Contrasting Design Approaches for Slab-on-Ground and Raised Floor Foundations on Expansive Soils

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Houston, Texas
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Outline

- Elements of design
- Site conditions
- Slabs-on-ground
- Raised floor foundations
- Costs

Elements of Design

- Structural requirements
  - Moments
  - Shear
  - Deflection

  As determined by site conditions

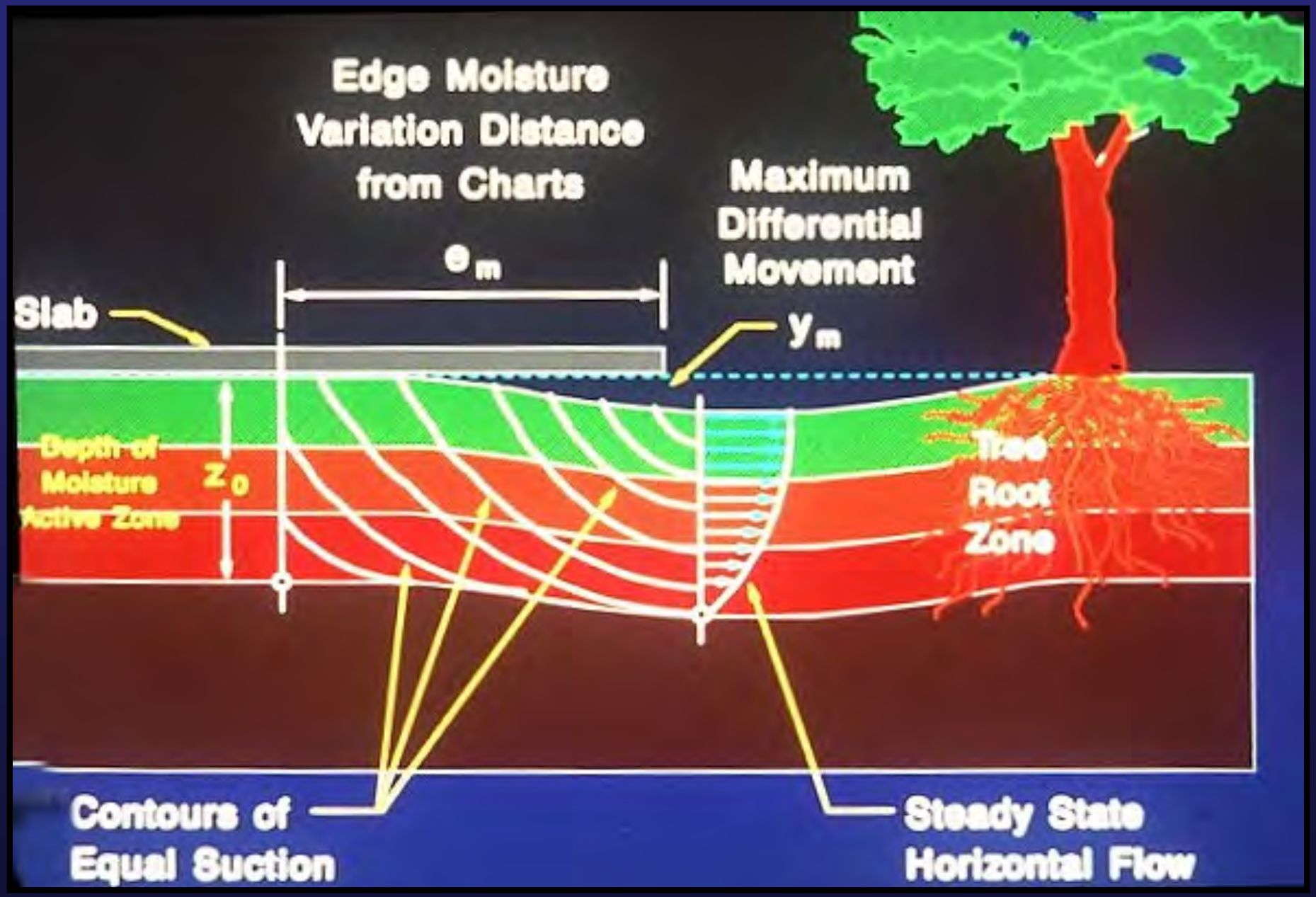
- Costs

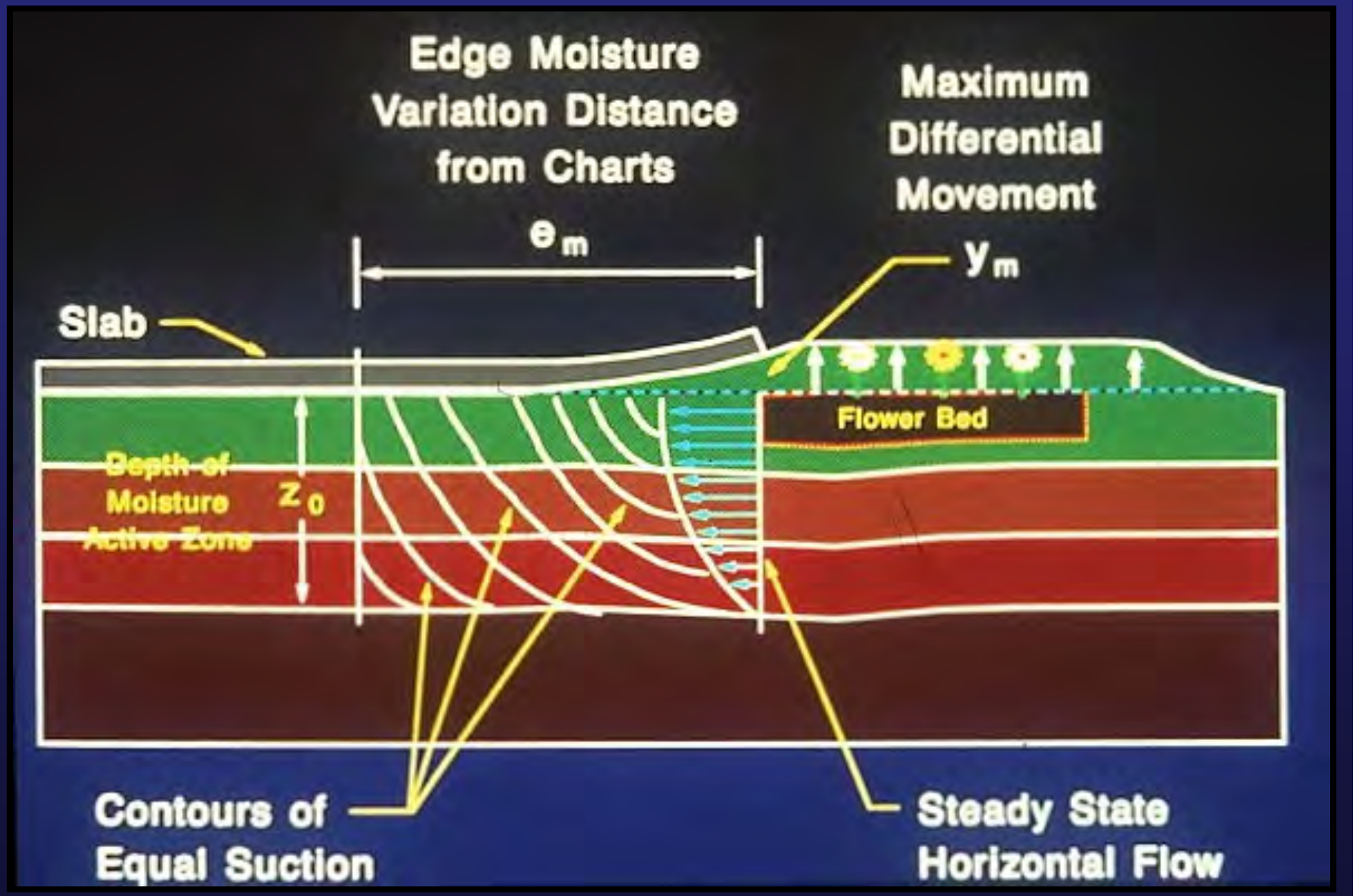
Site Conditions

- Soils
- Site hazards
  - Trees
  - Slopes
  - Drainage
- Building geometry

Slabs-on-Ground: Soils

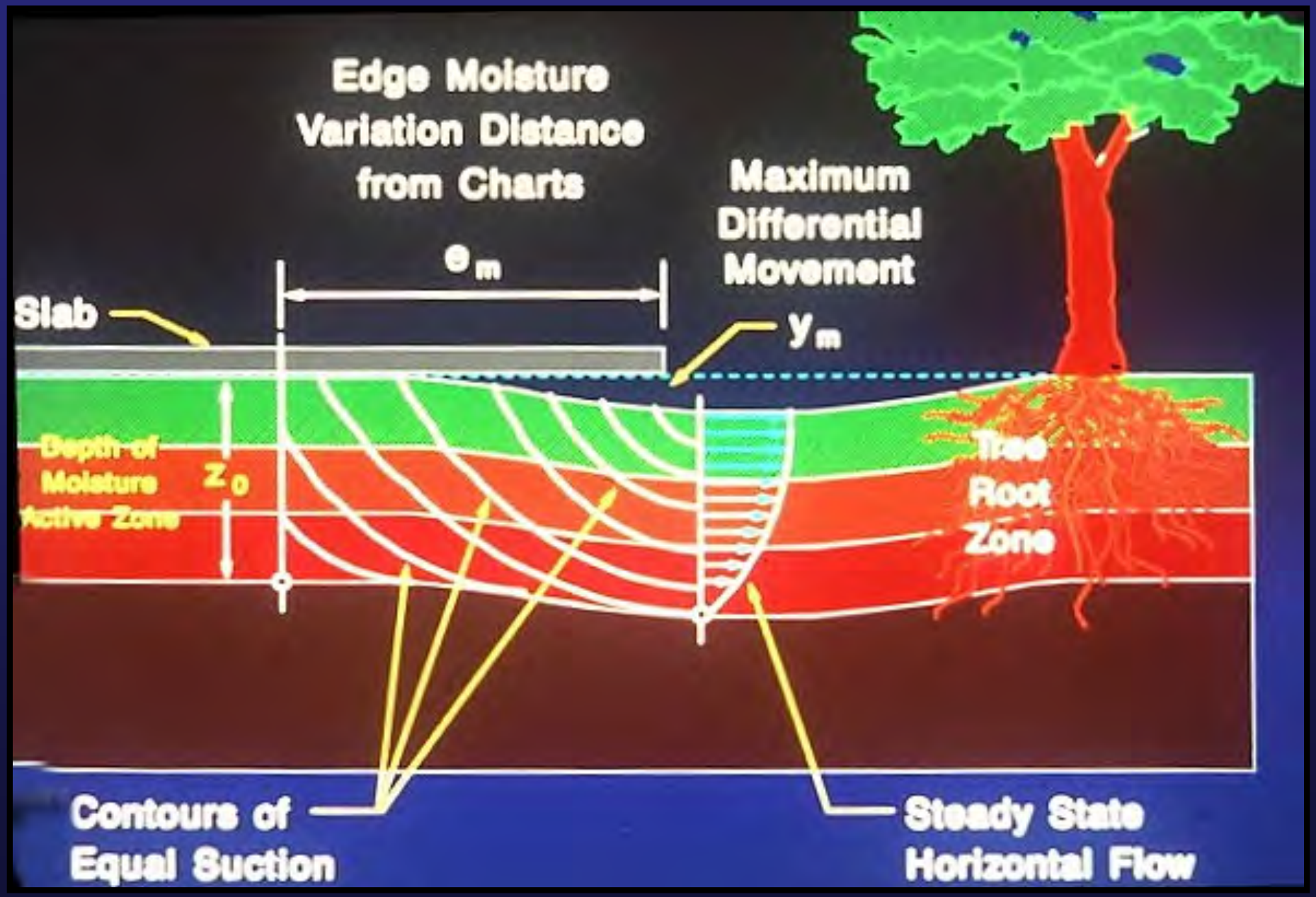
- y_m: differential movement of soil
  - Perimeter swelling
  - Perimeter shrinking
  - Center swelling
  - Center shrinking


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

Slabs-on-Ground: Soils

- e_m: edge moisture variation distance
  - Not a cantilever distance
  - A property of the soil mass
  - Depends on soil activity and cracking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e_m
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Tree
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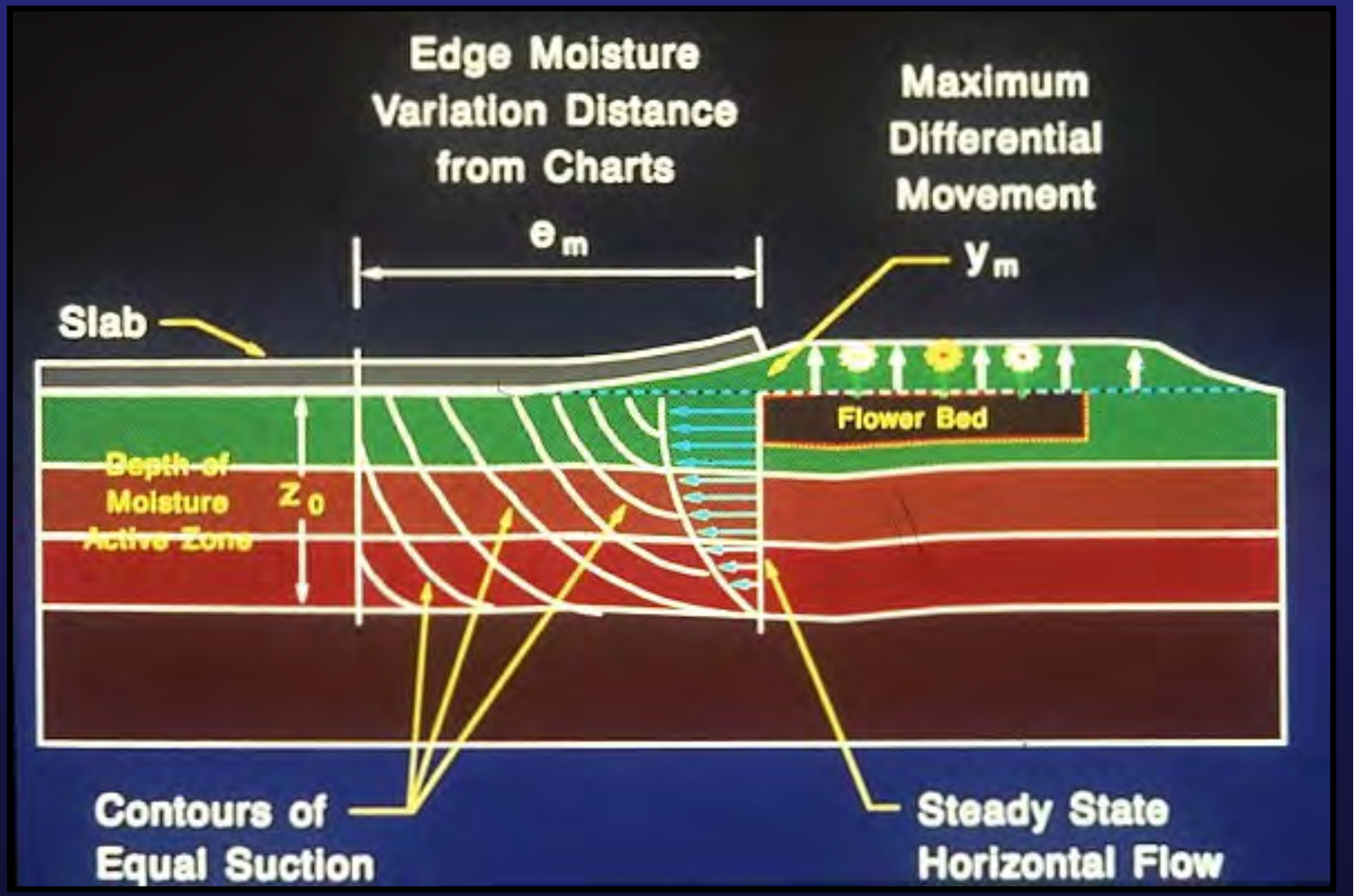
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y_m
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Flower Bed
Depth of
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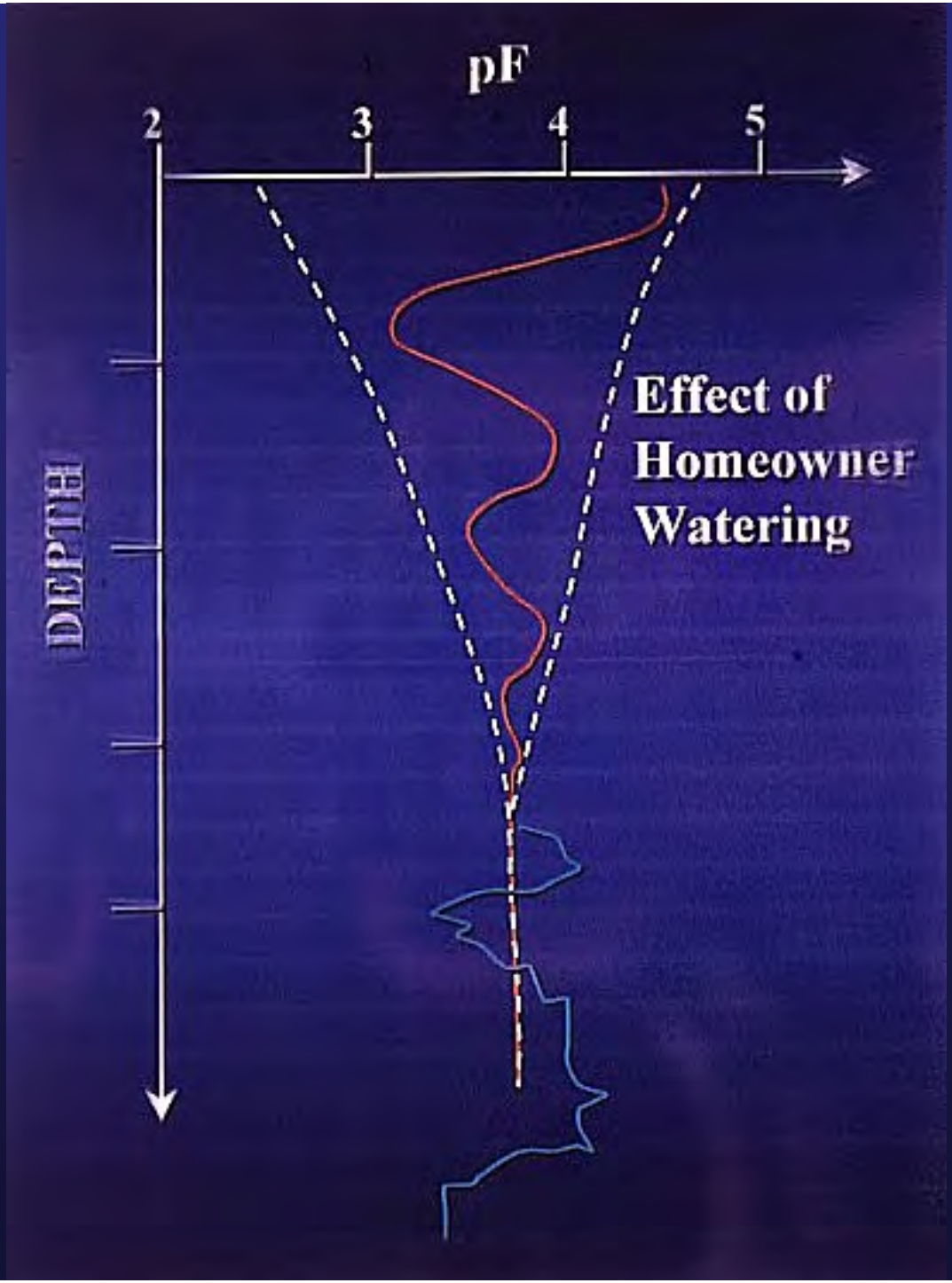
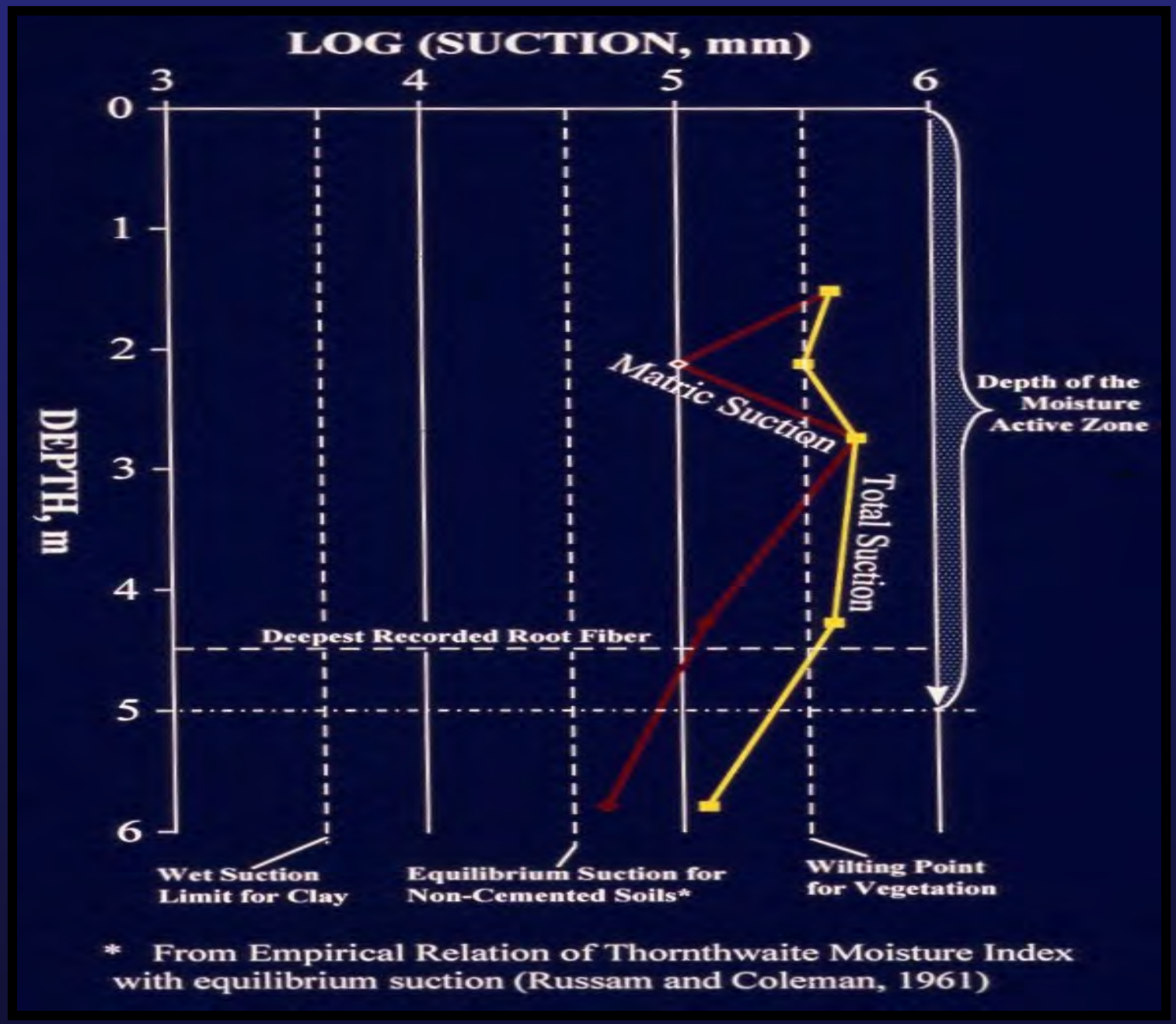
Active Zone
z_0
Contours of
Equal Suction
Steady State
Horizontal Flow

