Design of Geosynthetics for Embankments over Weak Soils

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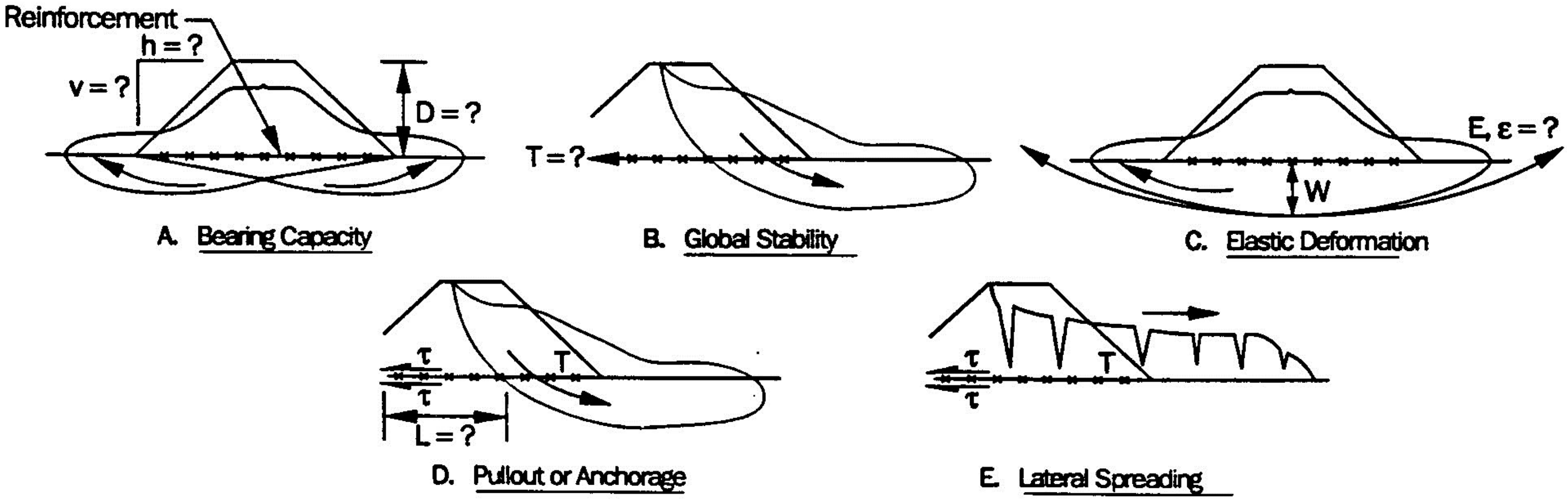
Outline of Presentation

- Introduction
- Basal Reinforcement
- Lightweight Backfill - Geofoam

Introduction

Possible Failure Modes



Examples of Embankment Failures

Courtesy of Bergado

Differential Settlement

Total Settlement

Total settlement

$$\delta_t = \delta_e + \delta_c + \delta_s$$

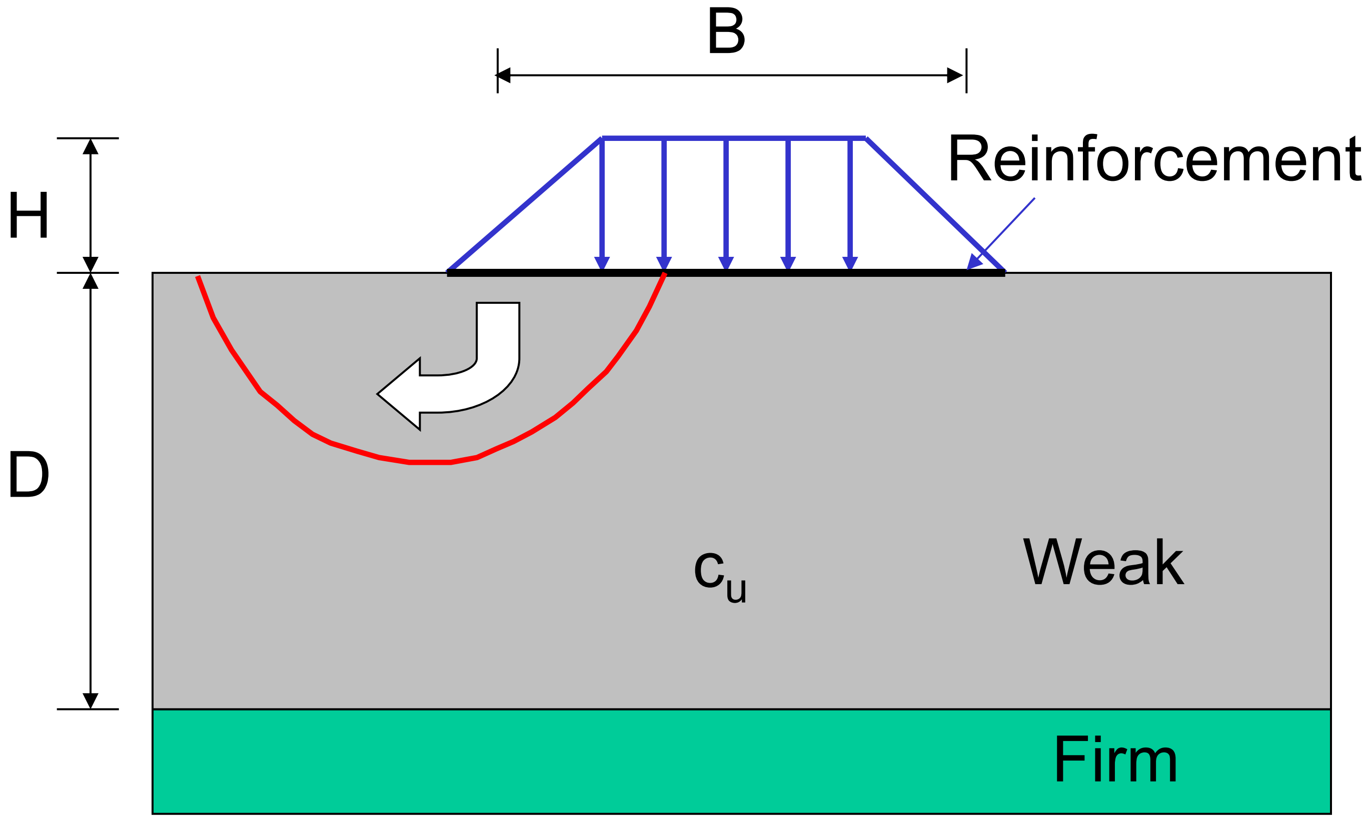
δ_e = immediate settlement (elastic deformation)

δ_c = primary consolidation settlement (due to dissipation of excess pore water pressure)

δ_s = secondary consolidation settlement (due to adjustment of soil fabric)

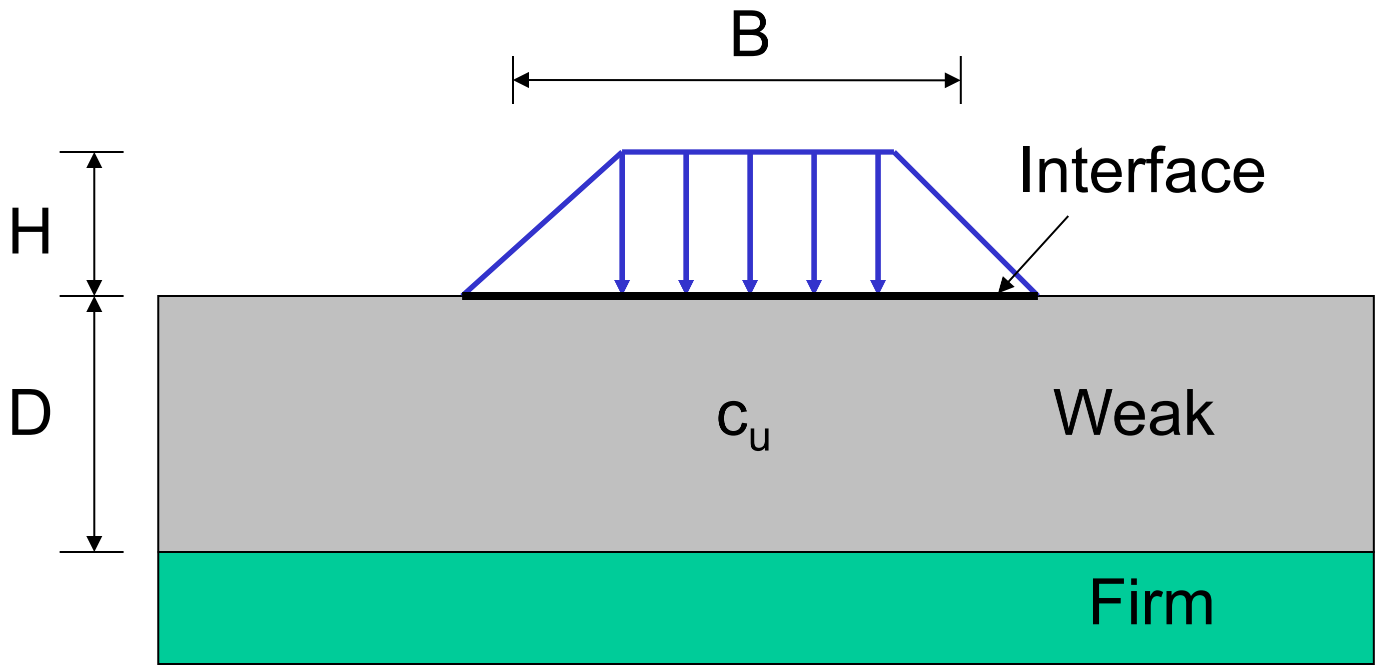
Basal Reinforcement

Deep Foundation Soils with Uniform Properties (D > 1.64B)

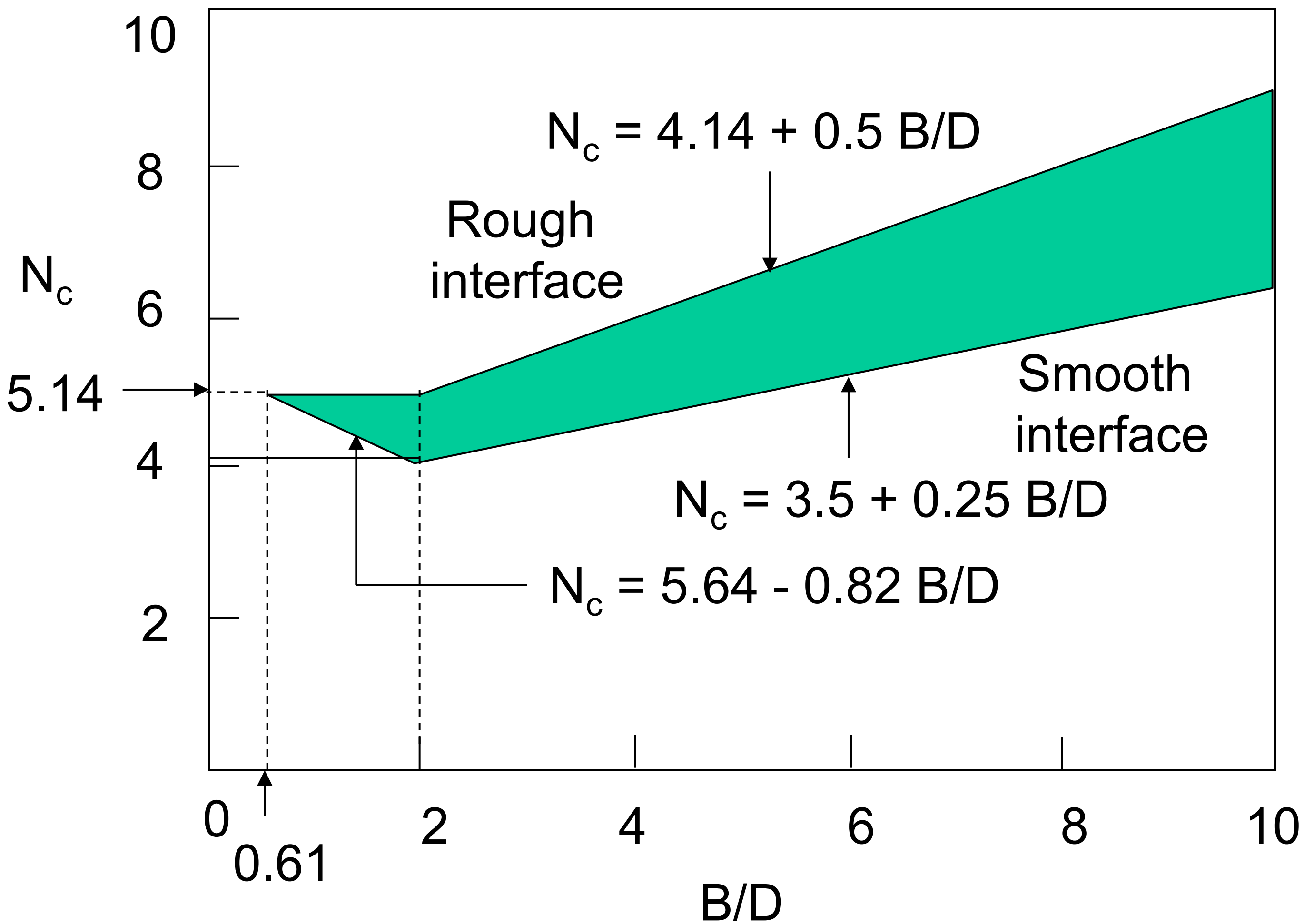


$$FS = N_c \, c_u / (\gamma H)$$

Bearing Capacity for Foundation Soil with Variable Thickness



N_c for Foundation Soil with Variable Thickness



Undrained Shear Strength

$$\frac{c_u}{\sigma'_{vc}} = S(OCR)^m$$

Ladd (1991)

S = 0.22 $\pm$ 0.03 for homogeneous sedimentary clays (above A-line)

S = 0.25 $\pm$ 0.05 for silts and organic clays (below A-line)

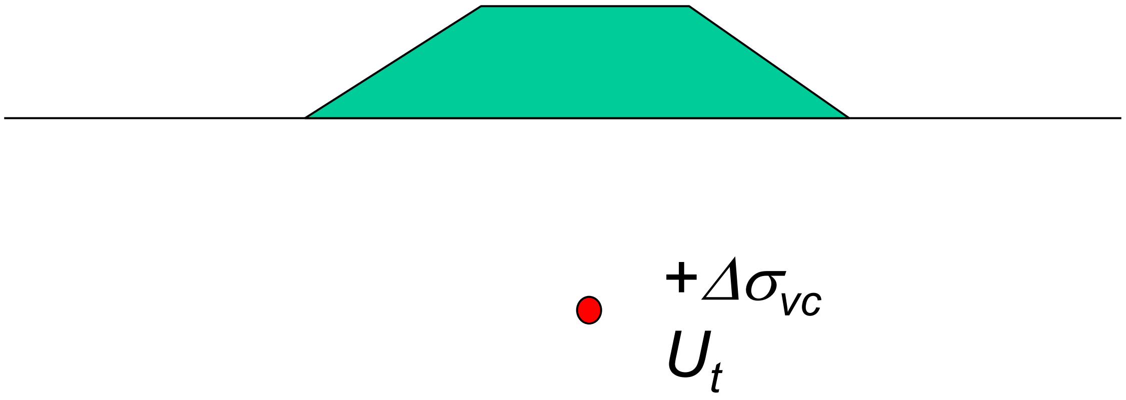
m = 0.88 (1 – C_r/C_c)

Strength Gain

For most staged constructions, *OCR = 1* and *S = 0.25* assumed

Strength gain after consolidation

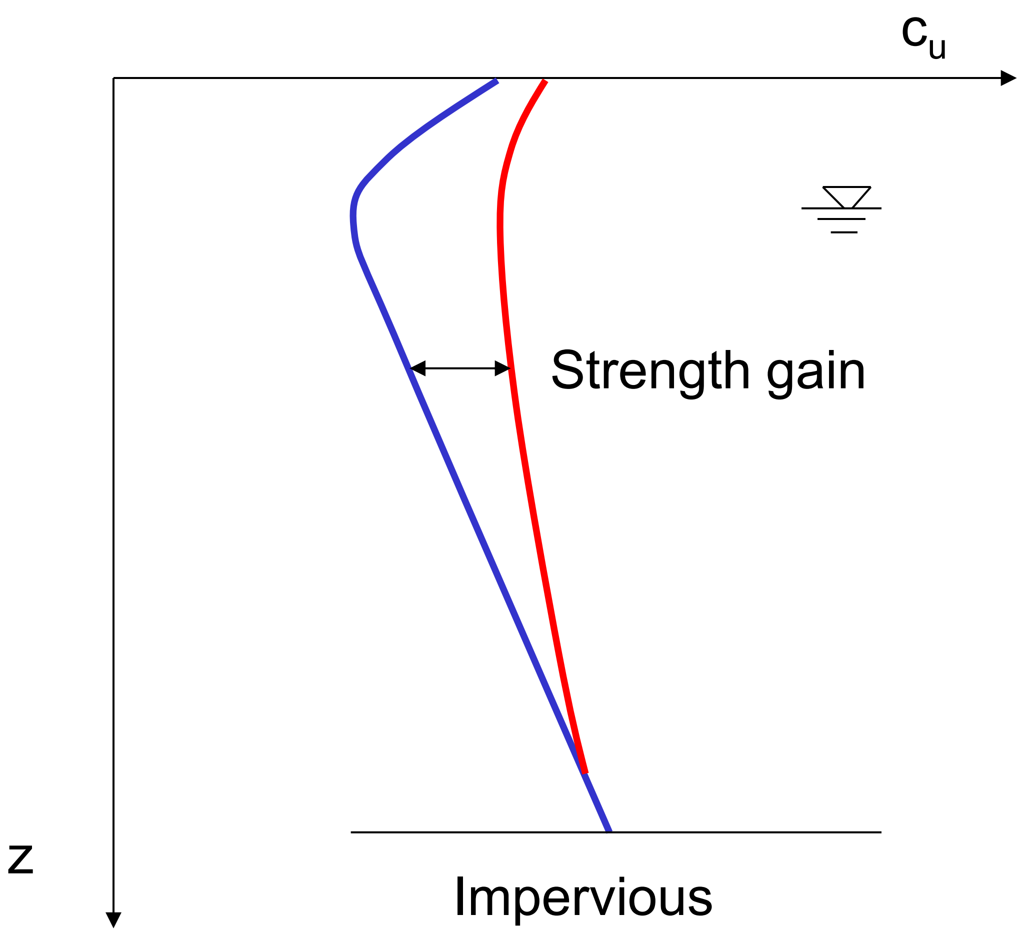
$$\Delta c_u = 0.25\Delta\sigma'_{vc} = 0.25U_t\Delta\sigma_{vc}$$



