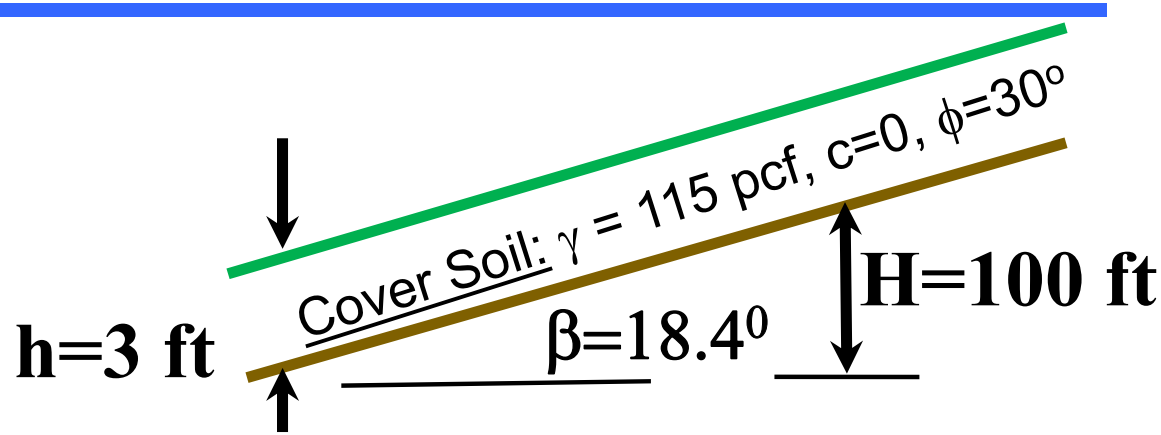
Reinforcement Design Example

Geosynthetic Data

δ = 14°

a = 0

NO Reinforcement (T=0)



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

$$FS = \frac{\tan\delta}{\tan\beta} + \left(\frac{h}{H}\right)\frac{\sin\phi}{\sin(2\beta)\cos(\beta+\phi)}$$

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

$$FS = 0.75 + 0.04 = 0.79$$

$$\boxed{FS = 0.79}$$

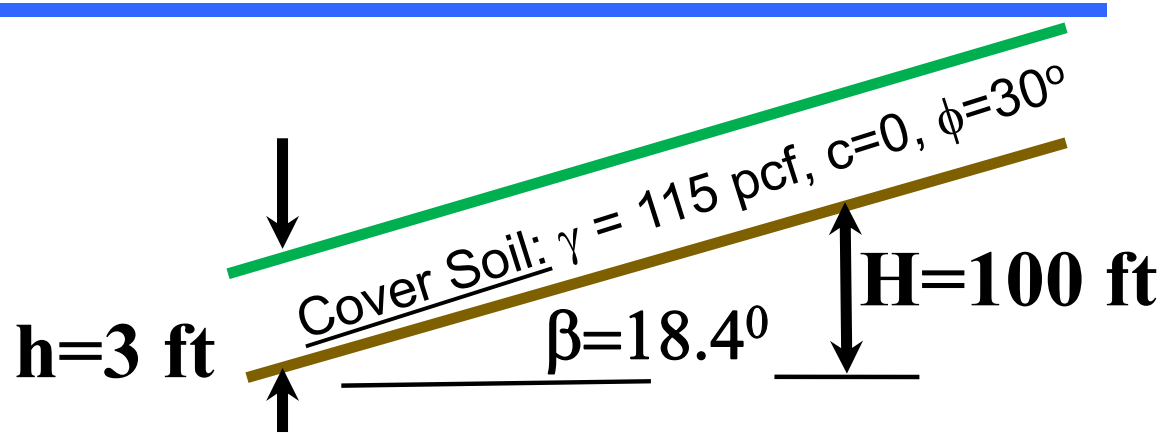
Reinforcement Required for FS≥1.5

Geosynthetic Data

$\delta = 14^o$

a = 0

T_{Reqd}=?



