UNSATURATED SOILS: SOME FUNDAMENTALS AND SOME APPLICATIONS

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- SOME FUNDAMENTALS
  - SUCTION
  - EFFECTIVE STRESS
  - STRENGTH
  - DEFORMATION
- SOME APPLICATIONS
  - ULTIMATE BEARING CAPACITY
  - MOVEMENT
  - COMPACTION
  - SLABS ON GRADE
  - TREES
  - EARTH PRESSURES
  - SLOPES

THE THREE ZONES

Soil State	Swell	Shrink
Unsaturated	Yes	No
Saturated	Yes	Yes
GWL		
Saturated	No	Yes

WATER NORMAL STRESS

TENSION | COMPRESSION

0

u_w (kPa)

~~(SUCTION)~~

~~(pF)~~

~~(PORE PRESSURE)~~

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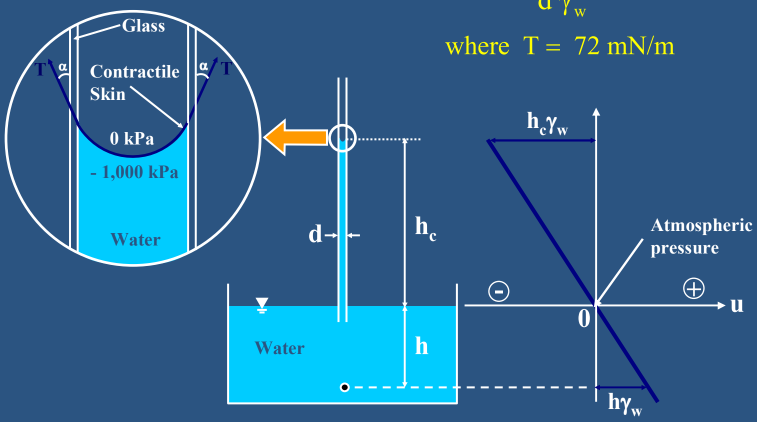
MATRIC WATER TENSION

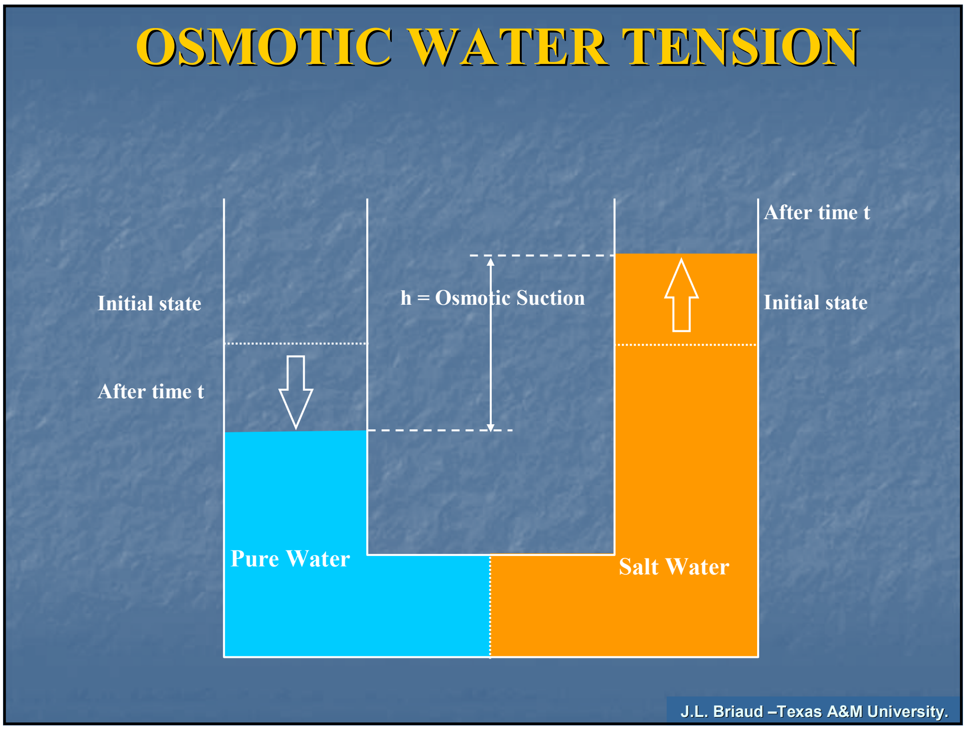
$$h_c = \frac{4\,T\cos\alpha}{d\,\gamma_w}$$

where $T = 72$ mN/m



The Water Strider

Force = 72 mN/m
Thickness = a few Angstroms
Stress >? 20 MPa


OSMOTIC WATER TENSION
Initial state
After time t
h = Osmotic Suction
After time t
Initial state
Pure Water
Salt Water
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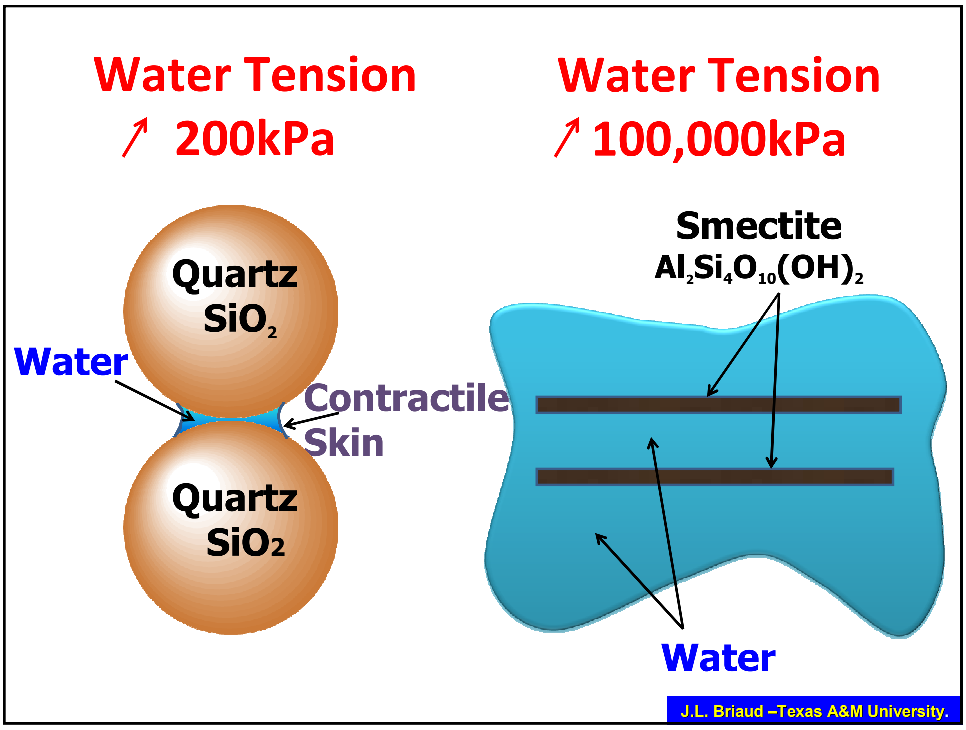
Water Tension
↗ 200kPa
Water Tension
↗ 100,000kPa
Quartz
SiO_2
Water
Contractile
Skin
Quartz
SiO_2
Smectite
$Al_2Si_4O_{10}(OH)_2$
Water
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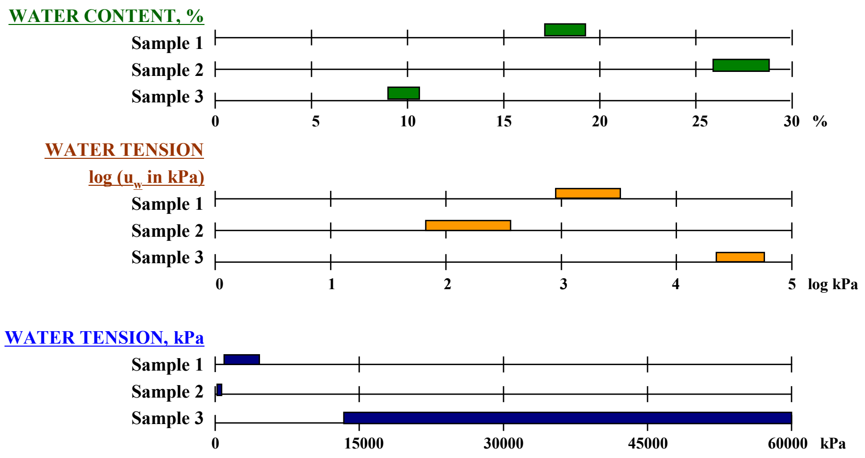
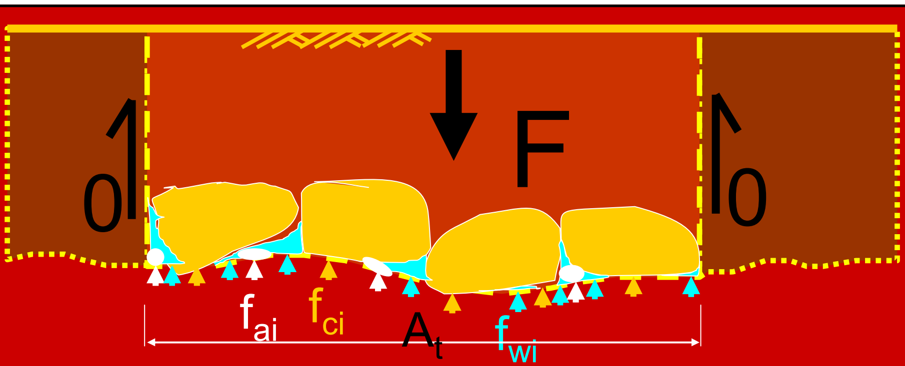
GARNER'S STUDY (2002)

3 samples at 3 water contents sent to 8 laboratories.