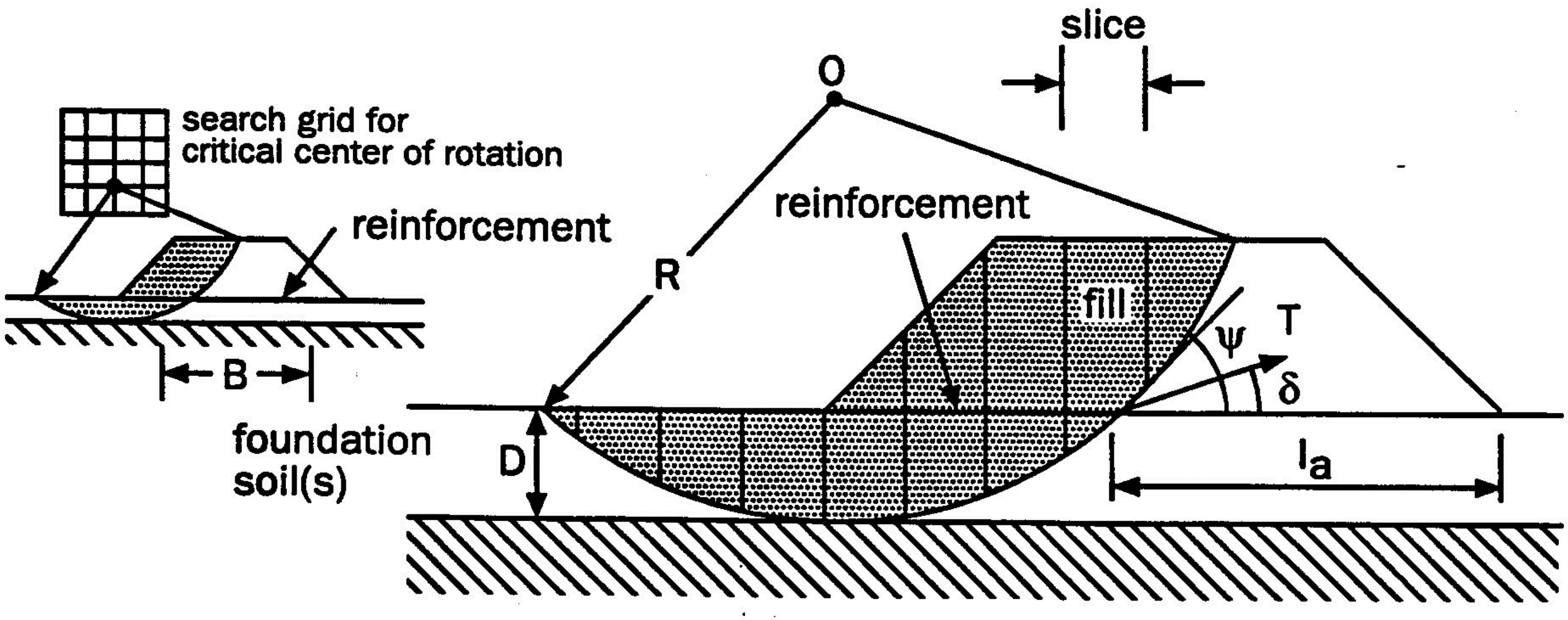
Total undrained shear strength

$$c_u = c_{u0} + \Delta c_u$$

Strength Profile Change



Circular Slip Analysis



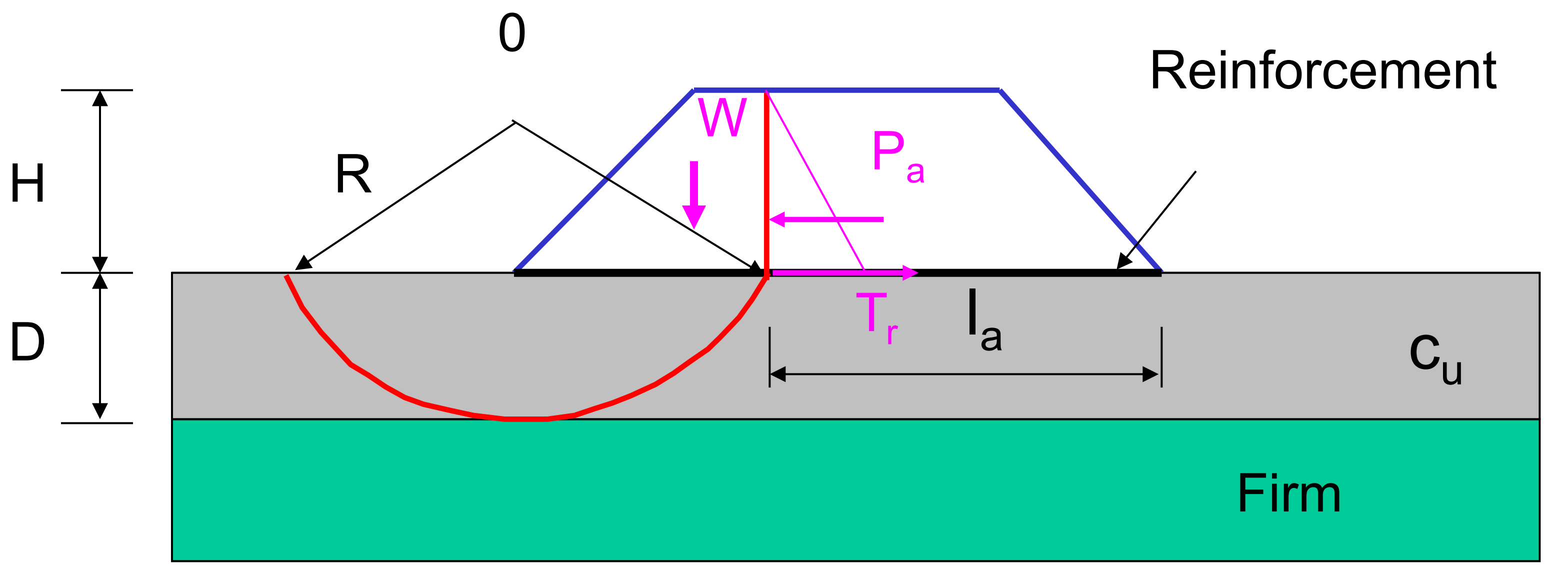
<u>Angle of geosynthetic rotation</u>

δ = 0 for brittle, strain-sensitive foundation soils

δ = ψ/2 for D/B < 0.4 and moderate to highly compressible soils

δ = ψ for D/B > 0.4 and highly compressible soils, reinforcement with high elongation potential (e > 10%) and large tolerable deformations

Modified Circular Slip Analysis

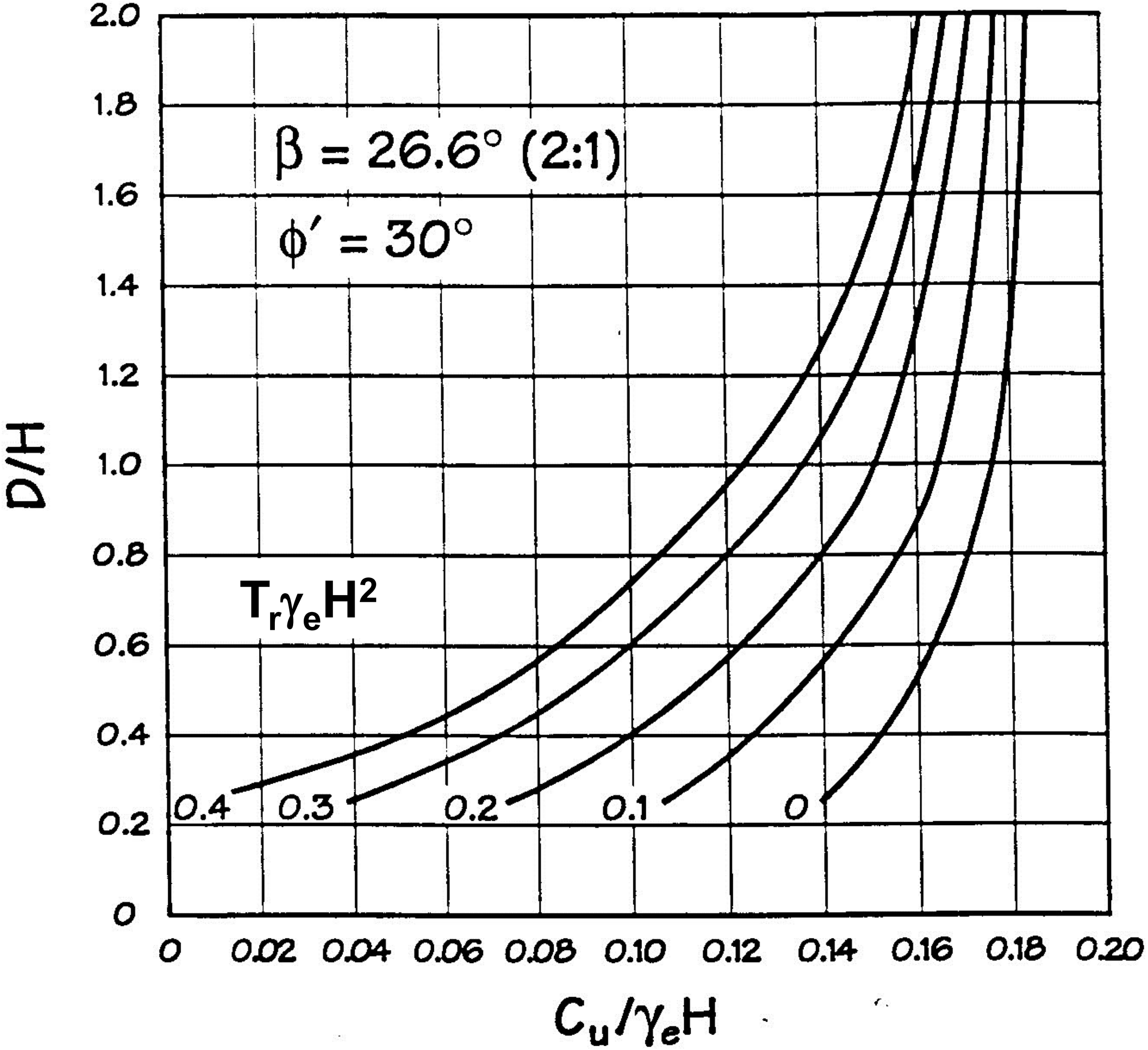


$T_r < T_a$ T_a = long-term allowable capacity of reinforcement (T_d or T_{po})

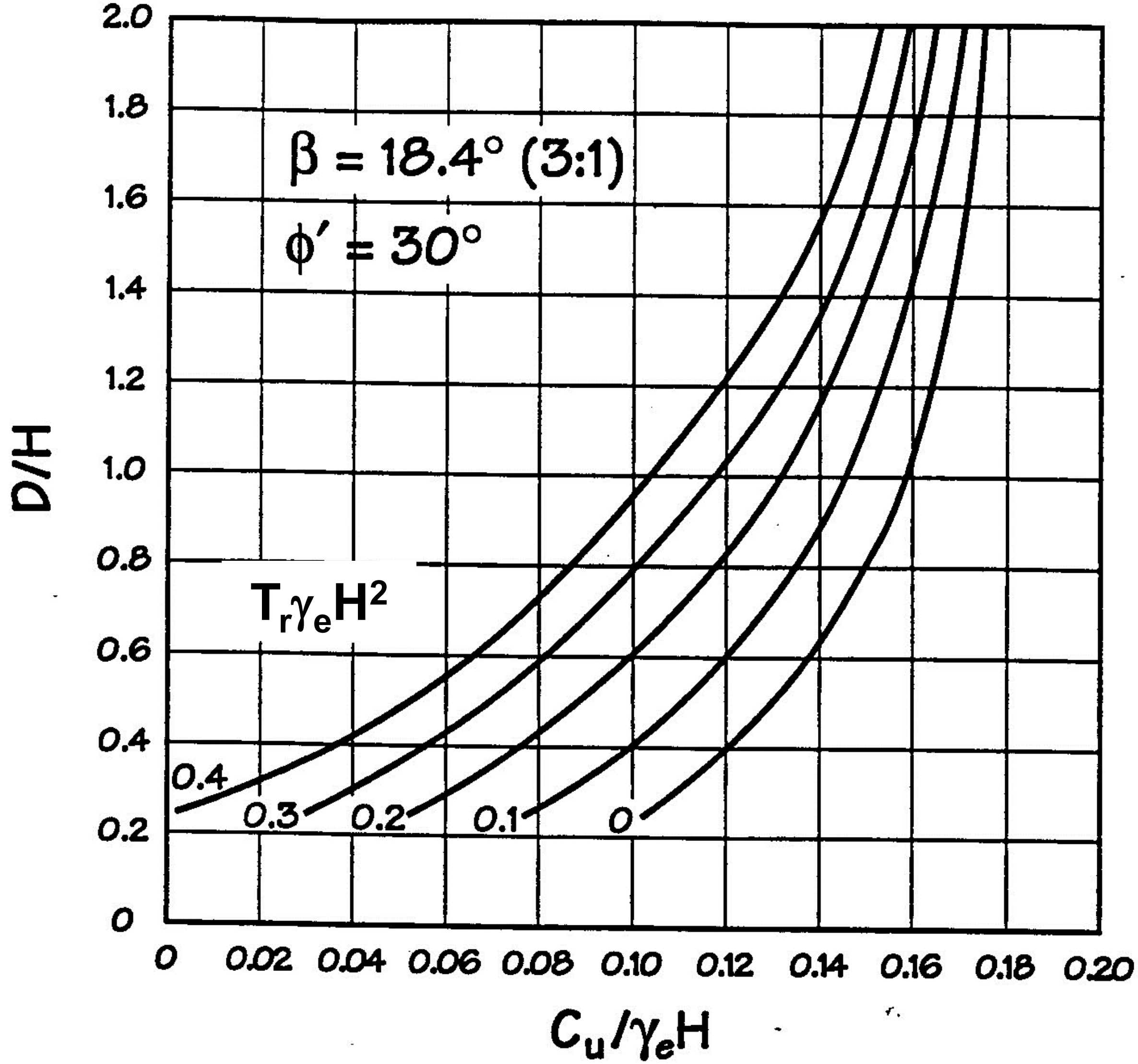
$T_{po} = c_g\, l_a/FS$ $c_g = C_i\, c_u$ FS = 1.3 (end of construction)

FS = 1.5 (long-term)