Slabs-on-Ground: Soils

- z_m: depth of the moisture active zone
  - Depth of shrinkage cracks created by roots (log for root fibers)
  - No deeper than soil at the wilting point of plants


MOISTURE ACTIVE ZONE
MOISTURE INACTIVE ZONE


pF
2
3
4
5
DEPTH
Effect of
Homeowner
Watering


LOG (SUCTION, mm)
3
4
5
6
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)

Slabs-on-Ground: Soils

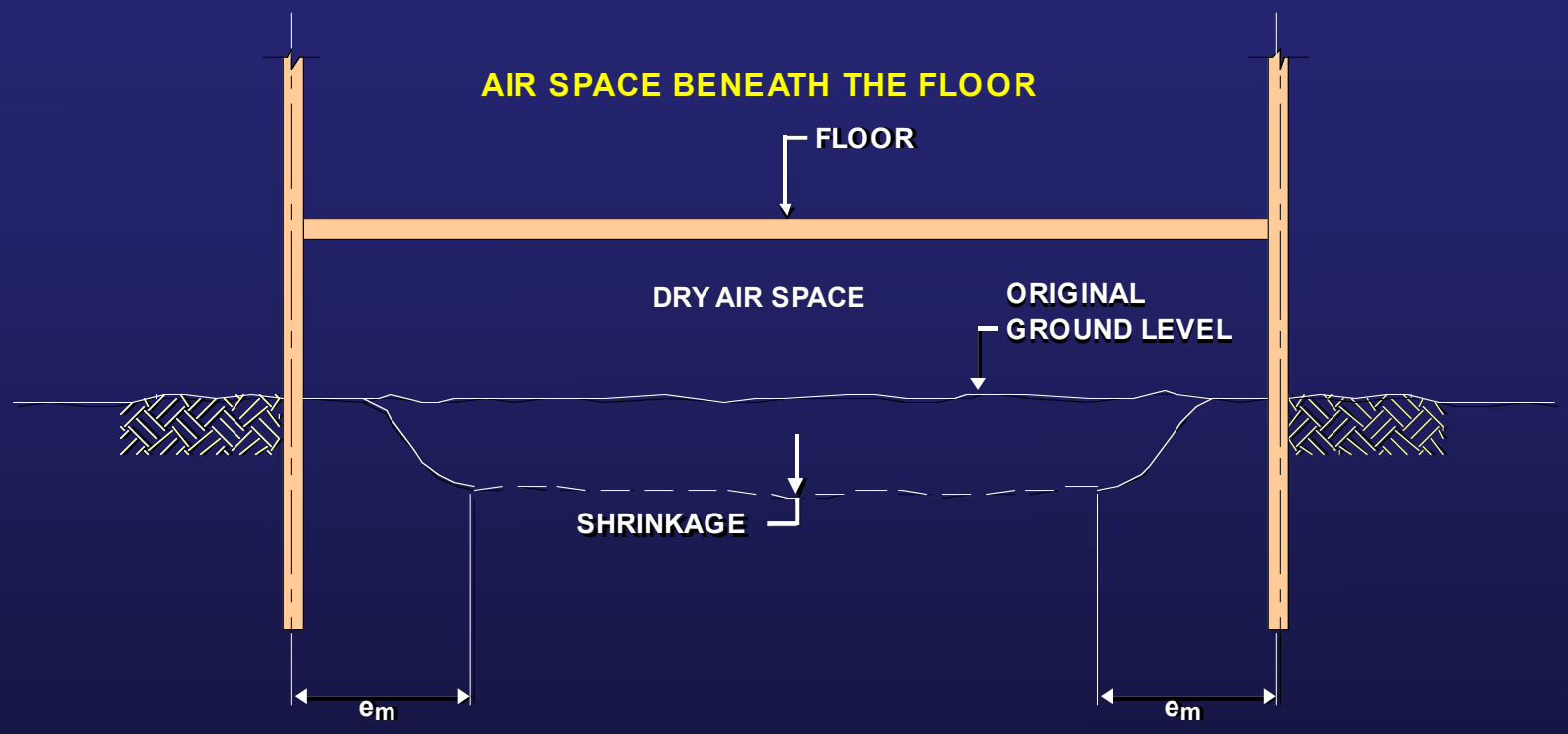
- z_A: depth of the movement active zone
  - Always shallower than z_m
  - Large factor in y_m


BMC WEST
281-342-4282

Raised Floor Foundations: Soils

- y_m: differential movement
  - Center drying, total shrinkage
  - Perimeter total swelling
    - Drainage
    - Flower beds
  - Perimeter total shrinking: trees
  - Downhill creep

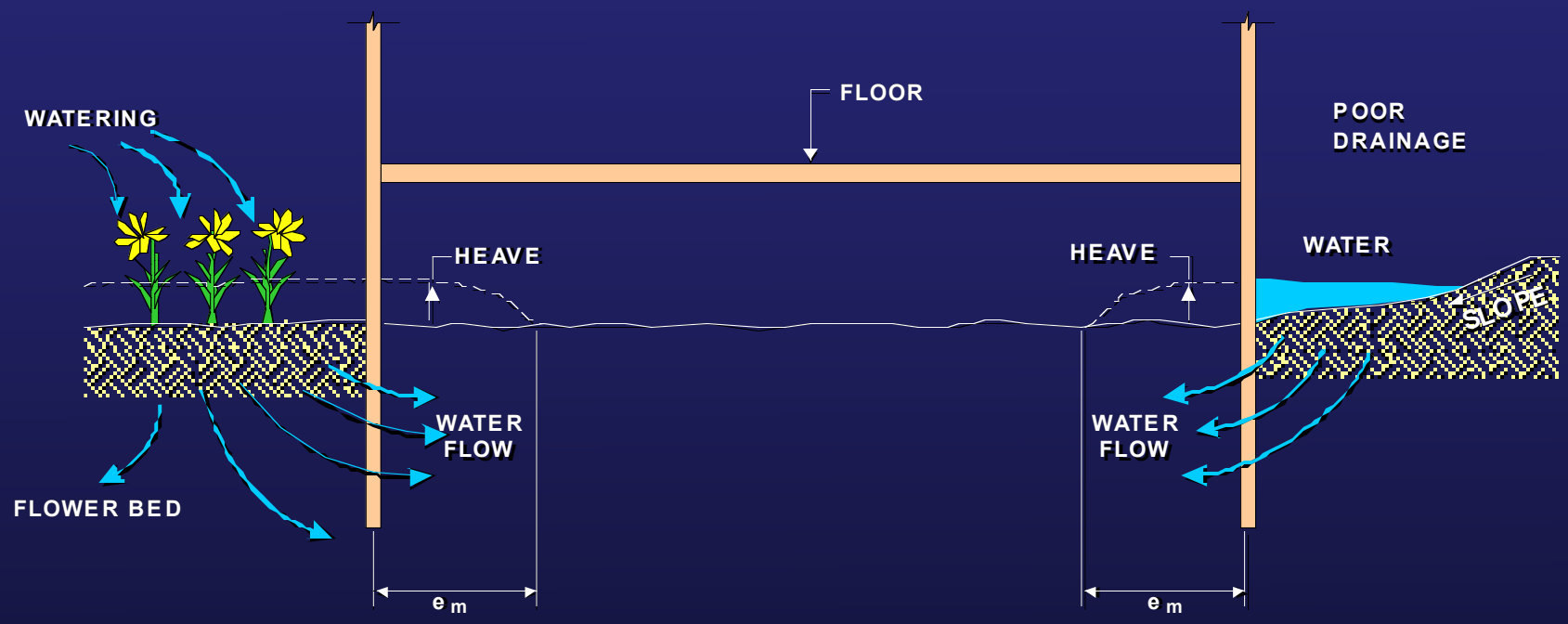
TOTAL MOVEMENT PATTERNS WITH RAISED WOOD FLOOR FOUNDATIONS



NOTE

AMOUNT OF SHRINKAGE DEPENDS ON THE LEVEL OF RELATIVE HUMIDITY IN THE AIR BENEATH THE FLOOR. THE LOWER THE RELATIVE HUMIDITY, THE GREATER WILL BE THE AMOUNT OF SHRINKAGE. INITIALLY, THE SOIL WILL BE AT OR ABOVE 98% RELATIVE HUMIDITY. e m IS THE EDGE MOISTURE VARIATION DISTANCE WHICH VARIES TYPICALLY BETWEEN 3 AND 9 FEET DEPENDING ON THE TYPE OF SOIL.

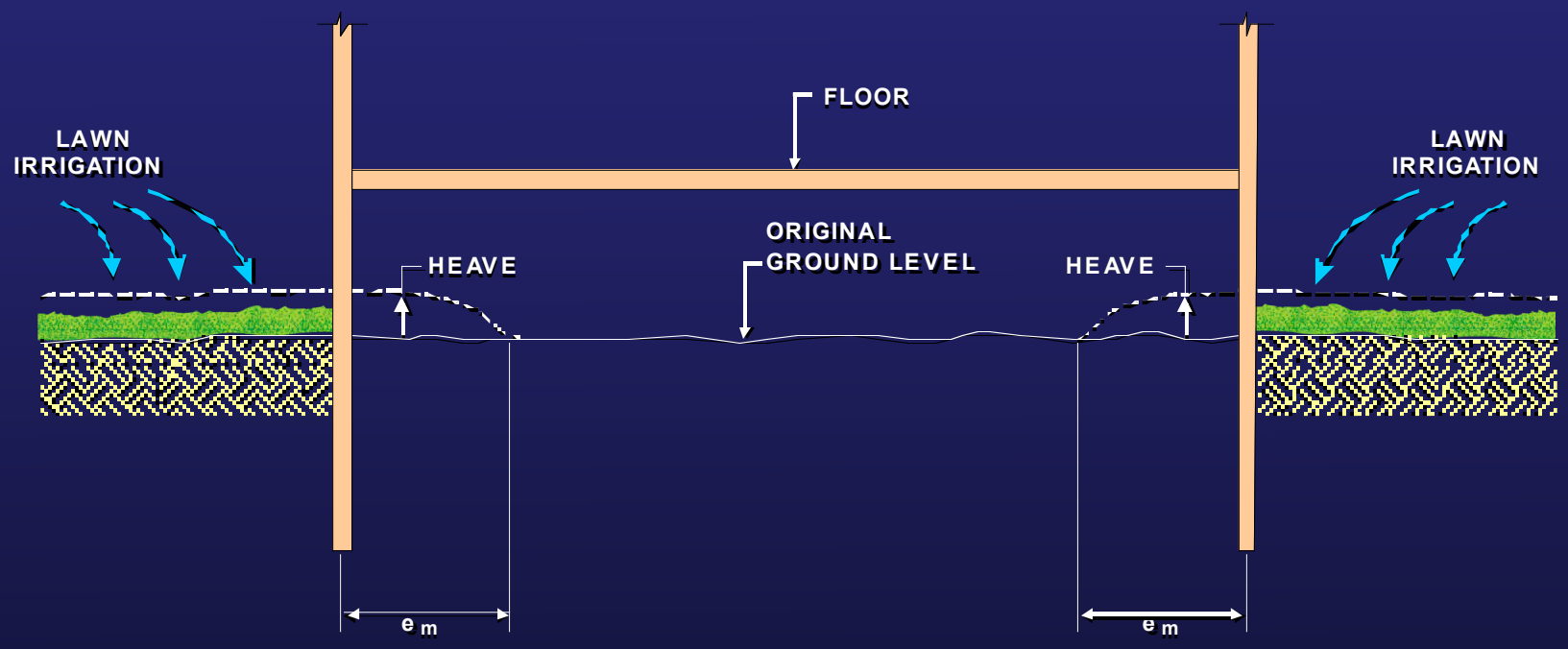
VERTICAL AND HORIZONTAL MOISTURE BARRIERS



NOTE

AMOUNT OF HEAVE DEPENDS ON THE AMOUNT OF WATER THAT IS MADE AVAILABLE TO THE SOIL AT THE EDGE OF THE BUILDING AND THE TYPE OF SOIL. e_m IS THE EDGE MOISTURE VARIATION DISTANCE WHICH VARIES TYPICALLY BETWEEN 3 AND 9 FEET DEPENDING ON THE TYPE OF SOIL.

LAWN IRRIGATION



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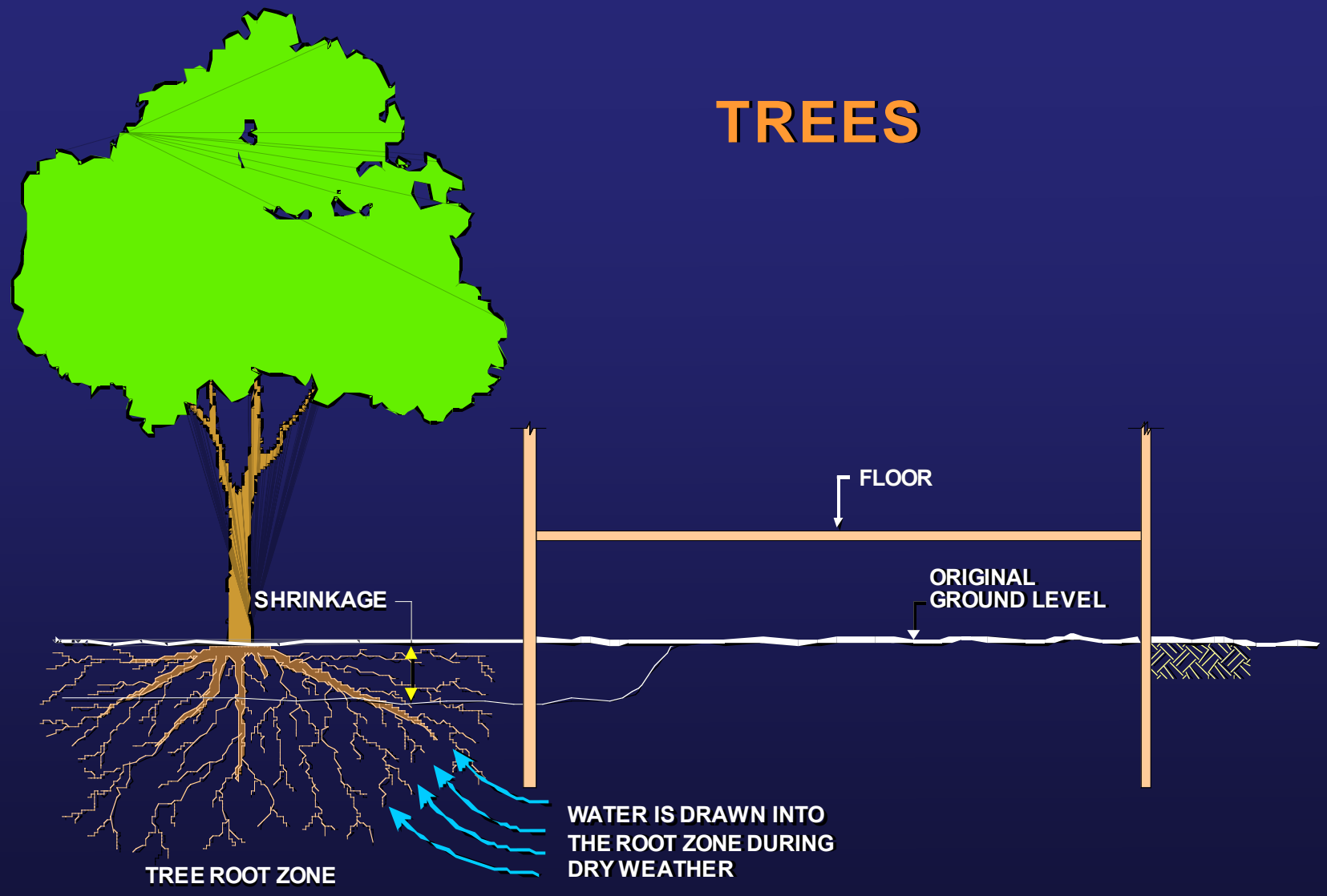
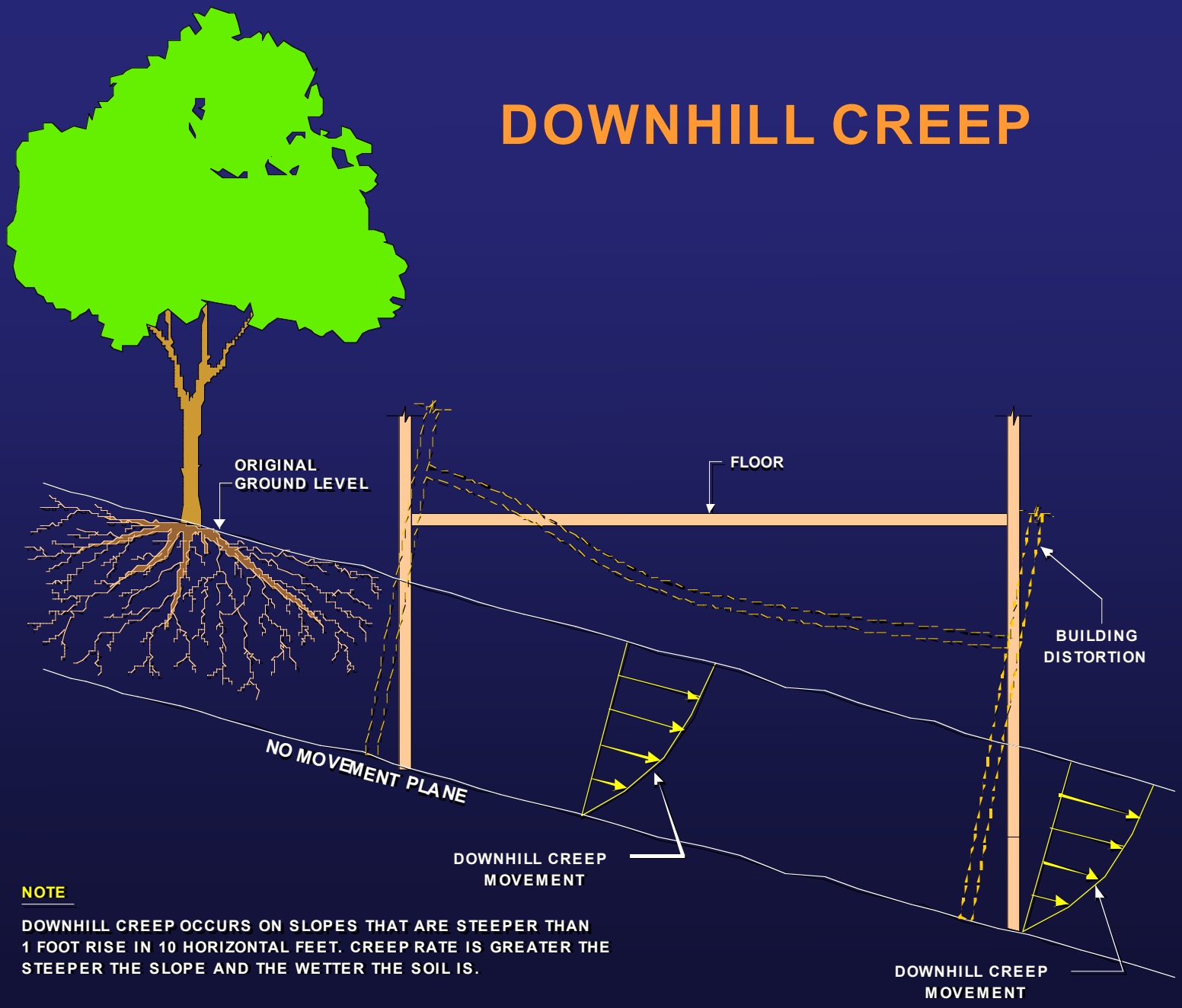
TREES



NOTE

AMOUNT OF SHRINKAGE DEPENDS ON THE DEPTH OF THE TREE ROOT ZONE, HOW FAR THE ROOTS PENETRATE BENEATH THE BUILDING, AND THE TYPE OF SOIL.

