Design of Structures to Resist the Pressures and Movements of Expansive Soils

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Foundation Performance Association

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Acknowledgements

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Eeshani Sood

Topics (1/2)

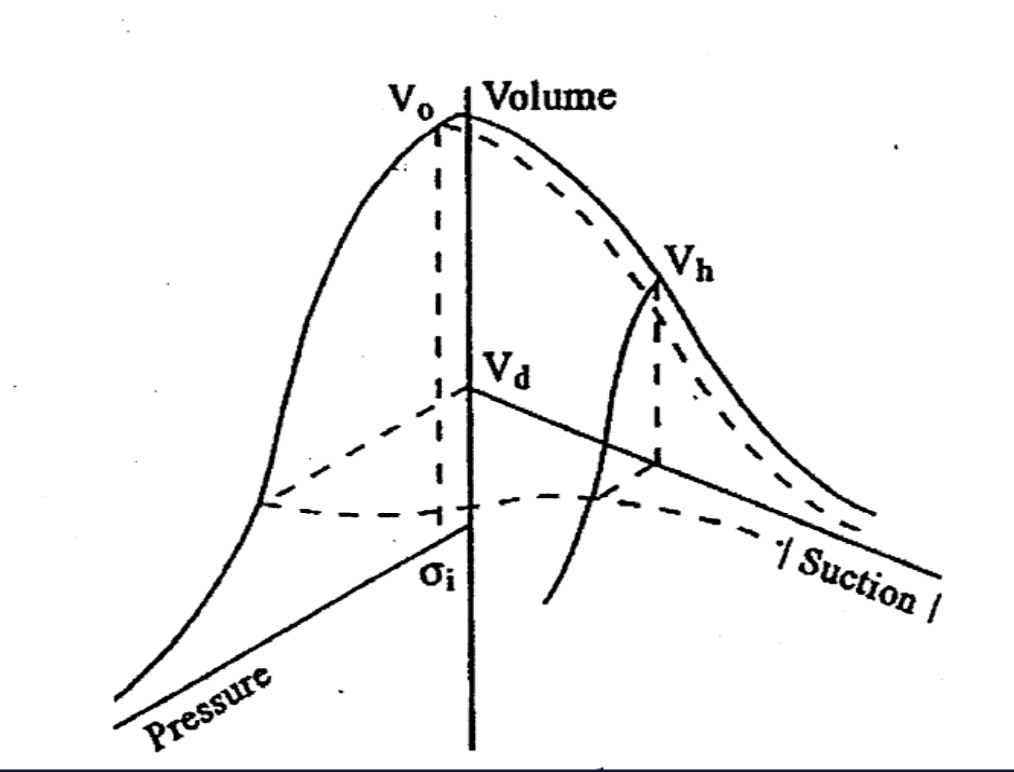
- Soil properties
- Suction envelopes
  - Climates
  - Trees
  - Drainage
- Pavement design
  - Concrete and asphalt
  - Stabilized layers
  - Vertical and horizontal moisture barrier

Topics (2/2)

- Shrinkage cracking design
- Shallow slope failure
- Slab-on-ground design
- Drilled pier design
  - Lateral pressures
  - Stresses, strains, movements
  - Comparison with field measurement
- Retaining wall design
  - Lateral pressures
  - Stresses, strains, movements
  - Comparisons with measurements

Volume Change

$$\frac{\Delta V}{V} = -\gamma_h \log_{10}\left(\frac{h_f}{h_i}\right) - \gamma_\sigma \log_{10}\left(\frac{\sigma_f}{\sigma_i}\right)$$ **(Lytton, 1977)**



Volume–Mean Principle Stress-Suction surface

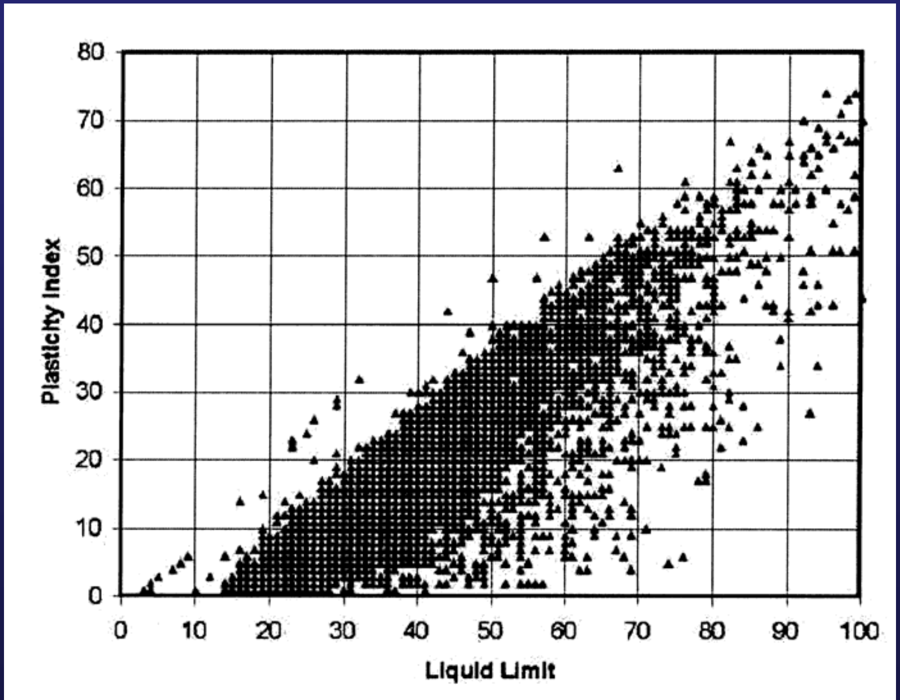
$$\frac{\Delta H}{H} = f\left(\frac{\Delta V}{V}\right)$$

$$f = 0.67 - 0.33\Delta pF$$

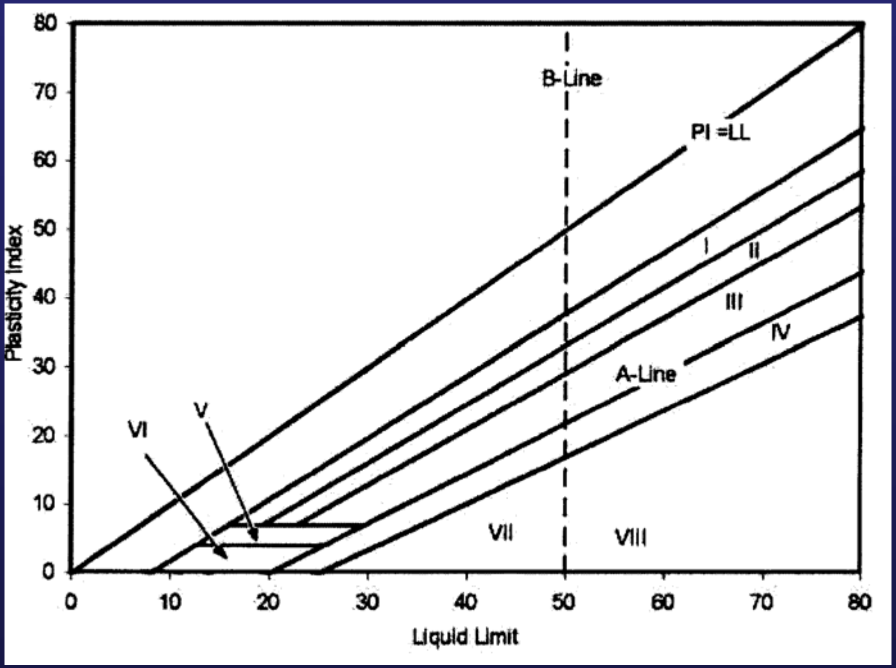
$$\left(\begin{array}{l} f = 0.5 \text{ when drying;} \\ f = 0.8 \text{ when wetting} \end{array}\right)$$

$$\Delta = \sum_{i=1}^{n} f_i \left[\frac{\Delta V}{V}\right]_i \Delta z_i$$

Volume Change



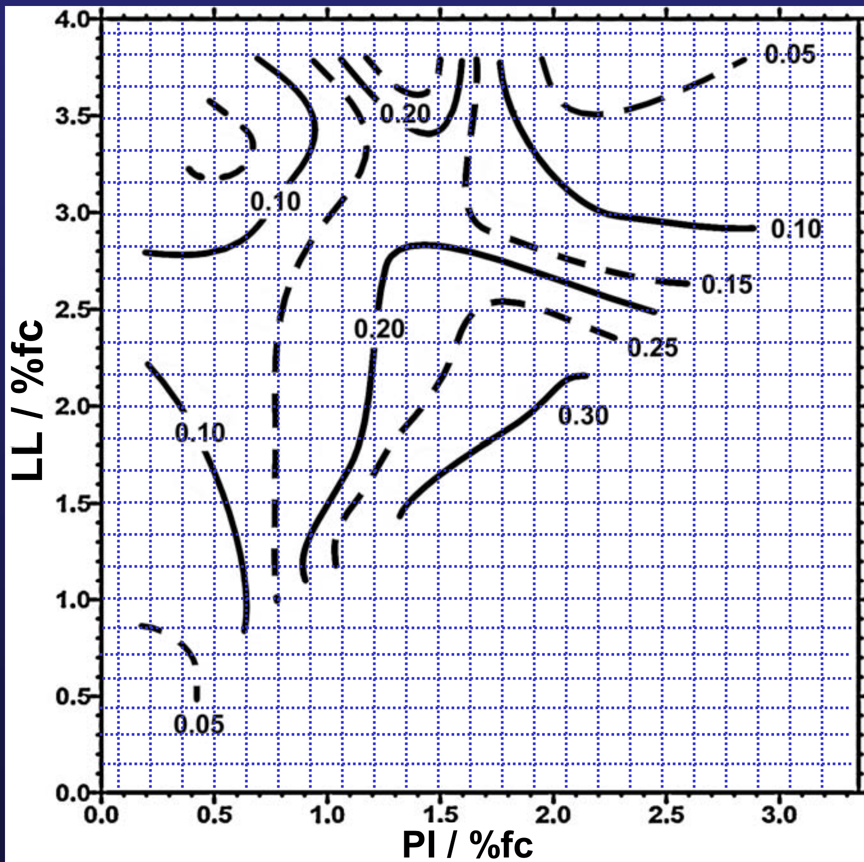
6500 Data from SSL
Of National Soil Survey Center



Partitioning Database
on Mineral Classification

(Covar and Lytton, 2001)

Volume Change



Zone III (Covar and Lytton, 2001)

$$\%f_c = \frac{\% - 2\,\mu m}{\% - No.200\,sieve}$$

$$\gamma_h = \gamma_0 \,\square \left[\frac{\% - 2\,\mu m}{\% - No.200\,sieve} \right]$$

$$\gamma_\sigma = \gamma_h \frac{1}{1 + \dfrac{h}{\theta \left(\dfrac{\partial h}{\partial \theta} \right)}}$$

(Lytton, 1994)

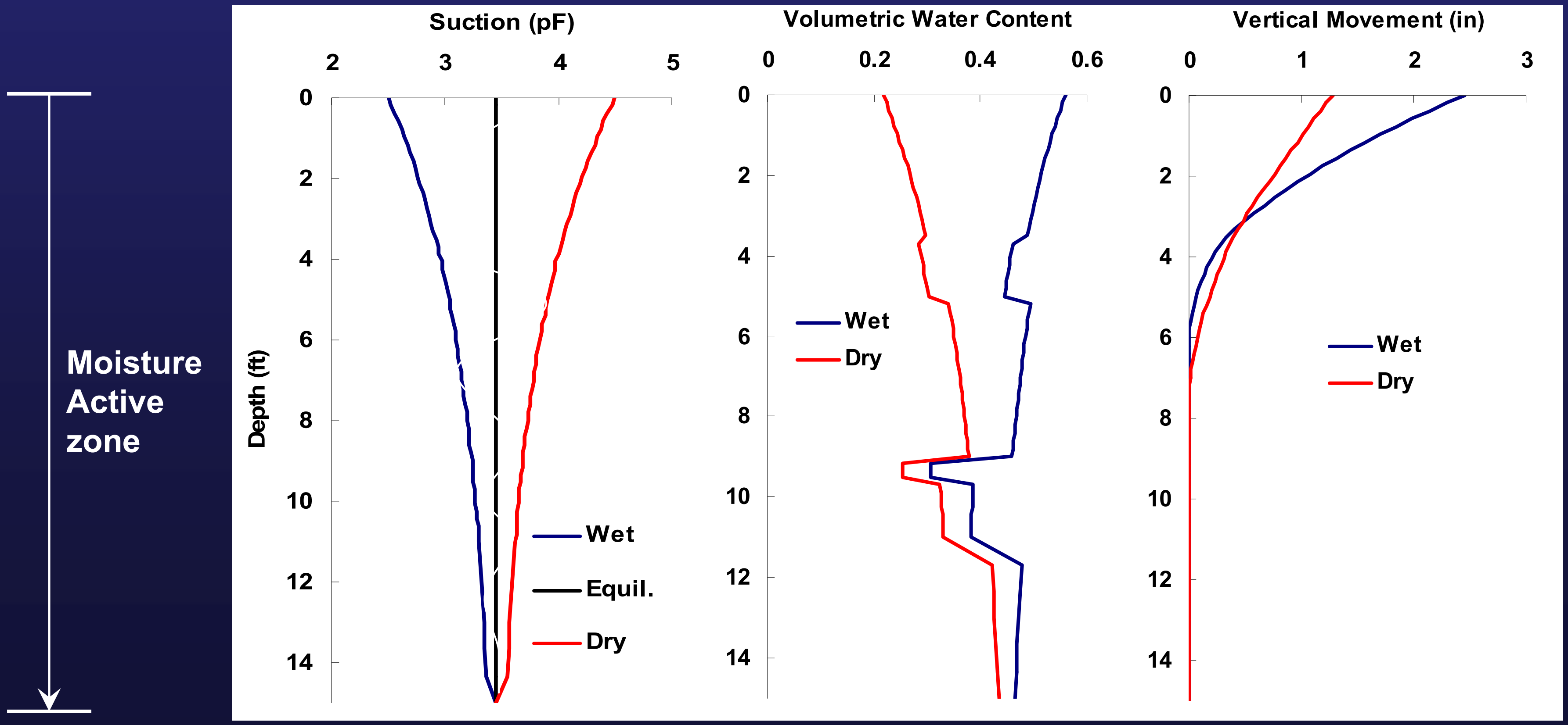
Exponential Suction Profile for Extreme Wetting and Drying Condition

$$U(Z,t) = U_e + U_o \exp\left(-\sqrt{\frac{n\pi}{\alpha}}Z\right)\cos\left(2\pi nt - \sqrt{\frac{n\pi}{\alpha}}Z\right)$$

Mitchell (1979)

$$U(Z) = U_e + U_o \exp\left(-\sqrt{\frac{n\pi}{\alpha}}Z\right)$$

Fort Worth Interstate 820



Volume Change

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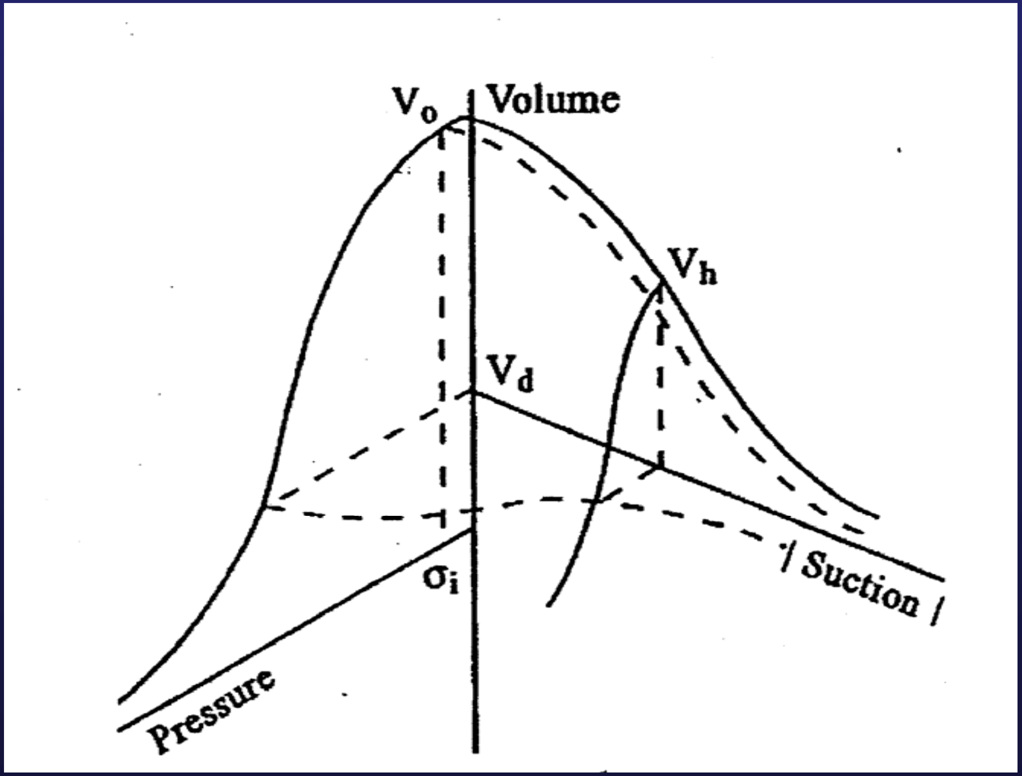

Volume–Mean Principle Stress-Suction surface

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$$\begin{pmatrix} f = 0.5 \text{ when drying;} \\ f = 0.8 \text{ when wetting} \end{pmatrix}$$

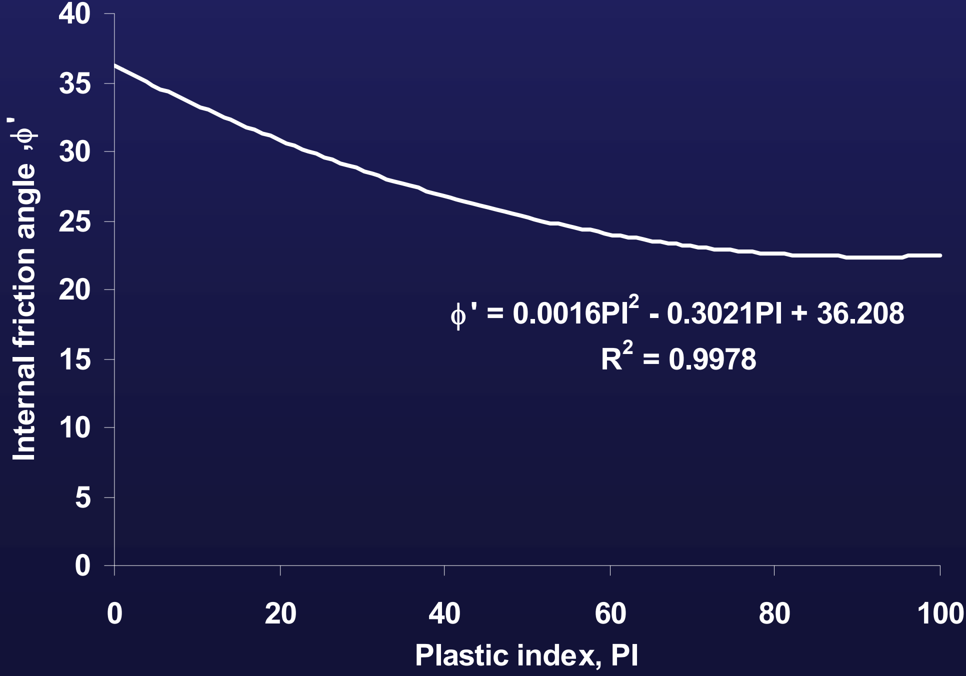
$$\Delta = \sum_{i=1}^{n} f_i \left[\frac{\Delta V}{V}\right]_i \Delta z_i$$

Lateral Pressure Coefficients

Conditions	K_o (after McKeen, 1981)	e	d	k	n
Cracked	0	0	0	0	1
Drying (Active)	1/3	1	0	0	1
Equilibrium (at rest)	1/2	1	1	0	1
Wetting (within movement active zone)	2/3	1	1	0.5	1
Wetting (below movement active zone)	1	1	1	1	1
Swelling near surface (passive earth pressure)	3	1	1	1	2

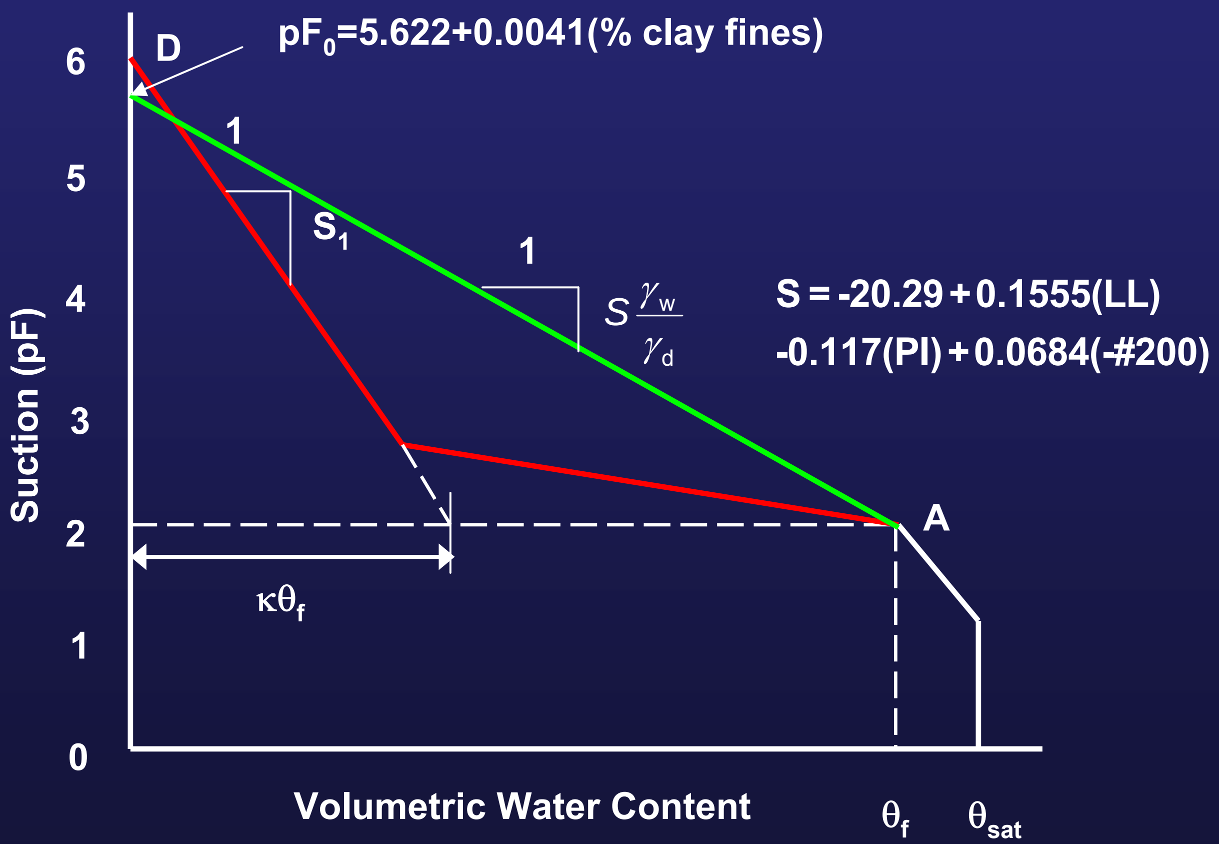
$$K_0 = e\left(\frac{1-\sin\phi'}{1+\sin\phi'}\right)\left(\frac{1+d\sin\phi'}{1-k\sin\phi'}\right)^n$$

(Lytton et al., 2006)



(after Holtz and Kovacs, 1981)

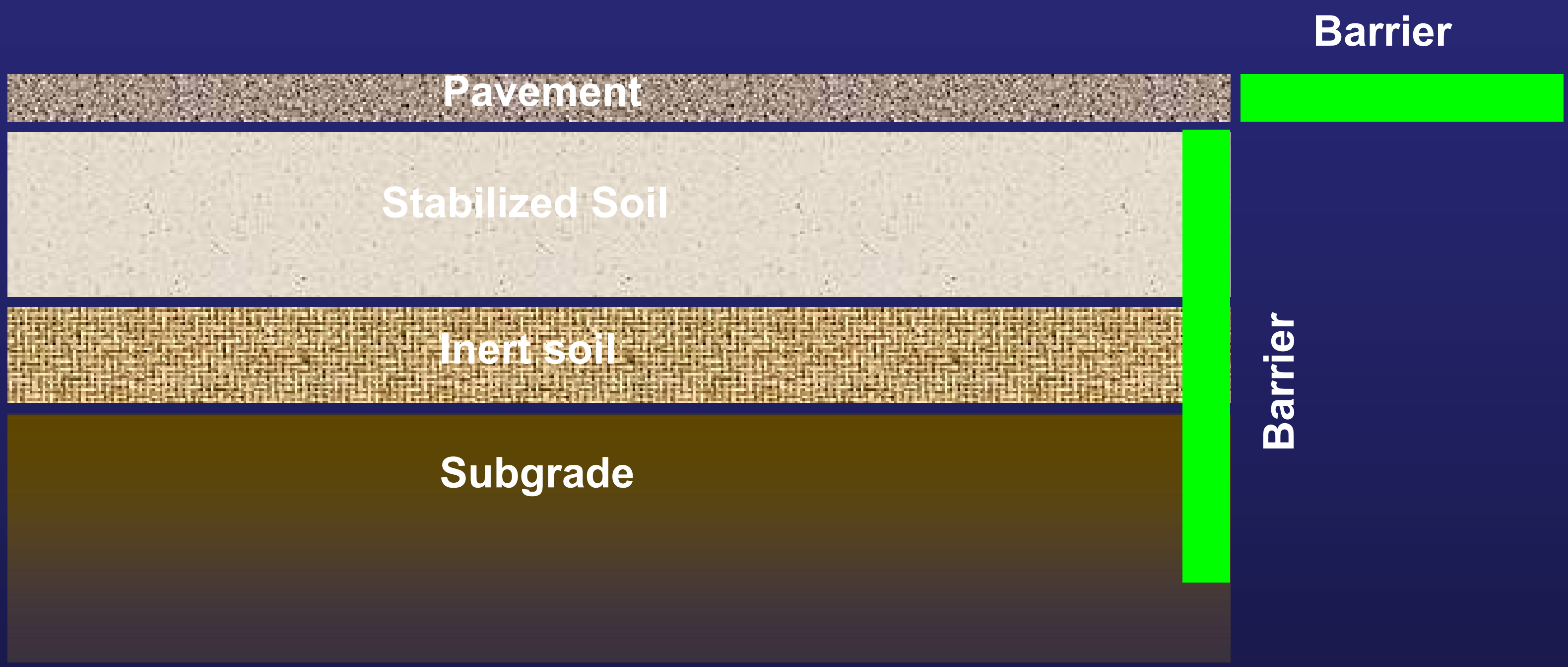
Volumetric Moisture Content and Suction Curves



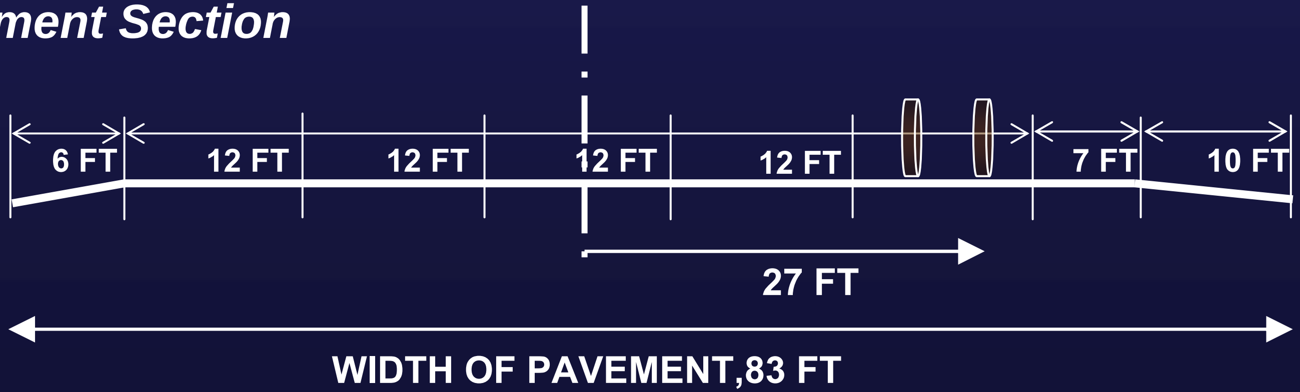
(Lytton et al., 2006)