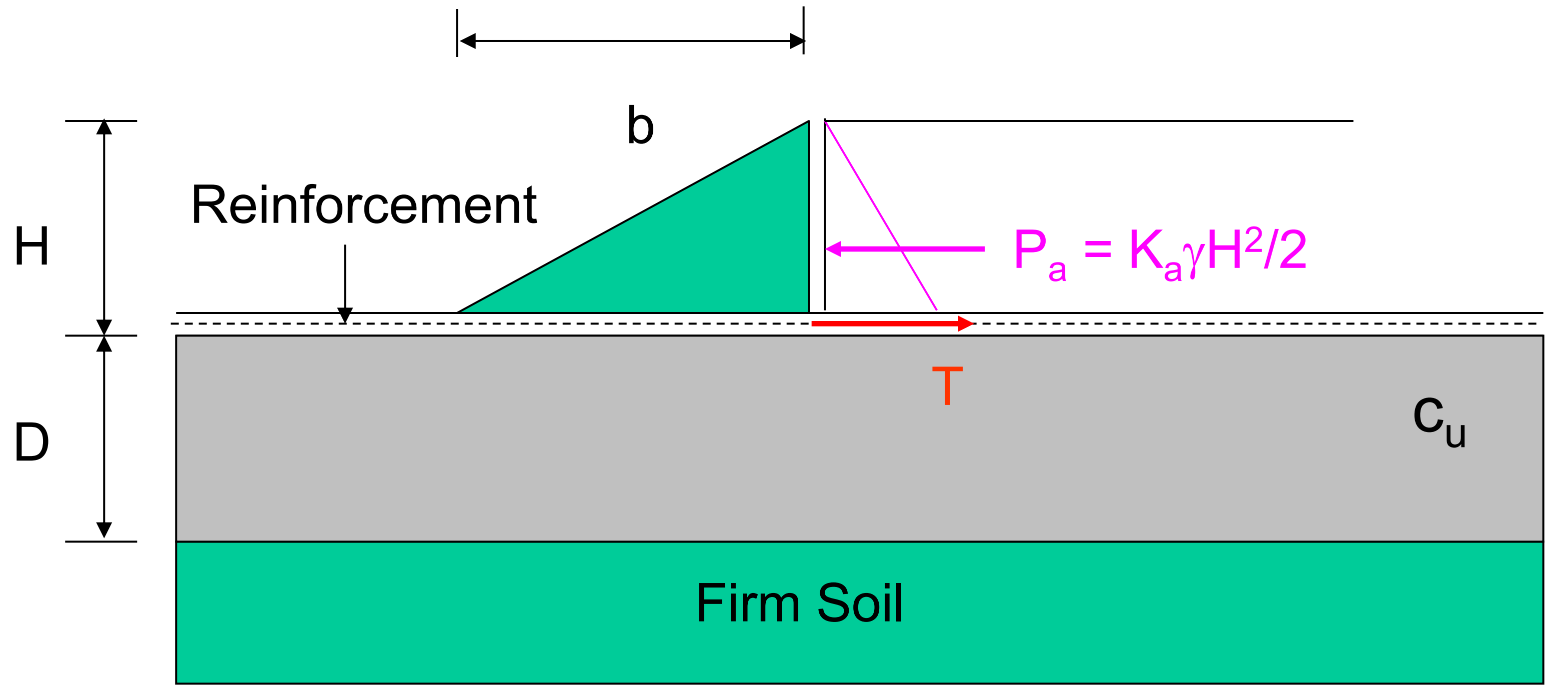
Design Chart for Rotation Failure



Design Chart for Rotation Failure



Lateral Spreading Analysis



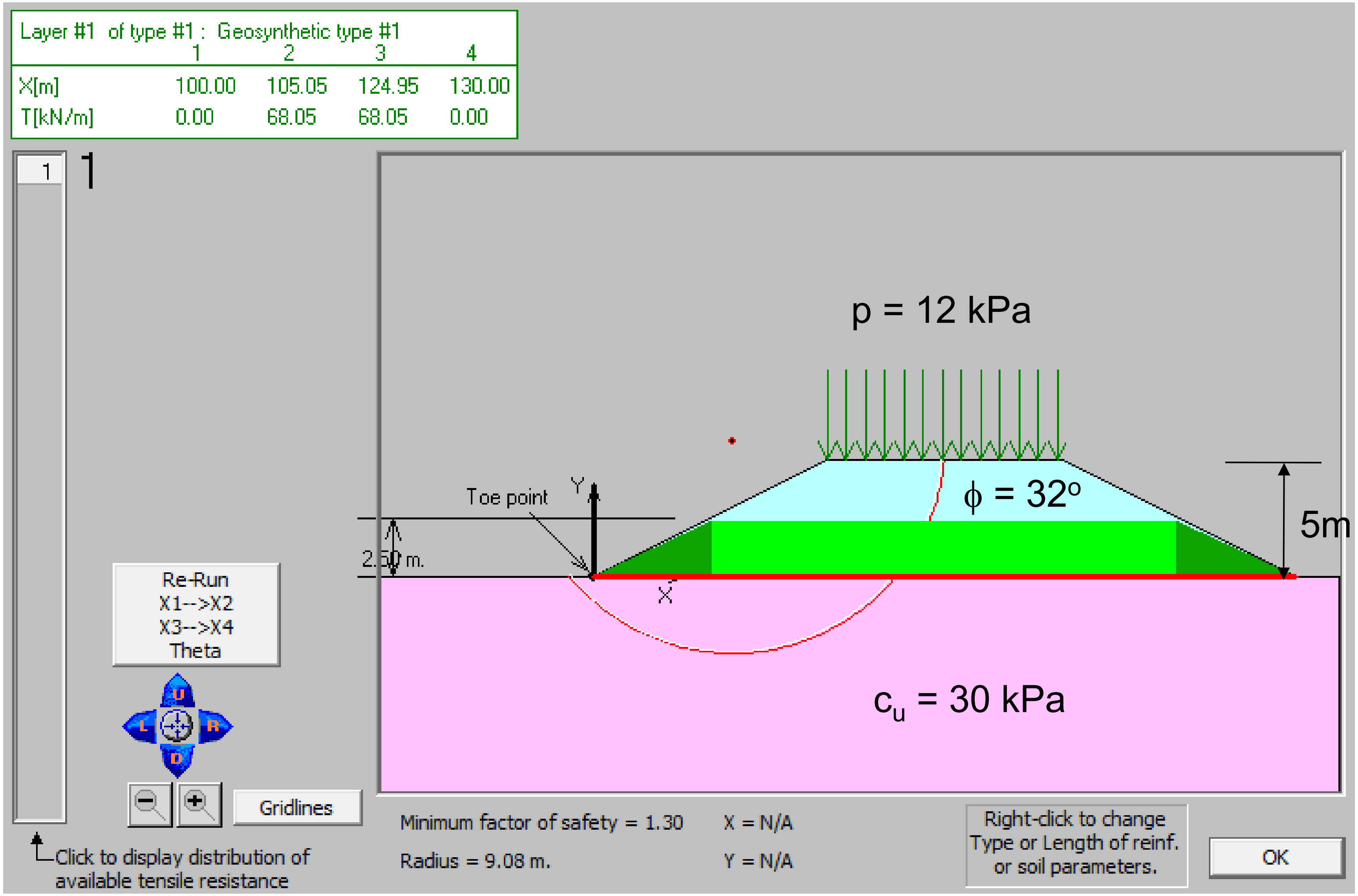
Sliding above the reinforcement $FS = b\gamma H\tan\phi_{sg}/(2P_a)$