DOWNHILL CREEP



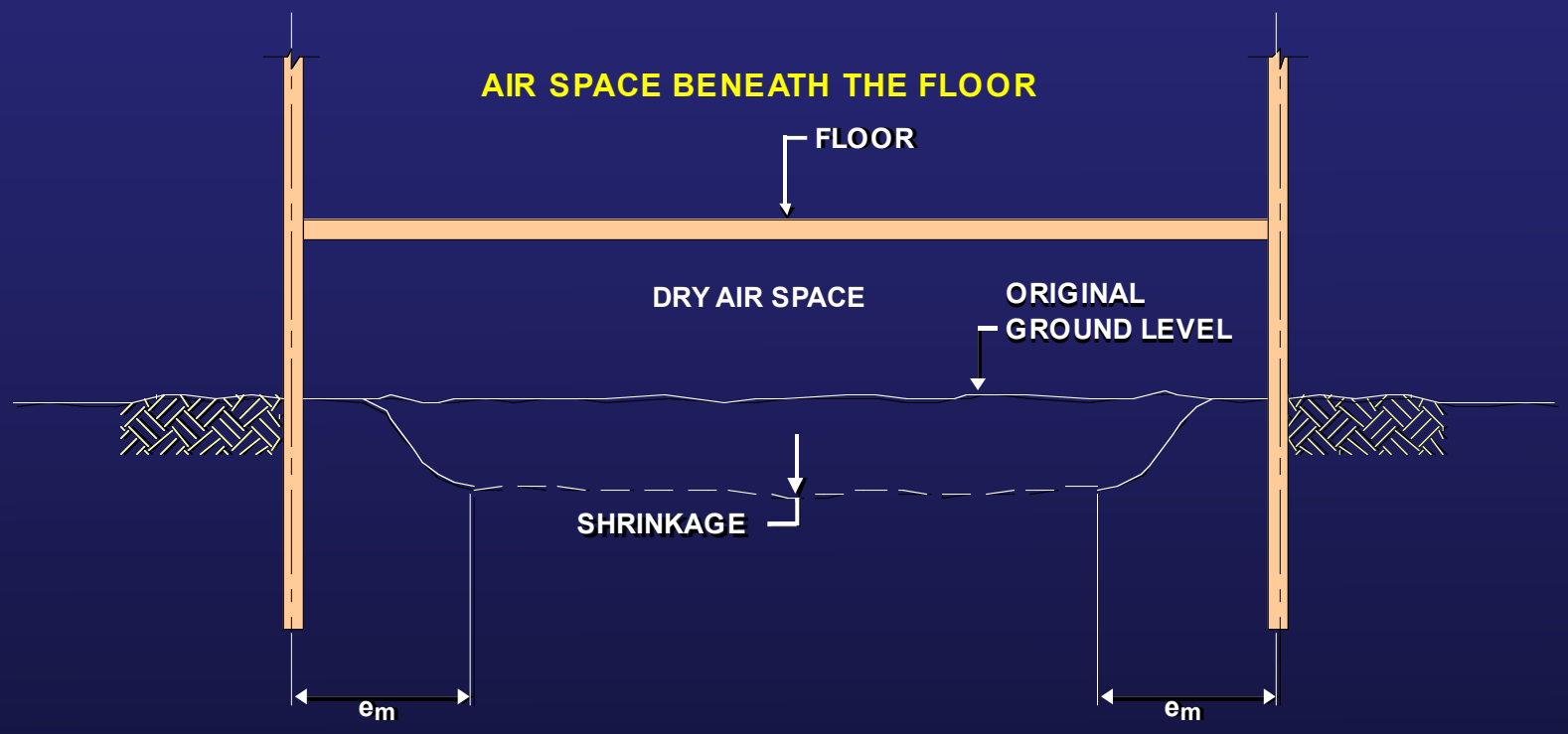
NOTE

DOWNHILL CREEP OCCURS ON SLOPES THAT ARE STEEPER THAN 1 FOOT RISE IN 10 HORIZONTAL FEET. CREEP RATE IS GREATER THE STEEPER THE SLOPE AND THE WETTER THE SOIL IS.

Raised Floor Foundations: Soils

- e_m: edge moisture variation distance
  - Not as important as with slabs on ground except around the perimeter

TOTAL MOVEMENT PATTERNS WITH RAISED WOOD FLOOR FOUNDATIONS



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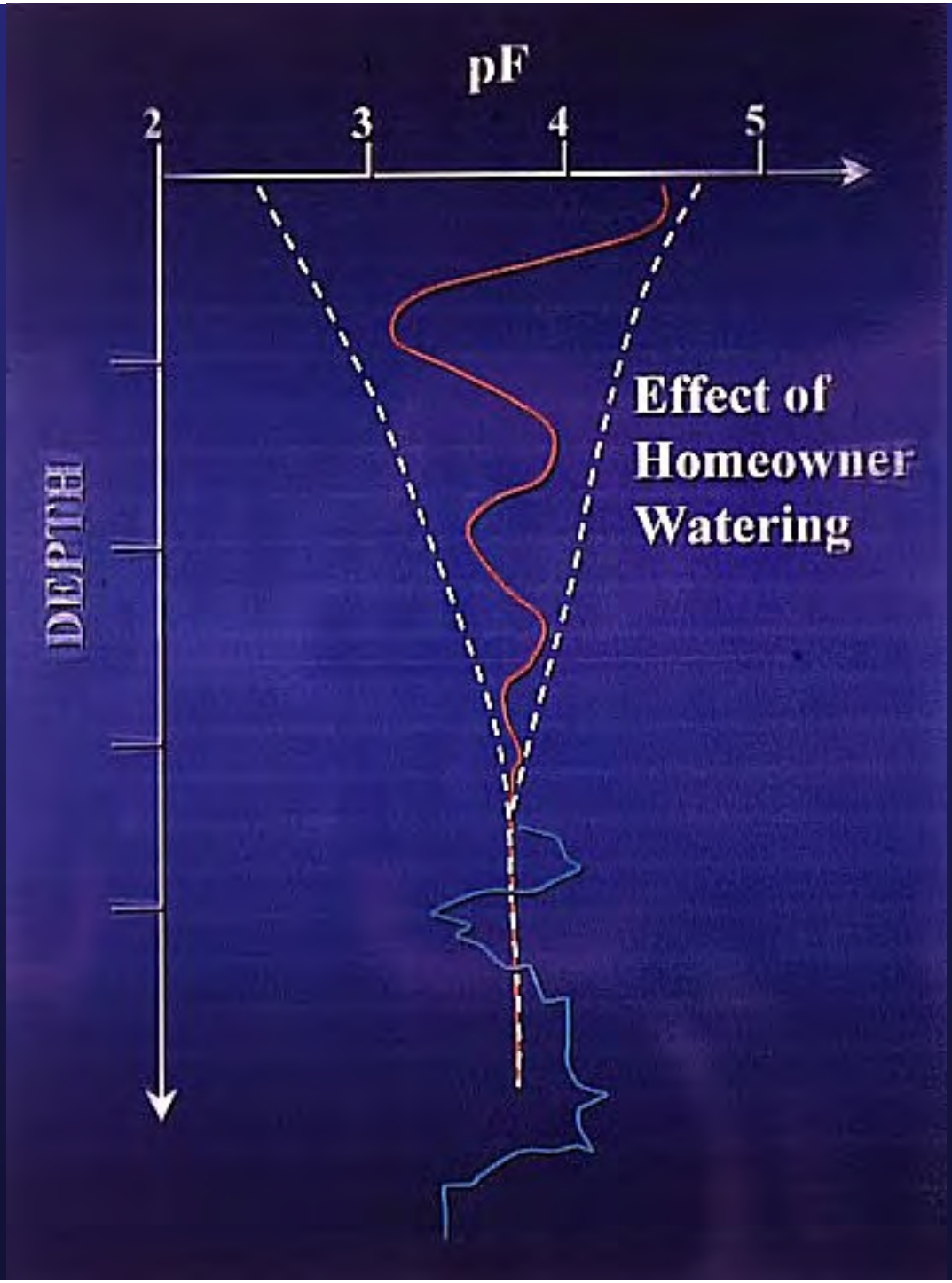
Raised Floor Foundations: Soils

- z_m: depth of the moisture active zone
  - Same factors as with slab on ground
  - Interest is in the total movement


pF
2
3
4
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Effect of
Homeowner
Watering

Raised Floor Foundations: Soils

- z_A: depth of movement active zone
  - Important to determine movement of supports
    - Pads
    - Spread footings
    - Posts

    } Objective: design for expected movement

    - Piers → Objective: small support movement
  - Which to use? Determined by costs

Slab-on-Ground: Site Hazards

- Trees
  - Shrinkage
  - Affects z_m, z_A, e_m, y_m
- Slopes
  - Like differential shrinkage
  - Rate depends on moisture
  - Affects z_m, y_m
- Drainage
  - Swelling
  - Affects e_m, y_m

Raised Floor Foundations: Site Hazards

- Trees: shrinkage reduces total differential movement
- Slopes
  - Like differential shrinkage
  - Rate depends on moisture
  - Affects z_m, y_m
- Drainage
  - Swelling
  - Increases total differential movement
  - Affects y_m

Slab-on-Ground: Building Geometry

- Shape factor affects structural design quantities
  - Moment
  - Shear
  - Differential deflection
- Shape factor

$$\frac{(\text{Perimeter})^2}{\text{Area}} \leq 24$$

  - Circle = 12.56
  - Square = 16
  - Rectangle = 3.7 ~ 1 $\Longrightarrow$ SF = 24

Raised Floor Foundations: Building Geometry

With adjustable floor elevation, does not matter

Slab-on-Ground: Structural Requirements

This is a soil-structure interaction problem.

- Soil is not a uniform pressure
- e_m is not a cantilever distance
- Structural properties of slab and soil are creep (long-term) properties

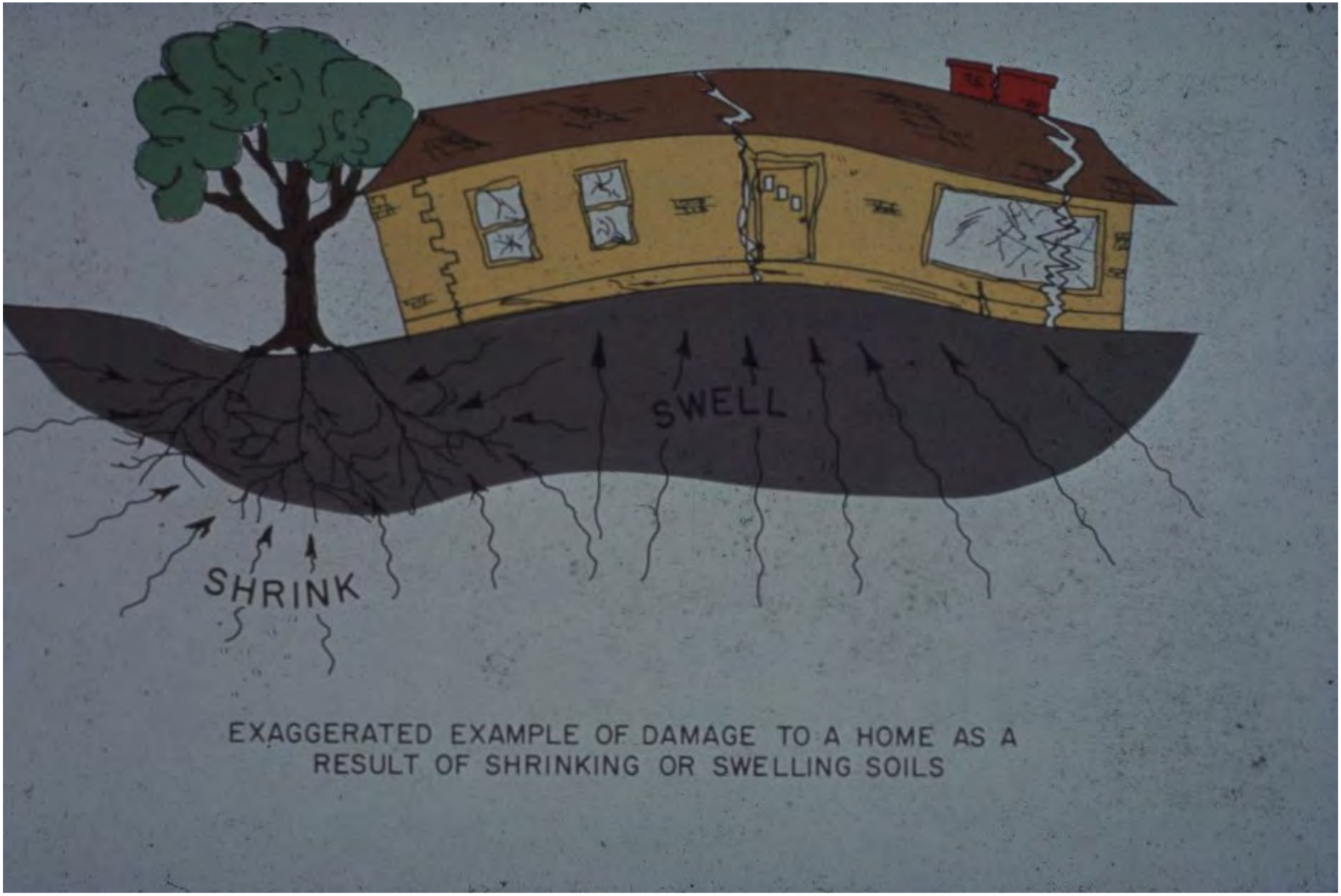
Slab-on-Ground: Structural Requirements

- Ground pressures never come close to bearing capacity
- z_m is dictated by site conditions and not by regional conditions
- y_m for both edge shrinking and edge swelling (> 1 inch) must be estimated accurately

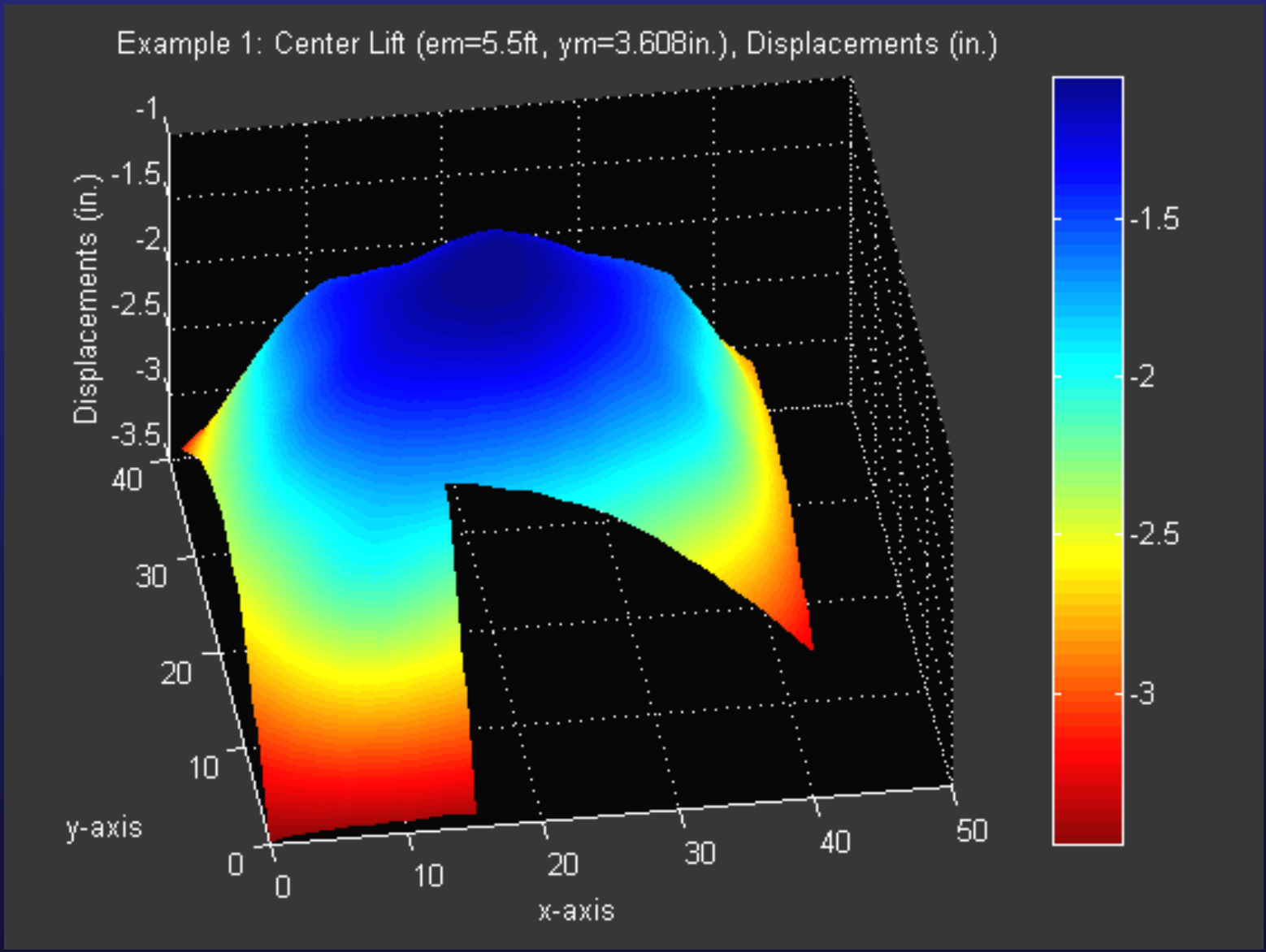
Slab-on-Ground: Structural Requirements

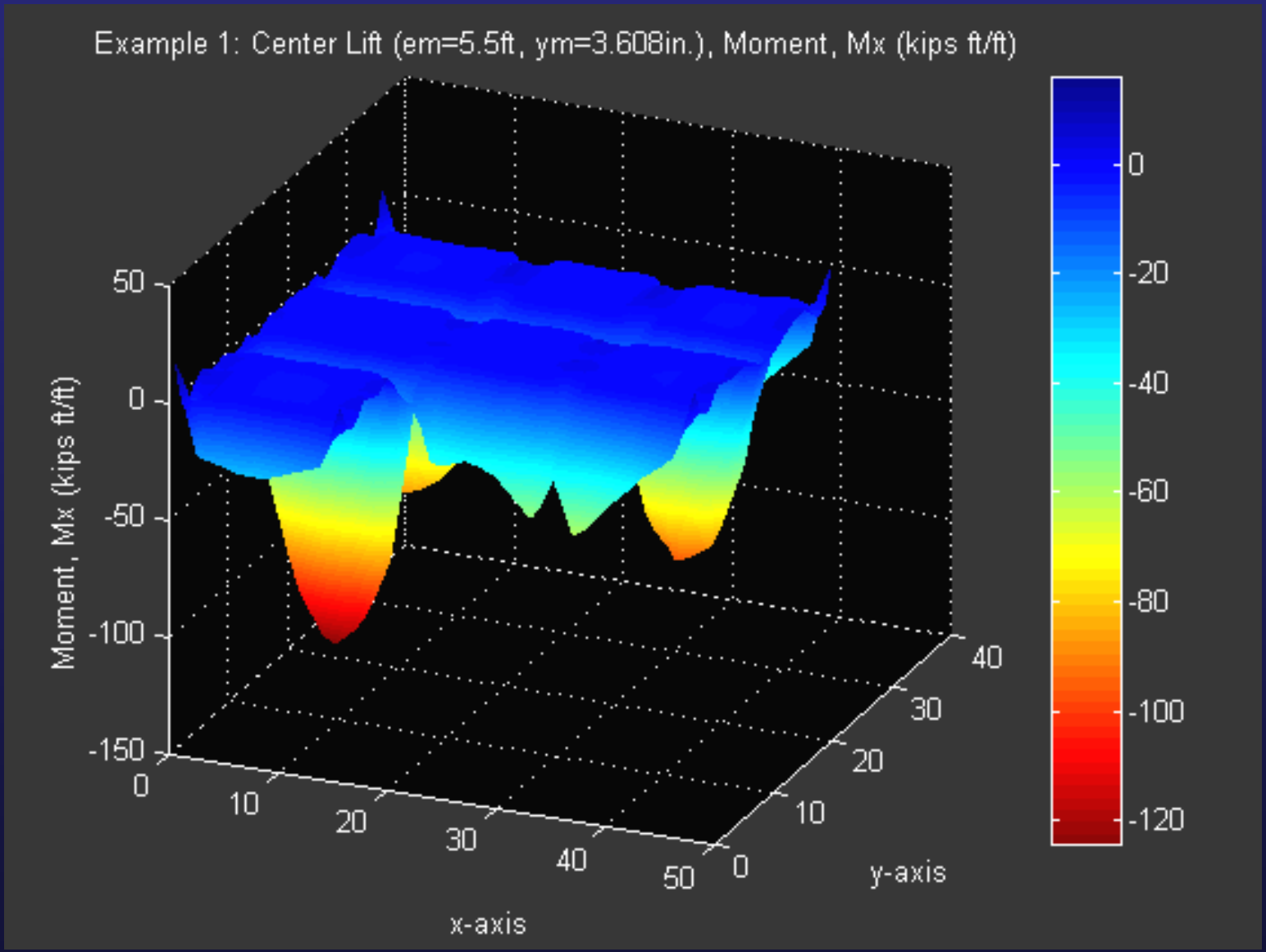
- e_m: for both edge shrinking and edge swelling is the most sensitive predictor of design moments, shears, and required stiffness, EI.