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

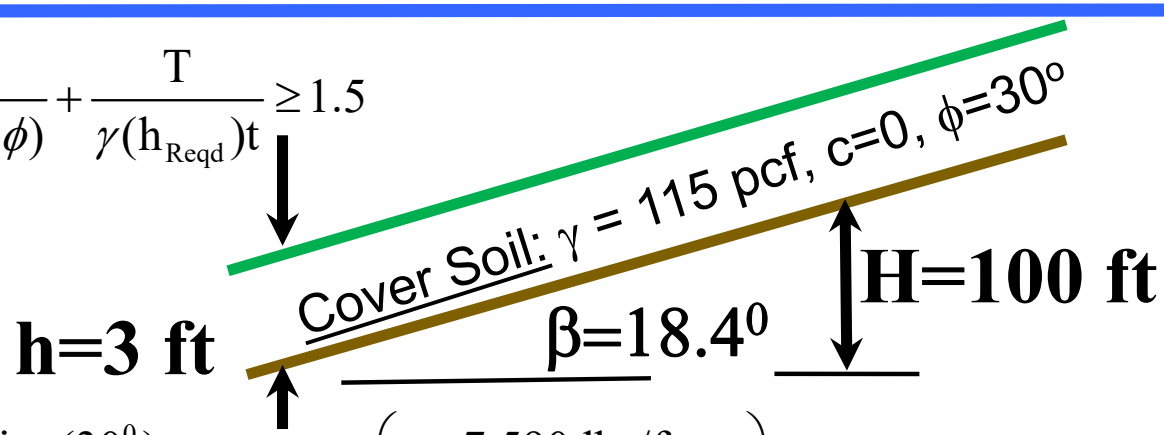
$$FS = \frac{\tan(14^o)}{\tan(18.4^o)} + \left(\frac{3'}{100'}\right)\frac{\sin(30^o)}{\sin(2*18.4^o)\cos(18.4^o+30^o)} + \frac{T_{Reqd}}{\gamma H * h} \geq 1.5$$

$$FS = 0.75 + 0.04 + \frac{T_{Reqd}}{115\,pcf\,(100\,ft)(3\,ft)} \geq 1.5$$

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

Max Slope Height for FS≥1.5 & T=7,590 lbs/ft

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



$$FS = \frac{\tan(14^0)}{\tan(18.4^0)} + \left(\frac{3\text{ ft}}{h_{Reqd}}\right)\frac{\sin(30^0)}{\sin(2*18.4^0)\cos(14^0+30^0)} + \left(\frac{7{,}590\text{ lbs/ft}}{115\text{pcf}*h_{Reqd}(3\,ft)}\right)$$

$$= 0.75 + \left(\frac{3.8}{h_{Reqd}}\right) + \left(\frac{22}{h_{Reqd}}\right) \geq 1.5$$

$$+ \left(\frac{25.8}{h_{Reqd}}\right) \geq 0.75$$

$$h_{Reqd} \leq 34.4\,ft$$

Geosynthetic Data

δ = 14°
a = 0
T=7,590 lbs/ft

Topics

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- Critical failure surface
- Slope stability methods
- 2D v. 3D stability analyses
- MSW Shear Strength
- Summary