Sliding below the reinforcement $FS = (bc_g + T)/(P_a)$

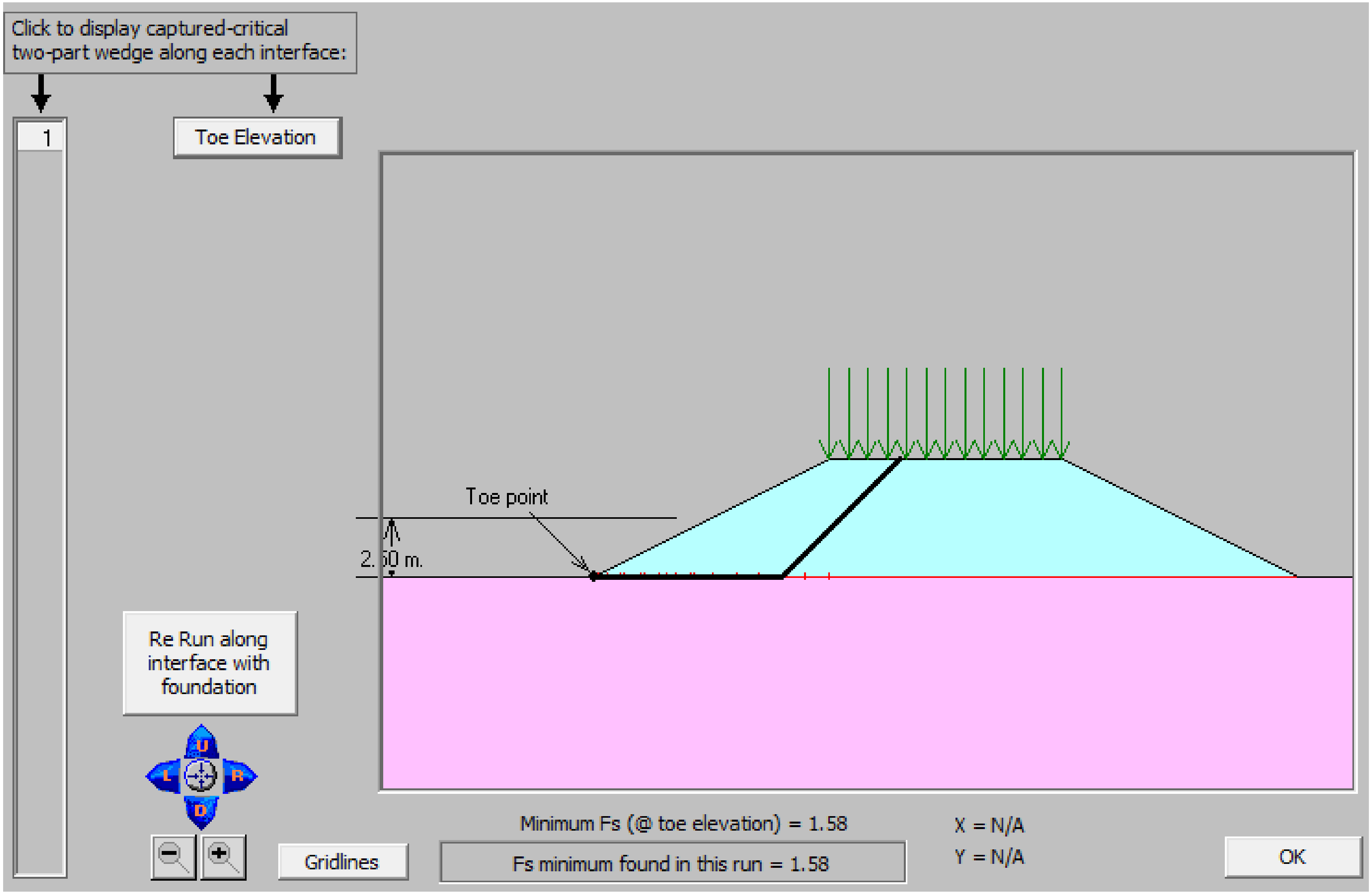
Typically, FS = 2

T at 5% elongation for granular fills
T at 2% elongation for cohesive fills

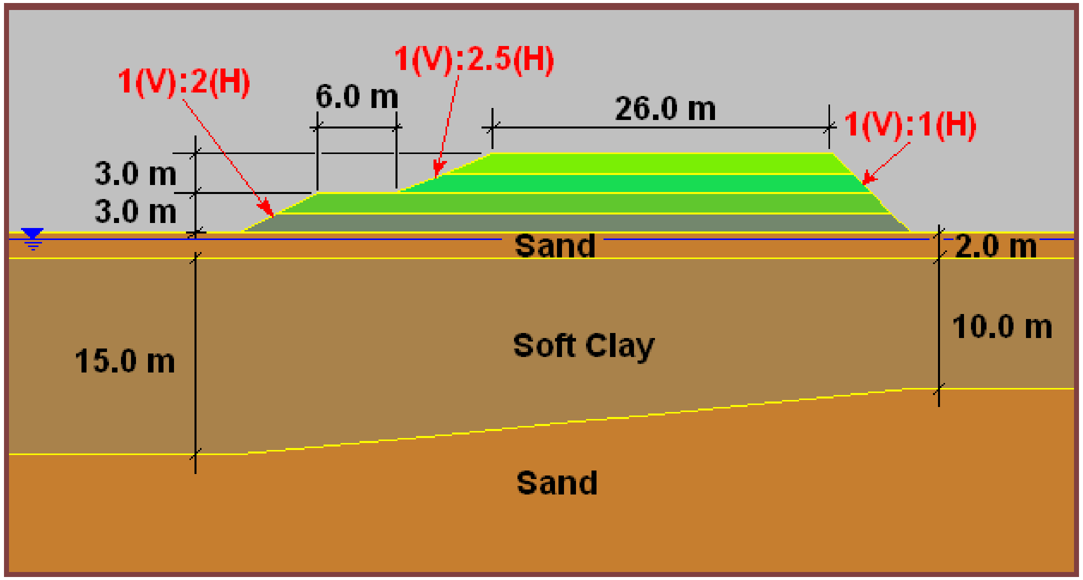
Design Software - ReSSA

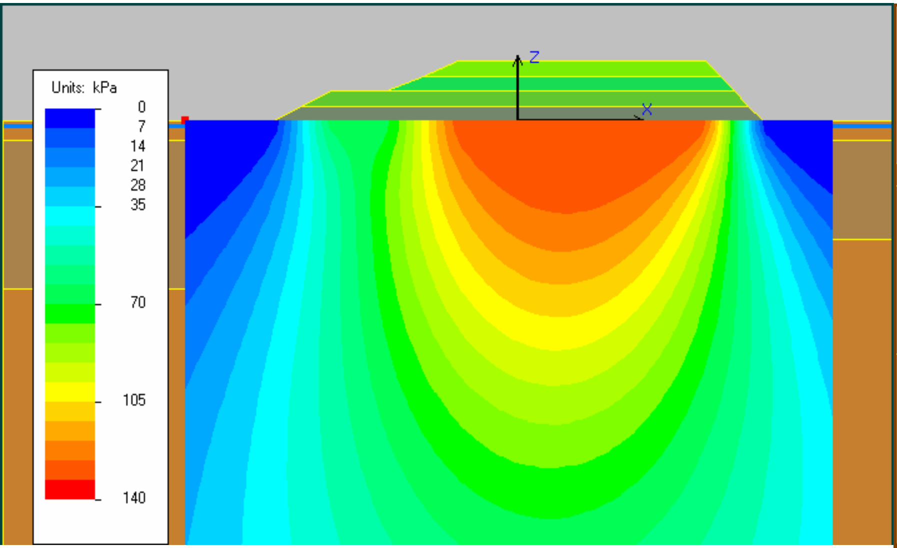


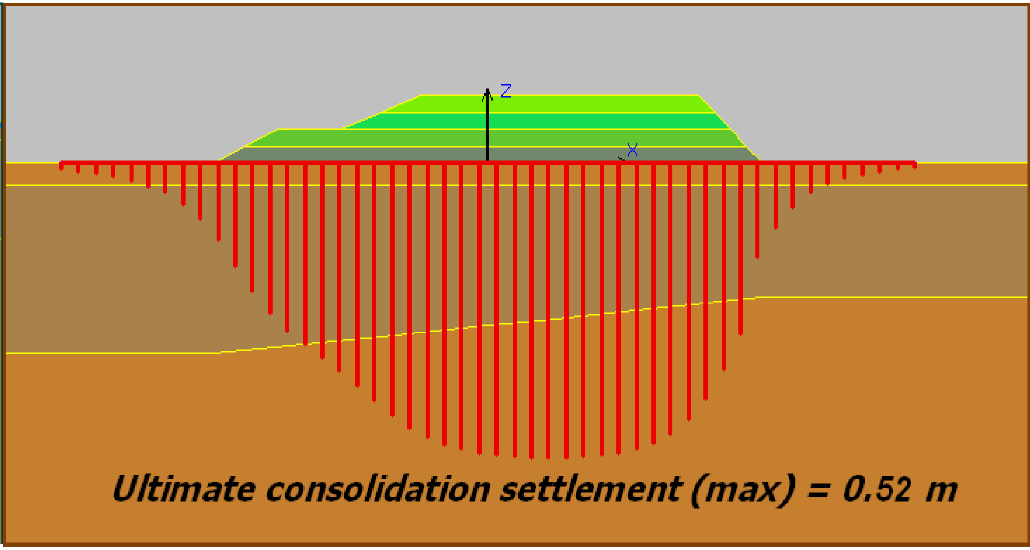
Design Software - ReSSA



Design Software - FoSSA

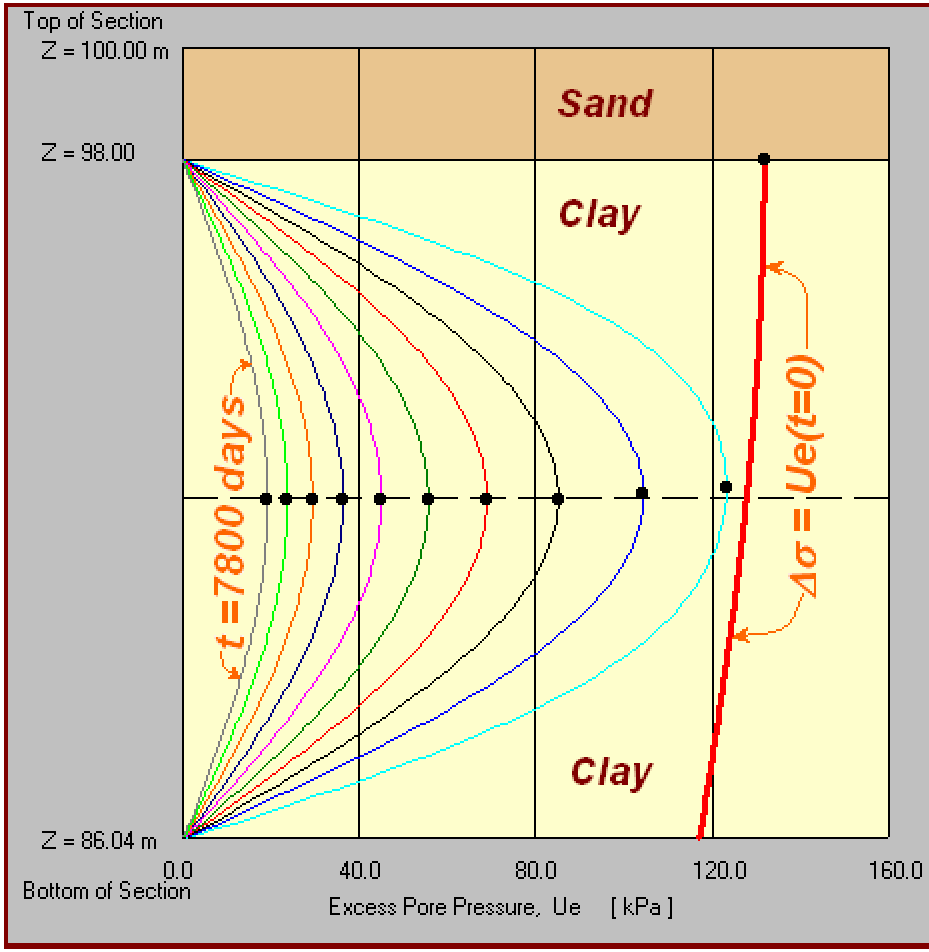


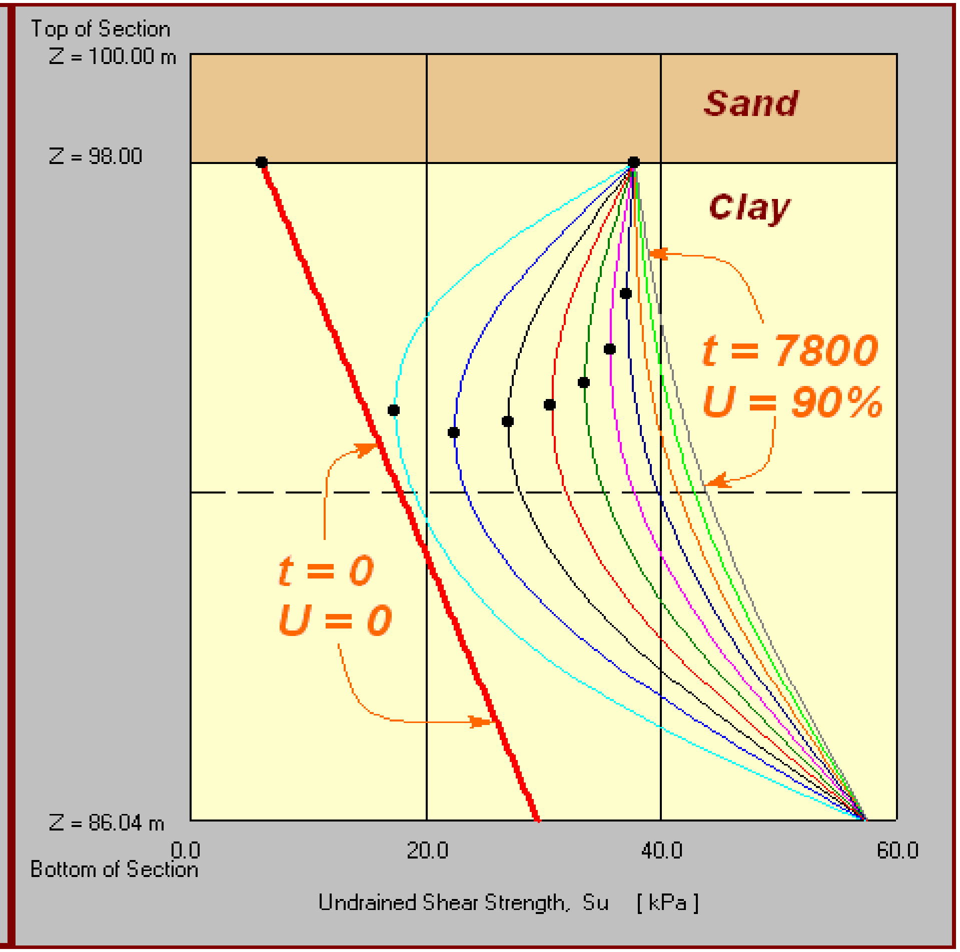




Courtesy of Leshchinsky

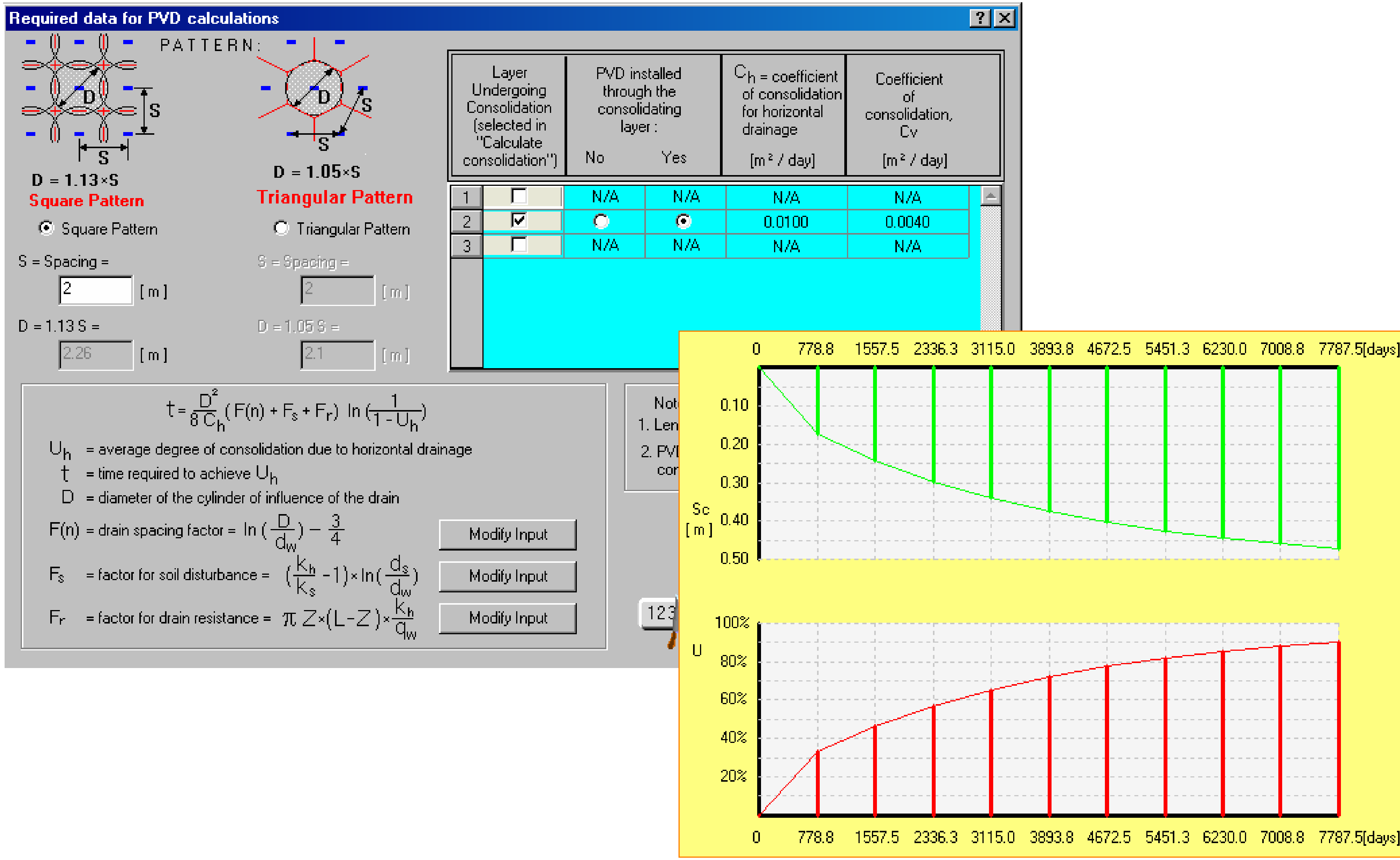
Design Software - FoSSA





Courtesy of Leshchinsky

Design Software - FoSSA



Courtesy of Leshchinsky

Lightweight Fill - Geofoam

NCHRP REPORT 529

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Guideline and Recommended Standard for Geofoam Applications in Highway Embankments

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

Geofoam

- Any manufactured material created by an internal expansion process that results in a material with a texture of numerous, closed, gas-filled cells using either a fixed plant or an in situ expansion process

- Include polymeric (plastic), glass (cellular glass), and cementitious foams

Geofoam

- Block or planar rigid cellular foam polymeric material
- Lightweight expanded polystyrene (EPS) or extruded polystyrene (XPS)
- Typical density: 11 to 29kg/m^3
- Main function is to reduce weight of earth earth structures
- Main problem is that Geofoam can be dissolved by gasoline

History

- Early 1960s initially for thermal insulation
- First use as lightweight fill is not known
- EPS-block geofoam used as lightweight fill worldwide since 1972
- EPS-block geofoam used as lightweight fill in U.S. since 1980s
- Early 1970s, XPS used for a bridge approach fill in Michigan

Various Lightweight Fill

Lightweight Fill Type	Unit Weight (pcf)	Specific Gravity	Approximate Cost ($/yd^3)
EPS (expanded polystyrene) block geofoam	0.75 to 2.0	0.01 to 0.03	26.76 to 49.70
Foamed portland-cement Concrete geofoam	21 to 48	0.3 to 0.8	49.70 to 72.63
Wood fiber	34 to 60	0.6 to 1.0	9.17 to 15.29
Shredded tires	38 to 56	0.6 to 0.9	15.29 to 22.94
Expanded shale & clay	38 to 65	0.6 to 1.0	30.58 to 42.05
Boiler slag	62 to 109	1.0 to 1.8	2.29 to 3.06
Air cooled blast furnace slag	69 to 94	1.1 to 1.5	5.73 to 6.88
Expanded blast furnace slag	Not provided	Not provided	11.47 to 15.29
Fly ash	70 to 90	1.1 to 1.4	11.47 to 16.06

Stark et al.