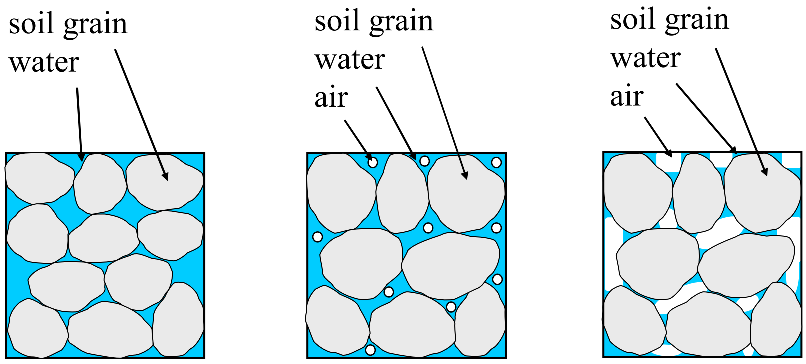




$$\frac{F}{A_t} = \frac{\sum f_{ci}}{A_t} + \frac{\sum f_{wi}}{A_t} + \frac{\sum f_{ai}}{A_t}$$

$$\sigma = \sigma' + \frac{u_w \sum a_{wi}}{A_t} + \frac{u_a \sum a_{ai}}{A_t}$$

$$\sigma = \sigma' + \alpha u_w + \beta u_a$$



Saturated

$u_w \neq 0$

$u_a = 0$

$\sigma' = \sigma - u_w$

Occluded Air

$u_w = u_a$

$\sigma' = \sigma - u_w$

$S > 85\%$

Continuous Air

$u_w \neq 0$

$u_a = 0$

$\sigma' = \sigma - \alpha u_w$

$S < 85\%$

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For Unsaturated Soils

The effective stress is

$$\sigma' = \sigma - \alpha\, u_w \qquad \text{with} \qquad \alpha \sim S$$

The effective stress controls the behavior of the soil skeleton for saturated soils and for unsaturated soils (in most cases)

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Shear Strength-unsaturated

$$s = c' + \sigma' \tan\phi'$$

$$s = c' + (\sigma - \alpha u_w - \beta u_a)\tan\phi'$$

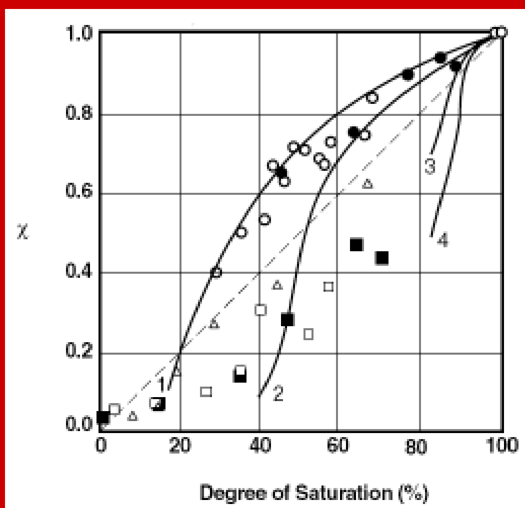
$$s = c' + (\sigma - \alpha u_w)\tan\phi'$$

$$\alpha = S \ (?)$$

$c' - \alpha u_w \tan\phi' =$ Apparent Cohesion

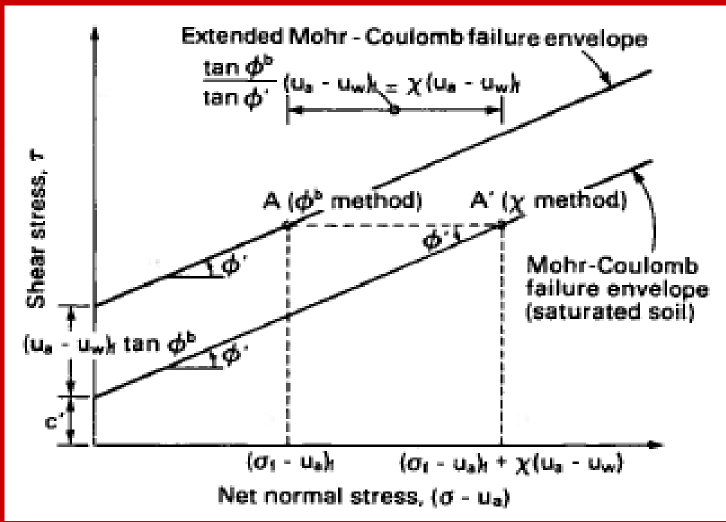
Shear Strength-unsaturated

α **vs S**



(Lu & Likos, 2004)

Shear Strength-unsaturated



(Fredlund & Rahardjo, 1993)

SHEAR STRENGTH-example

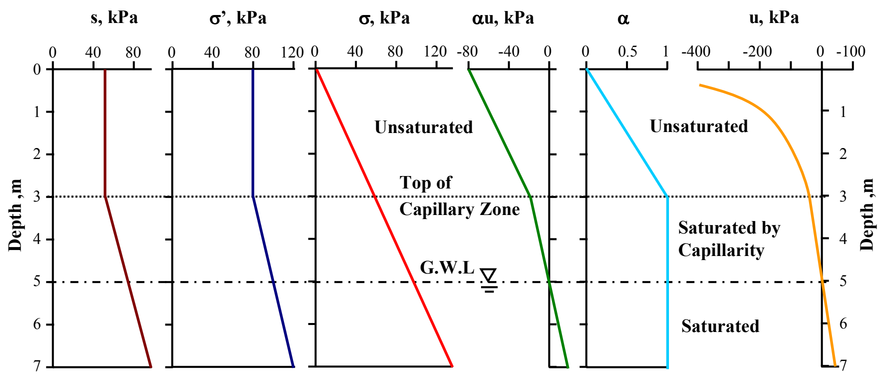
Example calculations (unsaturated):

c = 5 kPa, φ = 30 degrees, z = 1 m,
S = 35%, u_w = -1000 kPa, u_a = 0
s = 5 + (20 – 0.35x(-1000)) tan 30
s = 218.6 kPa

Example calculations (saturated):

c = 5 kPa, φ = 30 degrees, z = 1 m,
S = 100%, u_w = 10 kPa, u_a = 0
s = 5 + (20 – 1x10) tan 30
s = 10.8 kPa

EXAMPLE OF STRESS PROFILES



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THIS BEARING CAPACITY EQUATION DOES NOT WORK FOR UNSATURATED SOILS

$$p_u = cN_c + \frac{1}{2}\gamma B N_\gamma + \gamma D N_q$$

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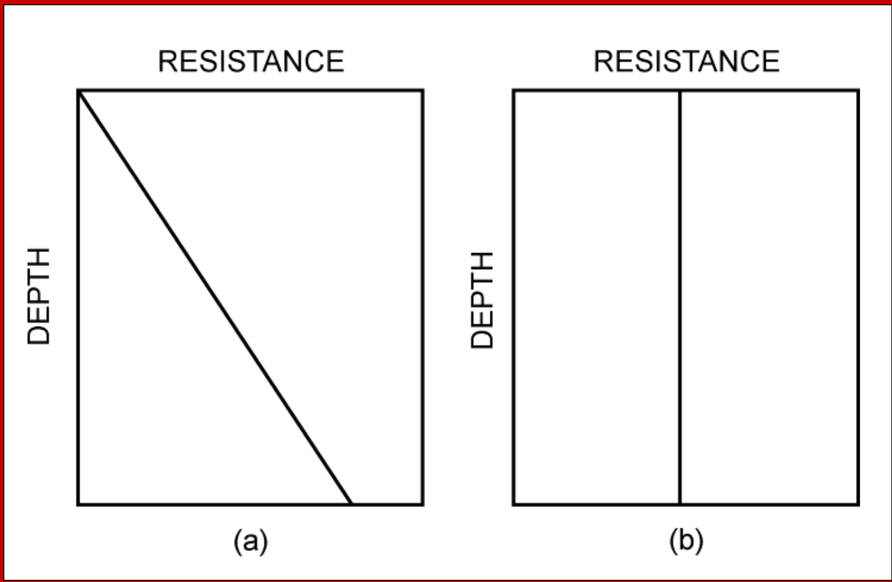

THIS BEARING CAPACITY EQUATION ALWAYS WORKS

$$p_u = k\,r$$

$$r = p_L, q_C, N, s_U$$

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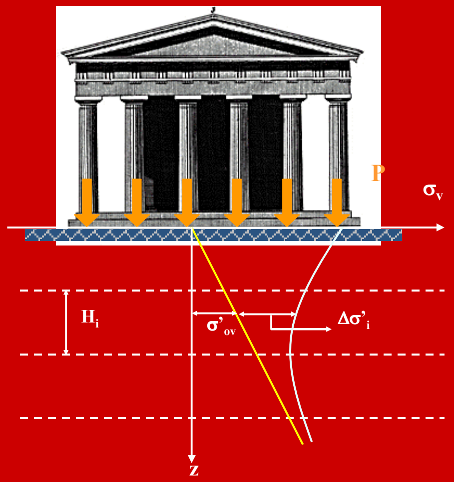
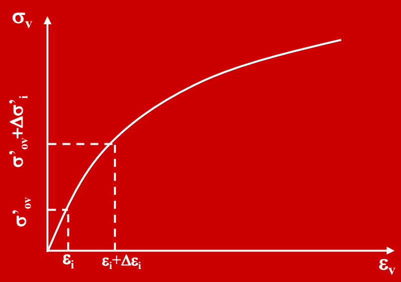
WEIGHT INDUCED SETTLEMENT

$$S = \sum H_i \, \Delta\varepsilon_i = \sum H_i \frac{\Delta\sigma_i}{E_i}$$





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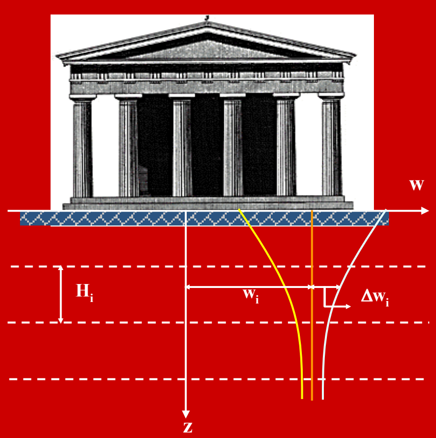
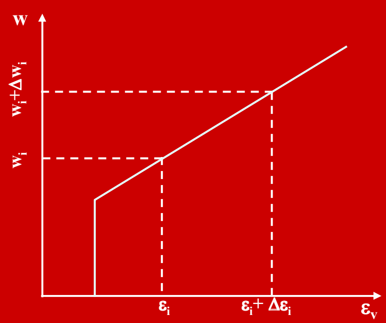
MOISTURE INDUCED MOVEMENT

$$S = \sum H_i \, \Delta\varepsilon_i = \sum H_i \, f \frac{\Delta w_i}{E_{wi}}$$