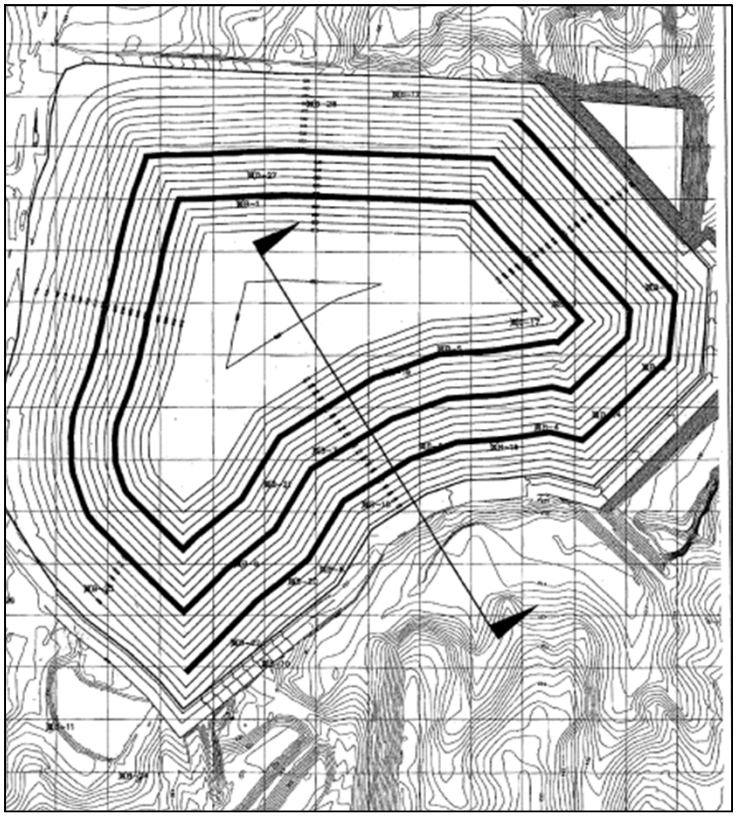
2D v. 3D Slope Stability

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

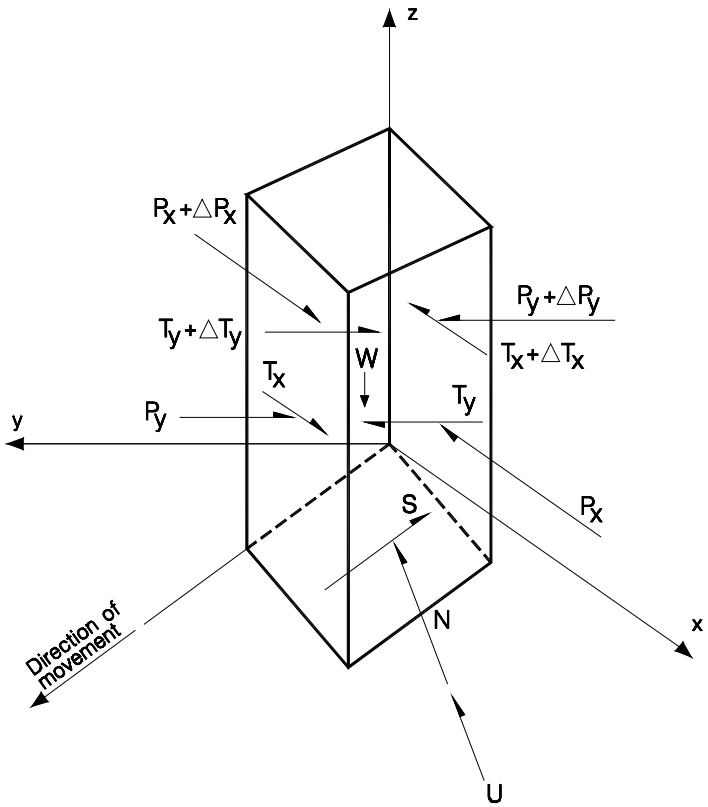
Comparison of 2D & 3D Stability

- $F_{3D} \geq F_{2D}$ 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 = Total weight of column

