REVISITATION
OF
EXPANSIVE SOILS

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Houston, Texas

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CONSTRUCTED WORKS IMPACTED BY EXPANSIVE SOILS

- ✓ Building Foundations
- ✓ Pavements
- ✓ Embankments, Cuts and Slopes

CONSTRUCTED WORKS IMPACTED BY EXPANSIVE SOILS

- ✓ Site Investigation
- ✓ Laboratory Characterization
- ✓ Relating Field-to-Lab Properties

Building Foundations

- ✓ Slabs
- ✓ Drilled Shafts
- ✓ Basements
- ✓ Retaining Walls
- ✓ Design Methods

Pavements

- ✓ New Construction
  - ✓ Airport
  - ✓ Highway
- ✓ Reliable Design Methods
- ✓ Sulfate Swell Problem
- ✓ Remediation

Embankments, Cuts, and Slopes

- ✓ Shallow Slope Failure
- ✓ Downhill Creep
- ✓ Dams and Levees

Site Investigation

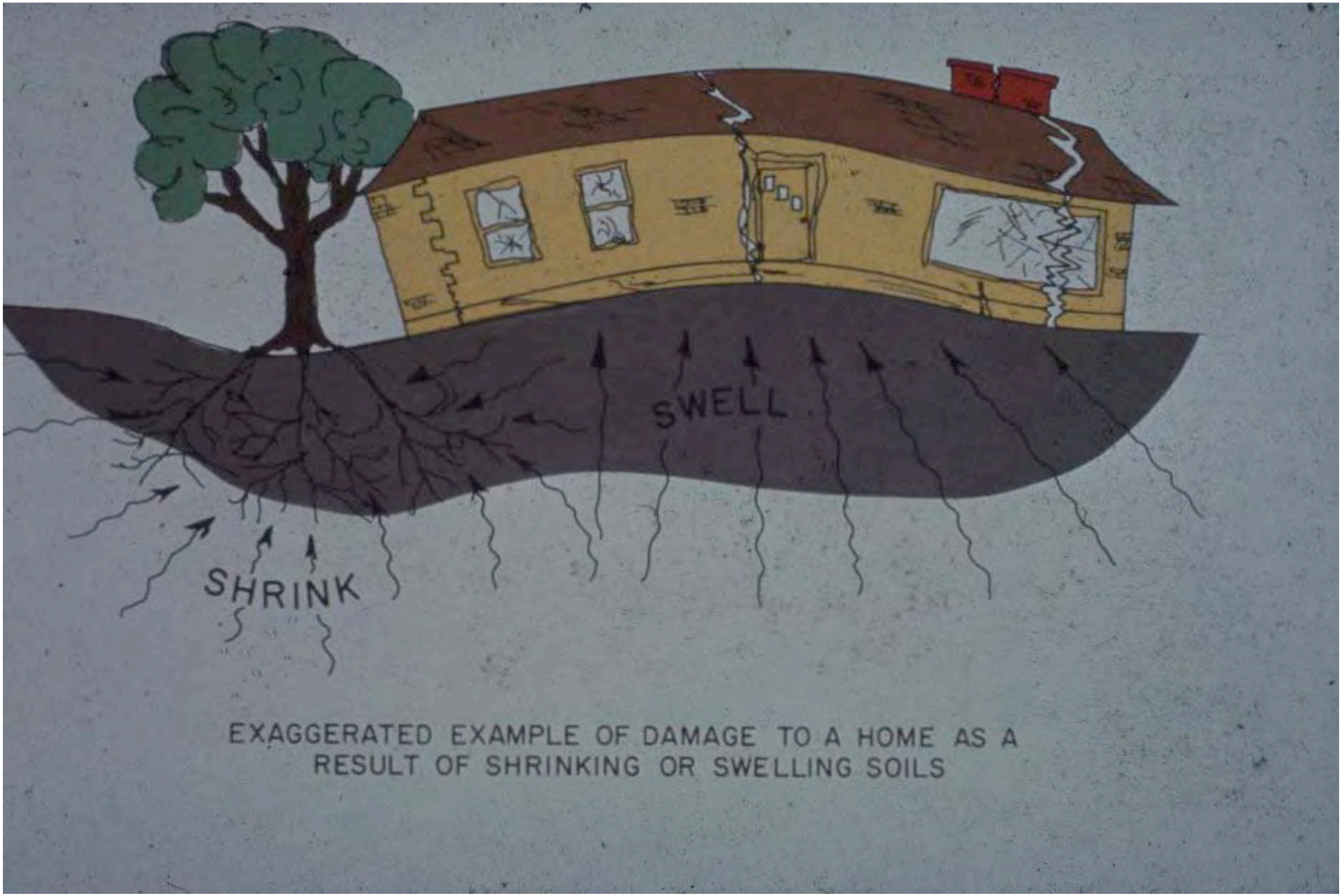
- ✓ Boring and Sampling
- ✓ Resistivity
- ✓ Conductivity for Soluble Sulfates
- ✓ Ground Penetrating Radar

Site Investigation

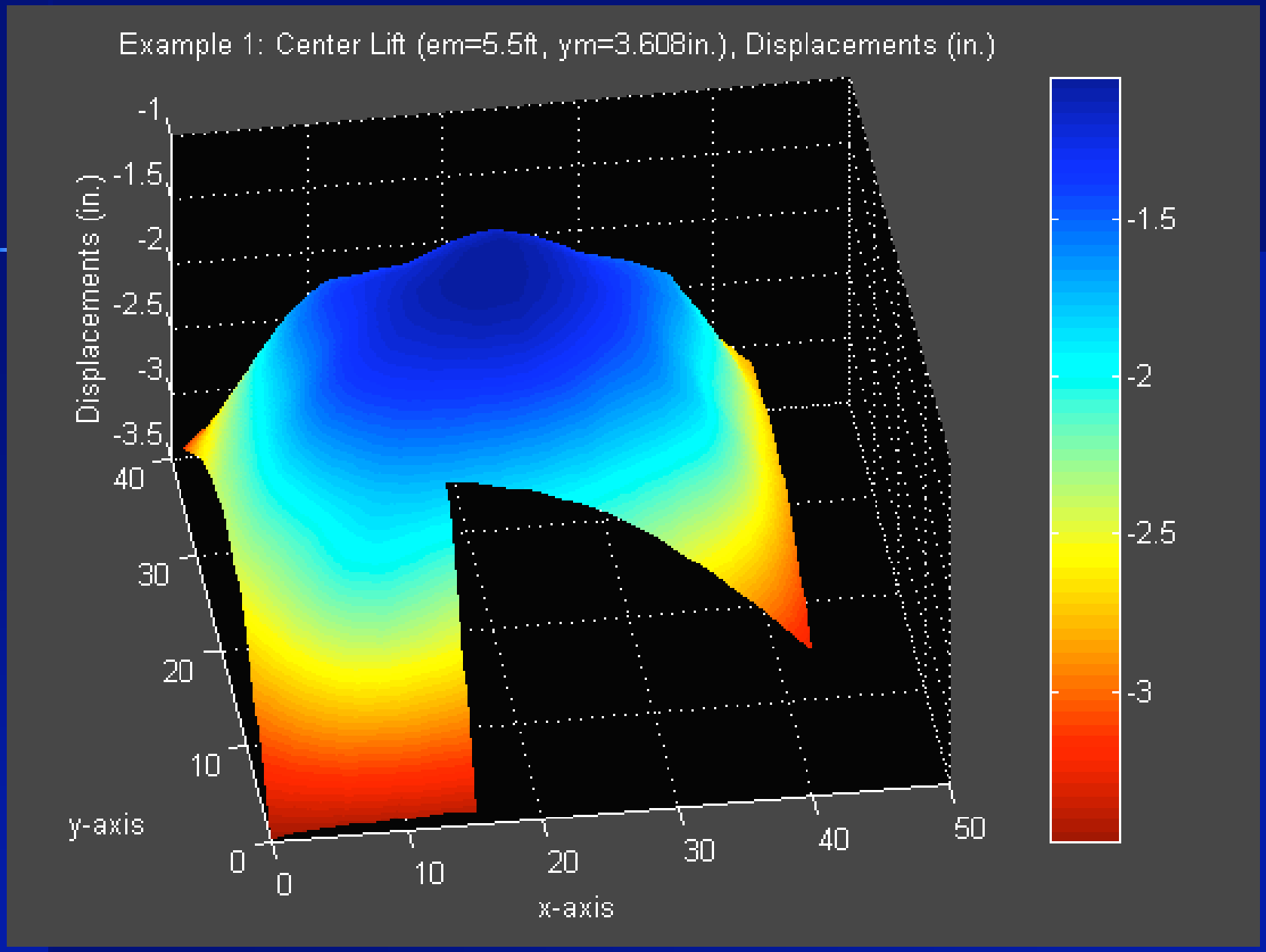
- ✓ Depth of the Active Zone
  - ✓ Moisture Active Zone
  - ✓ Movement Active Zone
- ✓ Vegetation
- ✓ Crack Fabric in Soil Masses
- ✓ Field-to-Laboratory Diffusivity Ratios

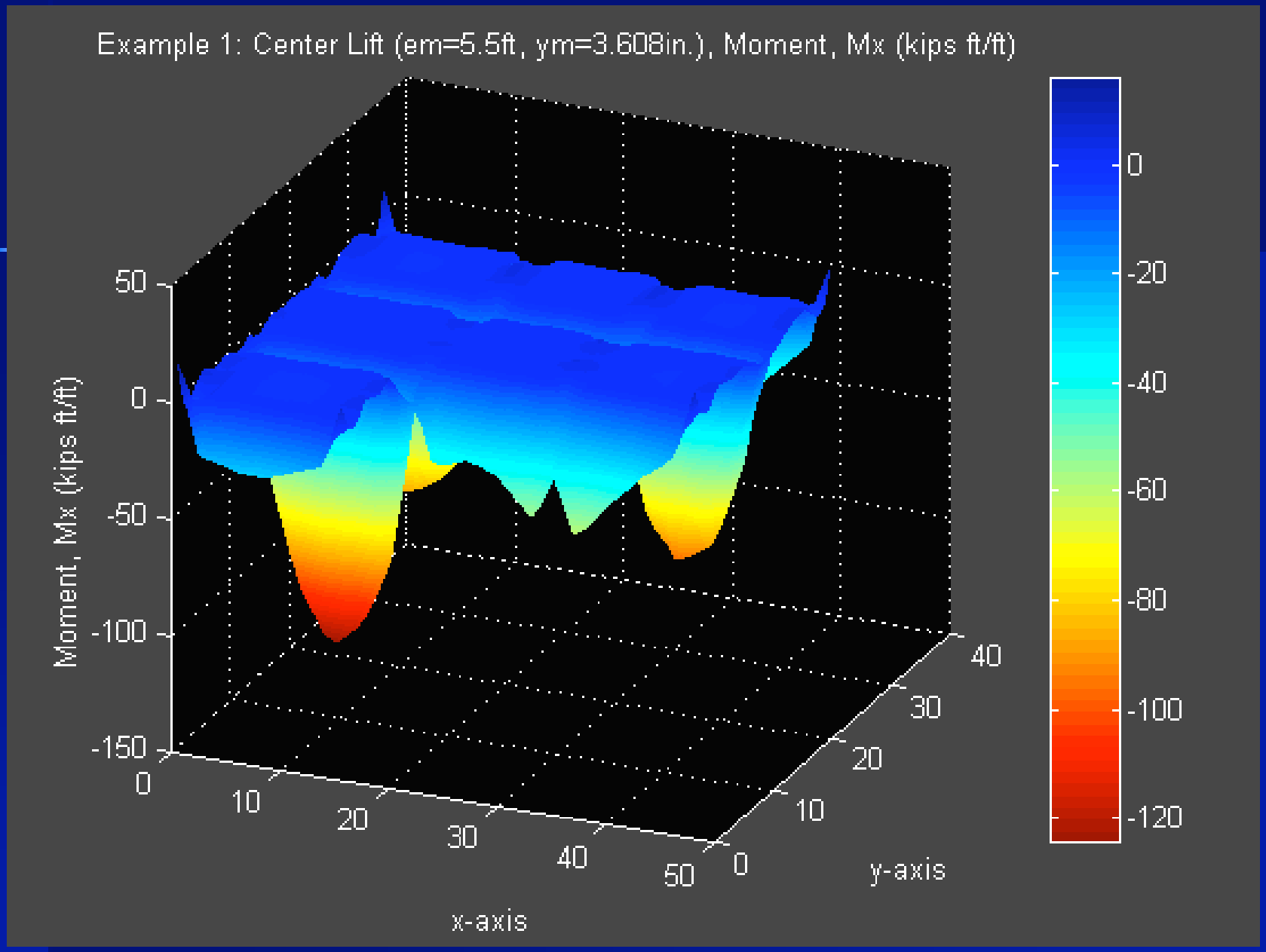
Laboratory Characterization

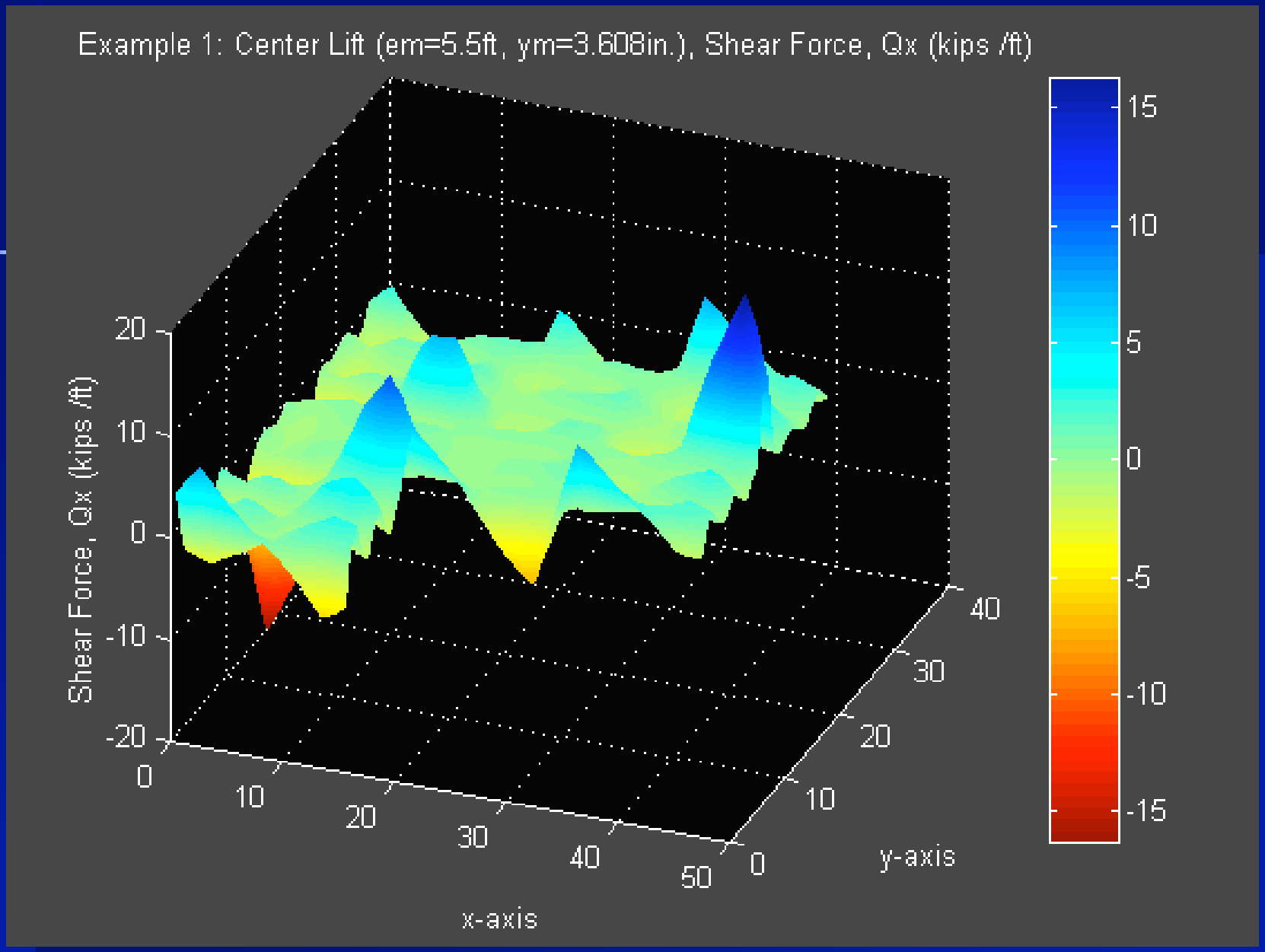
- ✓ Index Properties
- ✓ Suction Measurement
- ✓ Diffusivity Measurements
- ✓ Constitutive Relationships
  - ✓ Shallow Foundations
  - ✓ Major Earthworks



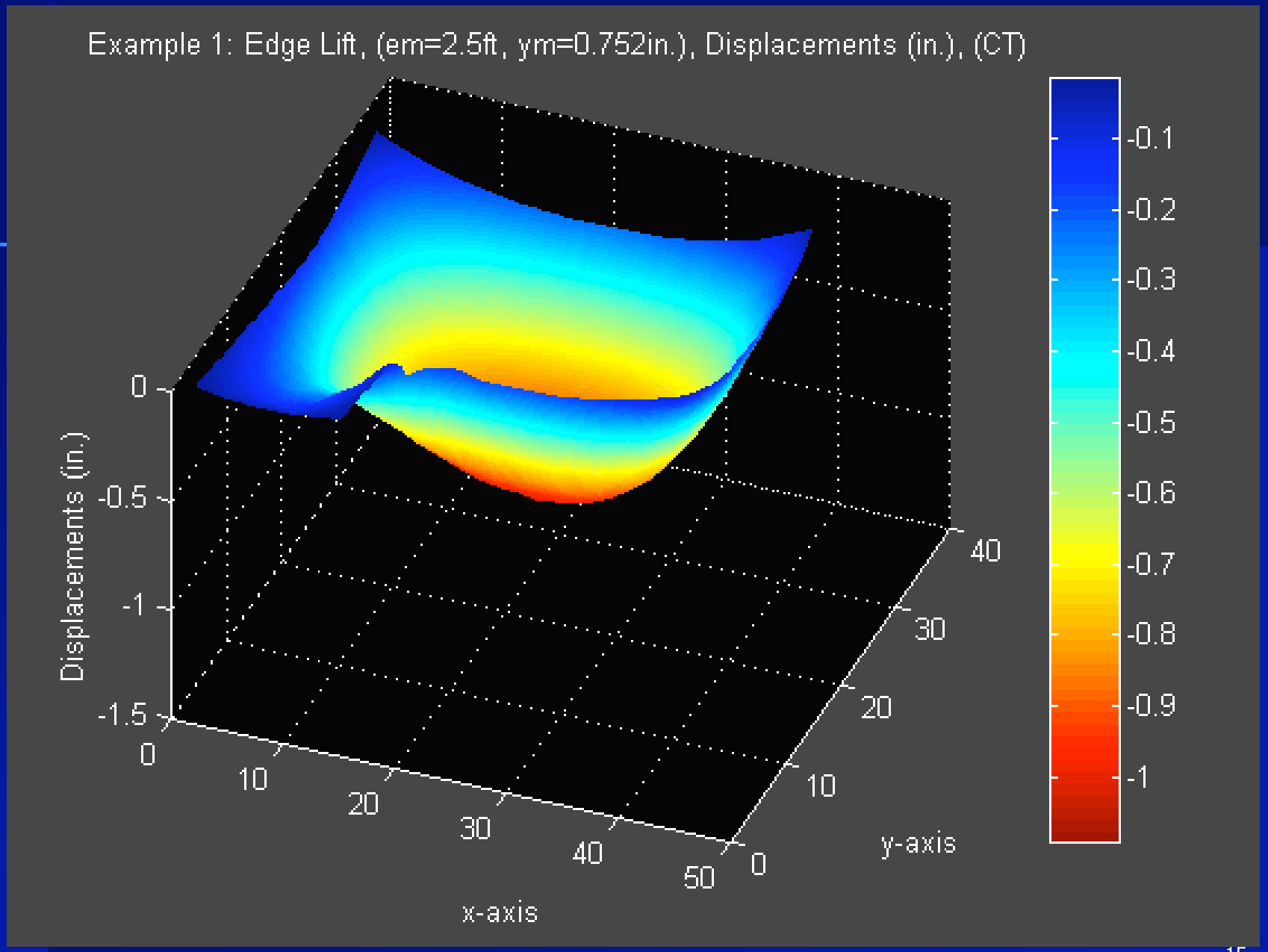
EXAGGERATED EXAMPLE OF DAMAGE TO A HOME AS A RESULT OF SHRINKING OR SWELLING SOILS