Pavement Design on Expansive Soils

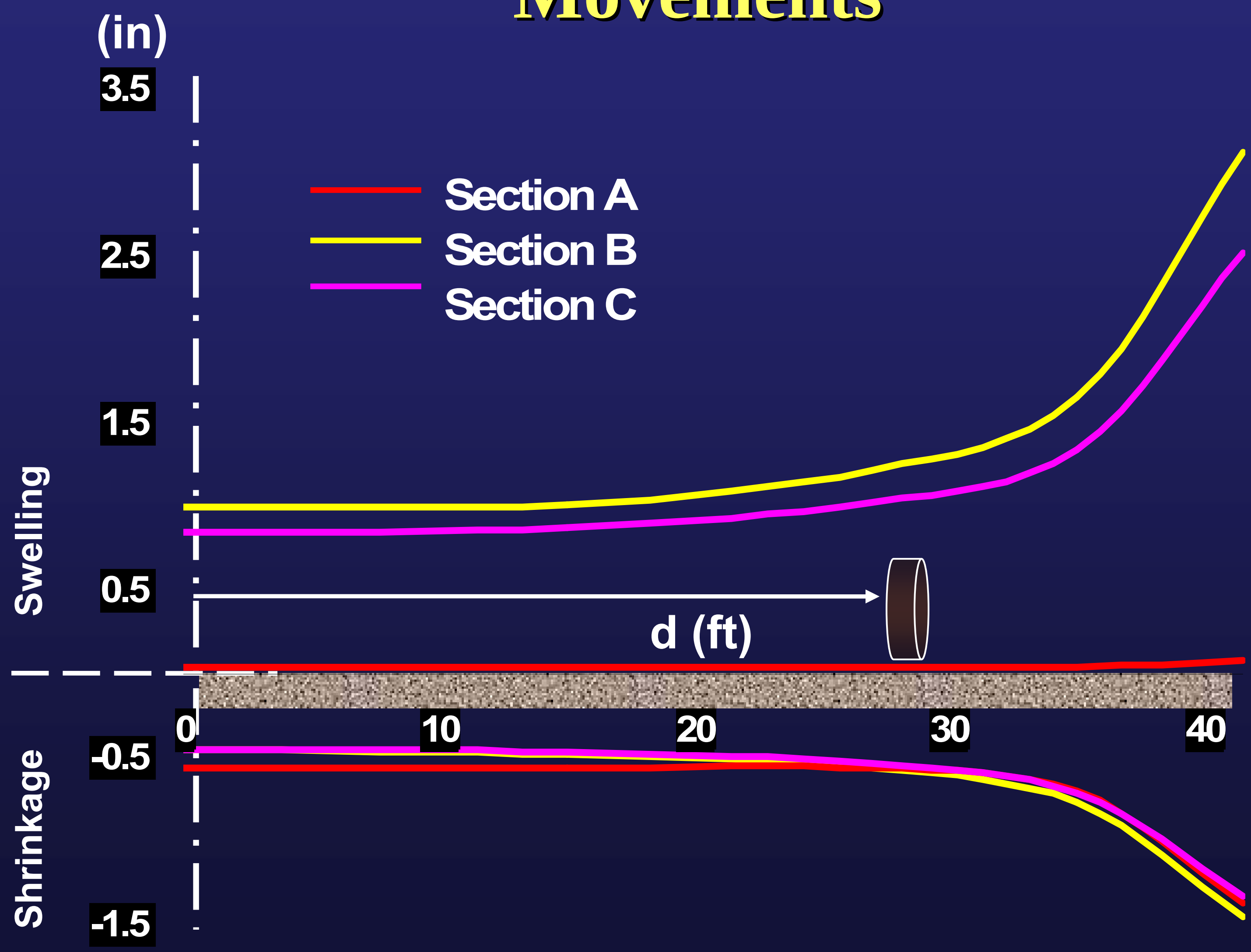
Pavement Treatments



Pavement Section

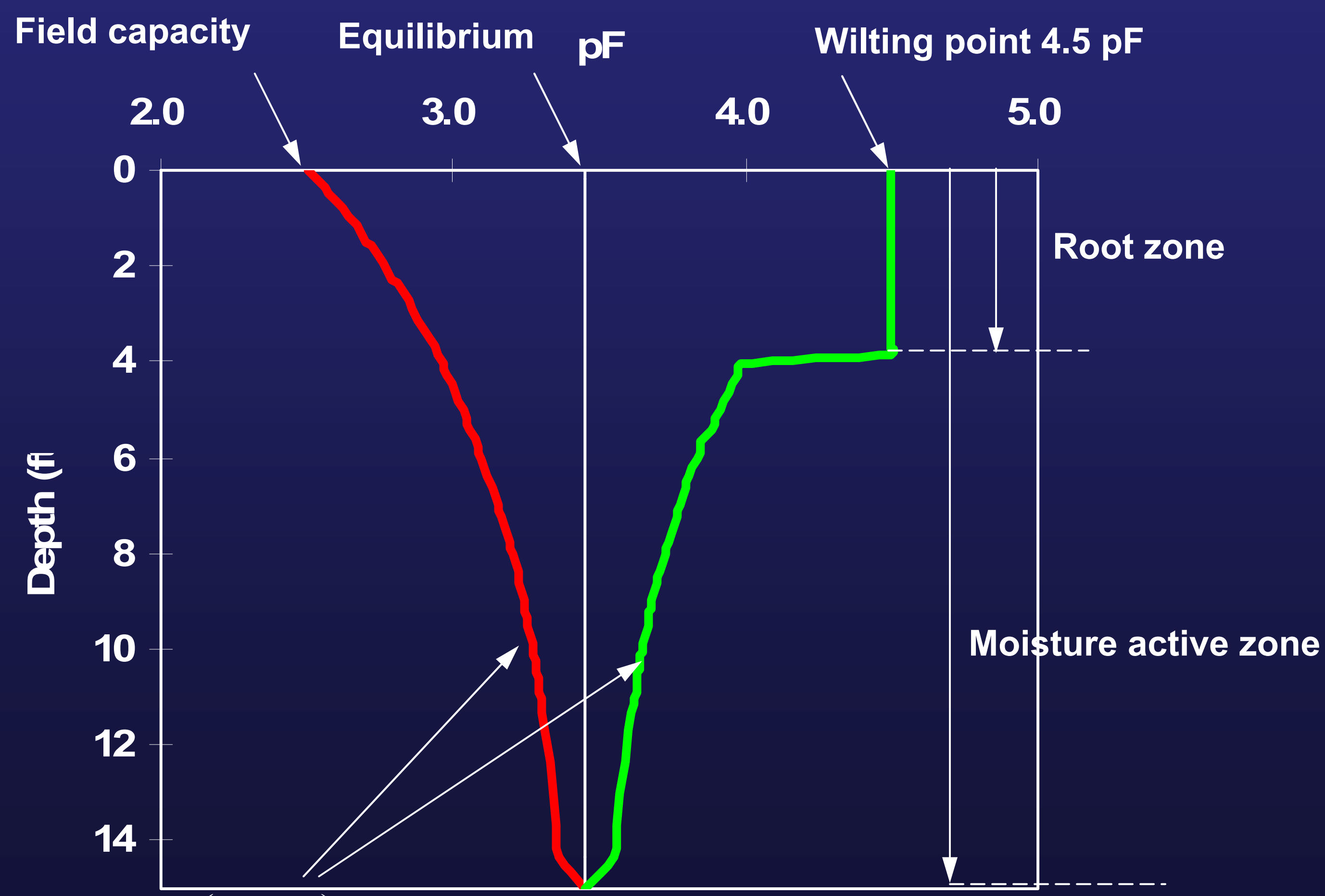


Transverse Distribution of Vertical Movements



Field Conditions

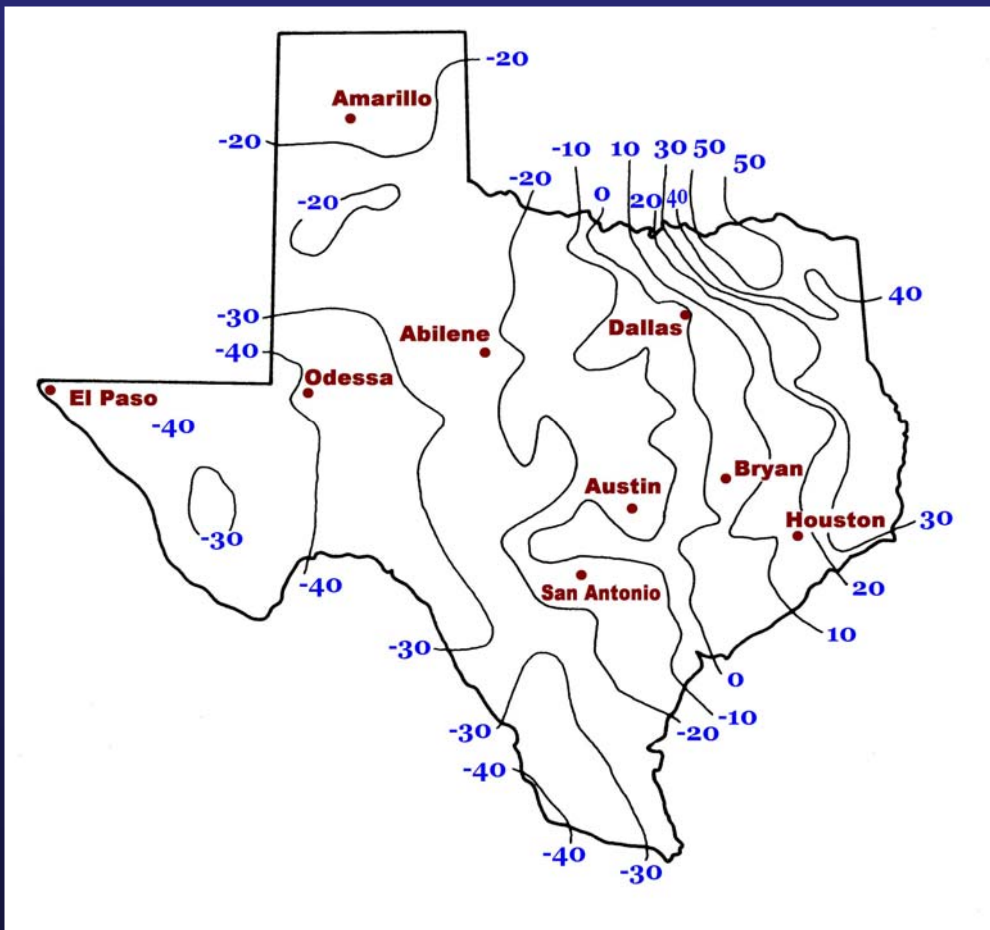
$$U_e = 3.5633\exp(-0.0051\,\mathrm{TMI})$$



$$U(Z) = U_e \pm U_0 \exp\left(-\sqrt{\frac{n\pi}{\alpha}}Z\right)$$

Climatic Conditions

Thornthwaite Moisture Index (TMI, 1948)



$$TMI = \frac{100R - 60DEF}{E_p}$$

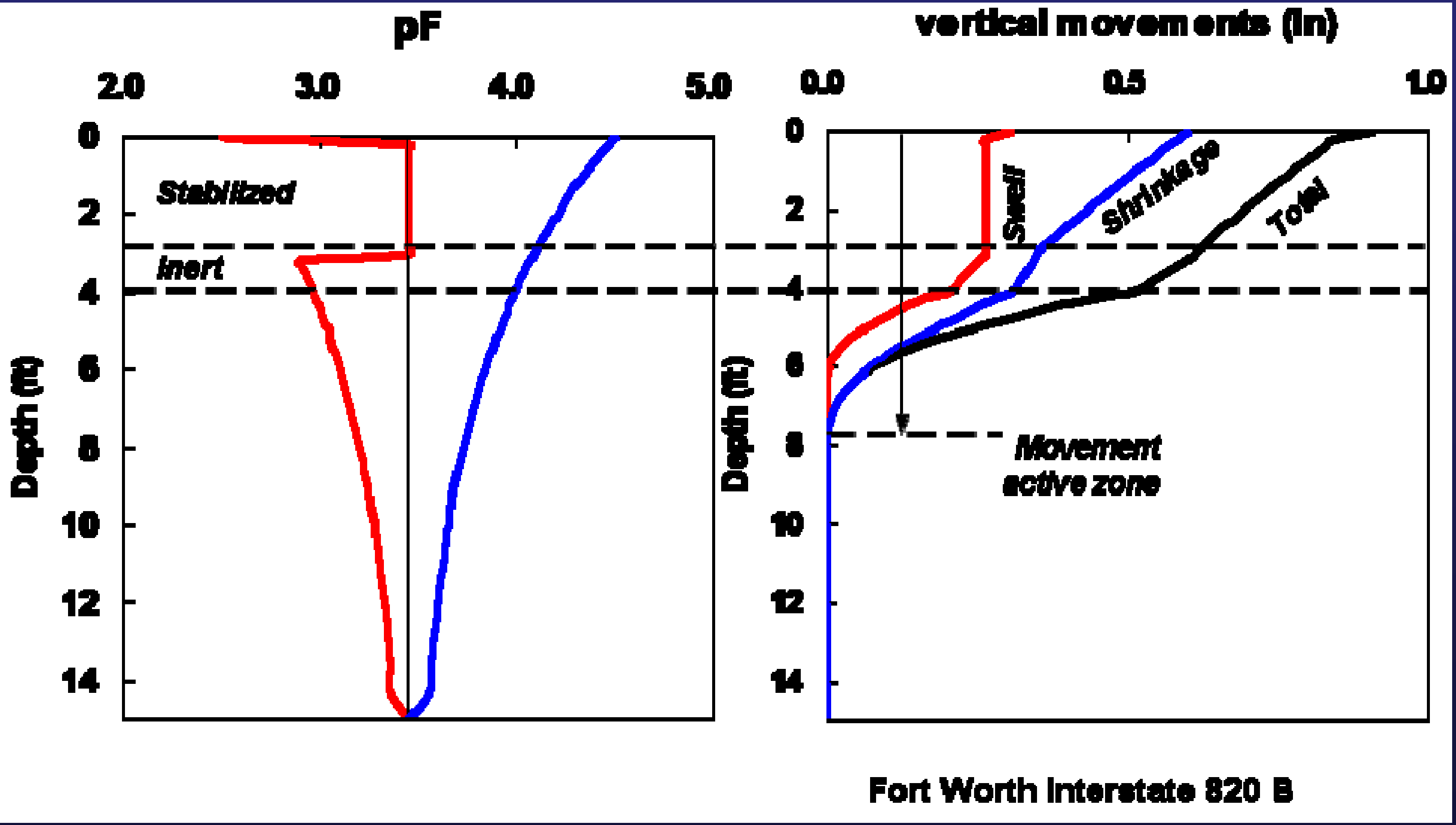
R = runoff moisture depth
DEF =deficit moisture depth
Ep = evapotranspiration

Roadside Drainage Conditions

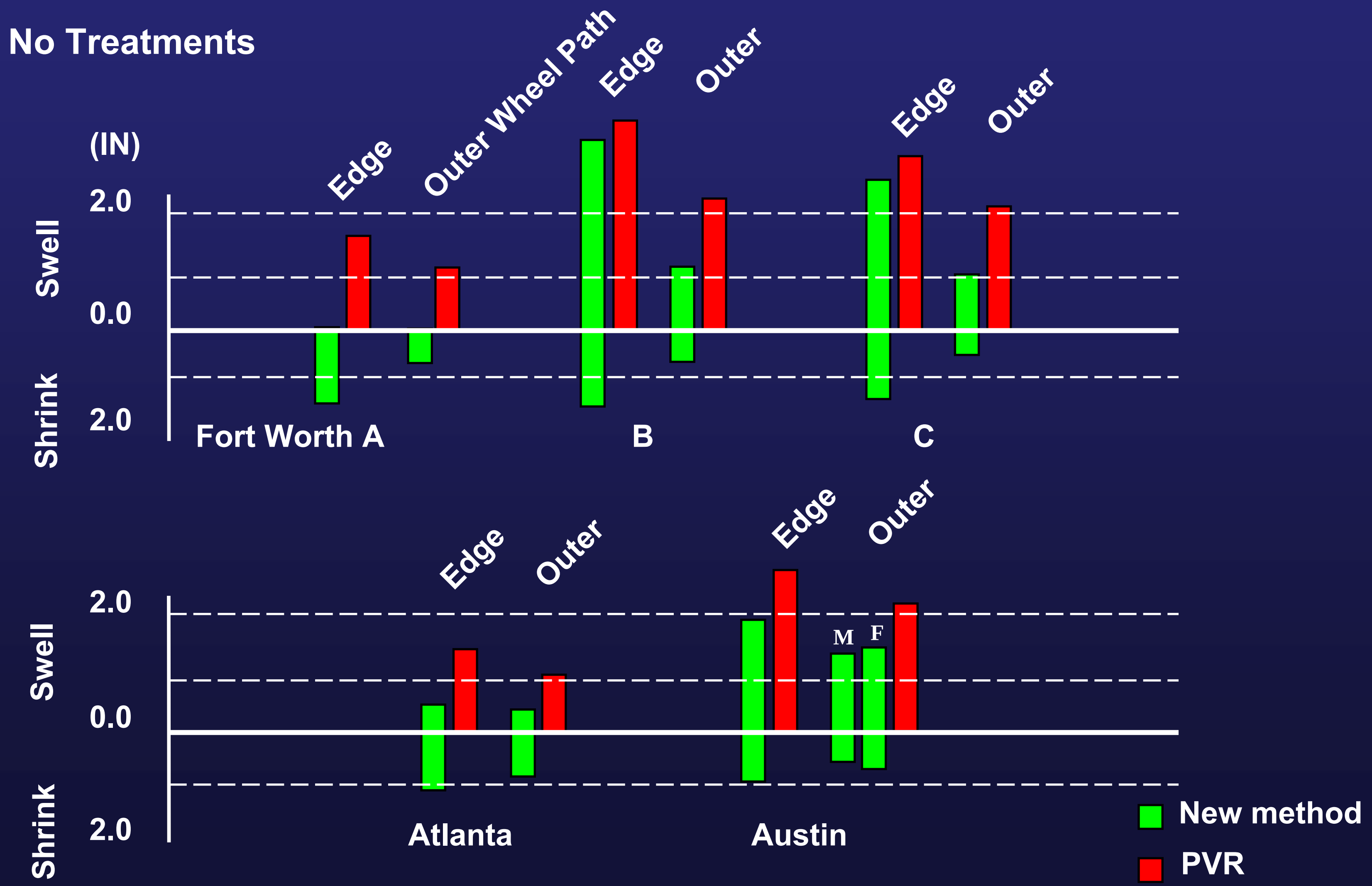
Longitudinal Drainage

Lateral Slope	Hill	Slope	Valley
Cut	2.3 pF	2.0 pF	2.0 pF
Flat	2.5 pF	2.2 pF	2.2 pF
Fill	2.6 pF	2.3 pF	2.3 pF

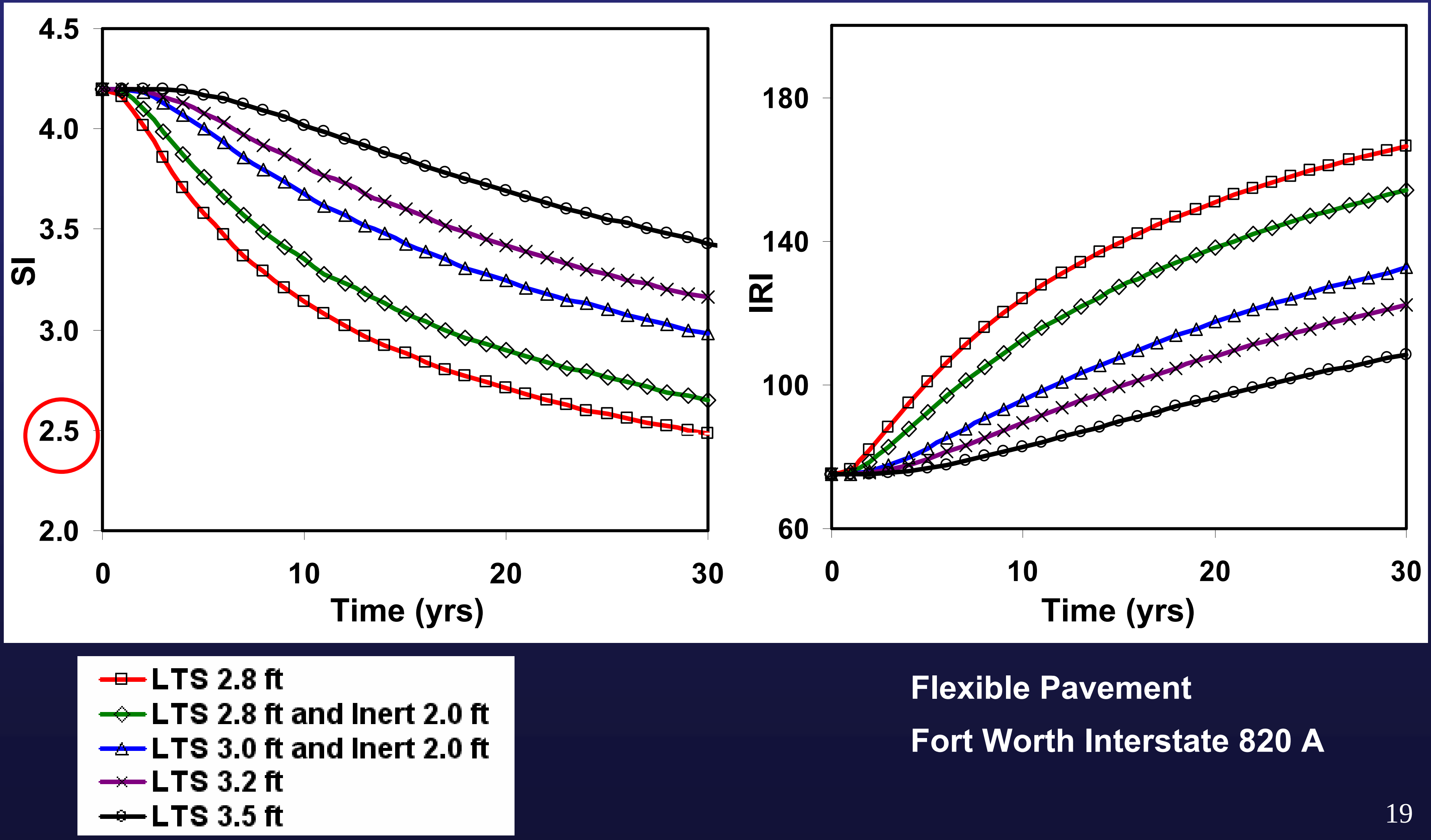
Calculated Vertical Movement



Comparison of PVR with Case Study Results



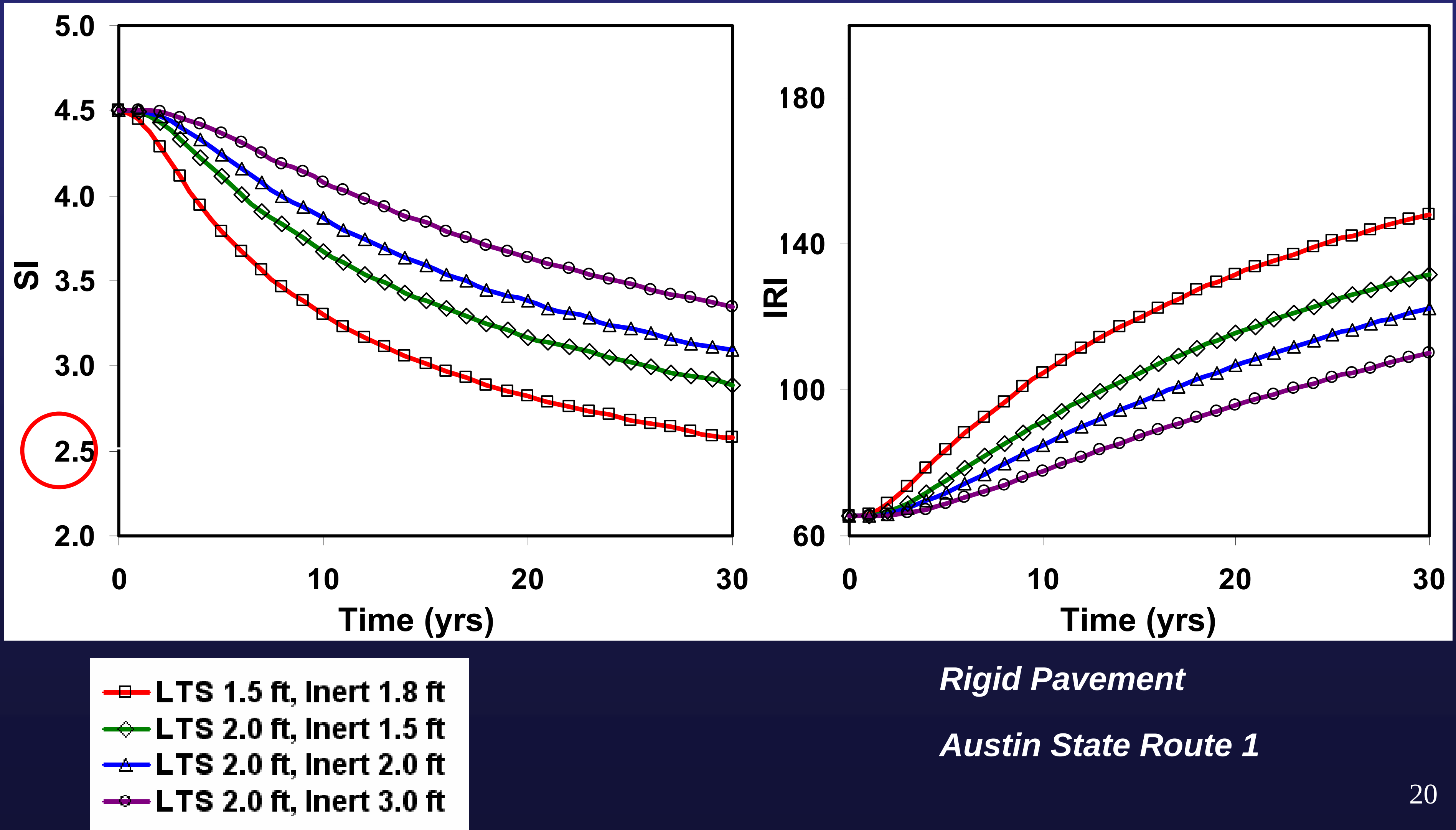
Acceptable Predicted Performance



Flexible Pavement

Fort Worth Interstate 820 A

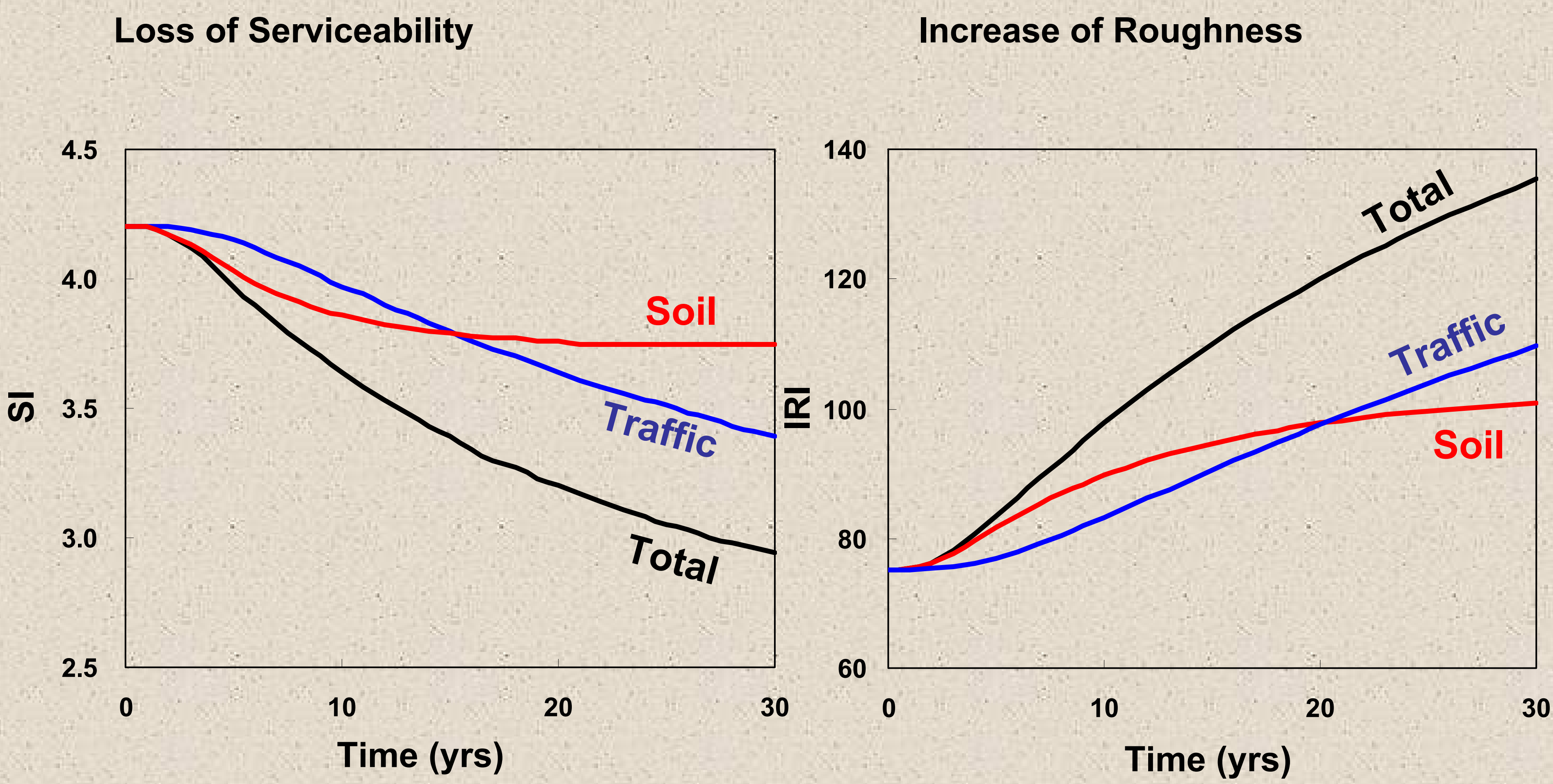
Acceptable Predicted Performance



Rigid Pavement

Austin State Route 1

Predicted Roughness with Time



SUBGRADE MOVEMENTS COMPARED WITH PVR FOR A MINIMUM ACCEPTABLE TREATMENT

Flexible Pavement **(IN)**

Case Sites		New Method				PVR	
		Edge			Outer	Edge	Outer
		Swell	Shrink	Total			
Fort Worth	A	0.02	1.12	1.14	0.42	1.21	0.81
	B	0.78	0.72	1.50	0.61	2.08	1.20
	C	0.72	0.73	1.45	0.57	2.08	1.20
Atlanta		0.30	1.06	1.36	1.08	1.28	0.88
Austin	Main	0.37	0.43	0.80	0.49	1.45	1.13
	Frontage	0.66	0.58	1.24	0.84	1.94	1.17

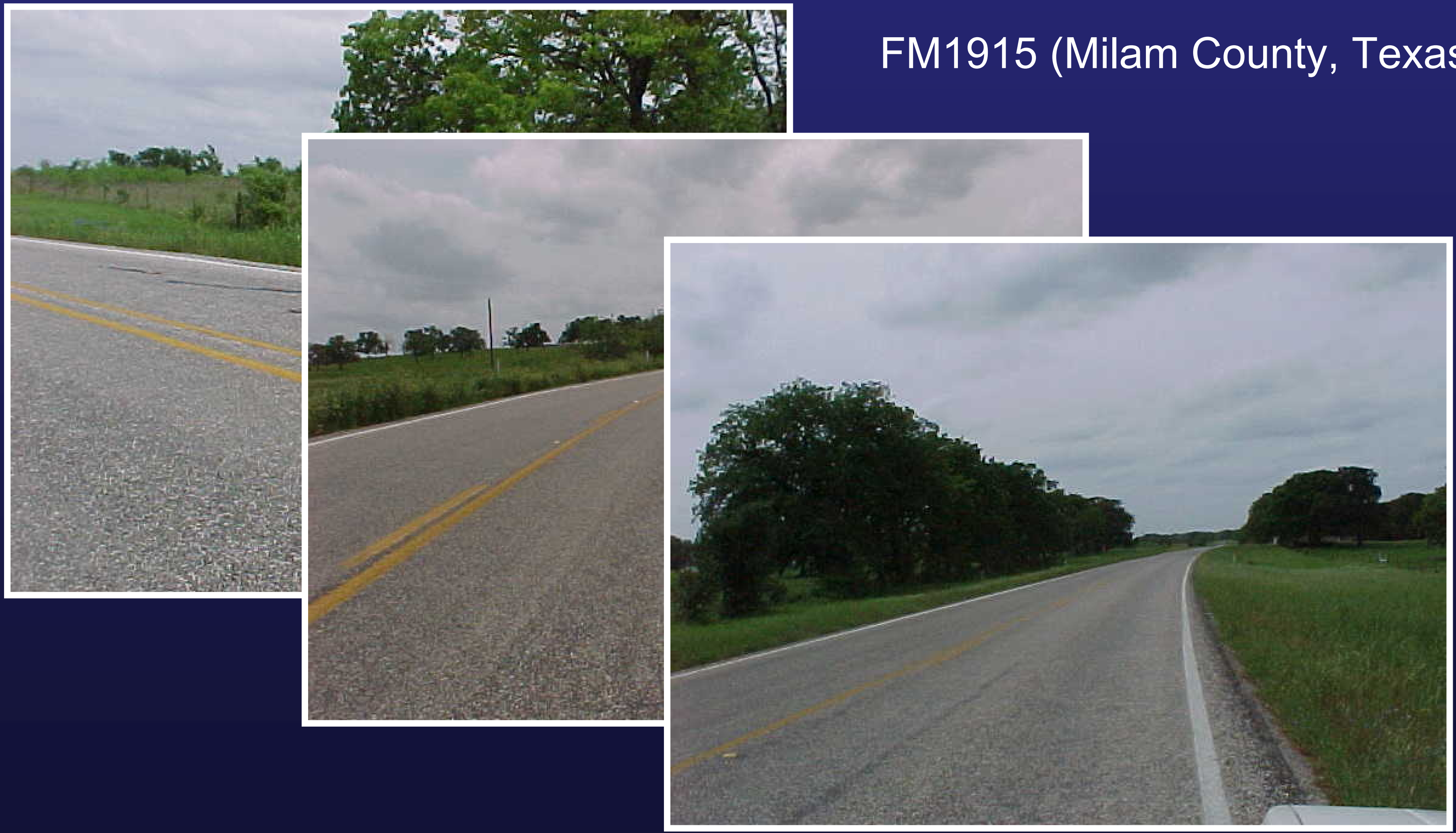
Avg. 0.67 in ***1.1 in***

Longitudinal Cracking over Expansive Soil

- Expansive soil
  - Experience volumetric change when subjected to moisture variation
- Longitudinal crack
  - Initiate in shrinking expansive subgrade
  - Propagate to pavement surface

Practice of Geogrid Reinforcement

FM1915 (Milam County, Texas)



Practice of Lime Treatment

Stress Analysis on Subgrade Soil

- Stress variable for saturated soil: $\sigma - u_w$
- Stress variable for unsaturated soil: $\sigma - u_a$, $u_a - u_w$
- Soil suction
  - ➢ The affinity of soil for water
  - ➢ Matric suction: negative water pressure
  - ➢ Osmotic suction: soluble salts in the soil water
- Constitutive equation to estimate the volumetric strain of unsaturated soil:

$$\frac{\Delta V}{V} = -\gamma_h \log_{10}\left(\frac{h_f}{h_i}\right) - \gamma_\sigma \log_{10}\left(\frac{\sigma_f}{\sigma_i}\right) - \gamma_\pi \log_{10}\left(\frac{\pi_f}{\pi_i}\right)$$

$$\frac{\Delta V}{V} = -\gamma_h \log_{10}\left(\frac{h_f}{h_i}\right) - \gamma_\sigma \log_{10}\left(\frac{\sigma_f}{\sigma_i}\right) - \gamma_\pi \log_{10}\left(\frac{\pi_f}{\pi_i}\right)$$

where

$\frac{\Delta V}{V}$ = volumetric strain;

h_i = initial value of matric suction;

h_f = final values of matric suction;

σ_i = initial value of mean principle stress;

σ_f = finial value of mean principle stress;

π_i = initial value of osmotic suction;