N = Normal force at the base

S = Resisting shear force at the base

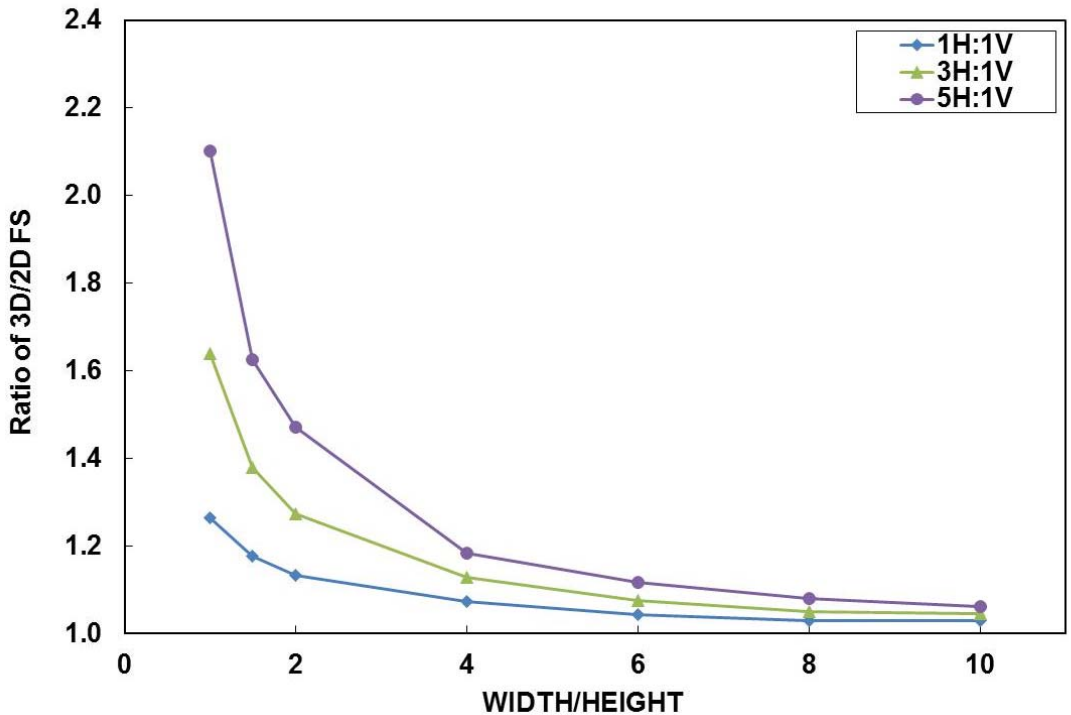
U = Pore water pressure resultant

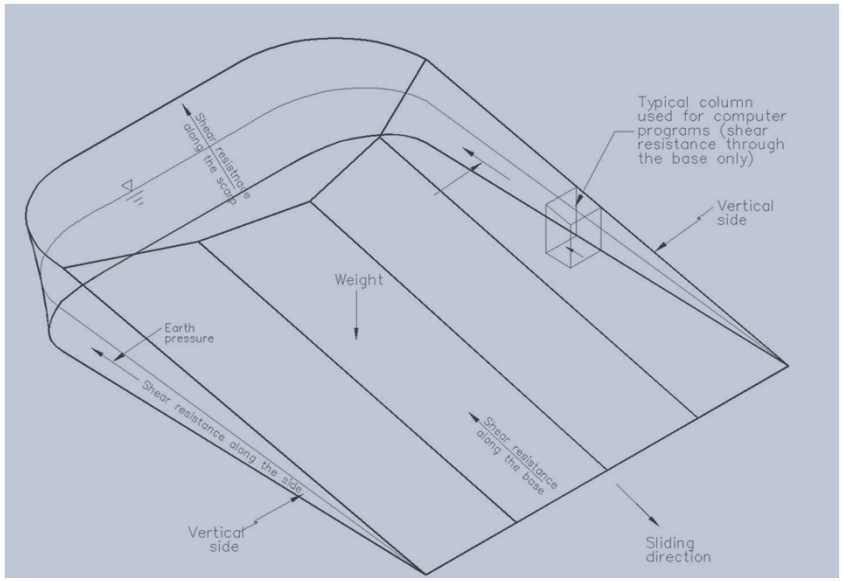
P_i and T_i = Intercolumn normal forces and horizontal shear forces in "i" direction, respectively

$\triangle P_i$ and $\triangle T_i$ = Change in intercolumn normal forces and horizontal shear forces in the "i" direction, respectively

Stark and Akhtar (2011)

Effects of 3D Side Resistance



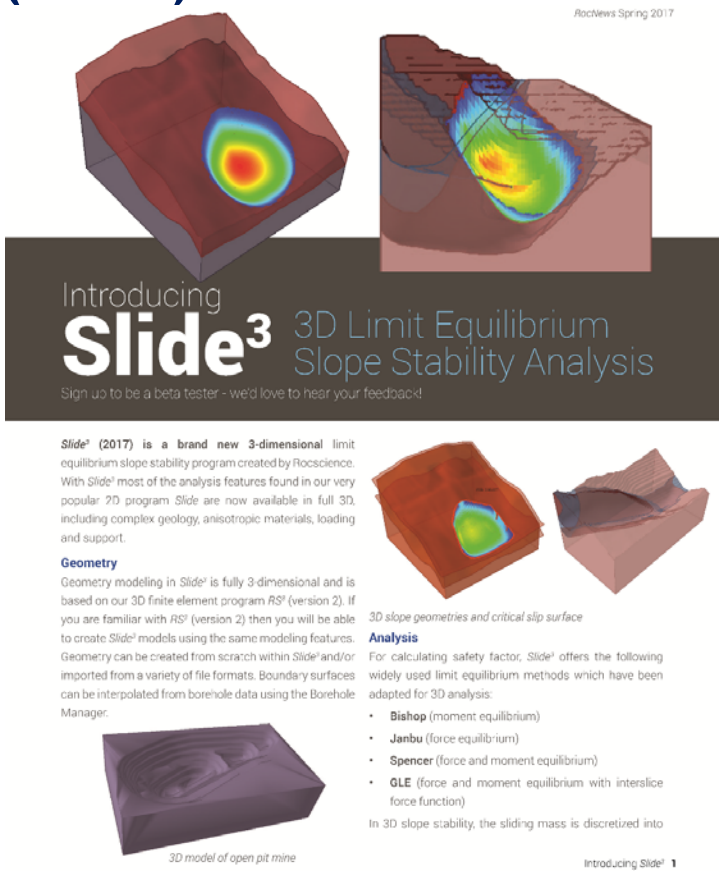


Stark and Akhtar (2011)

3D Slope Stability Software

- **CLARA 2.31 - Stark and Eid (1998)**
- **3DDEM-Slope**
- **Slide^3**

- **FLAC 3D**
- **PLAXIS 3D**
- **RS3**



RocNews Spring 2017

Introducing **Slide^3** 3D Limit Equilibrium Slope Stability Analysis

Sign up to be a beta tester - we'd love to hear your feedback!

***Slide^3* (2017) is a brand new 3-dimensional** limit equilibrium slope stability program created by Rocscience. With *Slide^3* most of the analysis features found in our very popular 2D program *Slide* are now available in full 3D, including complex geology, anisotropic materials, loading and support.

Geometry

Geometry modeling in *Slide^3* is fully 3-dimensional and is based on our 3D finite element program *RS^3* (version 2). If you are familiar with *RS^3* (version 2) then you will be able to create *Slide^3* models using the same modeling features. Geometry can be created from scratch within *Slide^3* and/or imported from a variety of file formats. Boundary surfaces can be interpolated from borehole data using the Borehole Manager.