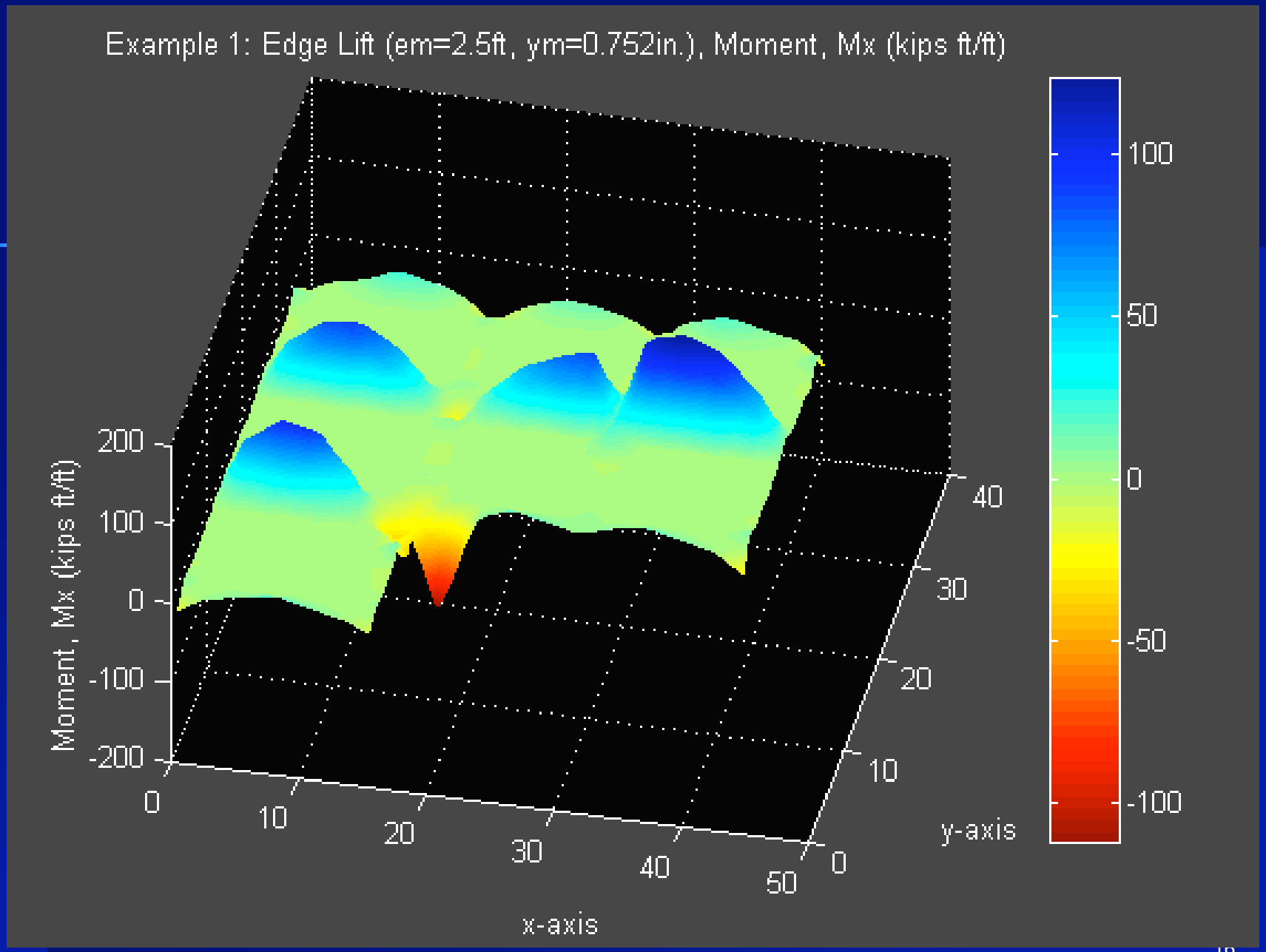

Example 1: Center Lift (em=5.5ft, ym=3.608in.), Displacements (in.)
Displacements (in.)
-1
-1.5
-2
-2.5
-3
-3.5
40
30
20
10
y-axis
0
0
10
20
30
40
50
x-axis
-1.5
-2
-2.5
-3

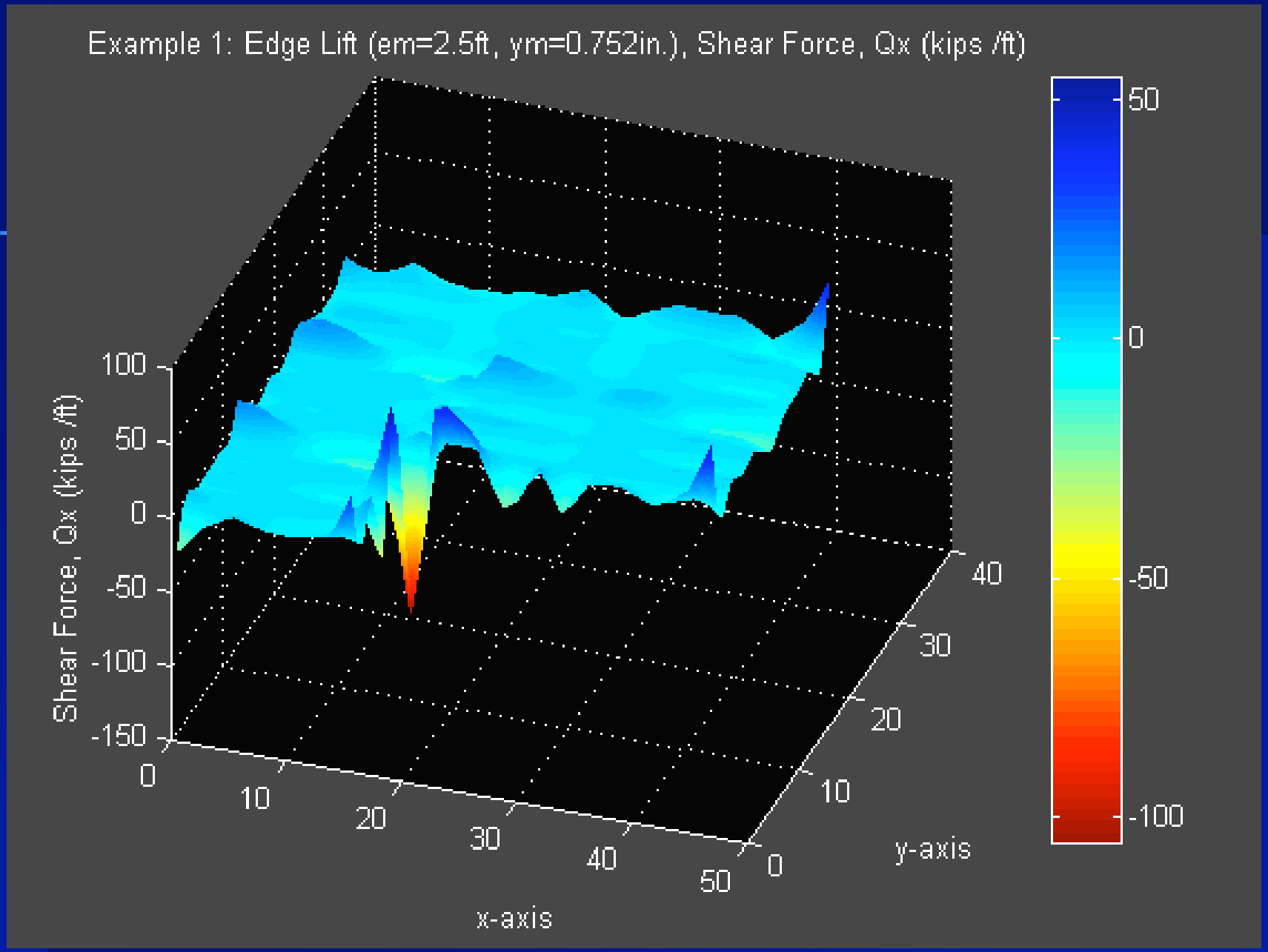

Example 1: Center Lift (em=5.5ft, ym=3.608in.), Moment, Mx (kips ft/ft)
Moment, Mx (kips ft/ft)
50
0
-50
-100
-150
0
10
20
30
40
50
x-axis
0
10
20
30
40
y-axis
0
-20
-40
-60
-80
-100
-120

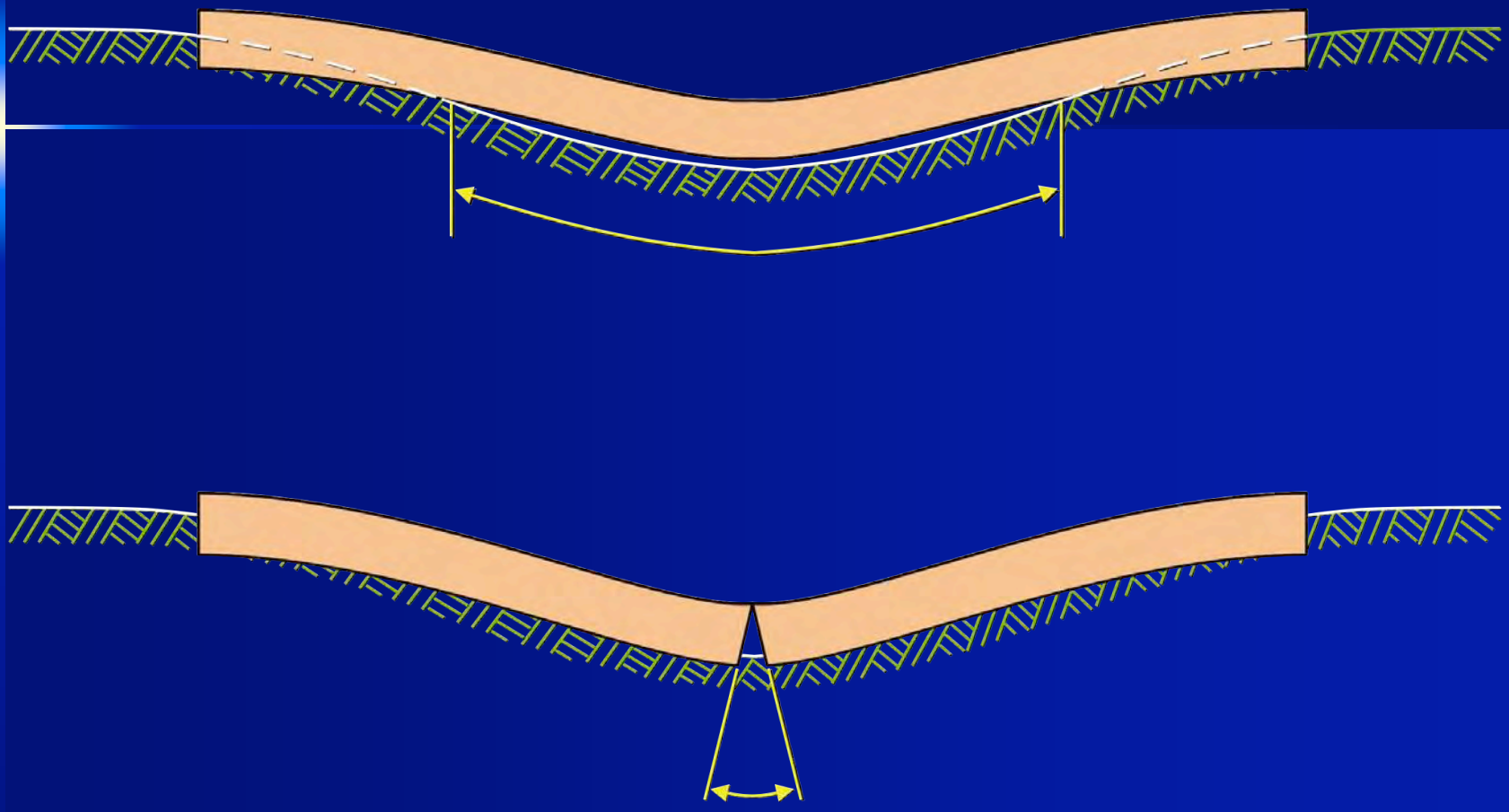

Example 1: Center Lift (em=5.5ft, ym=3.608in.), Shear Force, Qx (kips /ft)
Shear Force, Qx (kips /ft)
20
10
0
-10
-20
0
10
20
30
40
50
x-axis
0
10
20
30
40
y-axis
15
10
5
0
-5
-10
-15

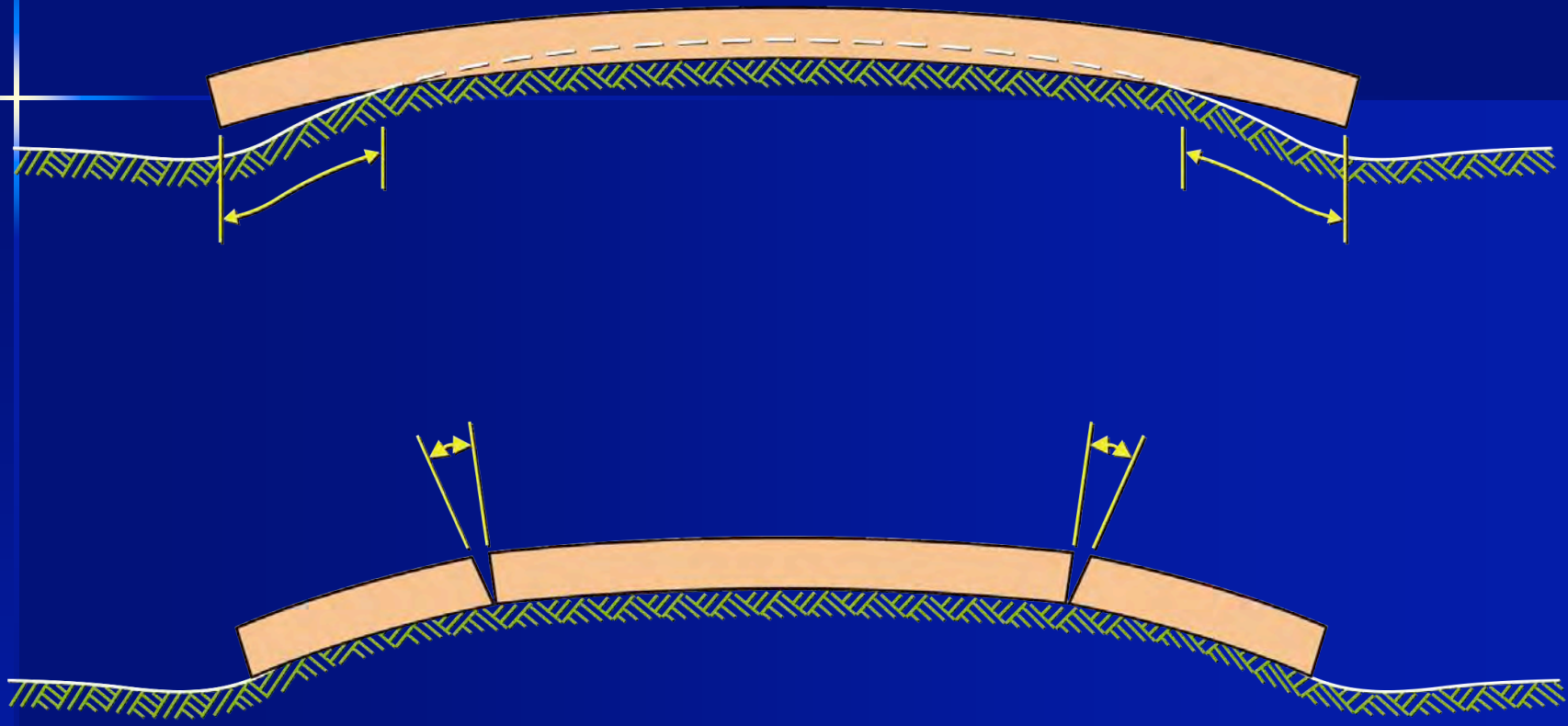

NO CHANGE
SWELL
SWELL
SHRINK


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

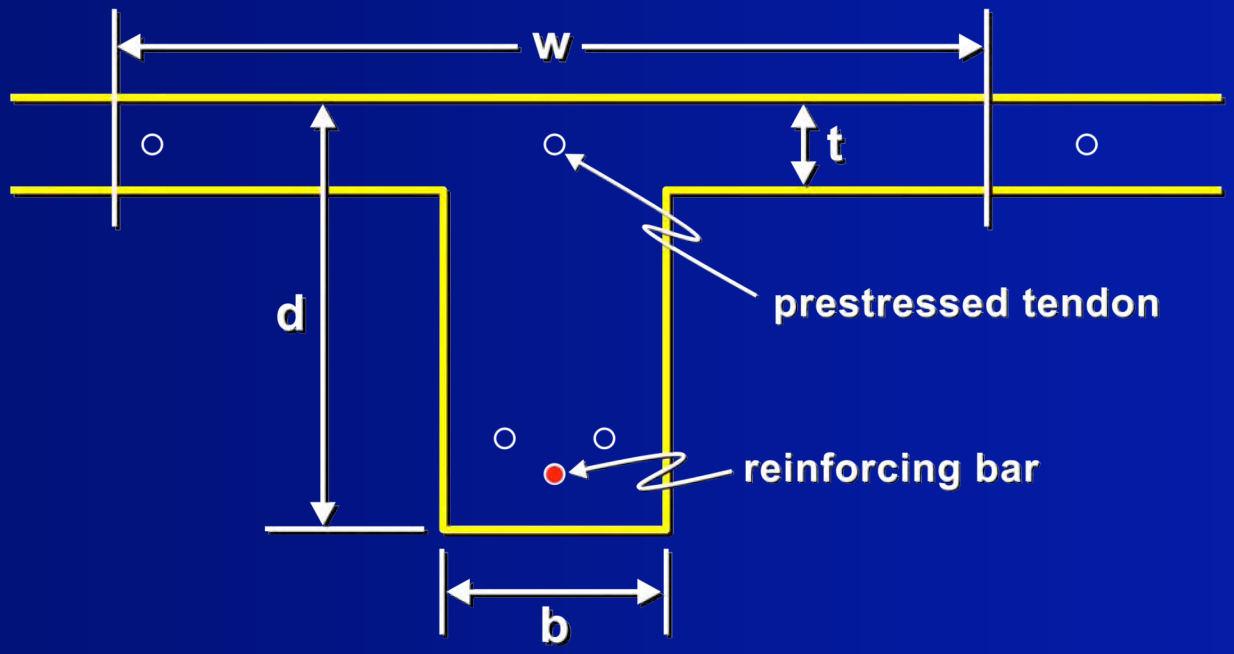

Example 1: Edge Lift (em=2.5ft, ym=0.752in.), Moment, Mx (kips ft/ft)
Moment, Mx (kips ft/ft)
200
100
0
-100
-200
0
10
20
30
40
50
x-axis
0
10
20
30
40
y-axis
100
50
0
-50
-100