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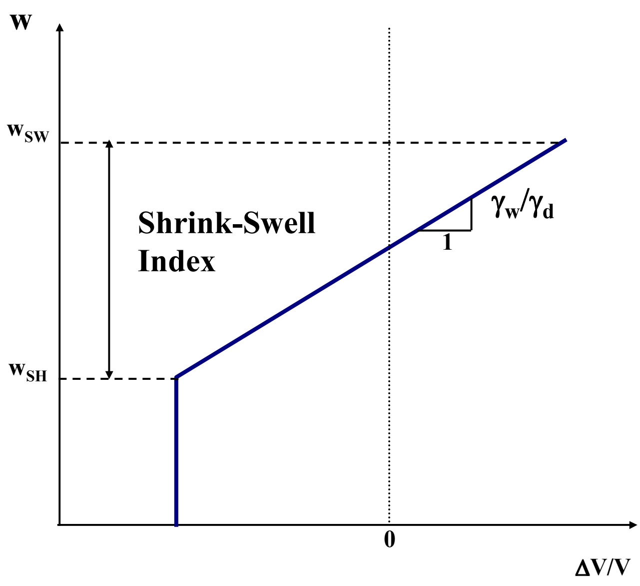

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CLASSIFICATION OF SHRINK-SWELL POTENTIAL ACCORDING TO SHRINK-SWELL INDEX

Potential	I_{ss}
Very High	> 60%
High	40 – 60
Moderate	20 – 40
Low	< 20%

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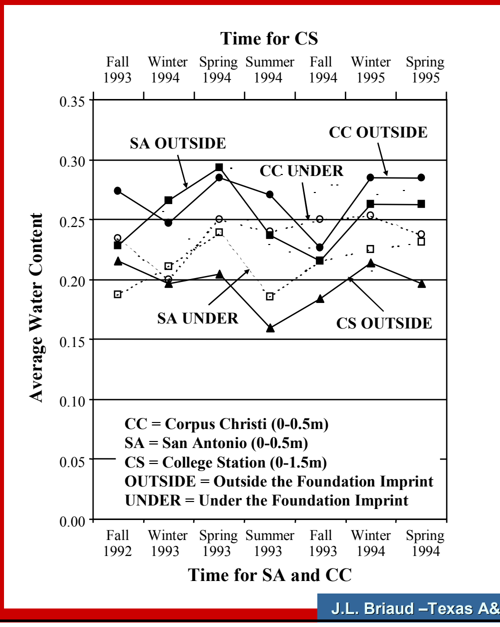
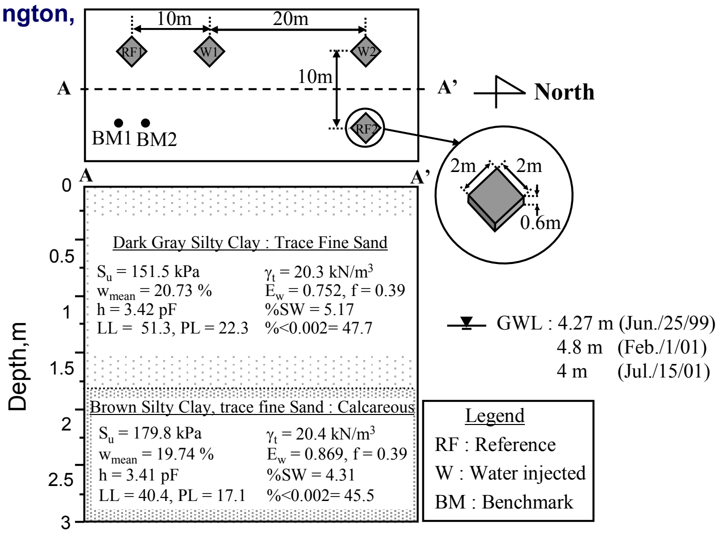
WATER CONTENT VARIATION AS A FUNCTION OF TIME

$$S = \sum H_i \, \Delta\varepsilon_i = \sum H_i \, f \frac{\Delta w_i}{E_{wi}}$$



Site in Arlington, Texas



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WATER INJECTION

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FOOTINGS

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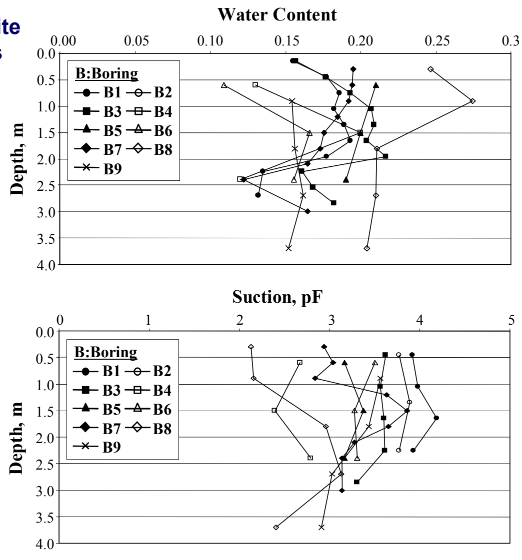
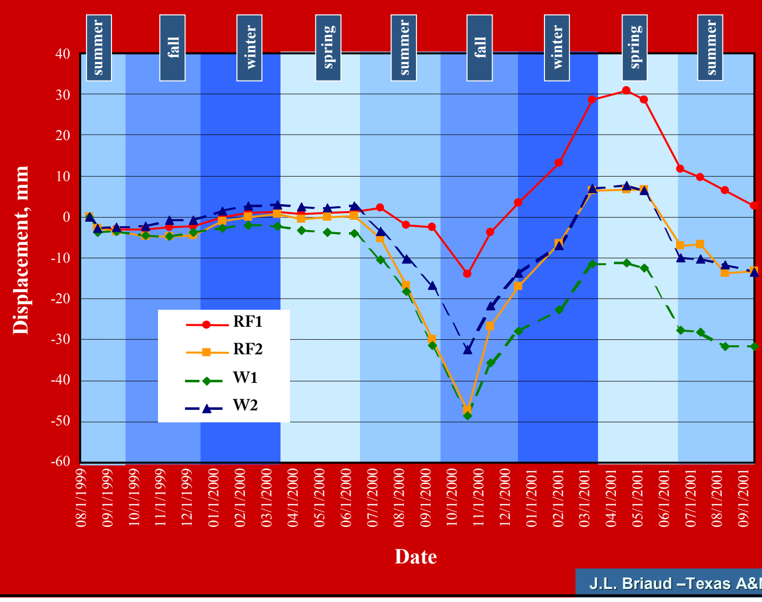
WATER CONTENT AND SUCTION vs. DEPTH

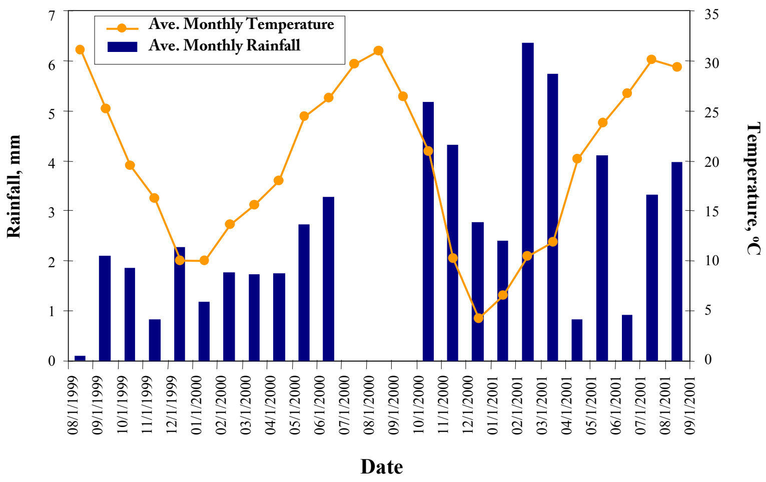
Footing RF1 at a site in Arlington, Texas



FOOTING MOVEMENT OVER TWO YEARS



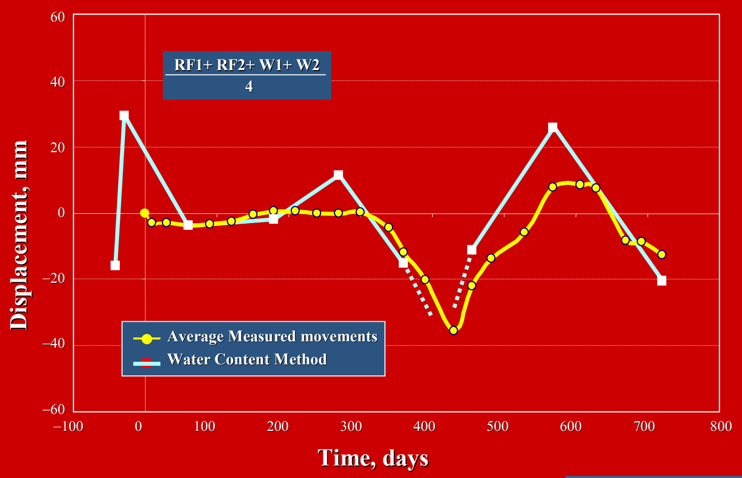
RAINFALL AND TEMPERATURE



PREDICTED AND MEASURED MOVEMENTS

Average of 4 Footings at a site in Arlington, Texas

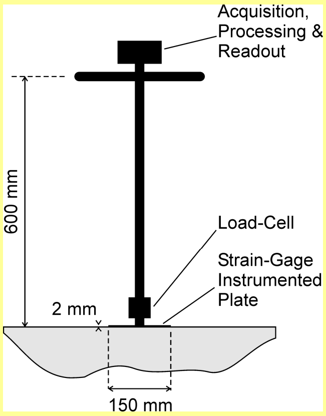
$$S = \sum H_i \,\Delta\varepsilon_i = \sum H_i \, f \,\frac{\Delta w_i}{E_{wi}}$$