GEOFOAM

GSI

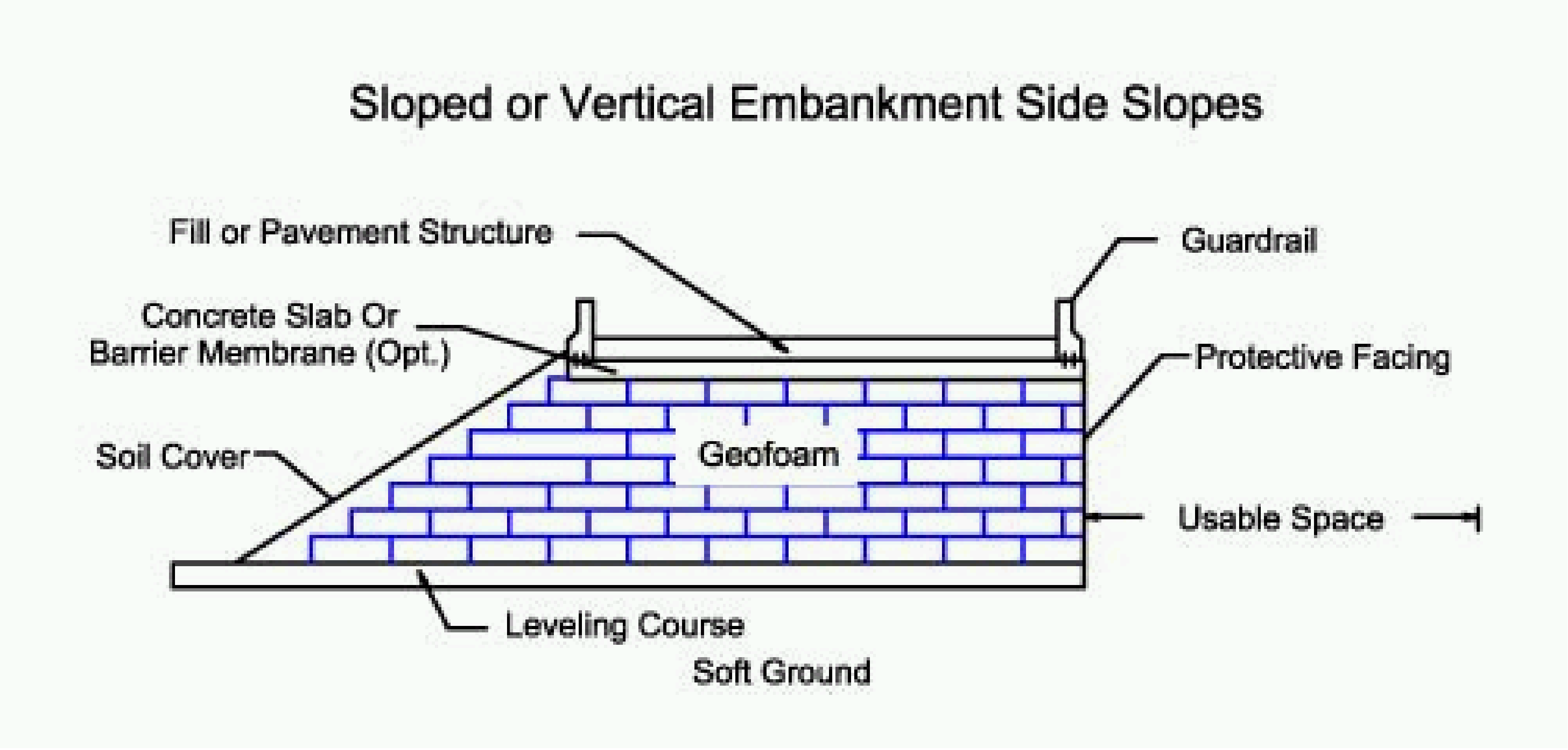
GeoFoam for Bridge Approach

Horvath

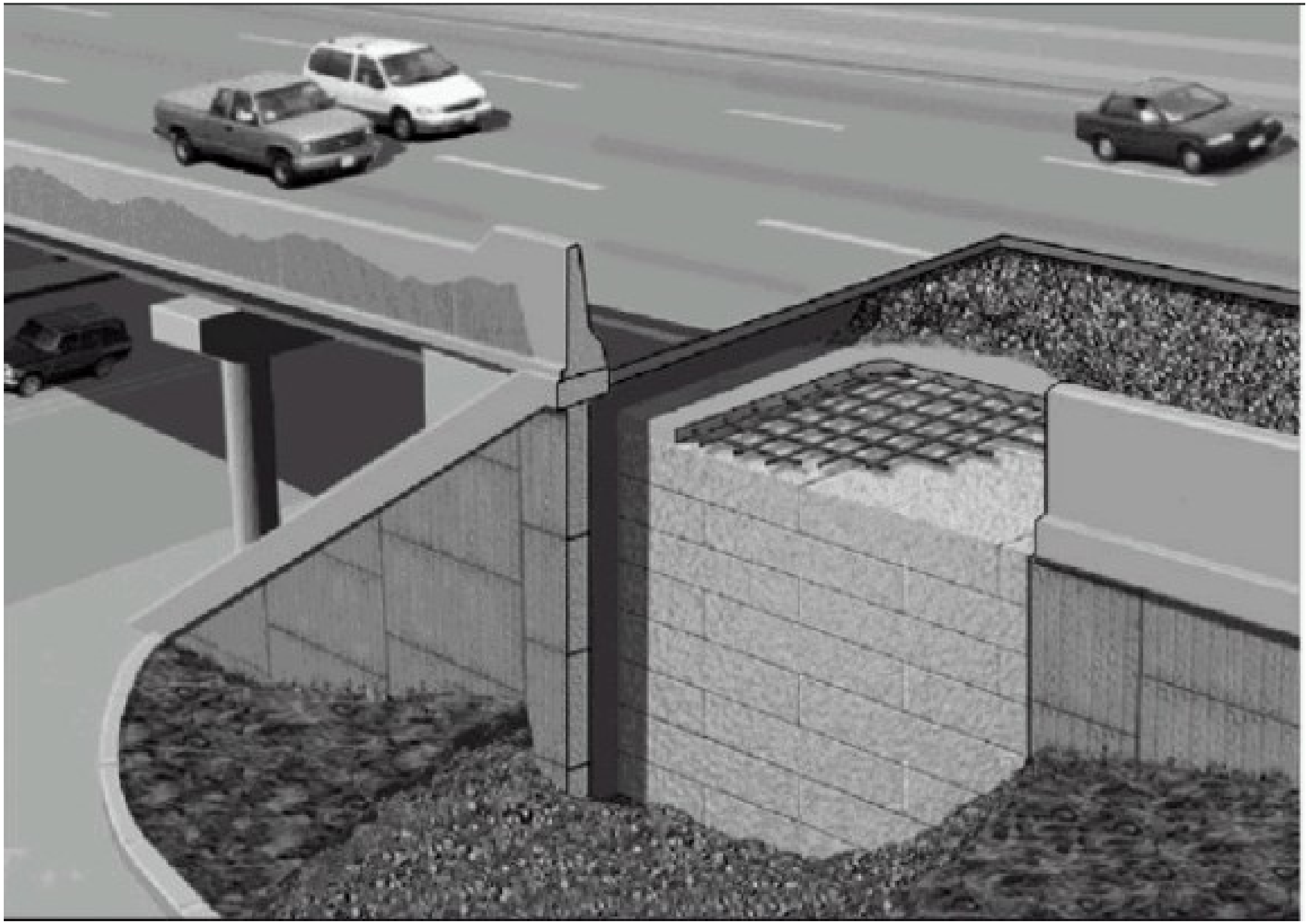
GeoFoam for Bridge Approach

Horvath

Geofoam for Embankment Fill



Geofoam for Bridge Abutment

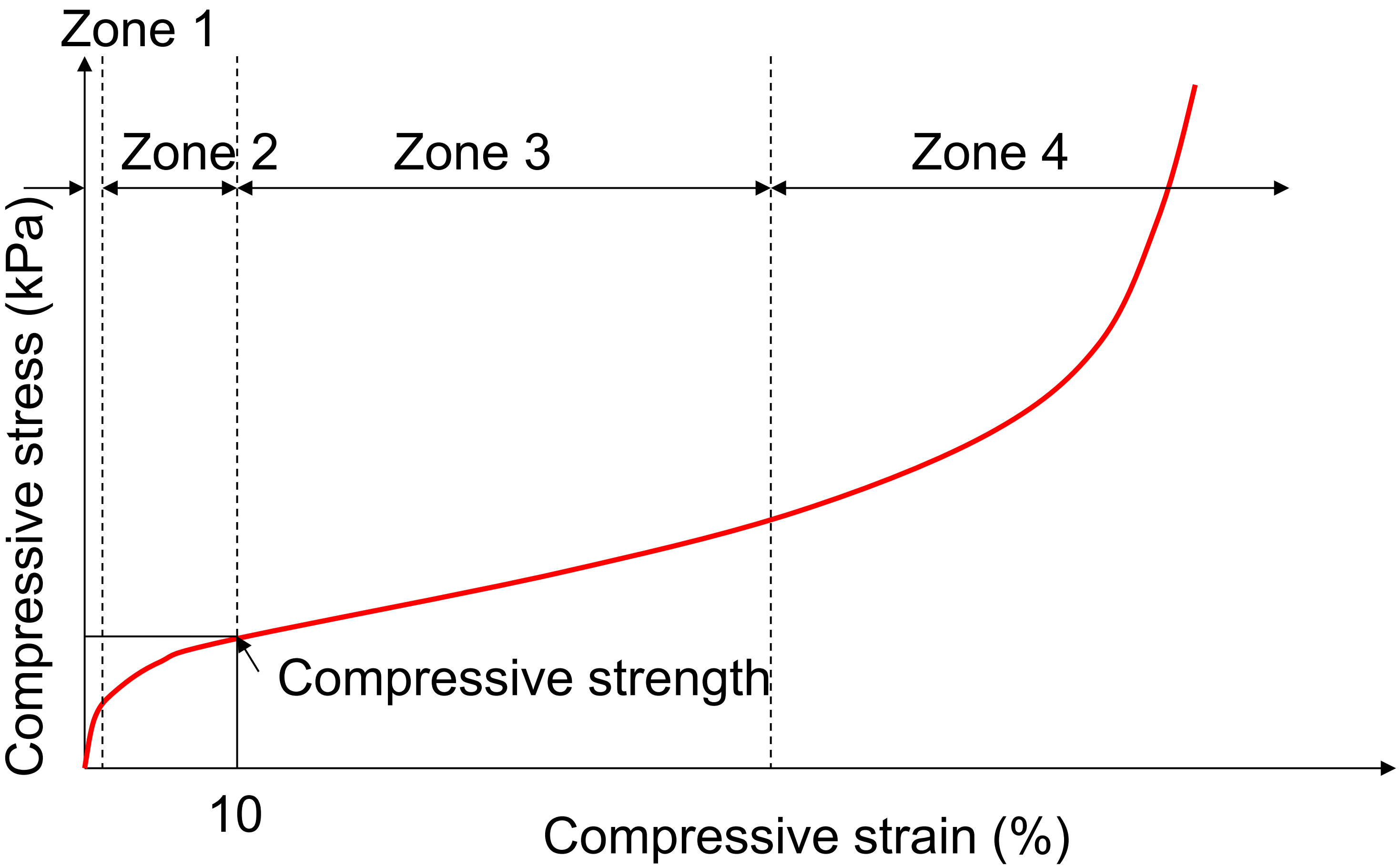


Geofoam used in I-15 Project

Commonly Manufactured Geofoam According to ASTM D6817

Dimension (mm)	All EPS types	All XPS types
Width	305 - 1219	406 - 1219
Length	1219 - 4877	1219 - 1743
Thickness	25 - 1219	25 - 102

Stress-Strain Behavior

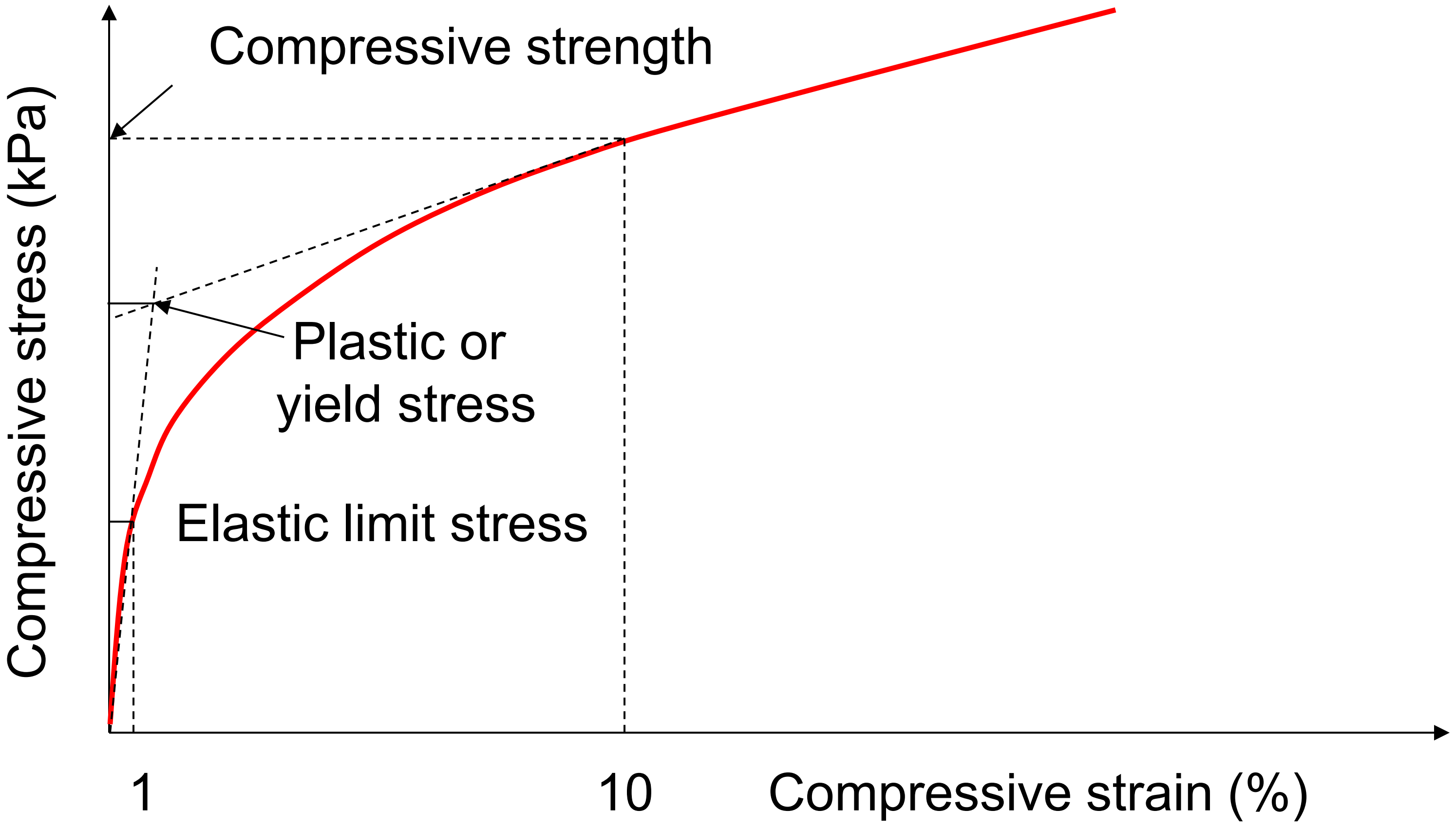


Zone 1: initial linear response Zone 2: yielding

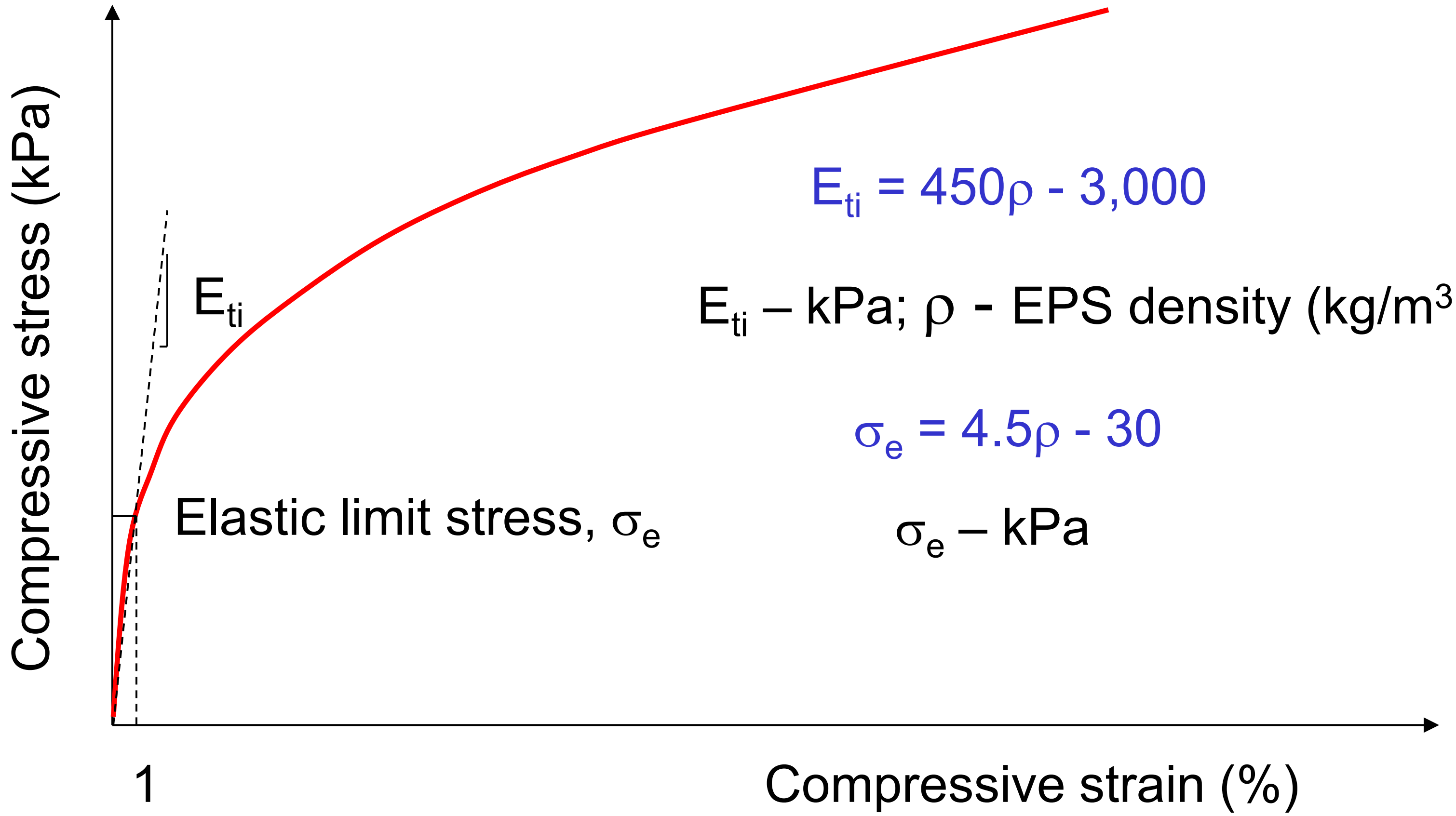
Zone 3: linear & work hardening in nature

Zone 4: non linear but still work hardening in nature

Definition of Modulus and Strength



Initial Tangent Young's Modulus



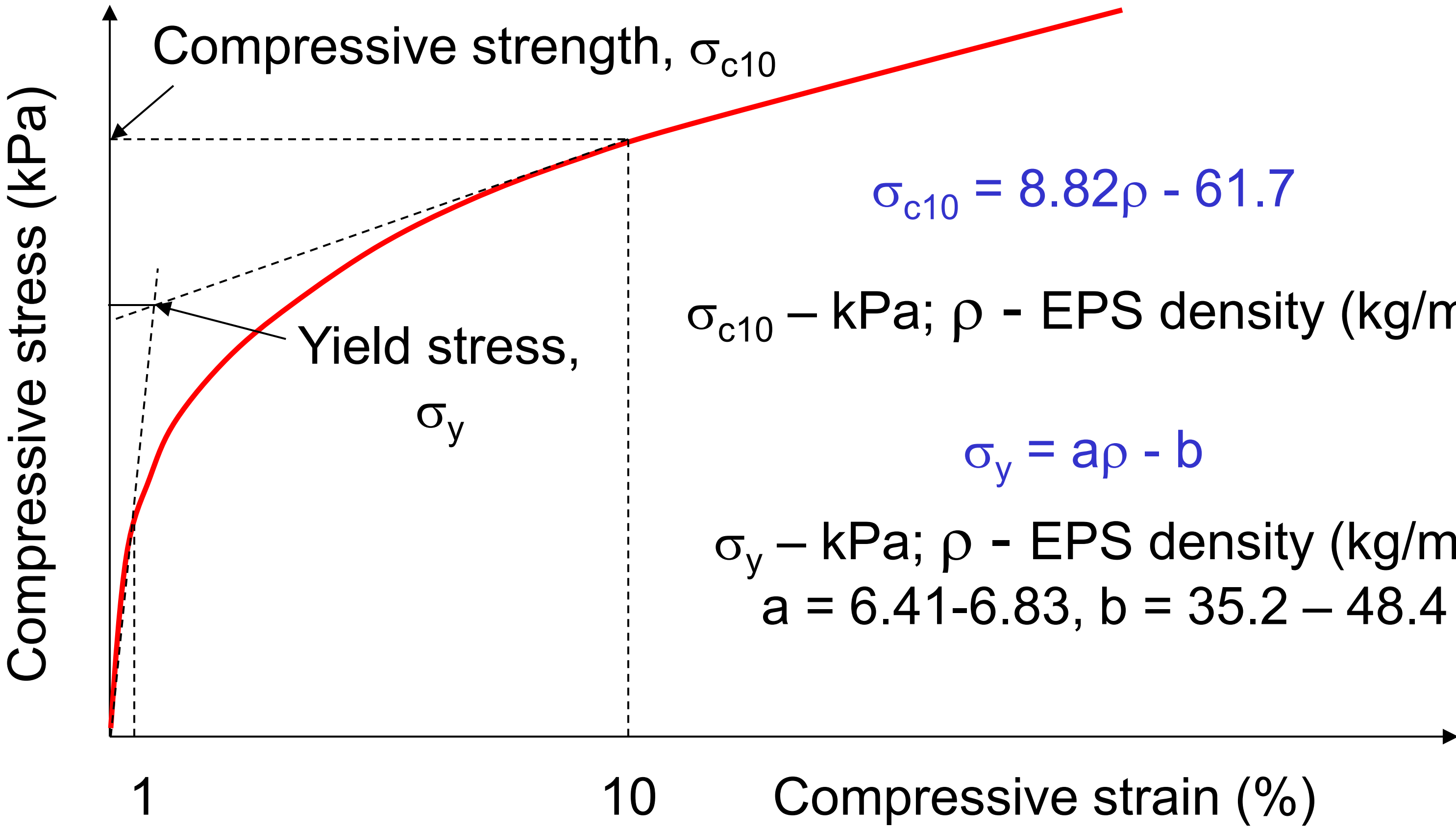
$E_{ti} = 450\rho - 3{,}000$

E_{ti} – kPa; ρ - EPS density (kg/m^3)