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

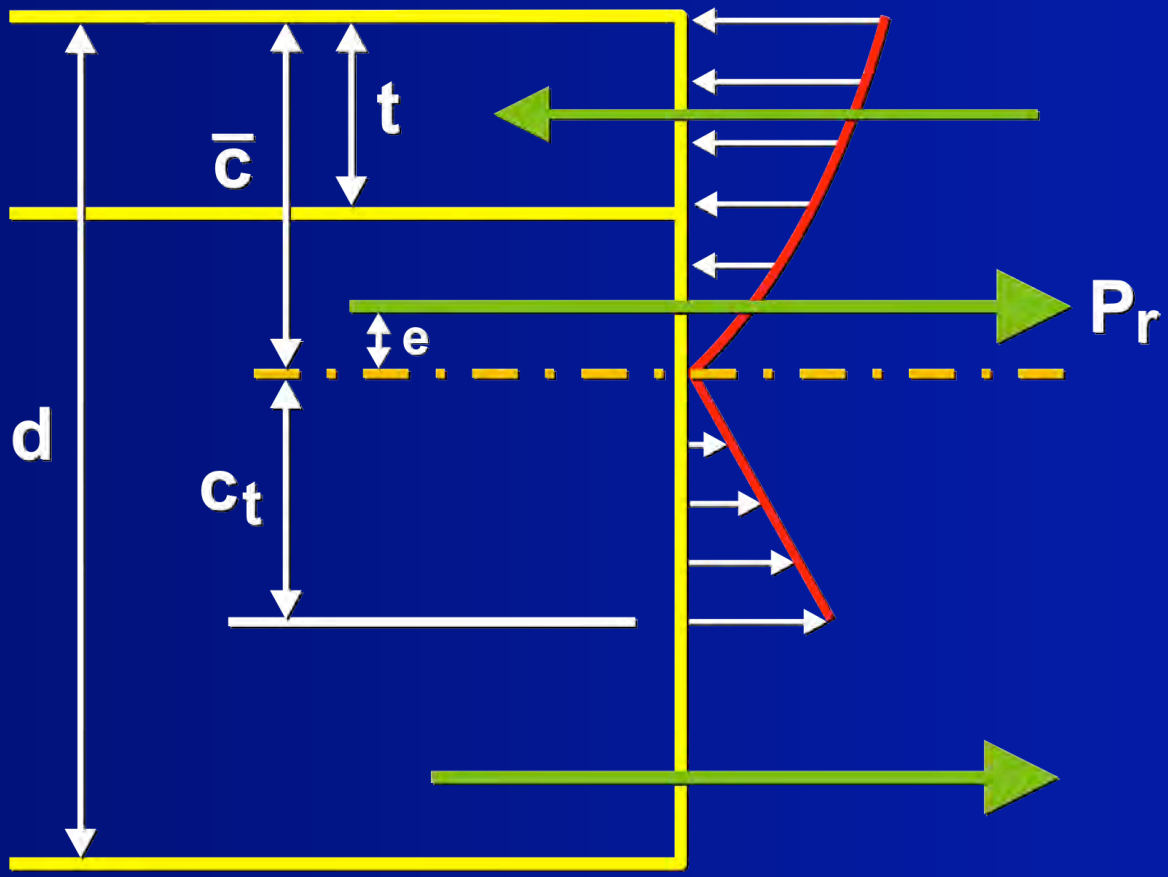




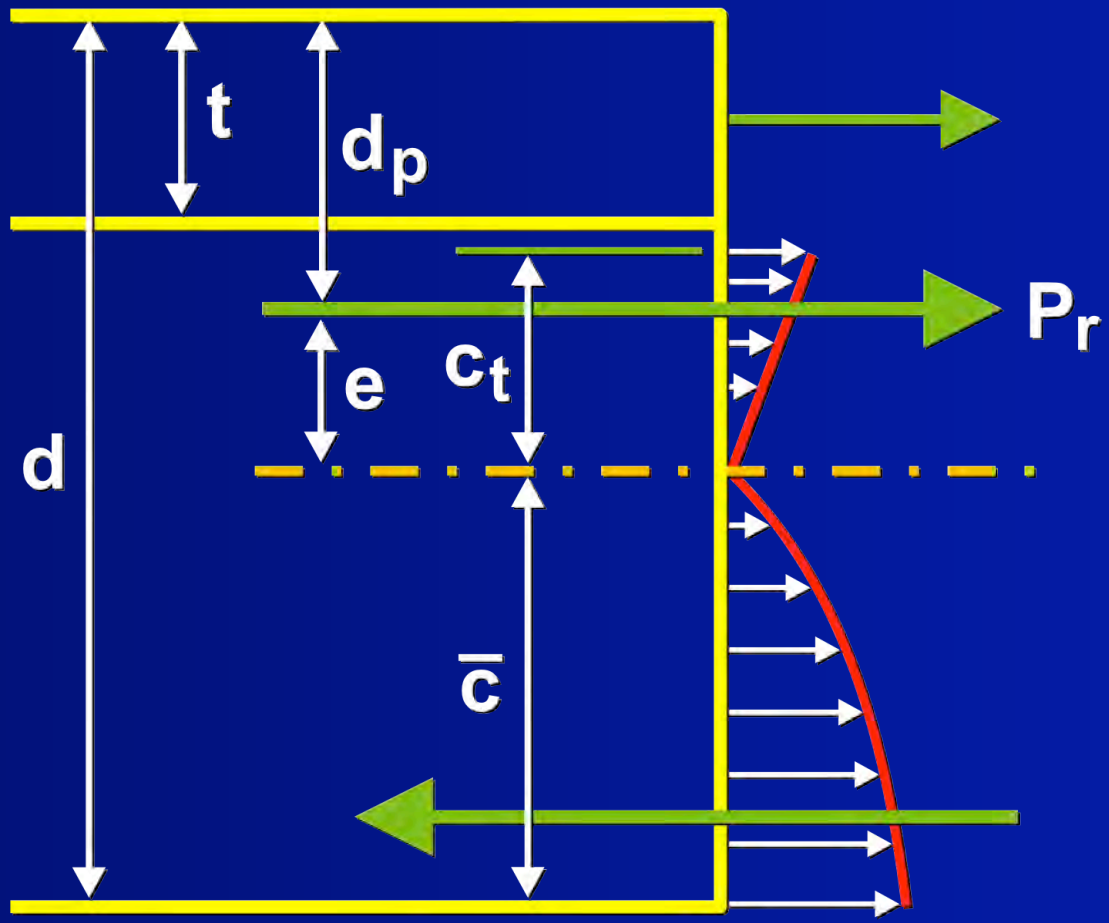
CURVATURE OF CRACKED CONCRETE CROSS-SECTIONS

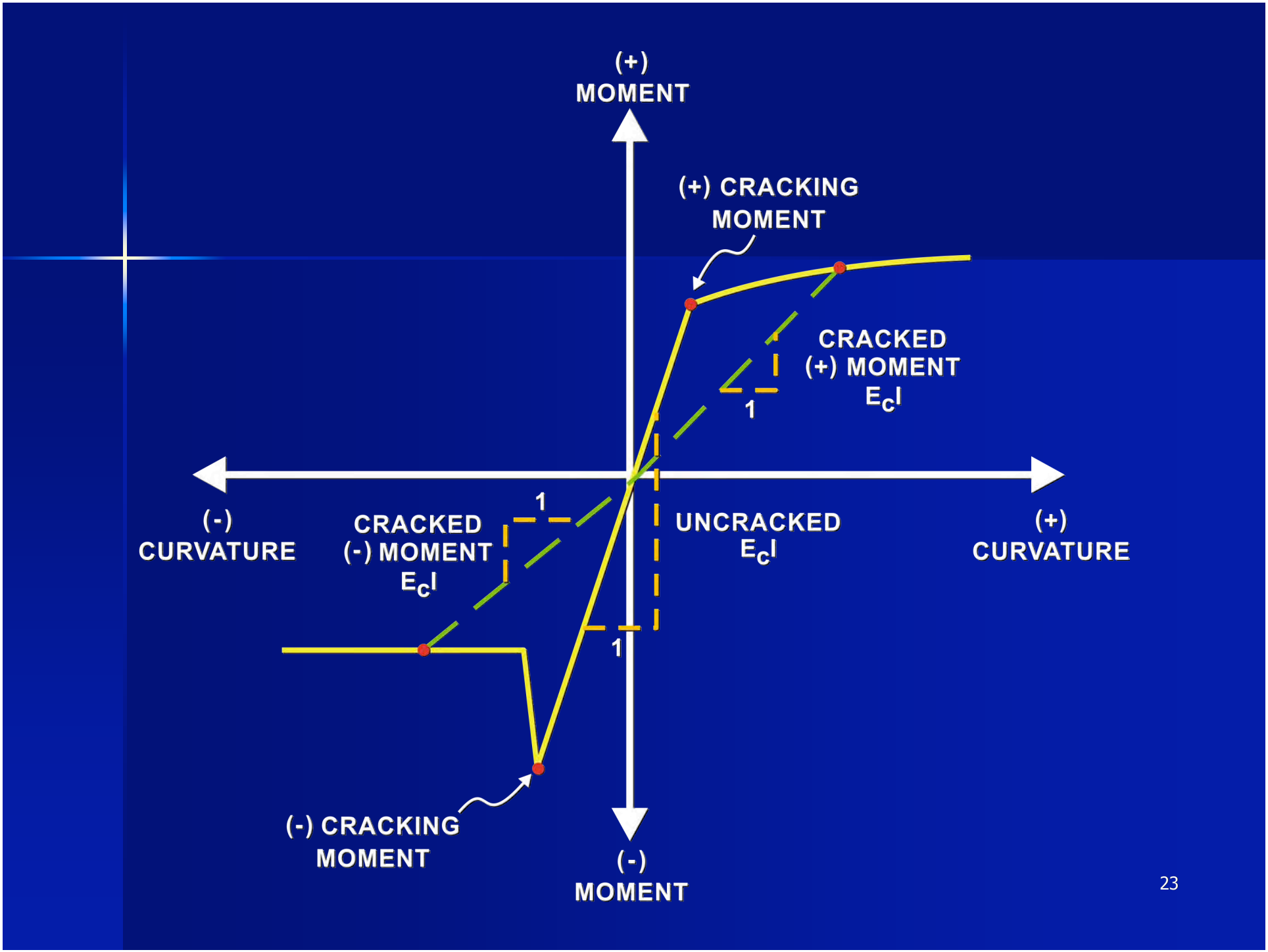


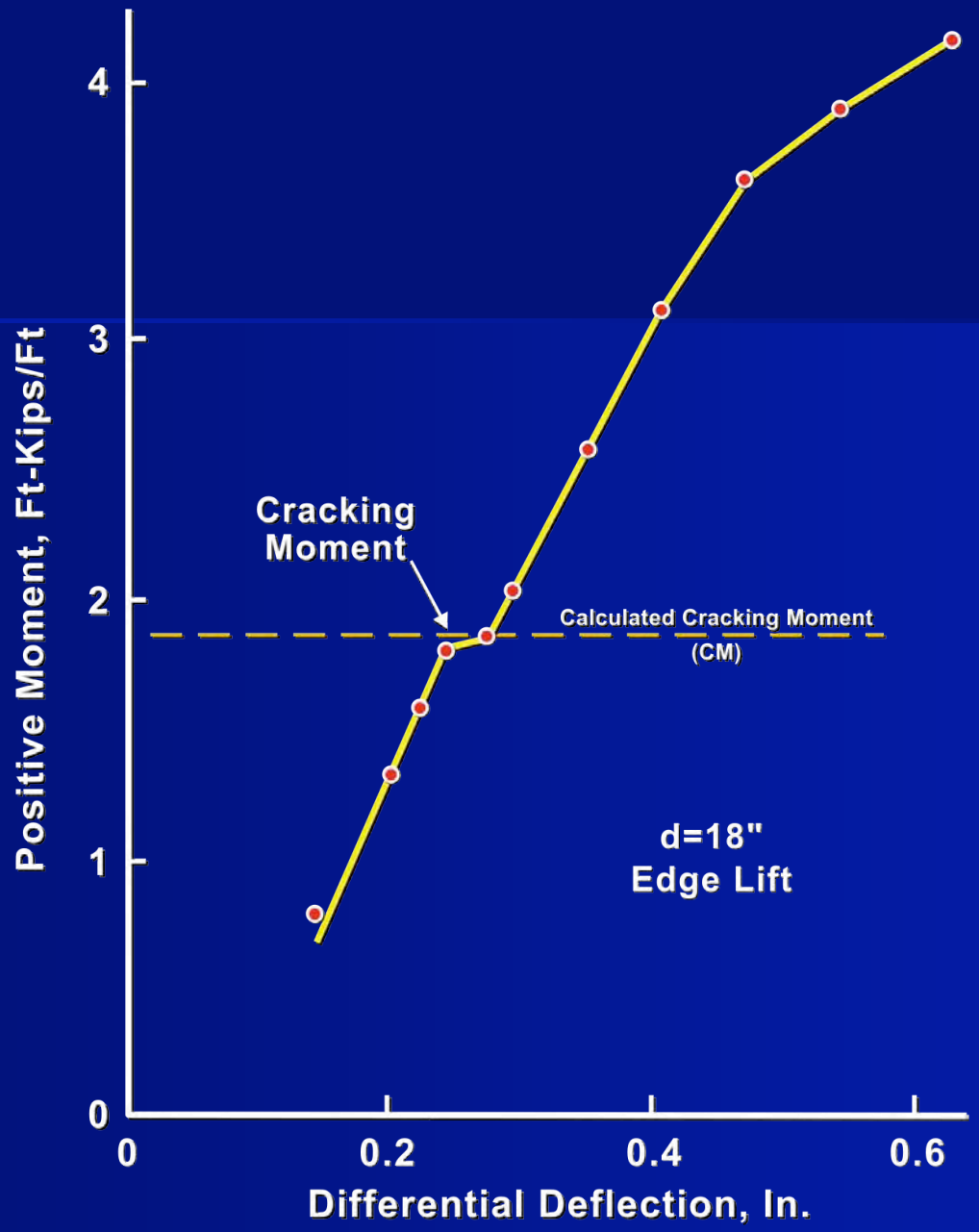
(+) MOMENT

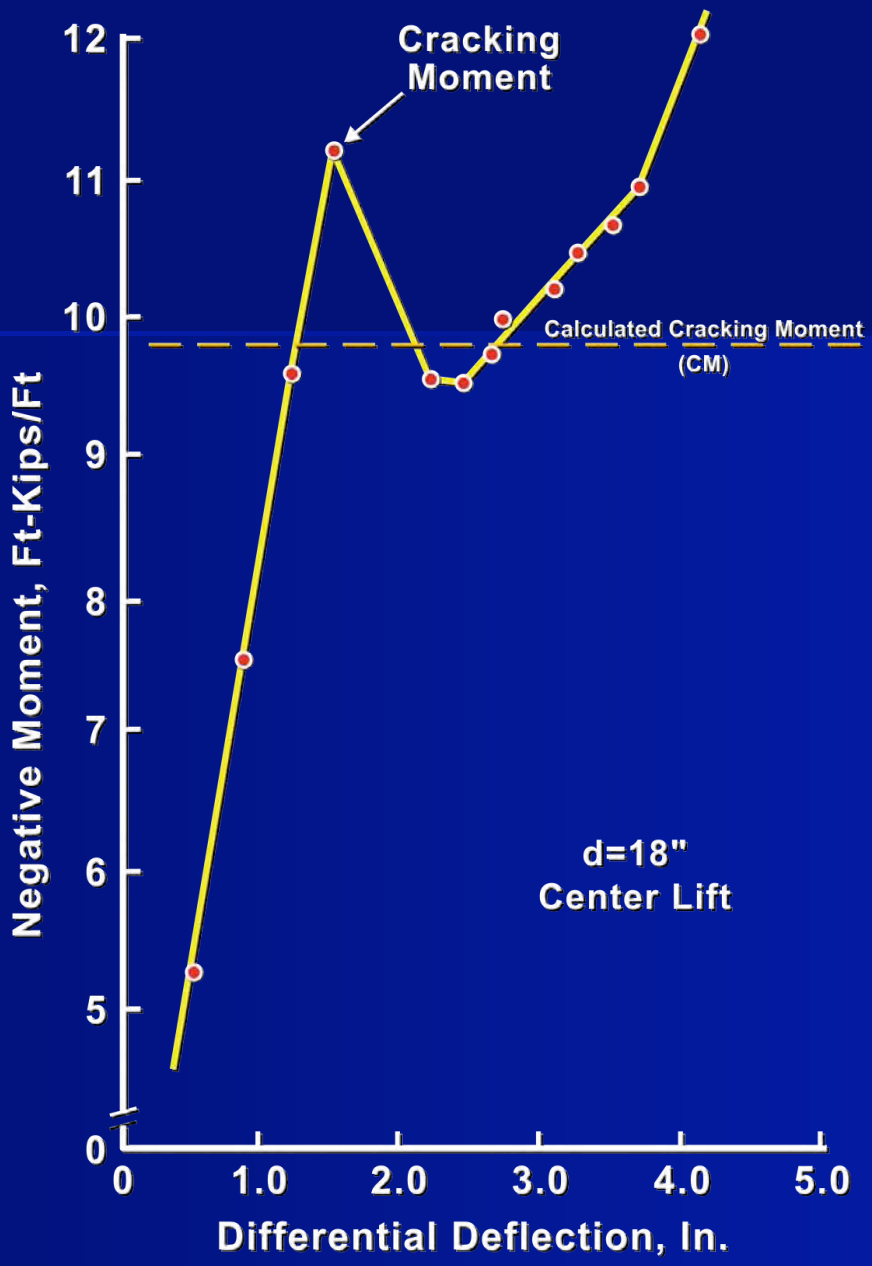


(-) MOMENT



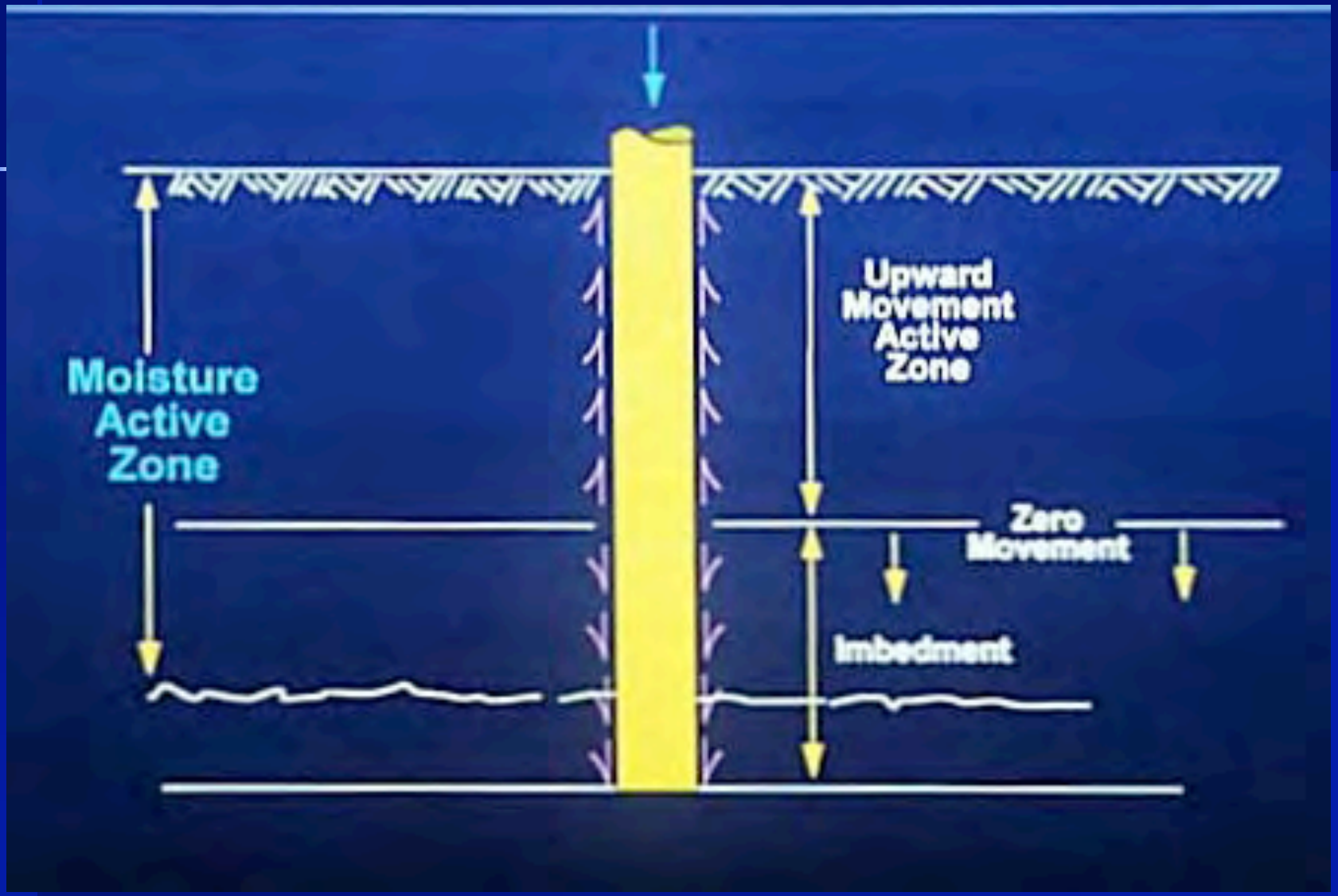

(+)
MOMENT
(+) CRACKING
MOMENT
CRACKED
(+) MOMENT
E_cI
1
(-)
CURVATURE
CRACKED
(-) MOMENT
E_cI
1
UNCRACKED
E_cI
(+)
CURVATURE
1
(-) CRACKING
MOMENT
(-)
MOMENT

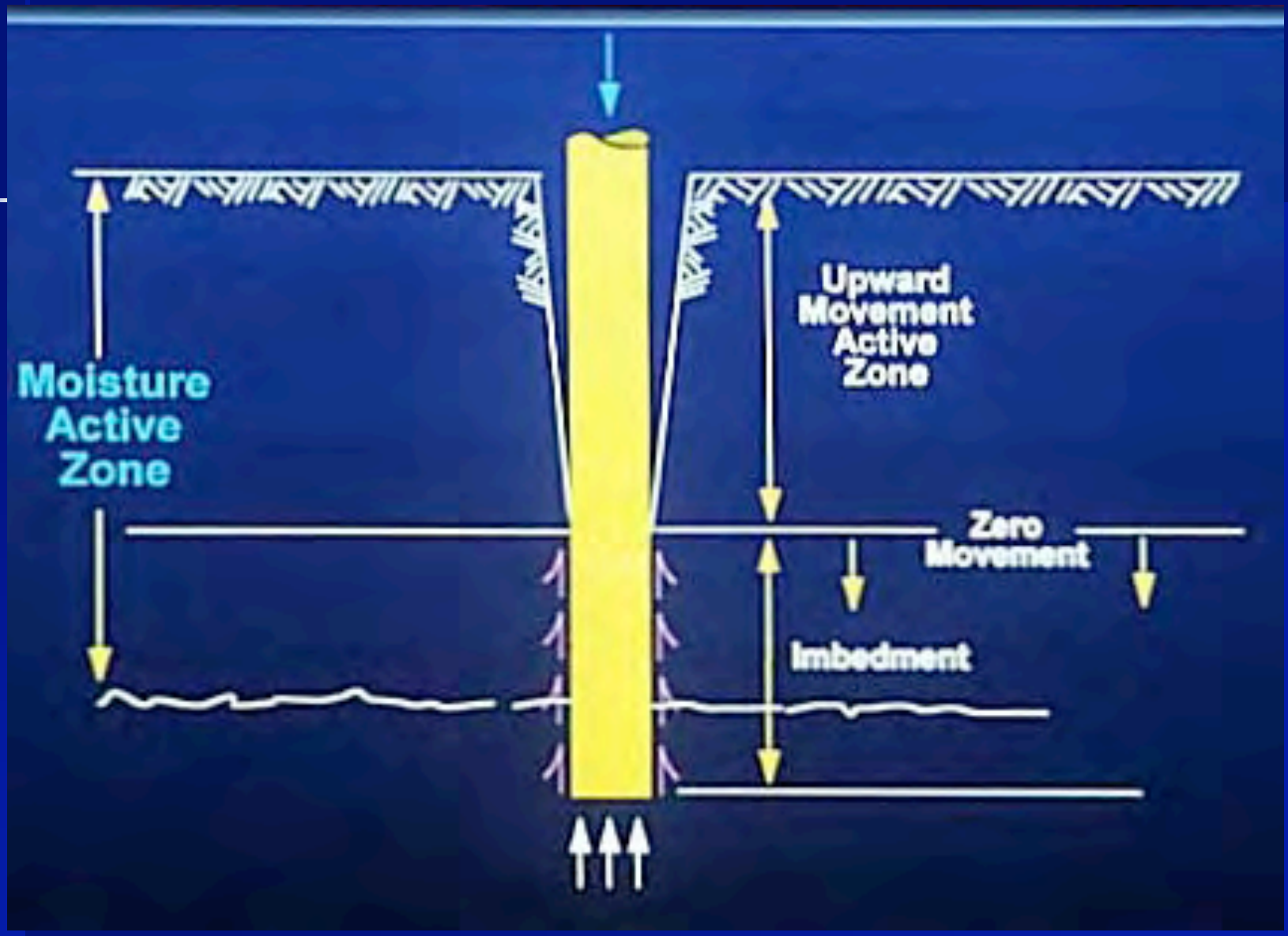

Positive Moment, Ft-Kips/Ft
4
3
2
1
0
Cracking
Moment
Calculated Cracking Moment
(CM)
d=18"
Edge Lift
0
0.2
0.4
0.6
Differential Deflection, In.