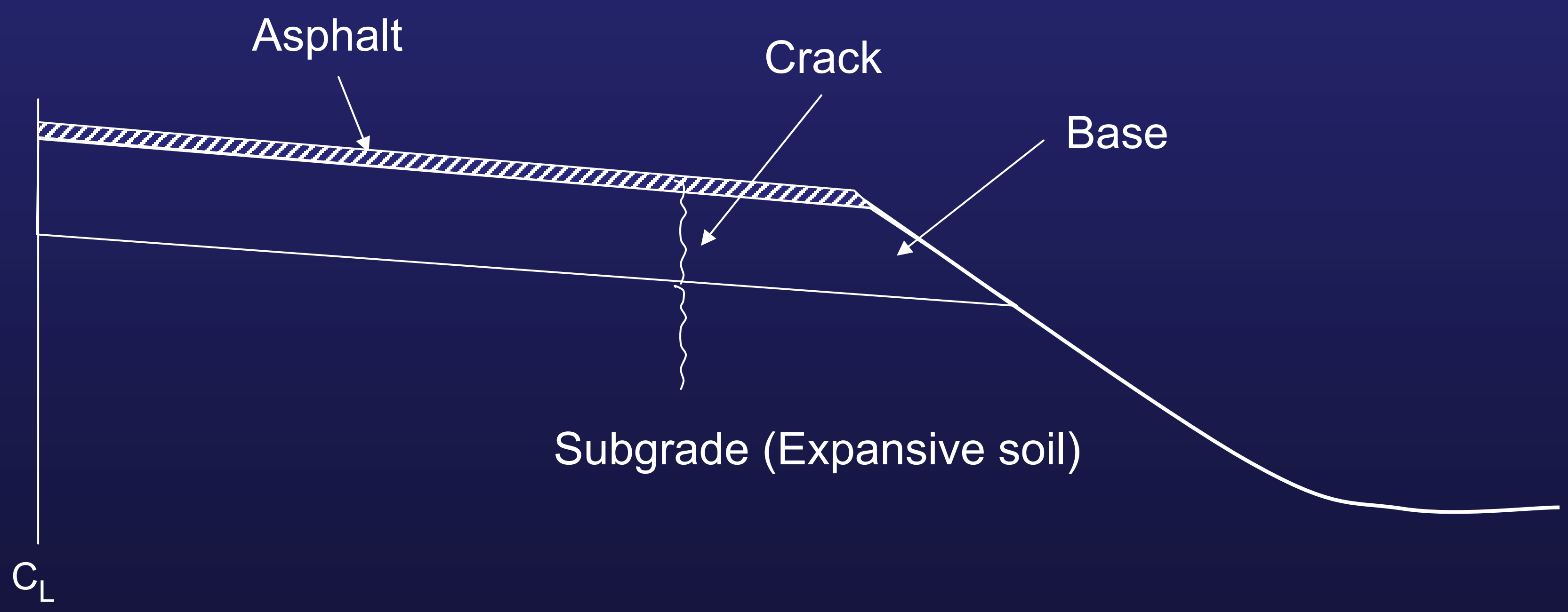
π_f = finial value of osmotic suction;

γ_h = matric suction compression index;

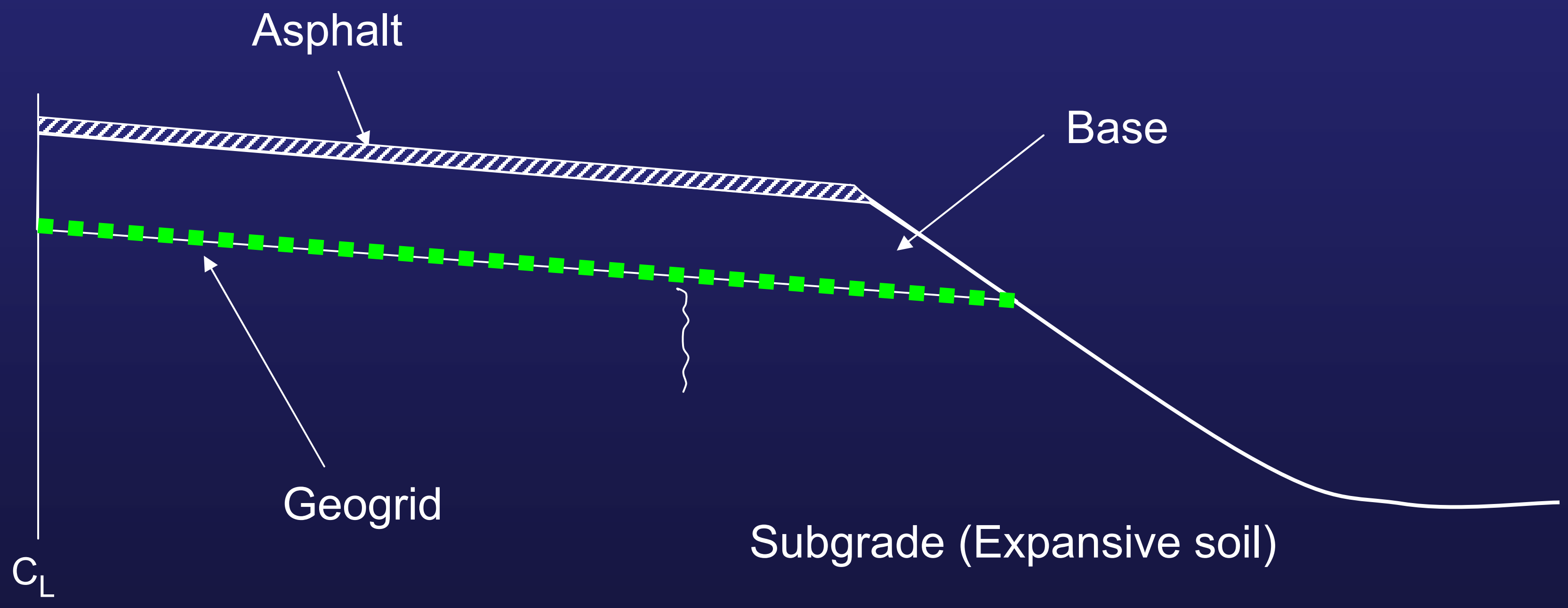
γ_σ = mean principal stress compression index; and

γ_π = osmotic suction compression index.

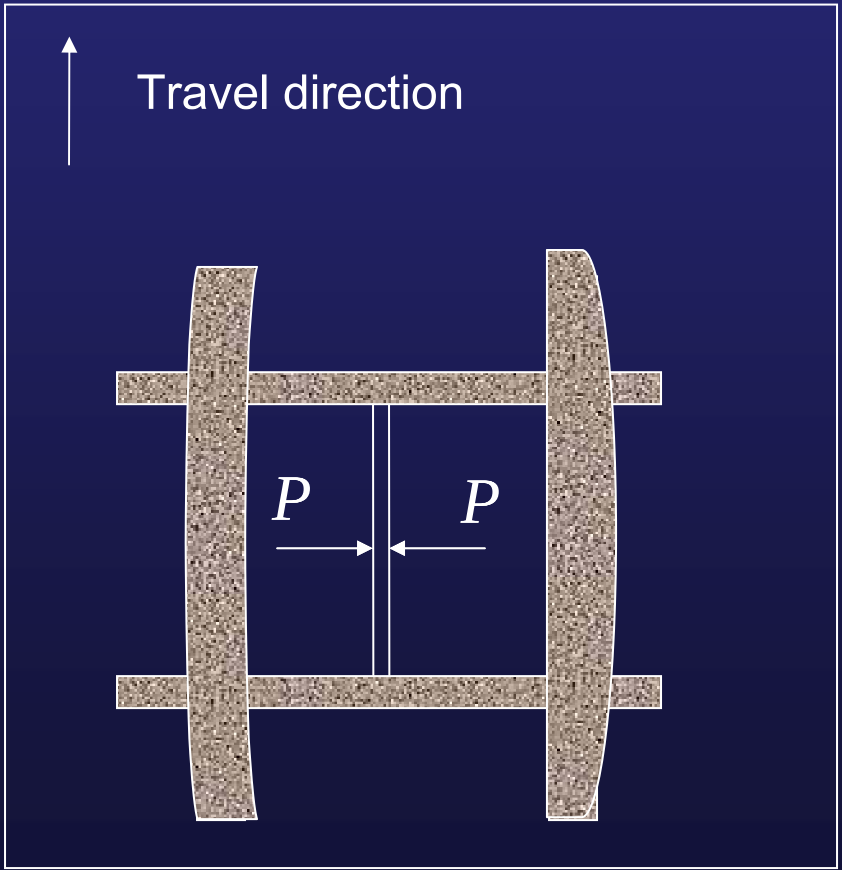
Without Geogrid Reinforcement…

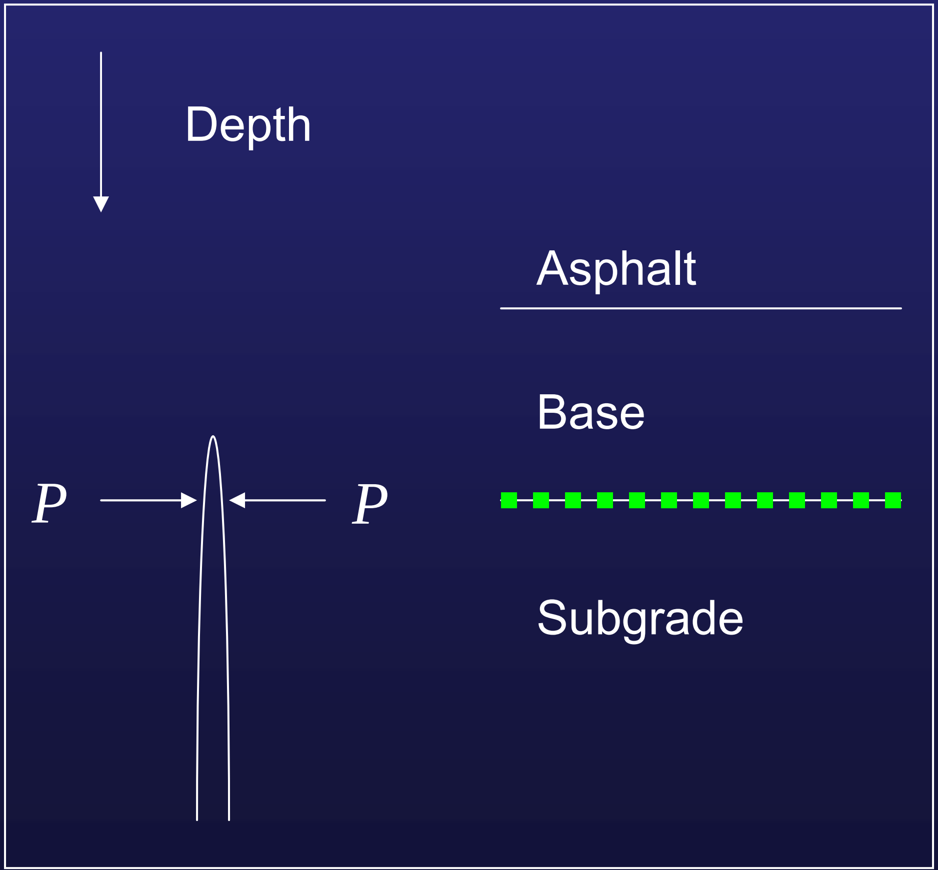


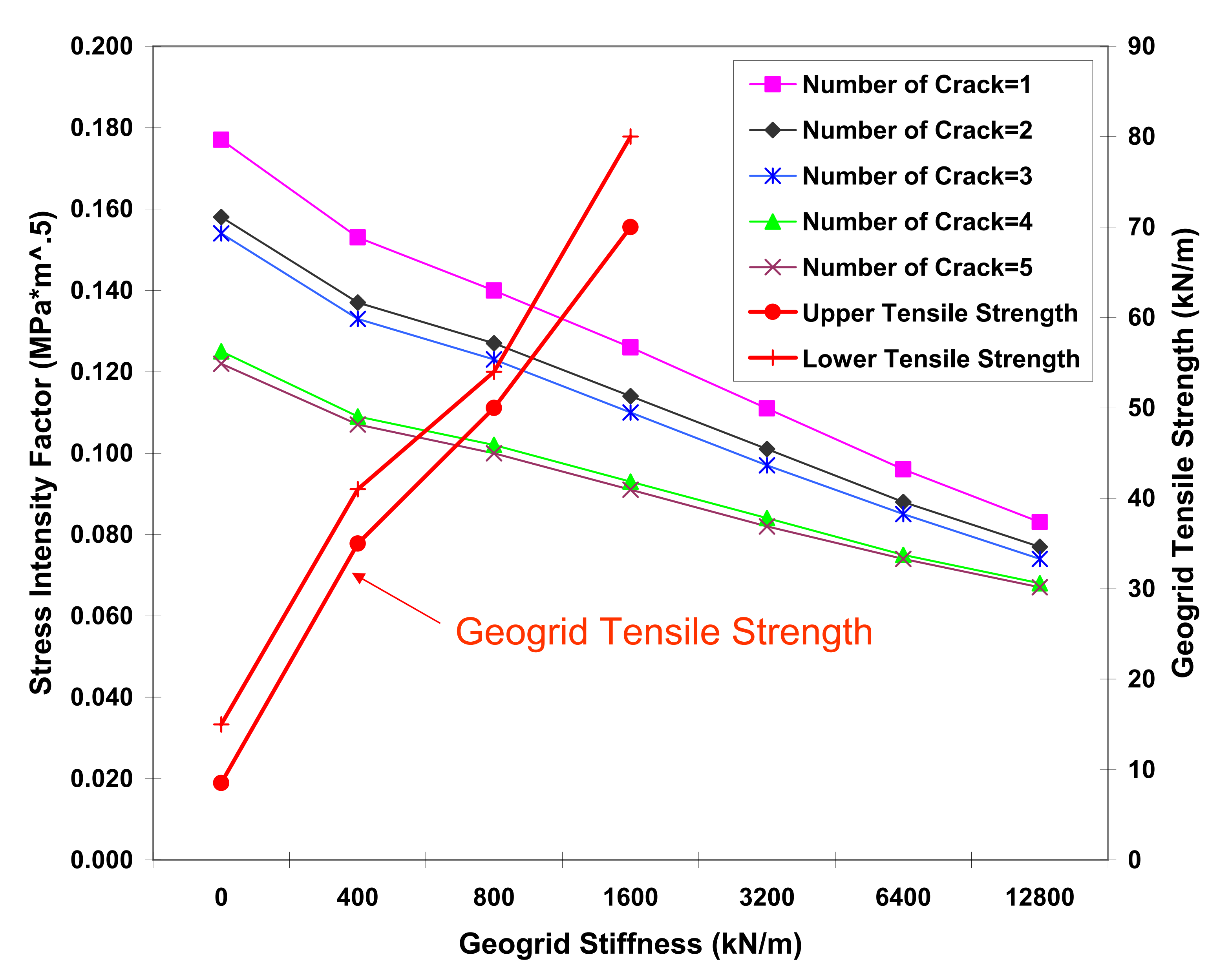
With Geogrid Reinforcement…



Mechanism of Geogrid Reinforcement

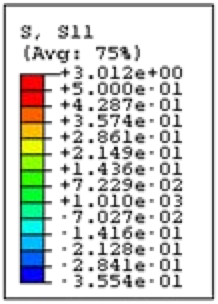


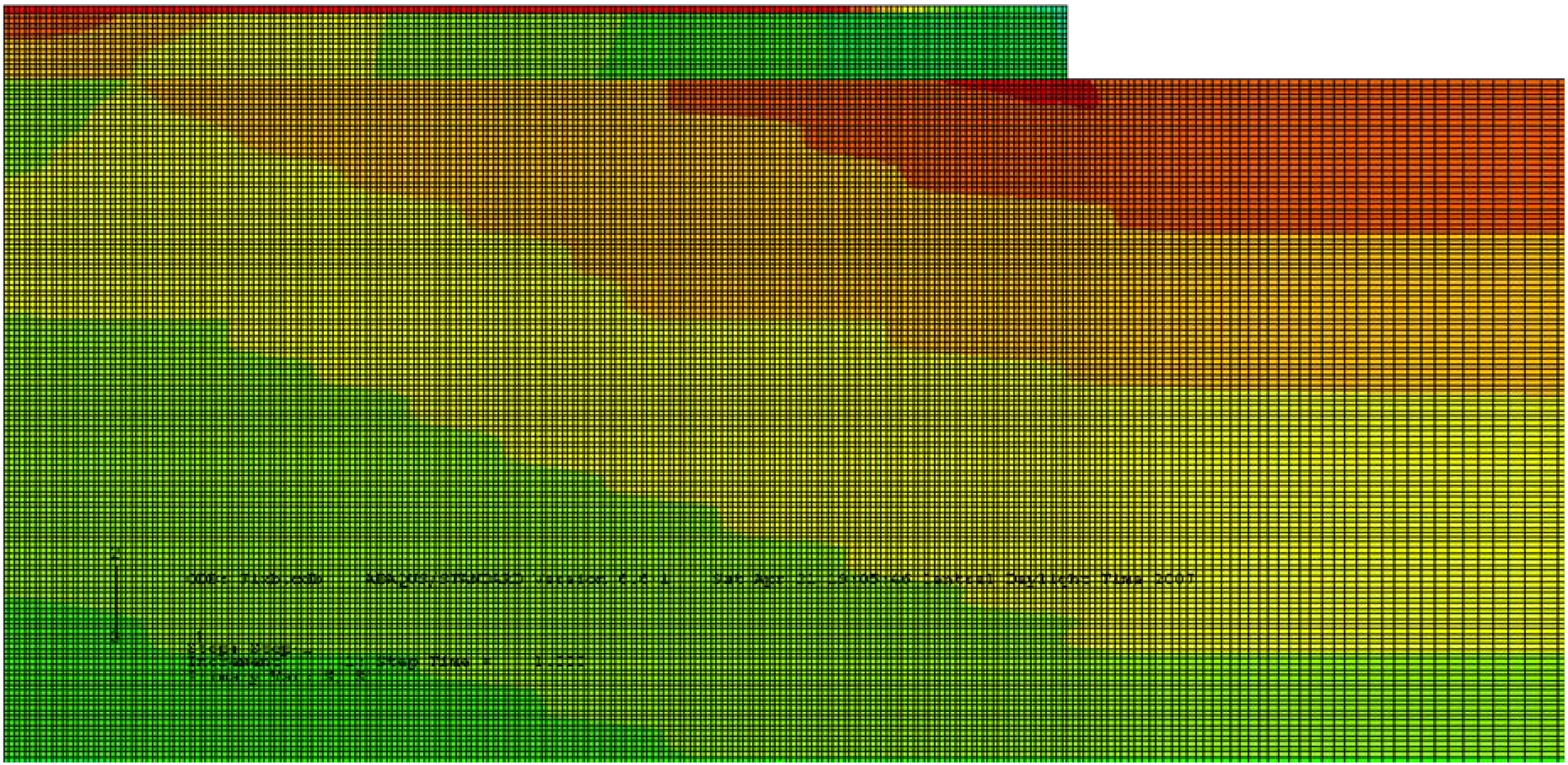




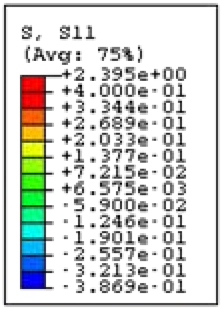
0.200
0.180
0.160
0.140
0.120
0.100
0.080
0.060
0.040
0.020
0.000
Stress Intensity Factor (MPa*m^.5)
90
80
70
60
50
40
30
20
10
0
Geogrid Tensile Strength (kN/m)
Number of Crack=1
Number of Crack=2
Number of Crack=3
Number of Crack=4
Number of Crack=5
Upper Tensile Strength
Lower Tensile Strength
Geogrid Tensile Strength
0
400
800
1600
3200
6400
12800
Geogrid Stiffness (kN/m)

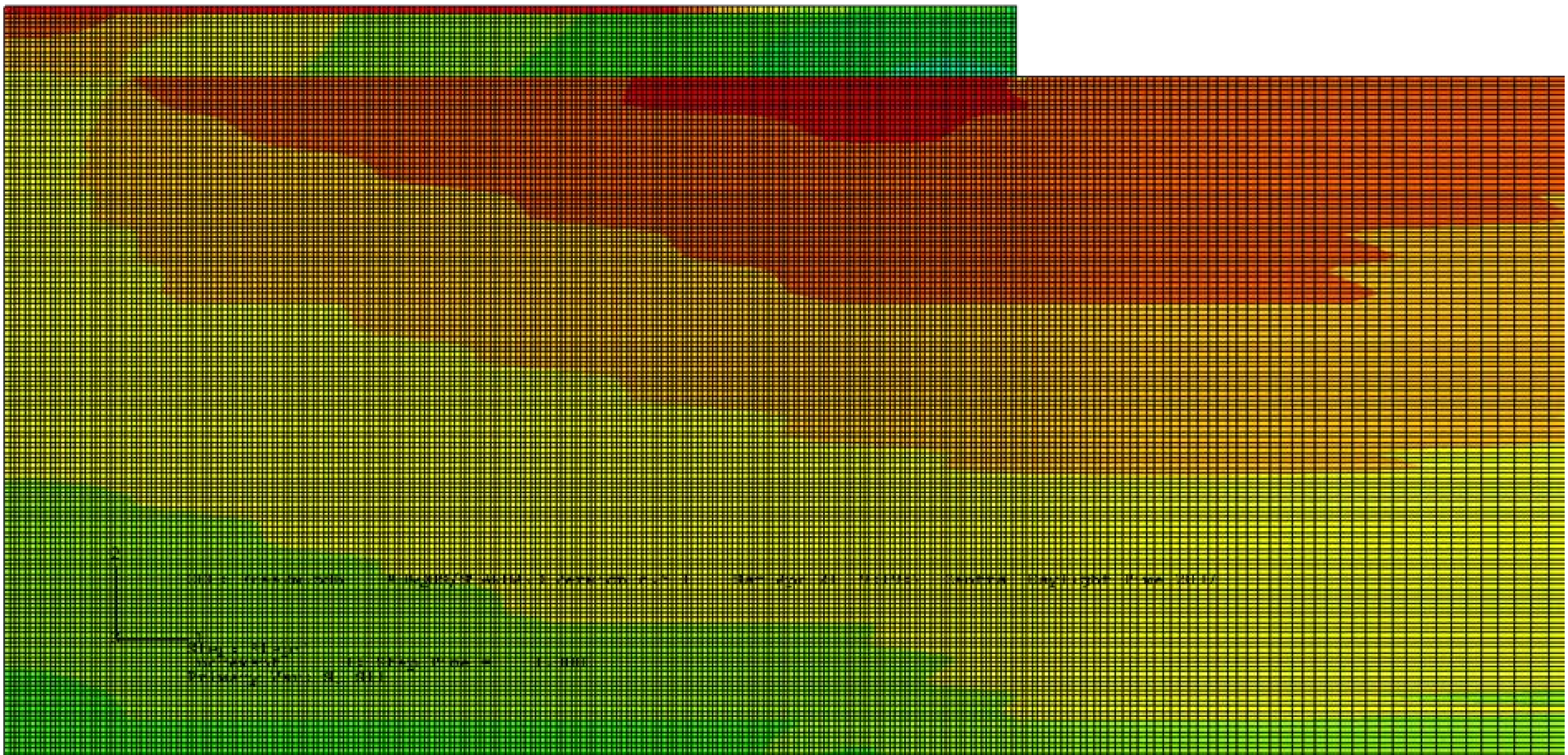
Transverse Stress Distribution in Pavement (Full Restraint)



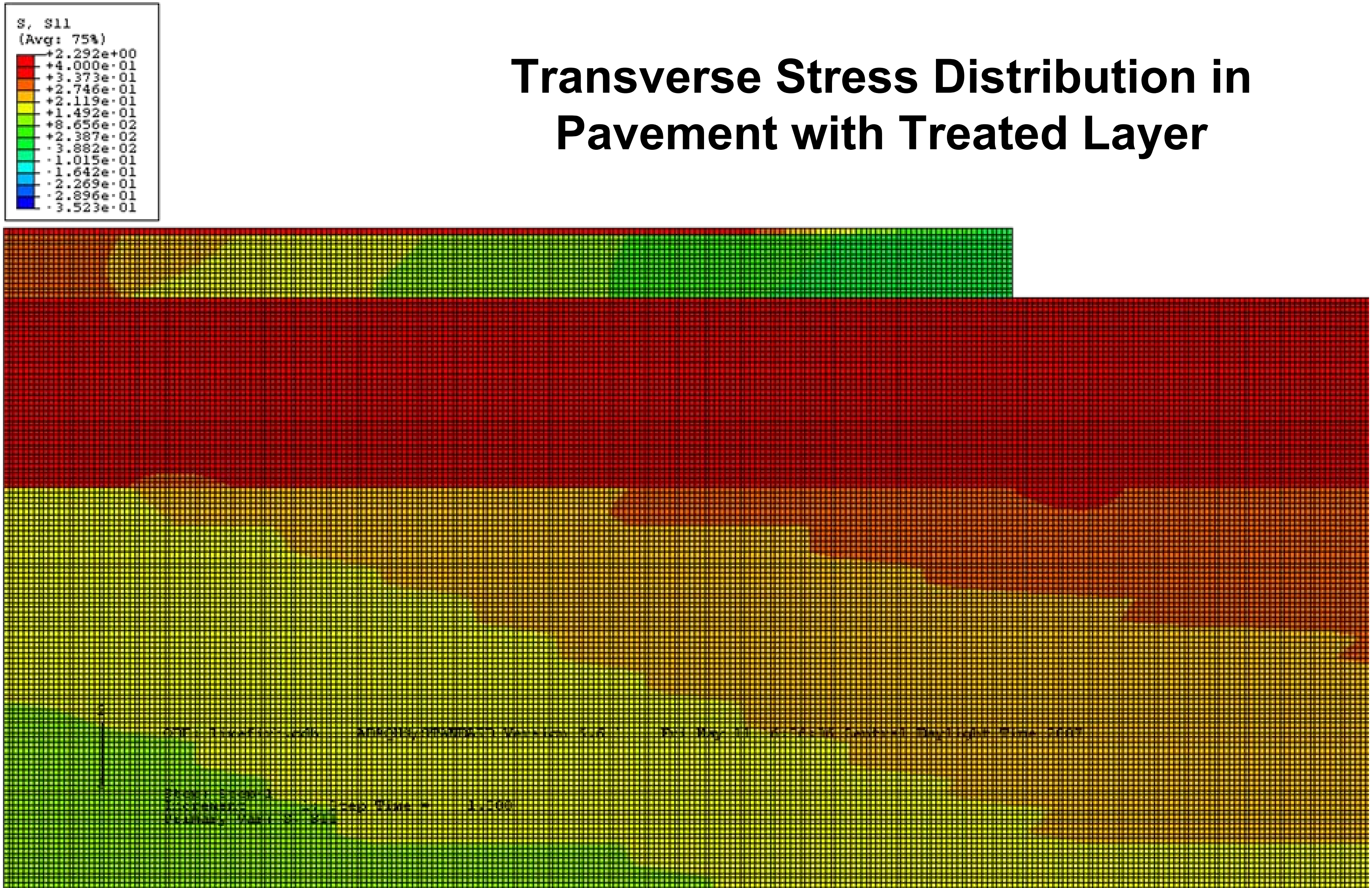


Transverse Stress Distribution in Pavement (Crack at Edge of Shoulder)