3D model of open pit mine

3D slope geometries and critical slip surface

Analysis

For calculating safety factor, *Slide^3* offers the following widely used limit equilibrium methods which have been adapted for 3D analysis:

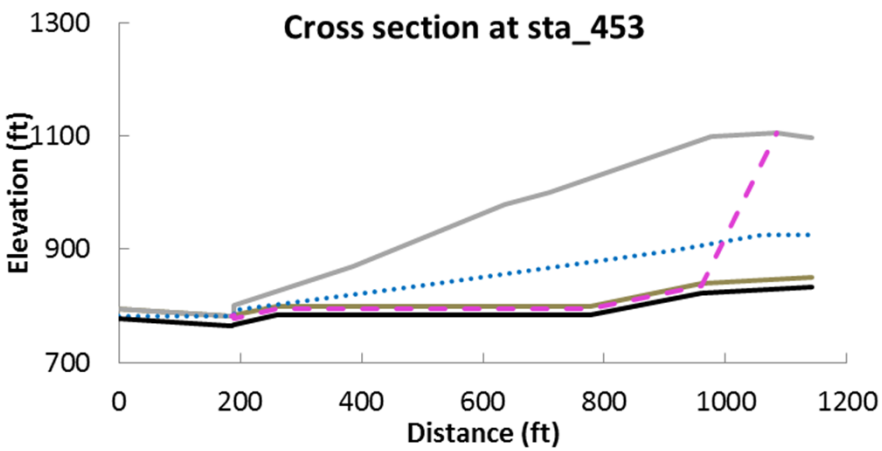
- **Bishop** (moment equilibrium)
- **Janbu** (force equilibrium)
- **Spencer** (force and moment equilibrium)
- **GLE** (force and moment equilibrium with interslice force function)

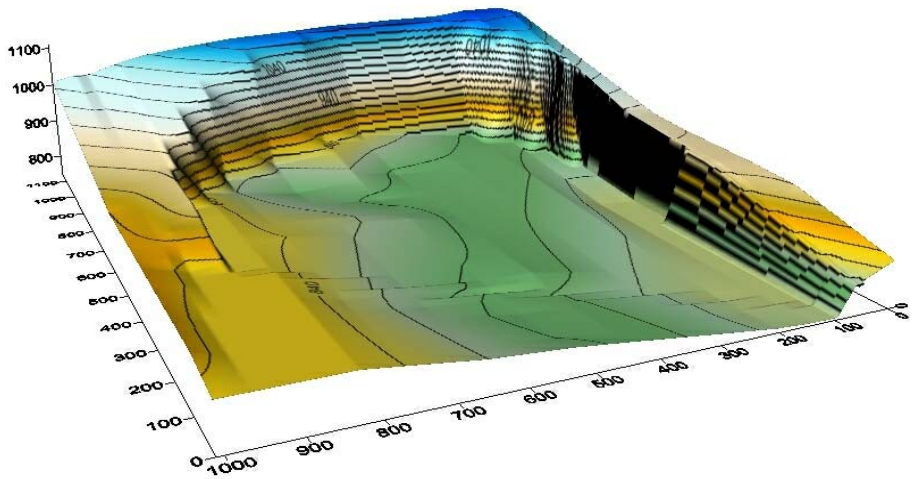
In 3D slope stability, the sliding mass is discretized into

Introducing *Slide^3* 1

3D Effects in Inverse-Analyses

- Translational failure
- Large MSW slope failure
- Stark et al. (2000)
- Slide mass » 1,000,000 m^3
- Average slope = 21°