Cracking Moment
Calculated Cracking Moment (CM)
d=18"
Center Lift
Negative Moment, Ft-Kips/Ft
Differential Deflection, In.
12
11
10
9
8
7
6
5
0
0
1.0
2.0
3.0
4.0
5.0

Prestress Compressive Stress and Eccentricity	Design Ratios of Moment and Curvature	Reinforcing			
		Post-Tensioning and Bonded Reinforcement		Post-Tensioning only	
		Negative Moment	Positive Moment	Negative Moment	Positive Moment
$P/A \approx 100$ psi $e \geq 2$ inch	$\frac{Mc\ max}{M\ design}$ $\frac{\phi\ eff}{\phi\ intact}$	1.12 - 1.39 1.44 - 1.77	1.17 - 1.50 1.92 - 3.18	0.87 - 1.19 1.00 - 1.77	0.69 - 1.4 1.40 - 3.4
$P/A \approx 100$ psi $e \approx 0$ in	$\frac{Mc\ max}{M\ design}$ $\frac{\phi\ eff}{\phi\ intact}$	1.07 - 1.38 1.39 - 1.83	1.31 - 2.08 1.81 - 2.84	0.70 - 1.56 1.04 - 1.93	1.16 - 2.13 1.30 - 2.70
$P/A \approx 50$ psi $e \geq 2$ inch	$\frac{Mc\ max}{M\ design}$ $\frac{\phi\ eff}{\phi\ intact}$	1.05 - 1.36 1.41 - 1.93	1.26 - 1.56 1.93 - 3.13	0.43 - 0.75 1.14 - 2.47	0.38 - 1.02 1.79 - 4.1
$P/A \approx 50$ psi $e \approx 0$ in	$\frac{Mc\ max}{M\ design}$ $\frac{\phi\ eff}{\phi\ intact}$	1.03 - 1.35 1.43 - 1.96	1.31 - 1.61 1.43 - 3.04	0.39 - 0.61 1.17 - 2.61	0.71 - 1.22 1.61 - 3.6

Prestress Compressive Stress and Eccentricity	Stiffening Beams	Reinforcing					
		Post-Tensioning With 0.2% Bonded Reinf.		Post-Tensioning with 1-4# Bar in Beam Stems		Post-Tensioning only	
	Depth x width	Negative Moment	Positive Moment	Negative Moment	Positive Moment	Negative Moment	Positive Moment
$P/A \approx 100$ psi $e \geq 2$ inch	36 x 12 28 x 12 20 x 10	1.12 - 1.26 1.16 - 1.29 1.27 - 1.39	1.17 - 1.22 1.32 - 1.50 1.38 - 1.50	0.89 0.94 1.06 - 1.14	0.47 - 0.72 1.00 - 1.05 1.18 - 1.27	0.88 0.87 - 0.89 1.02 - 1.19	0.69 - 0.85 1.08 - 1.18 1.25 - 1.47
$P/A \approx 100$ psi $e \approx 0$	36 x 12 28 x 12 20 x 10	1.07 - 1.20 1.13 - 1.36 1.25 - 1.38	1.31 - 1.46 1.57 - 2.08 1.49 - 1.65	0.73 - 0.76 0.85 1.00 - 1.08	1.07 - 1.11 1.25 - 1.35 1.36 - 1.73	0.70 - 0.72 0.73 - 0.76 0.93 - 1.56	1.16 1.30 - 1.59 1.46 - 2.13
$P/A \approx 50$ psi $e \geq 2$ inch	28 x 12 20 x 10	1.15 - 1.26 1.25 - 1.36	1.33 - 1.45 1.43 - 1.56	0.71 - 0.78 0.51 - 0.84	0.76 - 0.84 1.21 - 1.29	0.60 - 0.72 0.59 - 0.75	0.38 - 0.46 0.89 - 1.02
$P/A \approx 50$ psi $e \approx 0$	28 x 12 20 x 10	1.11 - 1.23 1.24 - 1.35	1.42 - 1.57 1.50 - 1.61	0.56 - 0.58 0.73 - 0.84	1.10 - 1.17 1.33 - 1.39	0.46 - 0.47 0.53 - 0.61	0.93 - 1.07 1.17 - 1.22


Moisture
Active
Zone
Upward
Movement
Active
Zone
Zero
Movement
Imbedment


Moisture
Active
Zone
Upward
Movement
Active
Zone
Zero
Movement
Imbedment

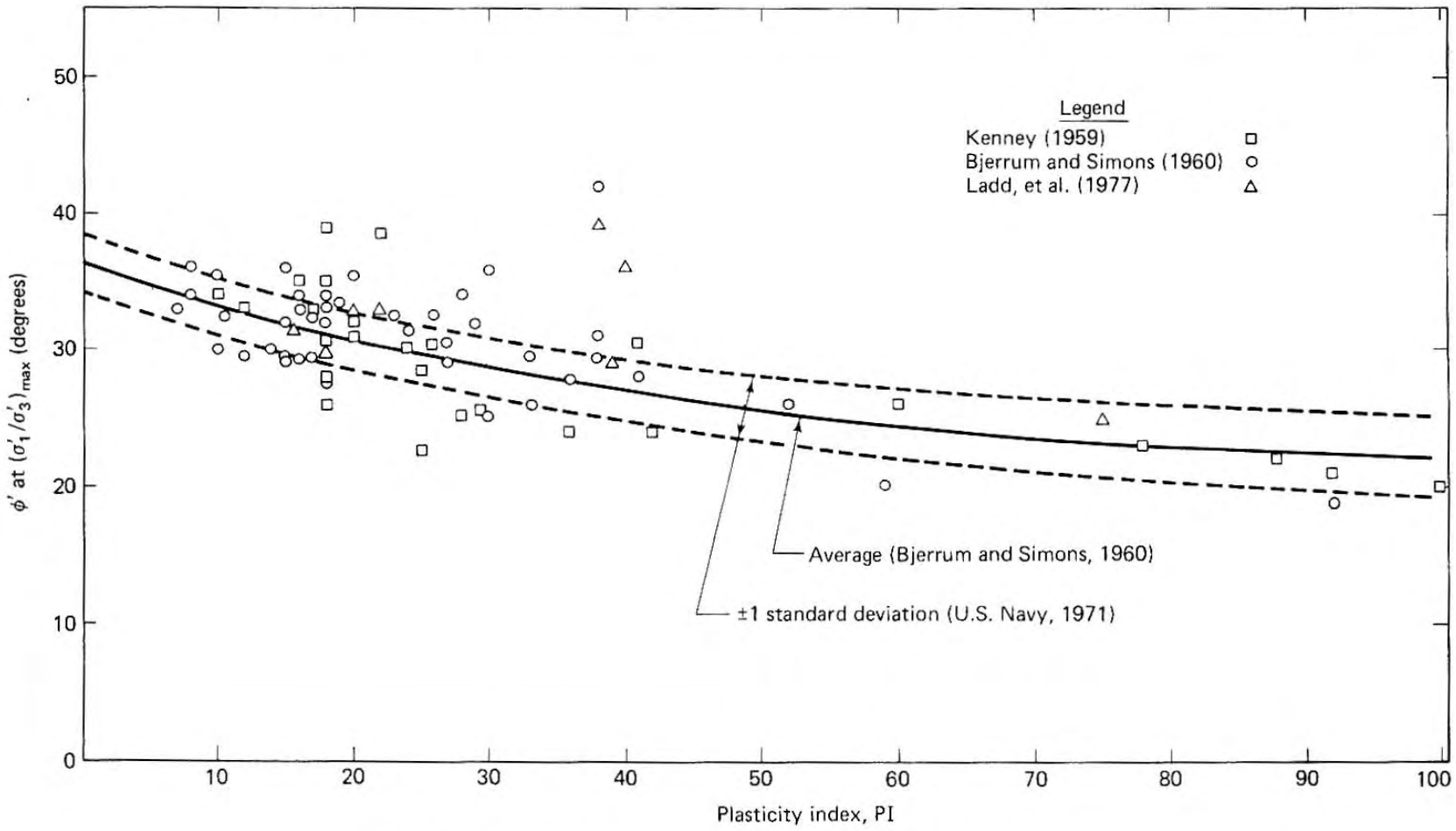
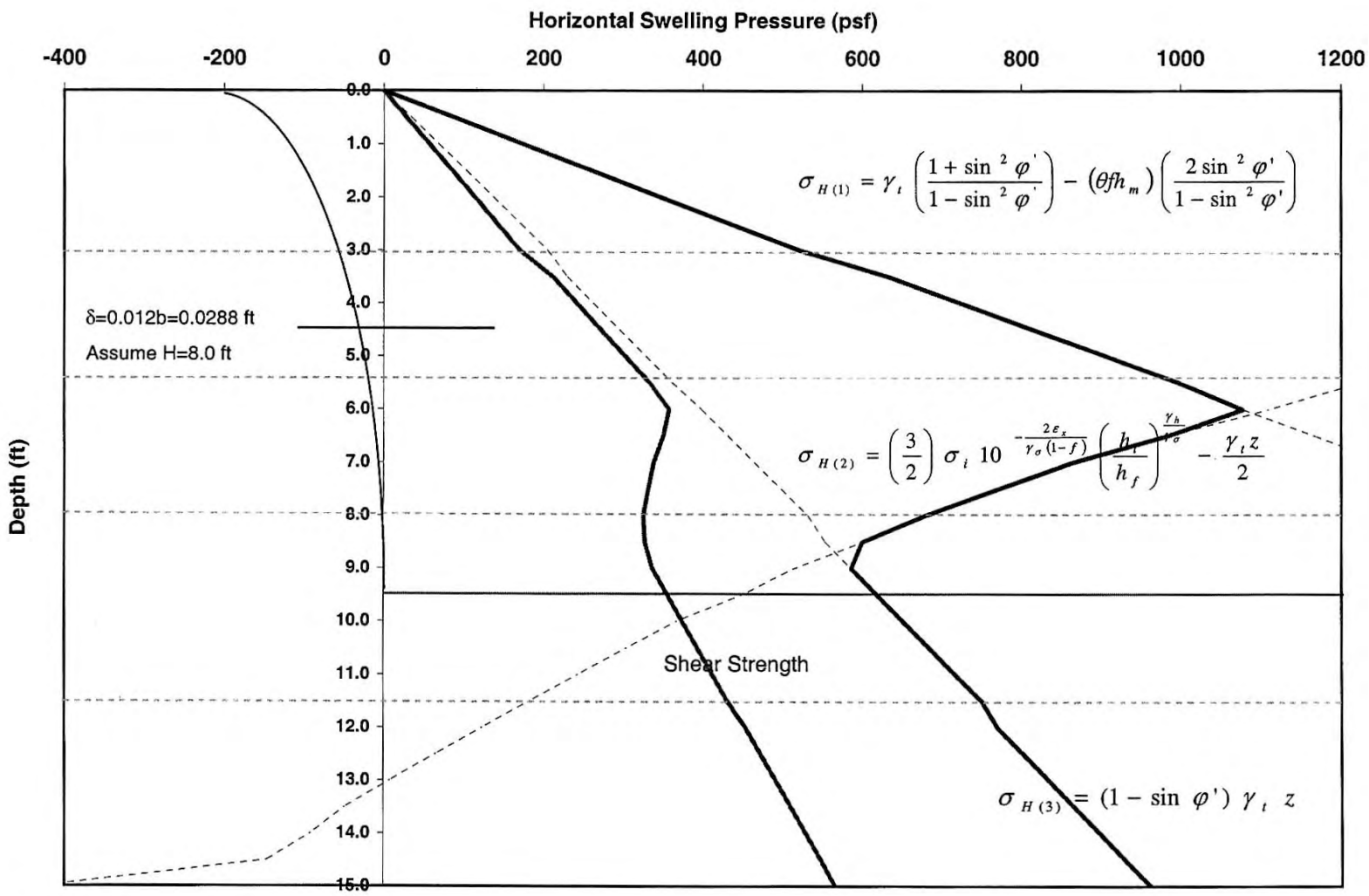


Fig. 11.27 Empirical correlation between ϕ' and PI from triaxial compression tests on normally consolidated undisturbed clays (after U.S. Navy, 1971, and Ladd, et al., 1977).

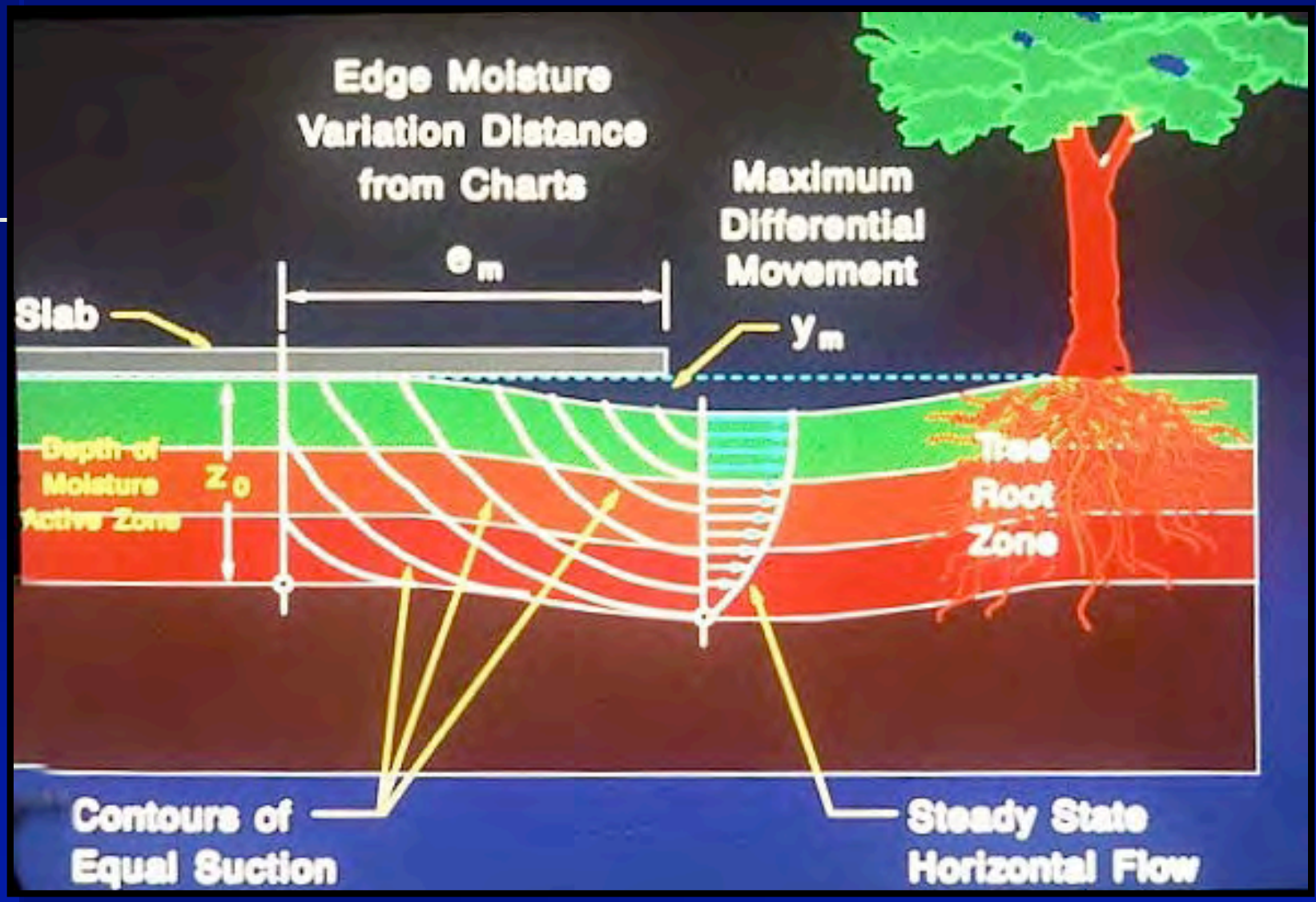

Horizontal Swelling Pressure (psf)
-400
-200
0
200
400
600
800
1000
1200
Depth (ft)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
12.0
13.0
14.0
15.0
δ=0.012b=0.0288 ft
Assume H=8.0 ft
$\sigma_{H(1)} = \gamma_t \left(\frac{1+\sin^2\varphi'}{1-\sin^2\varphi'}\right) - (\theta f h_m)\left(\frac{2\sin^2\varphi'}{1-\sin^2\varphi'}\right)$
$\sigma_{H(2)} = \left(\frac{3}{2}\right)\sigma_i \, 10^{-\frac{2\varepsilon_x}{\gamma_\sigma(1-f)}} \left(\frac{h_i}{h_f}\right)^{\frac{\gamma_h}{\gamma_\sigma}} - \frac{\gamma_t z}{2}$
Shear Strength
$\sigma_{H(3)} = (1-\sin\varphi')\,\gamma_t\, z$