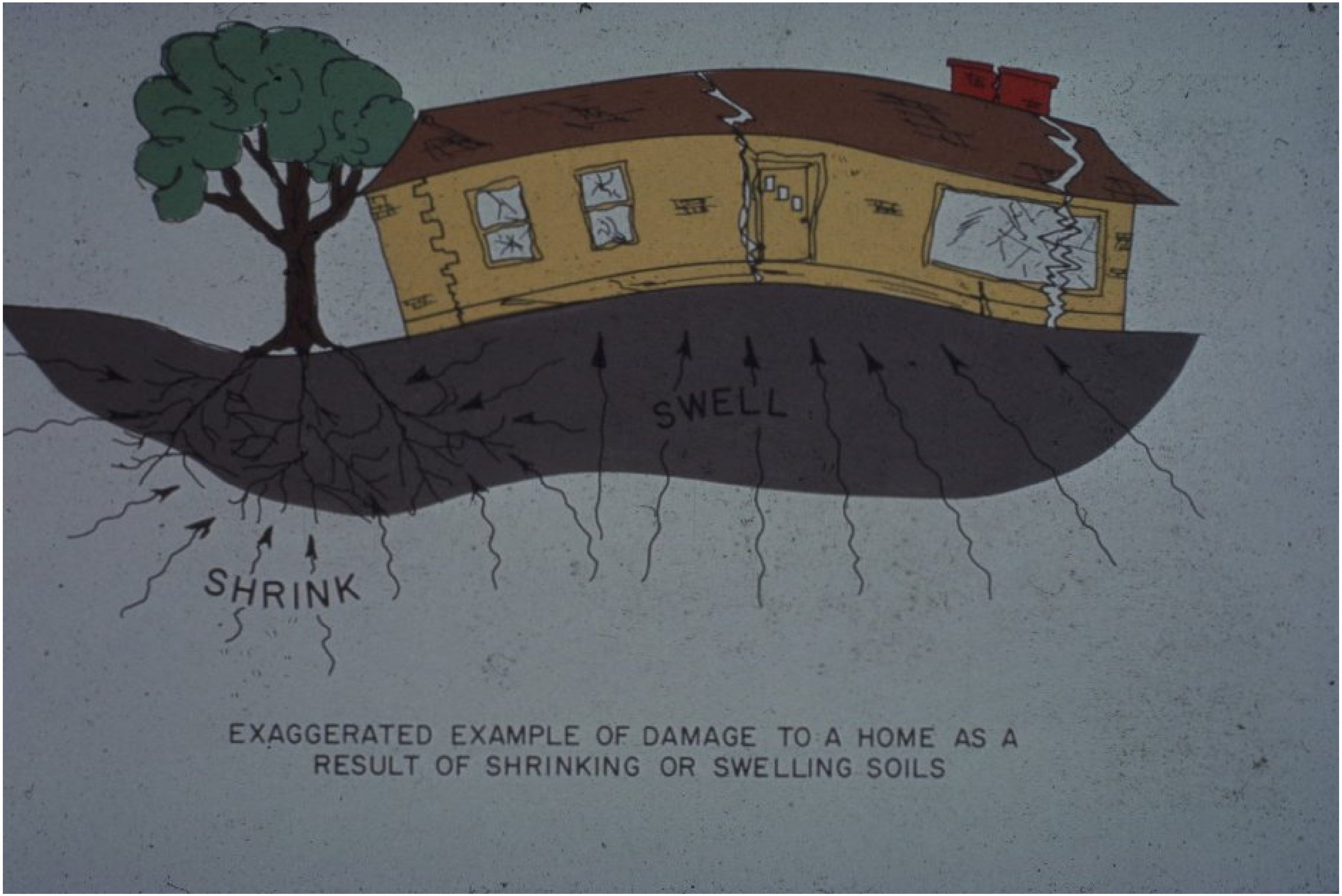


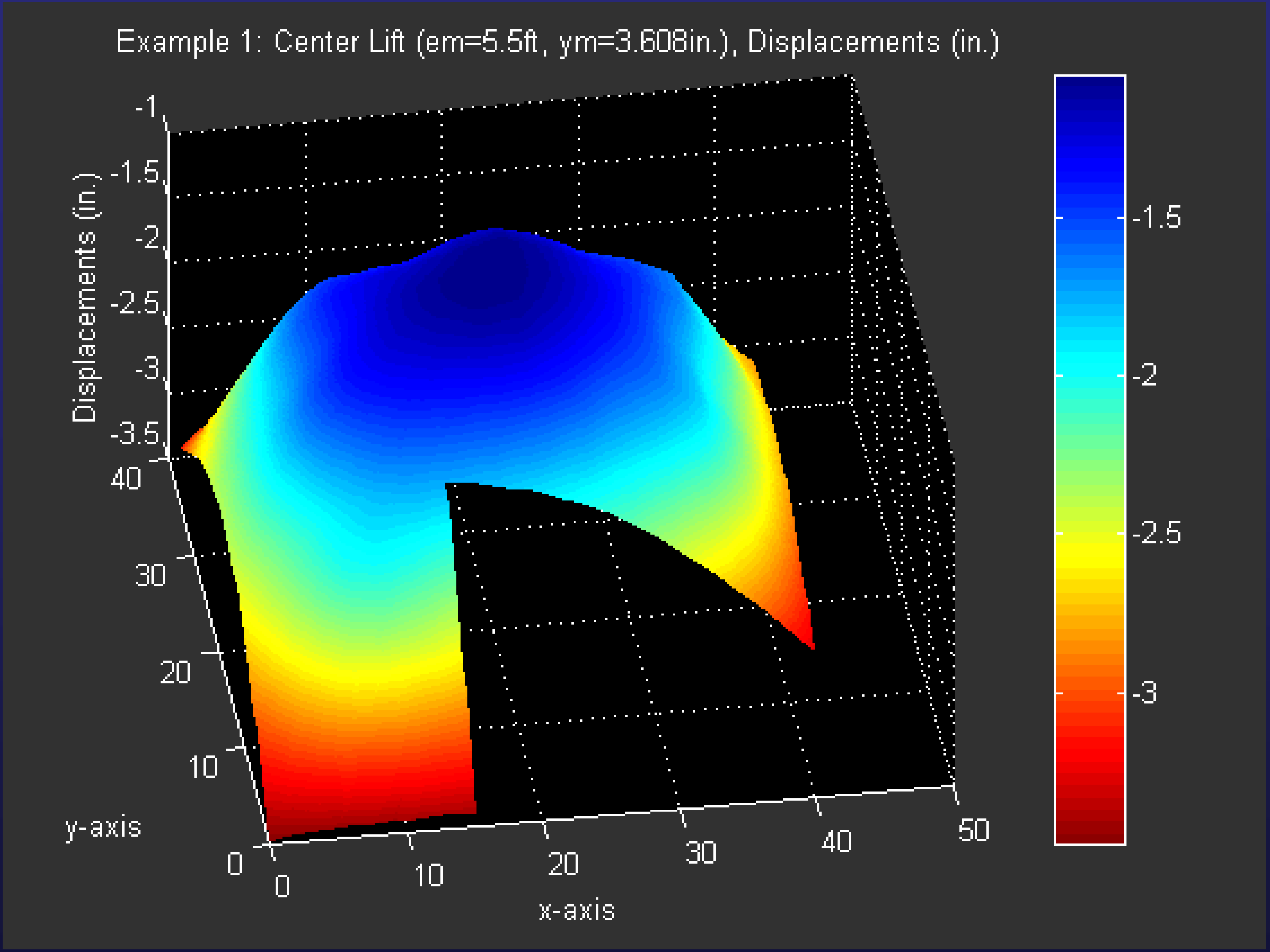


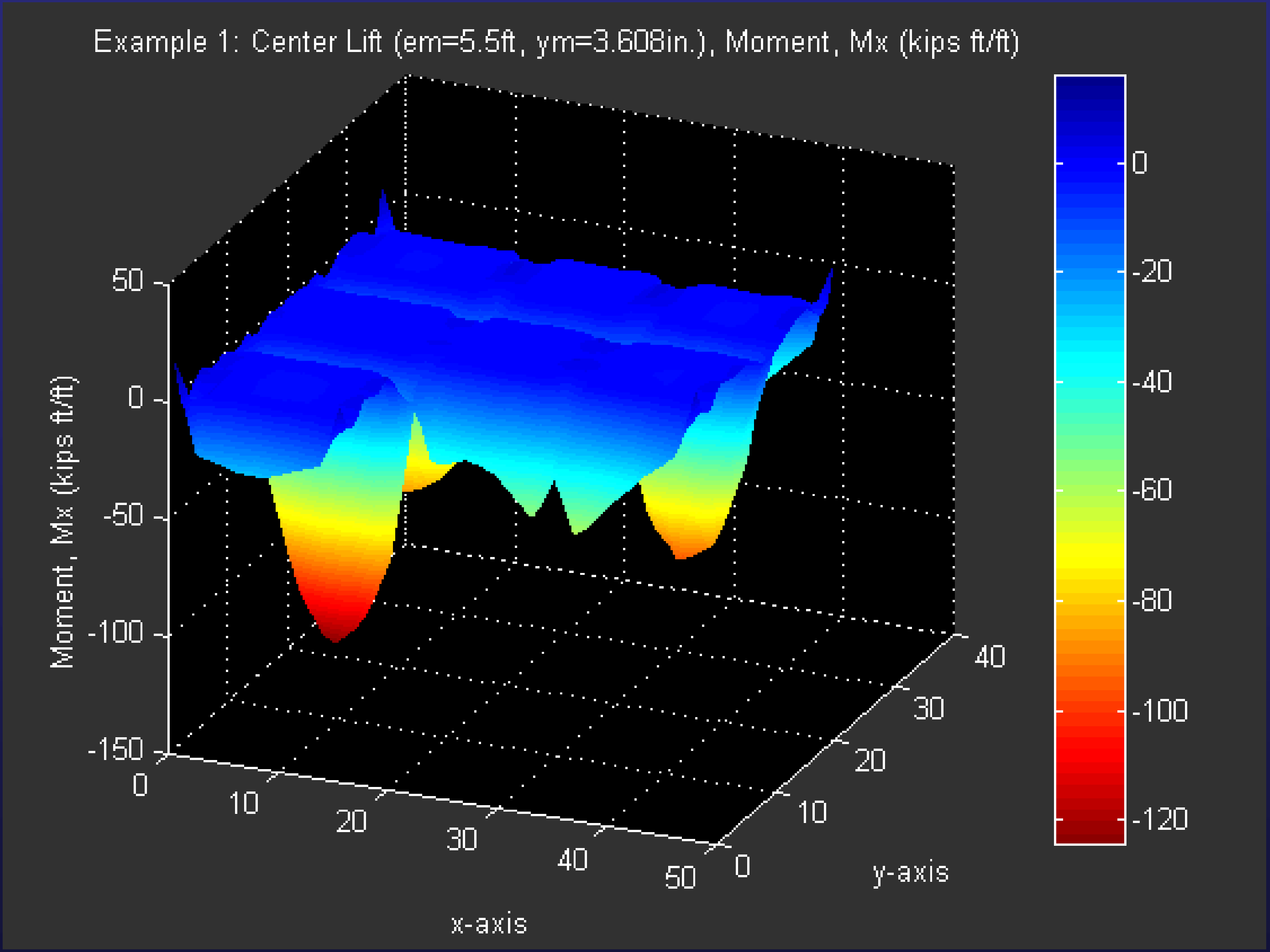
Transverse Stress Distribution in Pavement with Treated Layer



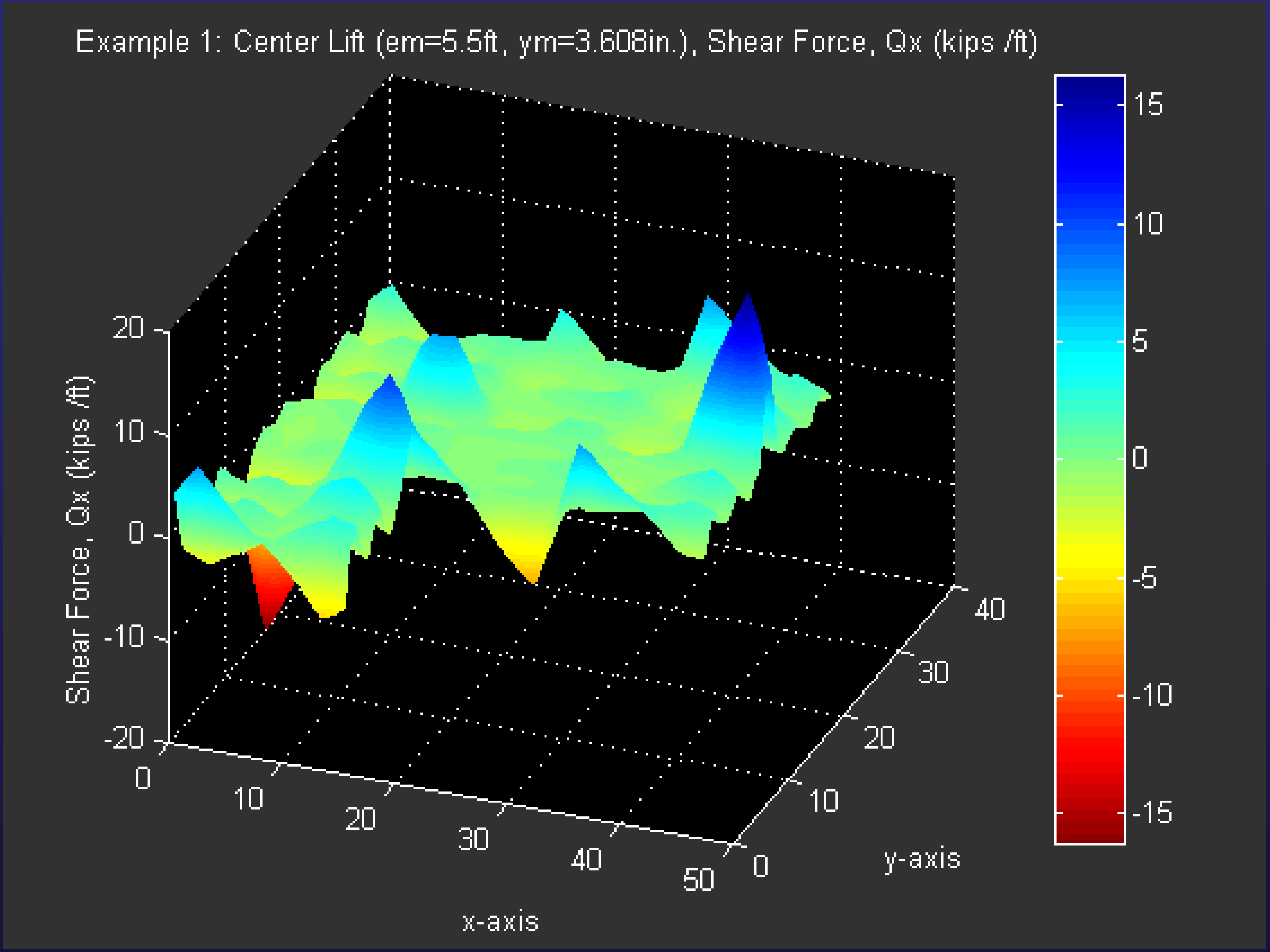
Slab-on-Ground Design

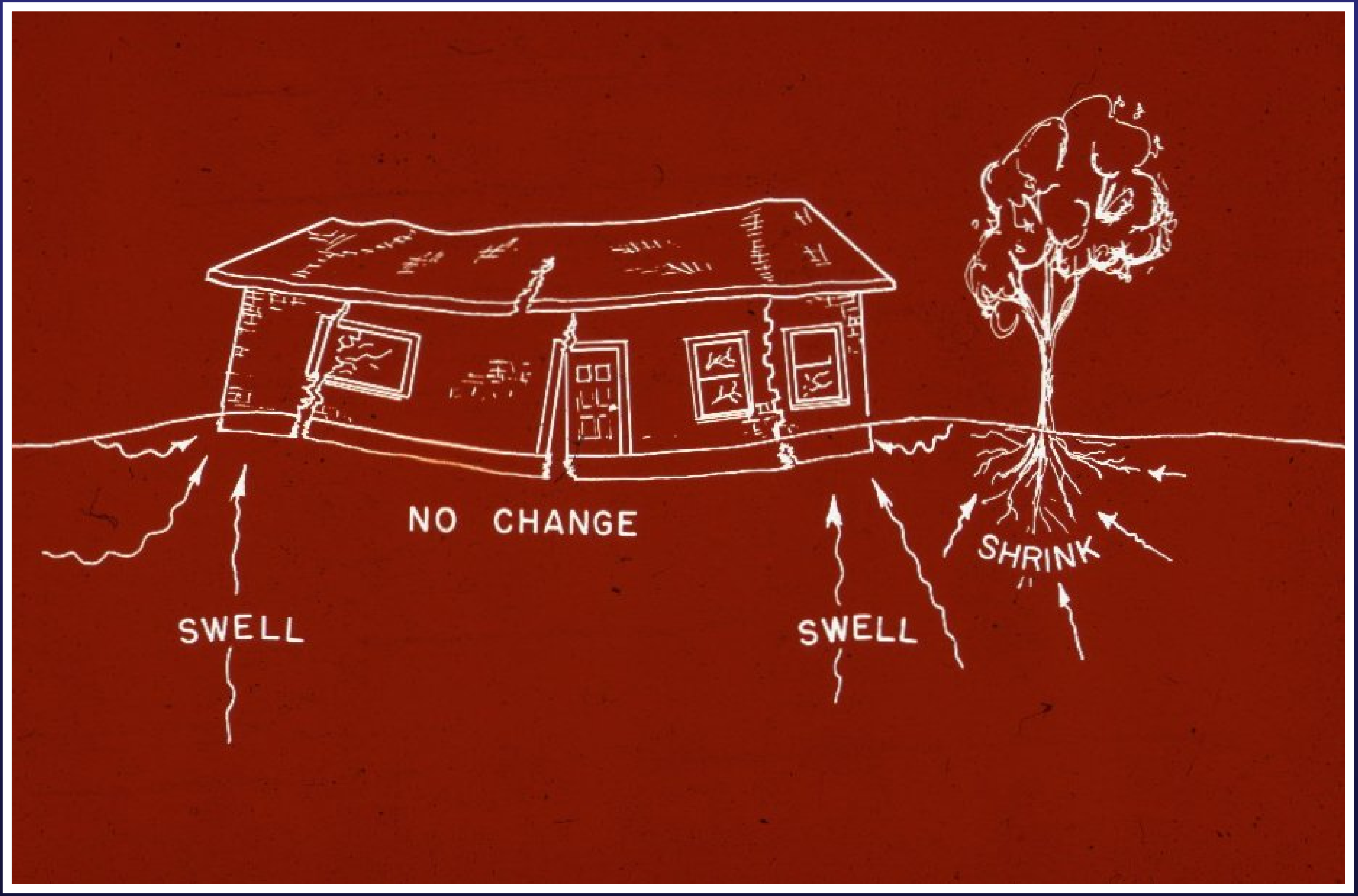

SWELL
SHRINK
EXAGGERATED EXAMPLE OF DAMAGE TO A HOME AS A
RESULT OF SHRINKING OR SWELLING SOILS

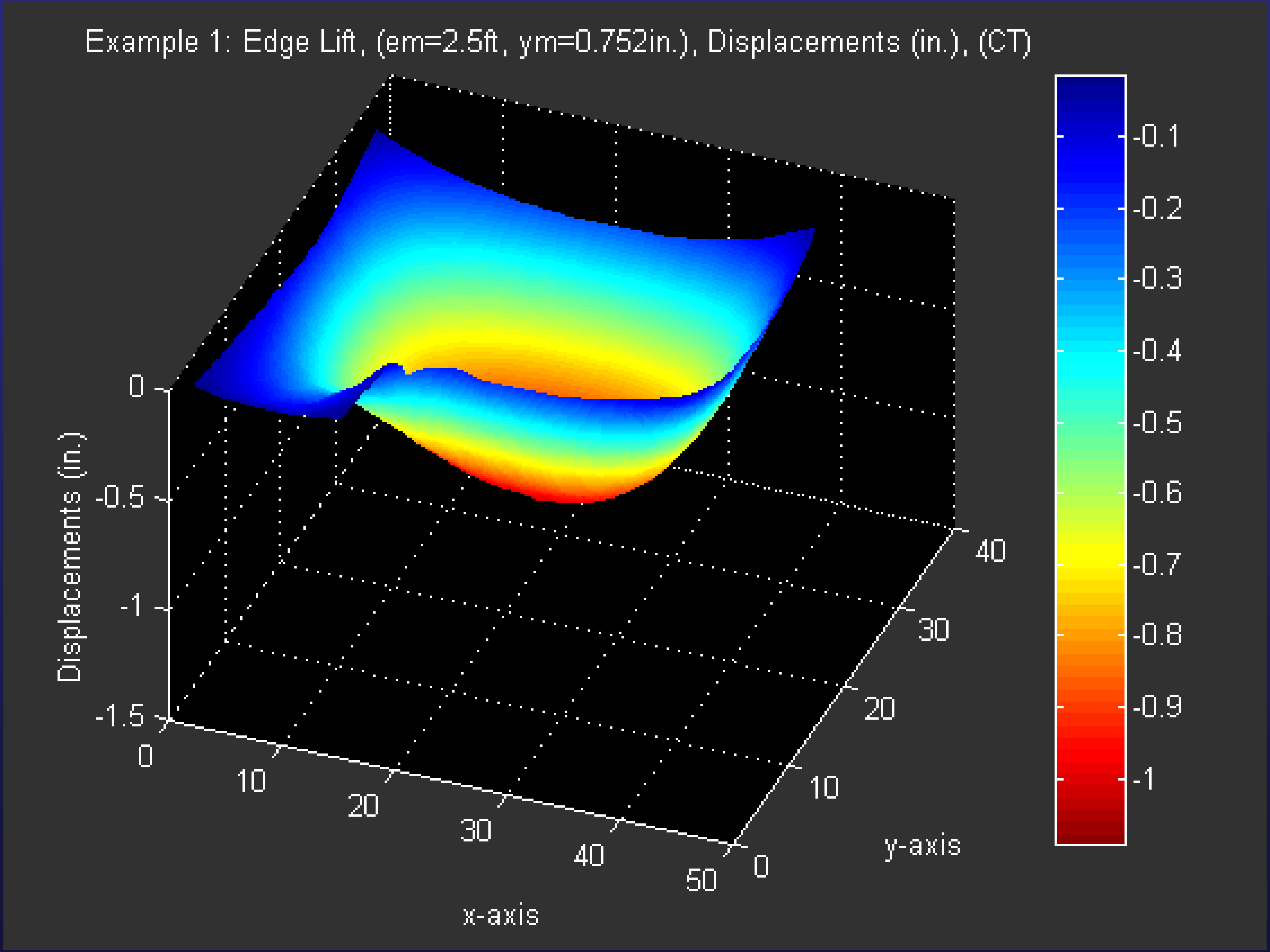

Example 1: Center Lift (em=5.5ft, ym=3.608in.), Displacements (in.)
Displacements (in.)
-1
-1.5
-2
-2.5
-3
-3.5
40
30
20
10
0
y-axis
0
10
20
30
40
50
x-axis
-1.5
-2
-2.5
-3

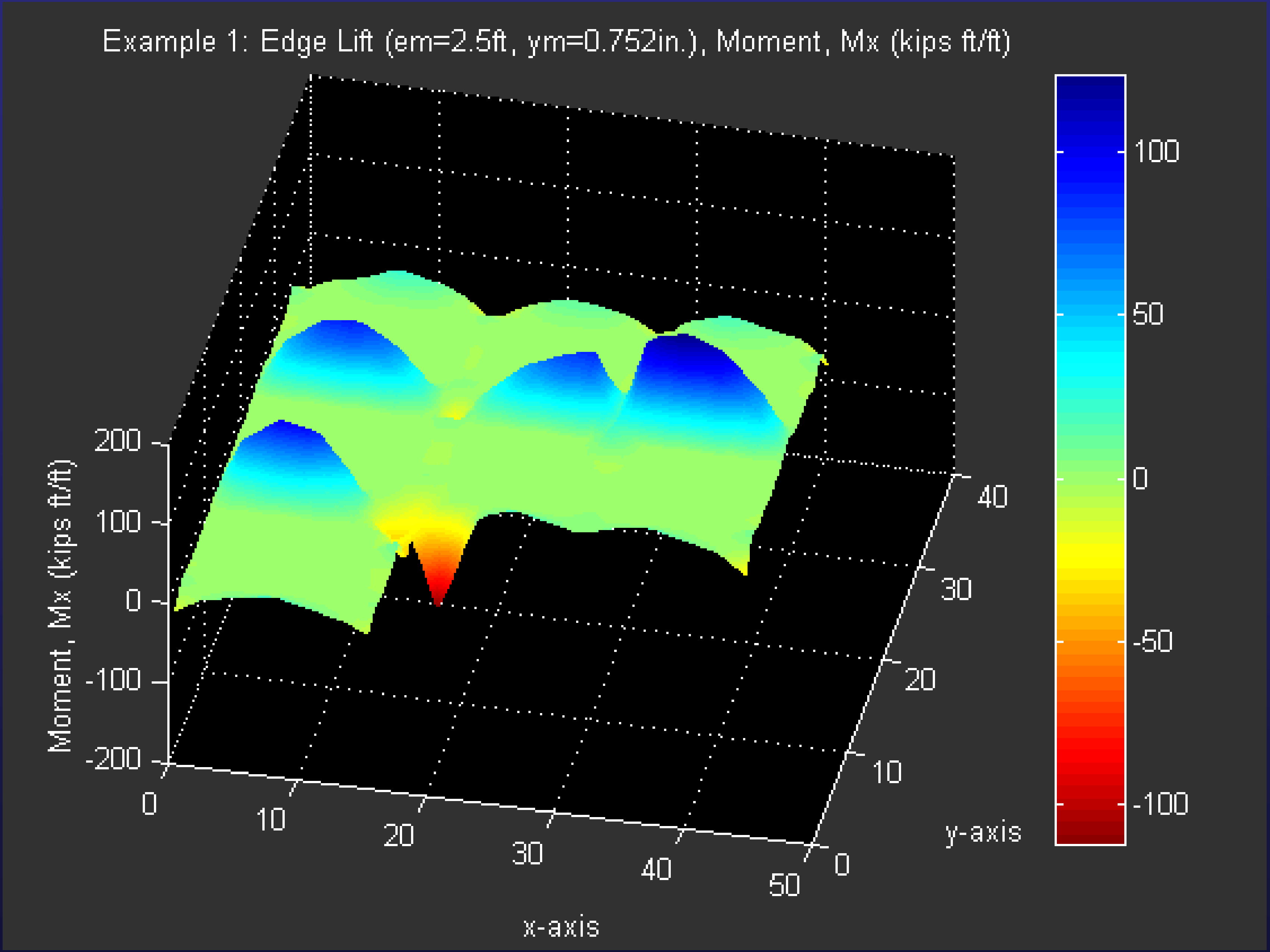


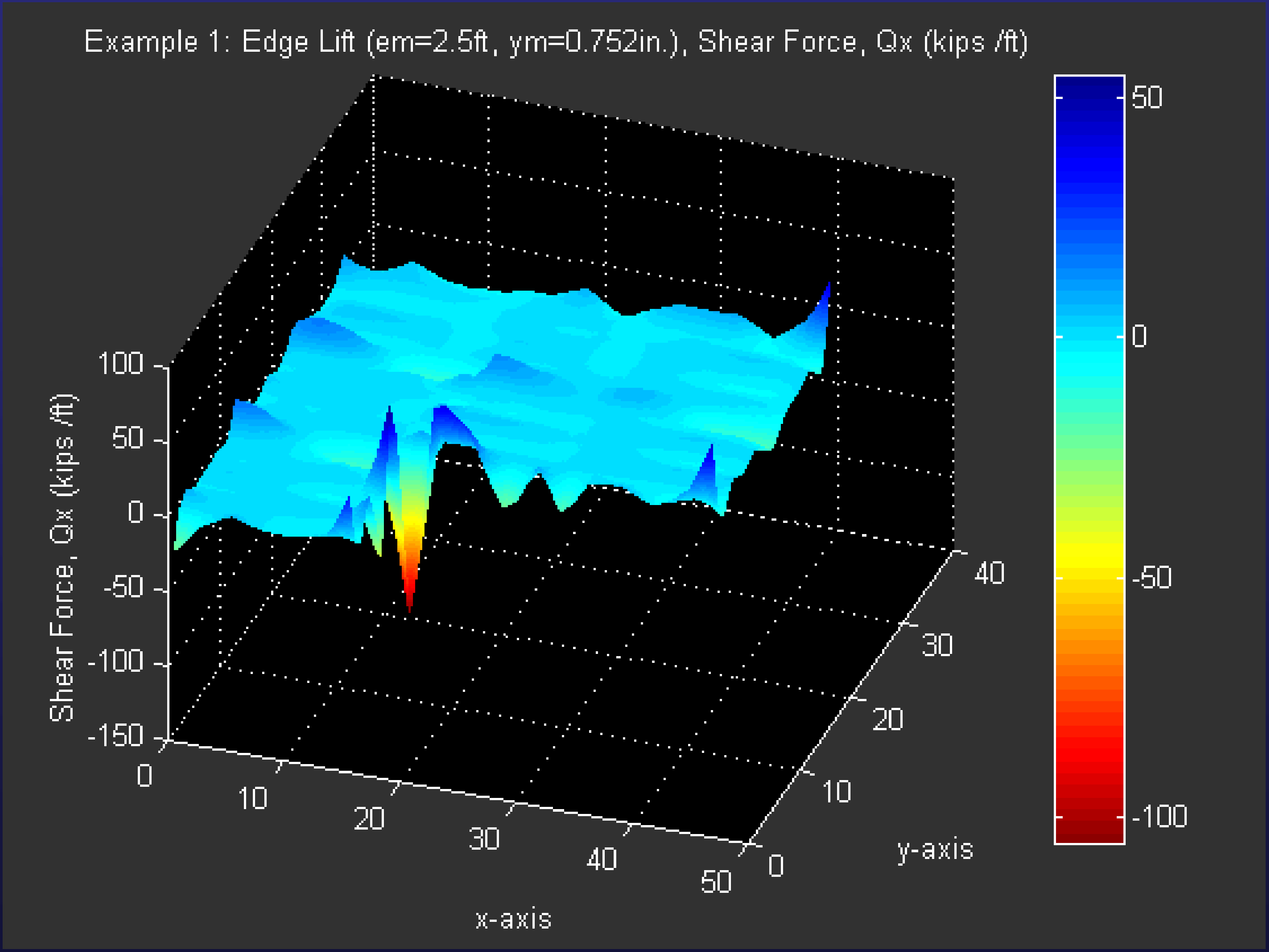
Example 1: Center Lift (em=5.5ft, ym=3.608in.), Moment, Mx (kips ft/ft)
Moment, Mx (kips ft/ft)
50
0
-50
-100
-150
0
10
20
30
40
50
x-axis
0
10
20
30
40
y-axis
0
-20
-40
-60
-80
-100
-120


Example 1: Center Lift (em=5.5ft, ym=3.608in.), Shear Force, Qx (kips /ft)
Shear Force, Qx (kips /ft)
20
10
0
-10
-20
0
10
20
30
40
50
x-axis
0
10
20
30
40
y-axis
15
10
5
0
-5
-10
-15

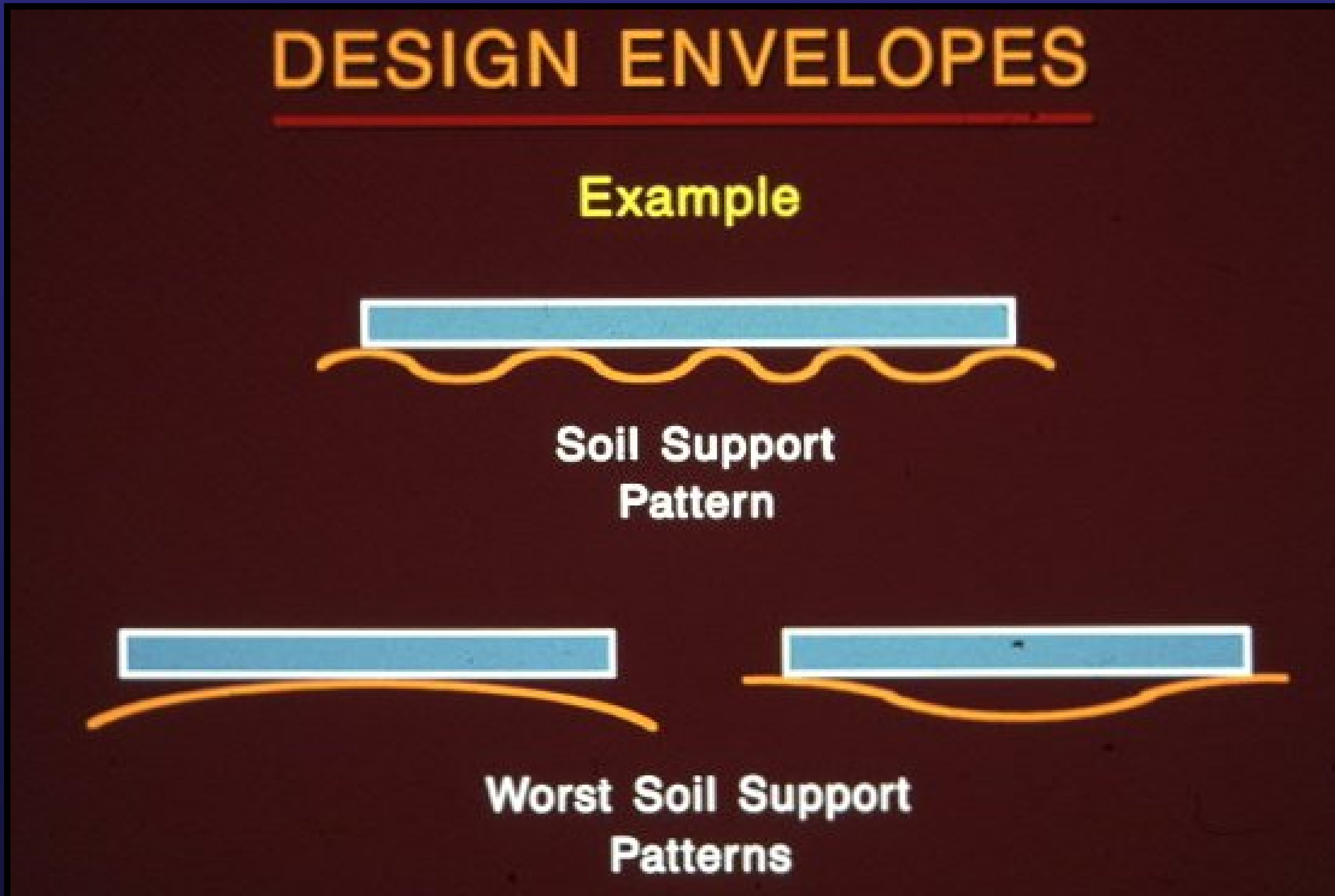

NO CHANGE
SWELL
SWELL
SHRINK

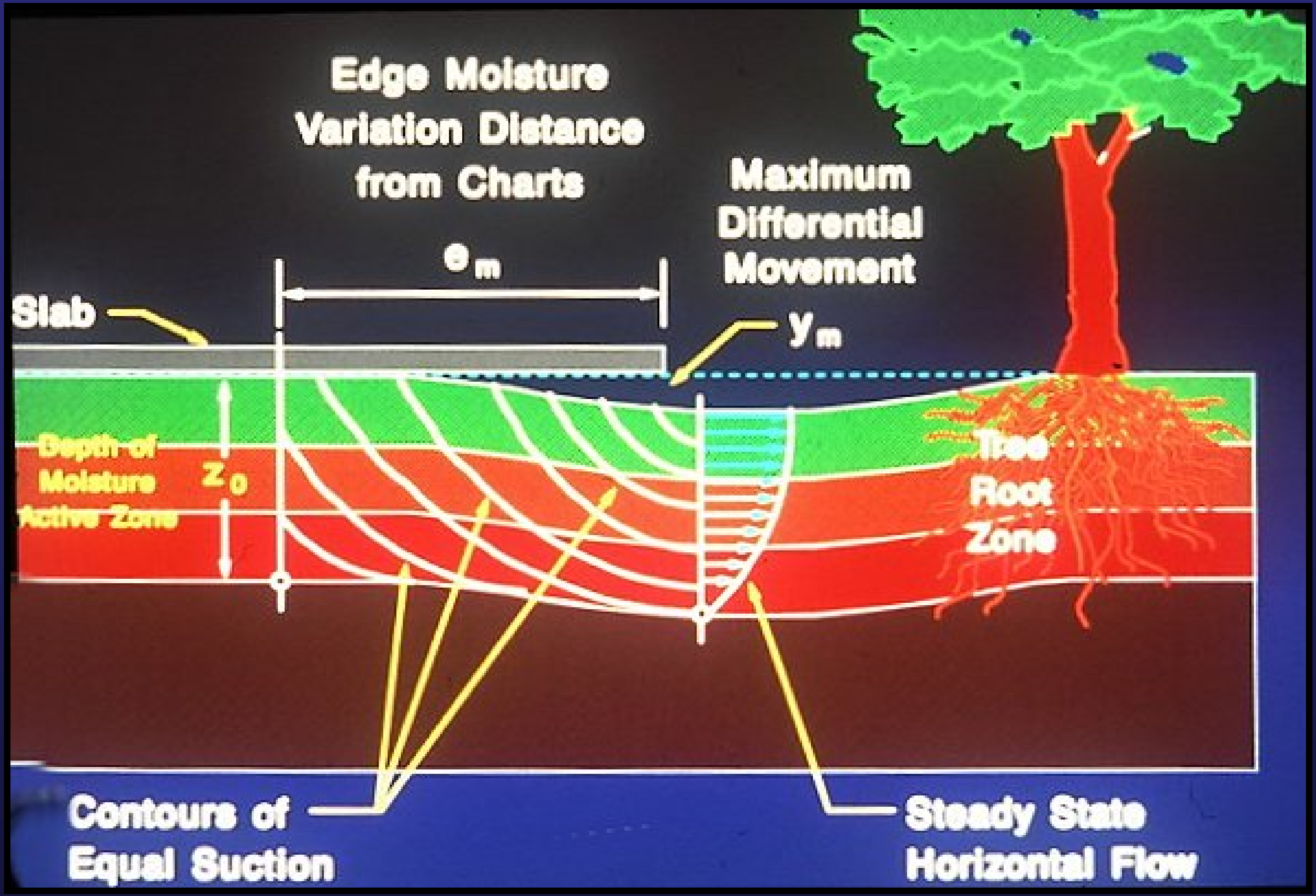

Example 1: Edge Lift, (em=2.5ft, ym=0.752in.), Displacements (in.), (CT)
Displacements (in.)
0
-0.5
-1
-1.5
0
10
20
30
40
50
x-axis
0
10
20
30
40
y-axis
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1