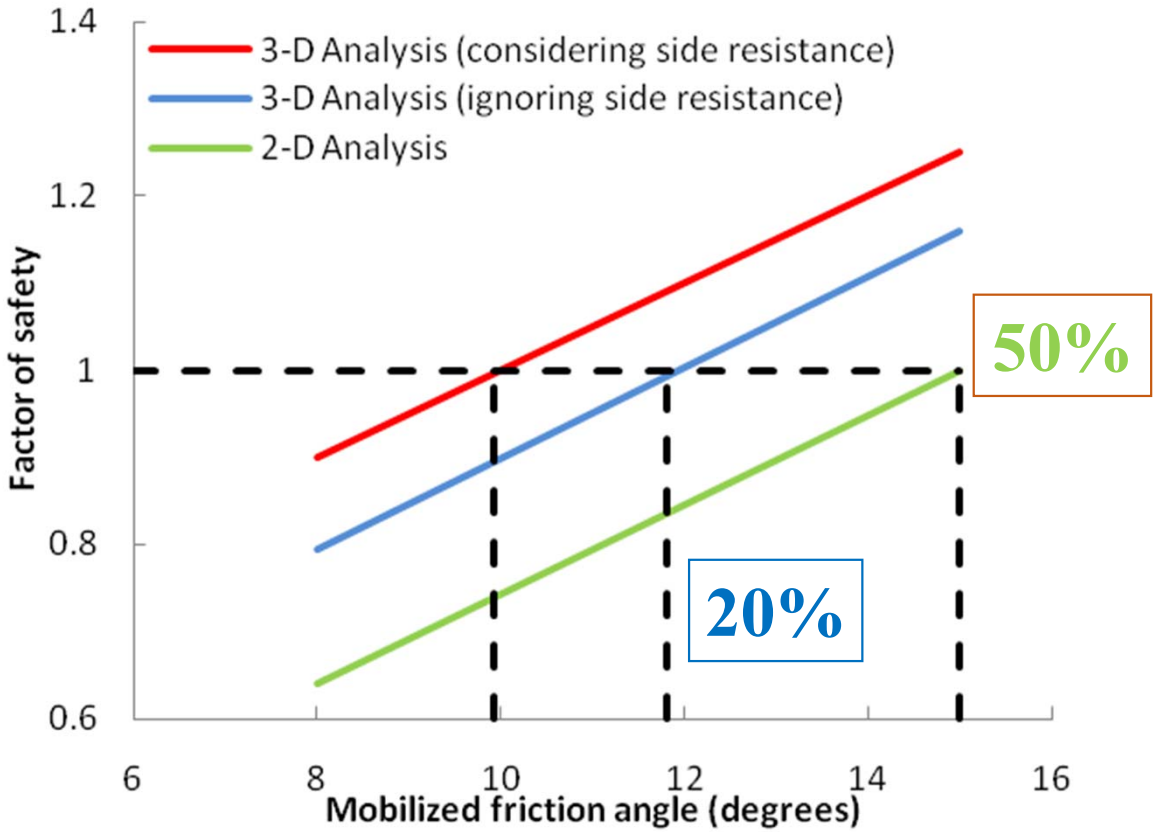


3D Effects in Inverse-Analyses

- **Results - 3D matches laboratory shear tests**

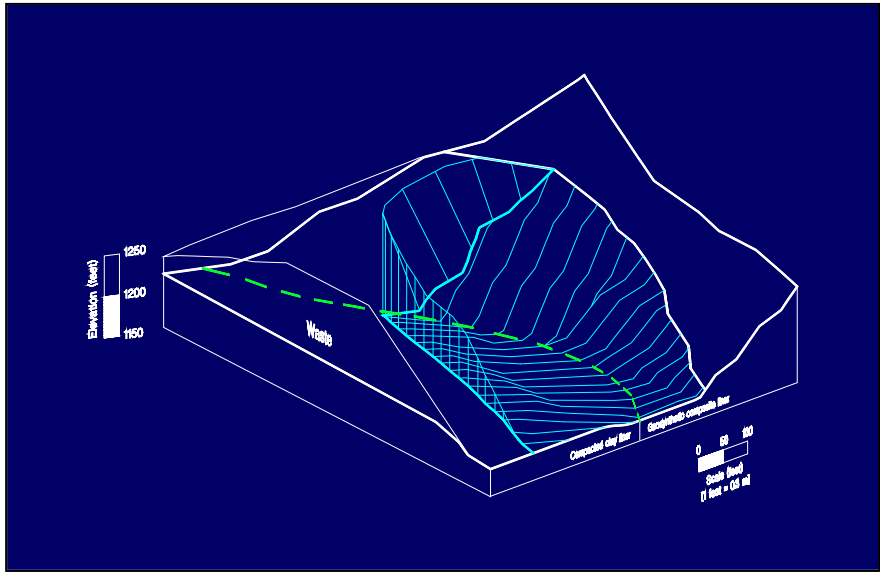
2D ANALYSIS OVERESTIMATES MOBILIZED FRICTION ANGLE BY 20-30%

Akhtar and Stark (2011)



3D Geometry

Stark and Eid (1998)