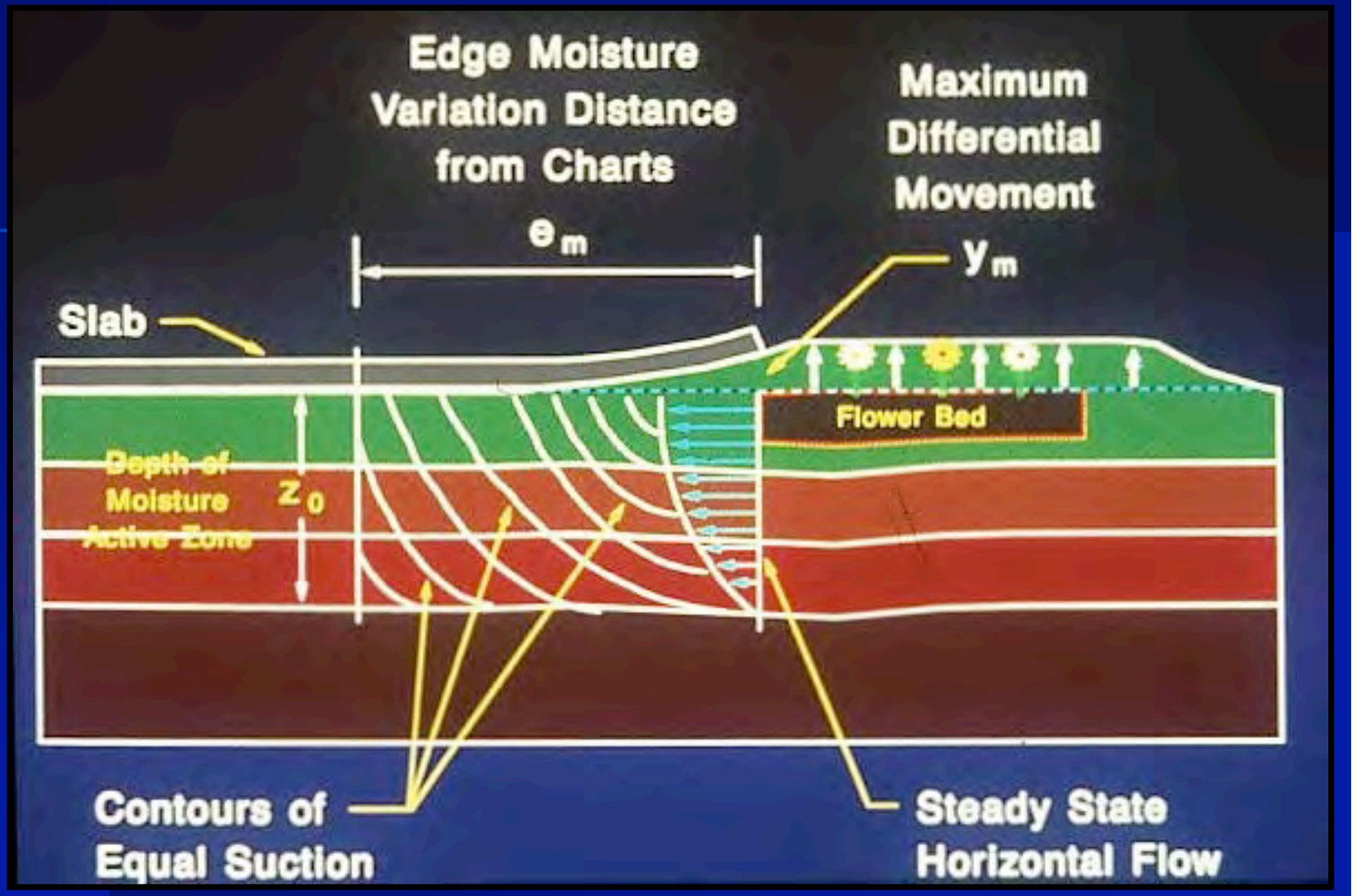
DESIGN ENVELOPES

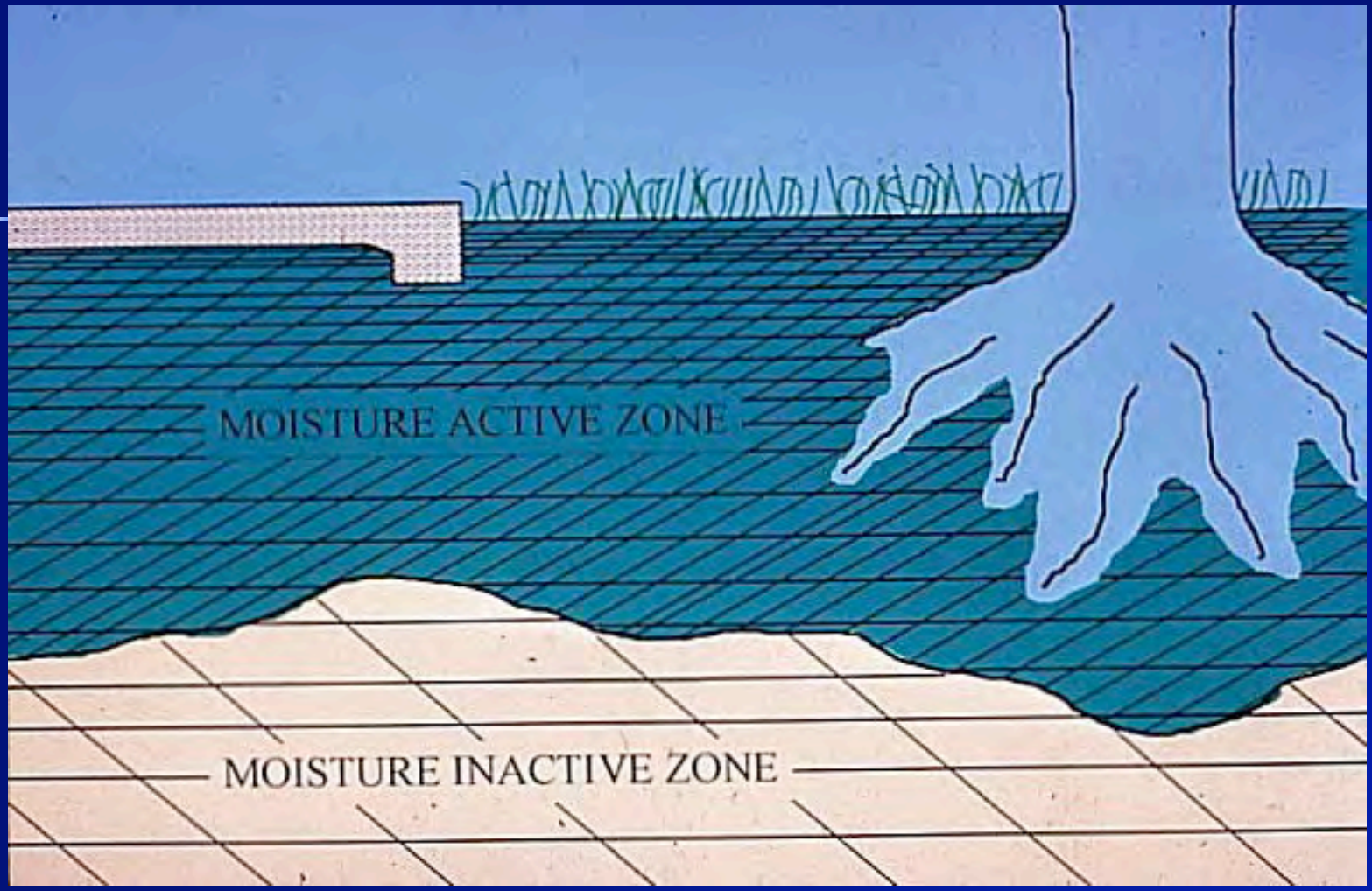
Example

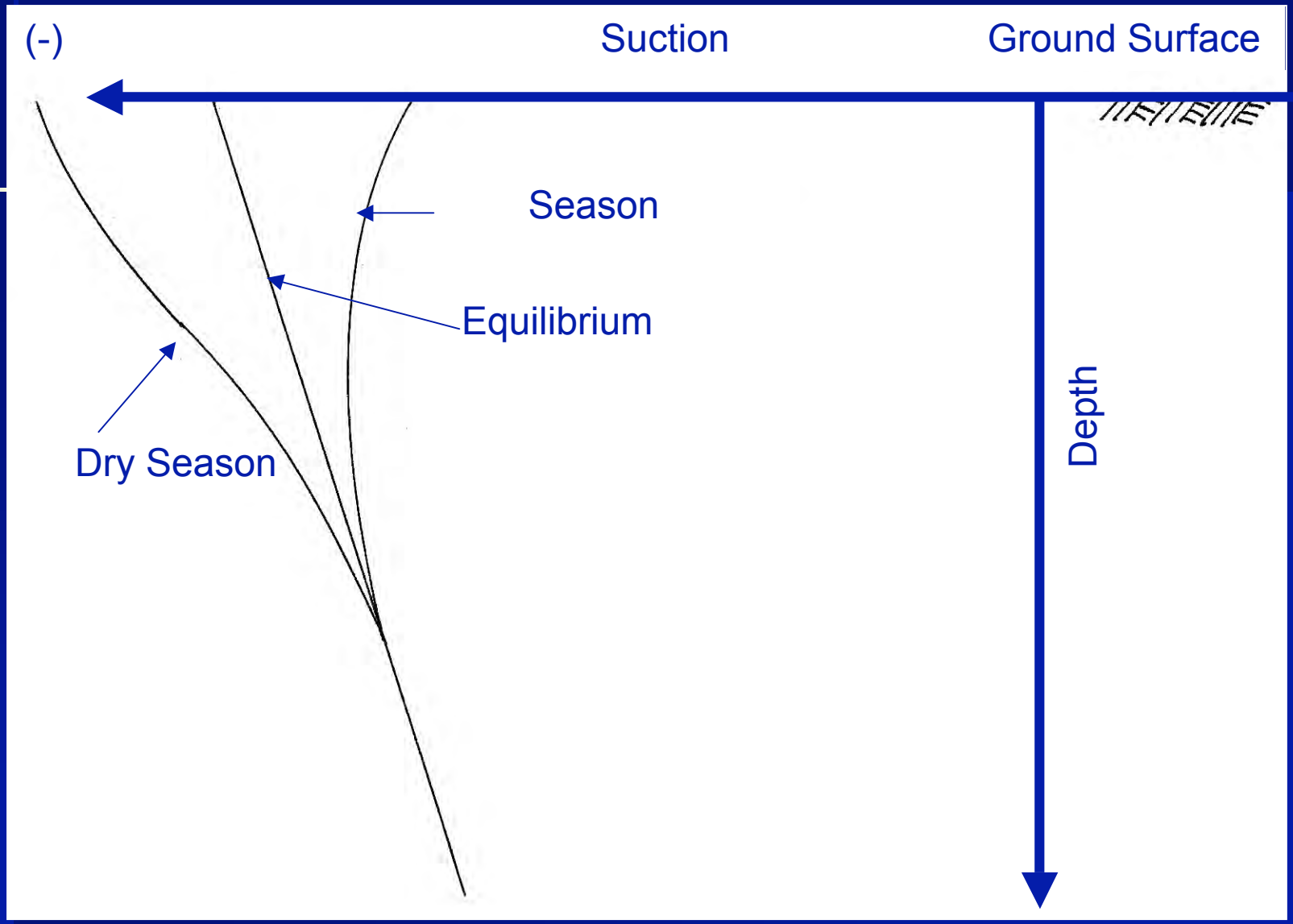
Soil Support
Pattern

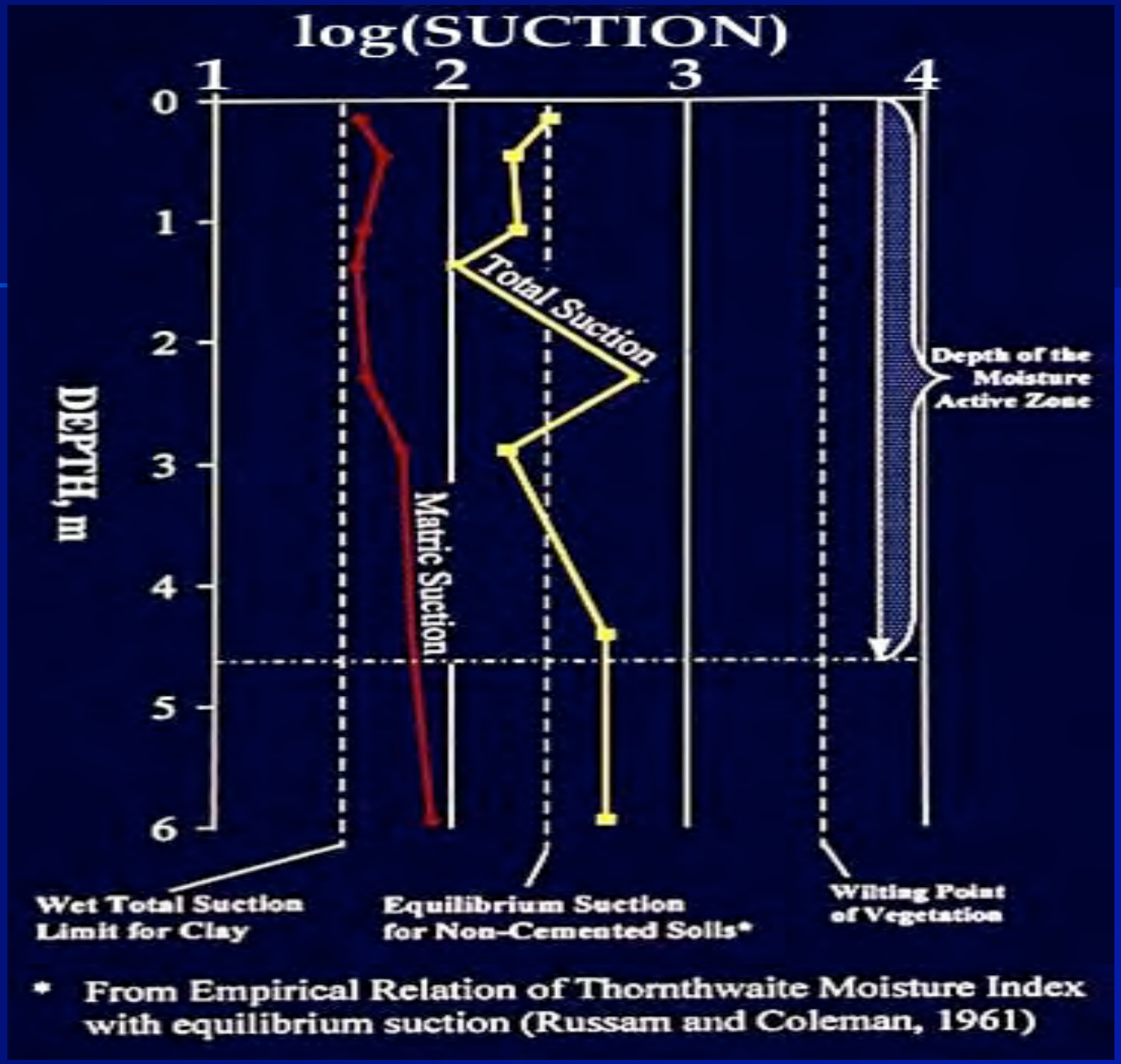
Worst Soil Support
Patterns

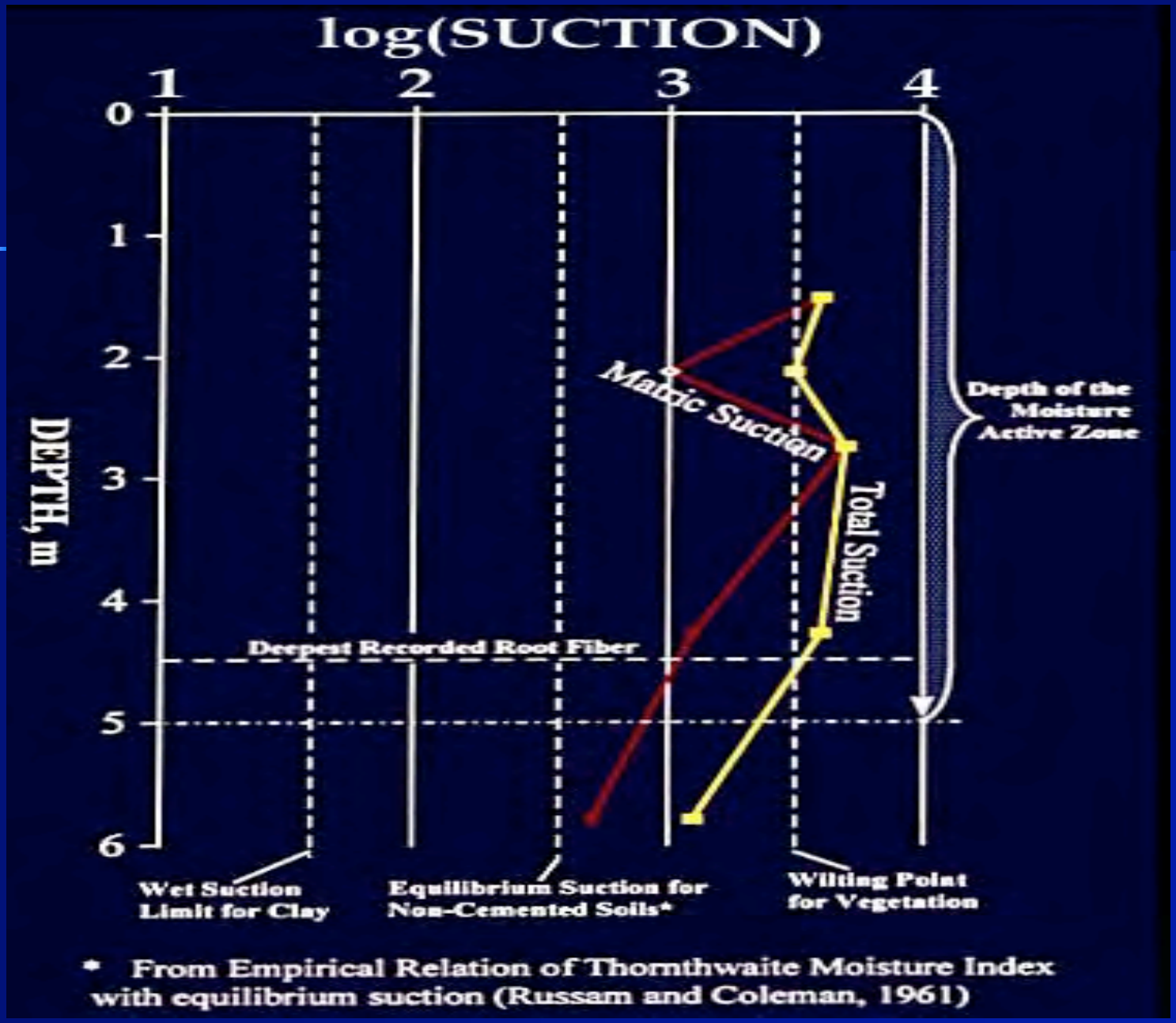

Edge Moisture
Variation Distance
from Charts
e_m
Maximum
Differential
Movement
y_m
Slab
Depth of
Moisture
Active Zone
z_0
Tree
Root
Zone
Contours of
Equal Suction
Steady State
Horizontal Flow

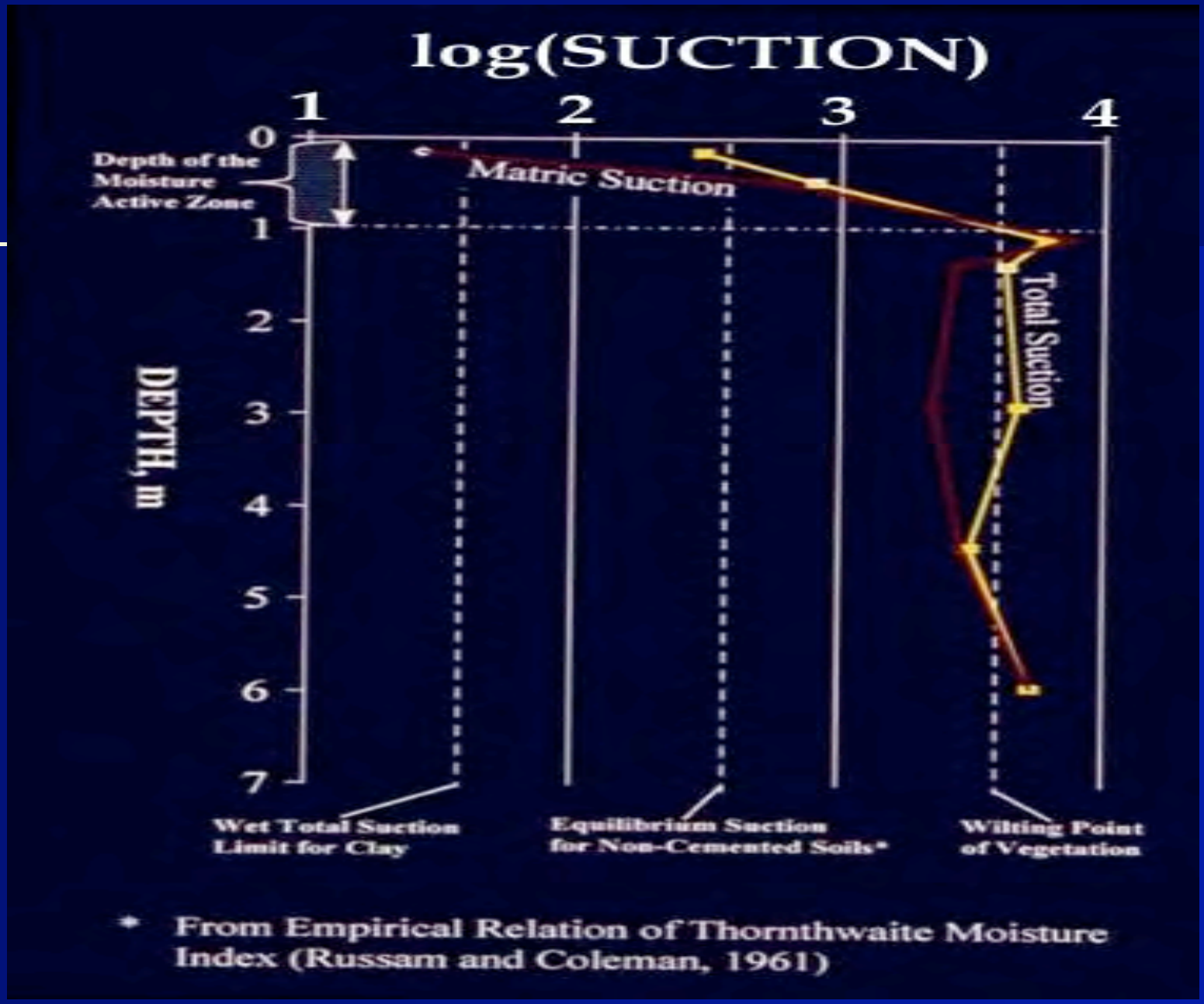

Edge Moisture
Variation Distance
from Charts
e_m
Maximum
Differential
Movement
y_m
Slab
Flower Bed
Depth of
Moisture
Active Zone
z_0
Contours of
Equal Suction
Steady State
Horizontal Flow

