SANBORN HEAD

Understanding Landfill Slope Failures and How to Prevent Them

Purpose and Learning Objectives

At the end of the presentation, you will be able to:

1. Identify when an evaluation of an engineered slope is required
2. Understand the theory behind commonly used analytical methods
3. Understand the types of laboratory tests performed to obtain engineering parameters
4. Apply the slope stability analytical methods to an engineered slope of concern
5. Evaluate the results of slope stability analyses

Outline

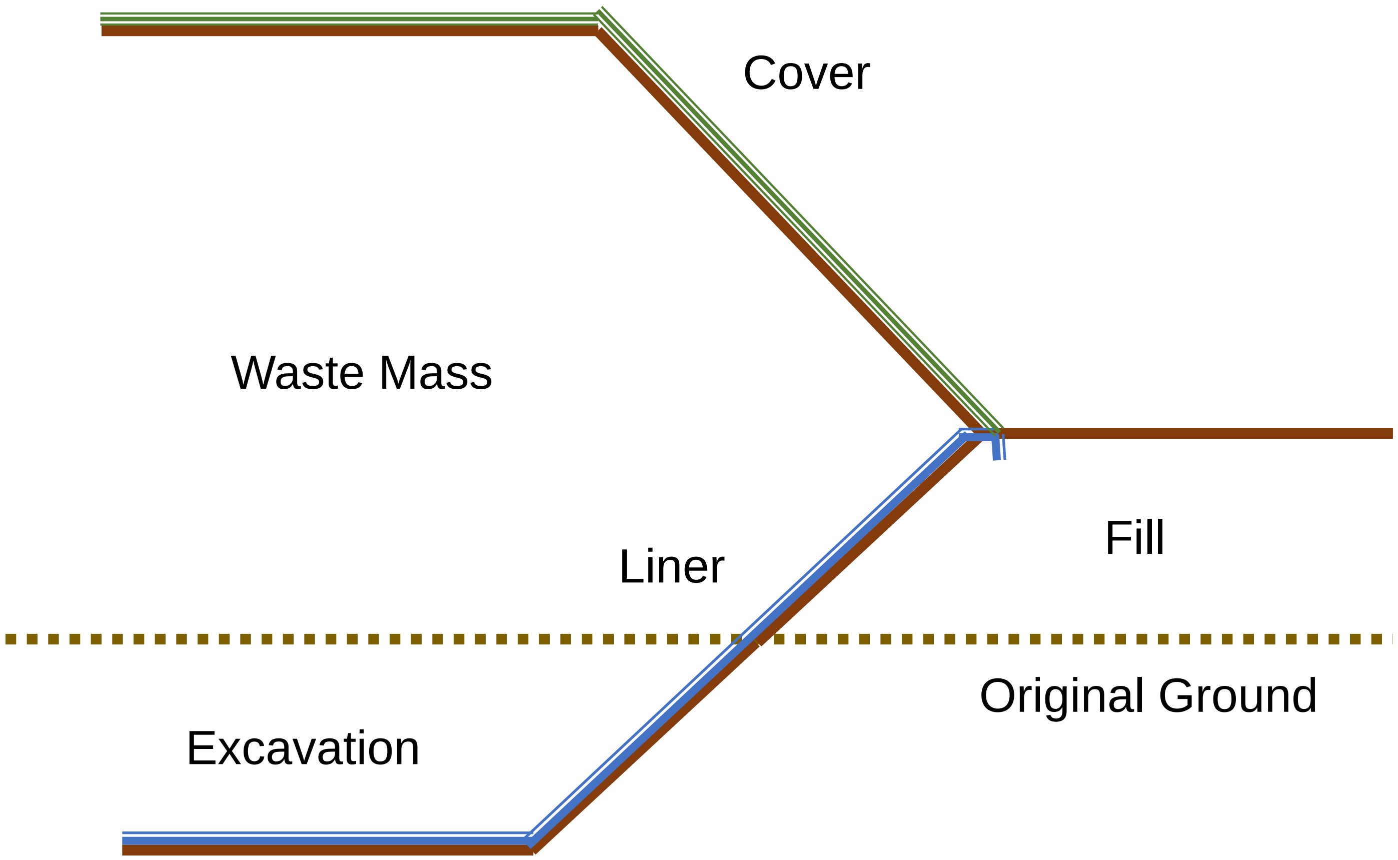
- Potential slope failure modes
- Components of a geosynthetic-lined landfill slope
- Factor of Safety
- Analytical methods
- Material testing methods
- Other considerations
- Construction specification recommendations
- Thoughts on preventing slope failures