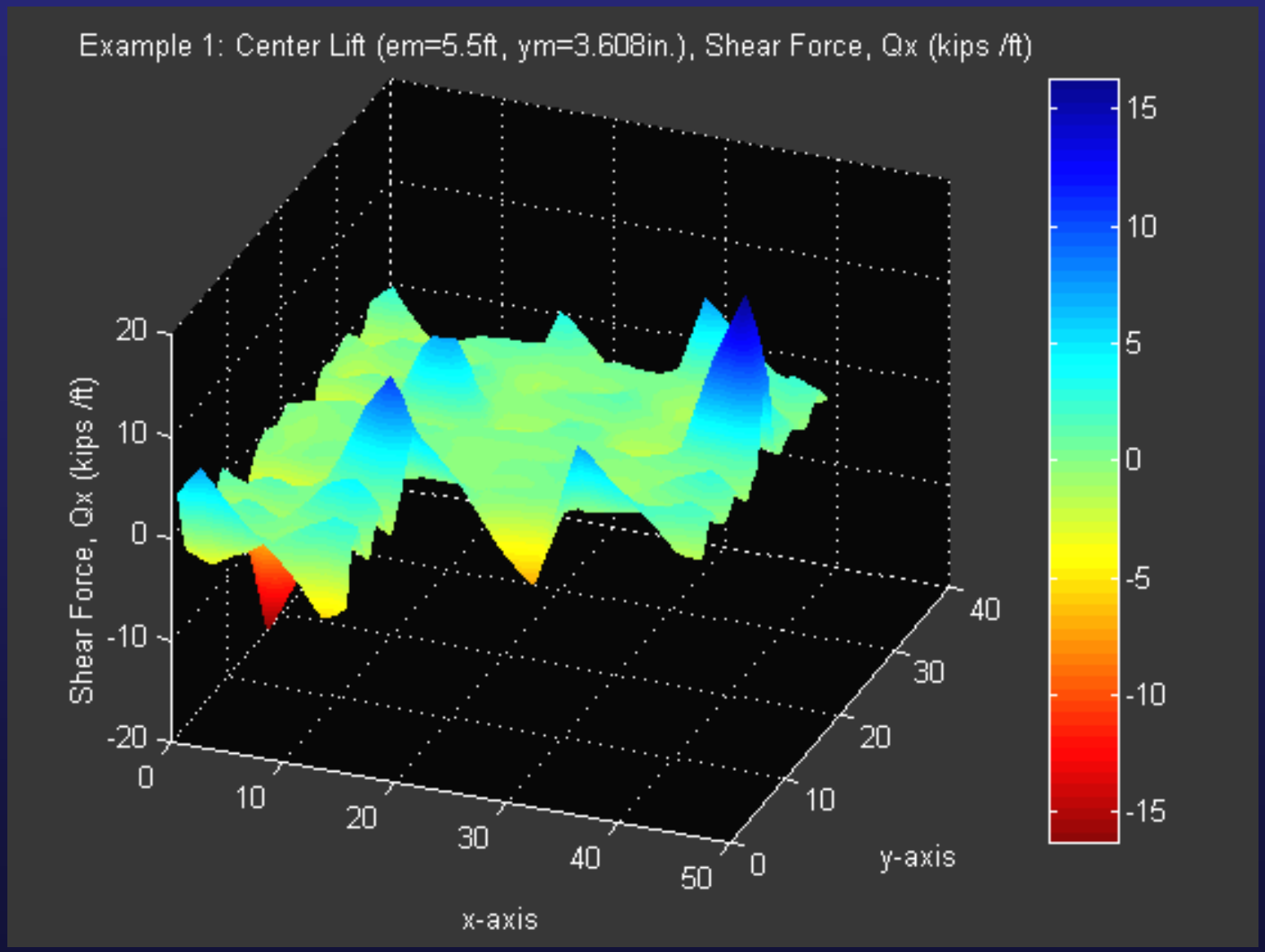
- z_A: is smaller than z_m and is dictated by site conditions and not by regional conditions

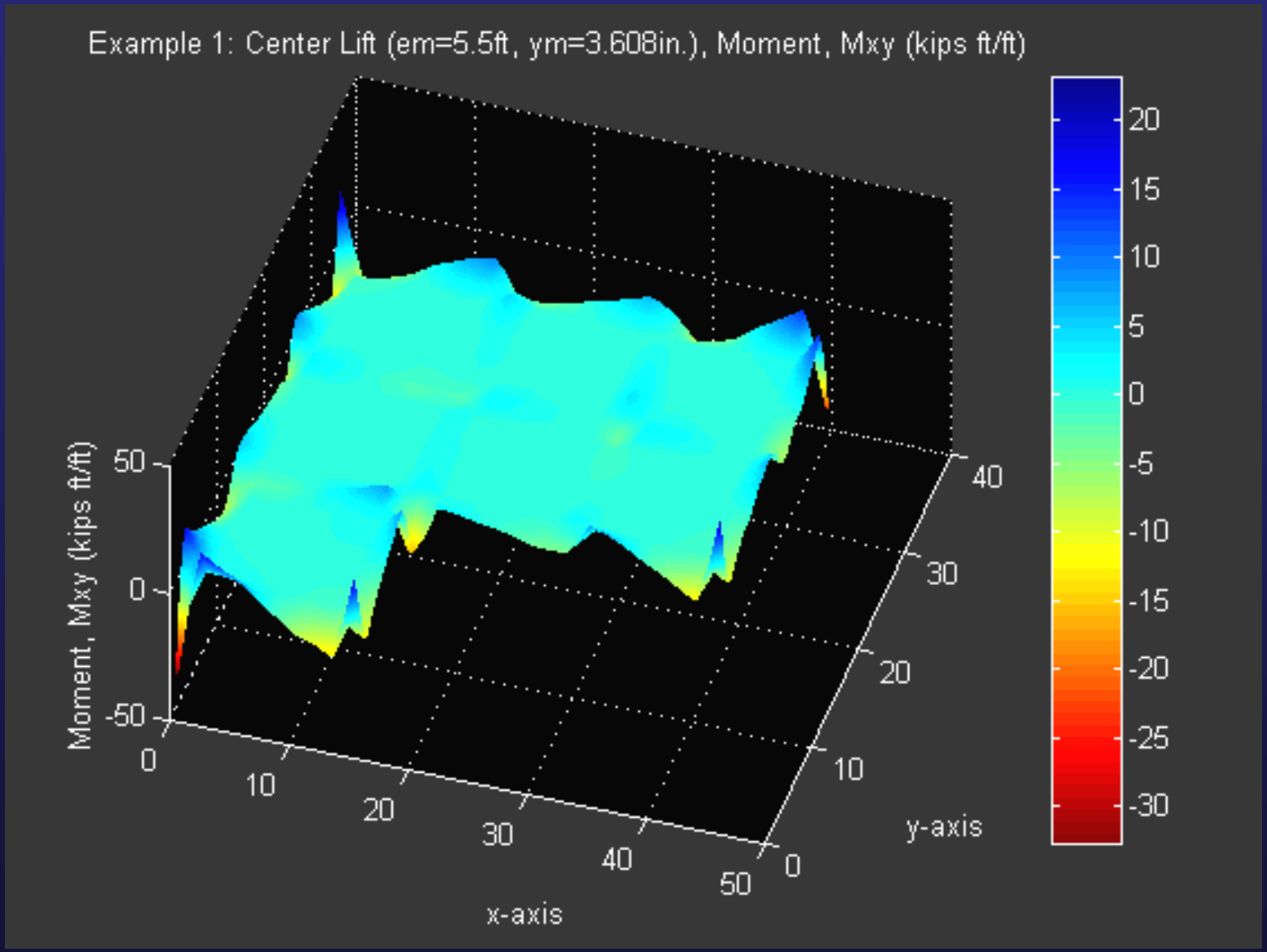


EXAGGERATED EXAMPLE OF DAMAGE TO A HOME AS A RESULT OF SHRINKING OR SWELLING SOILS

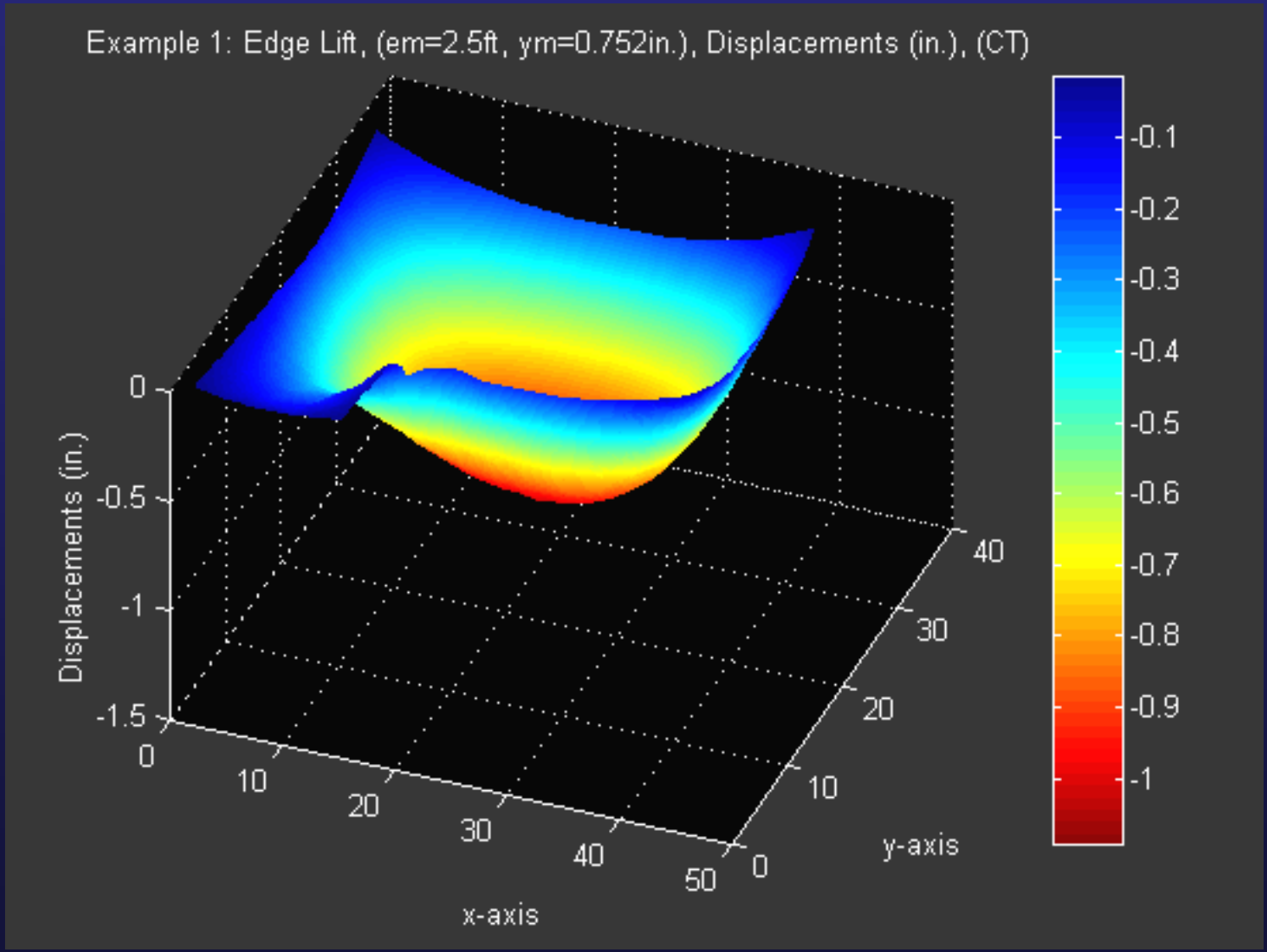

Example 1: Center Lift (em=5.5ft, ym=3.608in.), Displacements (in.)
Displacements (in.)
-1
-1.5
-2
-2.5
-3
-3.5
40
30
20
10
0
y-axis
0
10
20
30
40
50
x-axis
-1.5
-2
-2.5
-3

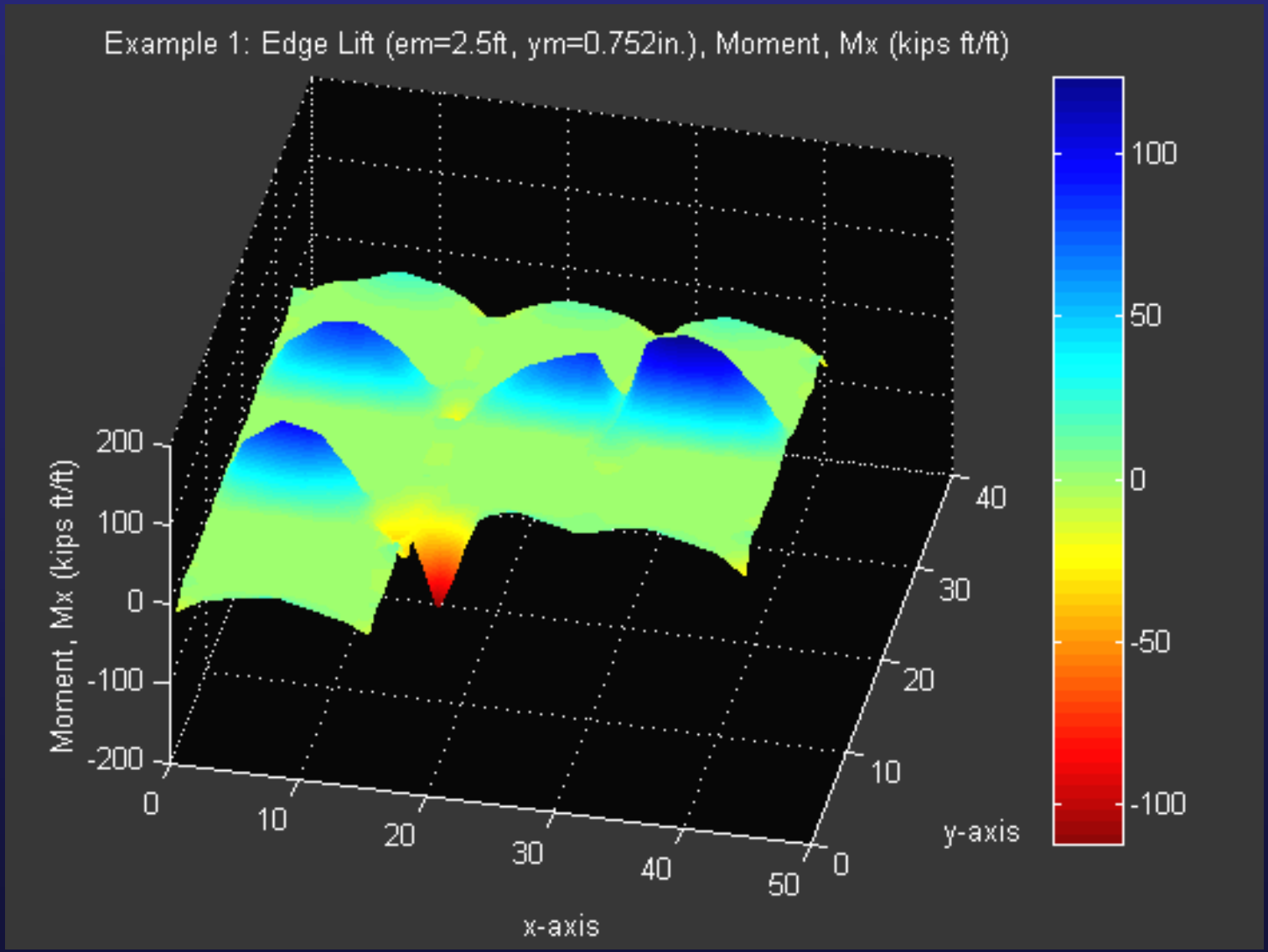

Example 1: Center Lift (em=5.5ft, ym=3.608in.), Moment, Mx (kips ft/ft)
Moment, Mx (kips ft/ft)
50
0
-50
-100
-150
0
10
20
30
40
50
x-axis
0
10
20
30
40
y-axis
0
-20
-40
-60
-80
-100
-120

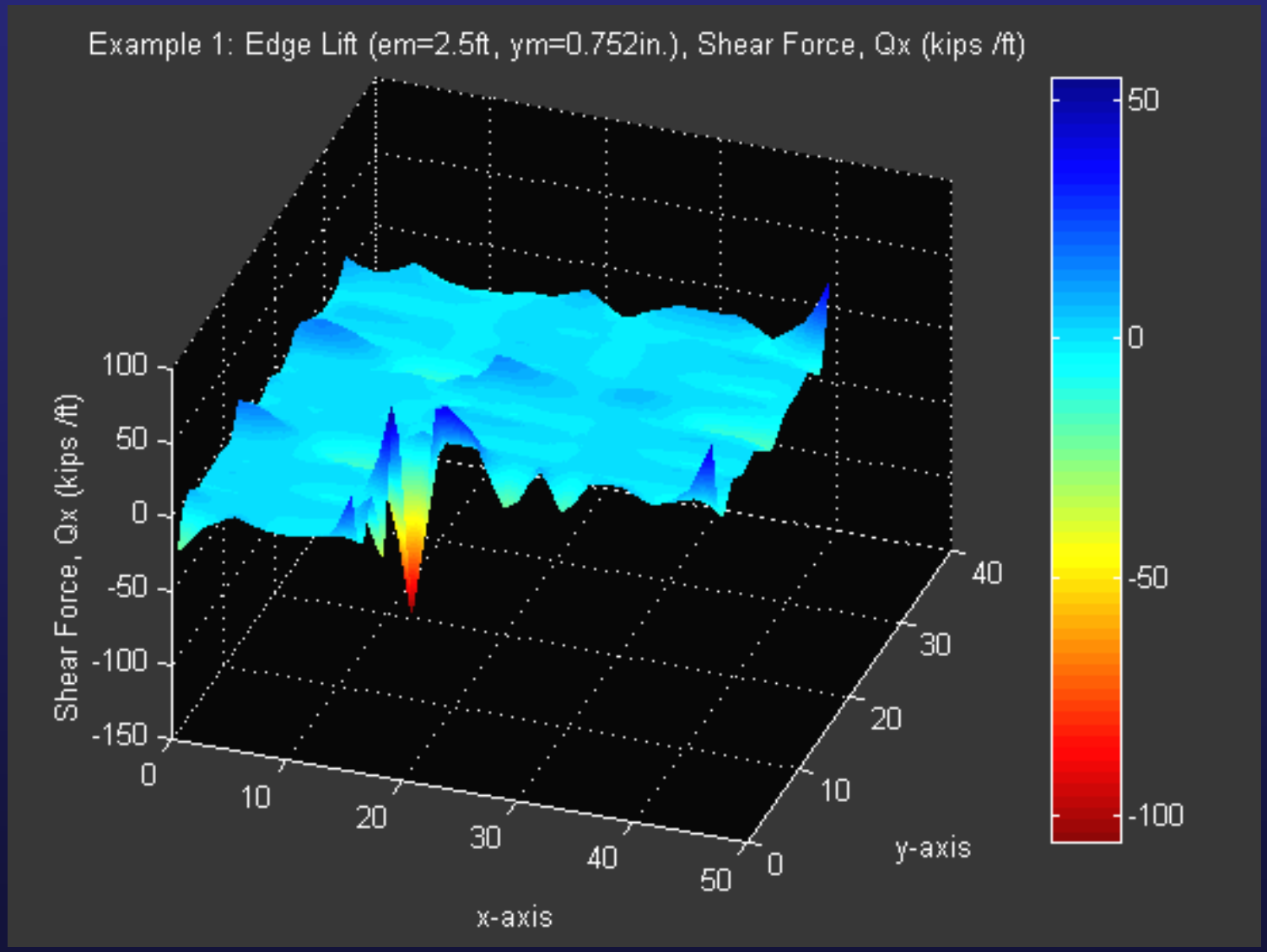

Example 1: Center Lift (em=5.5ft, ym=3.608in.), Shear Force, Qx (kips /ft)
Shear Force, Qx (kips /ft)
20
10
0
-10
-20
0
10
20
30
40
50
x-axis
0
10
20
30
40
y-axis
15
10
5
0
-5
-10
-15