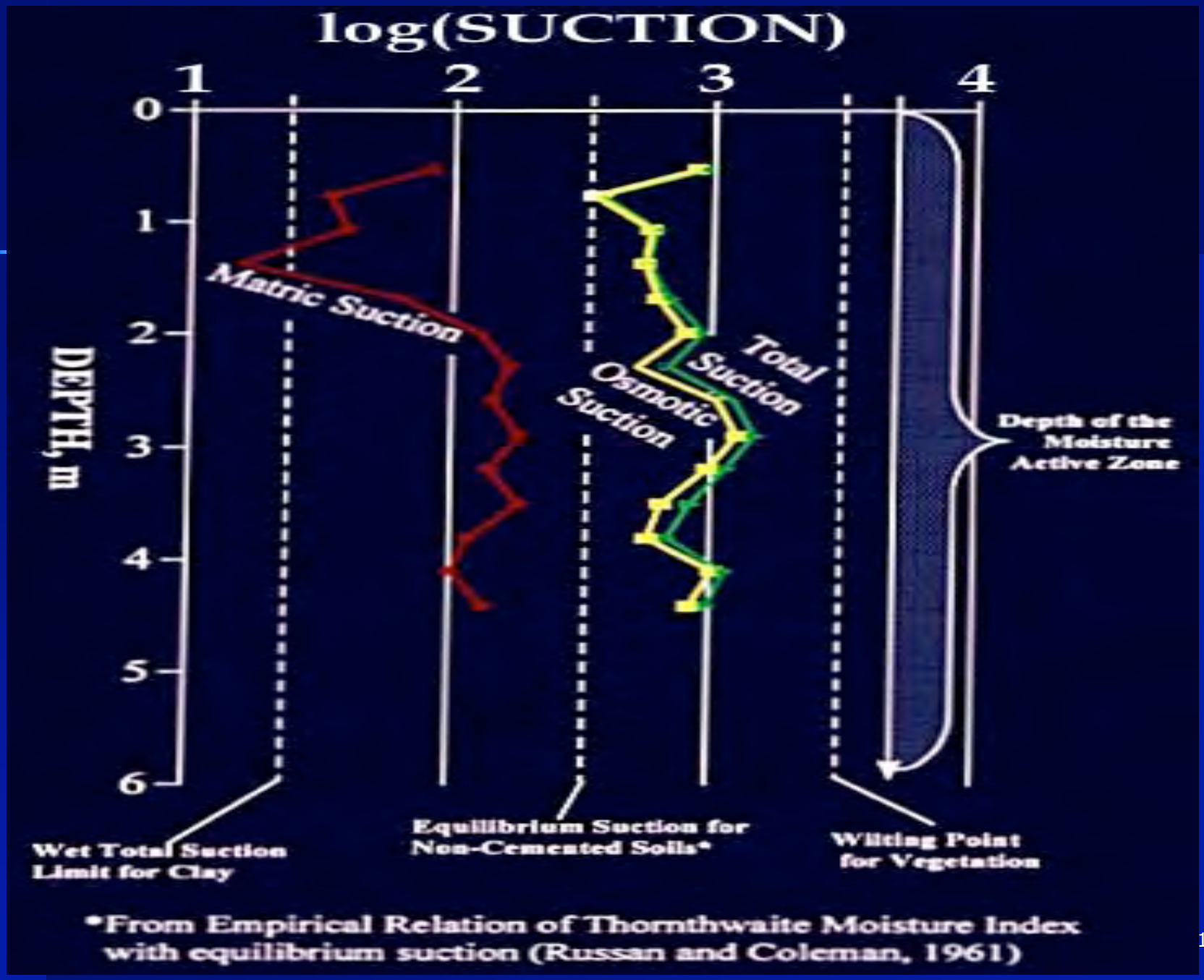

MOISTURE ACTIVE ZONE
MOISTURE INACTIVE ZONE


(-)
Suction
Ground Surface
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)

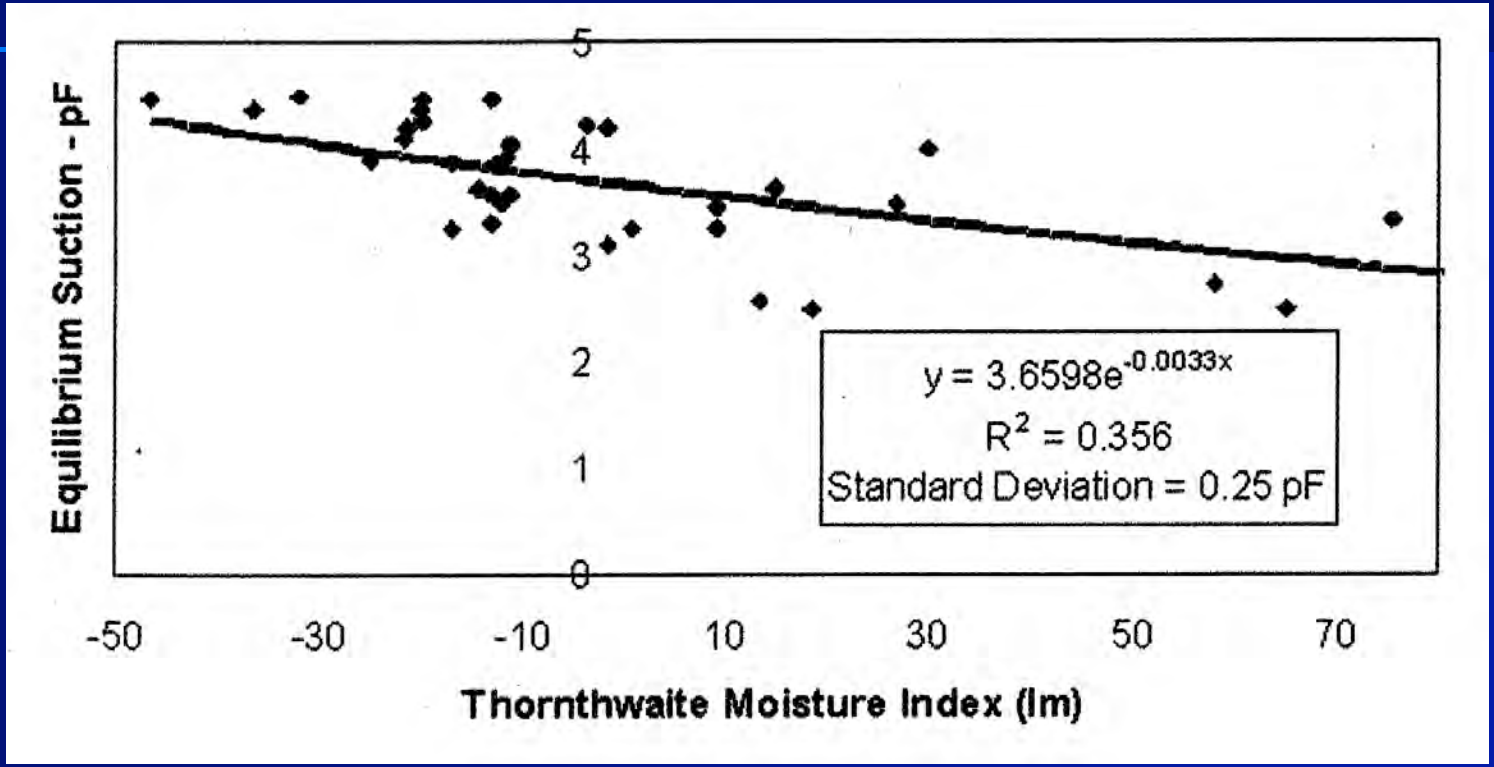

log(SUCTION)
1
2
3
4
0
1
2
3
4
5
6
DEPTH, m
Matric Suction
Total Suction
Depth of the Moisture Active Zone
Deepest Recorded Root Fiber
Wet Suction Limit for Clay
Equilibrium Suction for Non-Cemented Soils*
Wilting Point for Vegetation
* From Empirical Relation of Thornthwaite Moisture Index with equilibrium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

PTI 3rd Edition Manual

Equilibrium Soil Suction vs. TMI

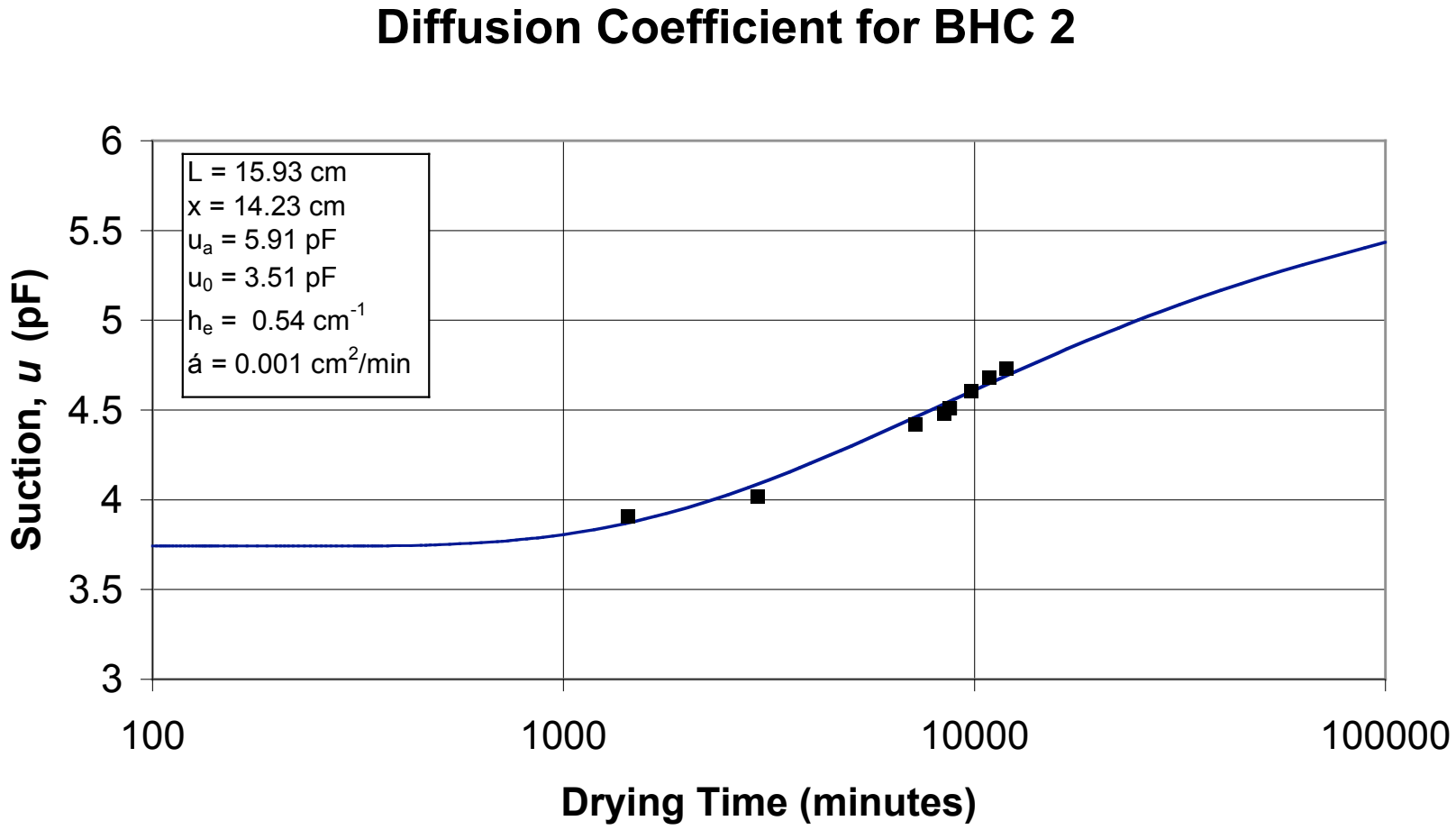


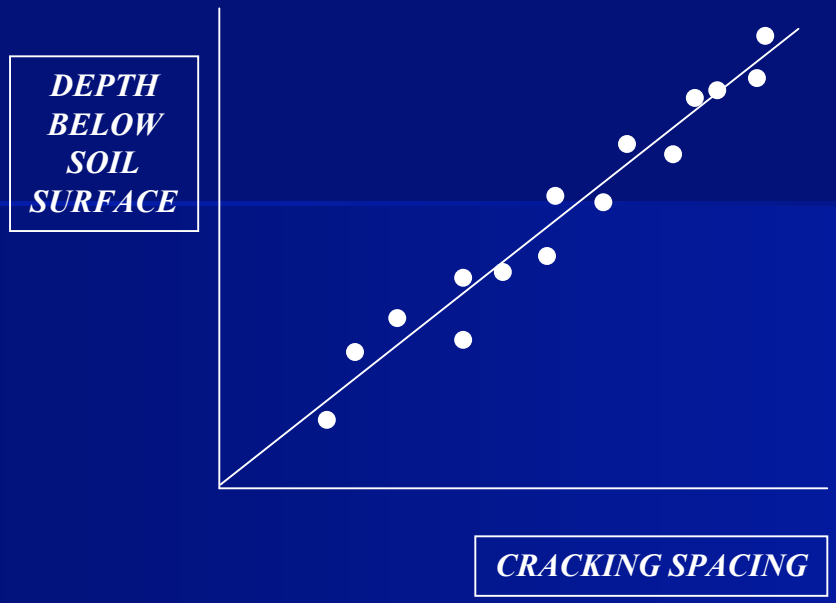
Note: Modified curve and equation of curve provided in 3rd Edition Manual.

Diffusion Test Setup

Psychrometer Installation

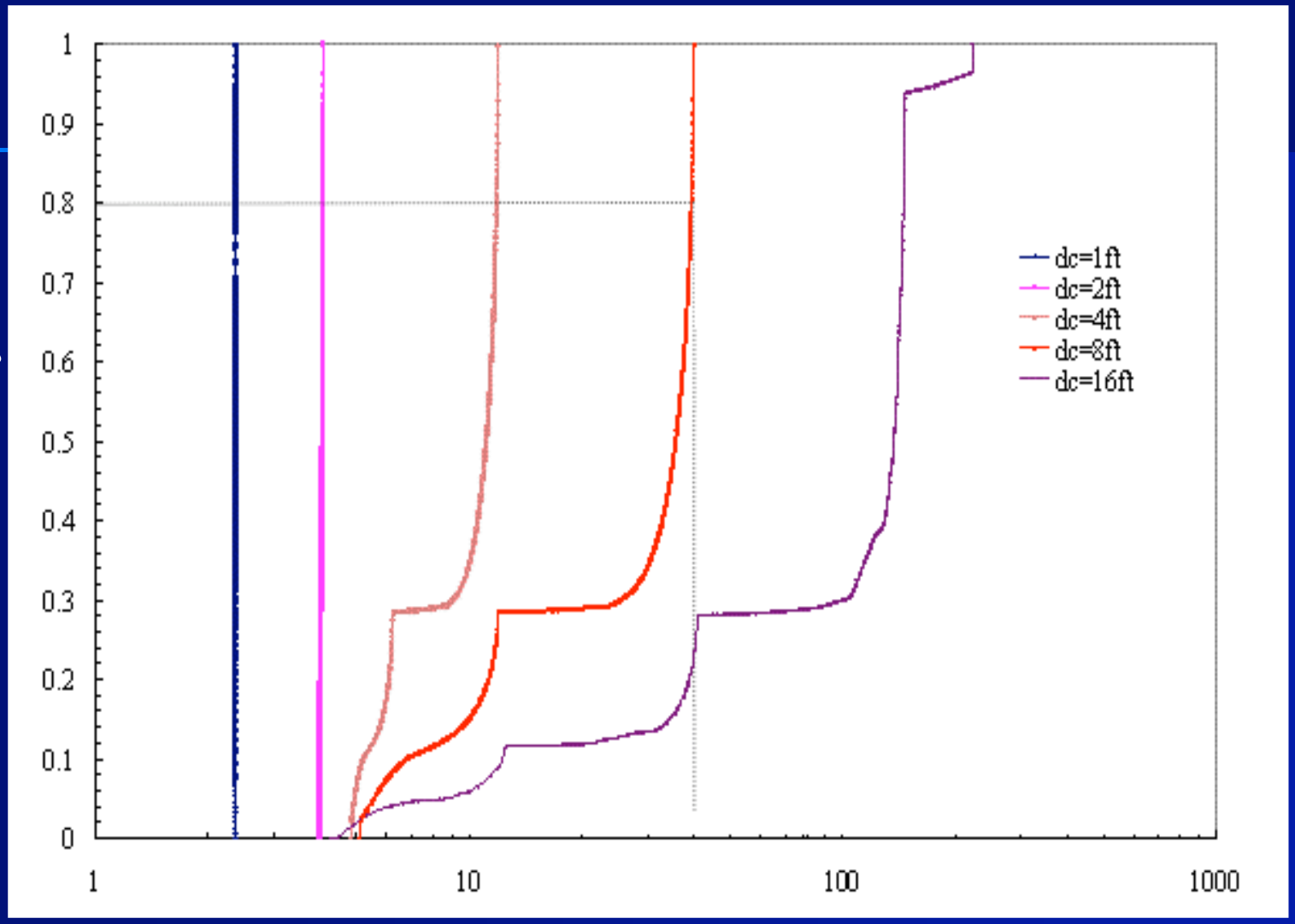
Diffusion Coefficient

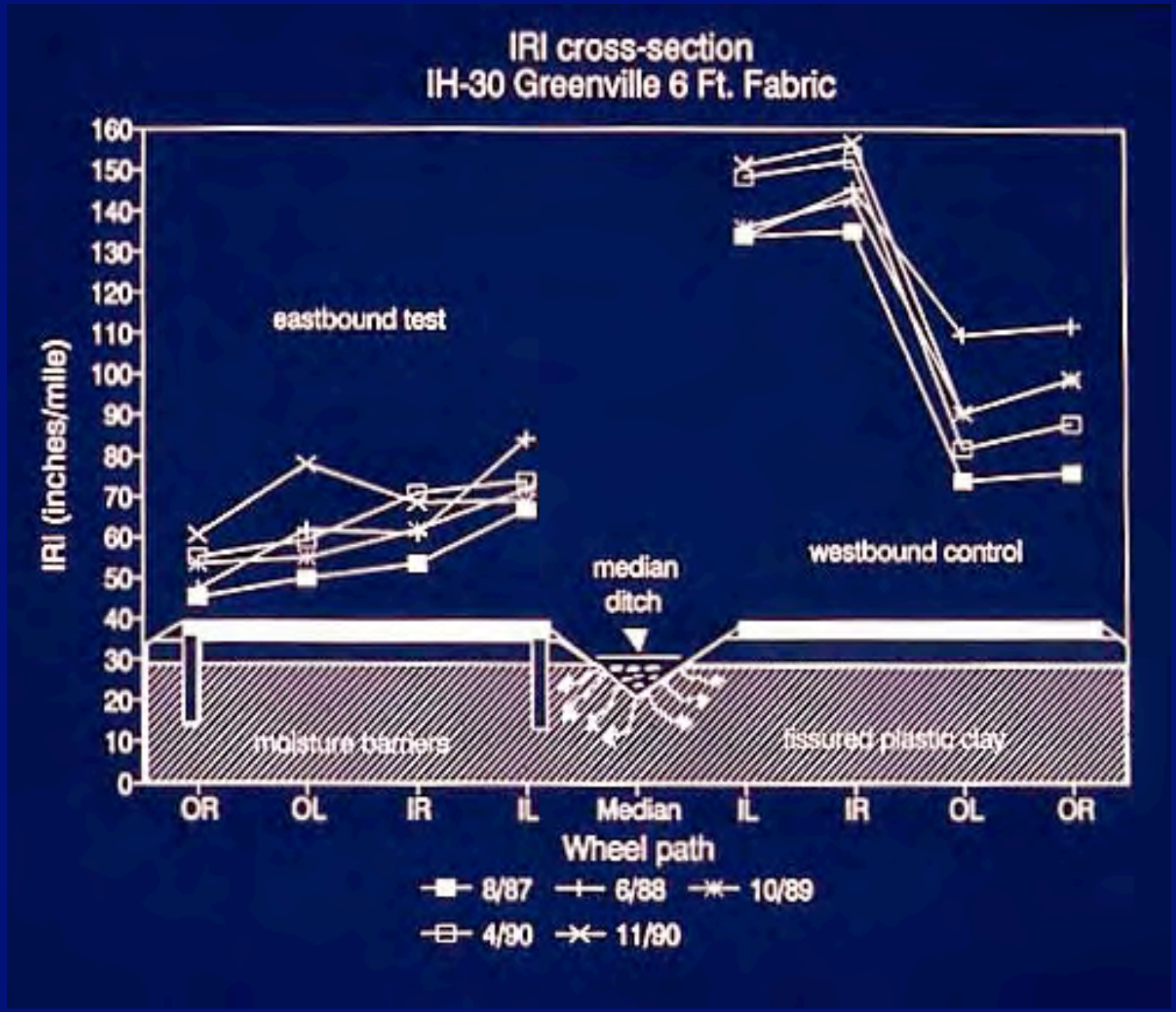




SOURCE : MICHAEL KNIGHT
PH. D. DISSERTATATION, GEOLOGY
UNIVERSITY OF MELBOURNE (AUSTRALIA)
1972

Field to laboratory diffusion coefficient ratio (Cont'd)




IRI cross-section
IH-30 Greenville 6 Ft. Fabric
IRI (inches/mile)
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
eastbound test
westbound control
median
ditch
moisture barriers
fissured plastic clay
OR
OL
IR
IL
Median
IL
IR
OL
OR
Wheel path
8/87
6/88
10/89
4/90
11/90

Design Program - Winpres

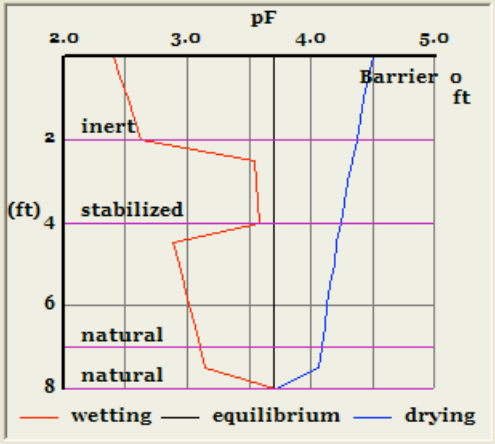
Calculated Vertical Movement

```
RIGID PAVEMENTS
INERT/STABILIZED/NATURAL
BARRIER DEPTH                = 0.00 ft

DEPTH OF ACTIVE ZONE         = 7.50 ft

VERTICAL SWELLING            = 0.220 ft
VERTICAL SHRINKAGE           = 0.071 ft
TOTAL 1-D MOVEMENT           = 0.291 ft

        2D VERTICAL MOVEMENT
DIST. FROM CENTER(ft) MOVEMENT(inches)
       6.00              2.16
       9.00              2.26
```