Let's go to the polls

1. Rate your experience related to landfill slope evaluations.
2. Global stability is ________________.

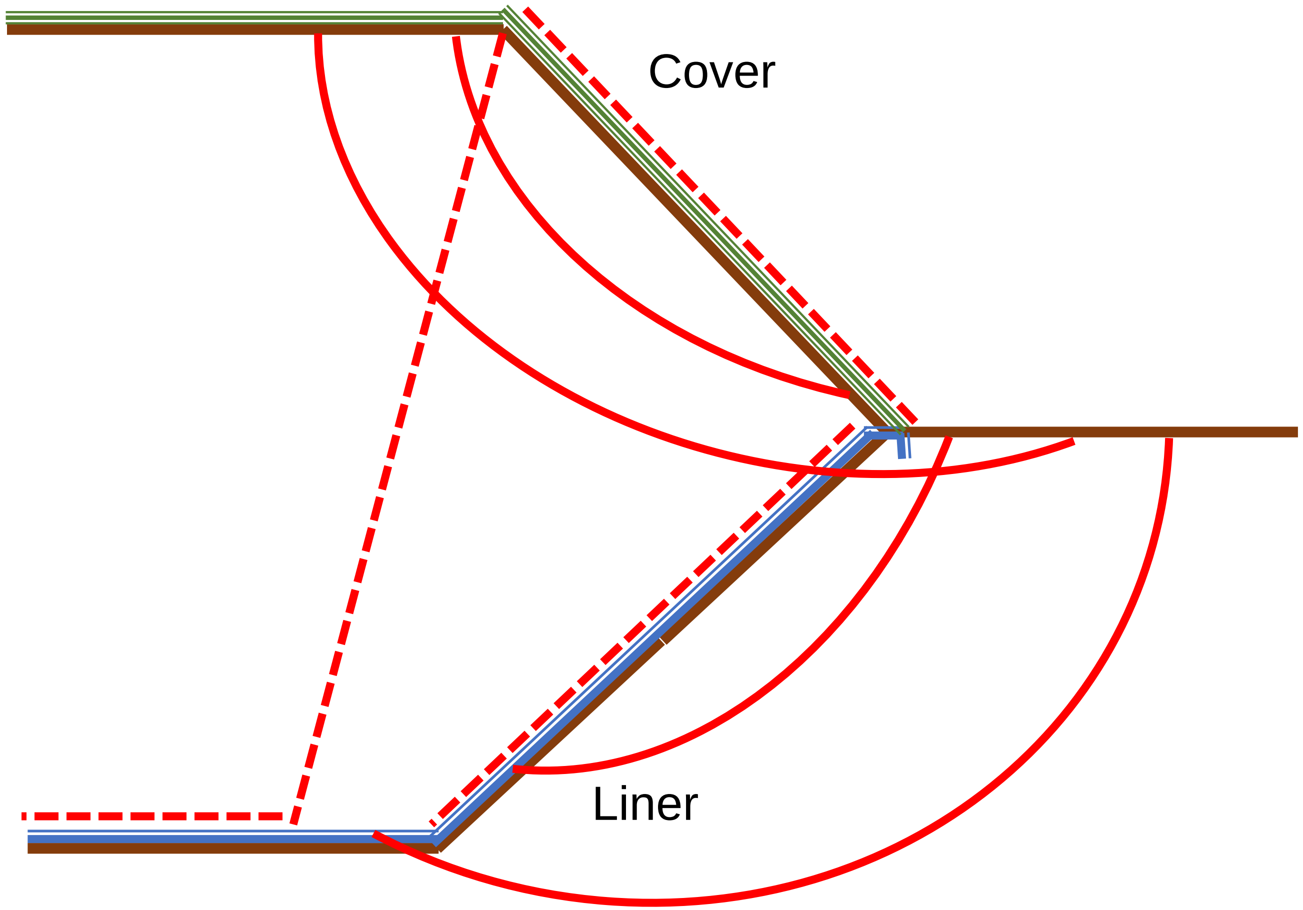
Landfill Slope Types

- Cut Slope
- Fill Slope
- Liner System
- Waste Mass
- Cover System

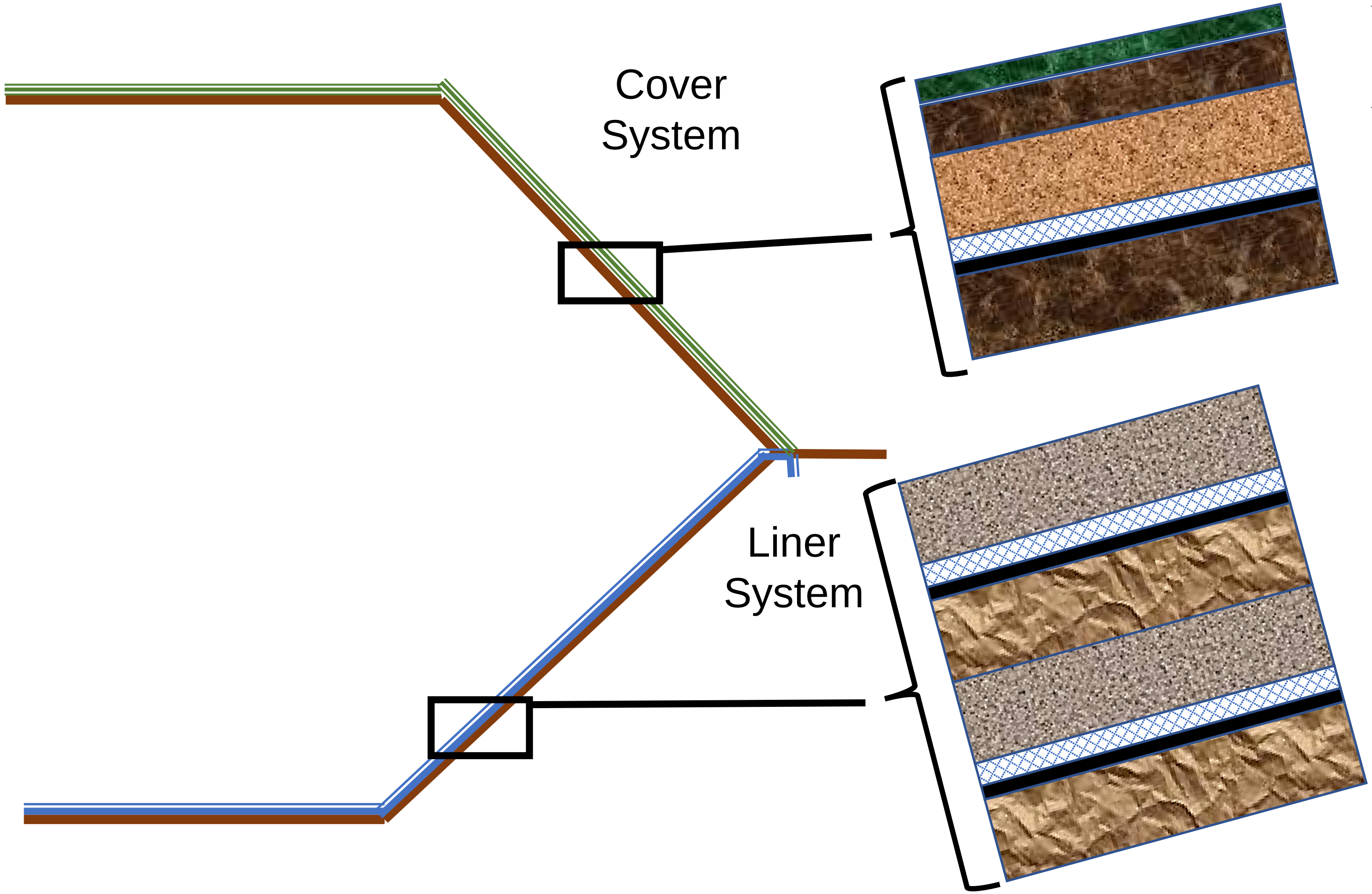


Potential slope failure modes

- Circular
  - Waste
  - Soil
- Block
  - Liner system
- Veneer
  - Cover system
  - Liner system



Geosynthetic-Lined Slope



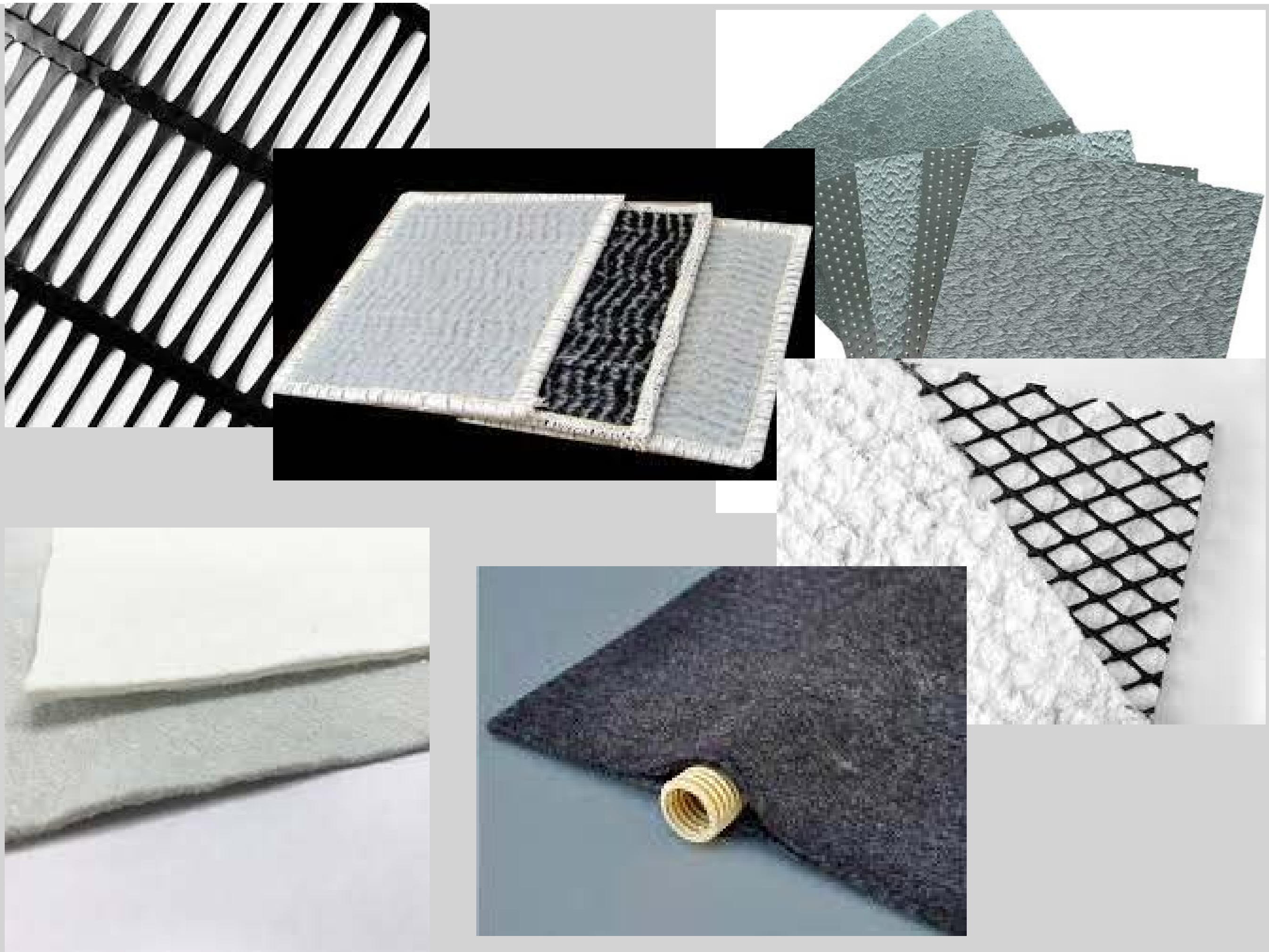
Vegetation
Topsoil
Vegetative Support Soil
Drainage Geocomposite
Geomembrane
Cover Soil