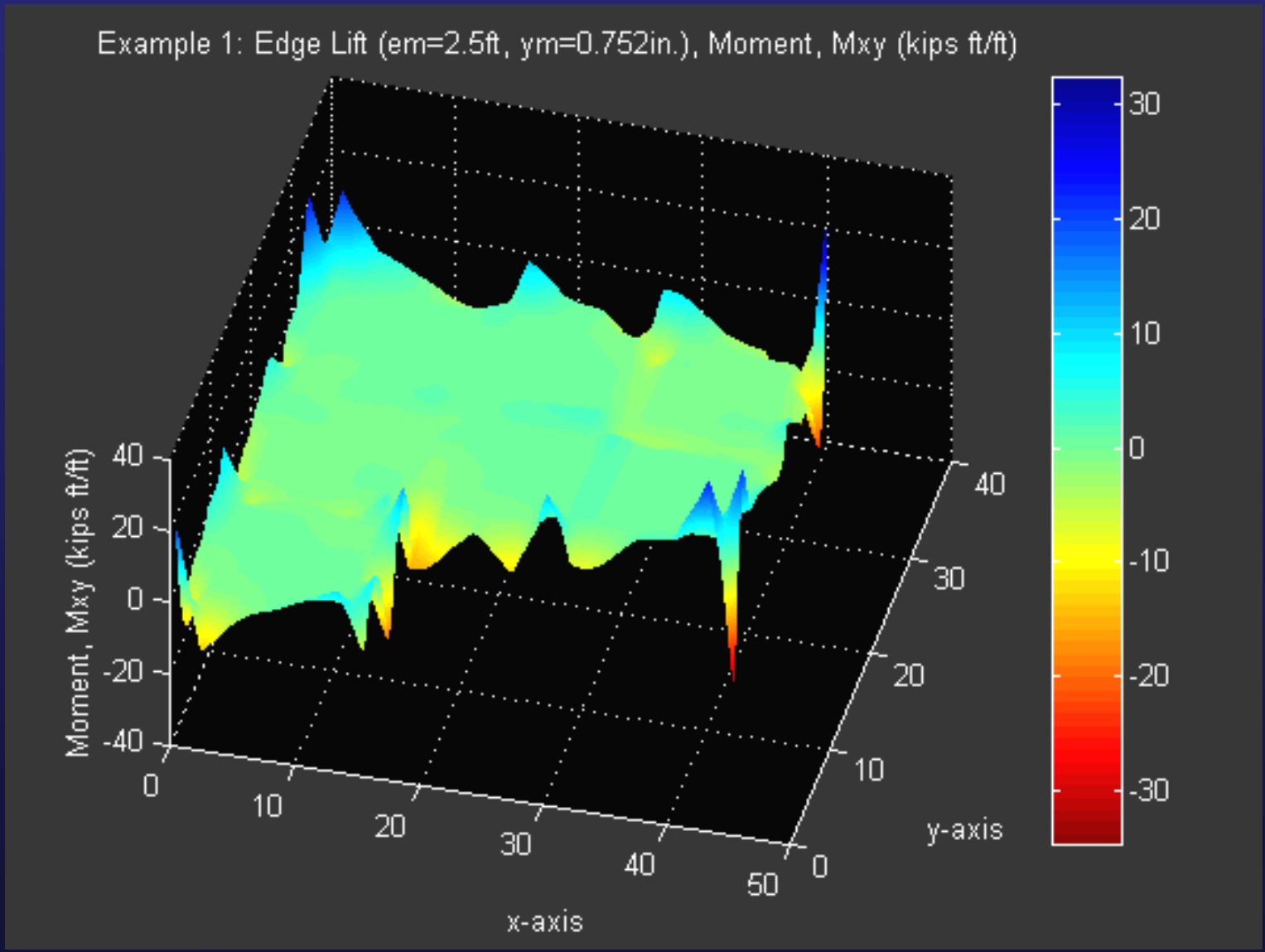

Example 1: Center Lift (em=5.5ft, ym=3.608in.), Moment, Mxy (kips ft/ft)
Moment, Mxy (kips ft/ft)
50
0
-50
0
10
20
30
40
50
x-axis
0
10
20
30
40
y-axis
20
15
10
5
0
-5
-10
-15
-20
-25
-30


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


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

Slab-on-Ground: Structural Requirements

- β – length = relative stiffness length

$$= \frac{1}{12}\sqrt[4]{\frac{E_c I}{E_s}}$$

E_c = creep stiffness of concrete
E_s = creep stiffness of soil

- Dictates what is a long- and short-slab (> 6β is long)
- Controls design quantities for long slabs

Design Criteria: Deflections / Tolerance

- Sensitivity of foundation and super structure (Δ/L)
- Differential ($\Delta_c + \Delta_s$)
  - As built (Δ_c)
  - Soil movement (Δ_s)
- Total
- Twisting

Design Criteria: Stiffness

- Substitute for deflection tolerance
- Enough concrete section to handle soil movement

Raised Floor Foundations: Structural Requirements

This is NOT a soil-structure interaction problem.

- Moment
- Shear
- Deflection

} criteria

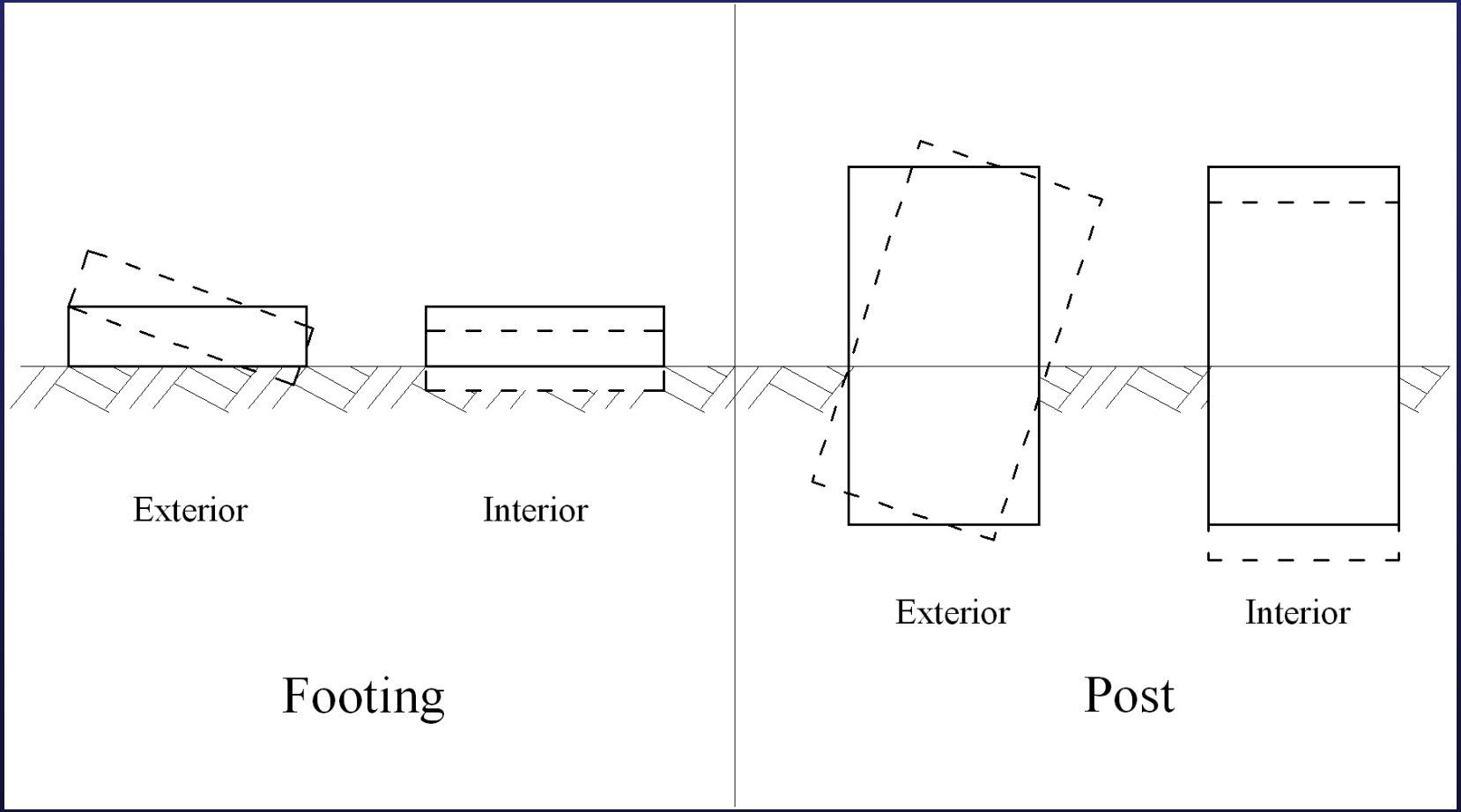
are the same as for column-supported structures.

Raised Floor Foundations: Structural Requirements

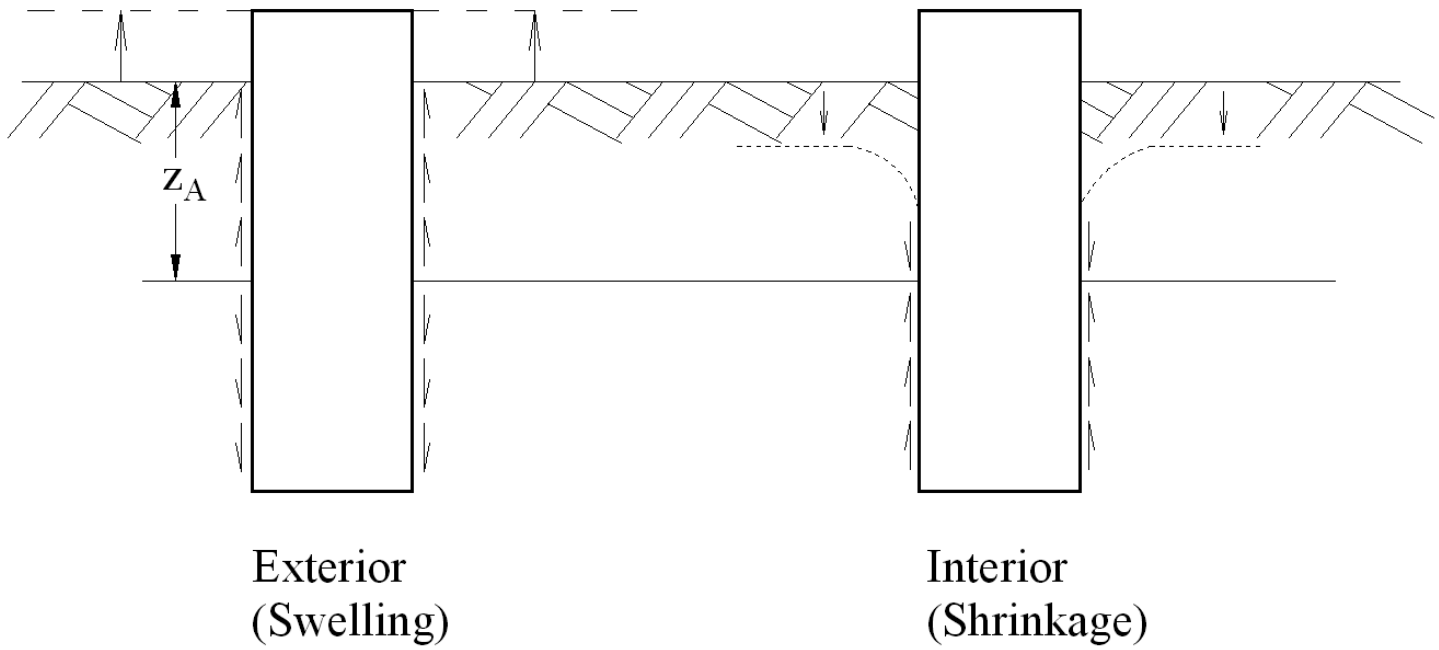
- Allowable deflections before adjusting support elevations dictate the design quantities of the floor supports

- Design of supporting footings, posts or piers is to make rough estimate of total movement
  - Vertical
  - Rotation