Example of same modulus test in lab and in field

BCD Test: Briaud Compaction Device

BCD on Proctor Mold



BCD in the Field

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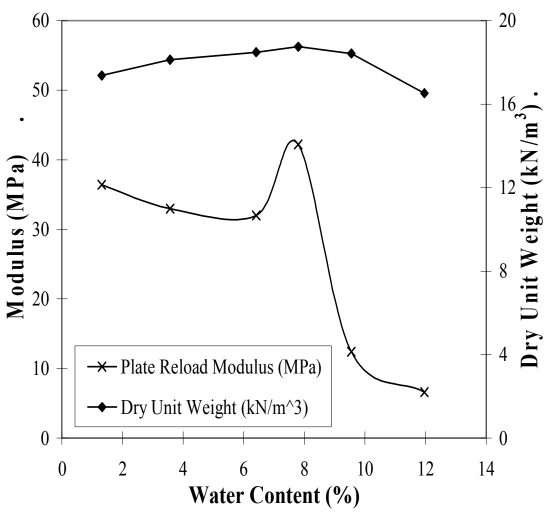
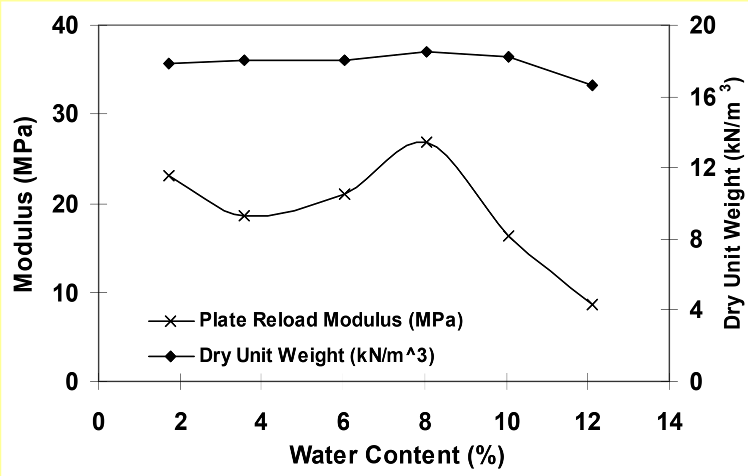


NGES Silty Sand (Mold #5)

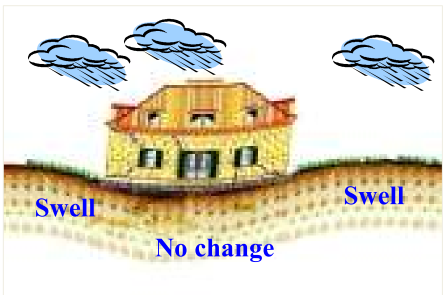


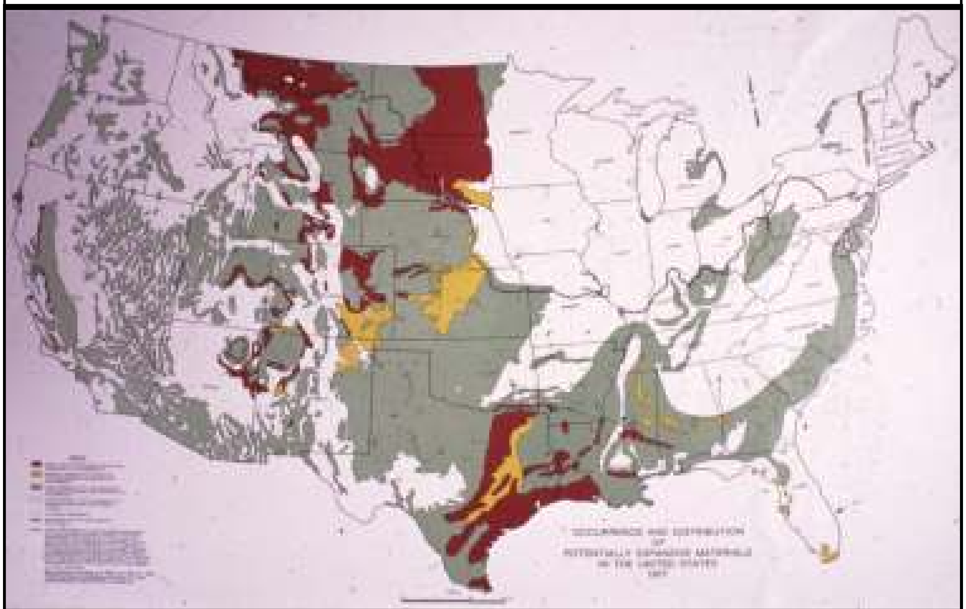
Modulus measured with BPT: Briaud Plate Test