Leachate Collection
Drainage Geocomposite (P)
Geomembrane (P)
Low Permeability Soil (P)
Leachate Detection
Drainage Geocomposite (S)
Geomembrane (S)
Low Permeability Soil (S)

P = Primary
S = Secondary

Slope Materials

1. Natural soil
2. Fill soil
3. Drainage soil (aggregate)
4. Geosynthetics
    a. Geogrid
    b. Geomembrane
    c. Geosynthetic clay liner
    d. Drainage geocomposite
    e. Geotextile



What is Factor of Safety?

Factor of Safety (FS) = ratio of capacity to demand.

$$FS = \frac{\sum \text{Resisting Forces}}{\sum \text{Driving Forces}}$$

- FS > 1.0 indicates that the slope is stable and the resisting forces of the slope along the slip surface exceed that of the driving forces.
- FS < 1.0 indicates that the slope is unstable and the resisting forces of the slope along the slip surface are less than the driving forces.

What is Limit Equilibrium?

- Limit Equilibrium = FS is constant over the entire slip surface.

$$\mathrm{FS} = \frac{\text{available shear strength (s)}}{\text{equilibrium shear stress } (\tau)}$$

$$s = c + \sigma \tan \emptyset \quad \text{[total stress]}$$

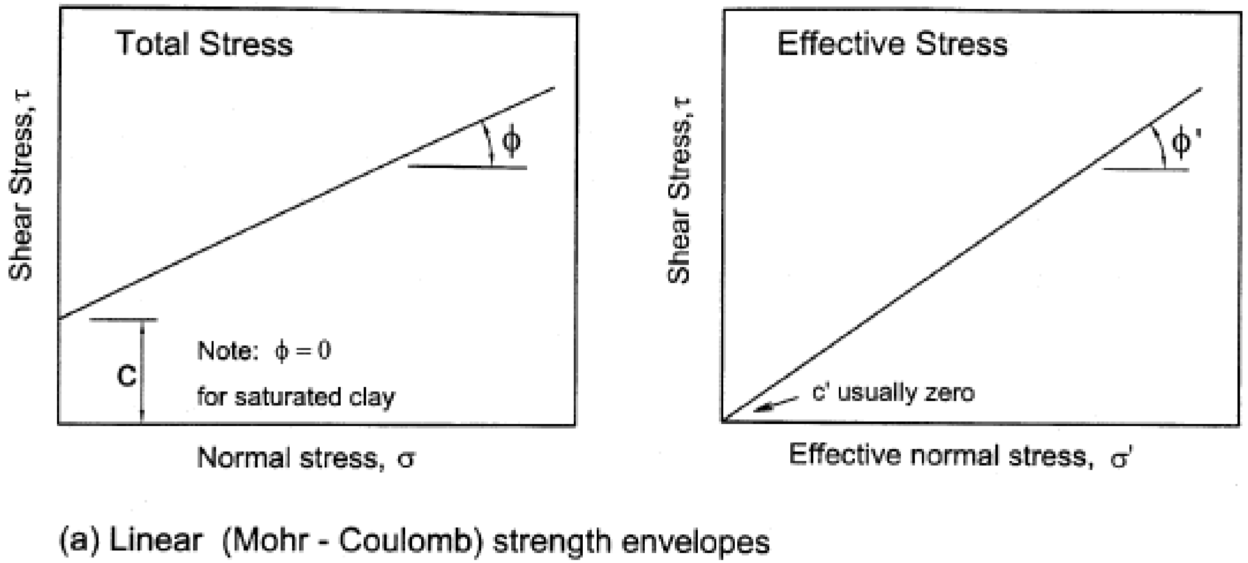
$$s = c' + (\sigma - \mathrm{u}) \tan \emptyset' \quad \text{[effective stress]}$$

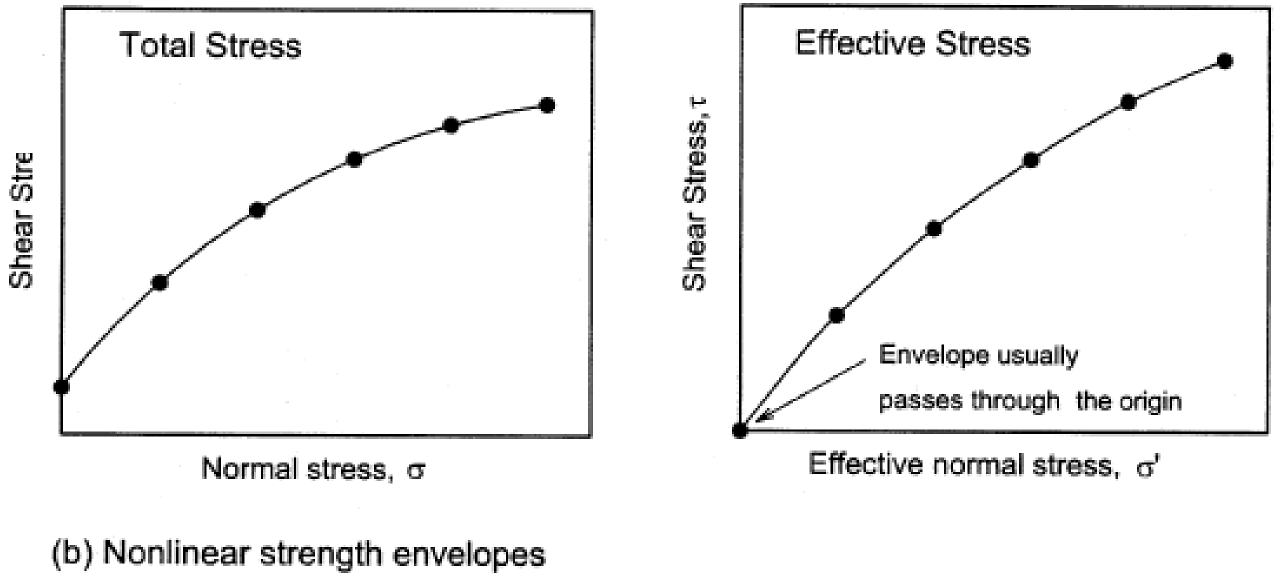
c and c' = Mohr-Coulomb cohesion, total and effective stress, respectively

$\emptyset$ and $\emptyset'$ = Mohr-Coulomb friction angle, total and effective stress, respectively