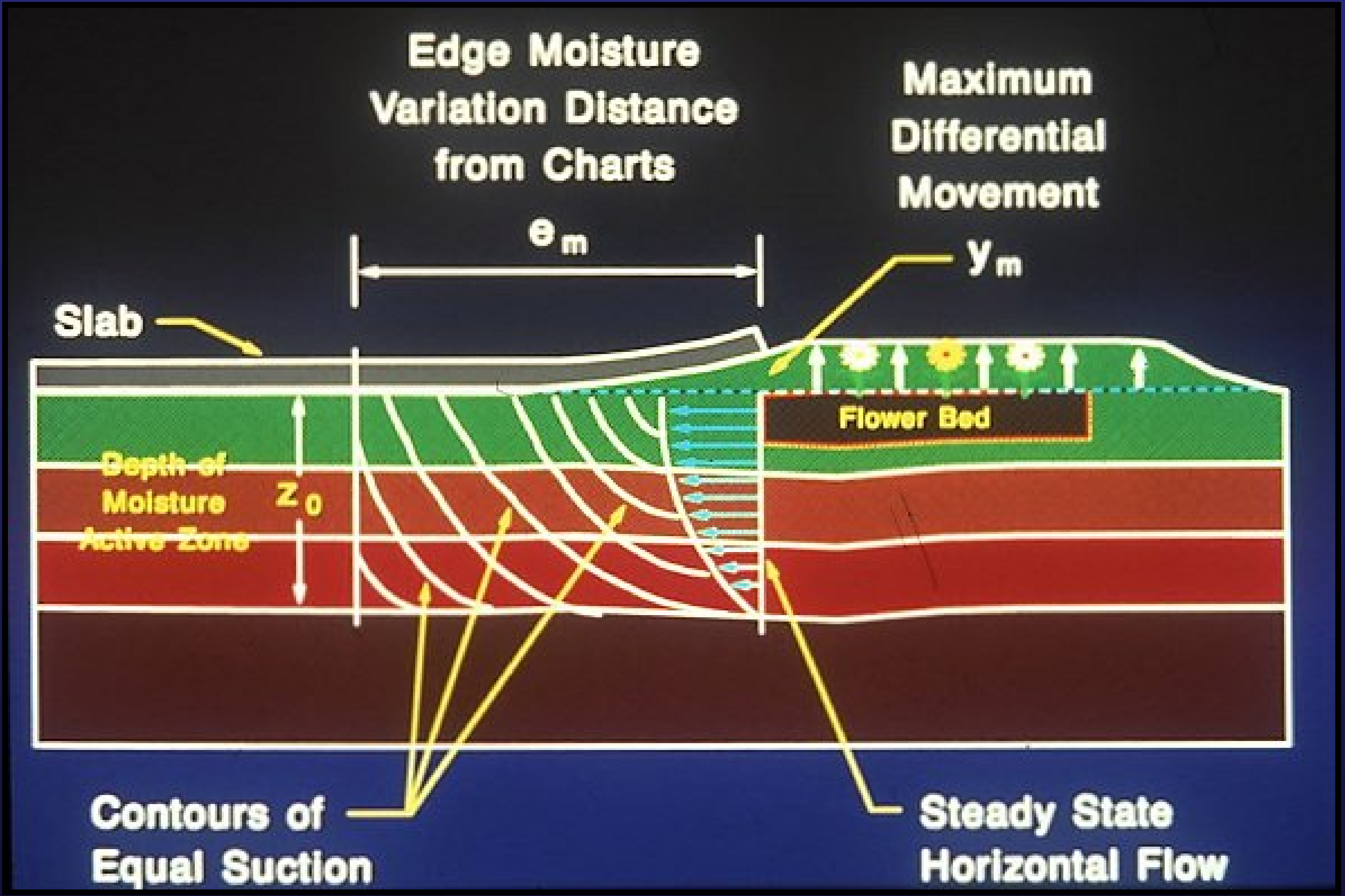

Example 1: Edge Lift (em=2.5ft, ym=0.752in.), Moment, Mx (kips ft/ft)
Moment, Mx (kips ft/ft)
200
100
0
-100
-200
0
10
20
30
40
50
x-axis
0
10
20
30
40
y-axis
100
50
0
-50
-100

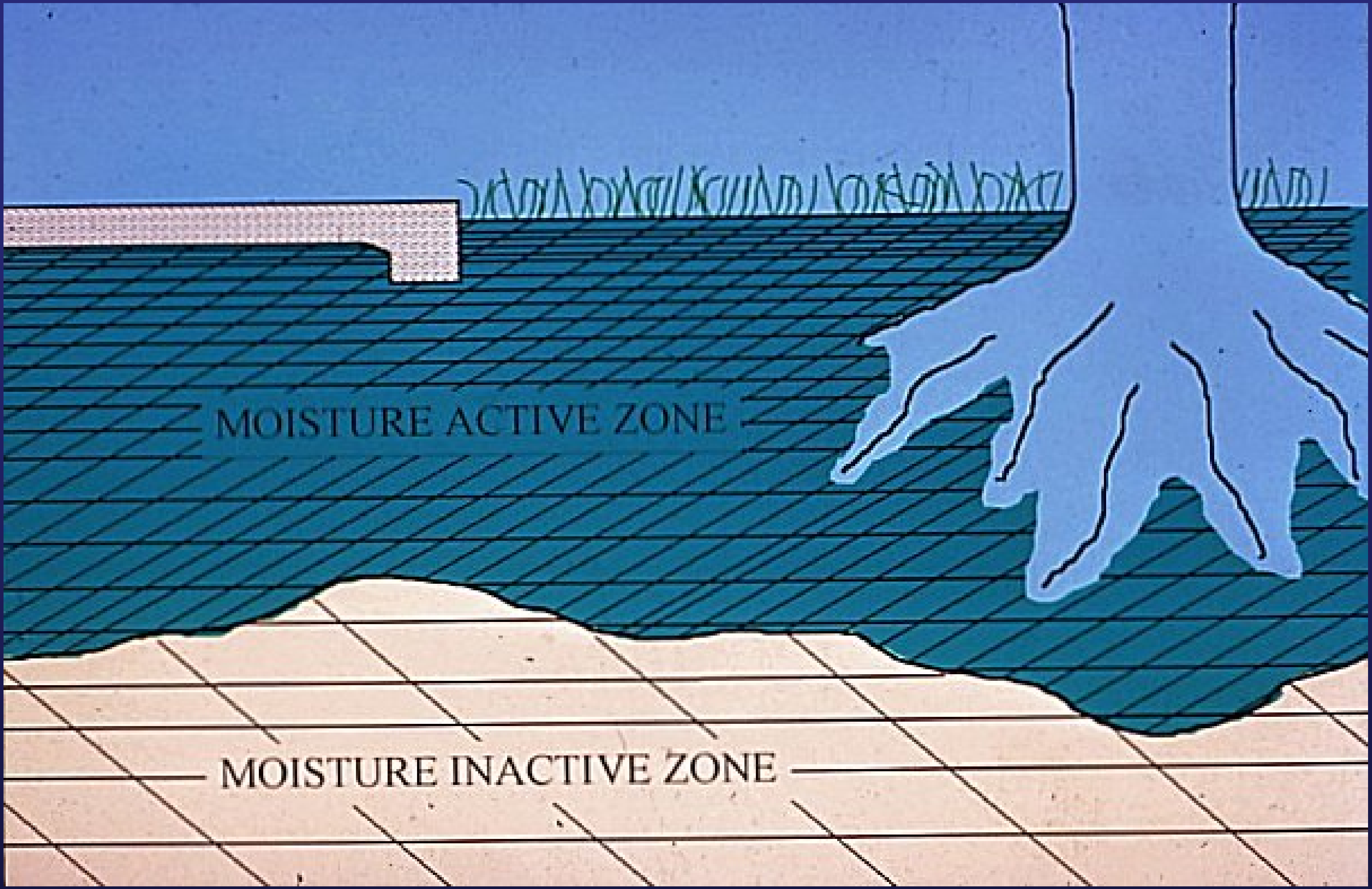


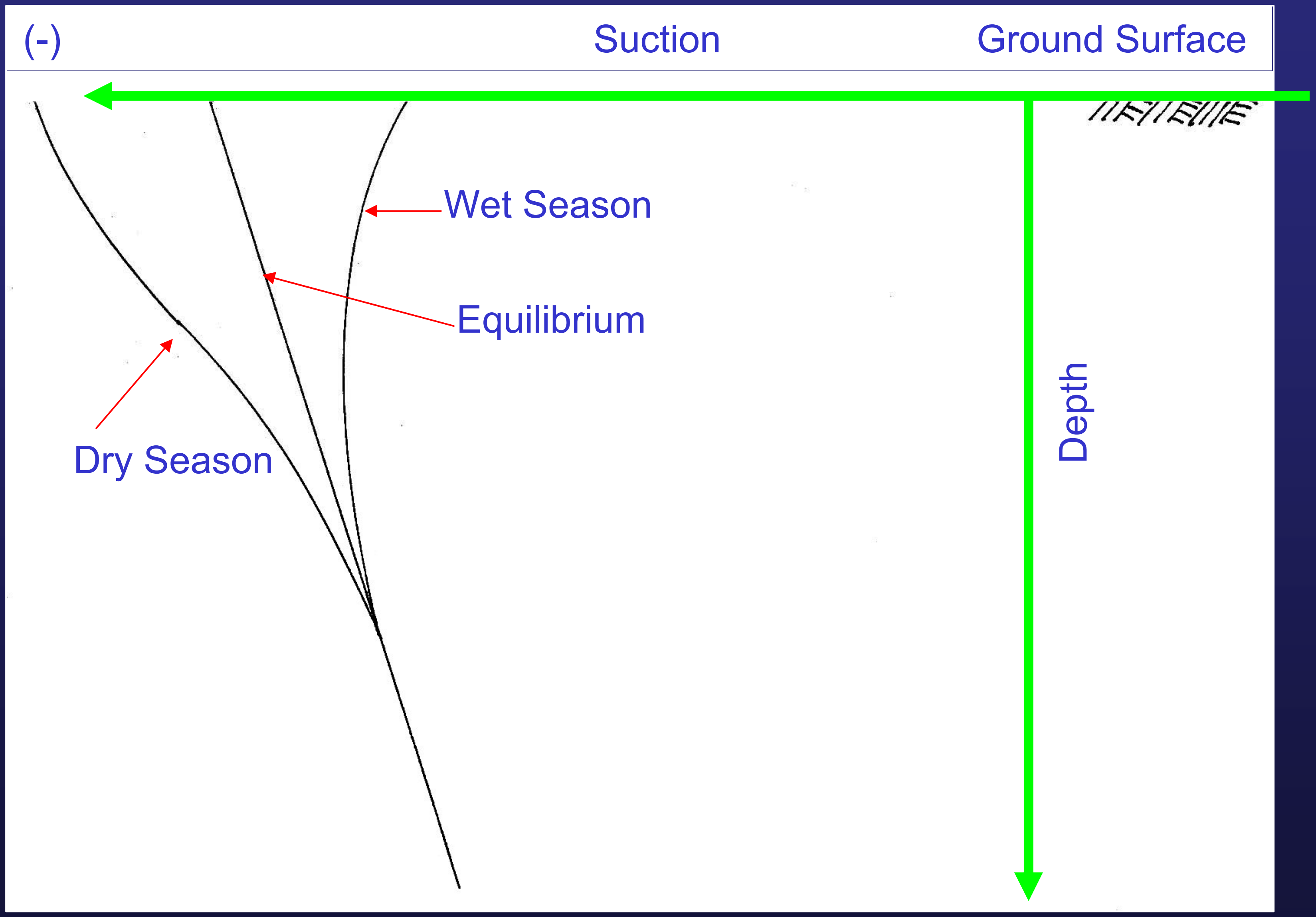
Example 1: Edge Lift (em=2.5ft, ym=0.752in.), Shear Force, Qx (kips /ft)
Shear Force, Qx (kips /ft)
100
50
0
-50
-100
-150
0
10
20
30
40
50
x-axis
0
10
20
30
40
y-axis
50
0
-50
-100

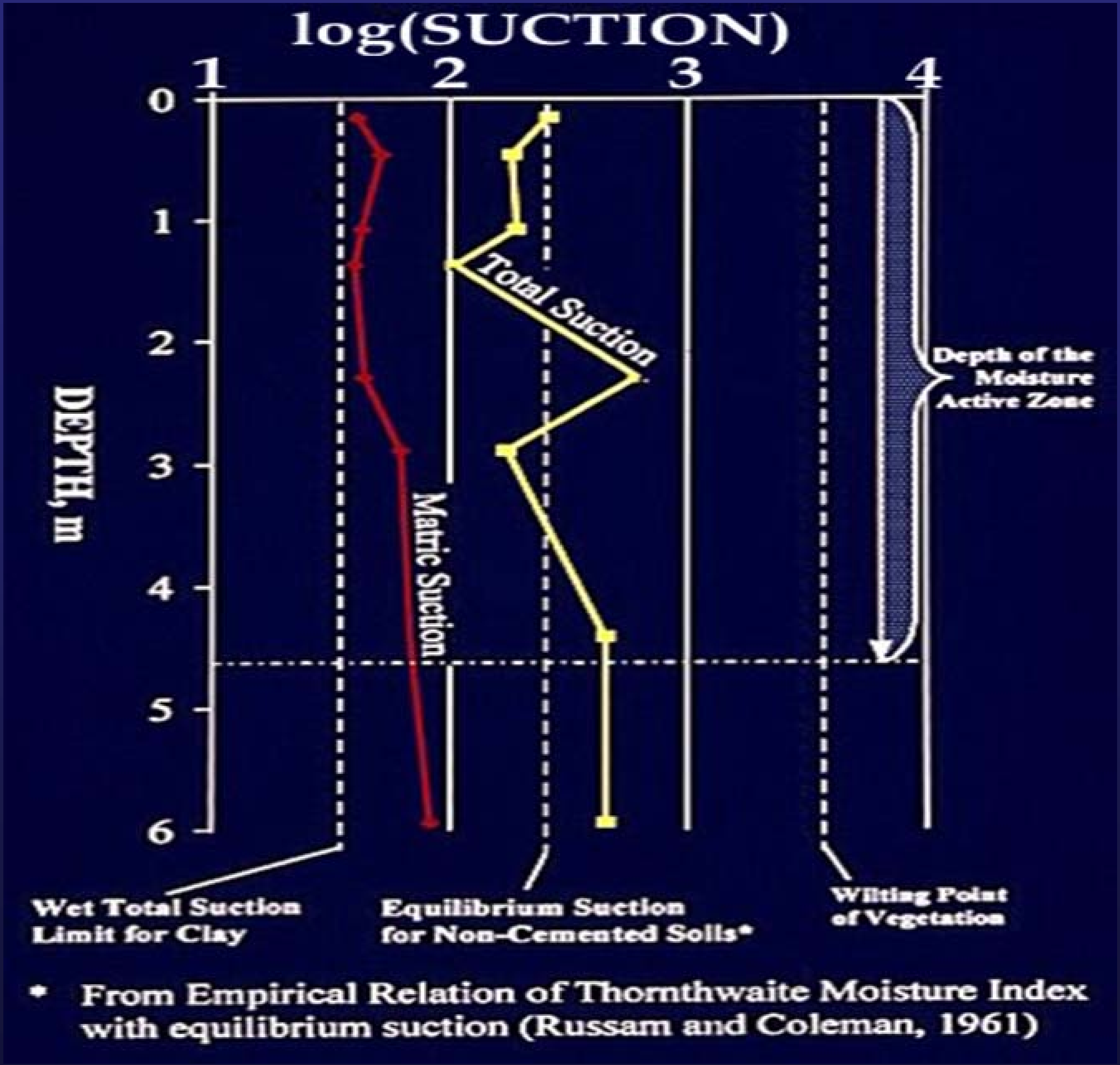

DESIGN ENVELOPES
Example
Soil Support Pattern
Worst Soil Support Patterns


Edge Moisture
Variation Distance
from Charts
e_m
Maximum
Differential
Movement
Slab
y_m
Depth of
Moisture
Active Zone
z_0
Tree
Root
Zone
Contours of
Equal Suction
Steady State
Horizontal Flow

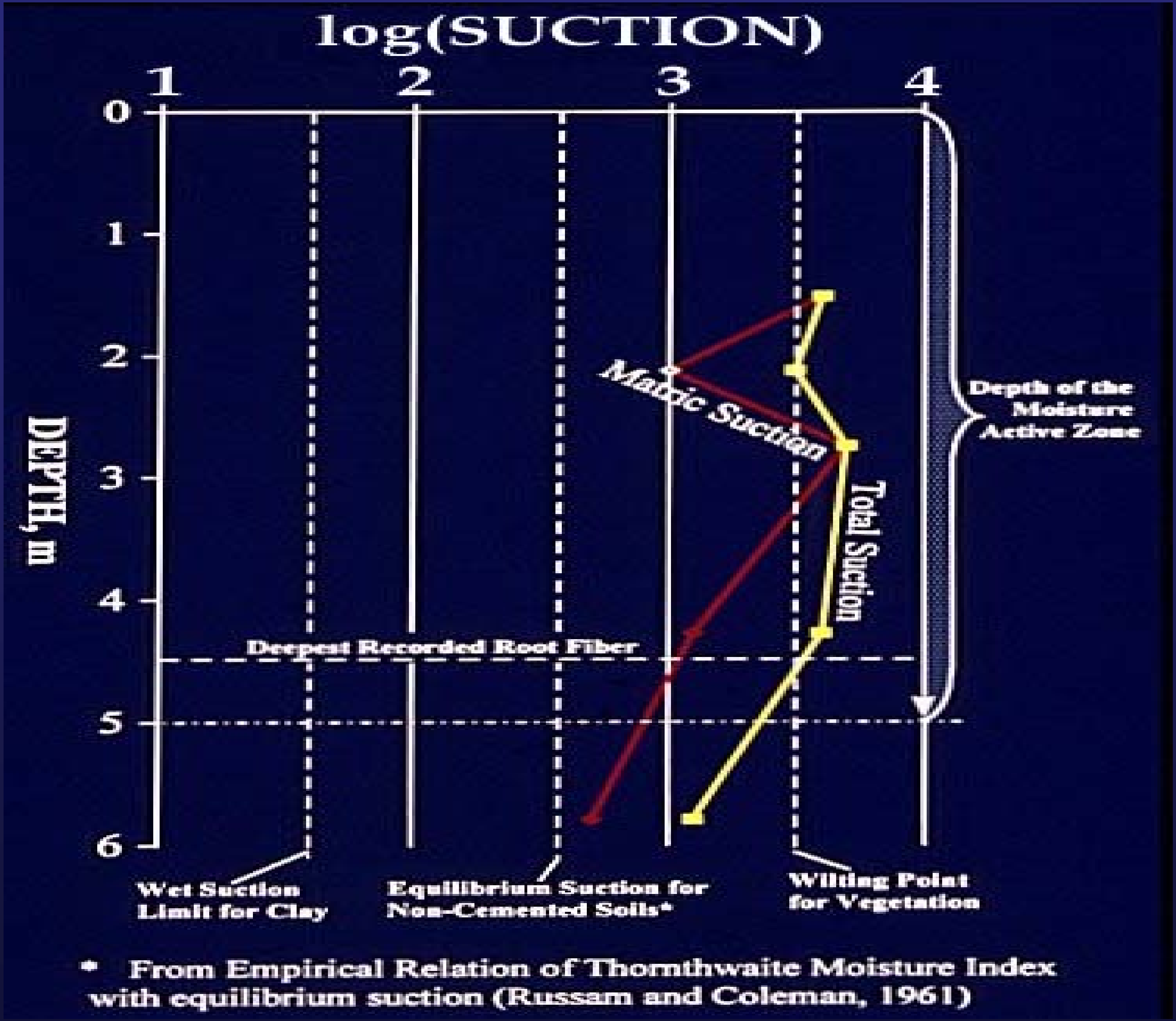

Edge Moisture
Variation Distance
from Charts
e m
Maximum
Differential
Movement
y m
Slab
Flower Bed
Depth of
Moisture
Active Zone
z 0
Contours of
Equal Suction
Steady State
Horizontal Flow

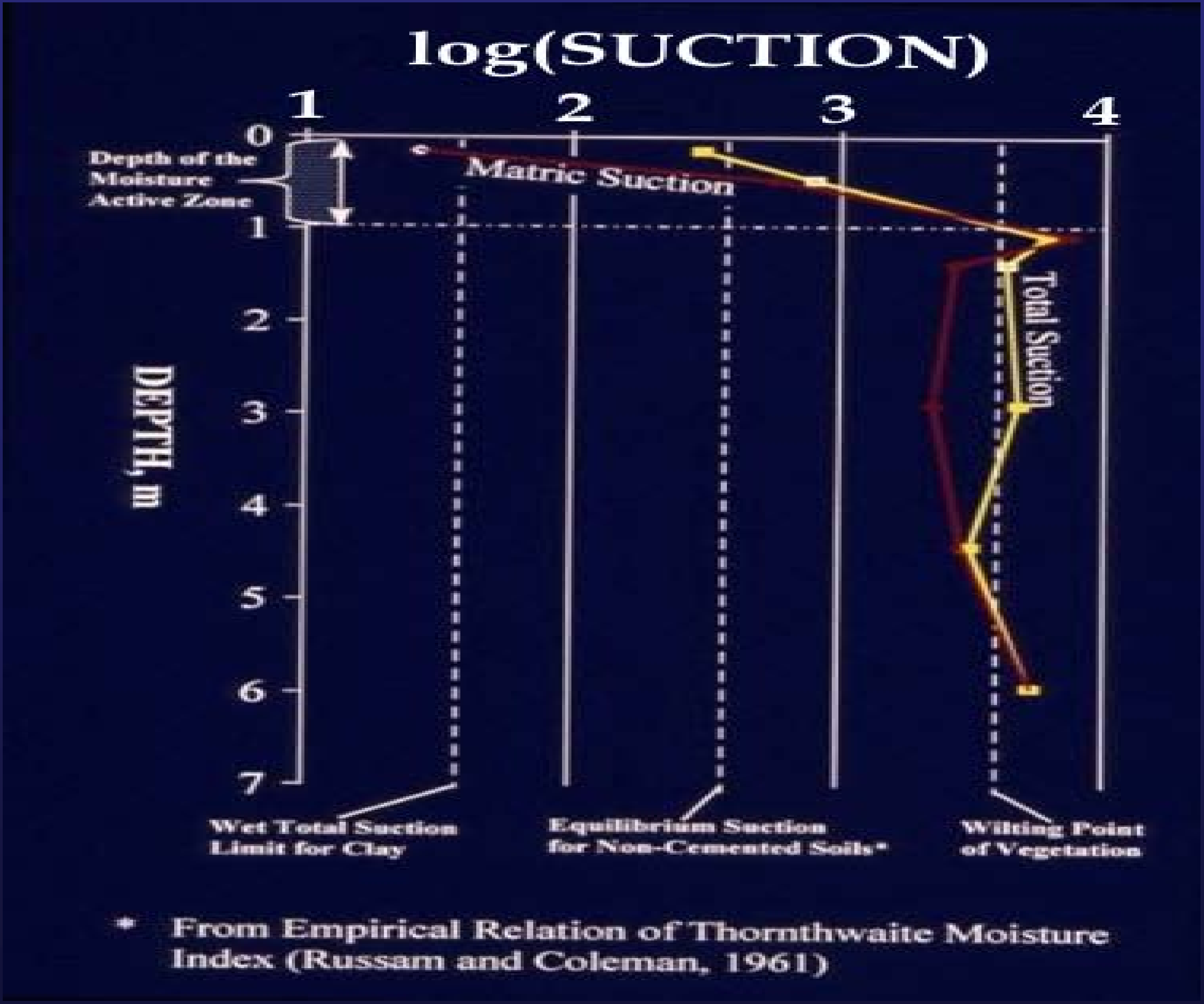

MOISTURE ACTIVE ZONE
MOISTURE INACTIVE ZONE

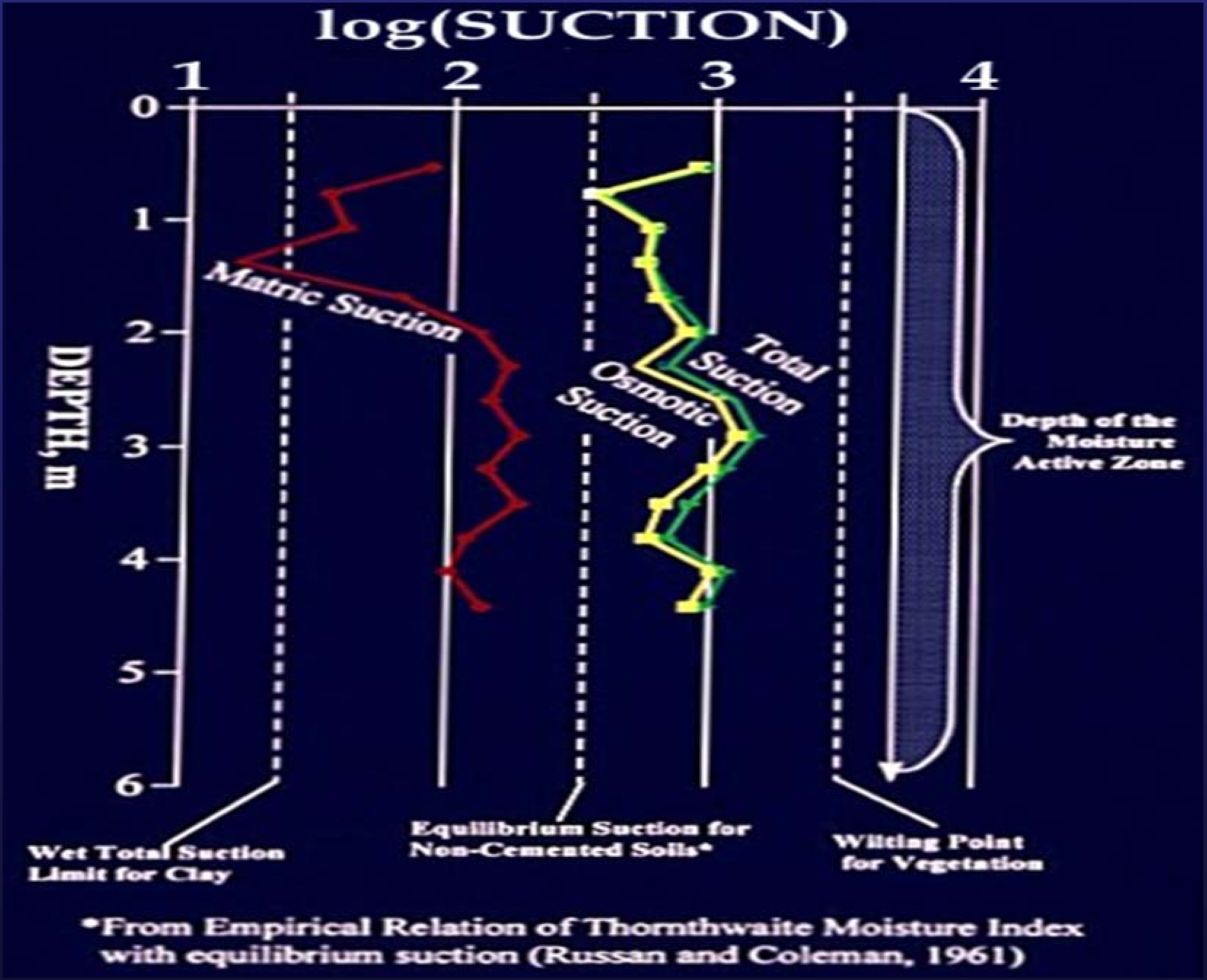

(-)
Suction
Ground Surface
Wet Season
Equilibrium
Dry Season
Depth



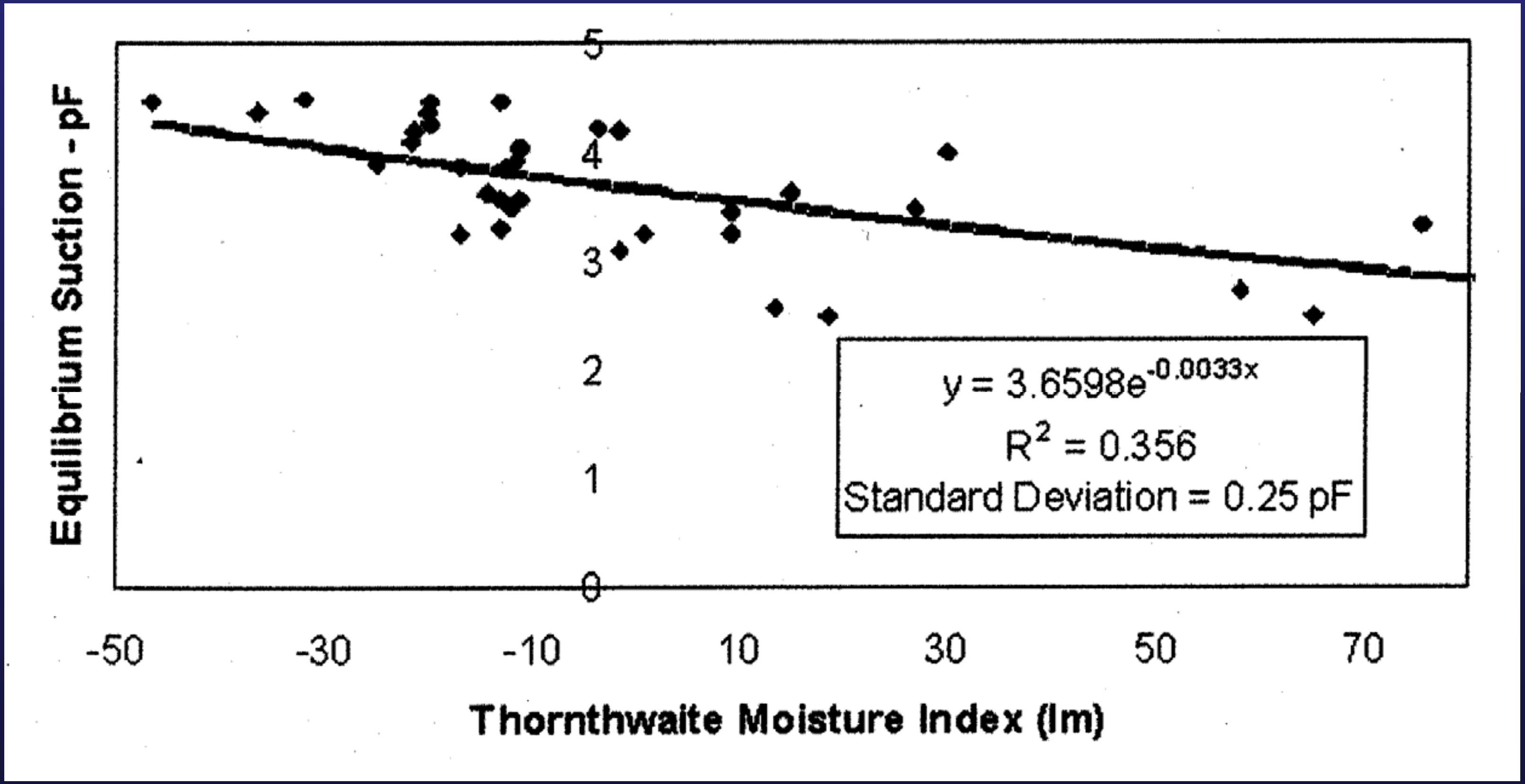
log(SUCTION)
1
2
3
4
0
1
2
3
4
5
6
DEPTH, m
Total Suction
Matric Suction
Depth of the Moisture Active Zone
Wet Total Suction Limit for Clay
Equilibrium Suction for Non-Cemented Soils*
Wilting Point of Vegetation
* From Empirical Relation of Thornthwaite Moisture Index with equilibrium suction (Russam and Coleman, 1961)