Movement Patterns

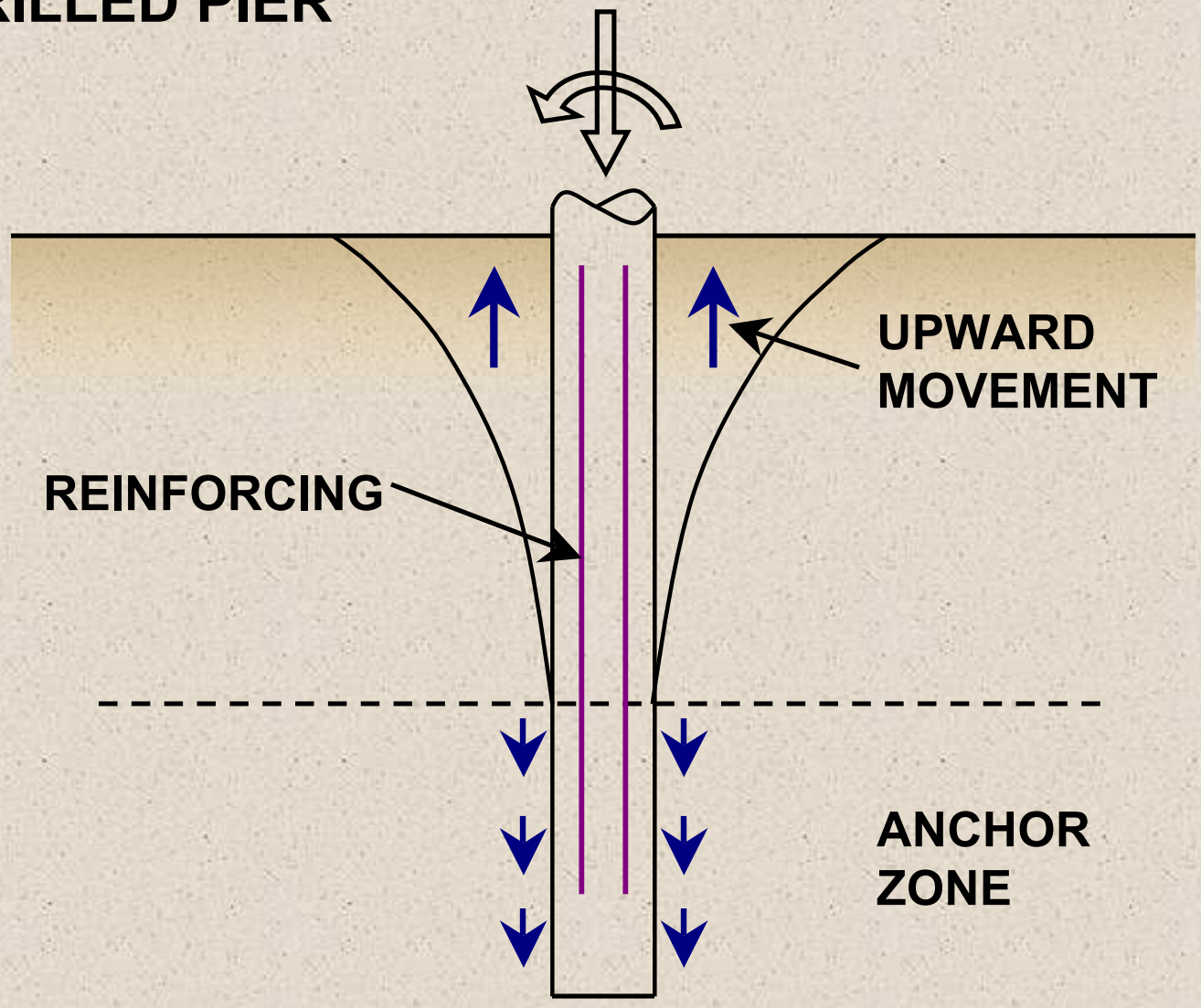


Movement Patterns

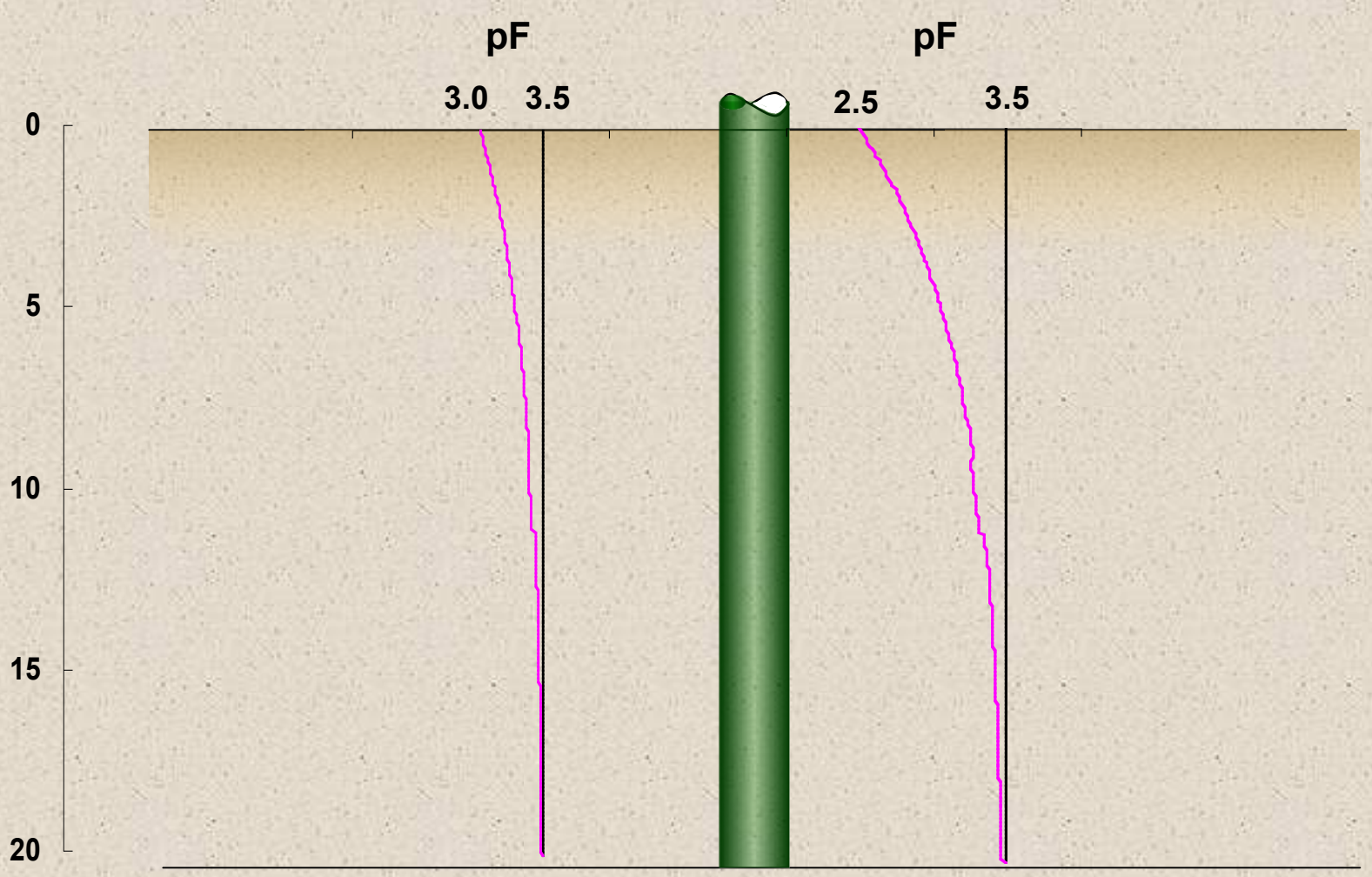


Pier

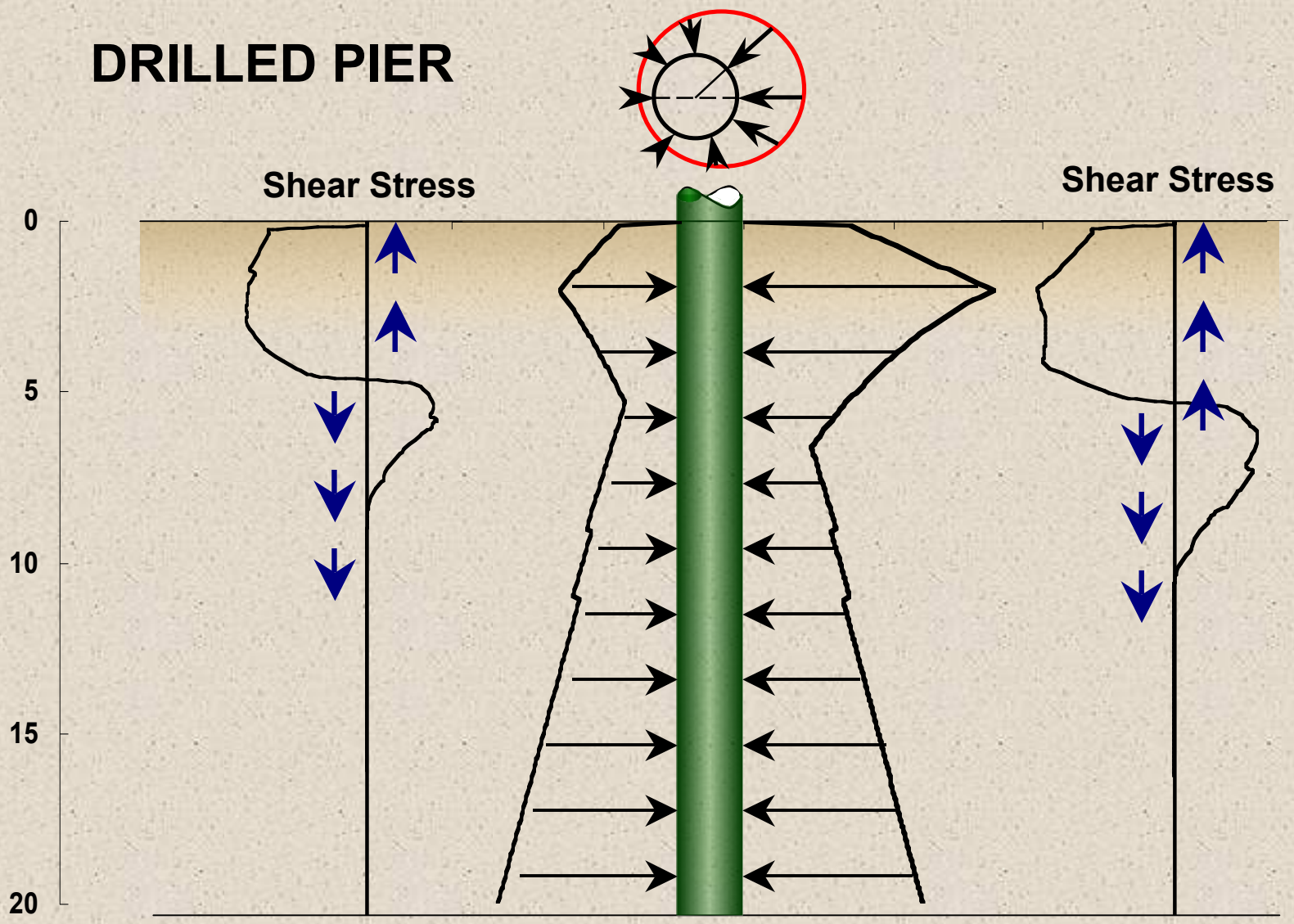
DRILLED PIER



DRILLED PIER



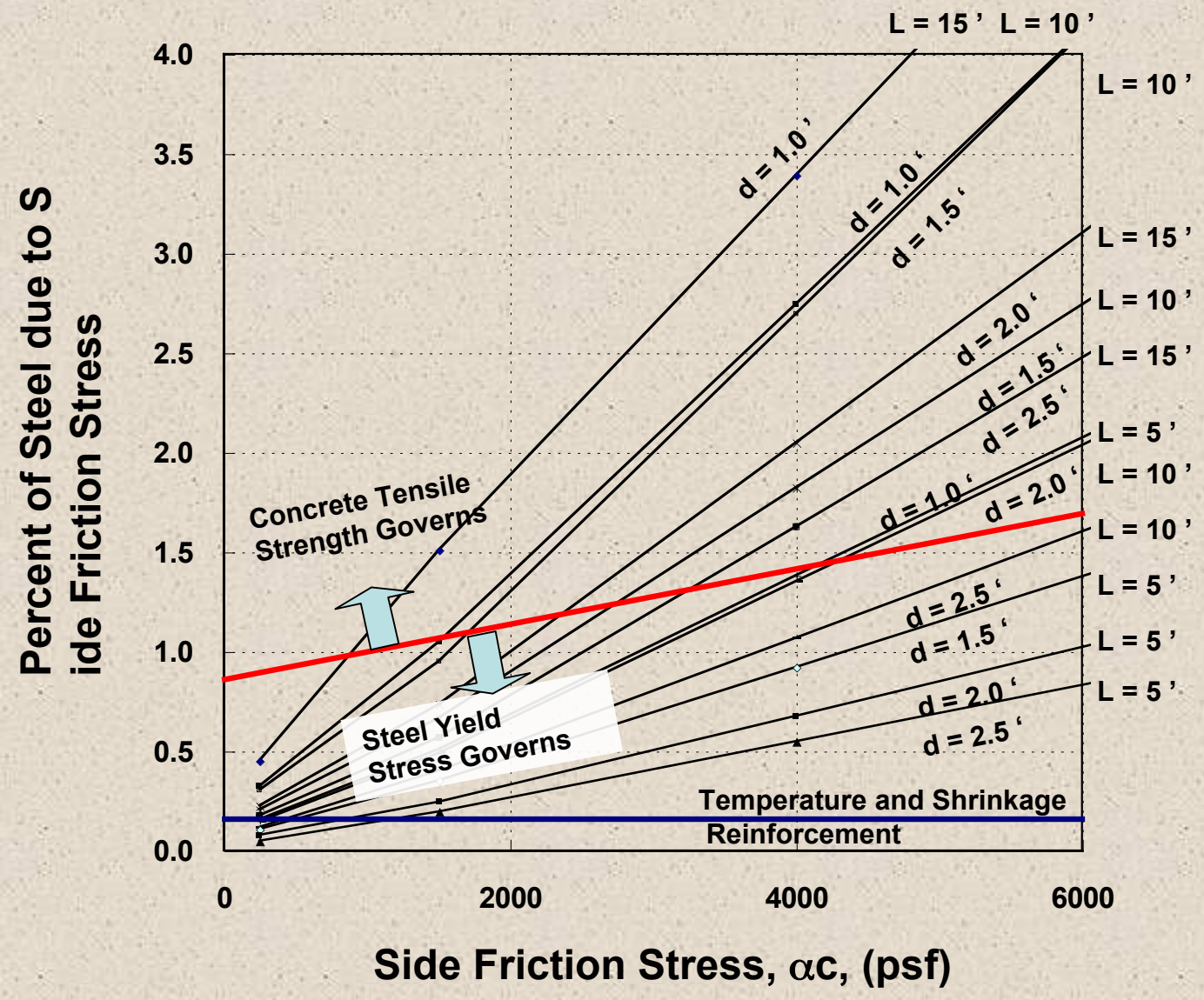
DRILLED PIER

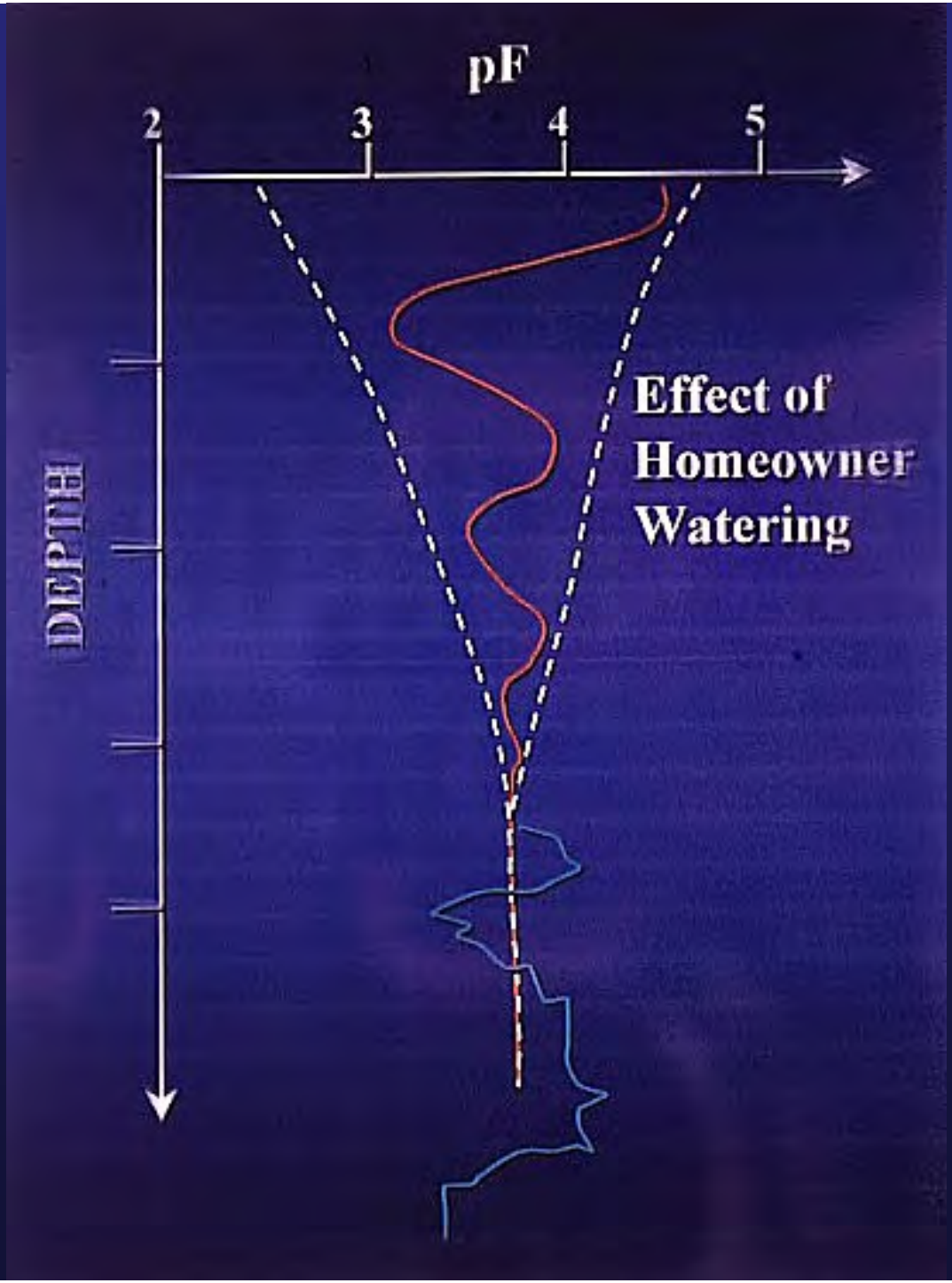


Horizontal Stress Distribution

DRILLED PIER

DRILLED PIER REINFORCEMENT




pF
2
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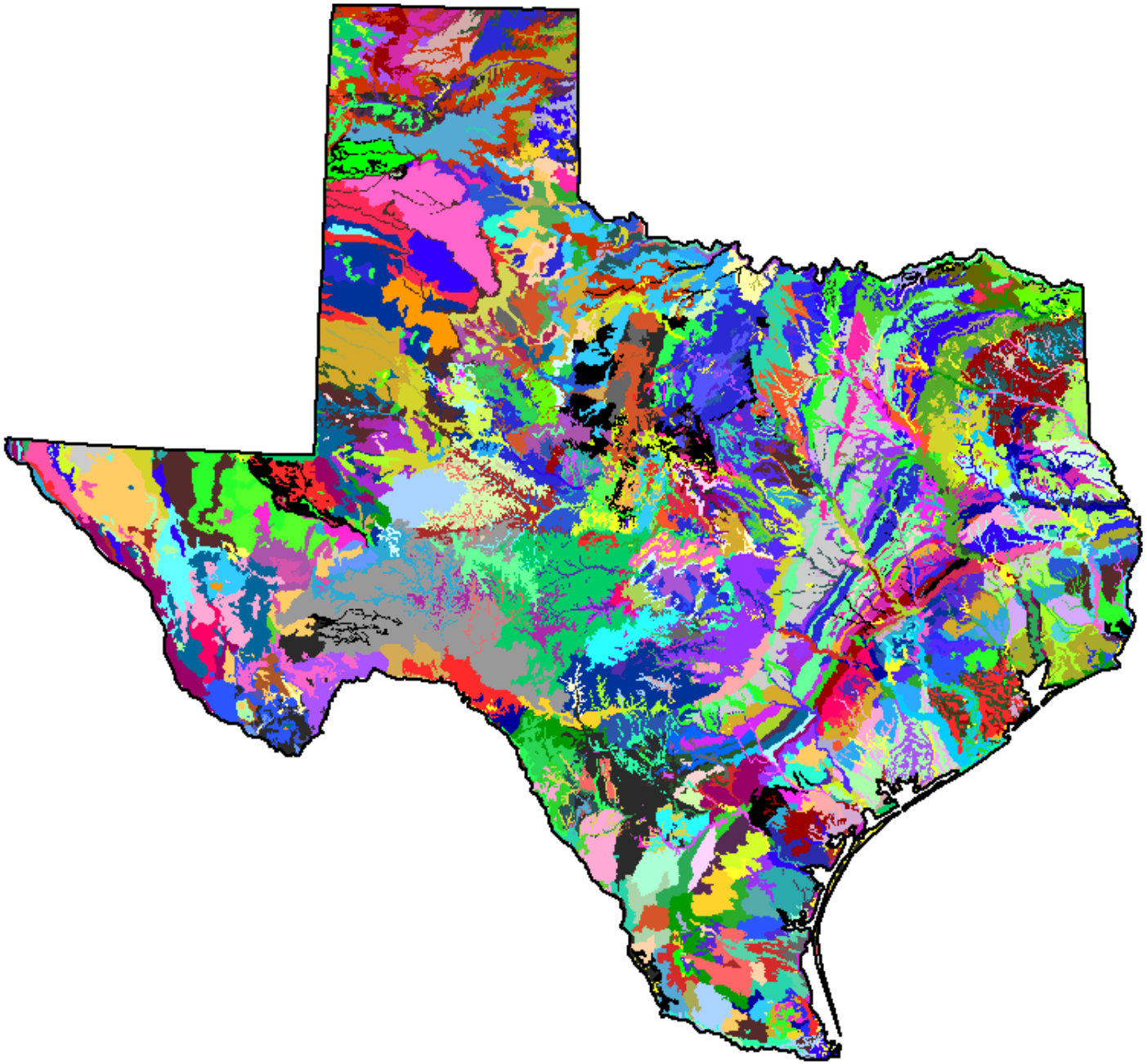
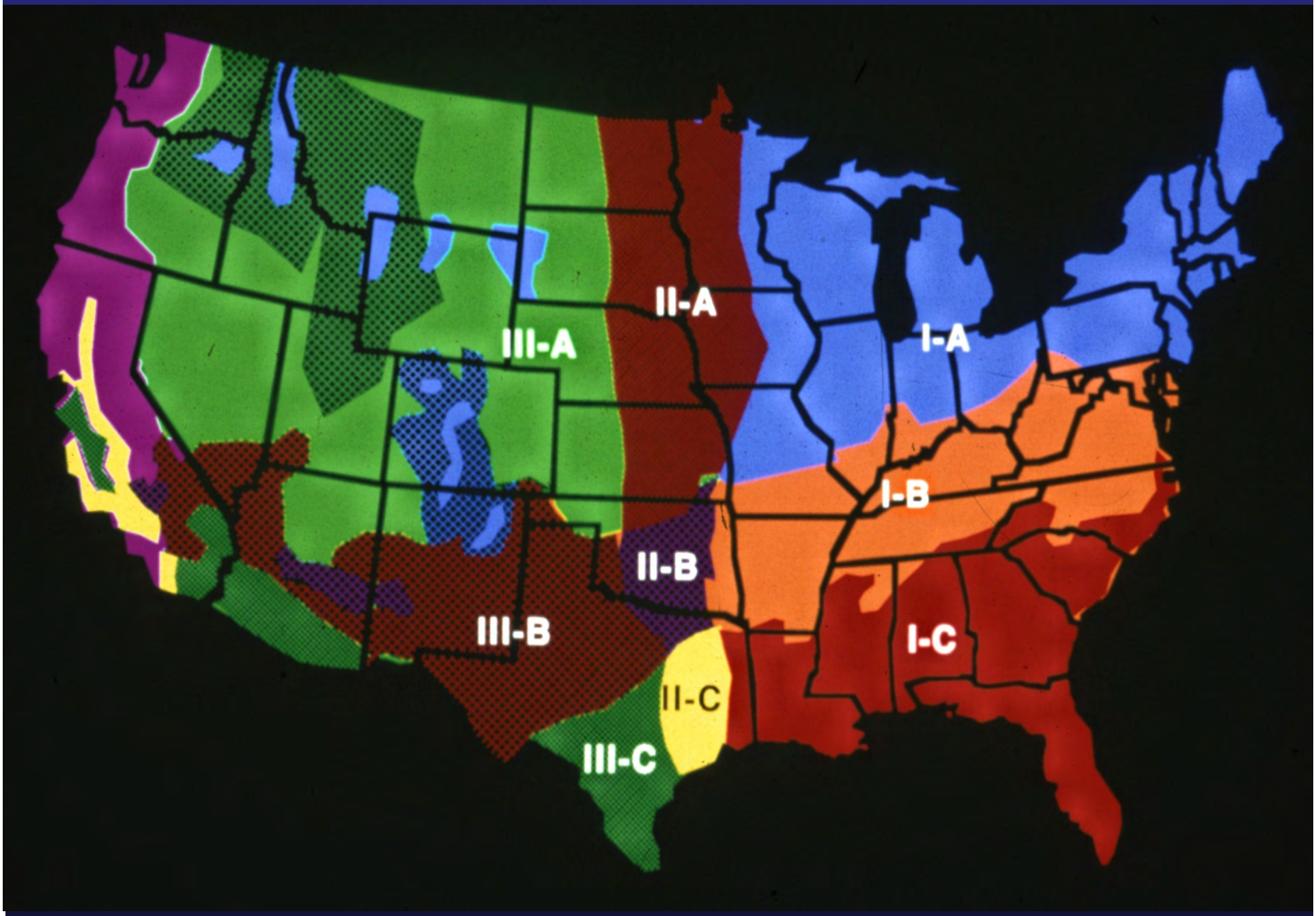
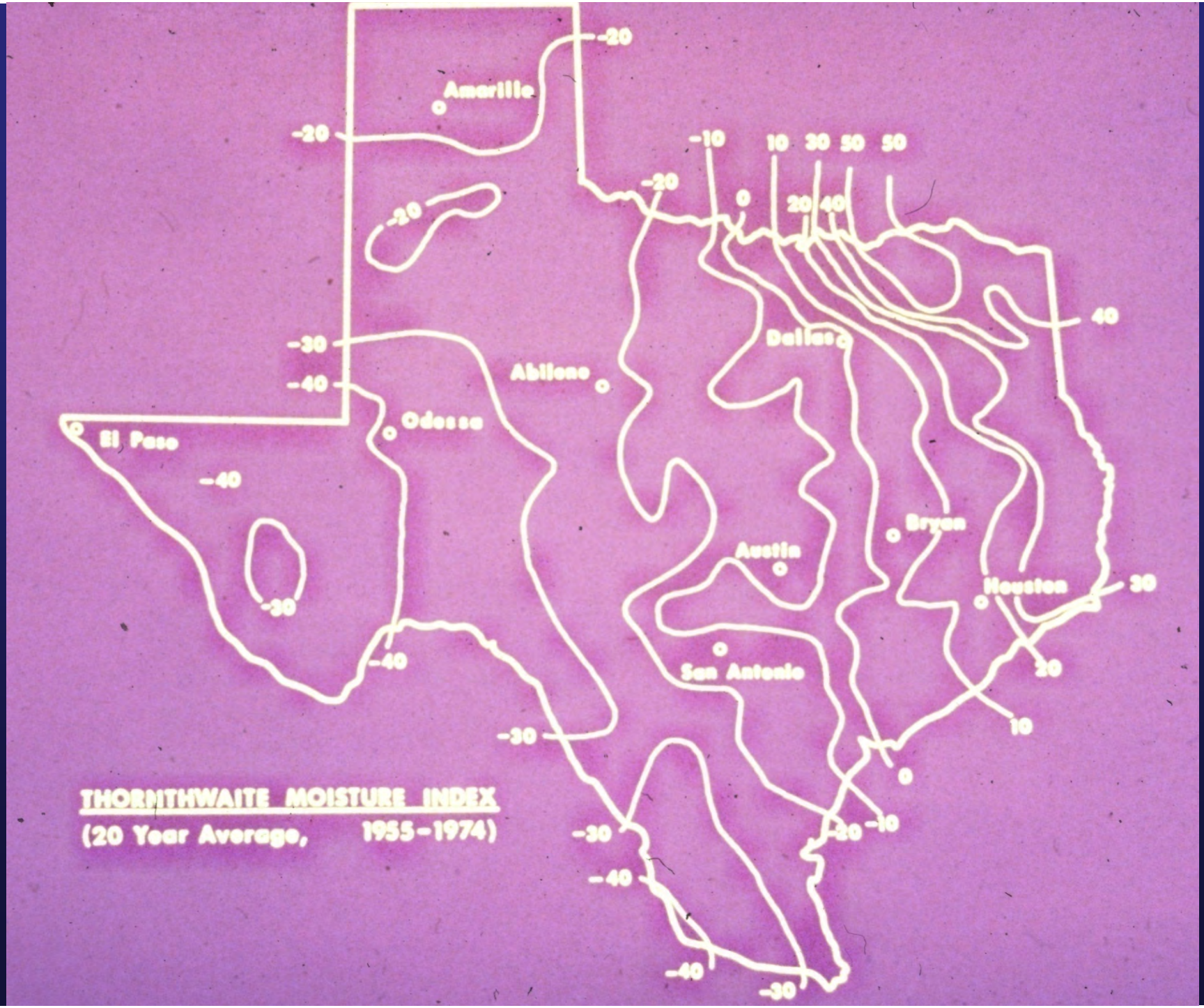
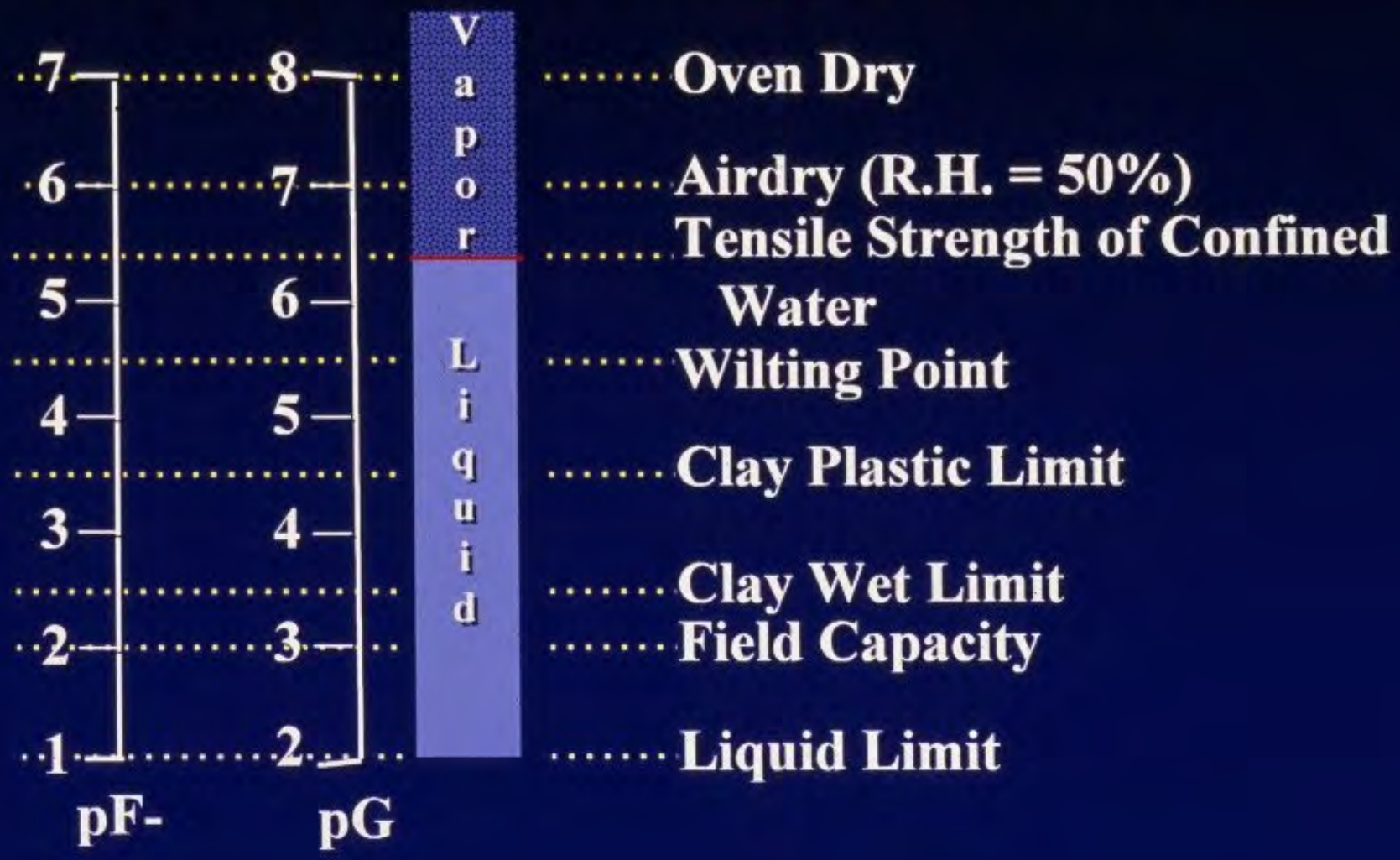
4
5
DEPTH
Effect of
Homeowner
Watering