TYPICAL DAMAGE CAUSED BY SHRINK-SWELL SOILS

SUMMER

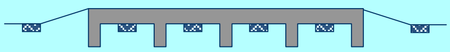
WINTER



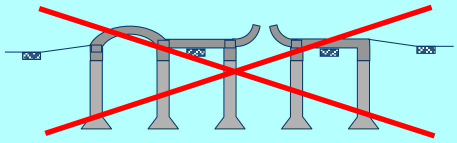


FOUNDATION SOLUTIONS

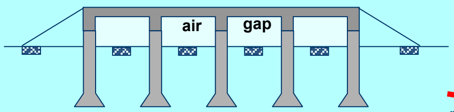
- Stiffened Slab on Grade



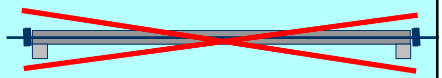
- Stiffened Slab on Grade and on Piers

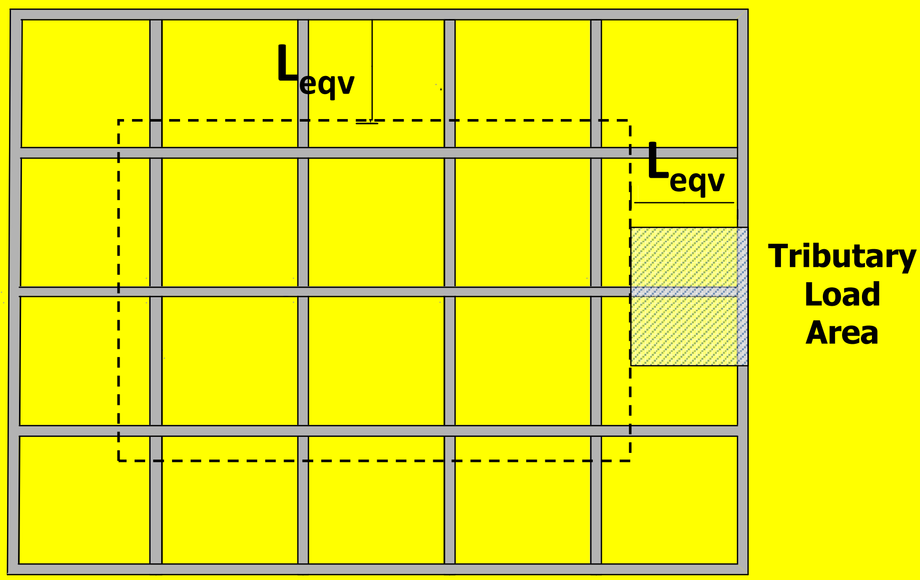


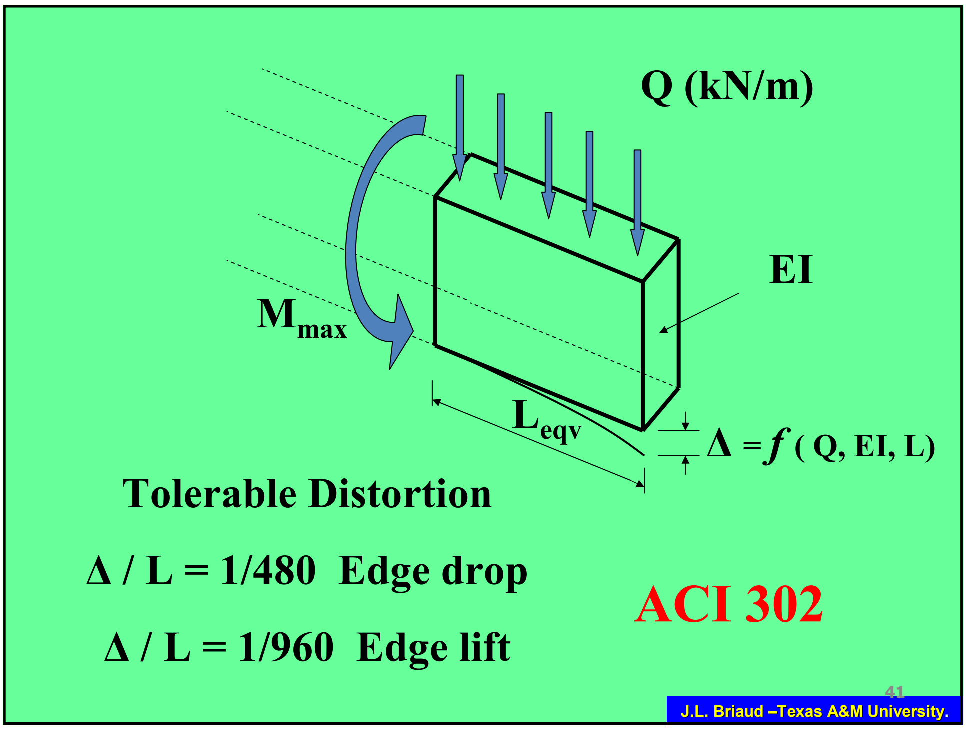
- Elevated Structural Slab on Piers



- Thin Post Tensioned Slab






Q (kN/m)
EI
M_{max}
L_{eqv}
Δ = f (Q, EI, L)
Tolerable Distortion
Δ / L = 1/480 Edge drop
Δ / L = 1/960 Edge lift
ACI 302
41
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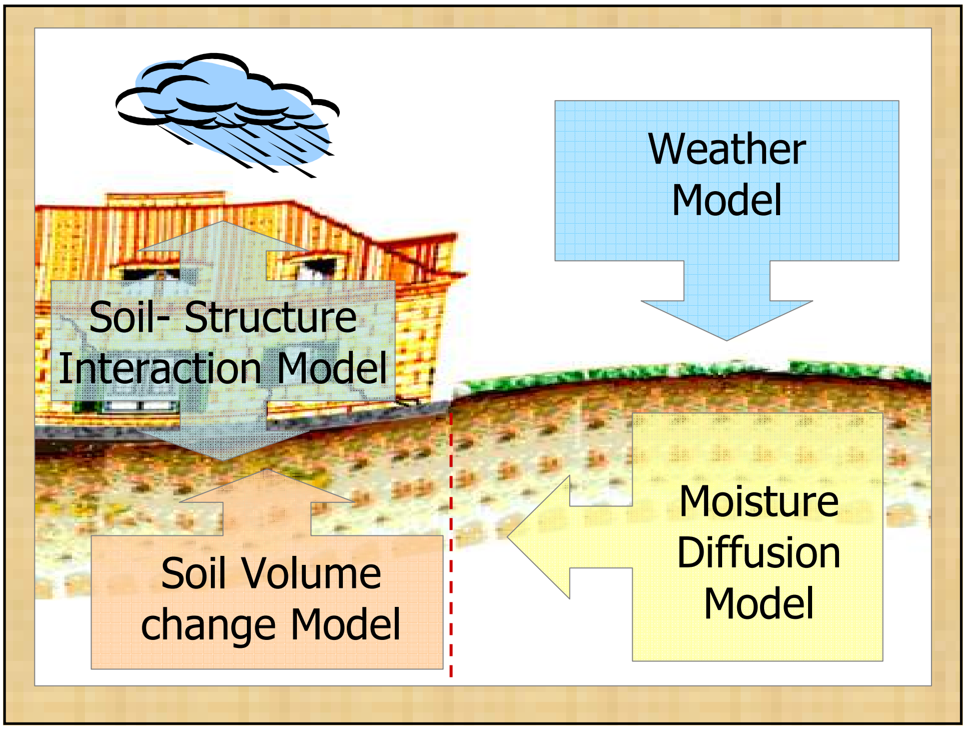
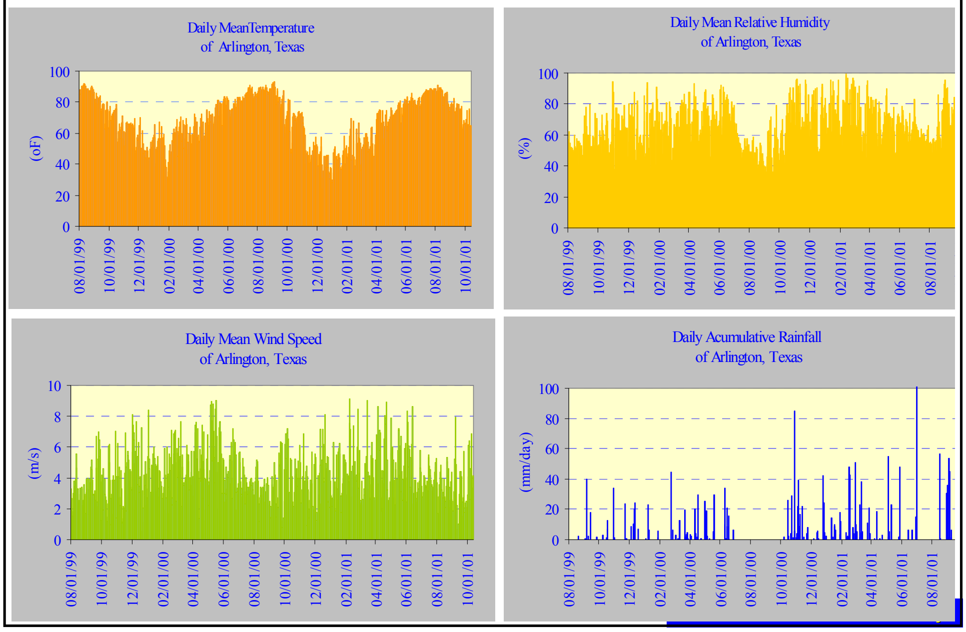
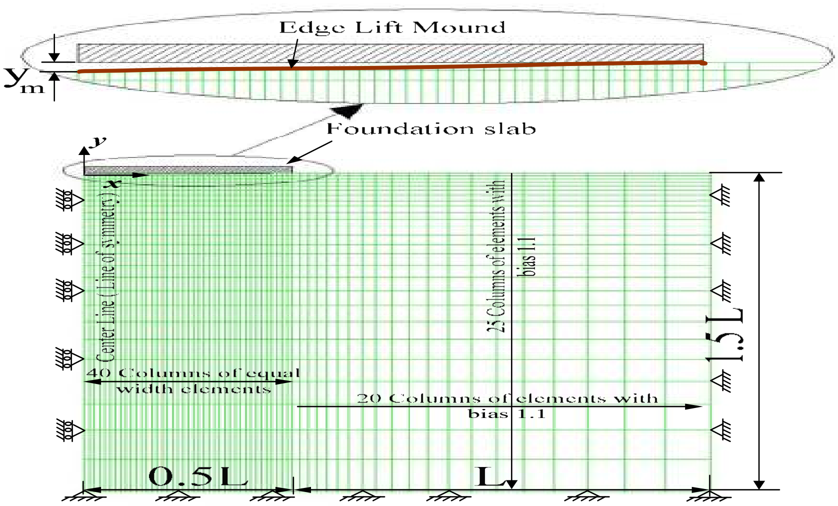

Weather Model
Soil- Structure Interaction Model
Moisture Diffusion Model
Soil Volume change Model

Input Weather Data (FAO 56)



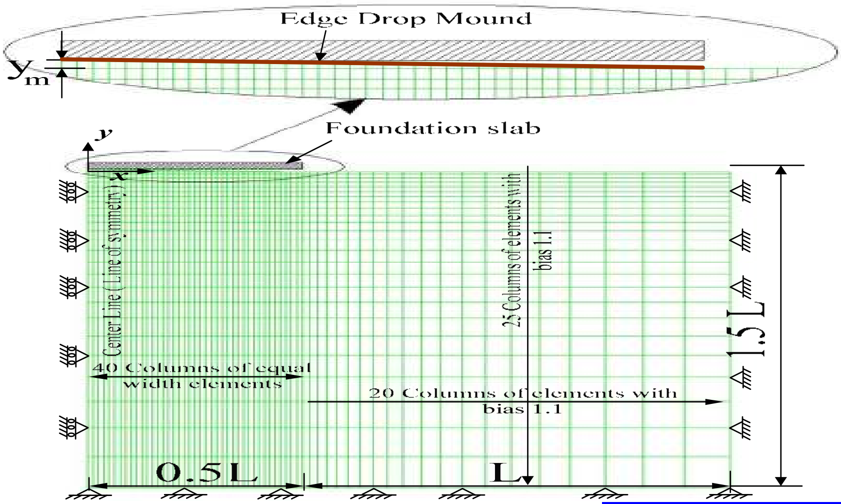
140 Abaqus simulations covering many weather, soil, and structure parameters