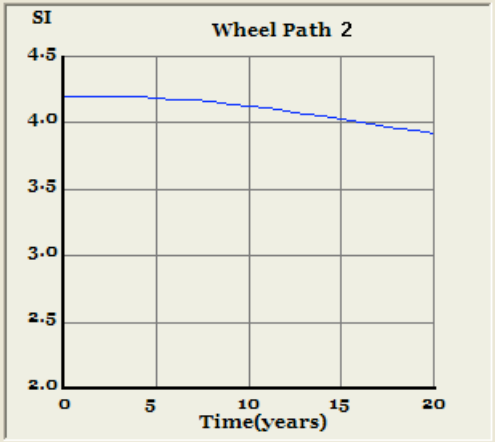
Output

```
COMPLETE OUTPUT FILE

PROJECT NAME              :Rigid-Natural-Inert-Sta. 1-3 (IH 635 Dallas)
PROJECT DATE              :December.20. 2003
PROJECT NUMBER            :00-0000-000
PROJECT ENGINEER          :Gyeong-Taek Hong

****************** INPUT DATA ******************

PAVEMENT TYPES            : RIGID PAVEMENTS

SOIL PROPERTIES
```

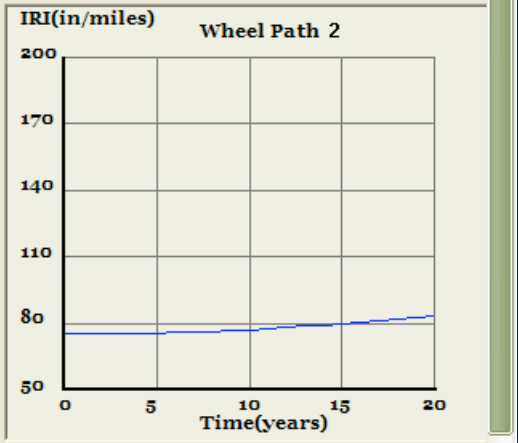
Suction Profile vs Depth



Serviceability Index vs time

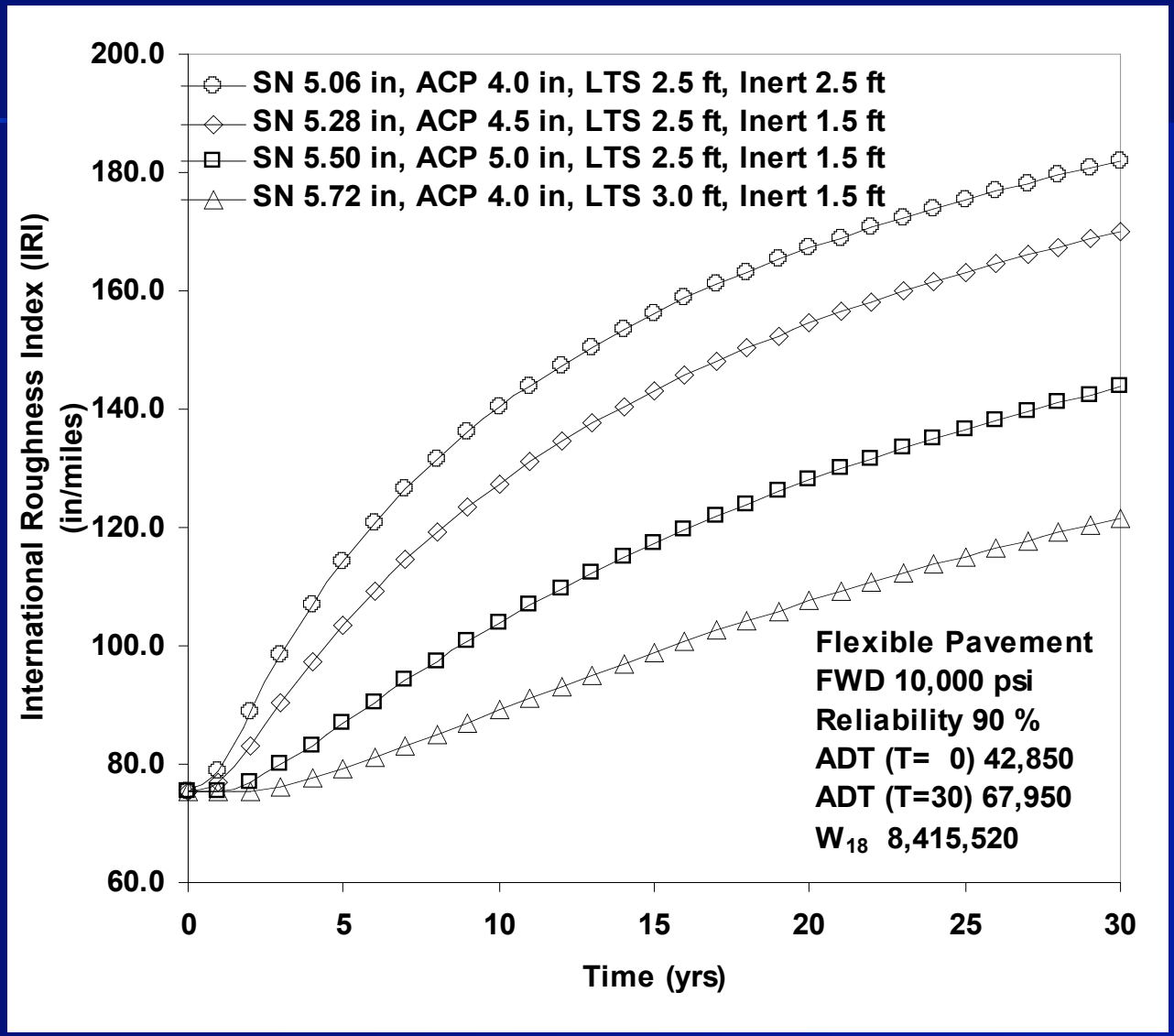


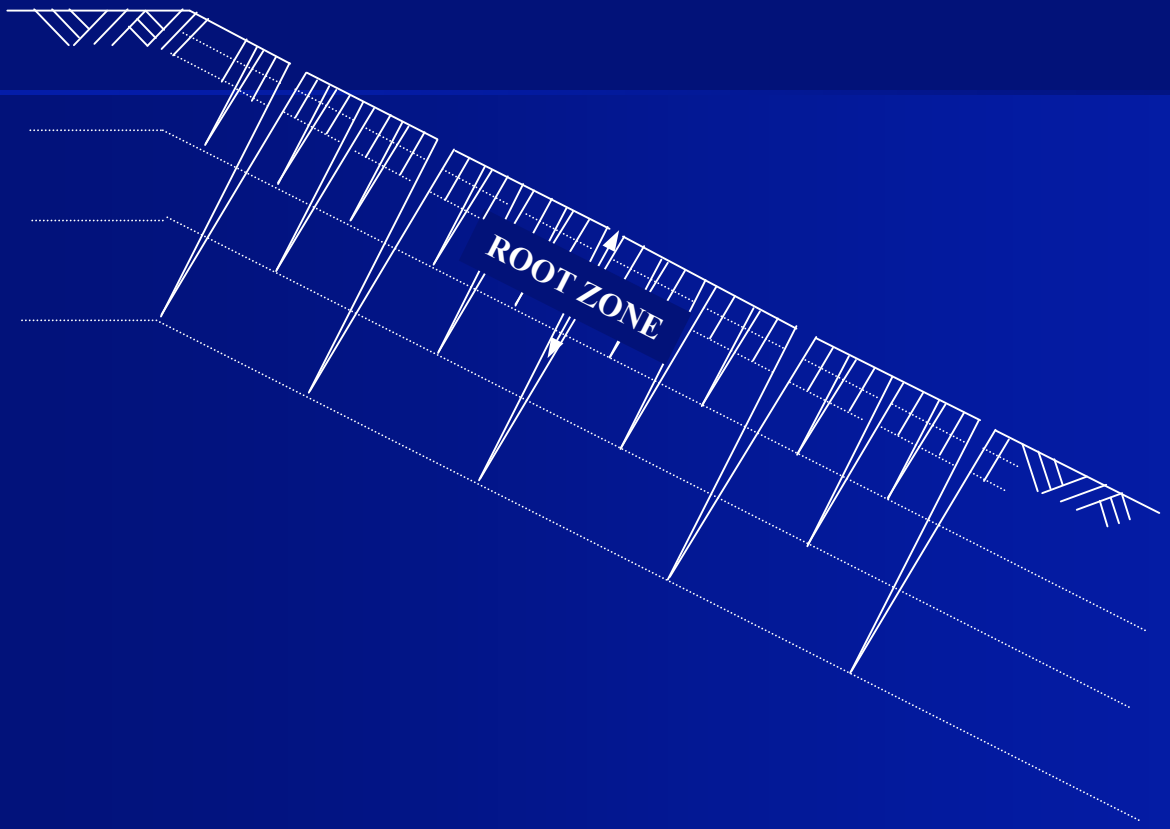
International Roughness Index vs time



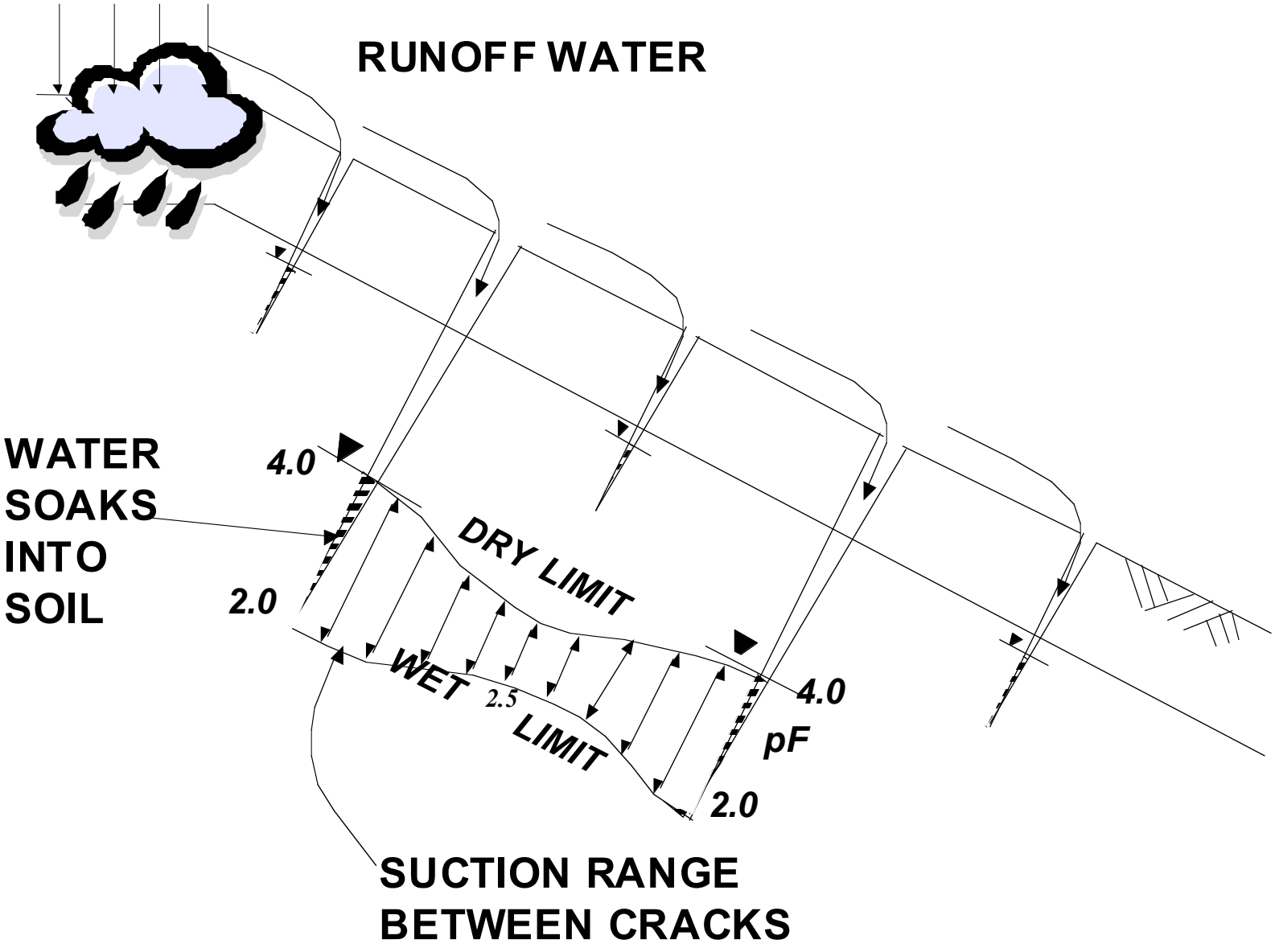
Input | Path 1 | Path 2 | Path 3

Design Program - Winpres
IRI versus Time





Crack Spacing Gets Larger with Depth


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

SULFATE SWELLING PROBLEMS

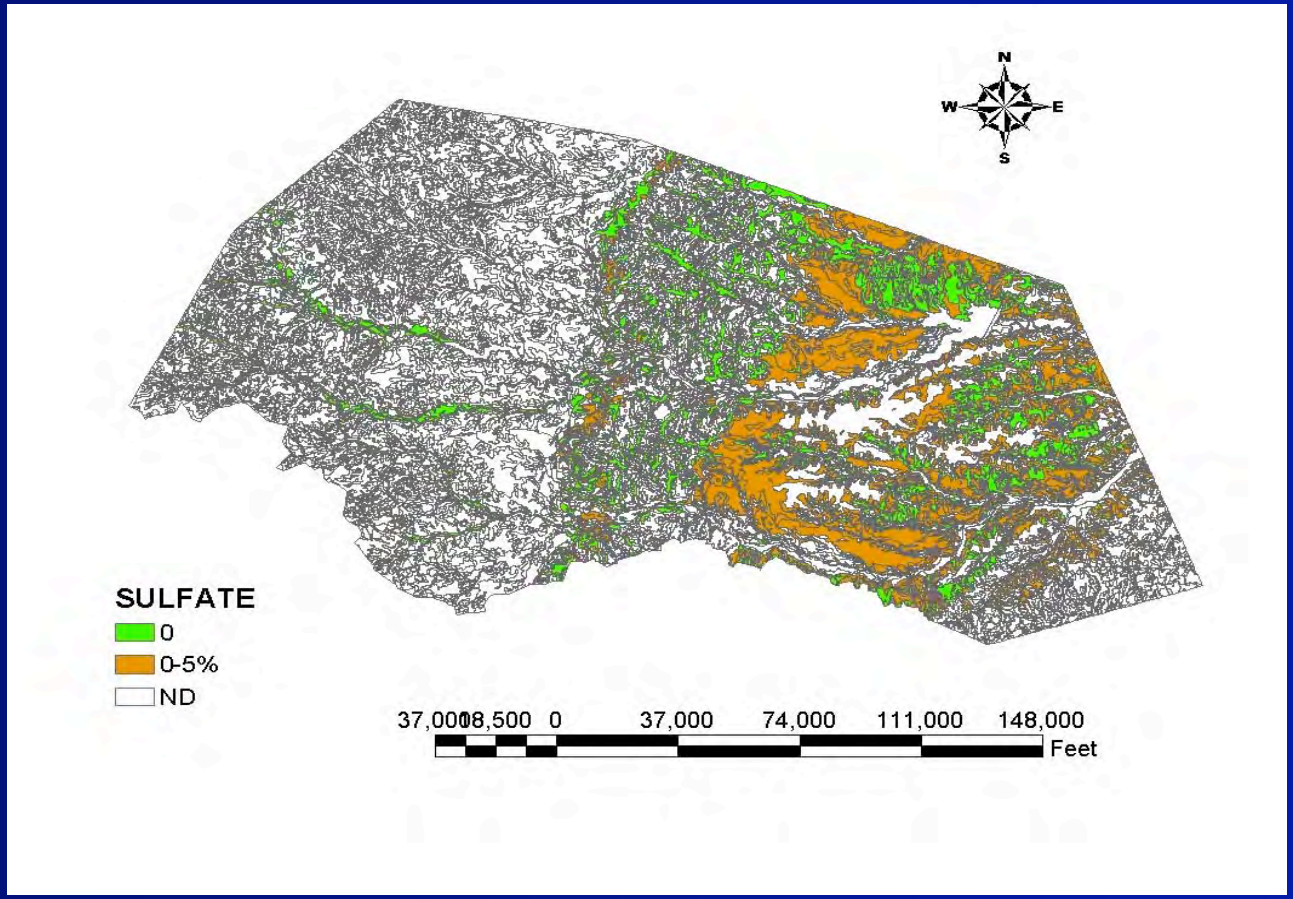
LIME +

SULFATE +

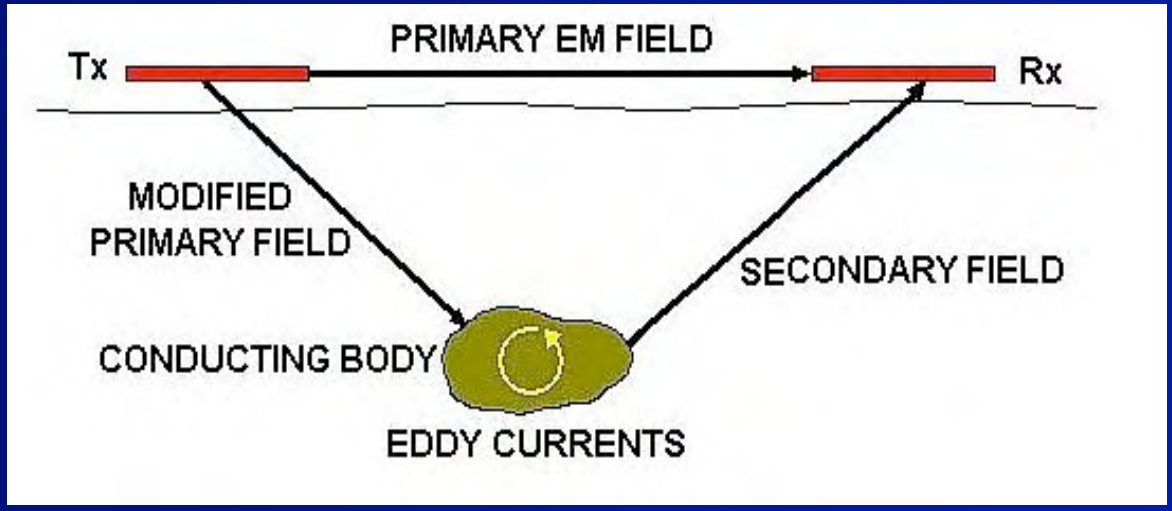
WATER +

CLAY = PAVEMENT BUCKLING

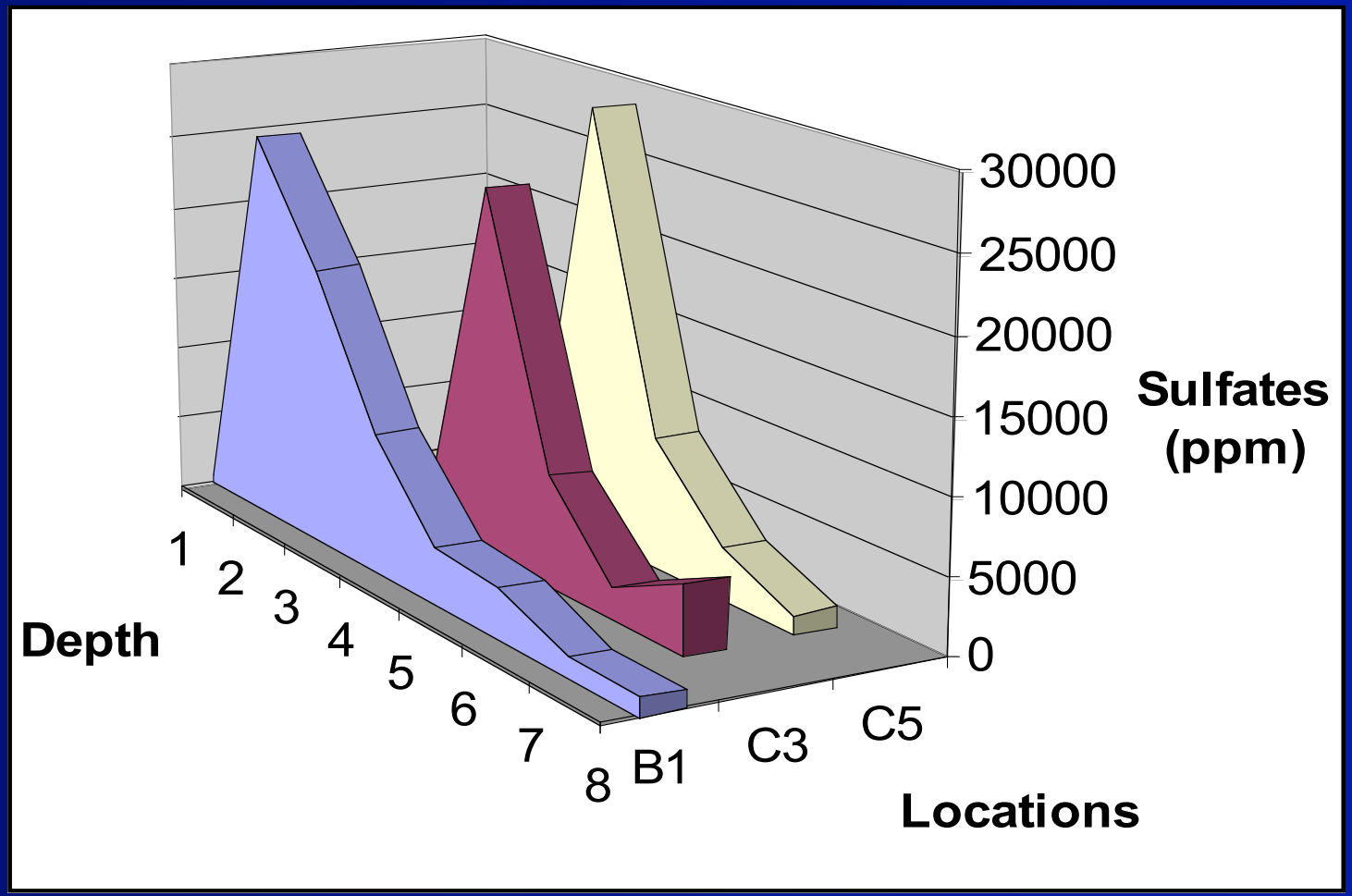
Williamson County Soil Map



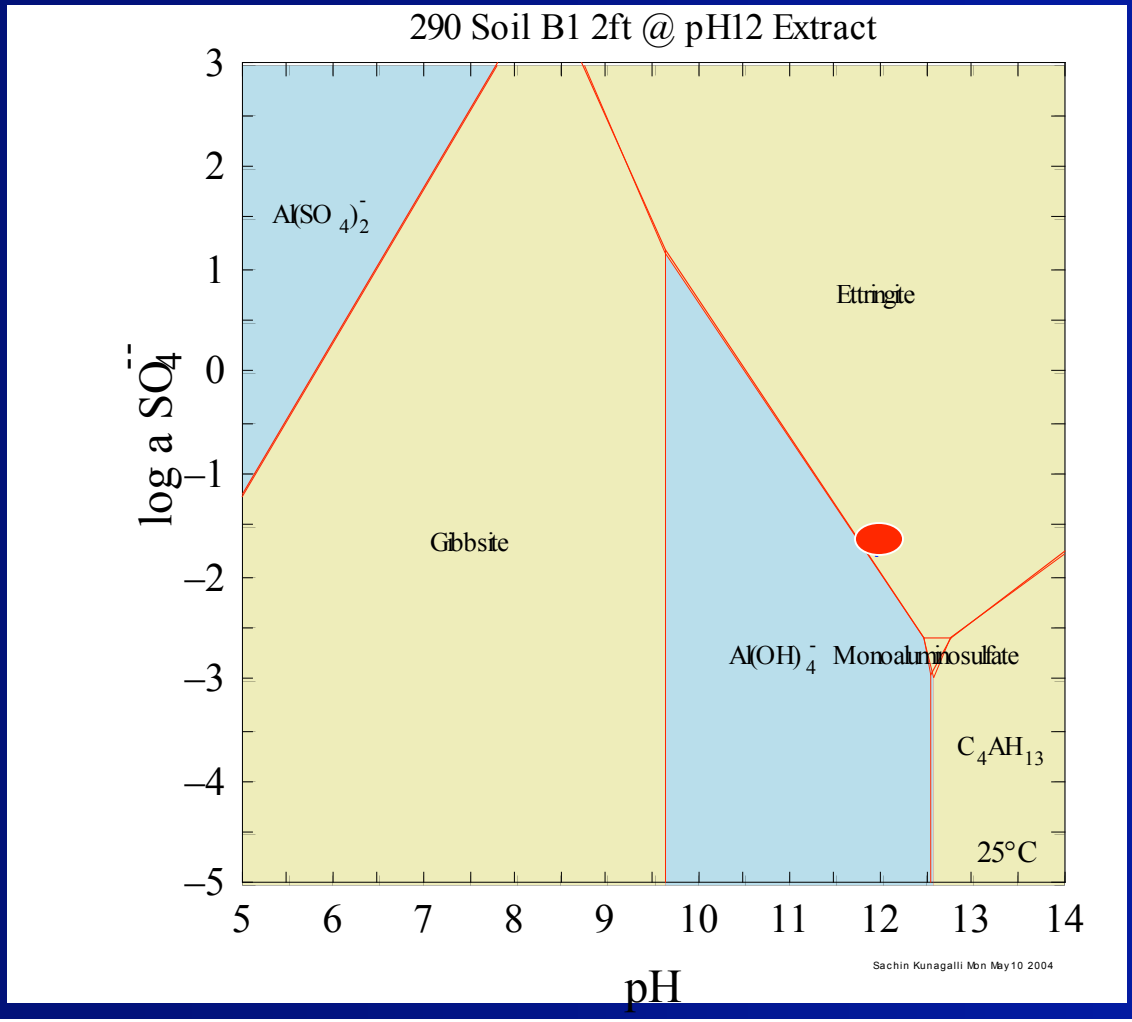
Magnetometer



Variation of Sulfate along slope of the surface