σ = Normal stress u = Pore pressure

Mohr-Coulomb Failure Diagram

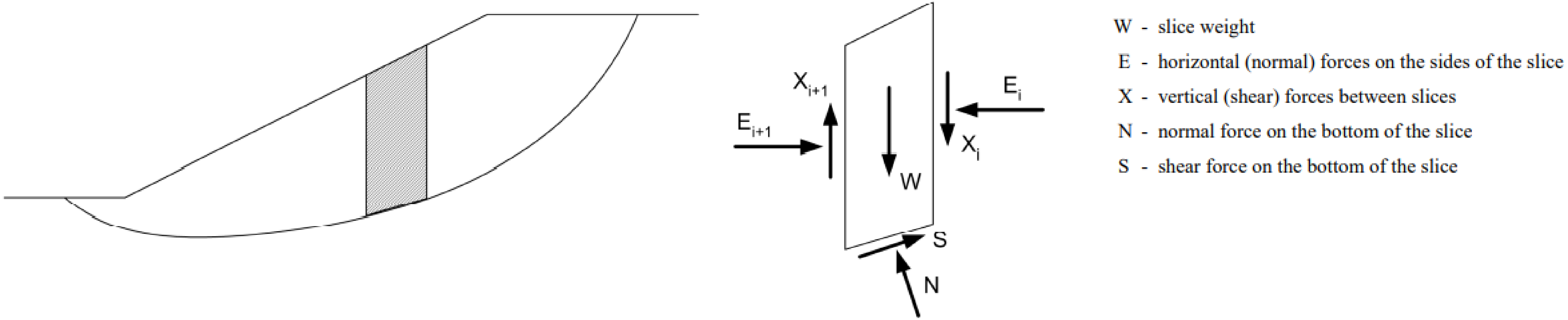




Reference: US Army Corps of Engineers (2003), Slope Stability, Engineering Manual, EM 1110-2-1902 Figure 2-1.

Analytical methods

Most common analytical methods calculate the FS by evaluating the 2-D slope in slices – static equilibrium – but the resulting FBD is statically indeterminate → assumptions must be made.

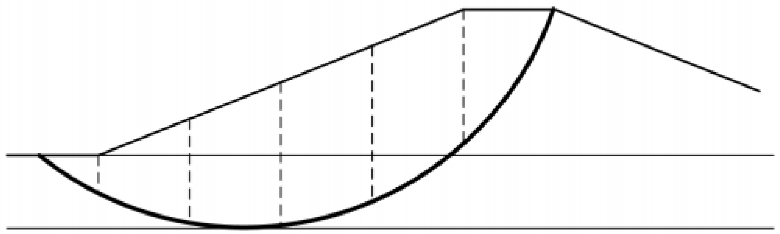


Reference: US Army Corps of Engineers (2003), Slope Stability, Engineering Manual, EM 1110-2-1902 Figure C-2.

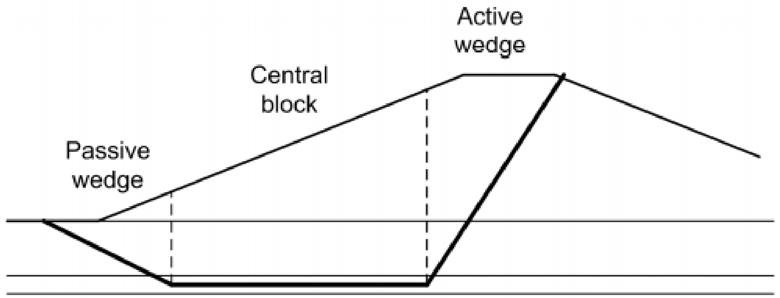
Analytical methods

- ❑ Calculation methods
  - ❑ Fellenius method (Ordinary Method of Slices)
  - ❑ Janbu's method
  - ❑ Simplified Bishop
  - ❑ Spencer's Method
  - ❑ Corps of Engineers' Modified Swedish Method
- ❑ Computer software

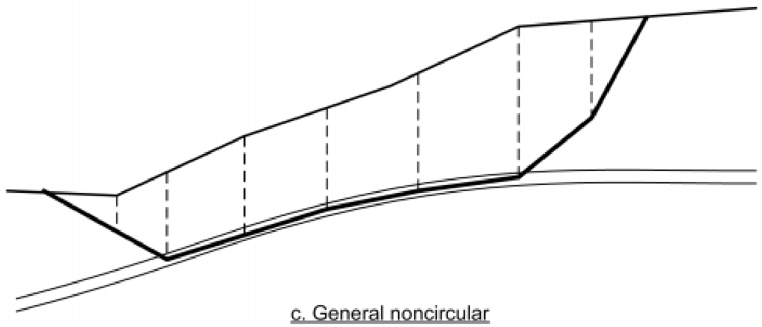
Reference: US Army Corps of Engineers (2003), Slope Stability, Engineering Manual, EM 1110-2-1902 Figure C-3.



a. Circular



b. Wedge



c. General noncircular

Material testing methods - Soil

- ❑ Unconsolidated-Undrained Triaxial Compression Test on Cohesive Soils (ASTM D2850)
- ❑ Consolidated Undrained Triaxial Compression Test for Cohesive Soils (ASTM D4767)
- ❑ Consolidated Drained Triaxial Compression Test for Soils (ASTM D7181)
- ❑ Direct Shear Test of Soils Under Consolidated Drained Conditions (ASTM D3080) – withdrawn in 2020
- ❑ Consolidated Undrained Direct Simple Shear Testing of Fine Grain Soils (ASTM D6528)

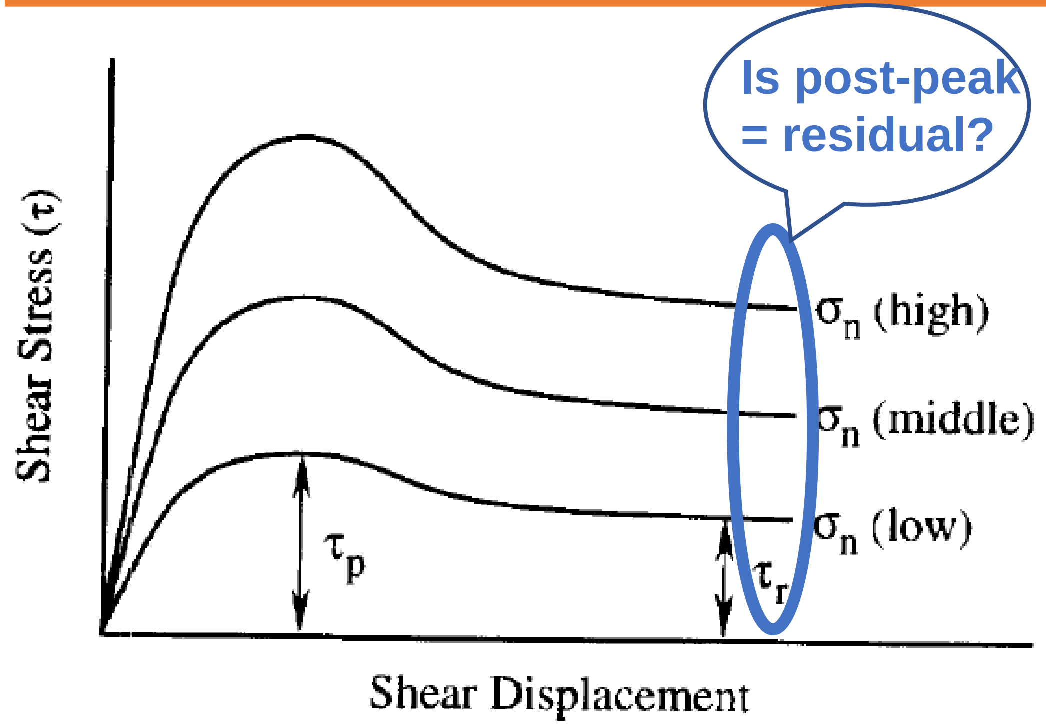
Material testing methods - Geosynthetics