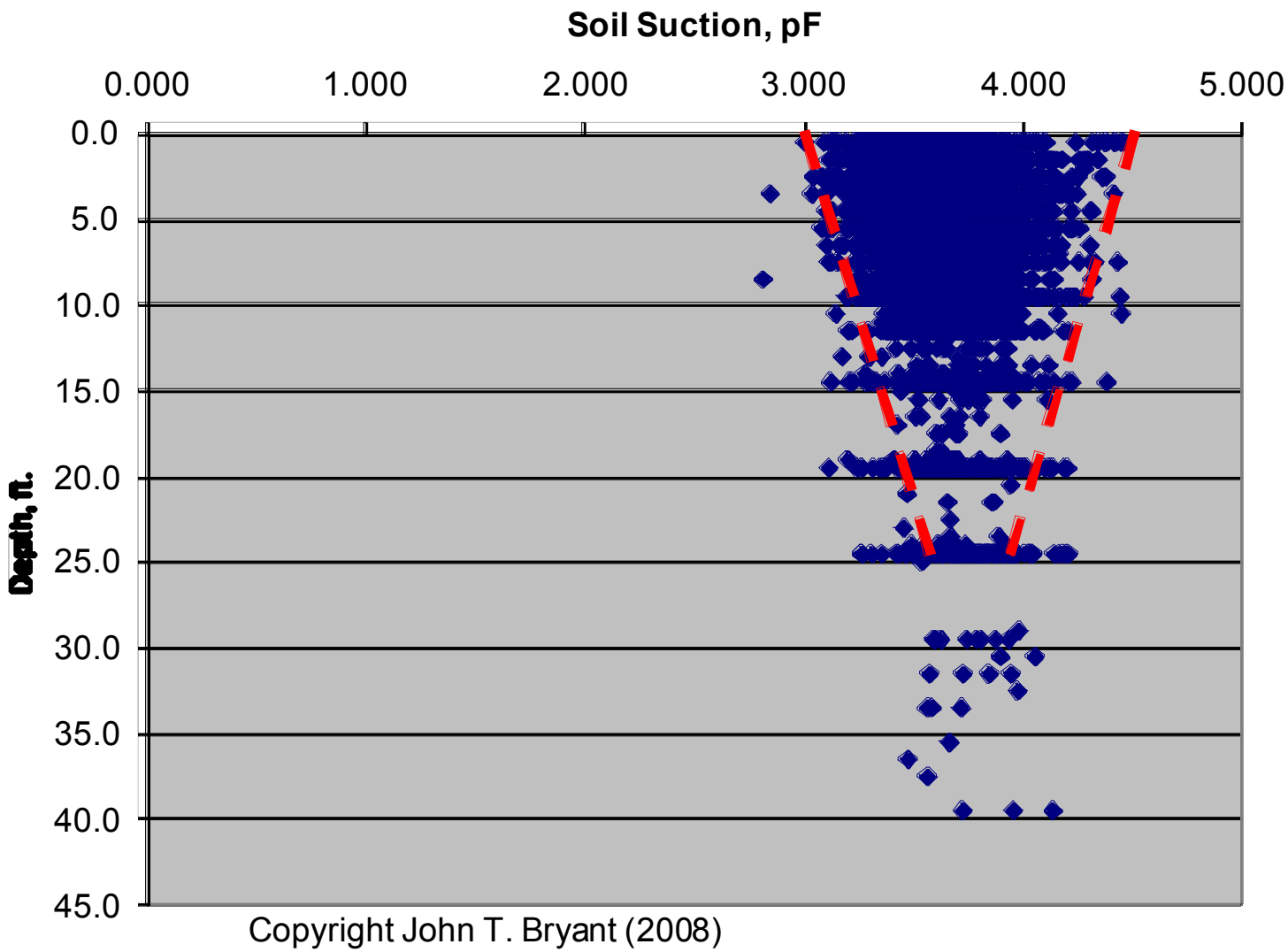

II-A
III-A
I-A
I-B
II-B
III-B
I-C
II-C
III-C


Amarillo
Abilene
Odessa
El Paso
Dallas
Austin
Bryan
Houston
San Antonio
-20
-20
-20
-20
-10
10
30
50
50
0
20
40
40
-30
-40
-40
-30
-40
-30
30
20
10
0
-10
-20
-30
-40
-40
-30
THORNTHWAITE MOISTURE INDEX
(20 Year Average, 1955-1974)

Physical Meaning of Scales

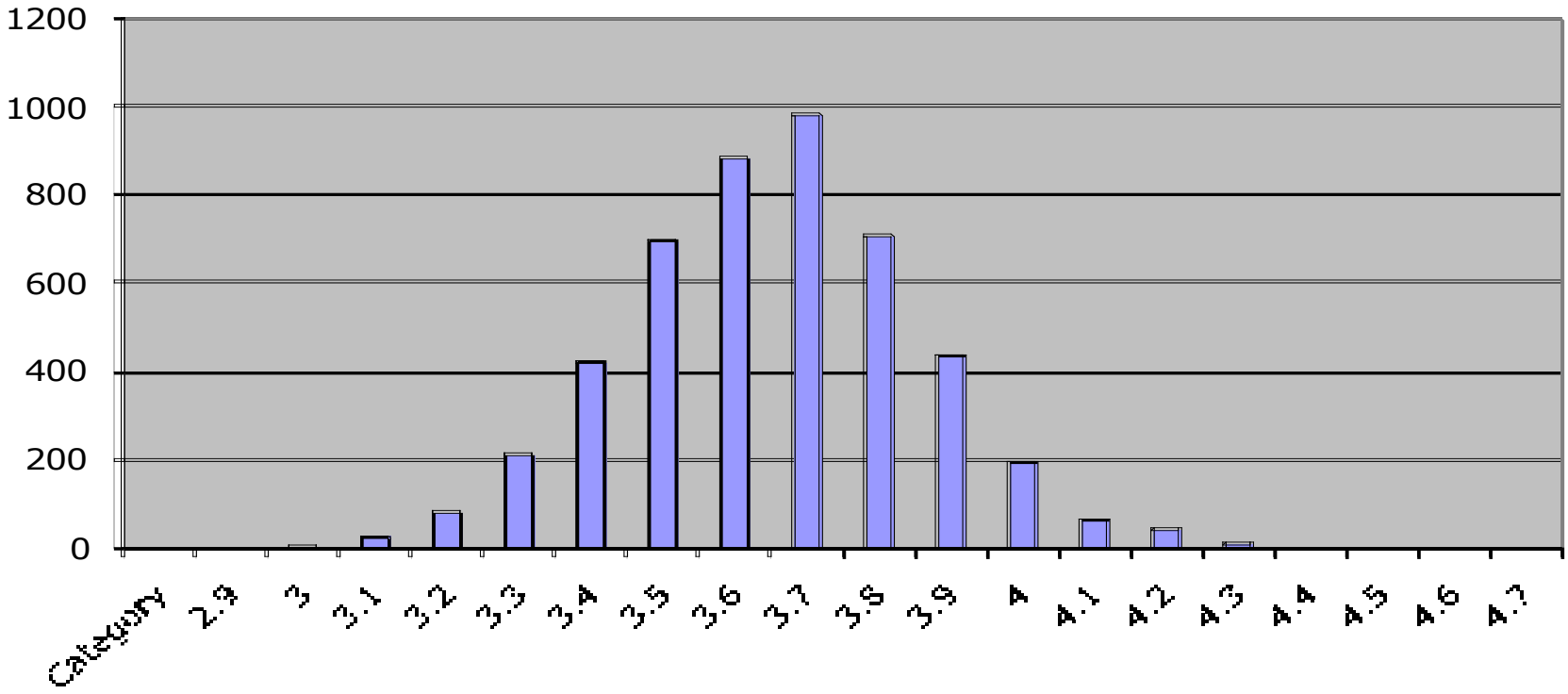


Empirically Measured Suctions
BCI 2002 to 2008 = 26,000+ Data Points

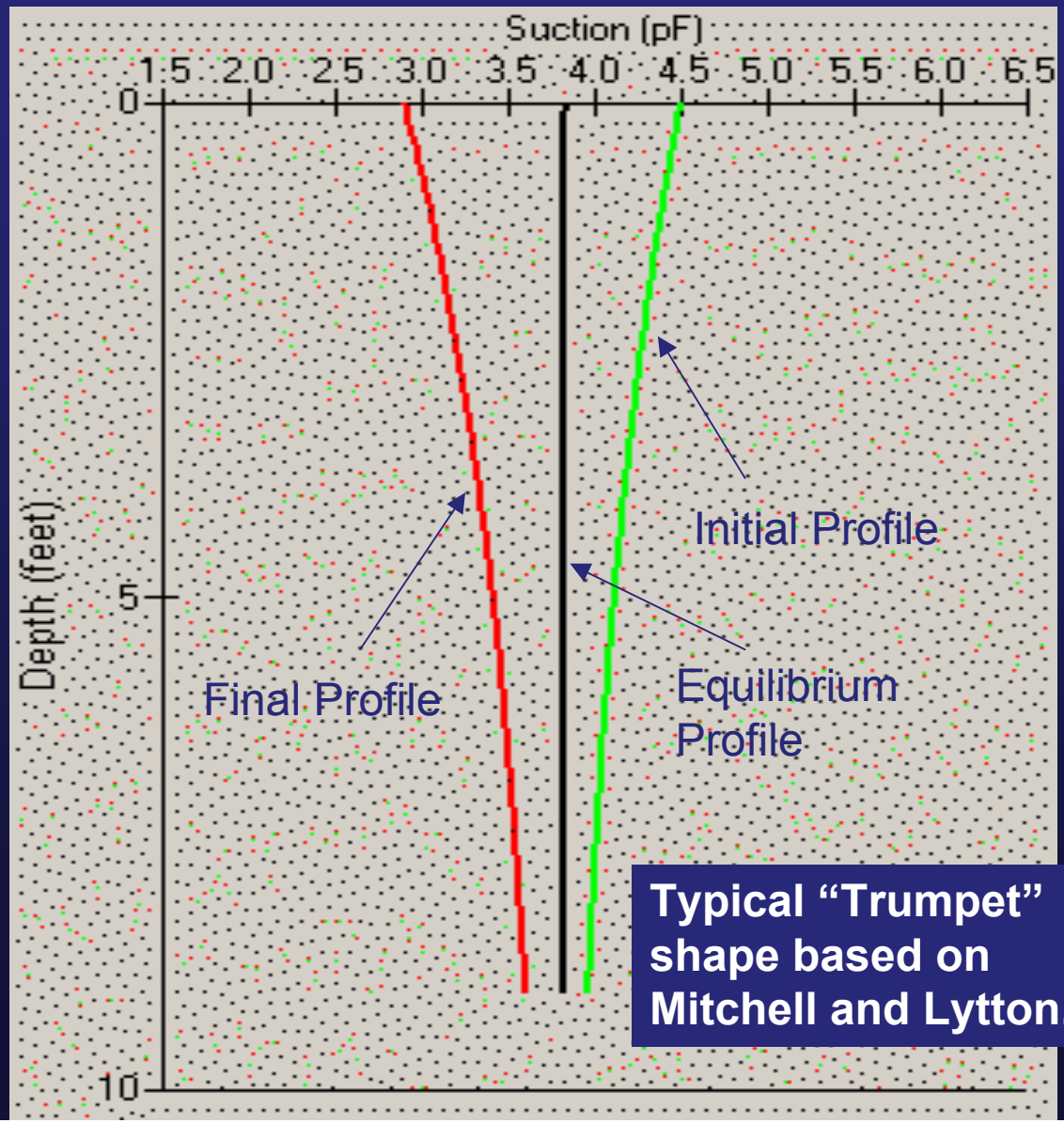


Reasonable Suction Change Range

2003 Total Soil Suction Data (4776 Observations)



Unsaturated Soil Mechanics
Typical Suction Envelope



Typical "Trumpet" shape based on Mitchell and Lytton.

Exponential Suction Profile for Extreme Wetting and Drying Condition

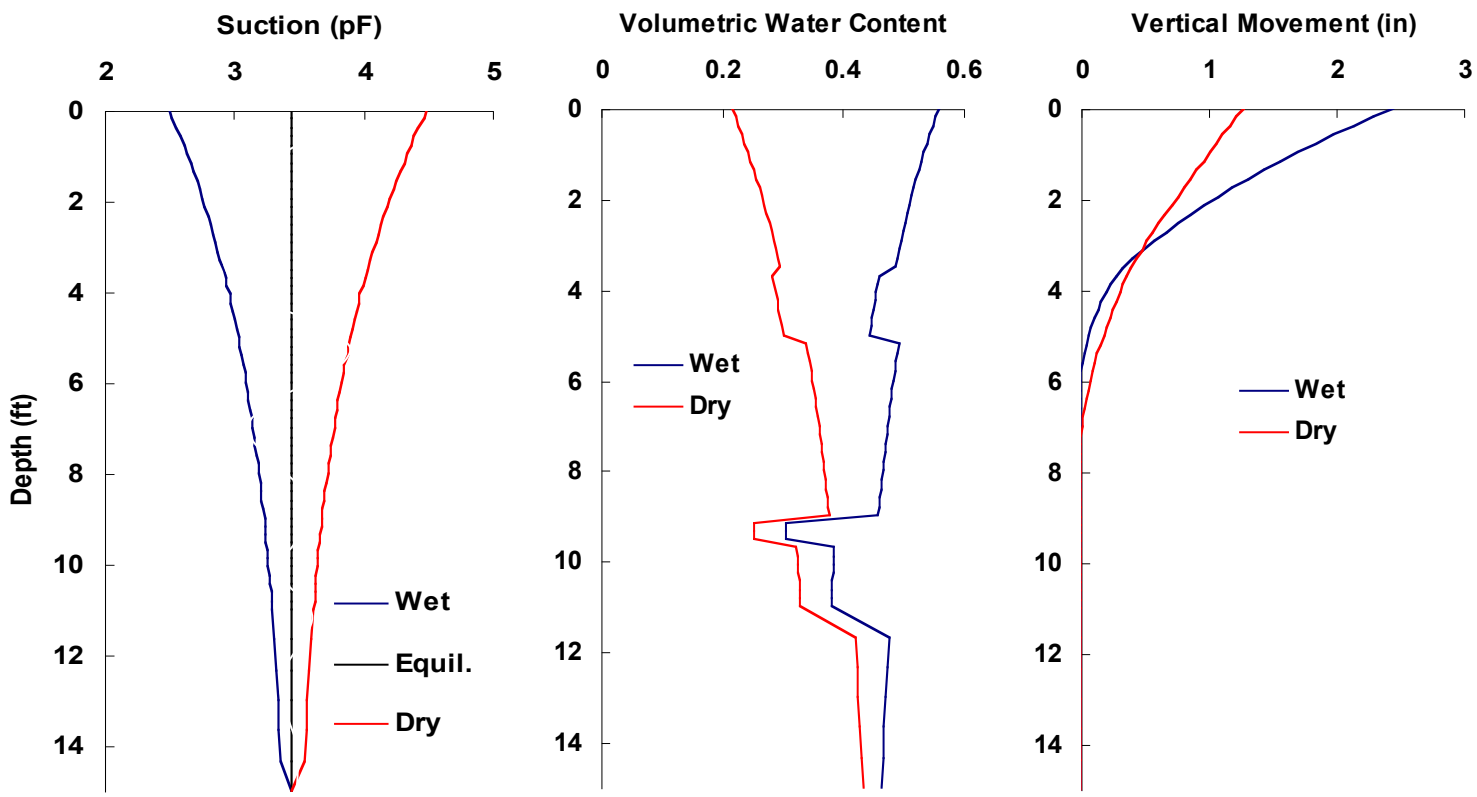
$$U(Z,t) = U_e + U_o \exp\left(-\sqrt{\frac{n\pi}{\alpha}}Z\right)\cos\left(2\pi nt - \sqrt{\frac{n\pi}{\alpha}}Z\right)$$