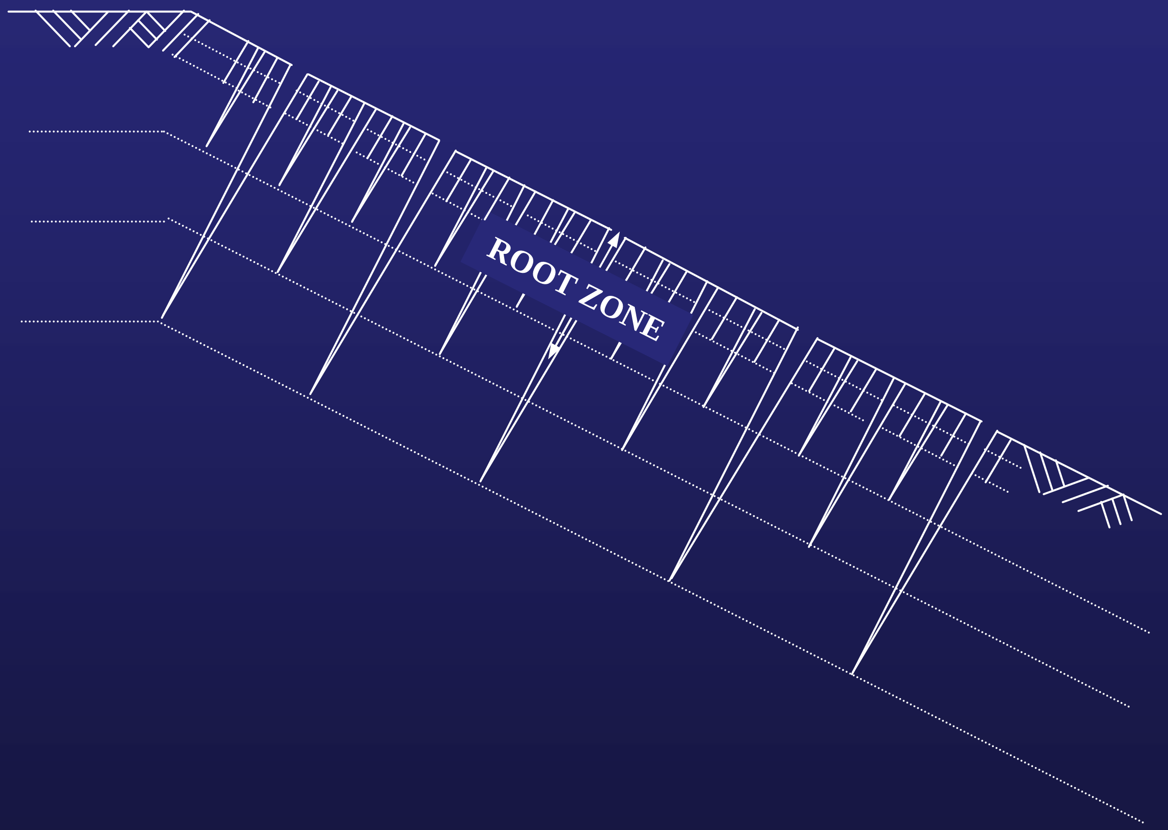

log(SUCTION)
1
2
3
4
0
1
2
3
4
5
6
DEPTH, m
Matric Suction
Total Suction
Depth of the Moisture Active Zone
Deepest Recorded Root Fiber
Wet Suction Limit for Clay
Equilibrium Suction for Non-Cemented Soils*
Wilting Point for Vegetation
* From Empirical Relation of Thornthwaite Moisture Index with equilibrium suction (Russam and Coleman, 1961)


log(SUCTION)
1
2
3
4
0
1
2
3
4
5
6
7
DEPTH, m
Depth of the
Moisture
Active Zone
Matric Suction
Total Suction
Wet Total Suction
Limit for Clay
Equilibrium Suction
for Non-Cemented Soils*
Wilting Point
of Vegetation
* From Empirical Relation of Thornthwaite Moisture
Index (Russam and Coleman, 1961)

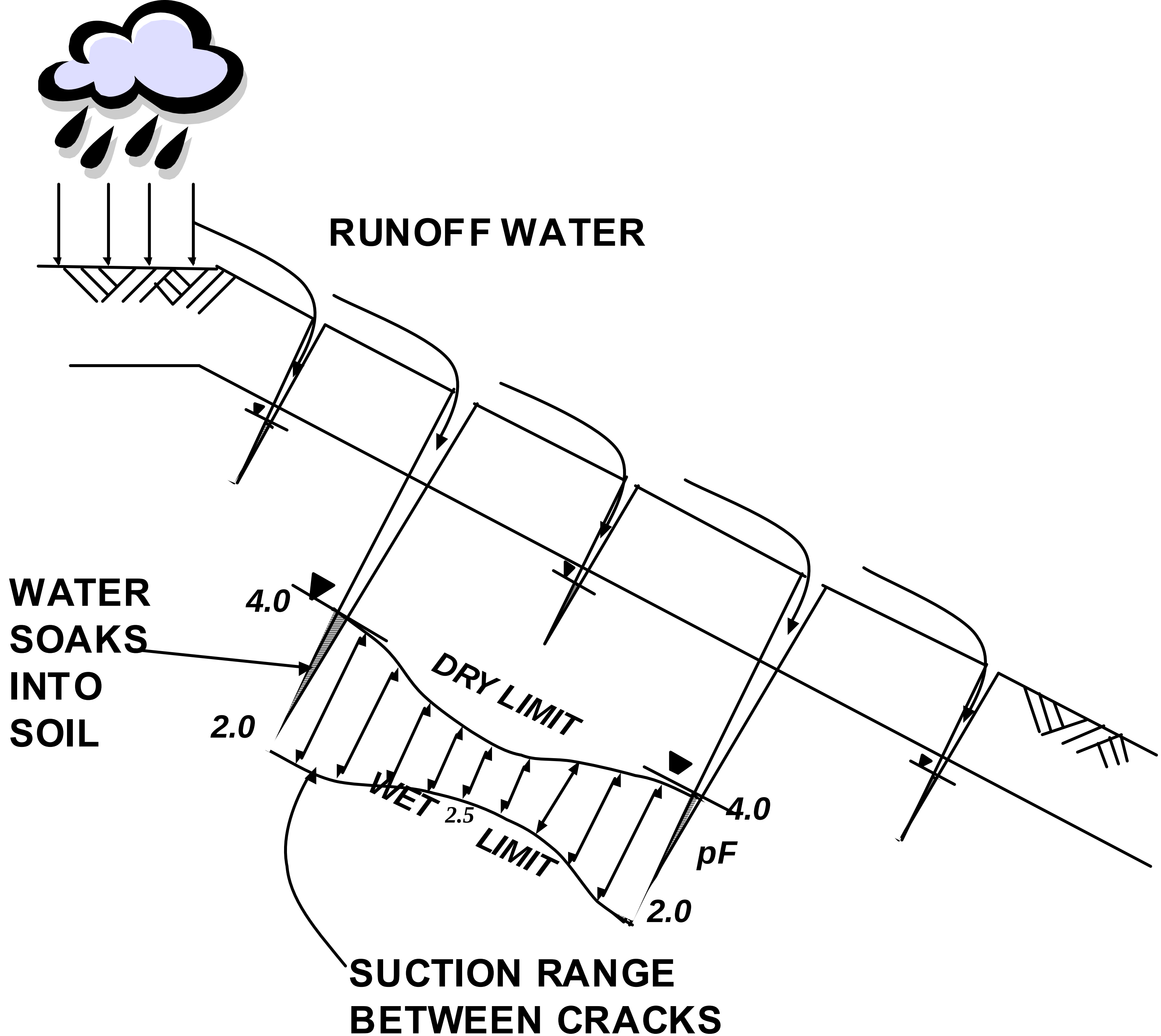

log(SUCTION)
1
2
3
4
0
1
2
3
4
5
6
DEPTH, m
Matric Suction
Total Suction
Osmotic Suction
Depth of the Moisture Active Zone
Wet Total Suction Limit for Clay
Equilibrium Suction for Non-Cemented Soils*
Wilting Point for Vegetation
*From Empirical Relation of Thornthwaite Moisture Index with equilibrium suction (Russan and Coleman, 1961)

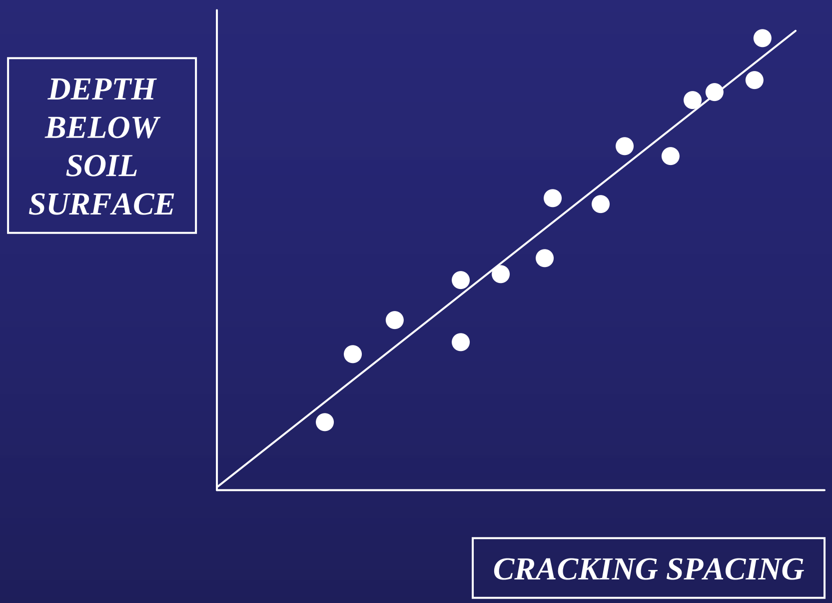
Equilibrium Soil Suction vs. TMI





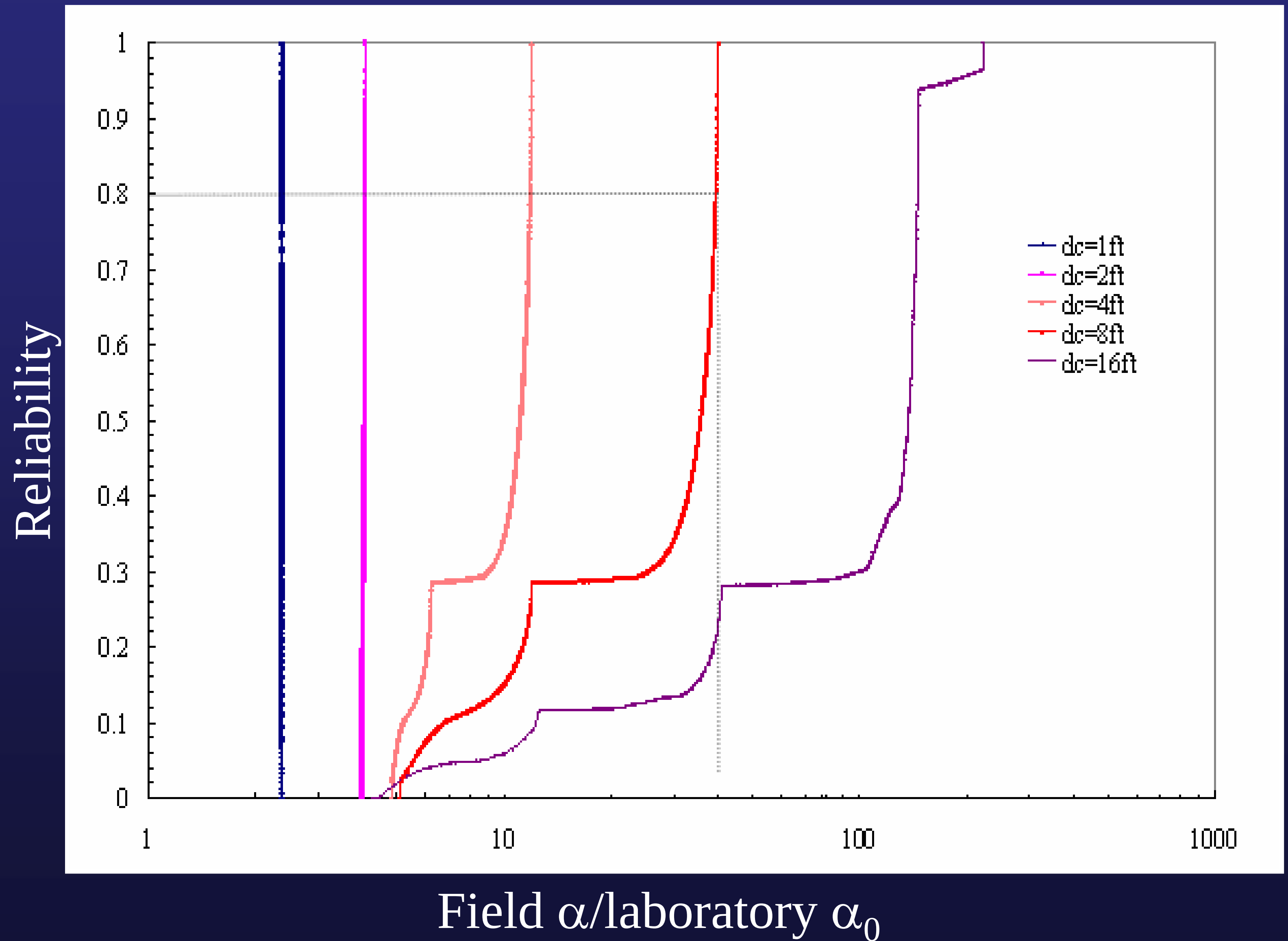
Crack Spacing Gets Larger with Depth


RUNOFF WATER
WATER SOAKS INTO SOIL
4.0
2.0
DRY LIMIT
WET 2.5 LIMIT
4.0
pF
2.0
SUCTION RANGE BETWEEN CRACKS



SOURCE : MICHAEL KNIGHT
PH. D. DISSERTATATION, GEOLOGY
UNIVERSITY OF MELBOURNE (AUSTRALIA)
1972

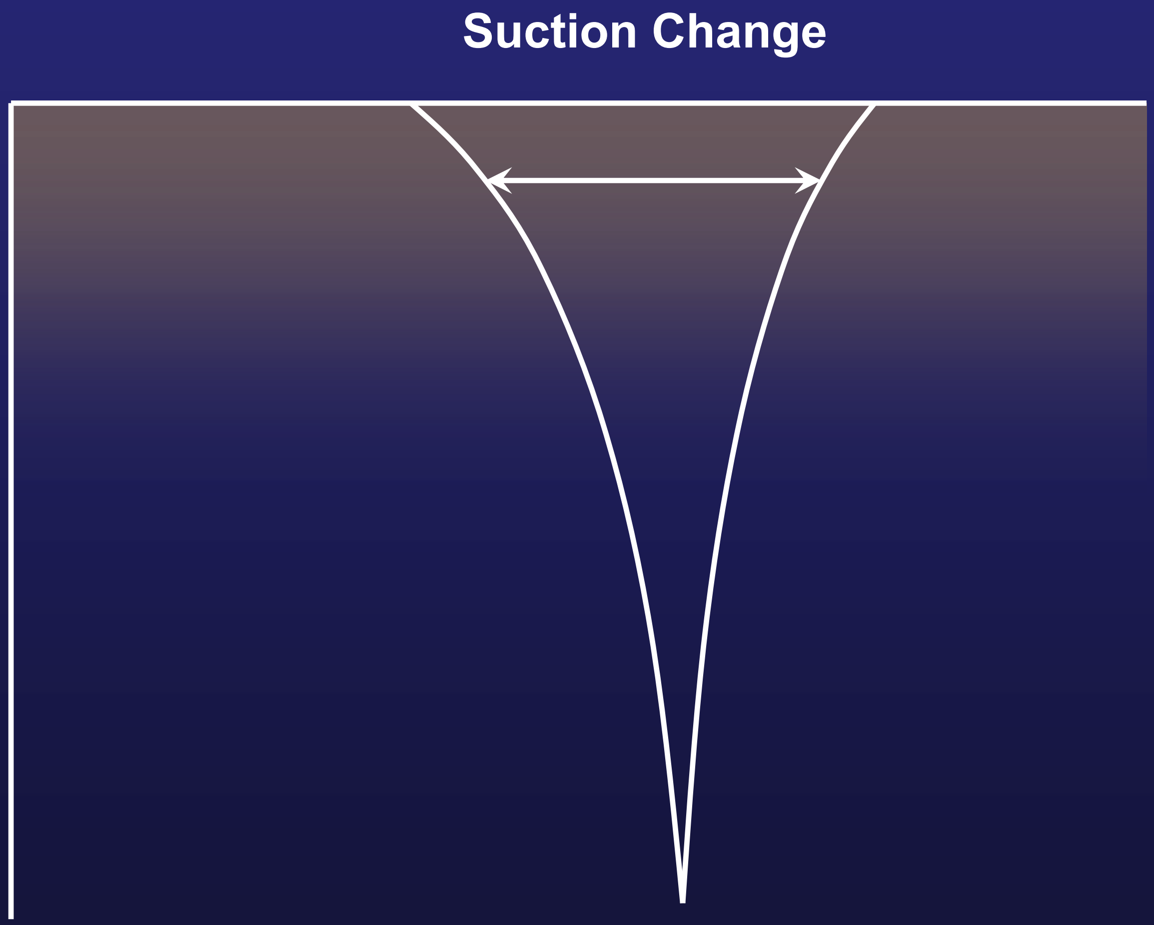
Field to laboratory diffusion coefficient ratio (Cont'd)



Drilled Pier Design

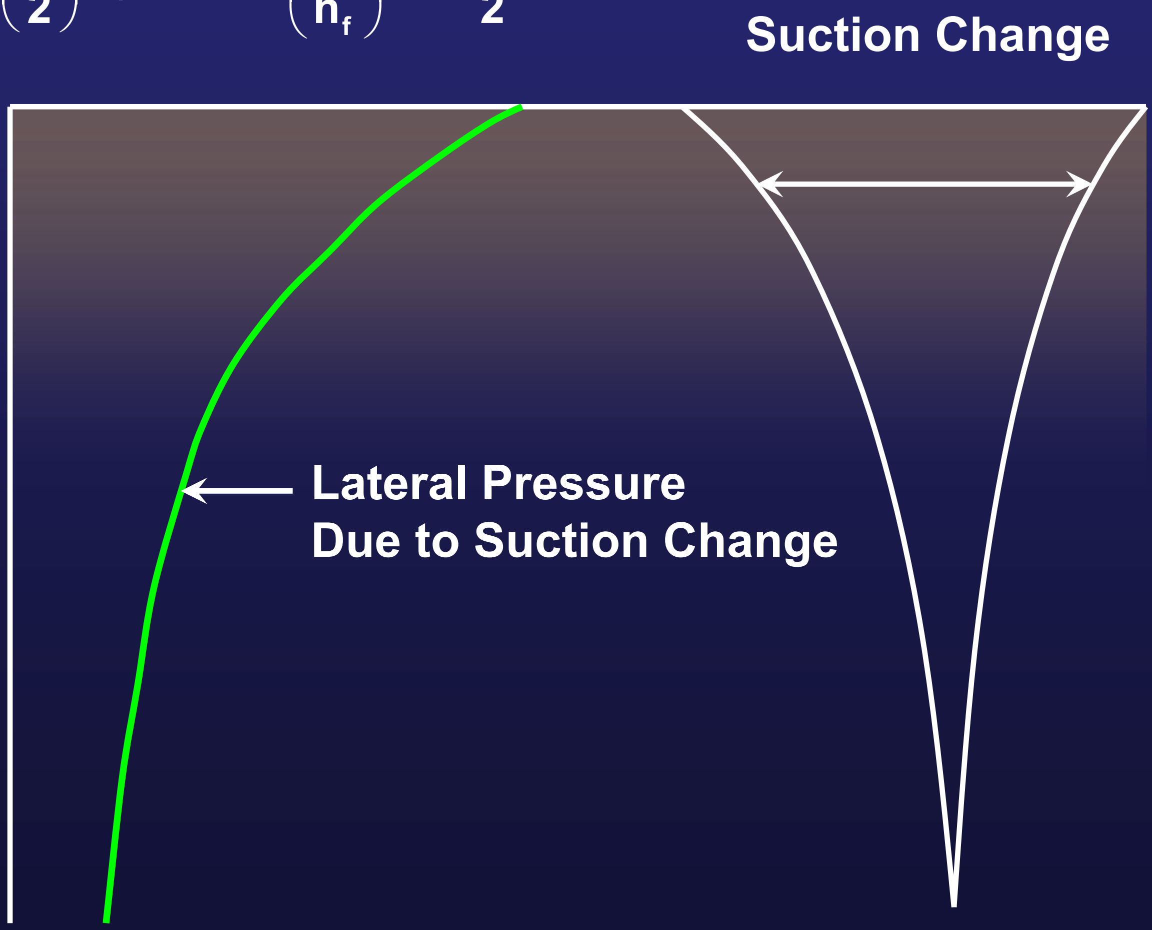
Retaining Wall Design

Lateral Earth Pressure Concept (1/5)

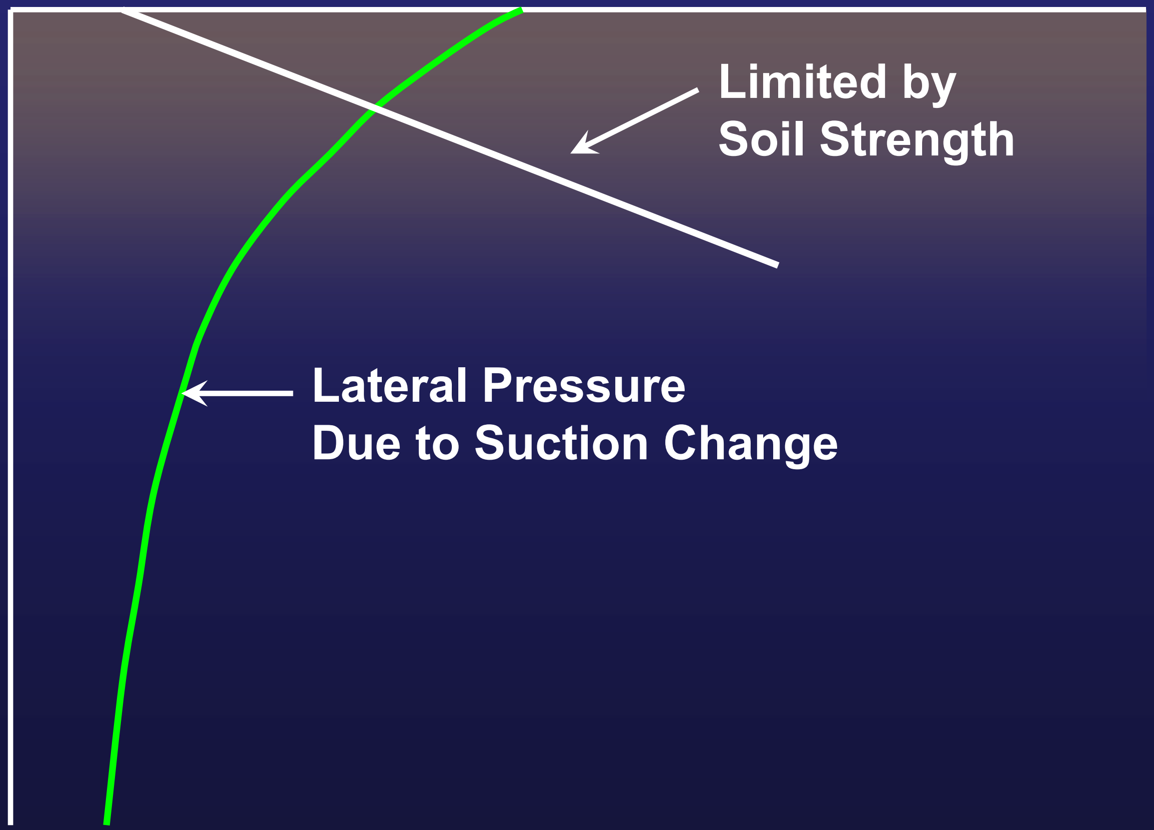


Lateral Earth Pressure Concept (2/5)

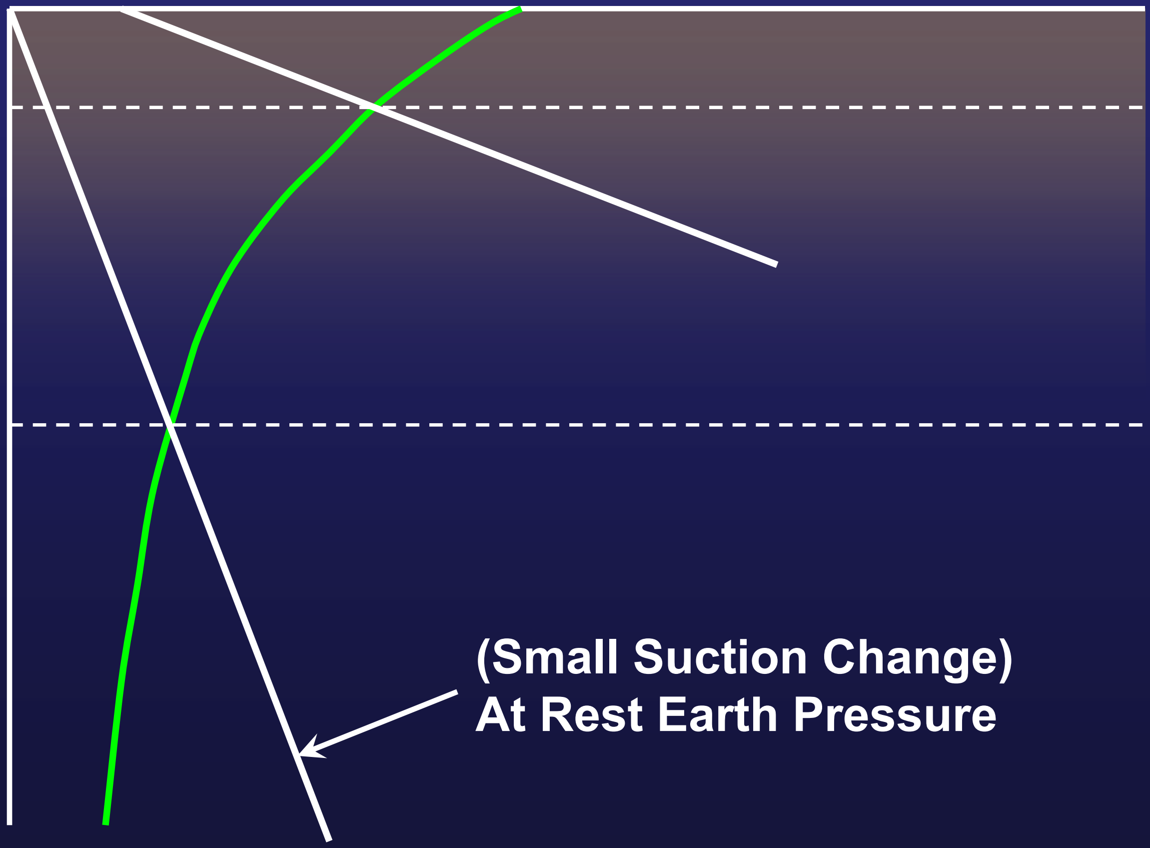
$$\sigma_h = k_0 \gamma_t z = \left(\frac{3}{2}\right) \sigma_i 10^{-\frac{2\varepsilon_h}{\gamma_\sigma (1-f)}} \left(\frac{h_i}{h_f}\right)^{\frac{\gamma_h}{\gamma_\sigma}} - \frac{\gamma_t z}{2}$$



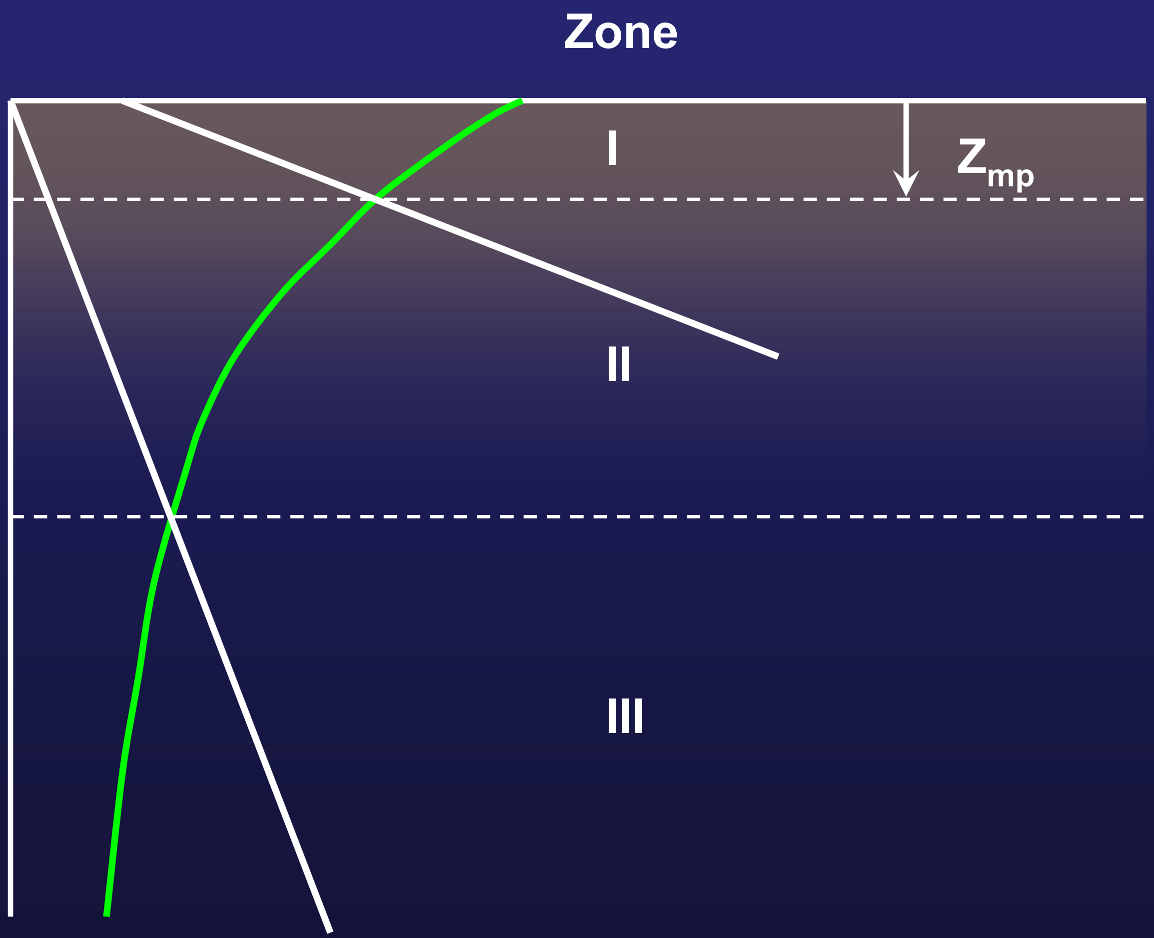
Lateral Earth Pressure Concept (3/5)



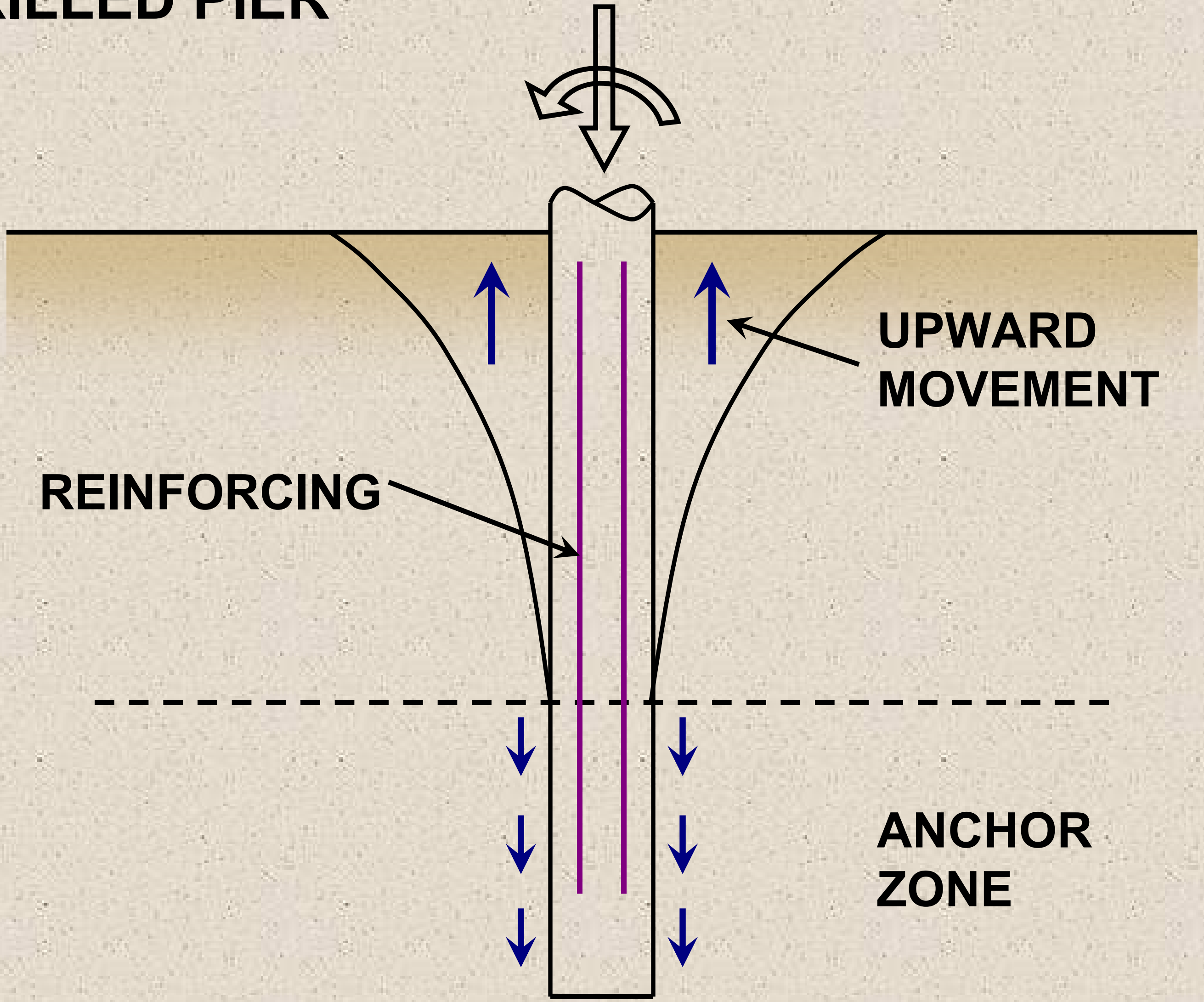
Lateral Earth Pressure Concept (4/5)