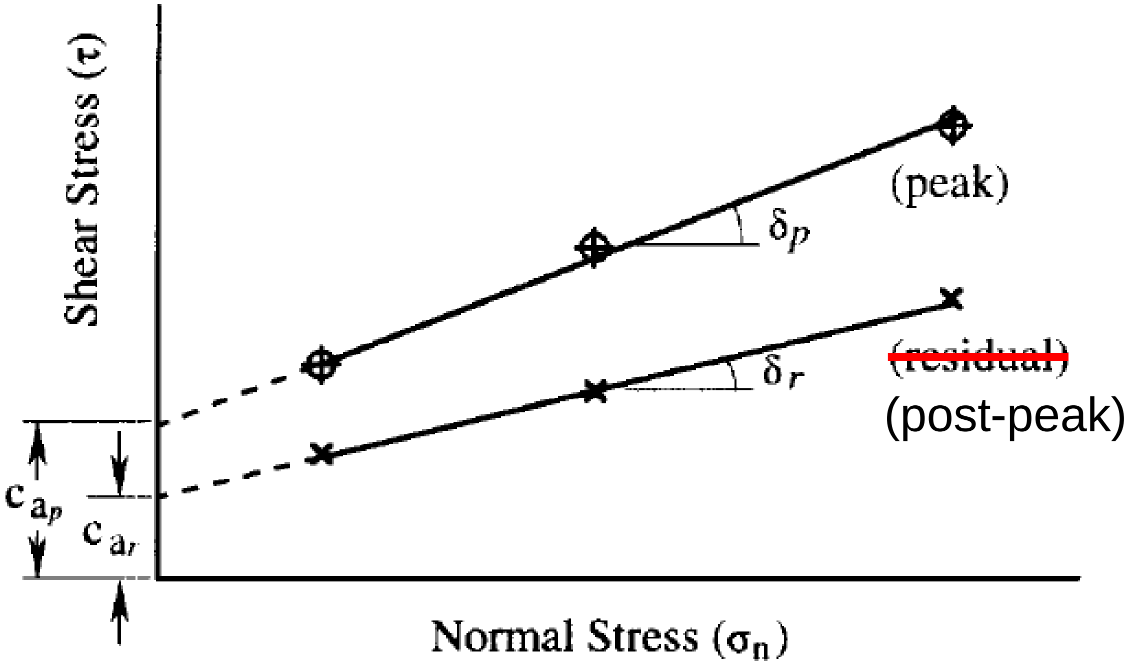
- Standard Test Method for Determining the Shear Strength of Soil-Geosynthetic and Geosynthetic-Geosynthetic Interfaces by Direct Shear (ASTM 5321)
- Standard Test Method for Determining the Internal and Interface Shear Strength of Geosynthetic Clay Liner by the Direct Shear Method (ASTM D6243)
- Standard Guide for Considerations When Evaluating Direct Shear Results Involving Geosynthetics (ASTM D7702)

Key issue with these tests are selecting the proper:

1. Normal loads
2. Shear rate

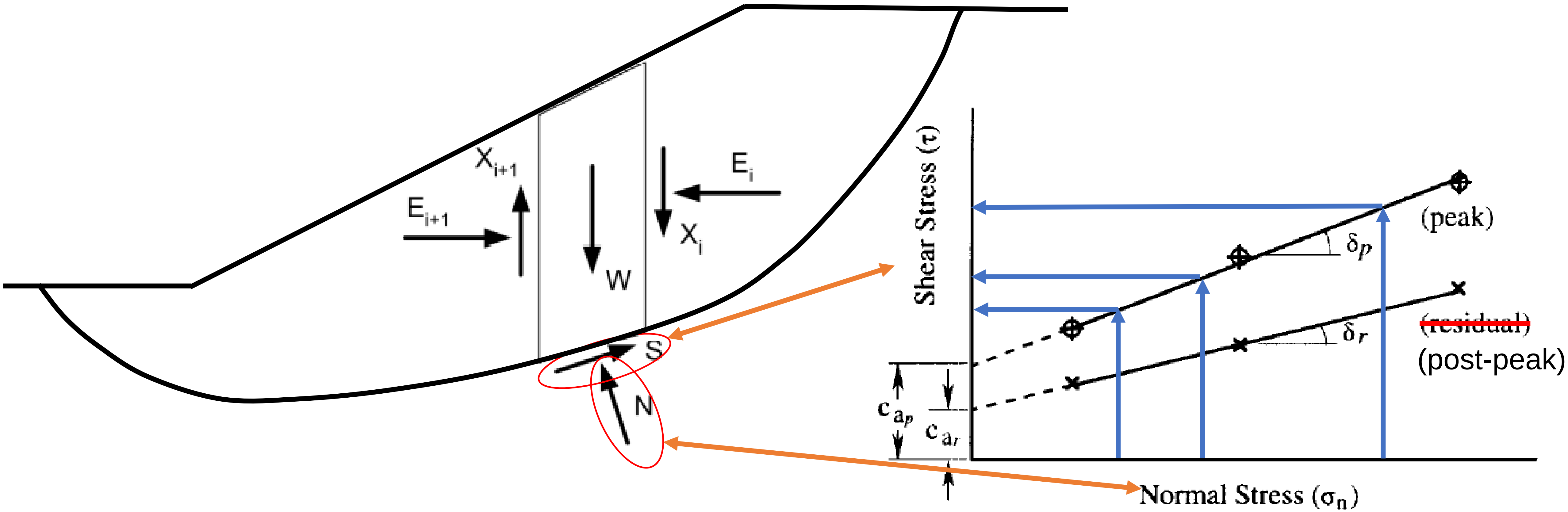
Shear Strength





Reference: Koerner, R.M. and Soong, T-Y, (1998), "Analysis and Design of Veneer Cover Soils," Sixth International Conference on Geosynthetics, Figure 2.

Shear Strength



Shear Strength

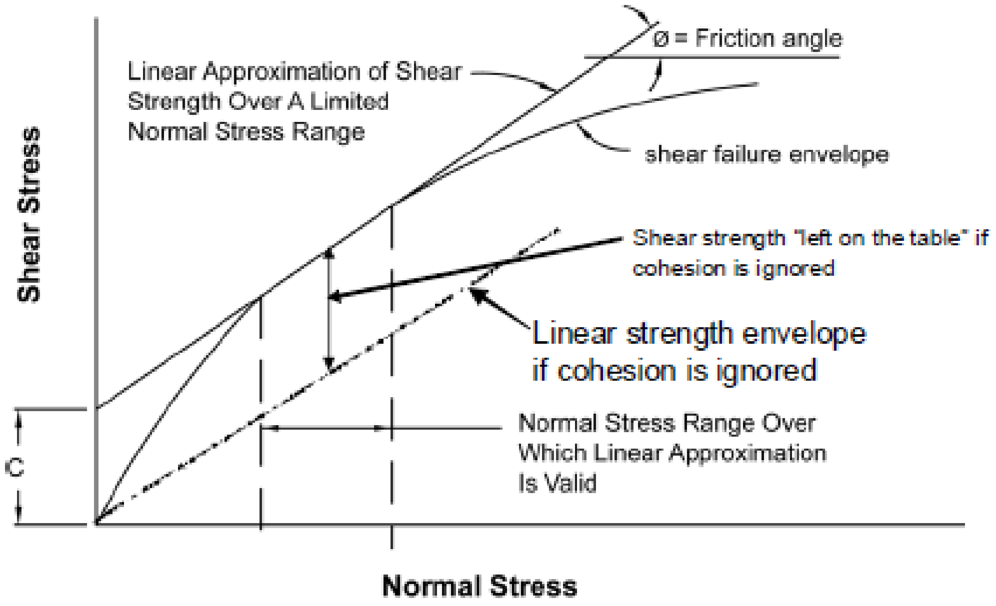


Figure 3 – Exaggerated Schematic of True Curvilinear Shear Strength Envelope, Linear Interpretation over a Selected Normal Stress Range, and the Penalty for Ignoring Cohesion