$\sigma_e = 4.5\rho - 30$

σ_e – kPa

Yield Stress & Compressive Strength



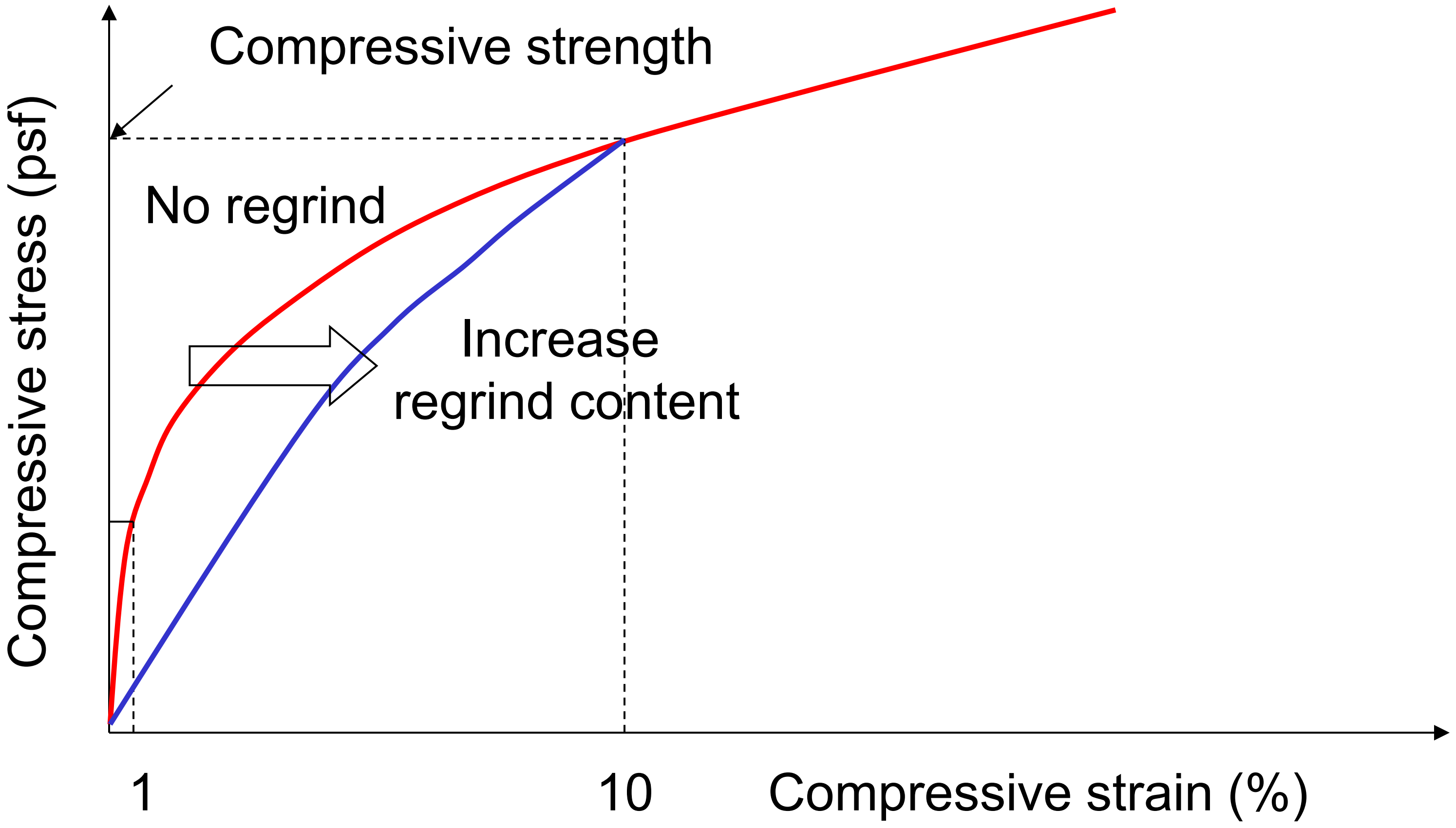
$\sigma_{c10} = 8.82\rho - 61.7$

σ_{c10} – kPa; ρ - EPS density (kg/m^3)

$\sigma_y = a\rho - b$

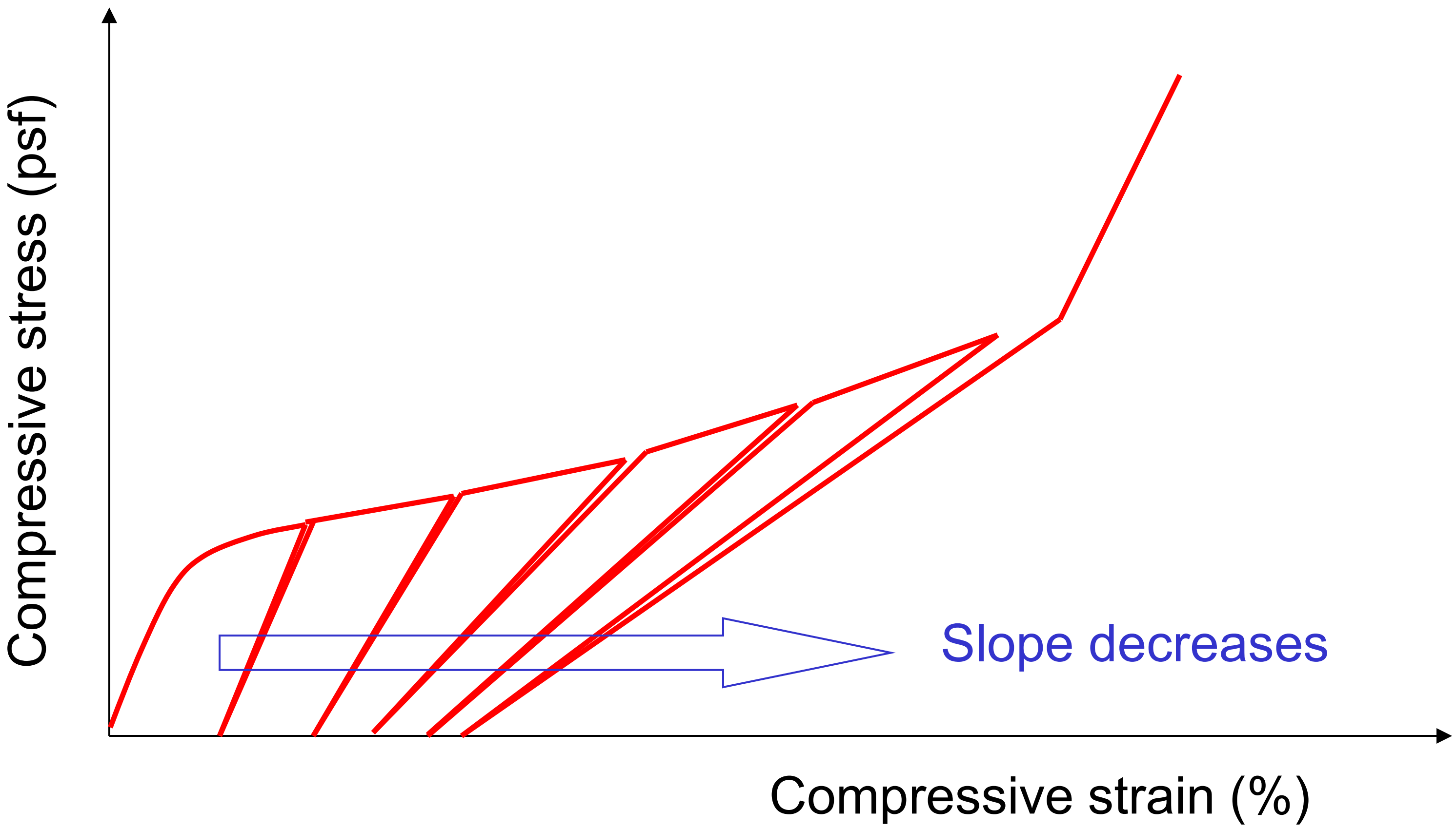
σ_y – kPa; ρ - EPS density (kg/m^3)
$a = 6.41\text{-}6.83$, $b = 35.2 – 48.4$

Effect of Regrind Content

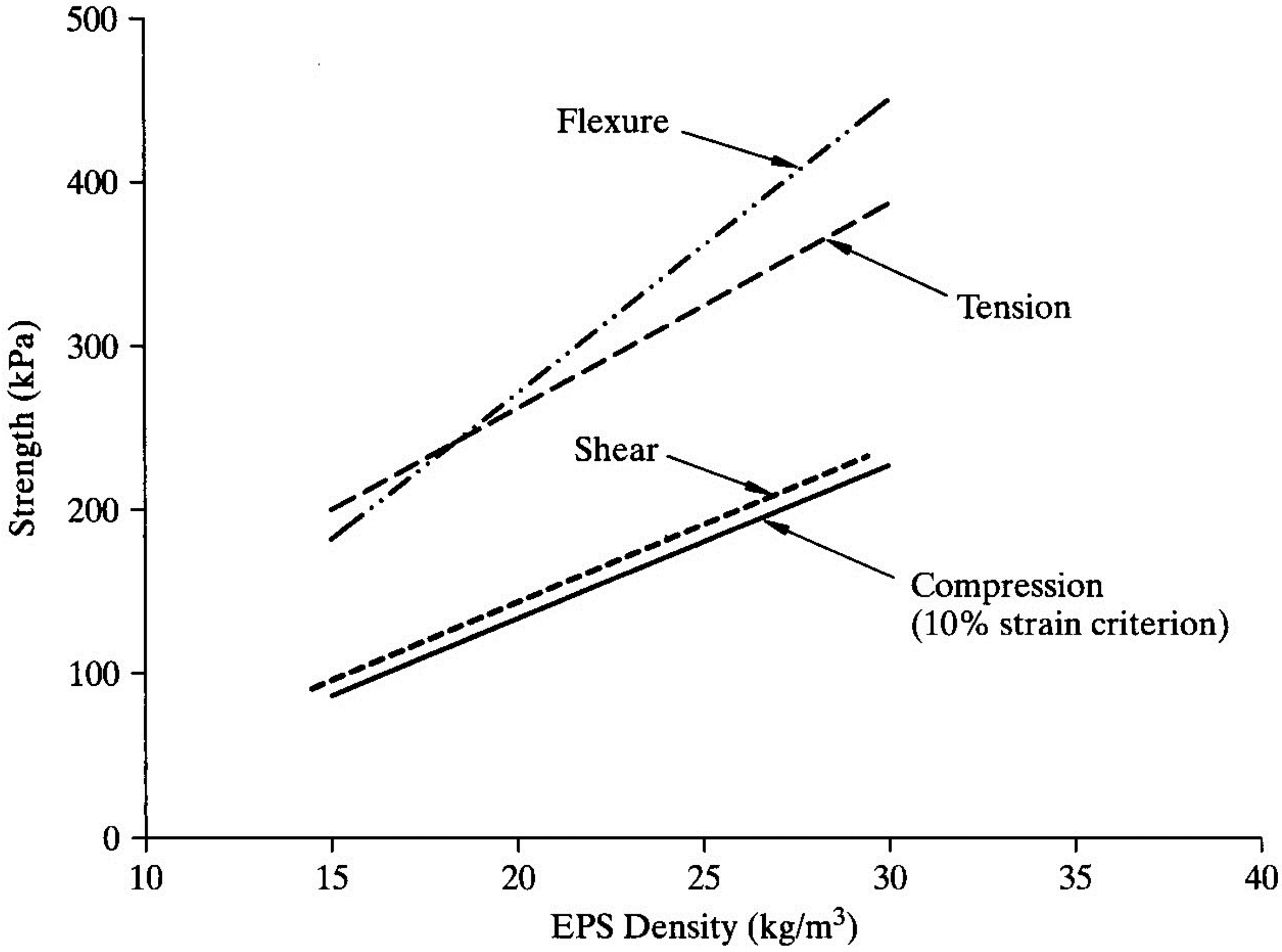


Cyclic Load Behavior

< elastic limit stress: no plastic strain upon stress removal & no degradation of E_{ti}



Various Strength Values of EPS



Styropor (1991)

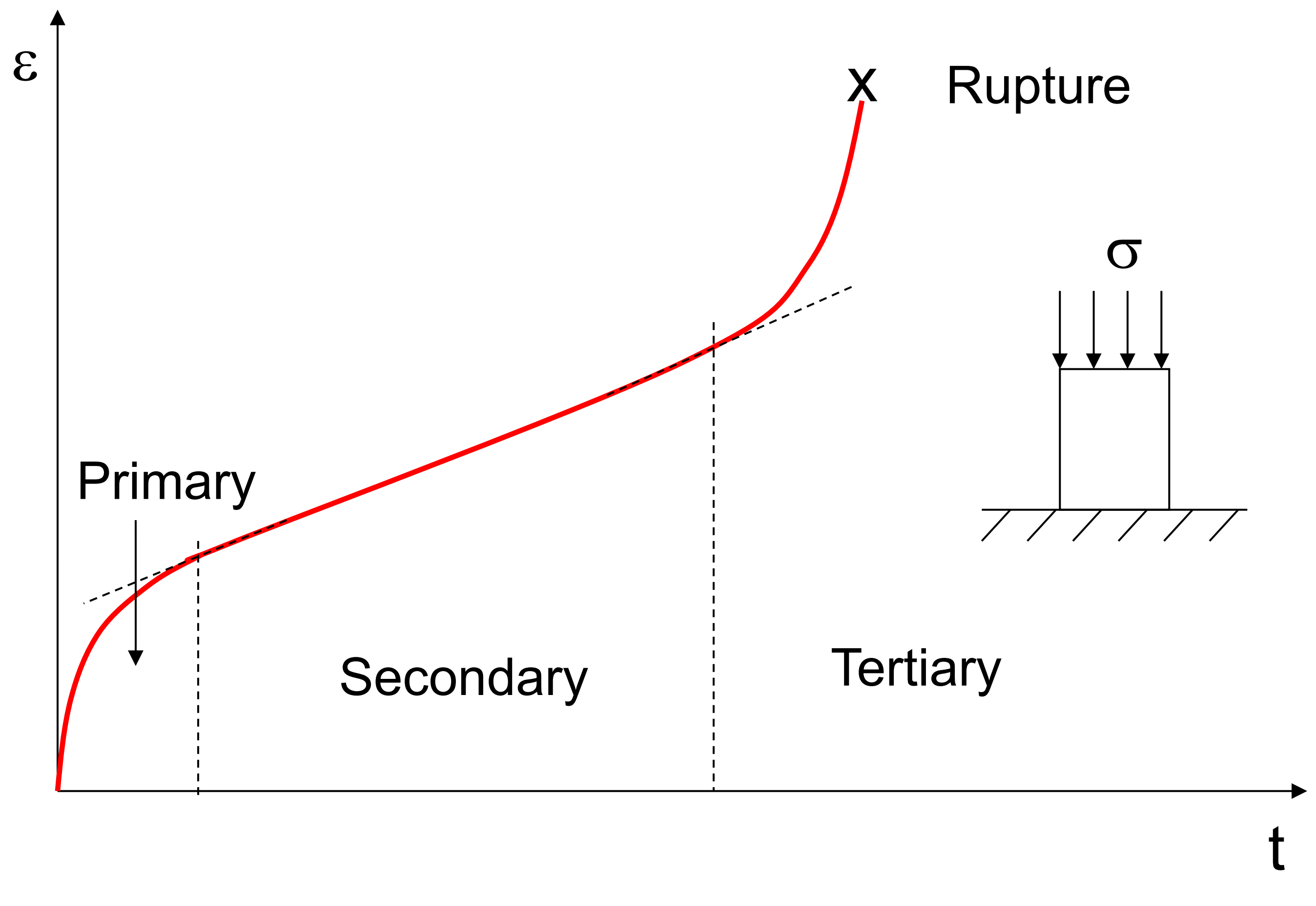
Poisson's Ratio and K_o

$$\nu = 0.0056\rho + 0.0024$$

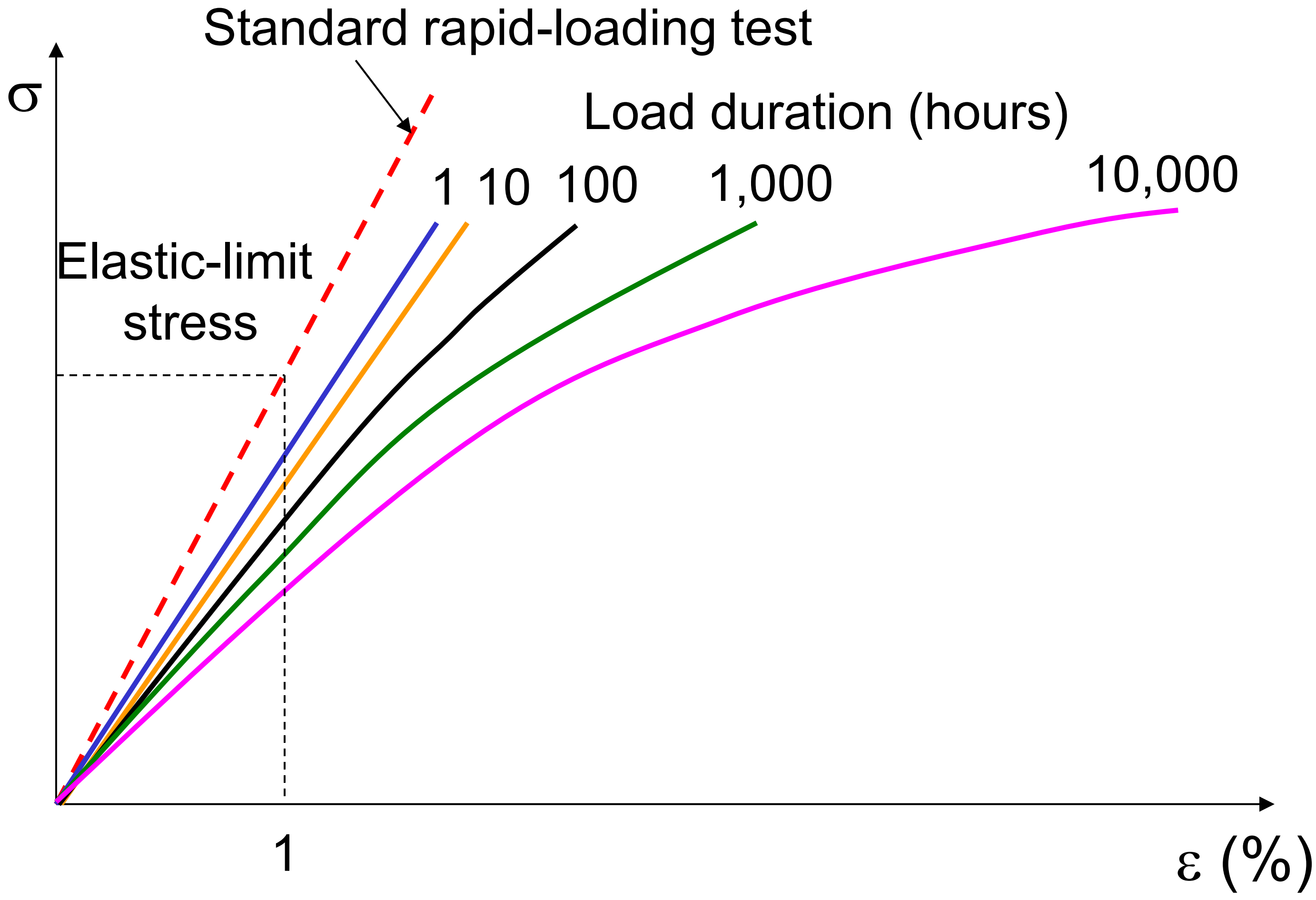
ρ - EPS density (kg/m^3)