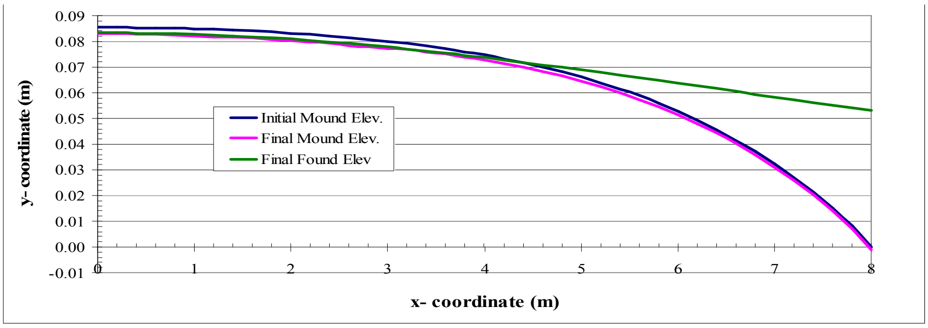
Edge Lift Case

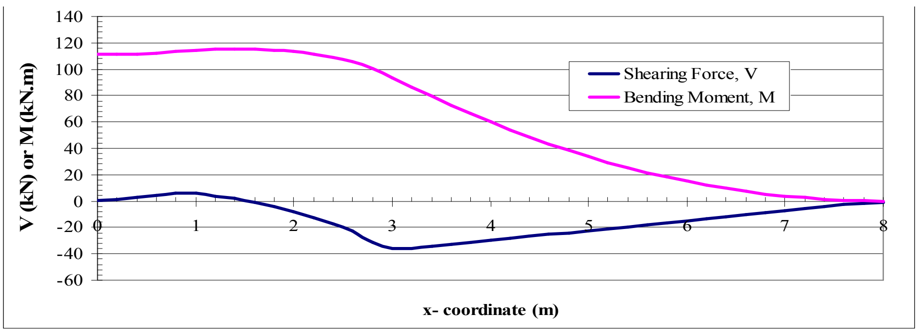


140 Abaqus simulations covering many weather, soil, and structure parameters

Edge Drop Case







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SOIL WEATHER INDEX I_{sw}

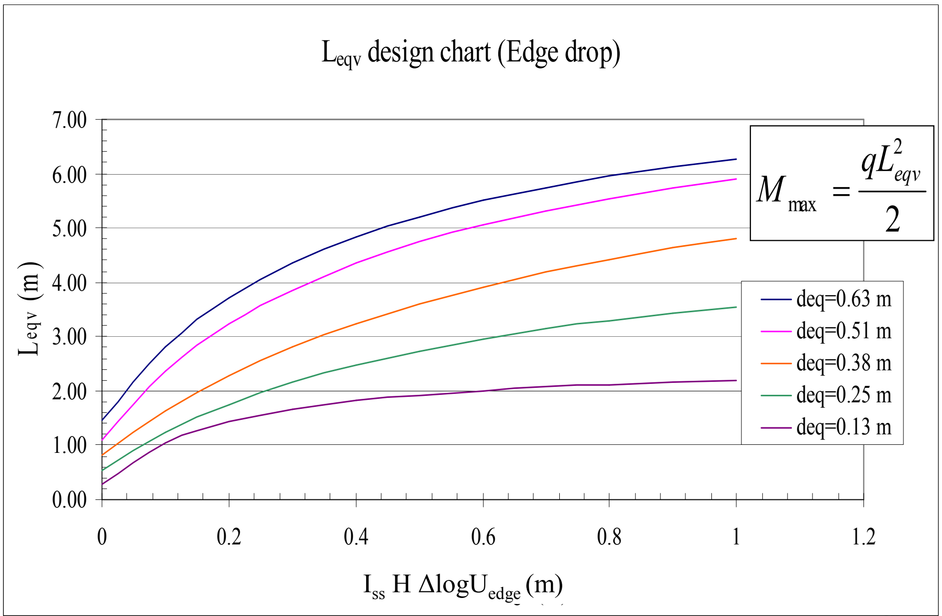
$$I_{sw} = I_{ss}\ H\ \Delta \log U_{edge}$$

$$\Delta \log U_{edge} = 0.5\ \Delta \log U_{ff}$$

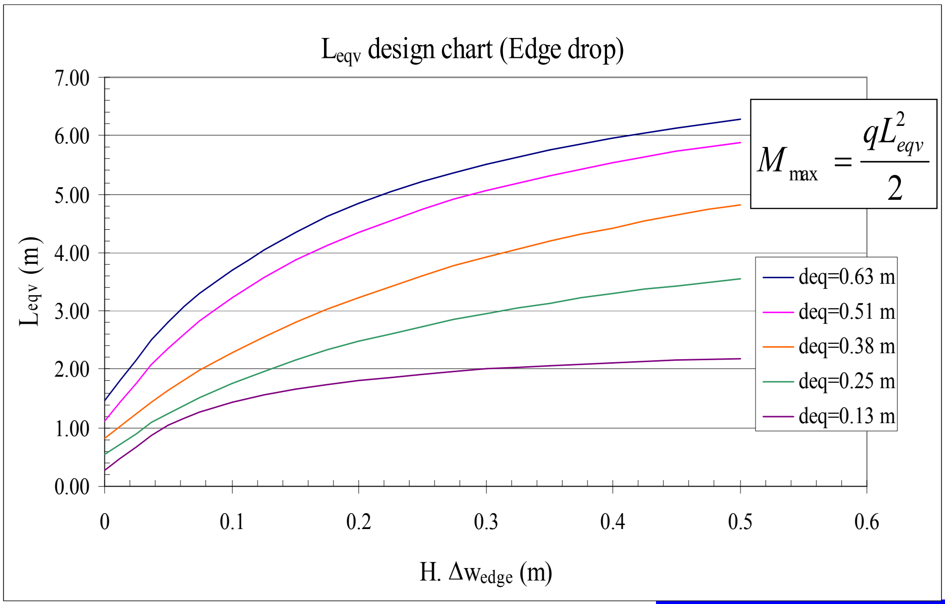
I_{ss} = shrink-swell index = $w_{sw} - w_{sh}$ (e.g. 0.2)
H = depth of shrink-swell movement (e.g. 3m)
$\Delta \log U_{ff}$ = change in water tension in the free field due to weather (e.g. 1.4)
$\Delta \log U_{edge}$ = change in water tension at the edge of the foundation and at the soil surface (e.g. 0.7)

$$I_{sw} = 0.2 \times 3 \times 0.7 = 0.42$$

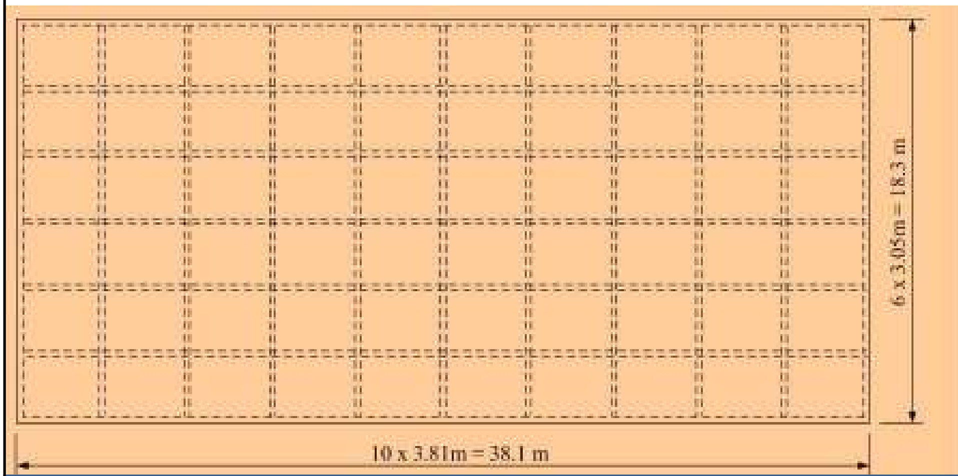
Water Tension based design charts (Edge drop)



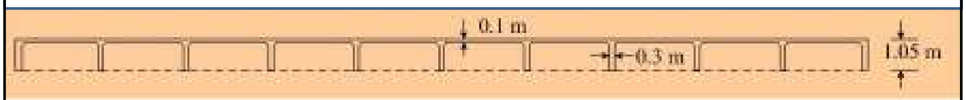
Water content based design charts (Edge drop)