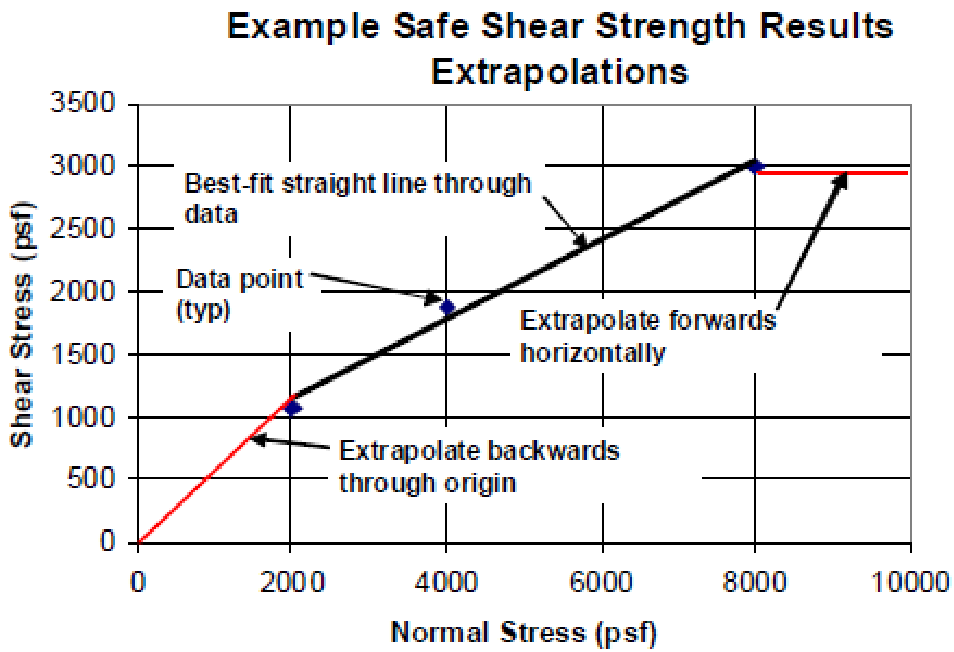
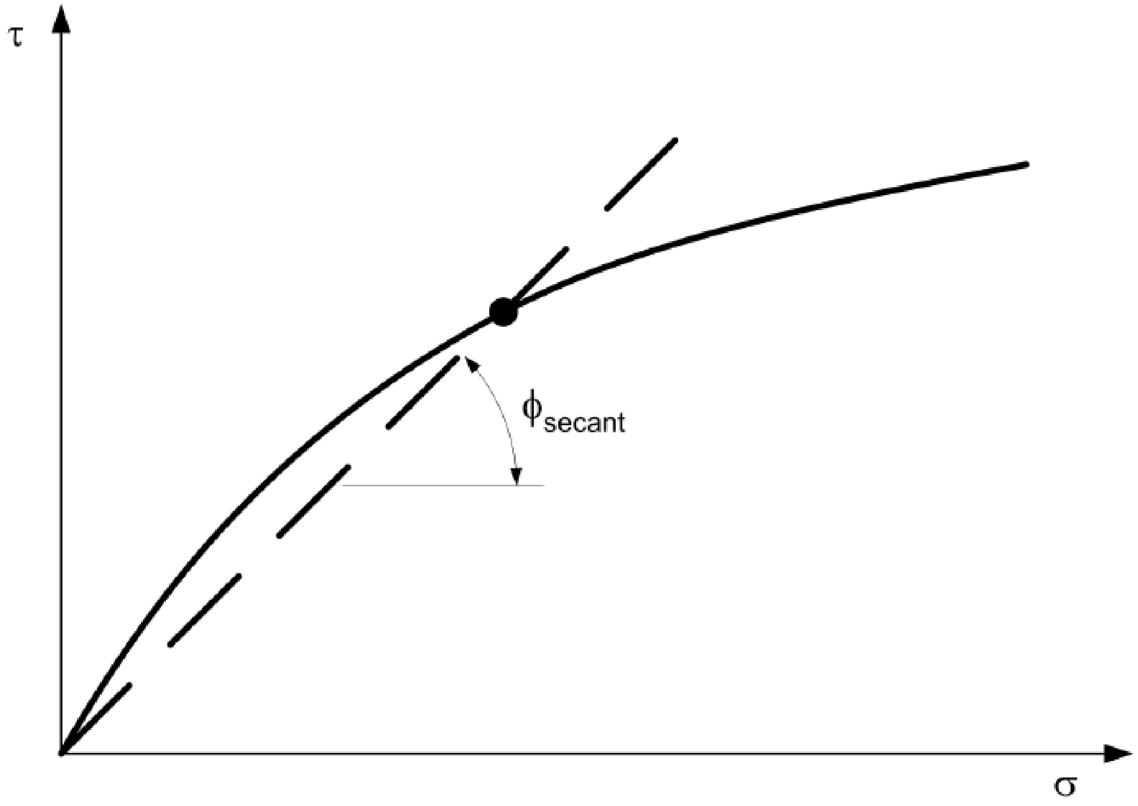


Figure 4 – Example of safe shear strength extrapolation.

Reference: Thiel, R. (2009) A Note Regarding Interpreting Cohesion (or Adhesion) and Friction Angle in Direct Shear Tests, Geotechnical Fabrics Report, V 27, N 2, April-May 2009, pp. 10-19

Shear Strength – Secant Angle



Reference: US Army Corps of Engineers (2003), Slope Stability, Engineering Manual, EM 1110-2-1902 Figure D-16.

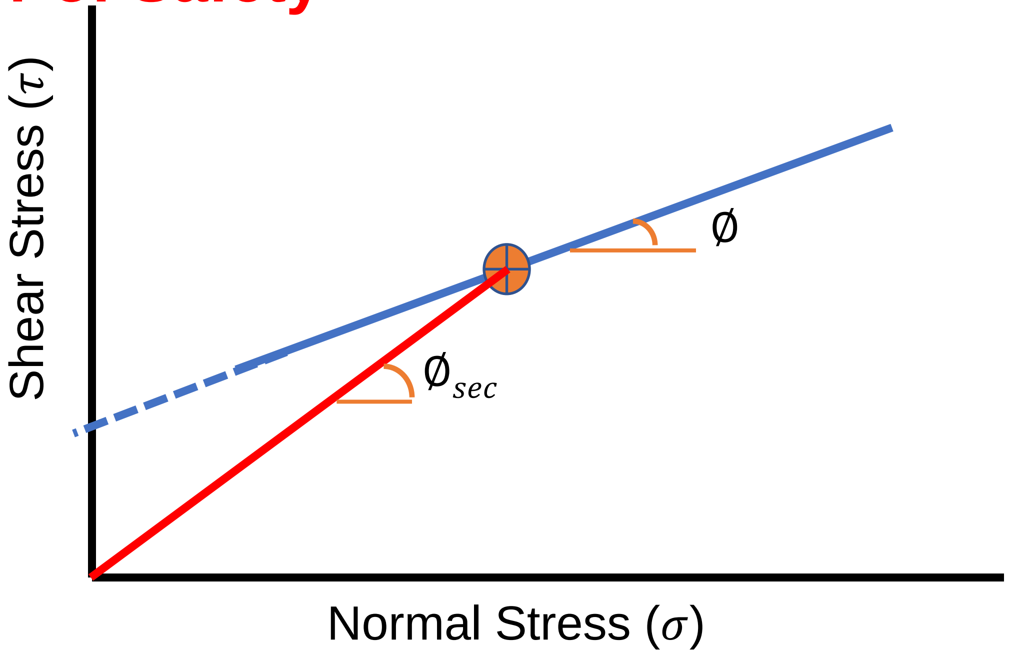
… for slope stability computations it is usually preferable to express the strength envelope in terms of a continuous function of shear strength versus normal stress, rather that as a series of discrete values of secant friction angle. (EM 1110-2-1902, p. D-24)