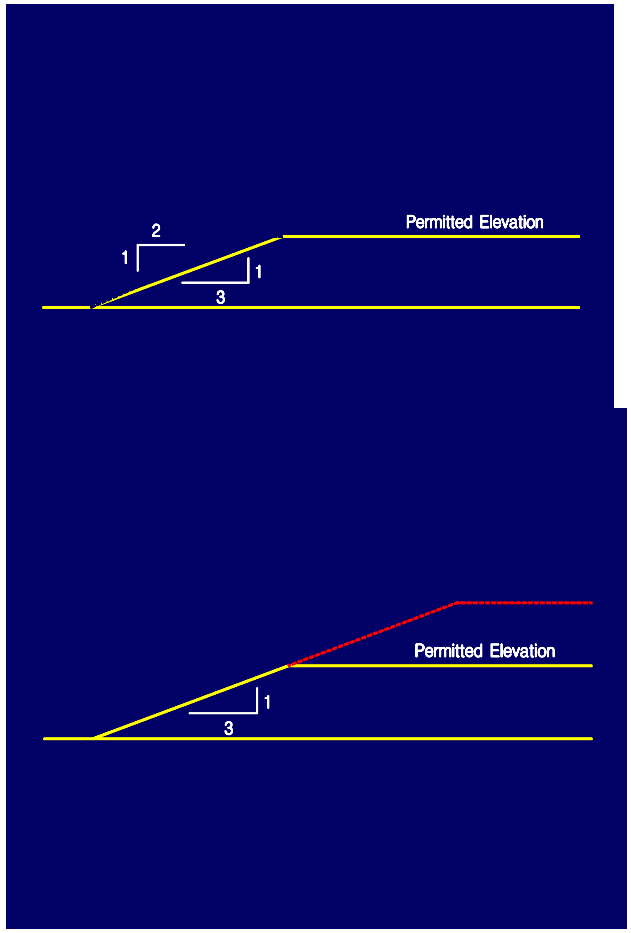
3D Geometry

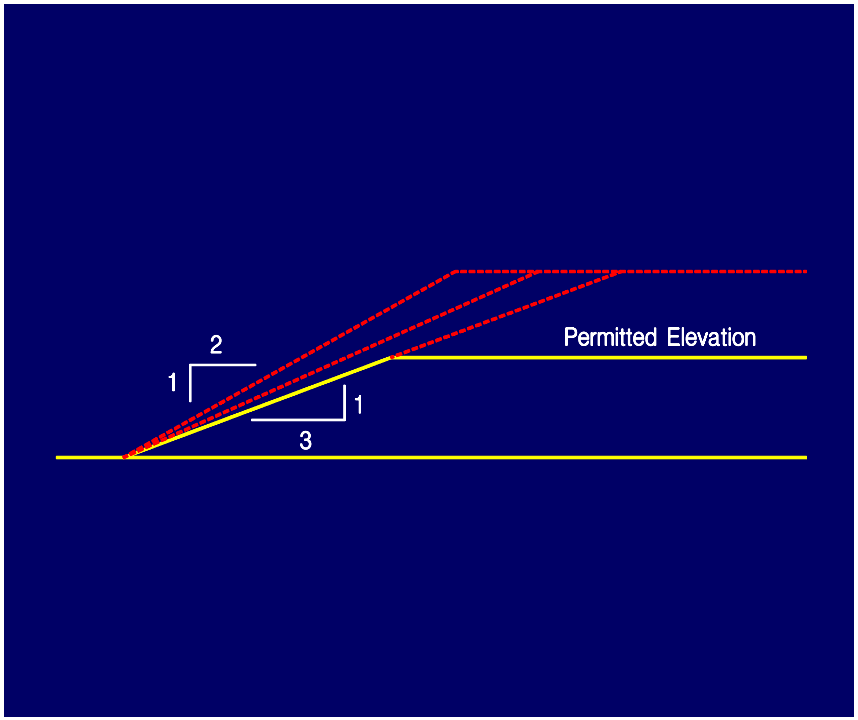
Stark and Eid (1998)