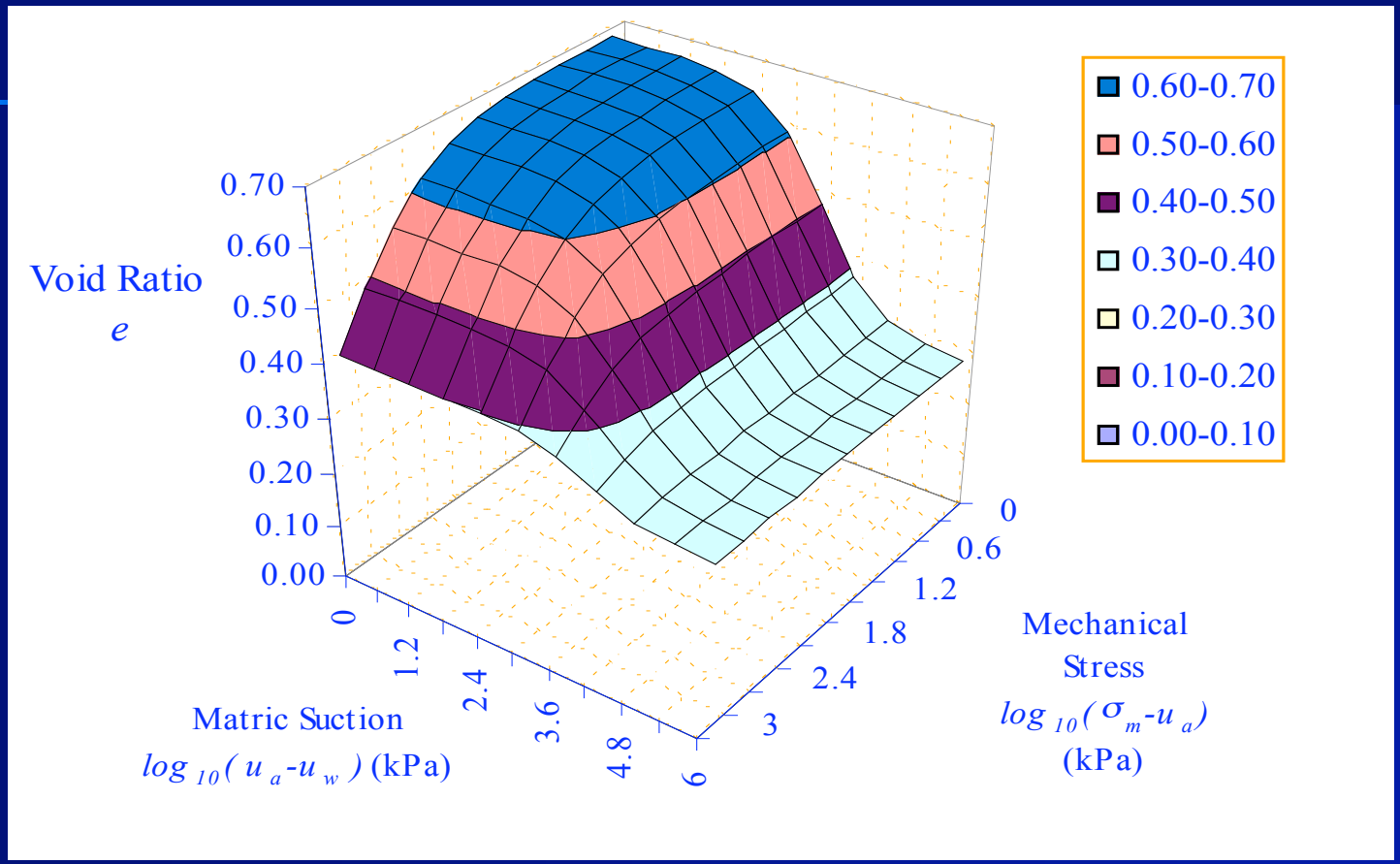


Stability Models or Phase Diagrams
290 Soil - Depth of 24-inches



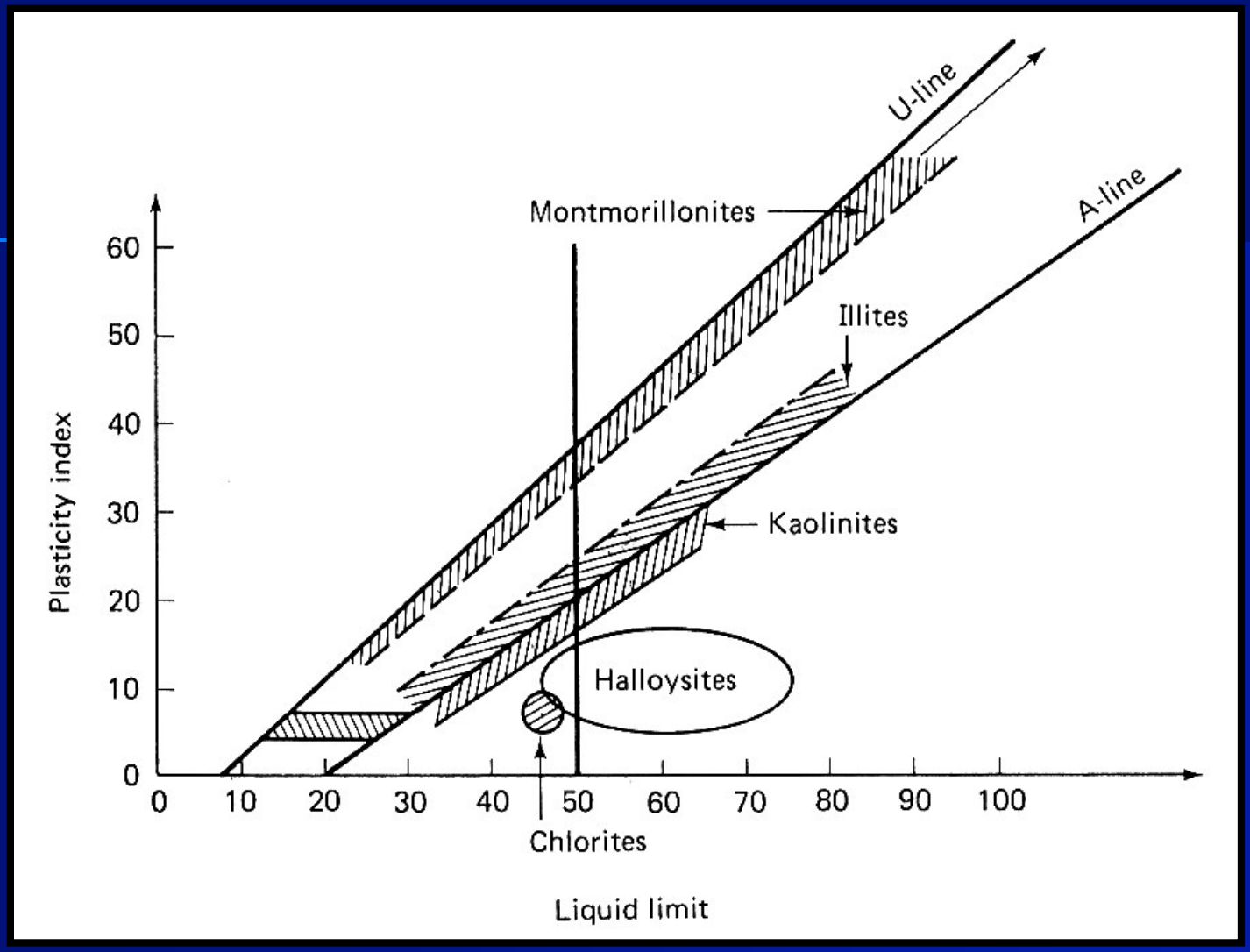
Soluble Sulfates = 18,700 ppm

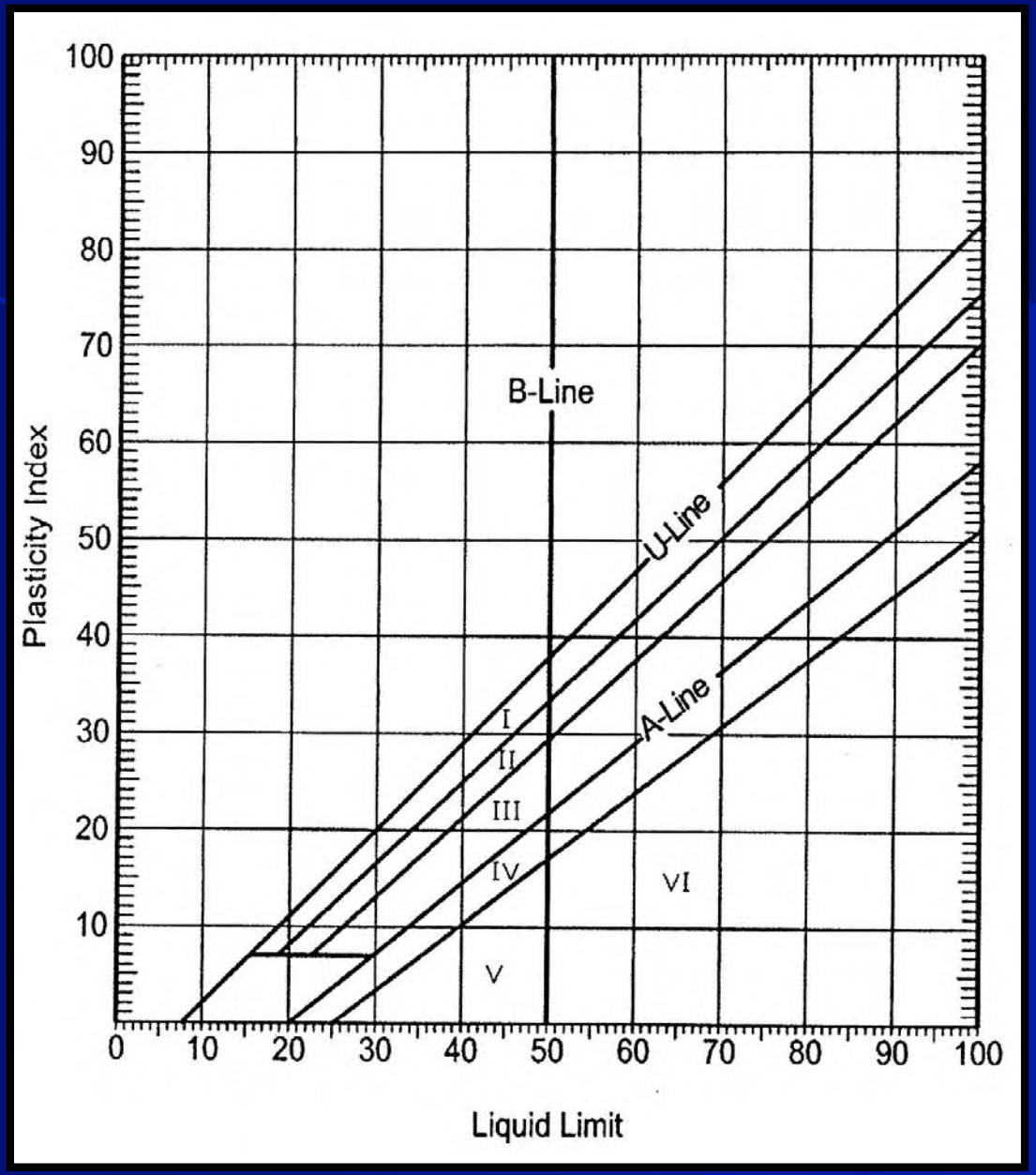
VOID RATIO CONSTITUTIVE SURFACE OF A SOIL AT ARLINGTON, TEXAS

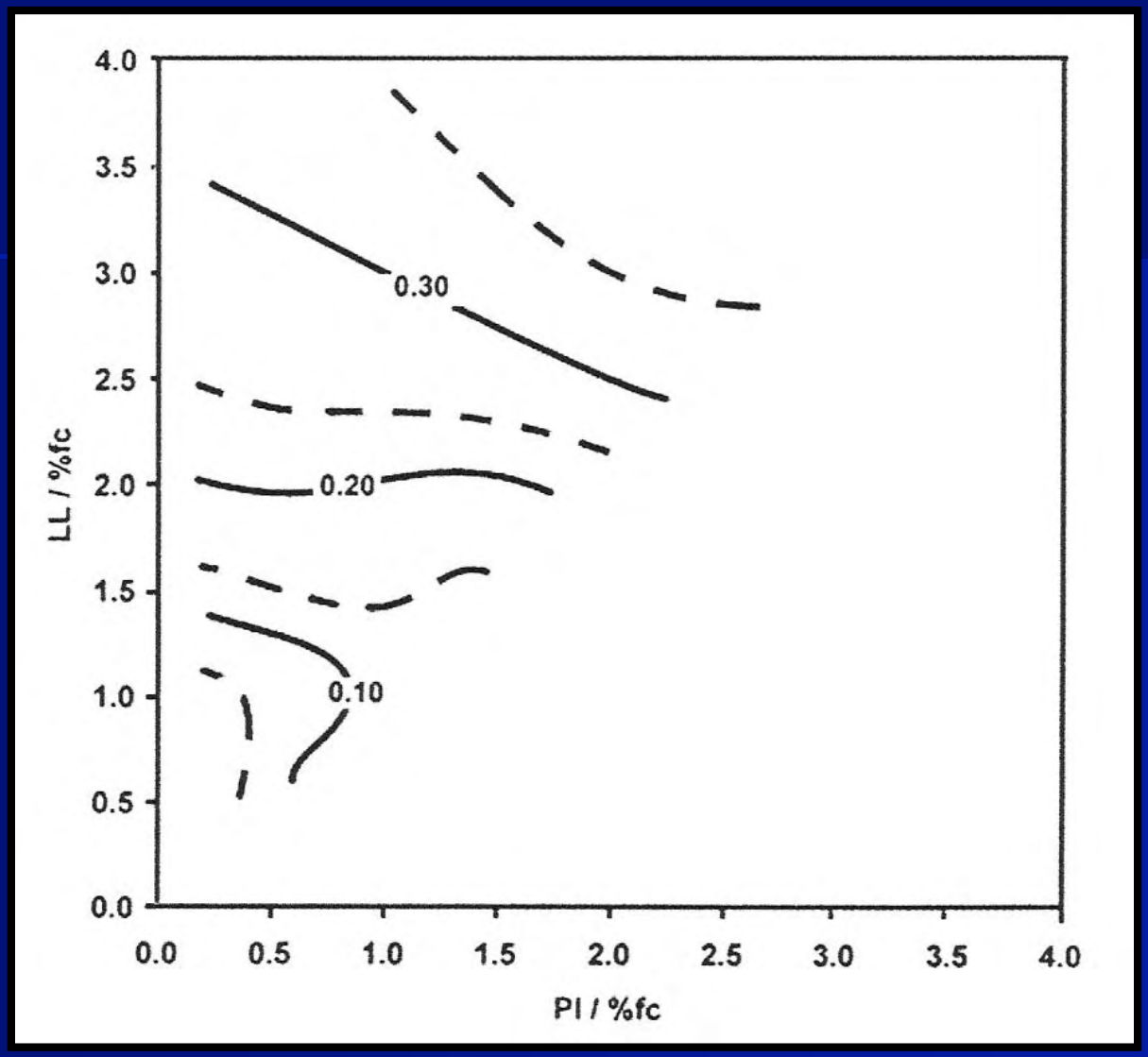


MATHMATICAL EXPRESSION:

$$\frac{(\sigma_v - u_a)}{10^{\left(0.422\ln\left(\frac{0.492}{(e-0.195)}-1\right)+2.640\right)}} + \frac{(u_a - u_w)}{10^{\left(0.456\ln\left(\frac{0.387}{e-0.299}-1\right)+3.624\right)}} = 1$$


U-line
A-line
Montmorillonites
Illites
Kaolinites
Halloysites
Chlorites
Plasticity index
Liquid limit
0
10
20
30
40
50
60
70
80
90
100


Plasticity Index
Liquid Limit
B-Line
U-Line
A-Line
I
II
III
IV
V
VI
0
10
20
30
40
50
60
70
80
90
100


4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
LL / %fc
0.30
0.20
0.10
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
PI / %fc

CONSTRUCTED WORKS IMPACTED BY EXPANSIVE SOILS

- ✓ Building Foundations
- ✓ Pavements
- ✓ Embankments, Cuts and Slopes

REVISITATION
OF
EXPANSIVE SOILS

ROBERT L. LYTTON, PhD

Foundation Performance Association

Houston, Texas

December 13, 2006