A key concept regarding secant friction angles is that you should never extrapolate a secant angle line beyond the normal load for which it is measured. Secant values are conservative as long as the secant values are derived from a test whose normal stress was greater than the normal stresses of the design. They can quickly become non-conservative if the same friction angle is used for higher normal loads. (Theil [2009] p. 14)

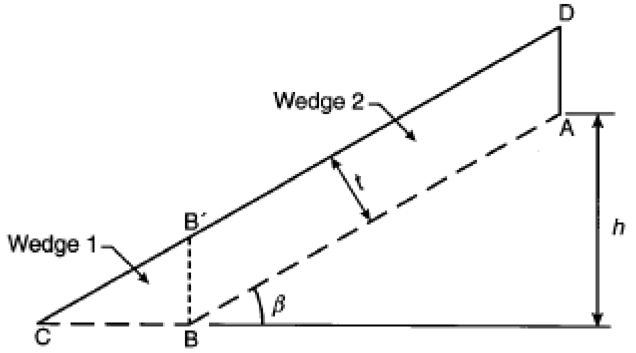
The secant friction angle….should not be confused with the Mohr-Coulomb friction angle. (ASTM D7702, Paragraph 7.5)

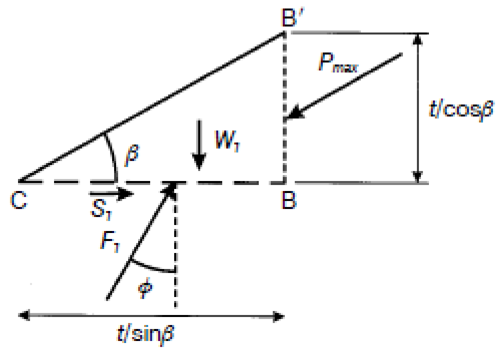
Secant Angle – Caution

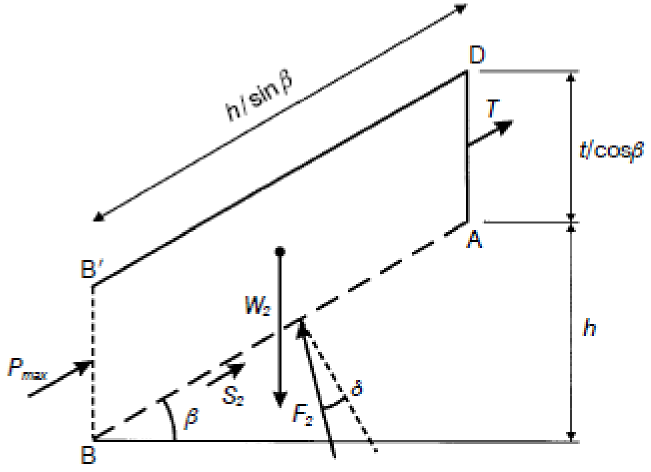
- **DON'T use the secant angle for veneer stability evaluations**
  - **The secant angle is typically greater than true friction angle and will result in an overestimate of shear strength and hence over predict the Factor of Safety**



Veneer Stability – Giroud method







$$FS = \frac{\tan\delta}{\tan\beta} + \frac{a}{\gamma t \sin\beta} + \frac{t}{h}\,\frac{\sin\emptyset}{\sin(2\beta)\cos(\beta+\emptyset)} + \frac{c}{\gamma h}\,\frac{\cos\emptyset}{\sin\beta\cos(\beta+\emptyset)} + \frac{T}{\gamma h t}$$

Reference: Giroud, J.P., Williams, N.D., Pelte, T., and Beech, J.F. (1995), “Stability of Geosynthetic-Soil Layered Systems on Slopes,” *Geosynthetics International*, Vol. 2, No. 6, Figures 5, 6a, and 7a, and Equation 12.

Veneer Stability – Koerner method

The expression for determining the factor of safety can be derived as follows:

Considering the active wedge,

$$W_A = \gamma h^2 \left(\frac{L}{h} - \frac{1}{\sin\beta} - \frac{\tan\beta}{2} \right) \quad (3)$$

$$N_A = W_A \cos\beta \quad (4)$$

$$C_a = c_a \left(L - \frac{h}{\sin\beta} \right) \quad (5)$$

By balancing the forces in the vertical direction, the following formulation results:

$$E_A \sin\beta = W_A - N_A \cos\beta - \frac{N_A \tan\delta + C_a}{FS} \sin\beta \quad (6)$$

Hence the interwedge force acting on the active wedge is:

$$E_A = \frac{(FS)(W_A - N_A \cos\beta) - (N_A \tan\delta + C_a)\sin\beta}{\sin\beta(FS)} \quad (7)$$

The passive wedge can be considered in a similar manner:

$$W_P = \frac{\gamma h^2}{\sin 2\beta} \quad (8)$$

$$N_p = W_P + E_P \sin\beta \quad (9)$$

$$C = \frac{(c)(h)}{\sin\beta} \quad (10)$$

By balancing the forces in the horizontal direction, the following formulation results:

$$E_P \cos\beta = \frac{C + N_P \tan\phi}{FS} \quad (11)$$

Hence the interwedge force acting on the passive wedge is:

$$E_P = \frac{C + W_P \tan\phi}{\cos\beta(FS) - \sin\beta \tan\phi} \quad (12)$$

By setting $E_A = E_P$, the resulting equation can be arranged in the form of the quadratic equation $ax^2 + bx + c = 0$ which in our case, using FS-values, is:

$$a(FS)^2 + b(FS) + c = 0 \quad (13)$$

where

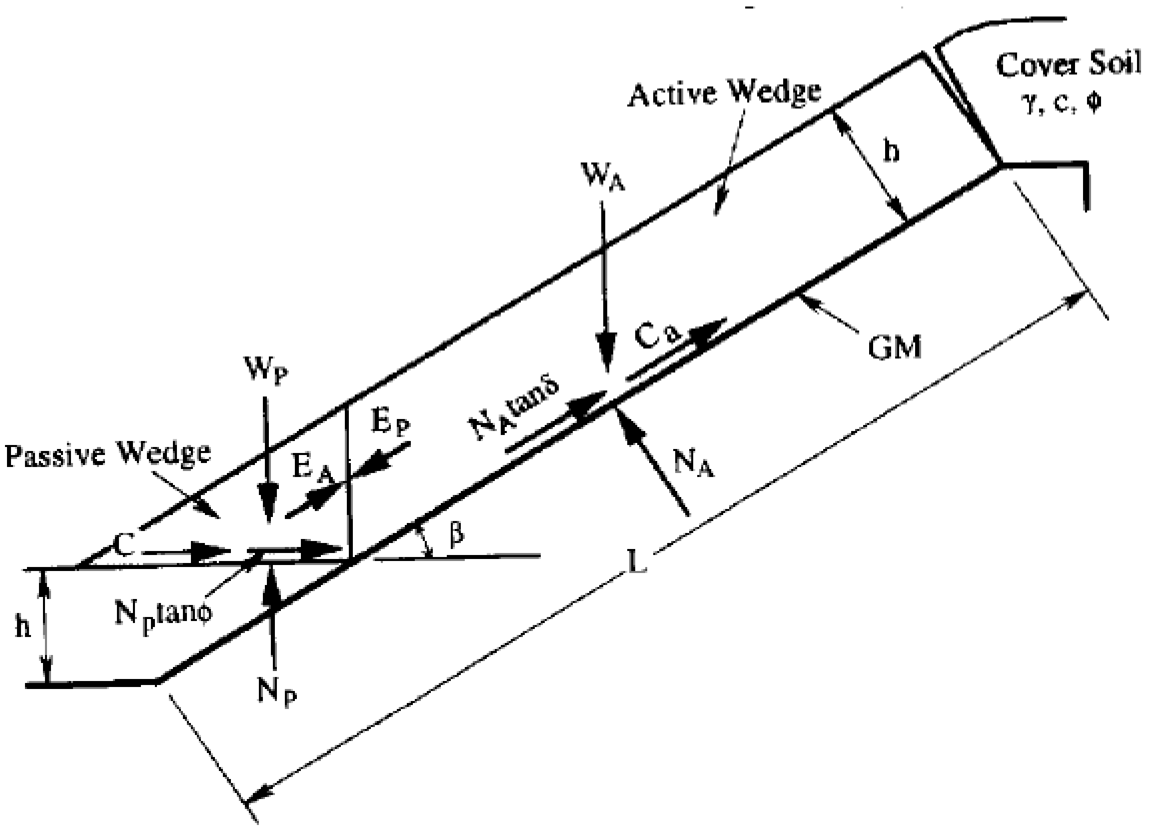
$$a = (W_A - N_A \cos\beta)\cos\beta$$

$$b = -\left[(W_A - N_A \cos\beta)\sin\beta \tan\phi + (N_A \tan\delta + C_a)\sin\beta\cos\beta + \sin\beta(C + W_P \tan\phi) \right]$$

$$c = (N_A \tan\delta + C_a)\sin^2\beta \tan\phi \quad (14)$$

The resulting FS-value is then obtained from the solution of the quadratic equation:

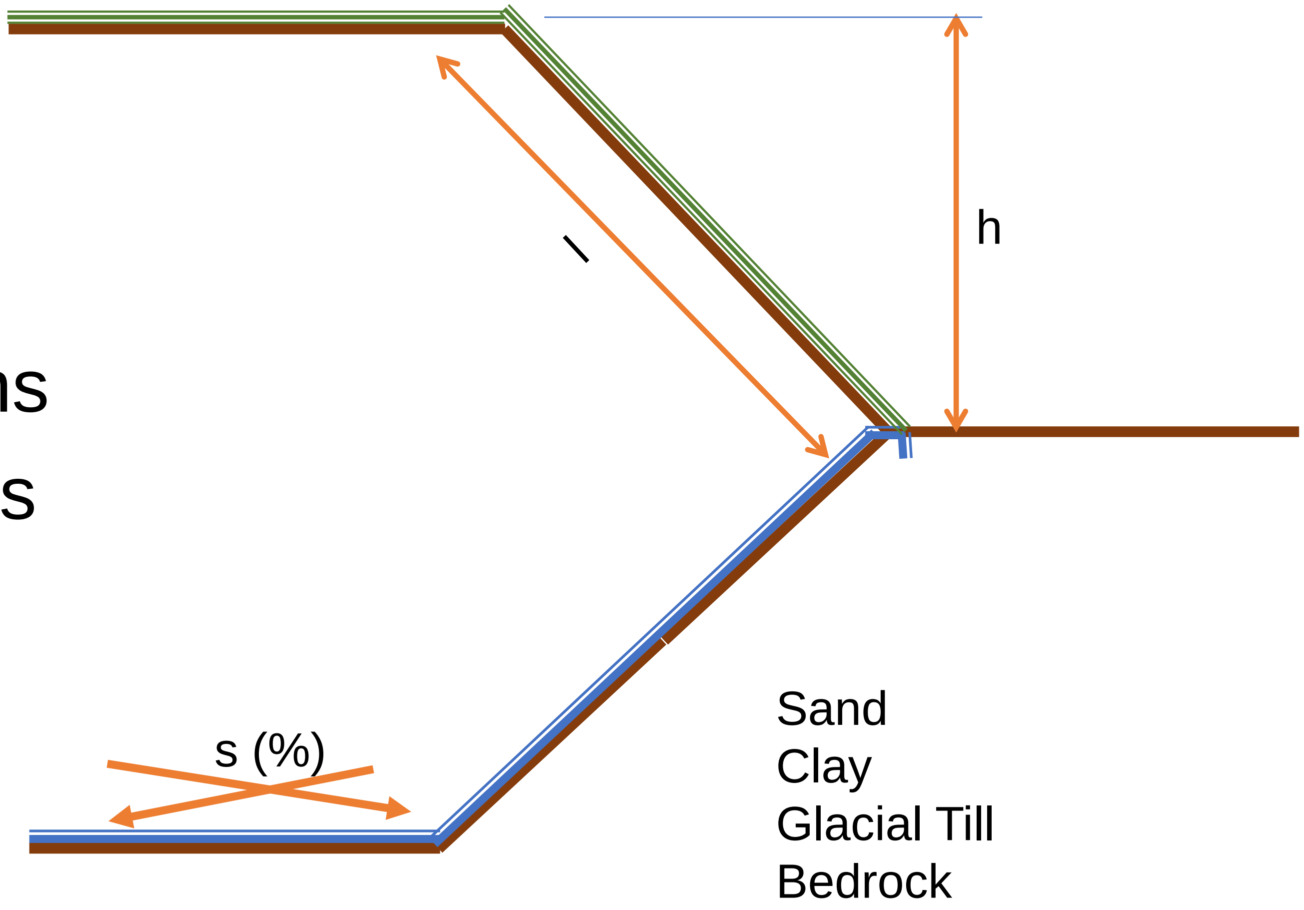
$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a} \quad (15)$$



Reference: Koerner, R.M. and Soong, T-Y, (1998), “Analysis and Design of Veneer Cover Soils,” Sixth International Conference on Geosynthetics, Equations 3 through 15 and Figure 3.

Other considerations - Global

- Select Critical Slope Conditions:
  - Slope height
  - Slope length
  - Inclination of landfill base
  - Foundation soil types
- Interim and final conditions
- Influence of water and gas pressure
- Seismic
- State-specific regulations



Let’s see what we learned

3. What slope conditions should be evaluated?
4. How do you evaluate the stability of a slope?
5. What is a Factor of Safety?

Construction specifications recommendations

- Define the desired shear strength profile
  - Do NOT only specify a friction angle
  - The friction angle is only part of what makes up the shear strength
  - Define desired shear strength based on a normal strength

Normal Stress (psf)	Peak Shear Stress (psf)	Post-Peak Shear Stress (psf)
4000	1200	800
8000	2500	1200
16000	5000	2500

EXAMPLE

- Define the material properties – soil and geosynthetics

Construction specifications recommendations

- Define the specific interfaces that need to be tested
- Define sample preparation (e.g., hydration, compaction, moisture content), and shear rate
- Define the construction loads over the geosynthetics and buffering
- Define the movement of construction equipment
- Define how stormwater is to be managed

Thoughts on preventing slope failures

- Hire designers and contractors who have experience
- Properly select construction materials
  - Geomembrane texturing
  - Geocomposite bond strengths
  - Placement of materials in section
- Understand the loading
  - Final configuration
  - Construction equipment

Thoughts on preventing slope failures

- Get good strength data and/or perform pre-design testing
- Identify the critical configurations to be evaluated
- OK to neglect cohesion/adhesion in design calculation
- Good Construction Quality Assurance is key
  - Pre-construction testing
  - Field and laboratory testing
  - Construction observations – look for potential issues

Thank You

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