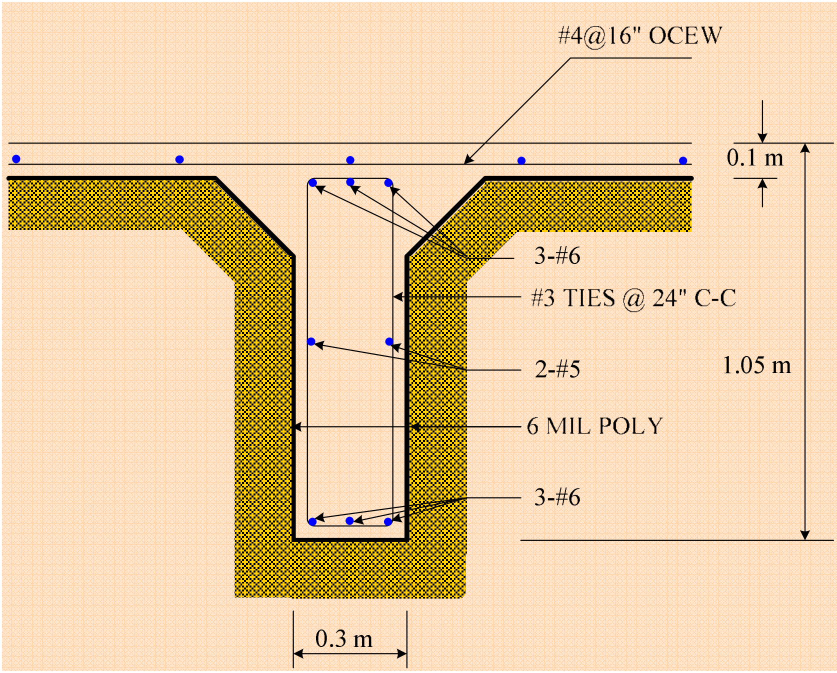


PLAN VIEW



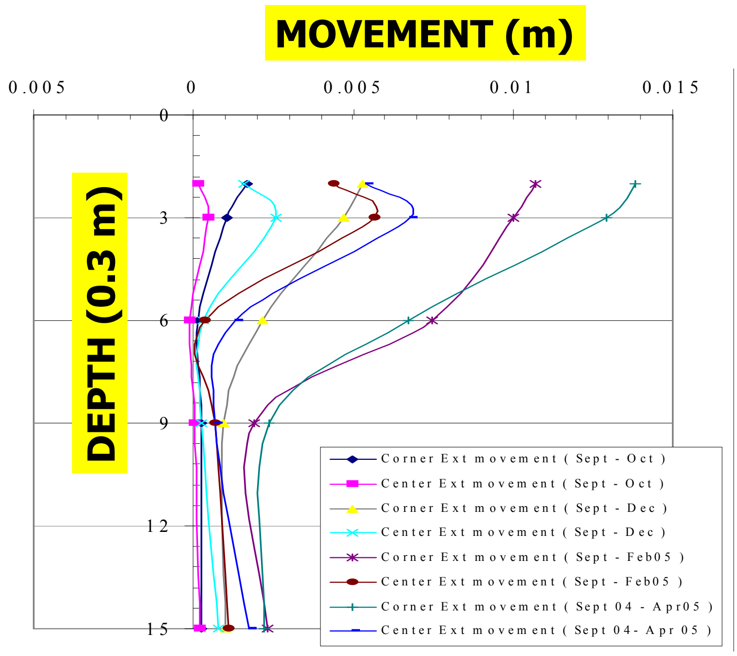
CROSS SECTION



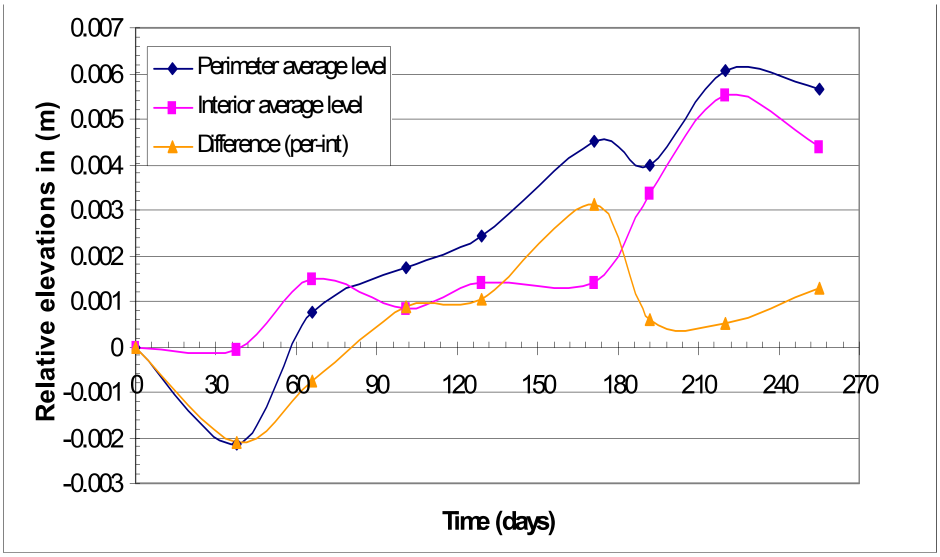


Excavation and steel - 16 July 2004

Completed Building



SLAB MOVEMENT over 1 YEAR



COST

Foundation with 1.05 m deep beams: 100 $/m^2$

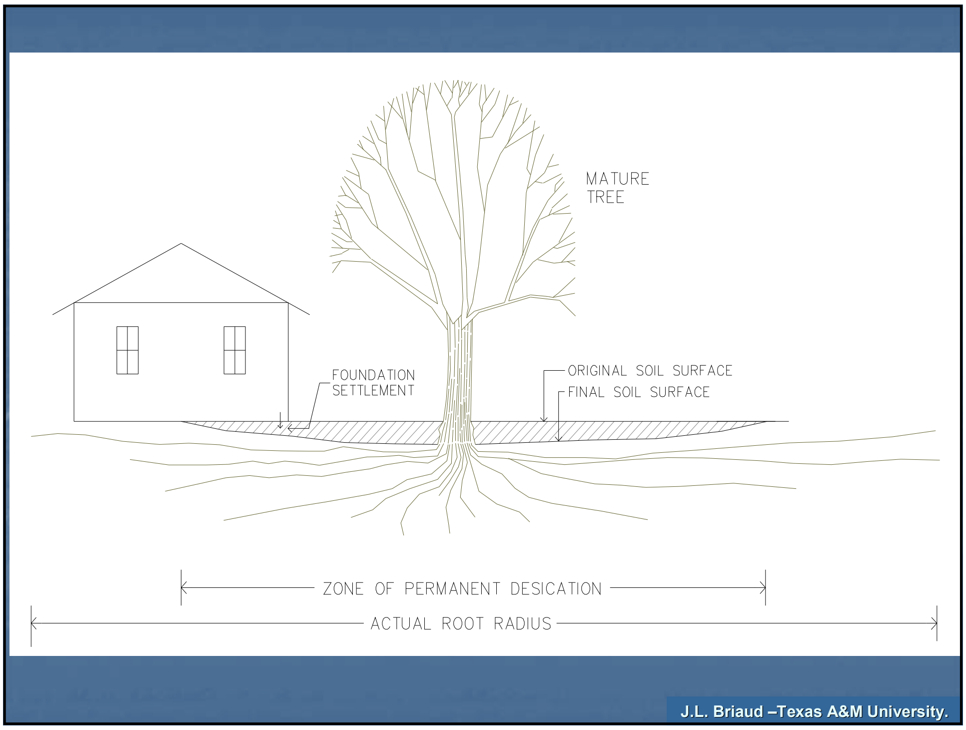
Foundation with 0.52 m deep beams: 60 $/m^2$

Completed Building: 1600 $/m^2$

Increase in cost: 40 $/m^2$ or
40/1600 = 2.5% of building cost

Slab stiffness increased 8 times $(1.05/0.52)^3$

Effects of trees on adjacent buildings


MATURE
TREE
FOUNDATION
SETTLEMENT
ORIGINAL SOIL SURFACE
FINAL SOIL SURFACE
ZONE OF PERMANENT DESICATION
ACTUAL ROOT RADIUS
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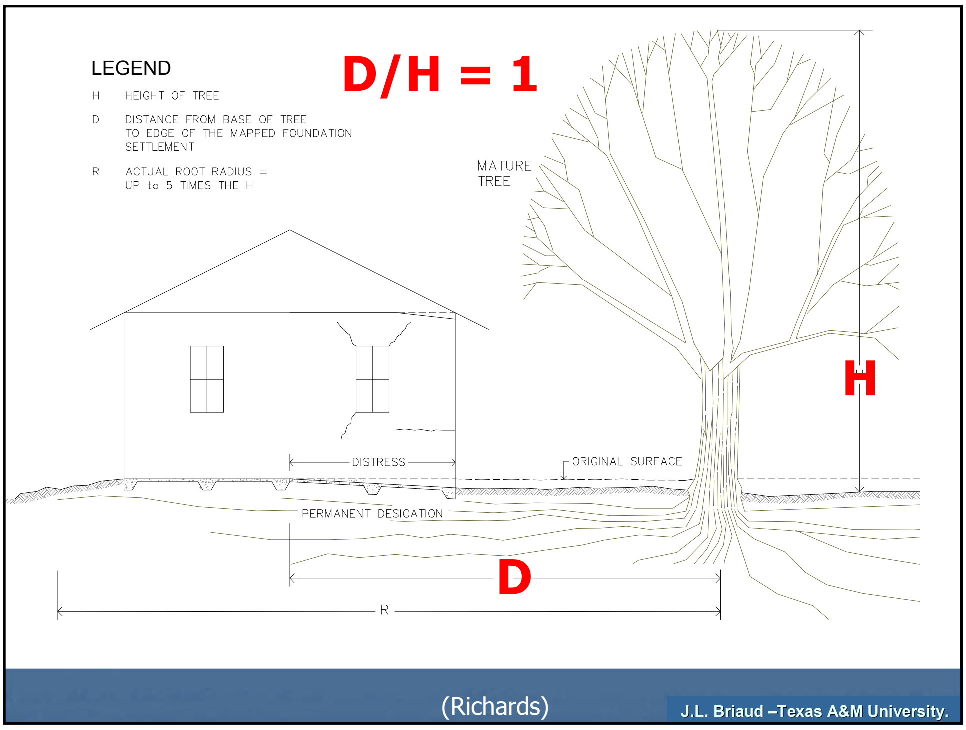
LEGEND
H HEIGHT OF TREE
D DISTANCE FROM BASE OF TREE TO EDGE OF THE MAPPED FOUNDATION SETTLEMENT
R ACTUAL ROOT RADIUS = UP to 5 TIMES THE H
D/H = 1
MATURE
TREE
H
DISTRESS
ORIGINAL SURFACE
PERMANENT DESICATION
D
R
(Richards)
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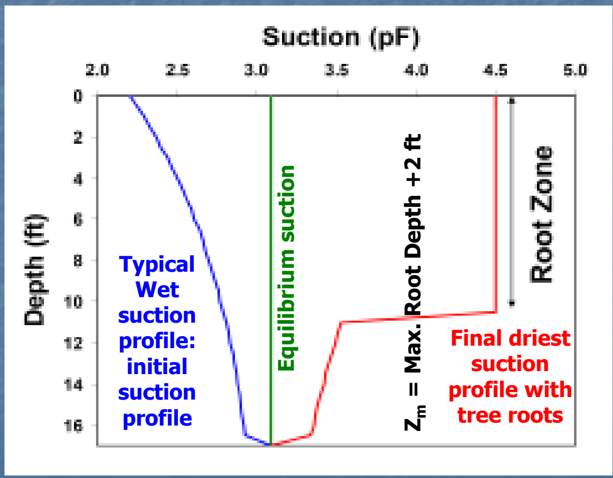
Effects of tree root on adjacent buildings



RETAINING WALLS-EARTH PRESSURE

$$\sigma_{ah} = K_a\,(\sigma'_{ov} + \Delta\sigma'_v) - 2c\,K_a^{0.5} + \alpha u_w$$

$$\sigma_{ah} = K_a\,(\sigma_{ov} + \Delta\sigma'_v) - 2c\,K_a^{0.5} + \alpha u_w\,(1\text{-}K_a)$$

where:

- σ_{ah} is the total active earth pressure
- K_a is the active earth pressure coefficient
- c is the effective stress cohesion intercept of the soil at depth z
- σ'_{ov} is the initial vertical effective stress at depth z
- $\Delta\sigma'_v$ is the change in vertical effective stress at depth z (due to load at the surface of the retained side)
- α is the ratio of water over total pore area (use 0 for unsaturated soils or soils in the capillary zone, and 1 for saturated soils under the GWT)
- u_w is the water stress (pore water pressure if saturated)

RETAINING WALLS-EARTH PRESSURE

$$\sigma_{ph} = K_p (\sigma'_{ov} + \Delta\sigma'_v) + 2c\, K_p^{0.5} + \alpha u_w$$

$$\sigma_{ph} = K_p (\sigma_{ov} + \Delta\sigma'_v) + 2c\, K_p^{0.5} + \alpha u_w (1-K_p)$$

where:

σ_{ph}	is the total passive earth pressure
K_p	is the passive earth pressure coefficient
c	is the effective stress cohesion intercept of the soil at depth z
σ'_{ov}	is the initial vertical effective stress at depth z
$\Delta\sigma'_v$	is the change in vertical effective stress at depth z (due to load at the surface of the retained side)
α	is the ratio of water over total pore area (use 0 for unsaturated soils or soils in the capillary zone, and 1 for saturated soils under the GWT)
u_w	is the water stress (pore water pressure if saturated)