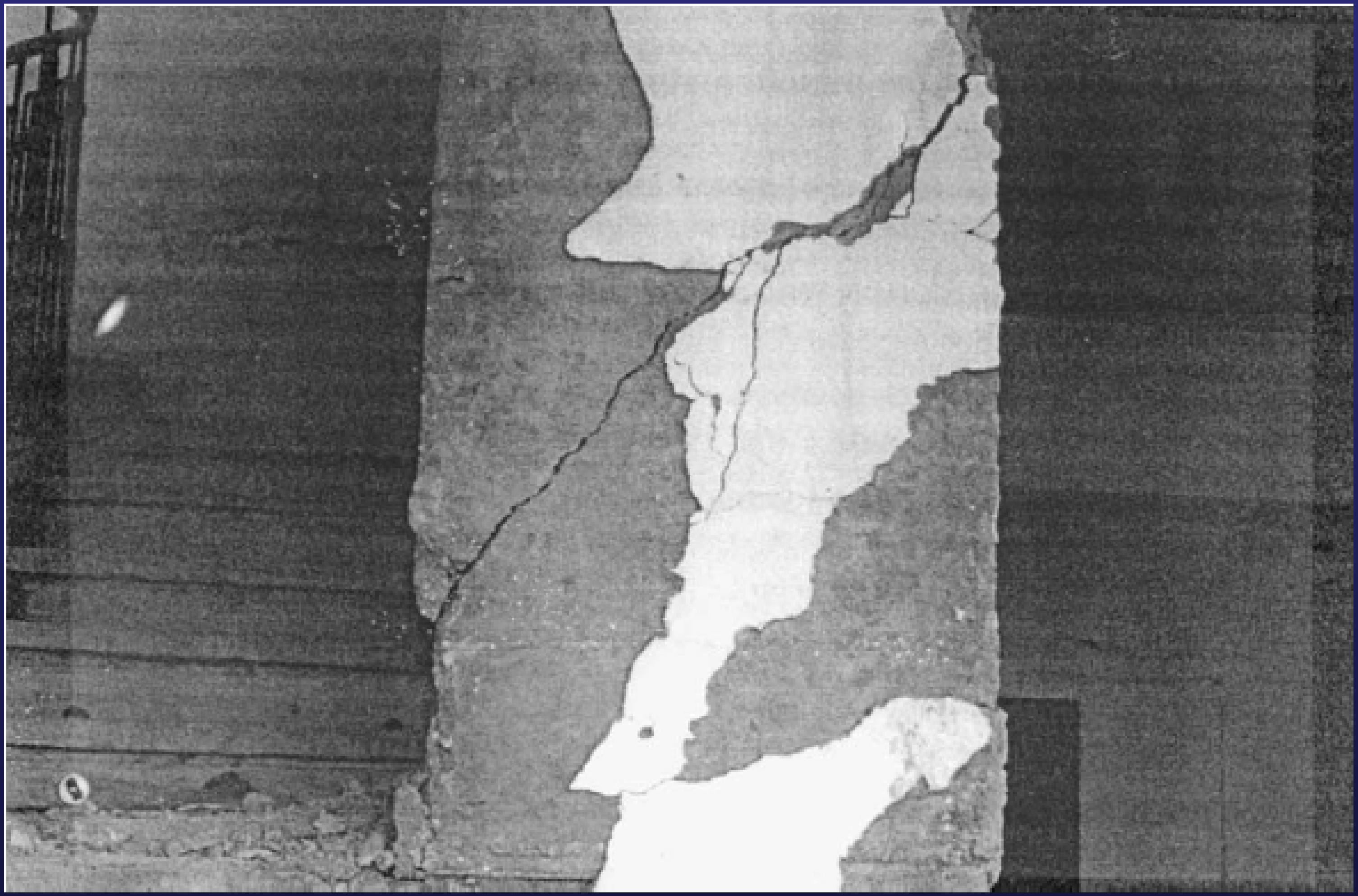


Lateral Earth Pressure Concept (5/5)



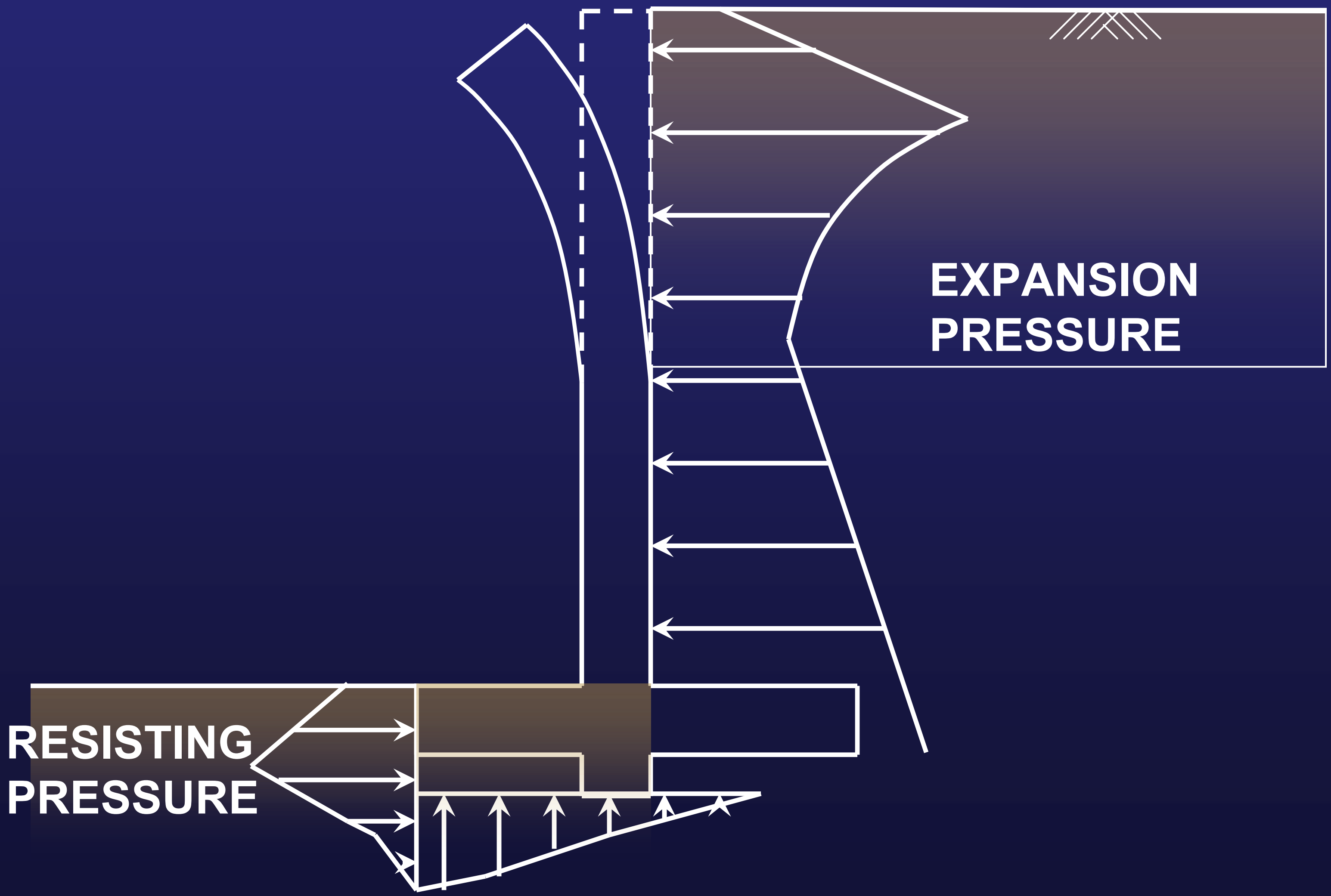
DRILLED PIER

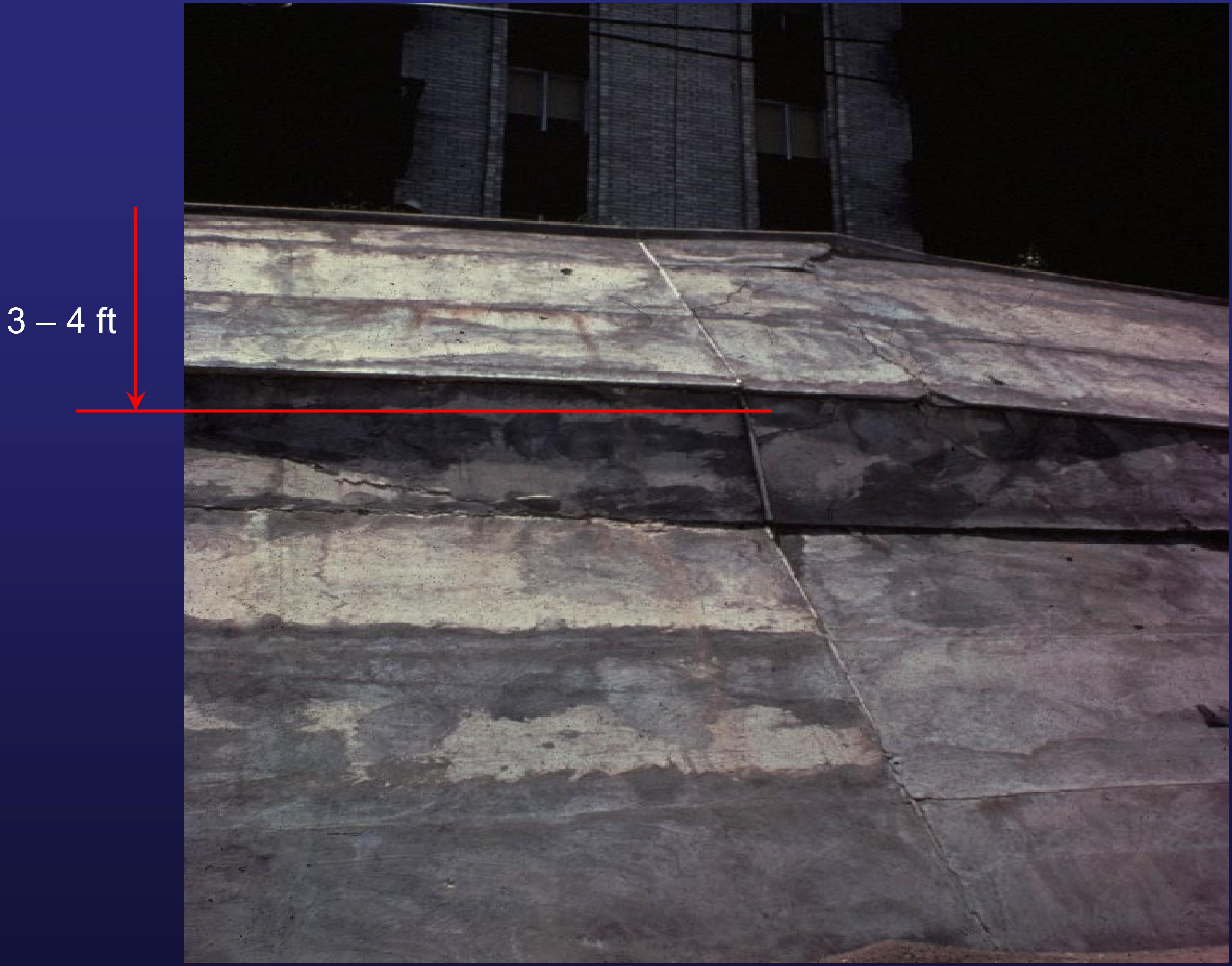




Severe damage to a reinforced concrete columns due to differential heave, in Saudi Arabia (Al-Shamrani and Dhowian, 2003)

Retaining Walls



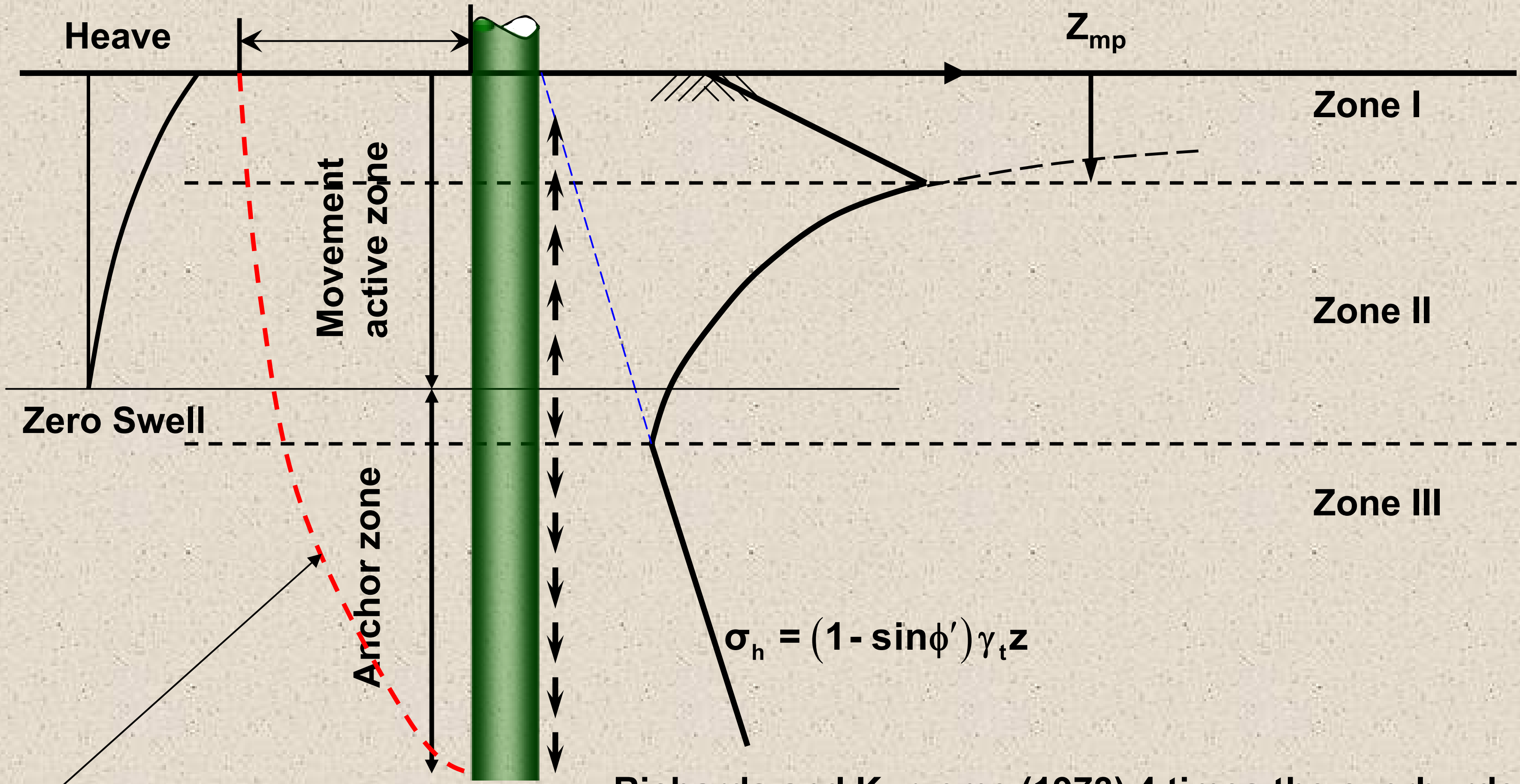

3 – 4 ft

Horizontal Earth Pressure in Expansive Soils

Horizontal Swelling Pressure Model

Z_{mp} = 3 - 5 ft
Joshi and Katti (1980); Komornik (1962); Brackely and Sanders (1992); Symons et al. (1989)

$z_{mp}\tan\left(45+\phi'/2\right) = 5 - 7\ \text{ft}$



Horizontal Active zone

$$XZ_i = z_{mp}\tan\left(45+\varphi'/2\right)\left[1-\left(\frac{z}{H}\right)^2\right]$$

Richards and Kurzeme (1973) 4 times the overburden
Joshi and Katti (1980) 42 psi @ 3 ft, lab
Komornik (1962) 55 psi @ 3 ft, lab
Brackely and Sanders (1992) 12 psi @ 3 ft, field

Williams and Jennings (1973)

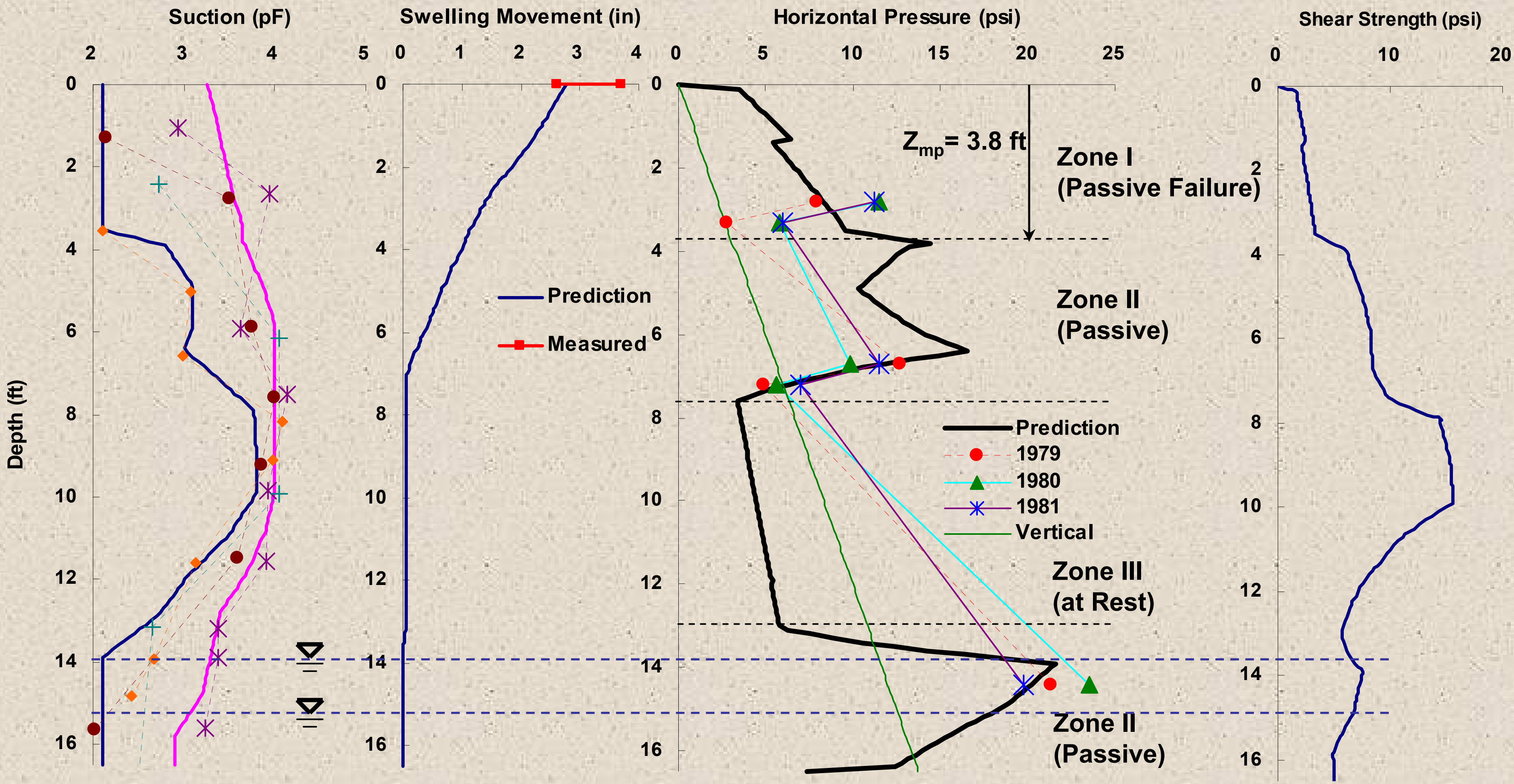
- **Fissures caused by a *passive failure* of the soil resulting from the horizontal pressure during seasonal swelling of the clay**

- **Mean angle of the fissure to the horizontal = 43 degree**
- **Silckensides occurs in soil which has PI >30, -2μm>30**

Leeuhof test site at Vereeniging, South Africa

Brackely and Sanders (1992)

Natural horizontal pressures measured in field



Seasonal range of suction
(In situ psychrometers)

Maximum pressures measured
at four depths in 1979,1980,1981
(In situ pressure cells)

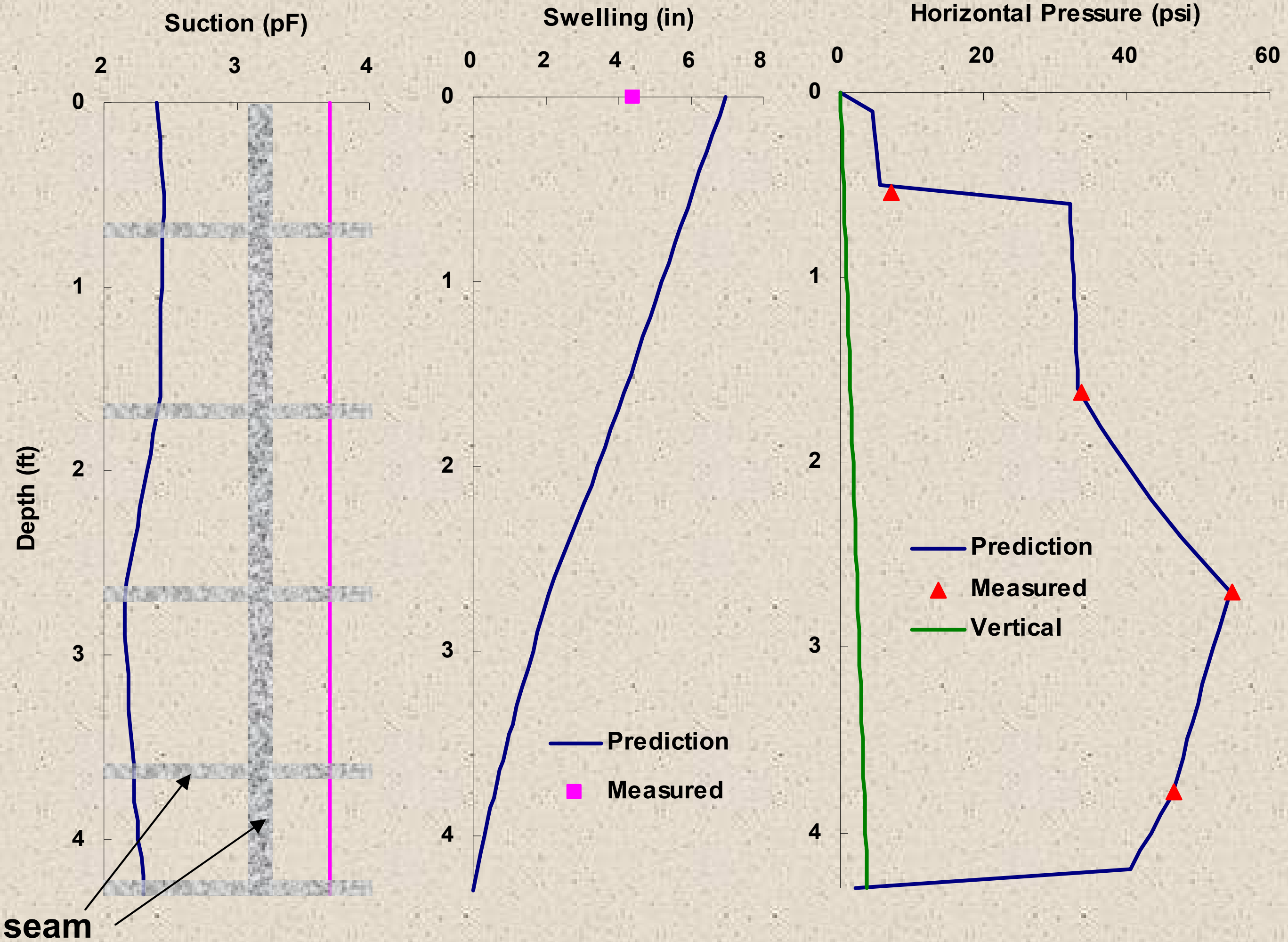
Komornik (1962)

Measured horizontal pressures in the large scale pile test

Soil Properties

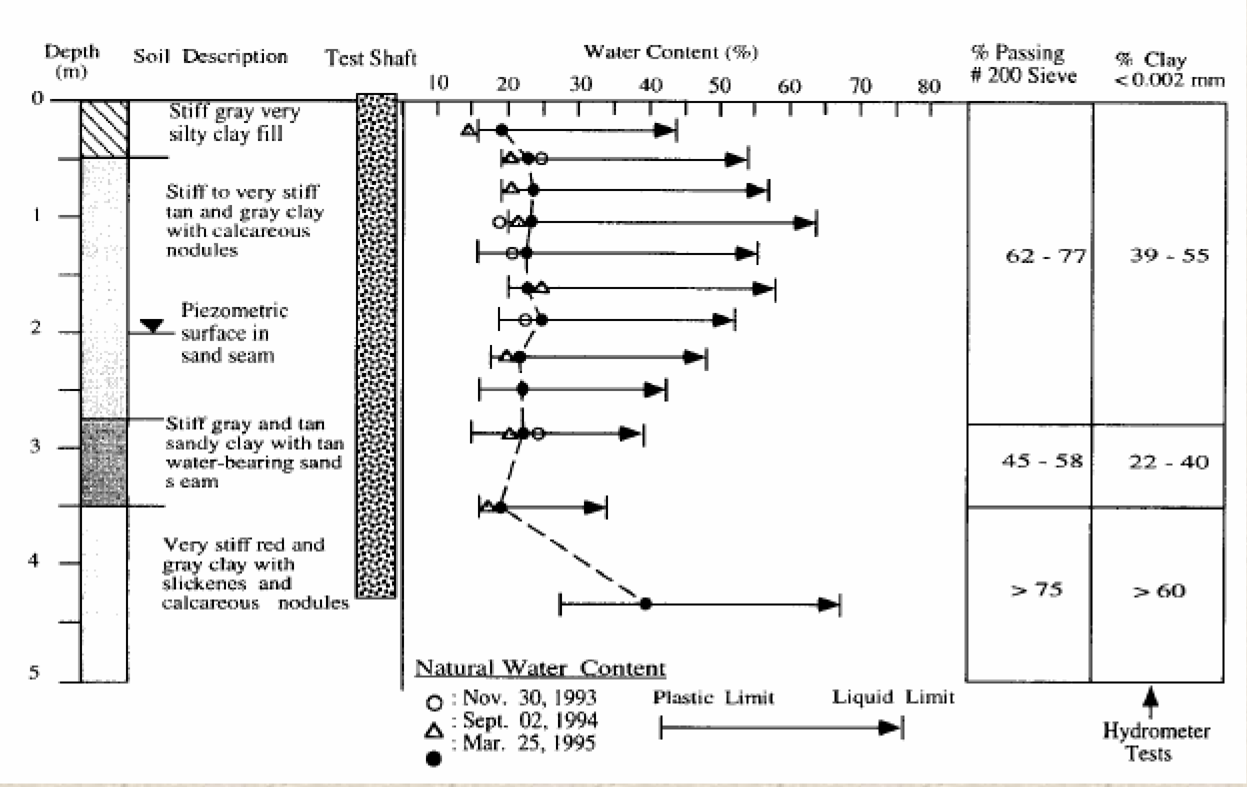
LL	76 %
PI	48 %
#200	90 %
-2μm	62 %

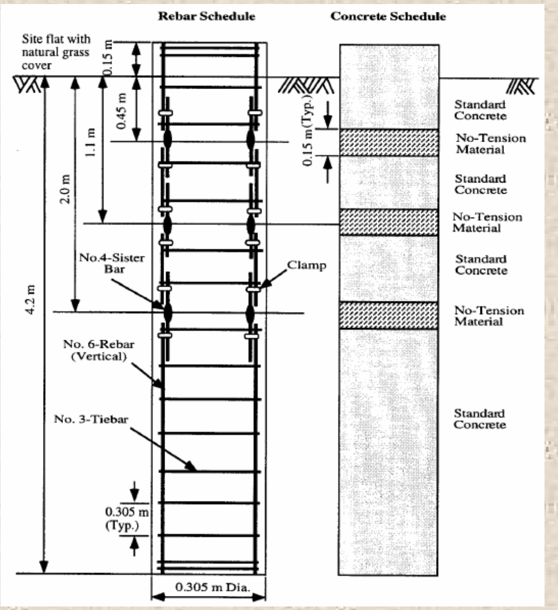
Site Kibbutz Mizra, Israel



Kim and O'Neill (1998)

Axial behavior of the pier

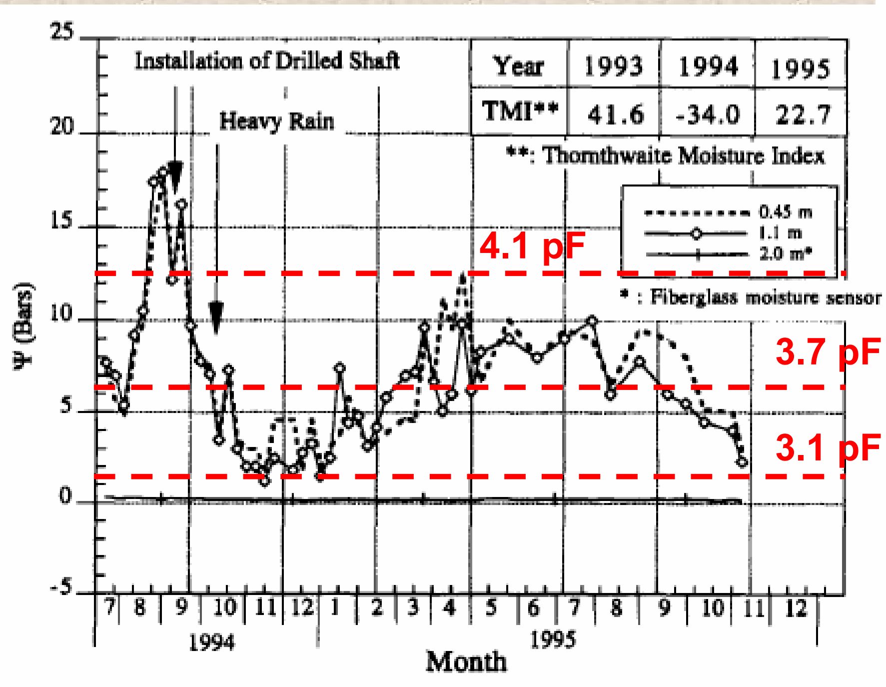




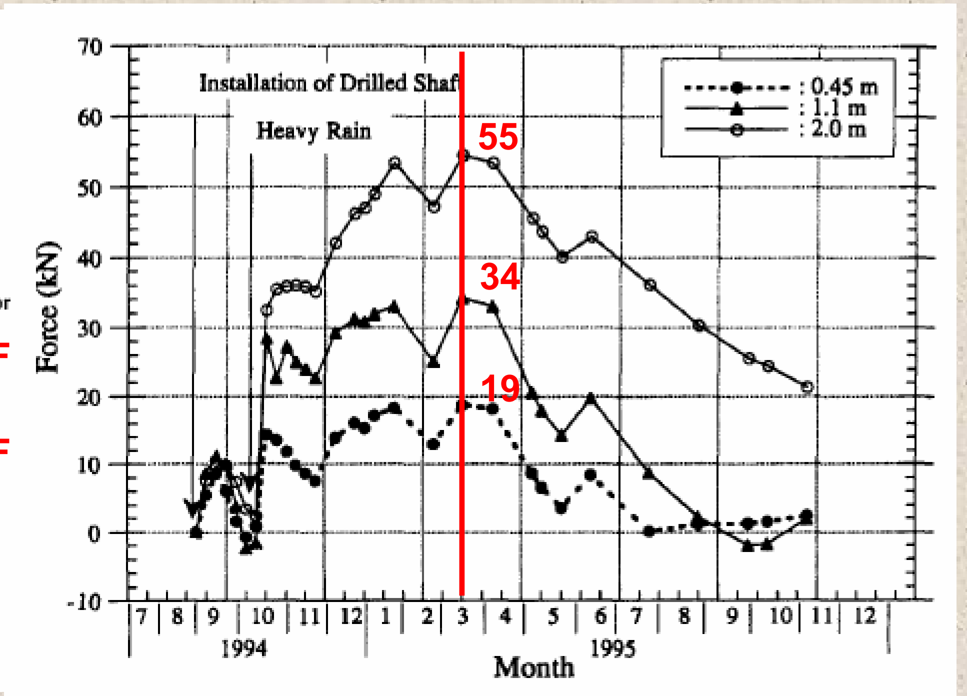
Test Site Stratigraphy (NGES-UH)