Mis-Use of 3D Analyses

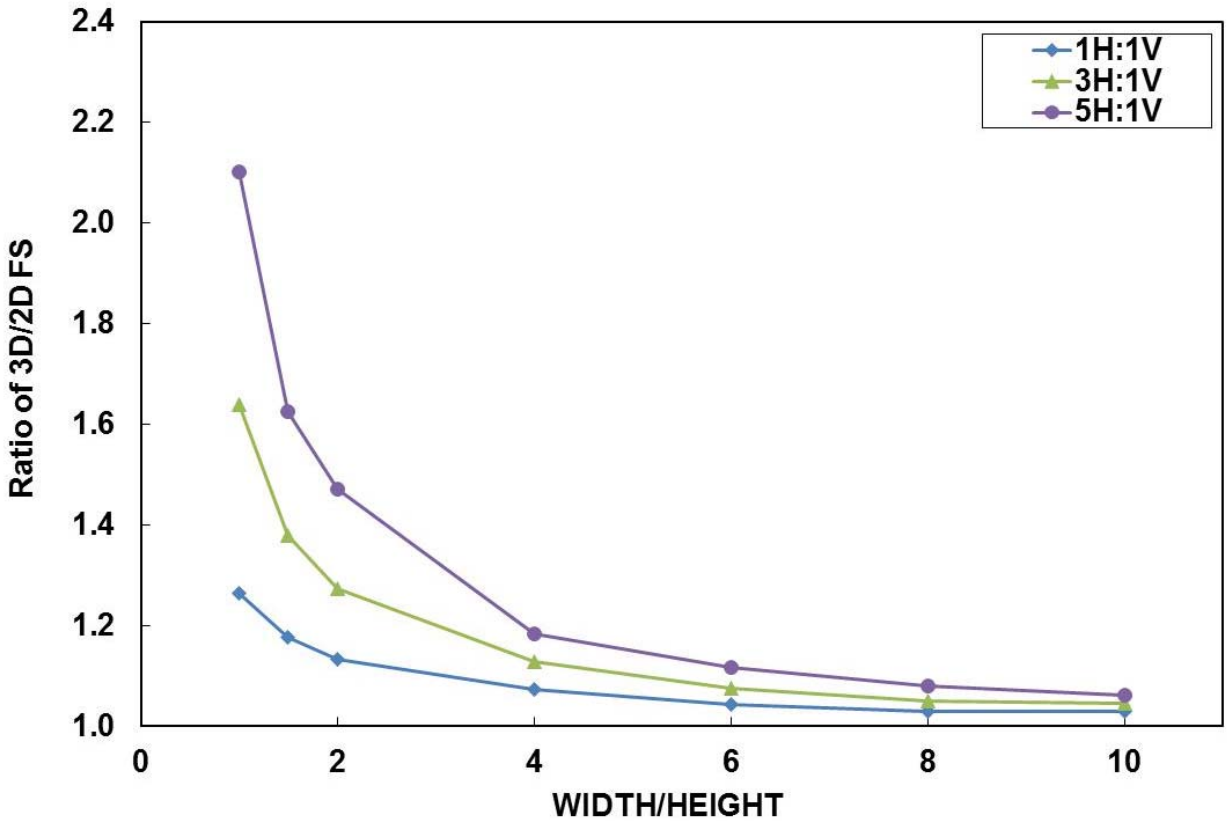
- **3D FS ≥ 2D FS For Appropriate Conditions**
- **NOT FOR MAXIMIZING SLOPES**
  REQUIRED 3D FS > 1.5
  UNCERTAINTIES IN SHEAR STRENGTHS
  TOO MANY FAILURES
- **NOT FOR SATISFYING REGULATIONS**

Mis-Use of 3D Analyses





REQUIRED 3D FACTOR OF SAFETY



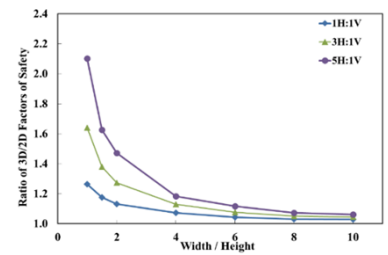
Stark & Akhtar (2011)

Required 3D FS = f(W/H)

Required 3-D Factor of Safety

- Most Conservative = 3-D FS Figure

$$FS_{3D-Min} = FS_{2D-Min} * Ratio_{3D/2D}$$



- 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)

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

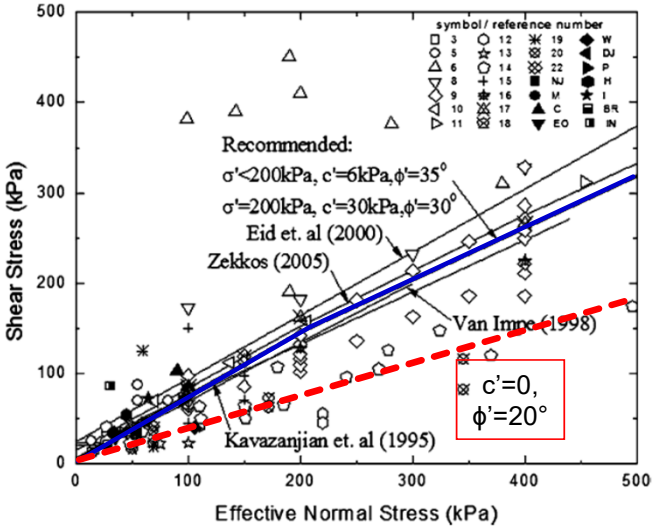
Summary of 3-D Analysis in Practice

- 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

Topics

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

MSW Shear Strength



(Stark et al. 2009)

<u>Normal</u>

- c'= 6 kPa, ϕ'=35° $\sigma'_v < 200$ kPa
- c'= 30 kPa, ϕ'=30° $\sigma'_v \geq 200$ kPa

<u>Thermally Degraded</u>

- c'= 0 kPa, ϕ'=20°

Summary

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

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Questions, Comments, Experiences...

Discussion

Session II: Slope Stability Analyses

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