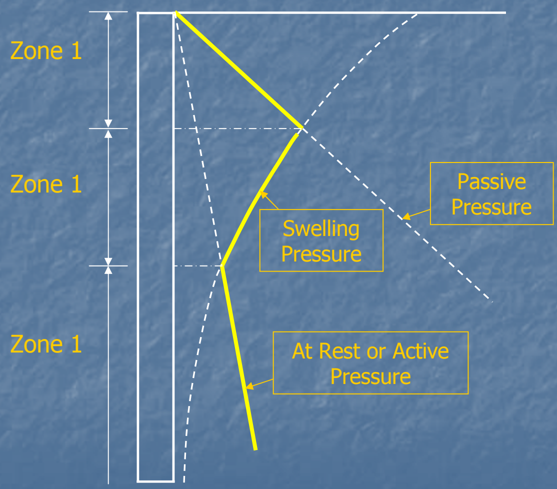
RETAINING WALLS-EARTH PRESSURE

$$\sigma_{ah} = \sigma_{ov} - 2s_u \quad ?$$

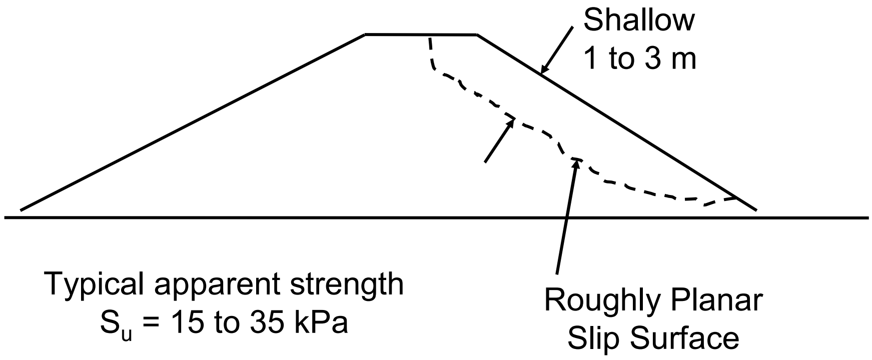
$$\sigma_{ph} = \sigma_{ov} + 2s_u \quad ?$$

Not applicable because of cracking

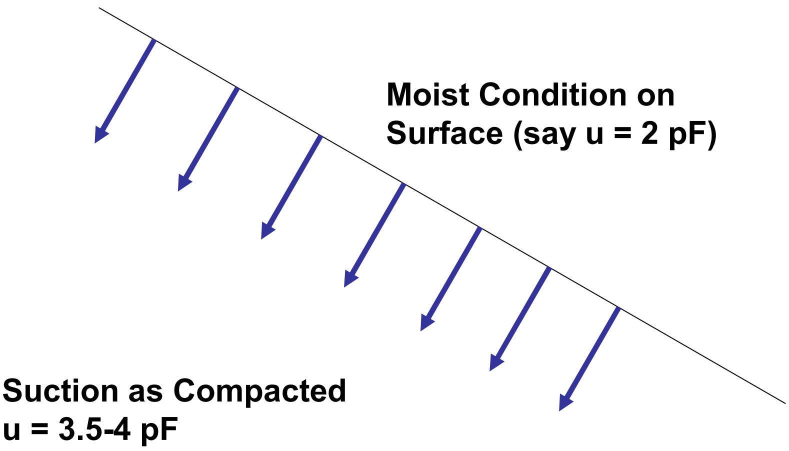
RETAINING WALLS-EARTH PRESSURE



Lytton, 2008



1. Loss of suction over time
2. Progressive failure and low residual friction angle



Moisture Migration into Intact Slope

Mitchell (1979)

Darcy's Law: + Unsaturated k

$$v = k \frac{dh}{dx} \qquad k = \frac{k_0\, h_0}{h}$$

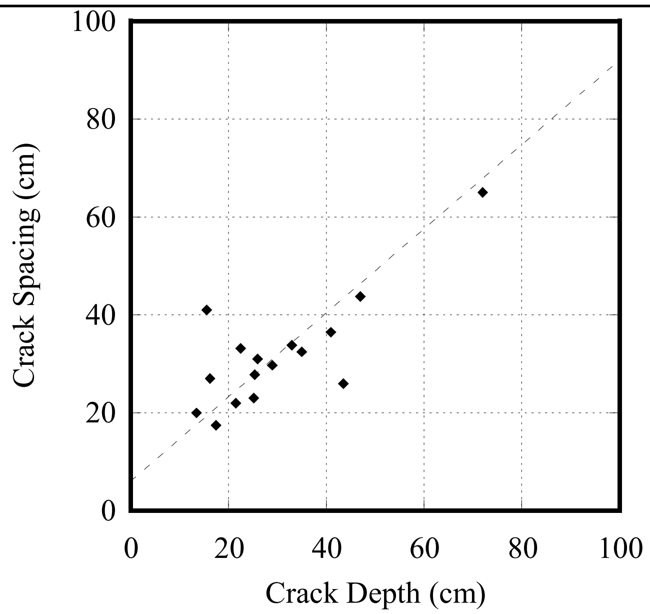
$$\Rightarrow \quad v = k_0\, h_0 \frac{dh / h}{dx} = k_0\, h_0 \frac{d\,(\log_e h)}{dx}$$

Unsteady Flow Equation

$$u = \log_{10} |h|$$

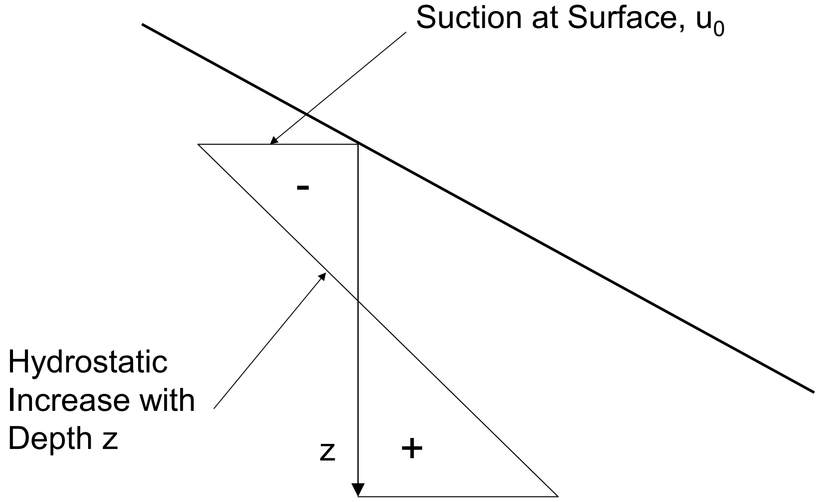
$$\alpha \frac{\partial^2 u}{\partial x^2} = \frac{\partial u}{\partial t}$$

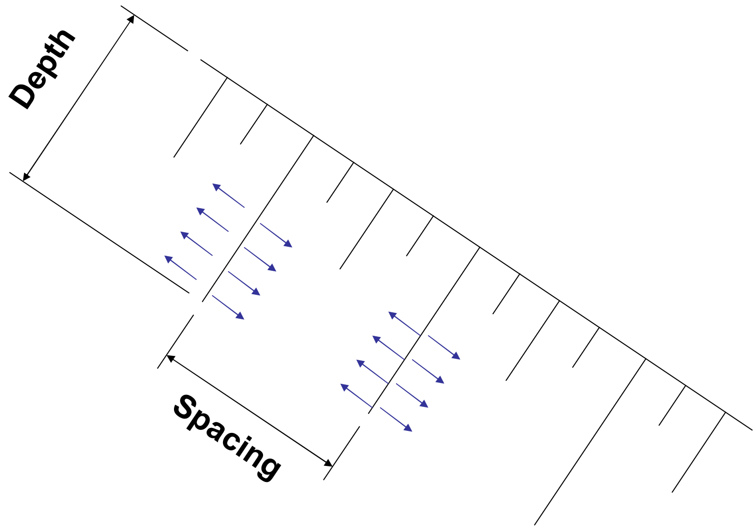
$$\alpha = \frac{S\, k_0\, h_0}{0.434} \frac{\gamma_w}{\gamma_d}$$



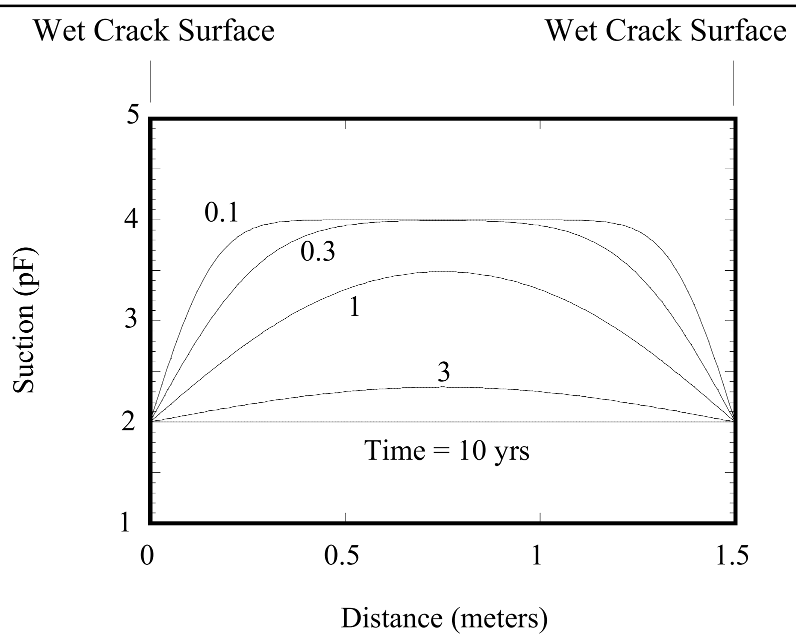
Crack Spacing versus Depth (Knight, 1972)

Pore Pressure Distribution





Moisture Migration into Cracked Slope



Moisture Infiltration from Wetted Crack Surfaces

Shear Strength-unsaturated

$$s = c' + (\sigma - \alpha u_w) \tan \phi'$$