$$K_o = \nu / (1 - \nu)$$

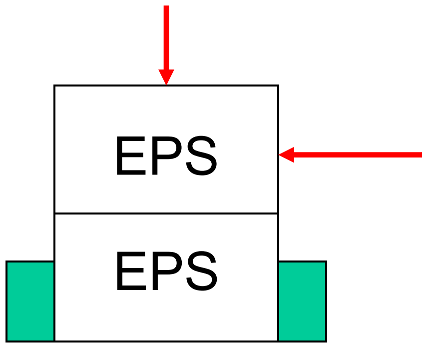
Creep



Isochronous Stress-Strain Curves



EPS/EPS Interface Strength

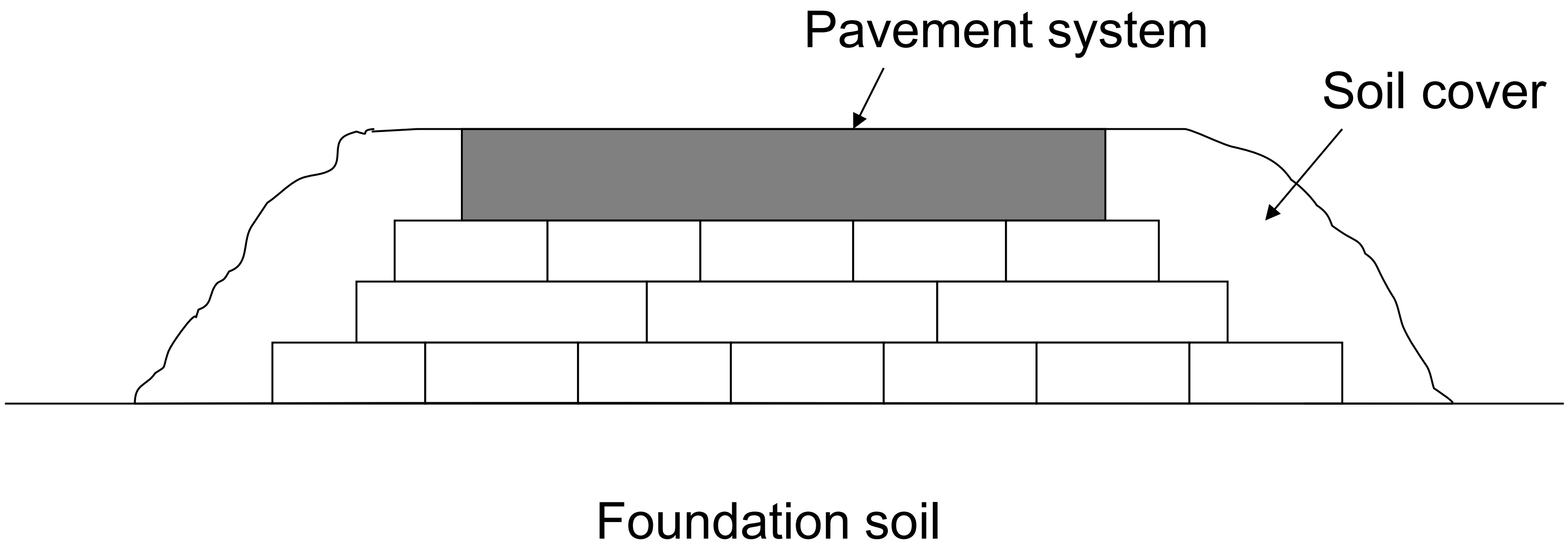


Shear strength

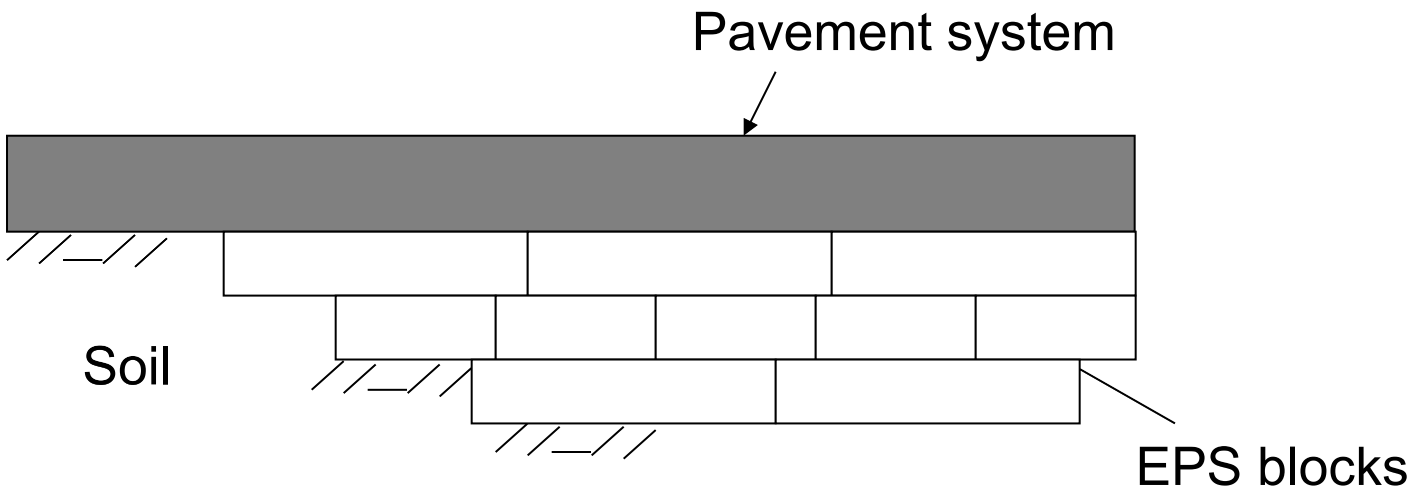
$$\tau = \mu \, \sigma_n = \sigma_n \tan\delta$$

Typically, μ = 0.5 to 0.7 or δ = 27^o to 35^o

Block Geofoam Embankment



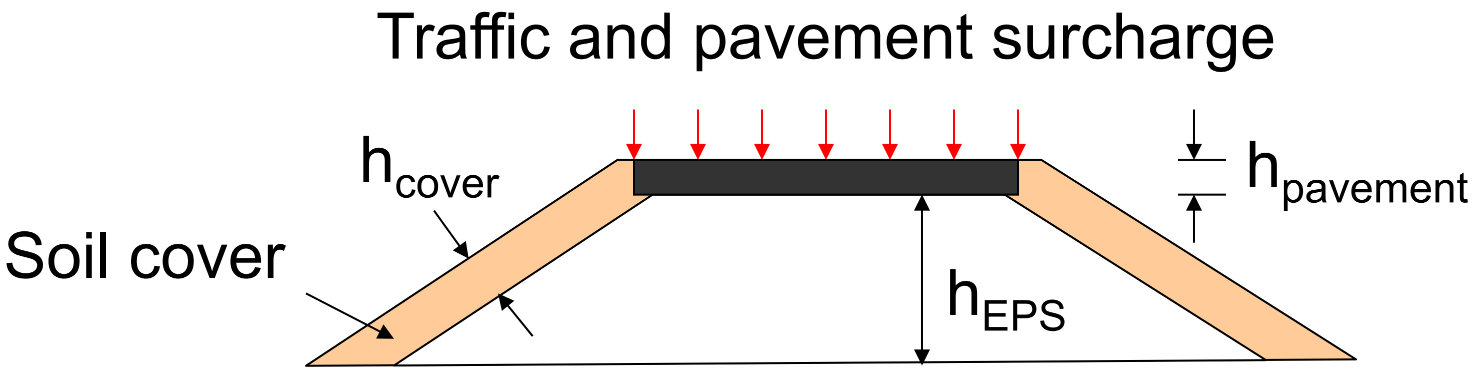
Typical EPS Block Transition to Subgrade



Overall Design Process

- Design for external (global) stability
  - total and differential settlement
  - bearing capacity and slope stability
  - hydrostatic uplift and translation due to water/wind
- Design for internal stability
  - short-term and long-term compression of geofoam
  - translation due to water/wind
- Design for pavement system
  - pavement rutting , cracking, or similar criterion

Definitions of Embankment



Total Settlement of EPS-Block Geofoam Embankment

$$\delta_{total} = \delta_{if} + \delta_i + \delta_c + \delta_s + \delta_{cf}$$

δ_{if} = immediate or elastic settlement of fill (including geofoam)

δ_i = immediate or elastic settlement of foundation soil

δ_c = primary consolidation settlement of foundation soil

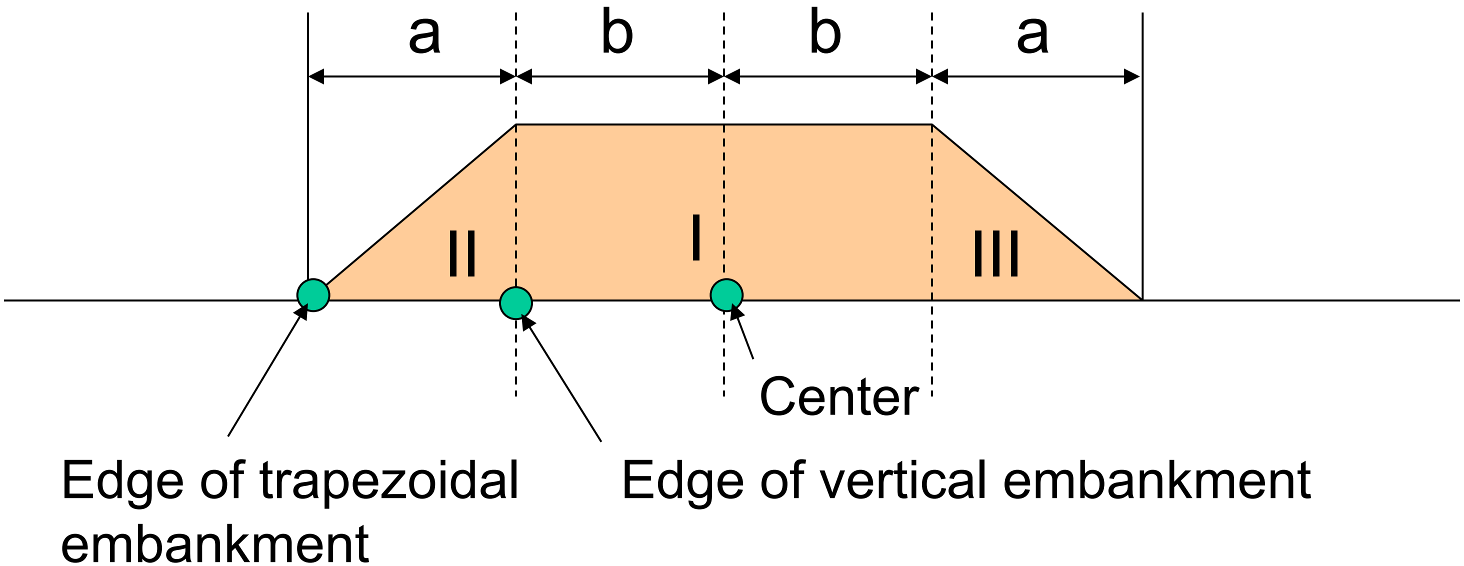
δ_s = secondary consolidation settlement of foundation soil

δ_{cf} = long-term vertical deformation (creep) of fill

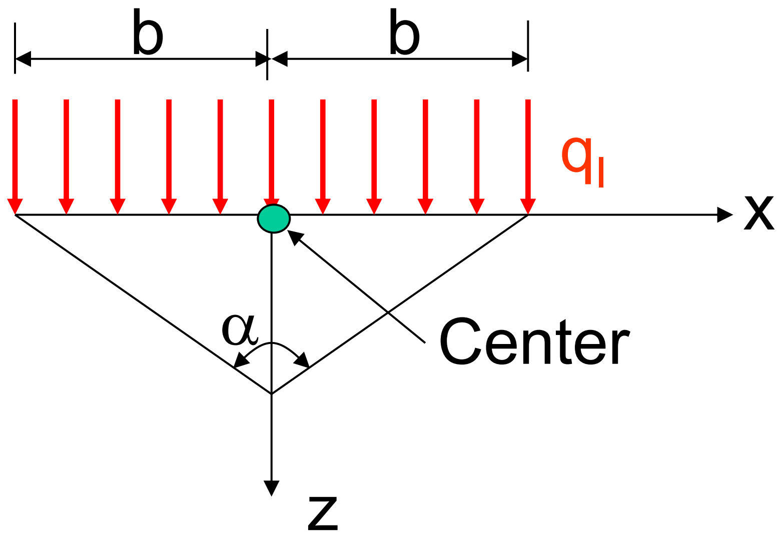
Recommendation:

Limit the immediate strain between 0.5% to 1.0% and $\delta_{if} + \delta_i + \delta_{cf}$ is negligible

Stress Distribution Analysis



Stress Distribution Analysis

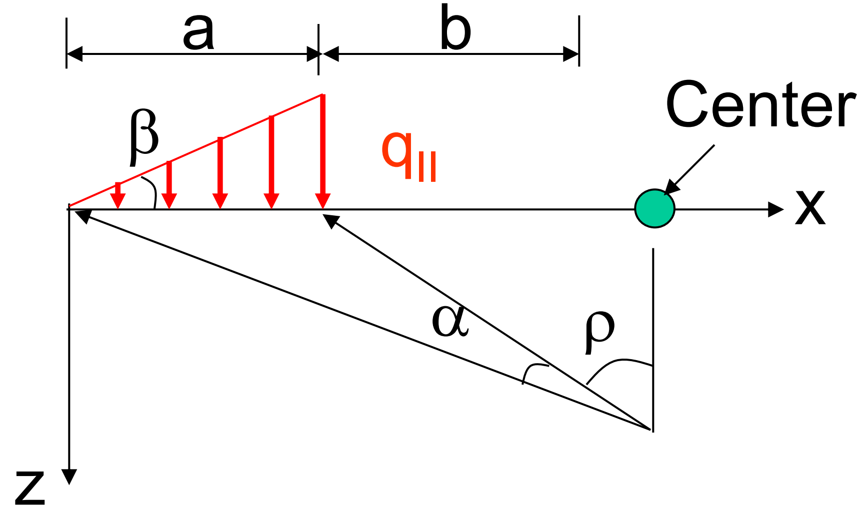


$$\Delta\sigma_{zI} = \frac{q_I}{\pi}(\alpha + \sin\alpha) \qquad \alpha = 2\arctan\left(\frac{b}{z}\right)$$

$$q_I = q_{fill} + q_{pavement}$$

$$q_{fill} = \gamma_{EPS} h_{EPS} \qquad q_{pavement} = \gamma_{pavement} h_{pavement}$$