Schedule of Rebar and Concrete in Drilled Shaft

Kim and O'Neill (1998)
Axial behavior of the pier

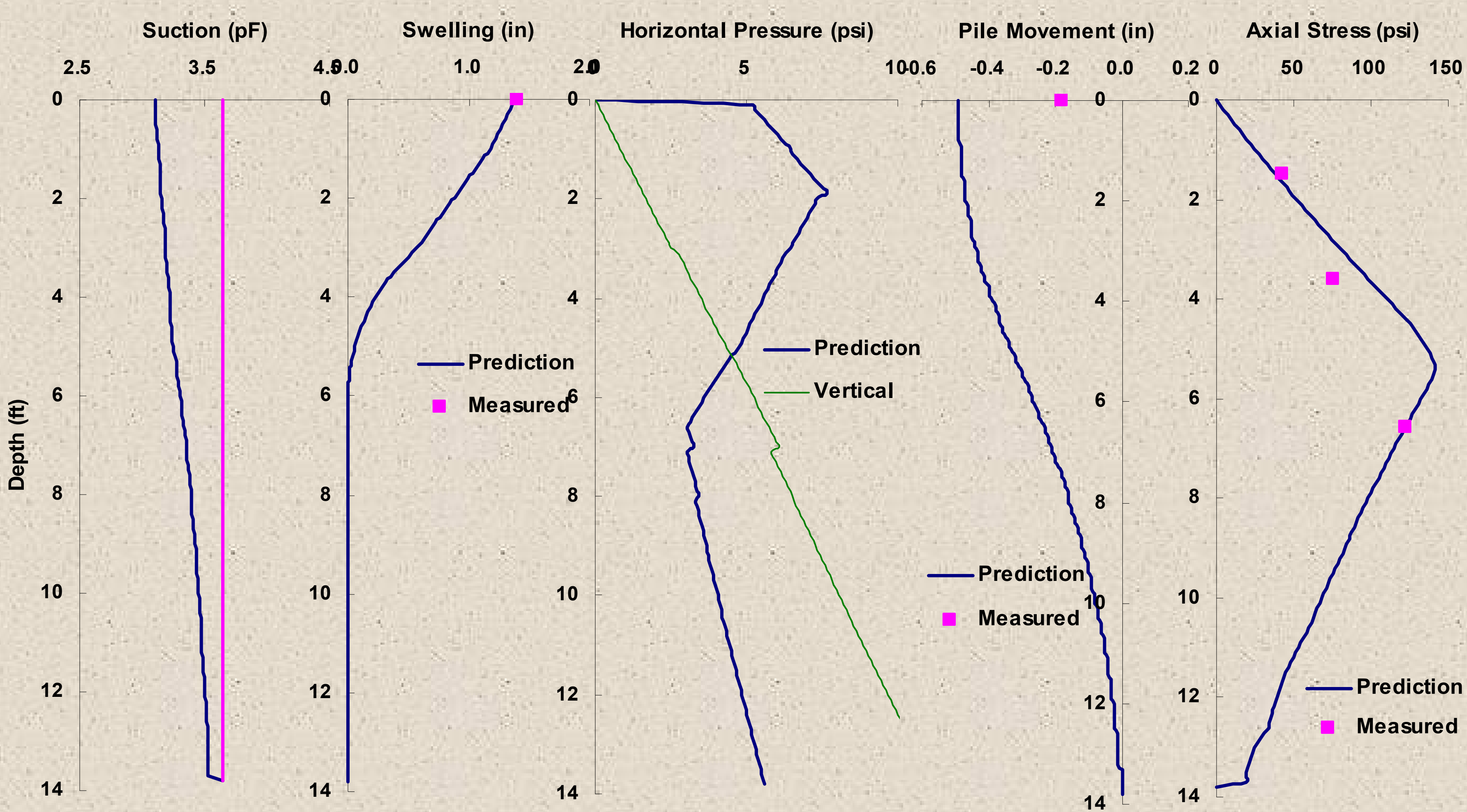


Bar versus Time(1 bar=100 kPa)

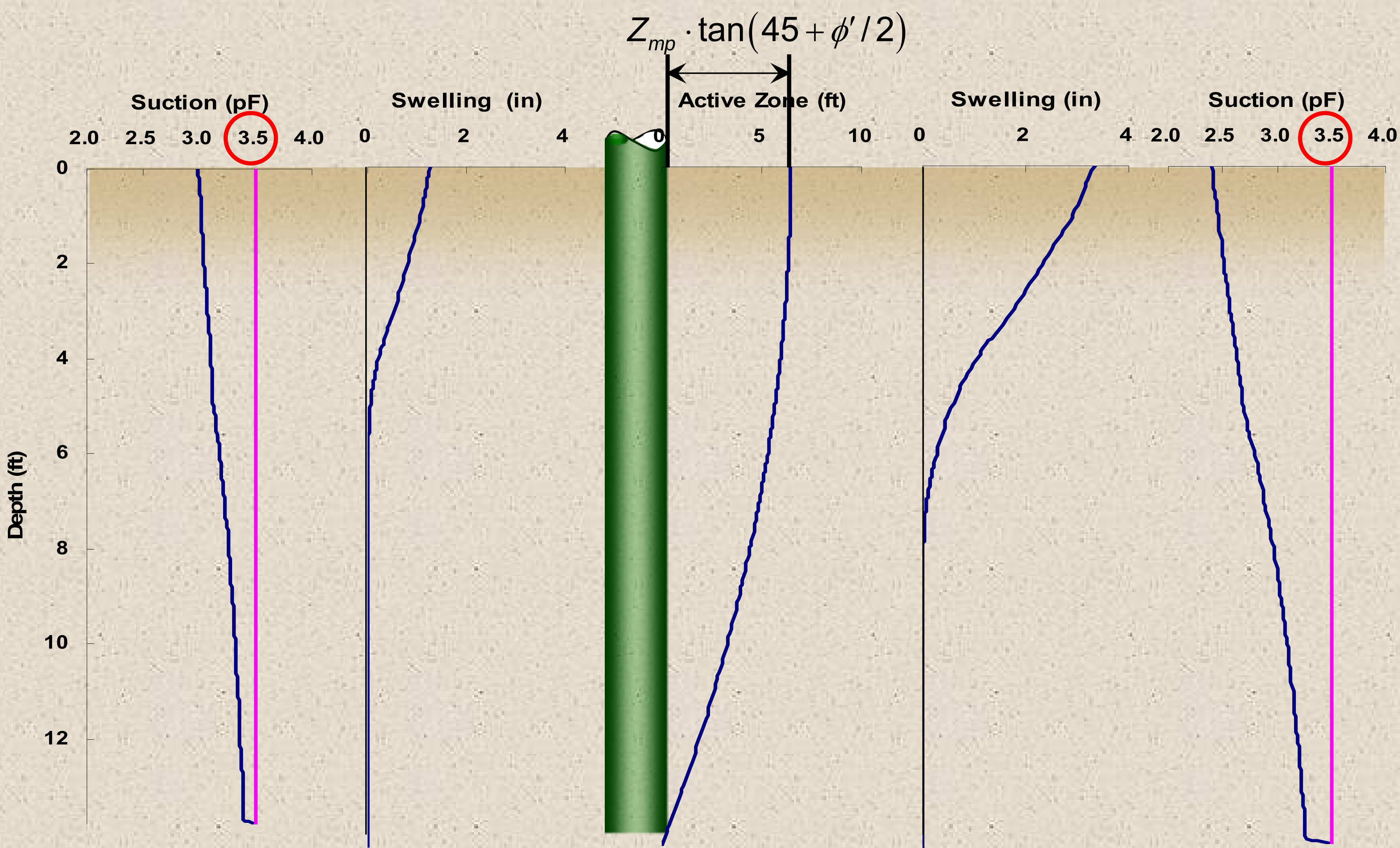


Uplift Force versus Time

Kim and O'Neill (1998)
Axial behavior of the pier

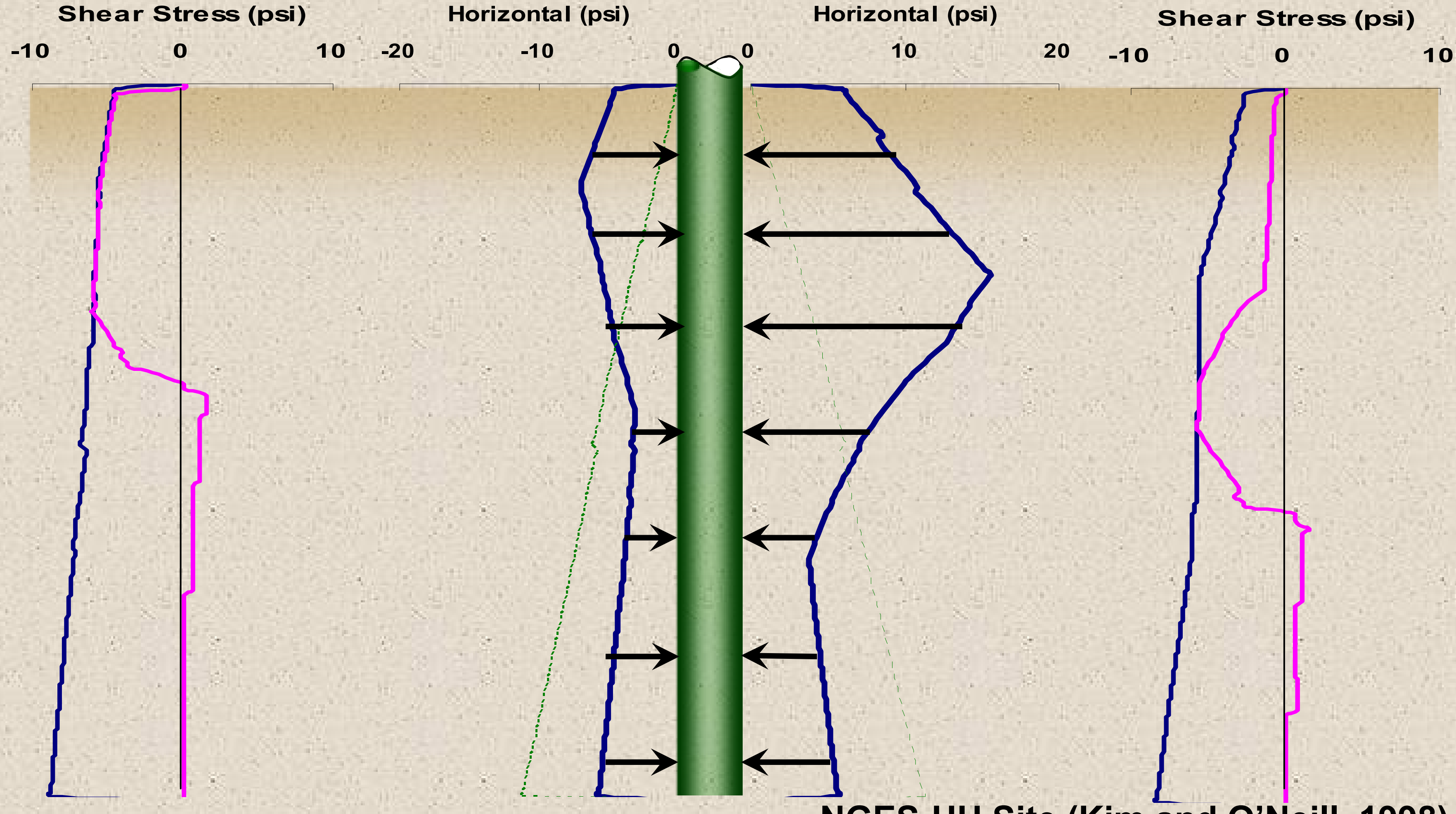


Case Study of Bending Behavior of the Pier
Uneven Wetting with Same Initial Condition



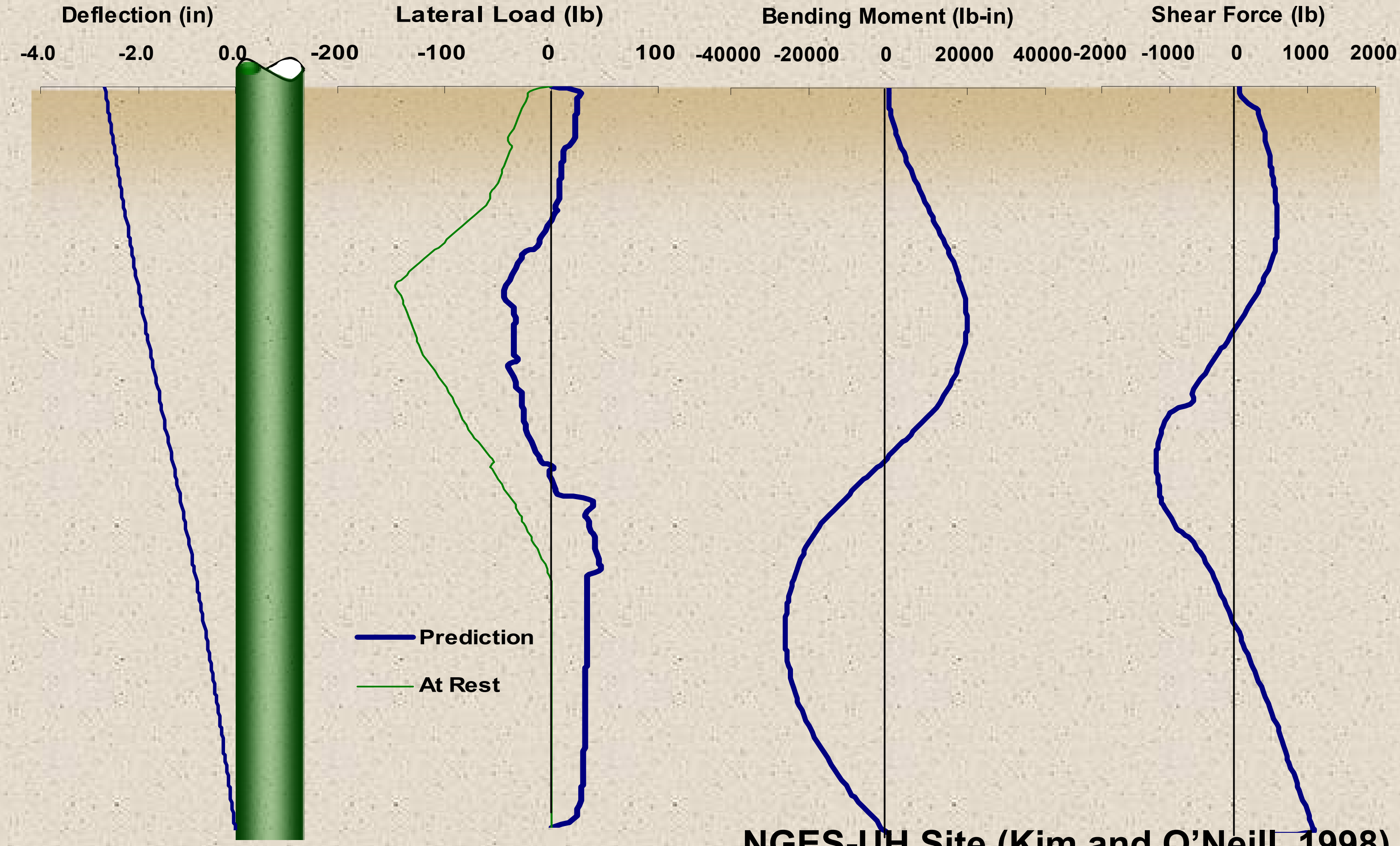
NGES-UH Site (Kim and O'Neill, 1998)

Case Study of Bending Behavior of the Pier
Uneven Wetting with Same Initial Condition



NGES-UH Site (Kim and O'Neill, 1998)

Case Study of Bending Behavior of the Pier
Uneven Wetting with Same Initial Condition



NGES-UH Site (Kim and O'Neill, 1998)

Retaining Wall Design

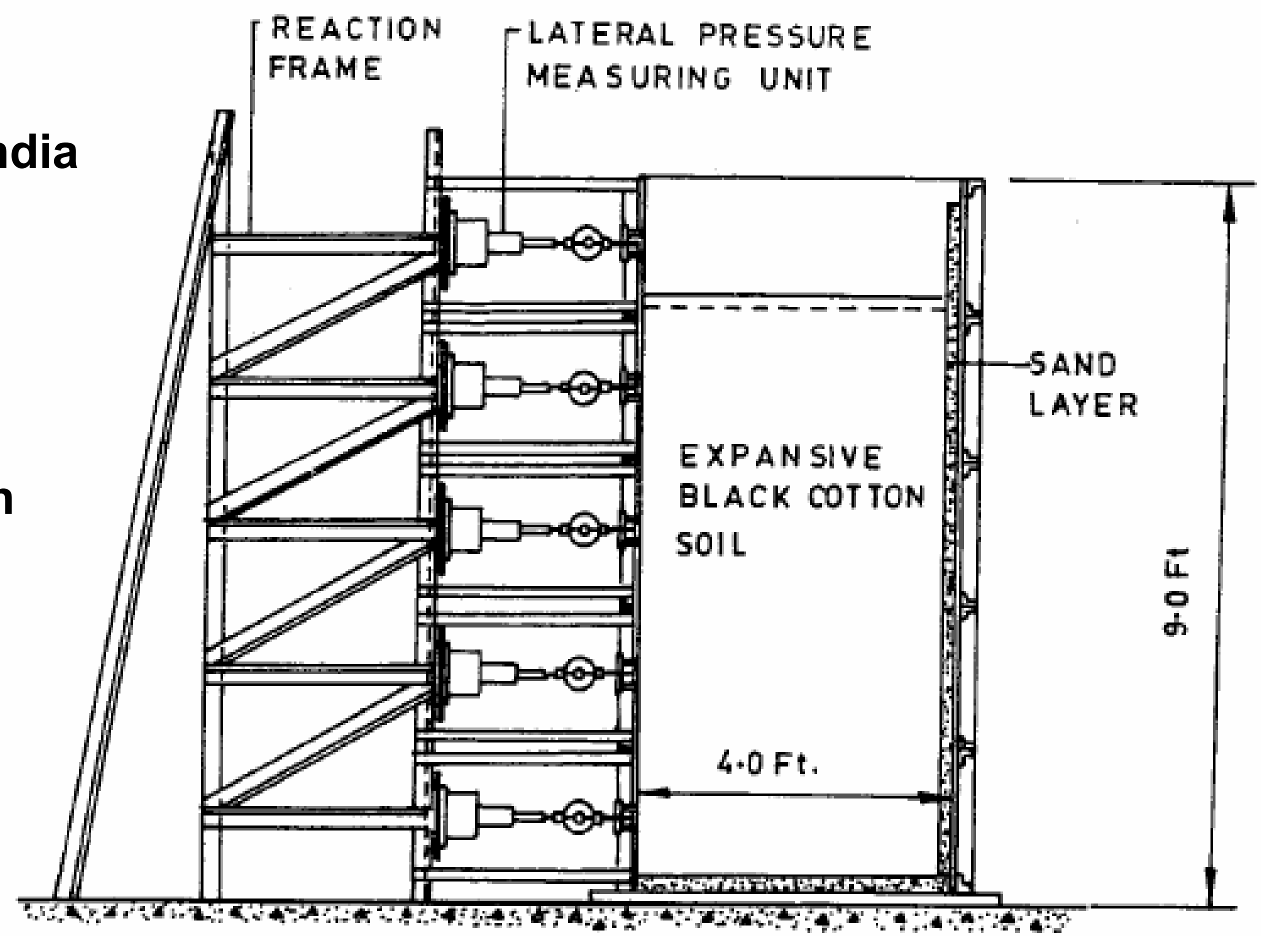
Katti et al. (1979)

Measured horizontal pressures in the large scale retaining wall test

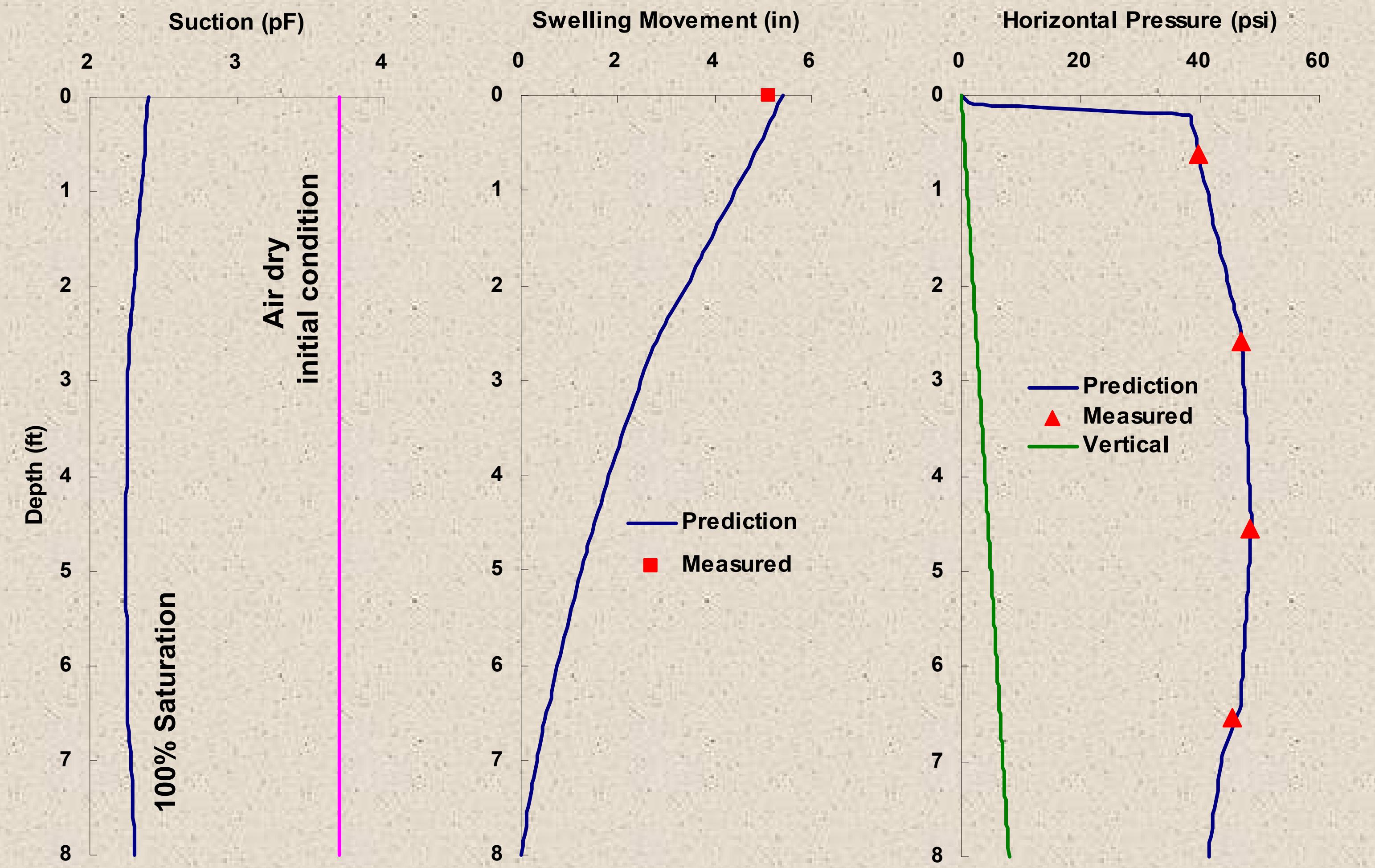
Black cotton soil, India

LL	**81.5 %**
PI	**38.3 %**
#200	**96.0 %**
-2μm	**56.0 %**

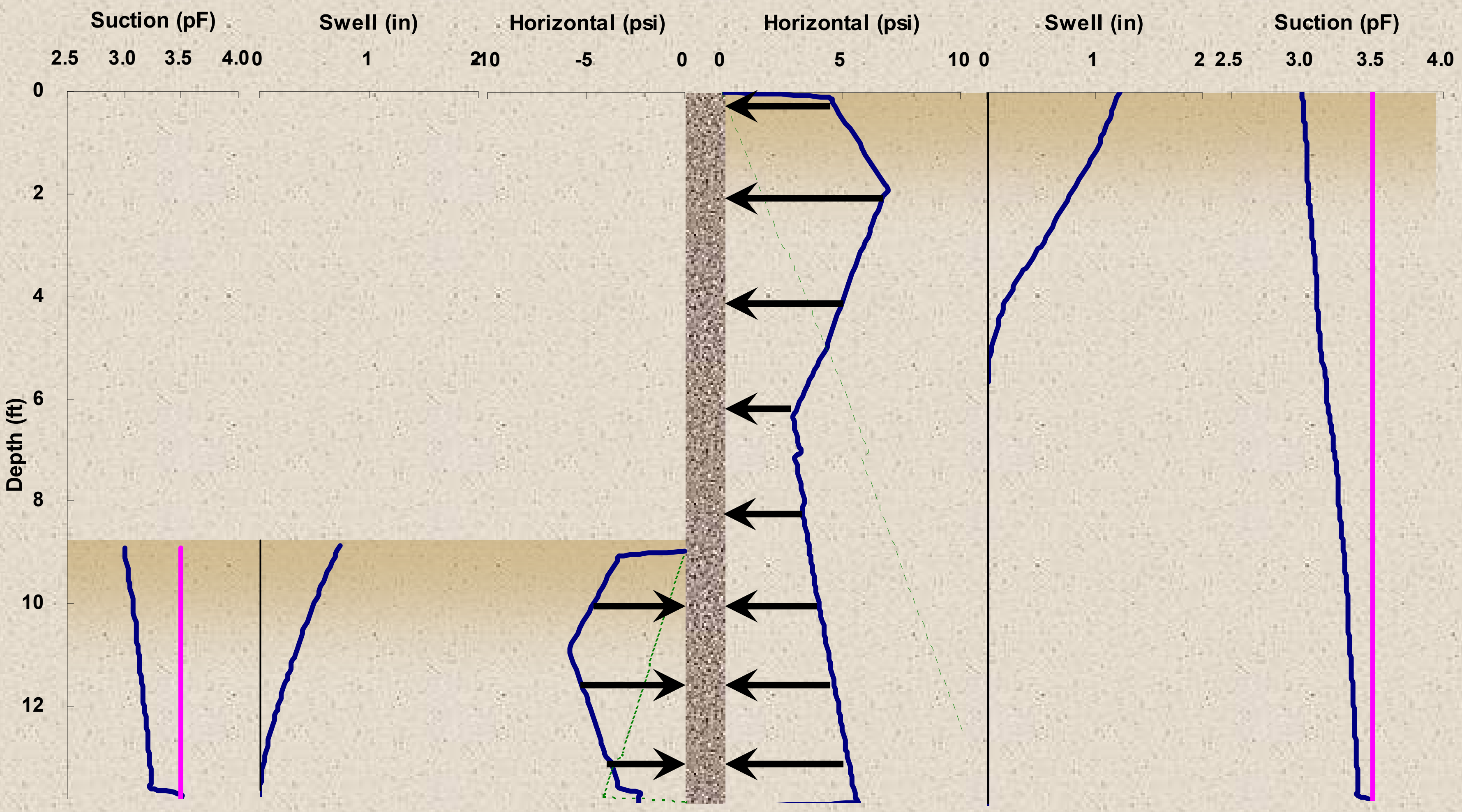
3 months saturation



Katti et al. (1979)
Measured horizontal pressures in the large scale retaining wall test

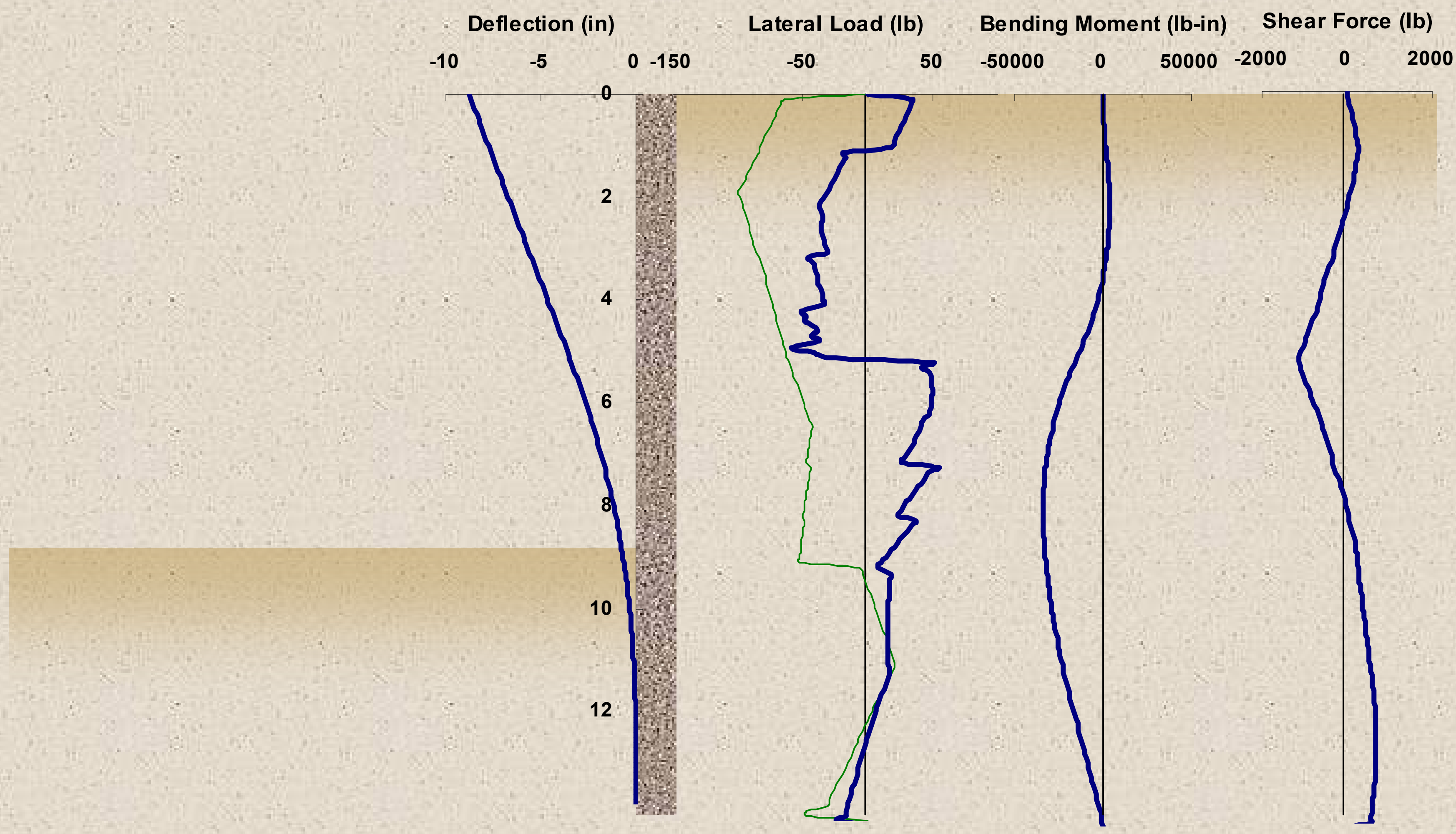


Case Study of Bending Behavior of the Retaining Wall



NGES-UH Site (Kim and O'Neill, 1998)

Case Study of Bending Behavior of the Retaining Wall



NGES-UH Site (Kim and O'Neill, 1998)

Topics (2/2)

- Shrinkage cracking design
- Shallow slope failure
- Slab-on-ground design
- Drilled pier design
  - Lateral pressures
  - Stresses, strains, movements
  - Comparison with field measurement
- Retaining wall design
  - Lateral pressures
  - Stresses, strains, movements
  - Comparisons with measurements

Topics (1/2)

- Soil properties
- Suction envelopes
  - Climates
  - Trees
  - Drainage
- Pavement design
  - Concrete and asphalt
  - Stabilized layers
  - Vertical and horizontal moisture barrier

Design of Structures to Resist the Pressures and Movements of Expansive Soils

Robert L. Lytton

Texas A&M University

Foundation Performance Association

December 12, 2007