Stress Distribution Analysis



$$\Delta\sigma_{zII} = \frac{q_{II}}{2\pi}\left(\frac{x}{0.5\mathrm{a}}\alpha - \sin 2\rho\right)$$

$$\rho = \arctan\left(\frac{b}{z}\right)$$

$$\alpha = \arctan\left(\frac{\mathrm{a}+\mathrm{b}}{z}\right) - \rho$$

$$q_{II} = q_{fill} + q_{cover}$$

$$q_{fill} = \gamma_{EPS} h_{EPS}$$

$$q_{cover} = \gamma_{cover} h_{cover} / \cos\beta$$

Total Increase in Vertical Stress at the Center

$$\Delta\sigma_{zcenter} = \Delta\sigma_{zI} + 2\cdot\Delta\sigma_{zII}$$

Bearing Capacity of Embankment

Ultimate bearing capacity

$$q_{ult} = cN_c + 0.5\gamma BN_\gamma + \gamma D_f N_q$$

For soft soil under undrained condition

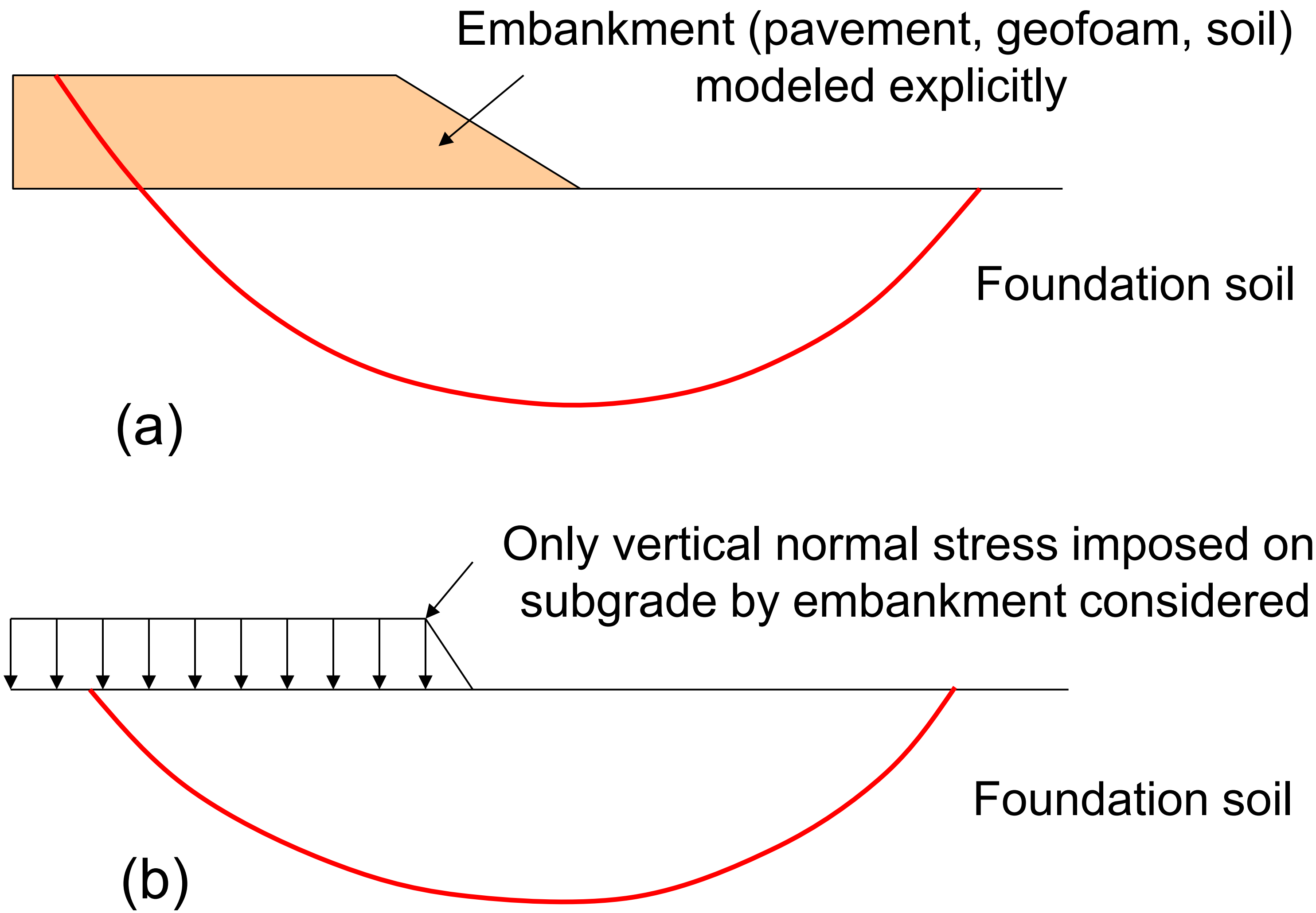
$$q_{ult} \approx 5c_u \qquad FS = \frac{q_{ult}}{q_{allow}} = \frac{5c_u}{q_{allow}} = 3$$

Required undrained shear strength

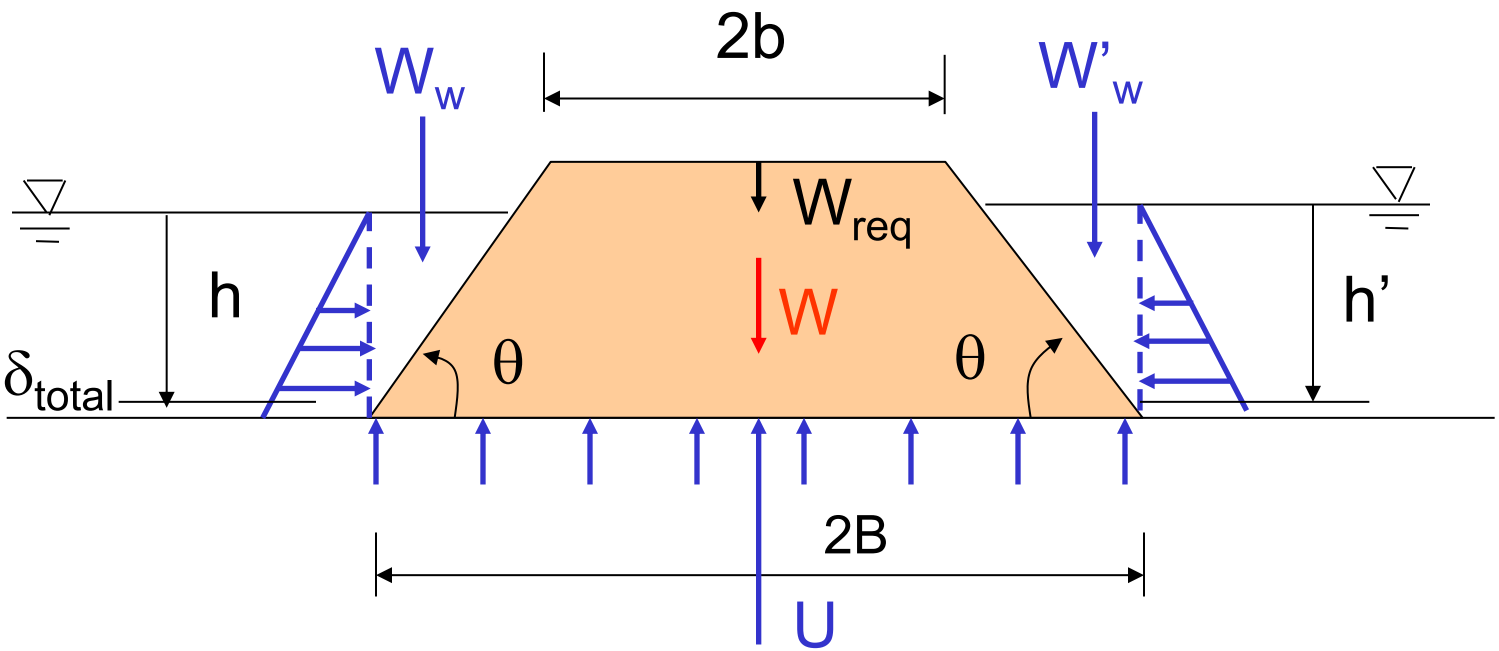
$$c_u = \frac{3}{5}\left\{\left[\frac{\left(\sigma_{n,pavement} + \sigma_{n,traffic}\right)\cdot 2b}{2b + h_{EPS}} + \frac{\gamma_{EPS} h_{EPS}}{2}\right]\right\}$$

$$\approx \frac{198b}{5\left(2b + h_{EPS}\right)} + 0.3h_{EPS}$$

Typical Slope Modes of Failure



Hydrostatic Uplift Stability

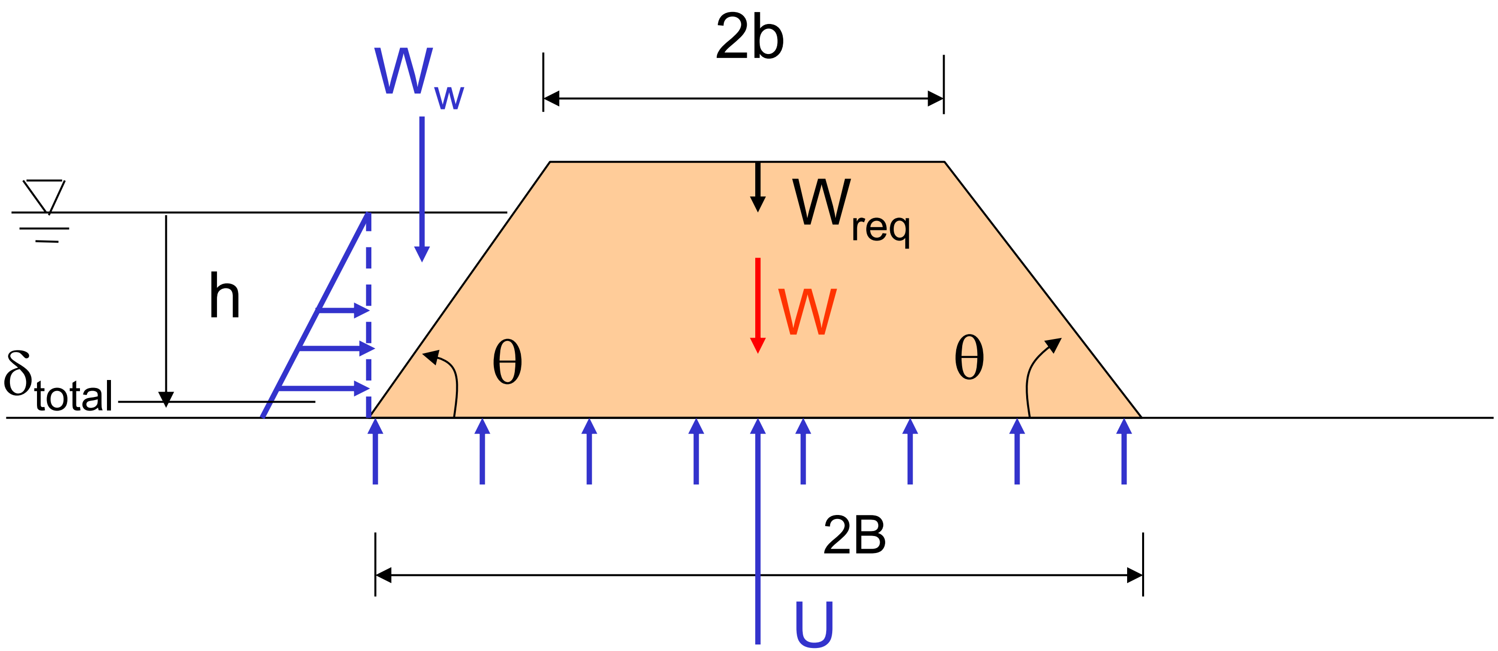


$$FS = \frac{W_{EPS} + W_w + W_w' + W_{req}}{\gamma_w (h + \delta_{total}) \cdot (2B)}$$

W_{req} = required overburden force to stabilize the EPS blocks

$$W_{req} < (\gamma_{pavement} h_{pavement} \cdot 2b) - (\gamma_{EPS} h_{pavement} \cdot 2b) + W_{cover}$$

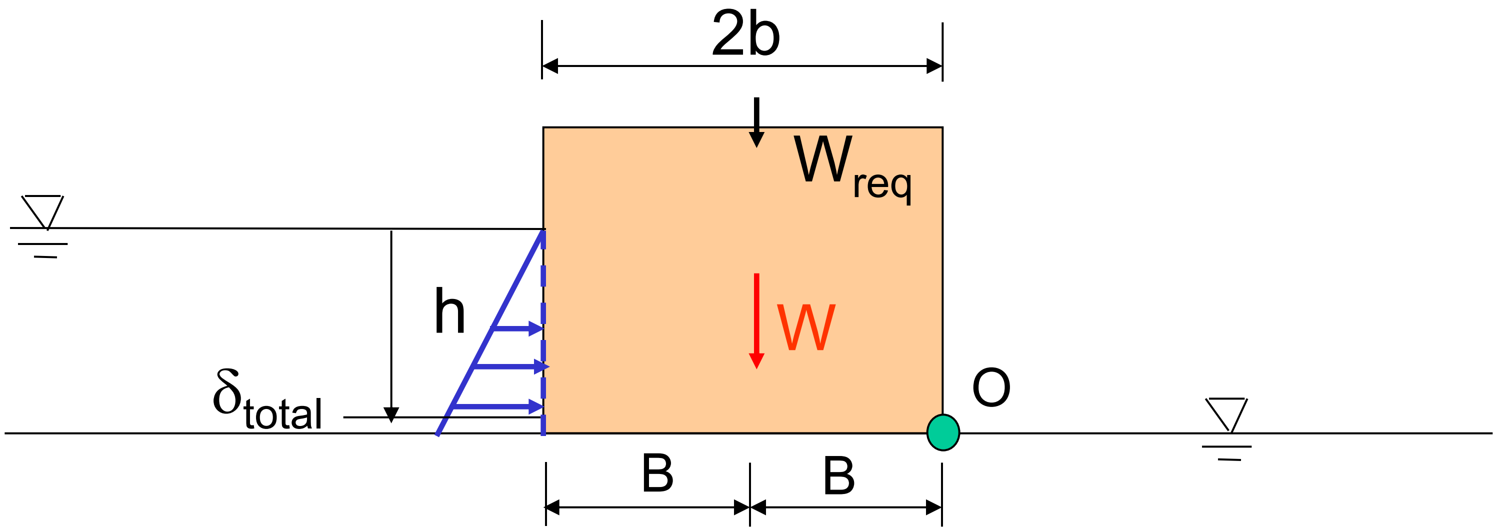
Translation due to Water



$$FS = \frac{\sum \text{horizontal resisting forces}}{\text{horizontal driving forces}} = \frac{c \cdot A + \left(\sum N - \sum U\right)\tan\delta}{\sum F_H}$$

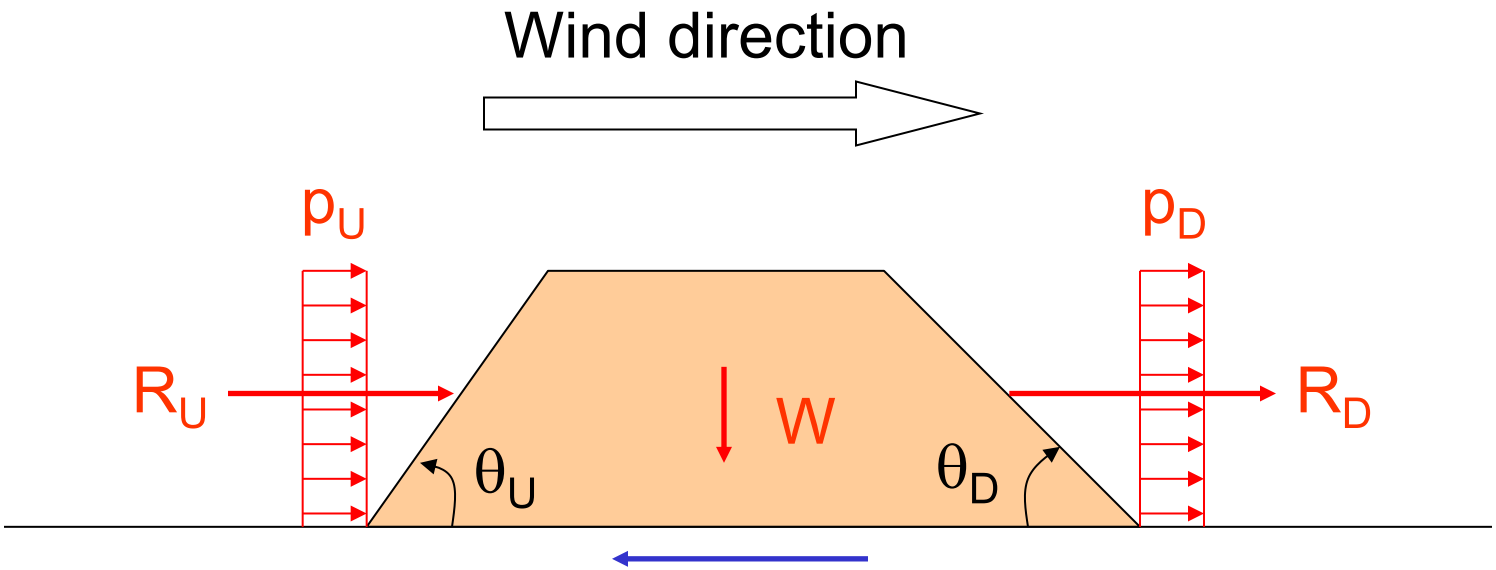
$$FS = \frac{\left[\left(W_{EPS} + W_W + W_{req}\right) - 0.5\left(h + \delta_{total}\right)\gamma_w \cdot \left(2B\right)\right]\tan\delta}{0.5\gamma_w\left(h + \delta_{total}\right)^2}$$

Overturning due to Water



$$FS = \frac{\sum \text{stabilizing moments}}{\sum \text{overturning moments}} = \frac{b\left(W_{EPS} + W_{req}\right)}{(1/6)\left(h + \delta_{total}\right)^3 \gamma_w}$$

Wind-Loading Analysis



$p_U = 0.75V^2 \sin\theta_U$ $p_D = 0.75V^2 \sin\theta_D$

V = the wind speed in meters per second
p_U and p_D = horizontal stresses by wind (kPa)

Seismic Stability Analysis