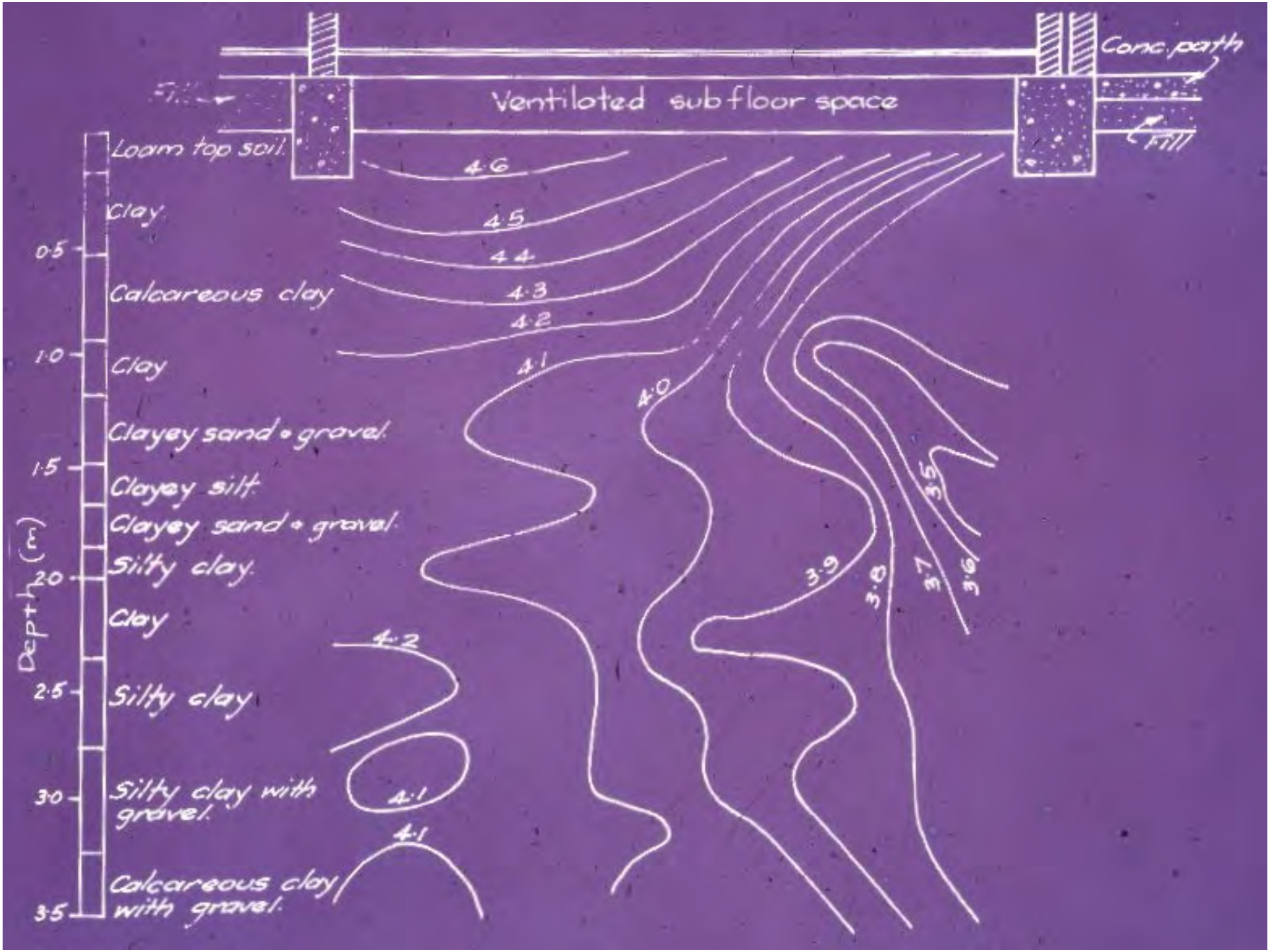
Mitchell (1979)

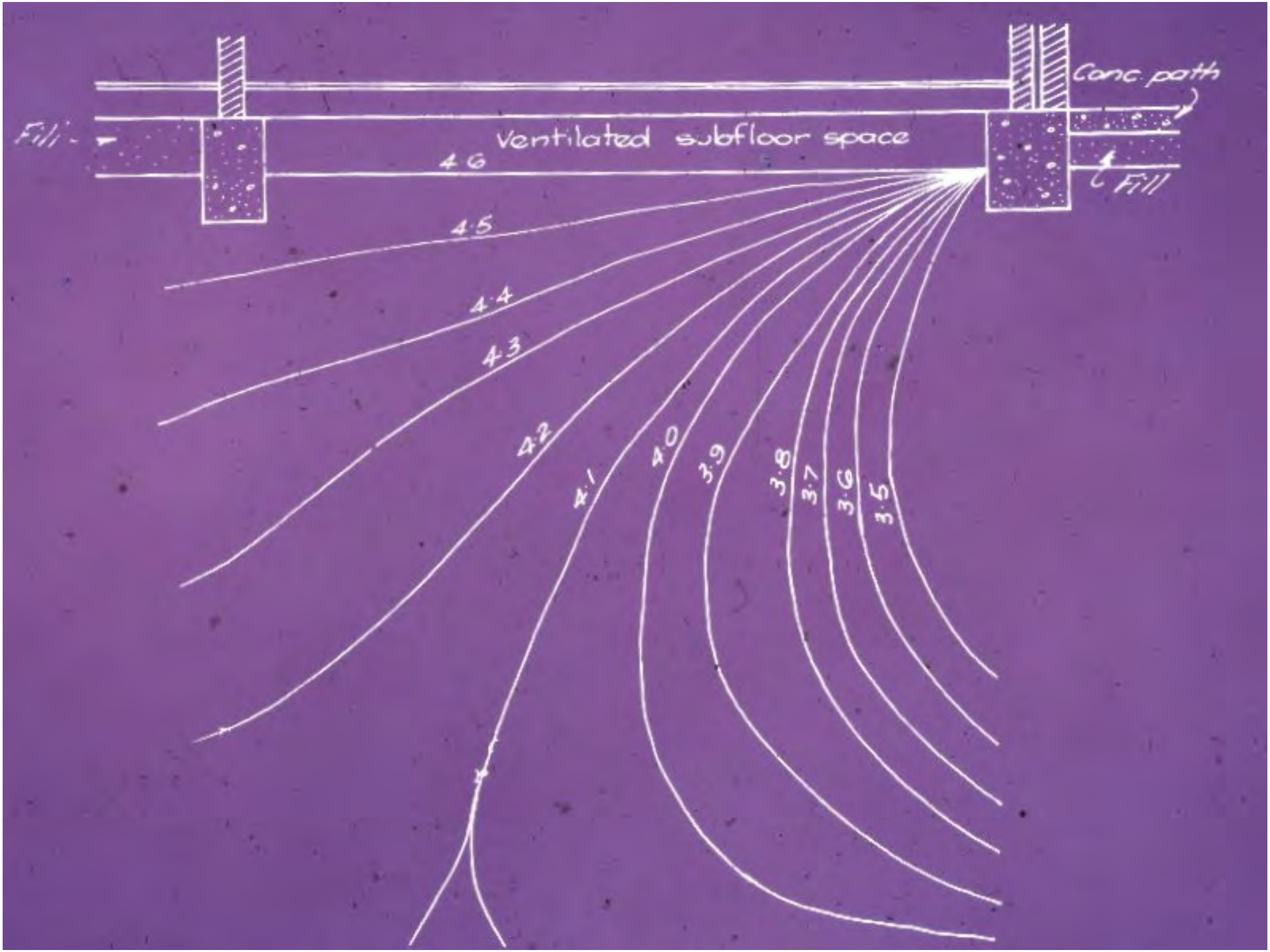
$$U(Z) = U_e + U_o \exp\left(-\sqrt{\frac{n\pi}{\alpha}}Z\right)$$

Fort Worth Interstate 820

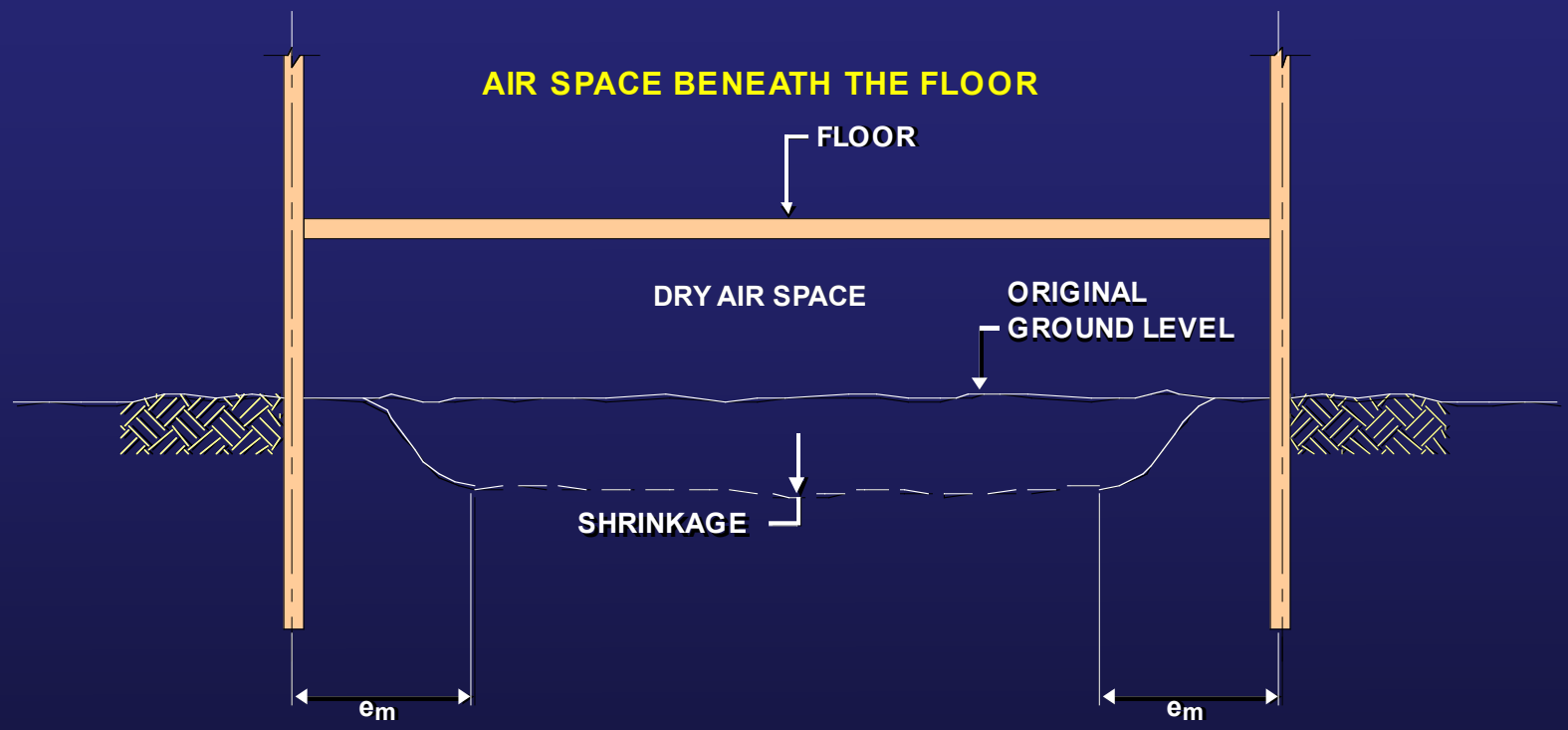
Moisture Active zone




Conc. path
Ventiloted sub floor space
Fill
Fill
Loam top soil
Clay
Calcareous clay
Clay
Clayey sand & gravel
Clayey silt
Clayey sand & gravel
Silty clay
Clay
Silty clay
Silty clay with gravel
Calcareous clay with gravel
Depth (m)
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.6
4.5
4.4
4.3
4.2
4.1
4.0
3.9
3.8
3.7
3.6
3.5
4.2
4.1
4.1


Conc. path
Fill
Ventilated subfloor space
Fill
4·6
4·5
4·4
4·3
4·2
4·1
4·0
3·9
3·8
3·7
3·6
3·5

TOTAL MOVEMENT PATTERNS WITH RAISED WOOD FLOOR FOUNDATIONS



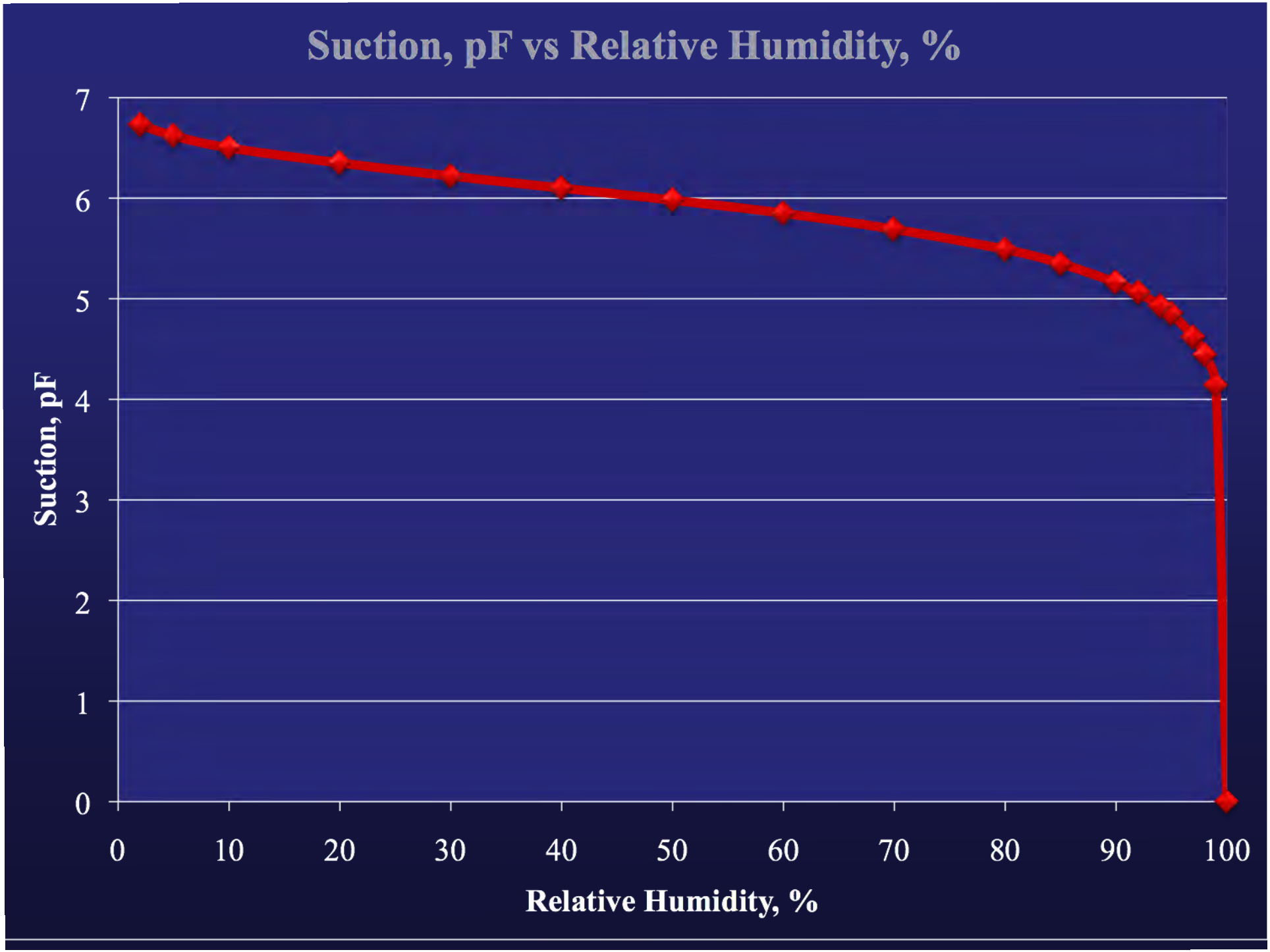
NOTE

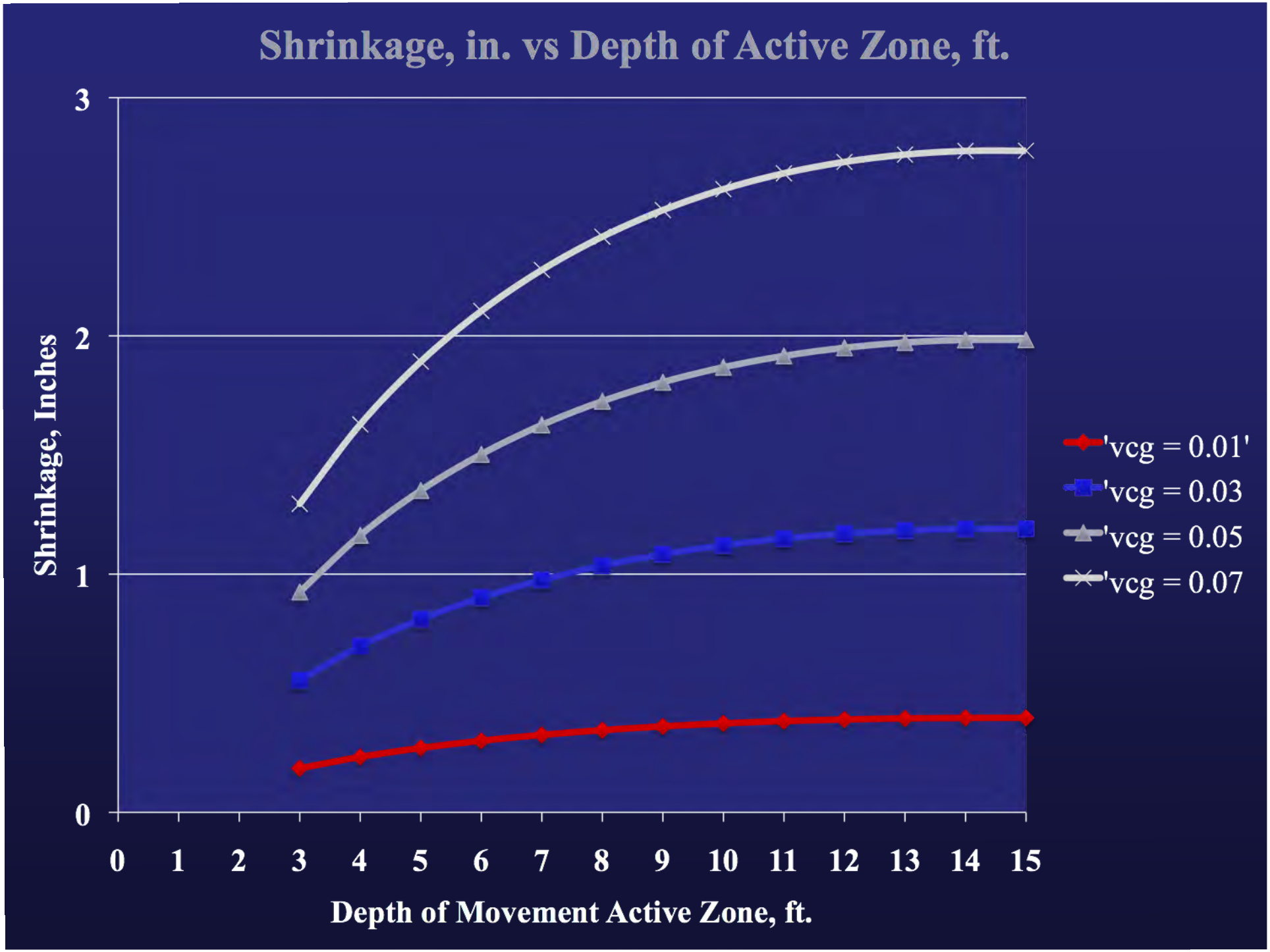
AMOUNT OF SHRINKAGE DEPENDS ON THE LEVEL OF RELATIVE HUMIDITY IN THE AIR BENEATH THE FLOOR. THE LOWER THE RELATIVE HUMIDITY, THE GREATER WILL BE THE AMOUNT OF SHRINKAGE. INITIALLY, THE SOIL WILL BE AT OR ABOVE 98% RELATIVE HUMIDITY. e m IS THE EDGE MOISTURE VARIATION DISTANCE WHICH VARIES TYPICALLY BETWEEN 3 AND 9 FEET DEPENDING ON THE TYPE OF SOIL.

Raised Floor Foundation Boundary Conditions

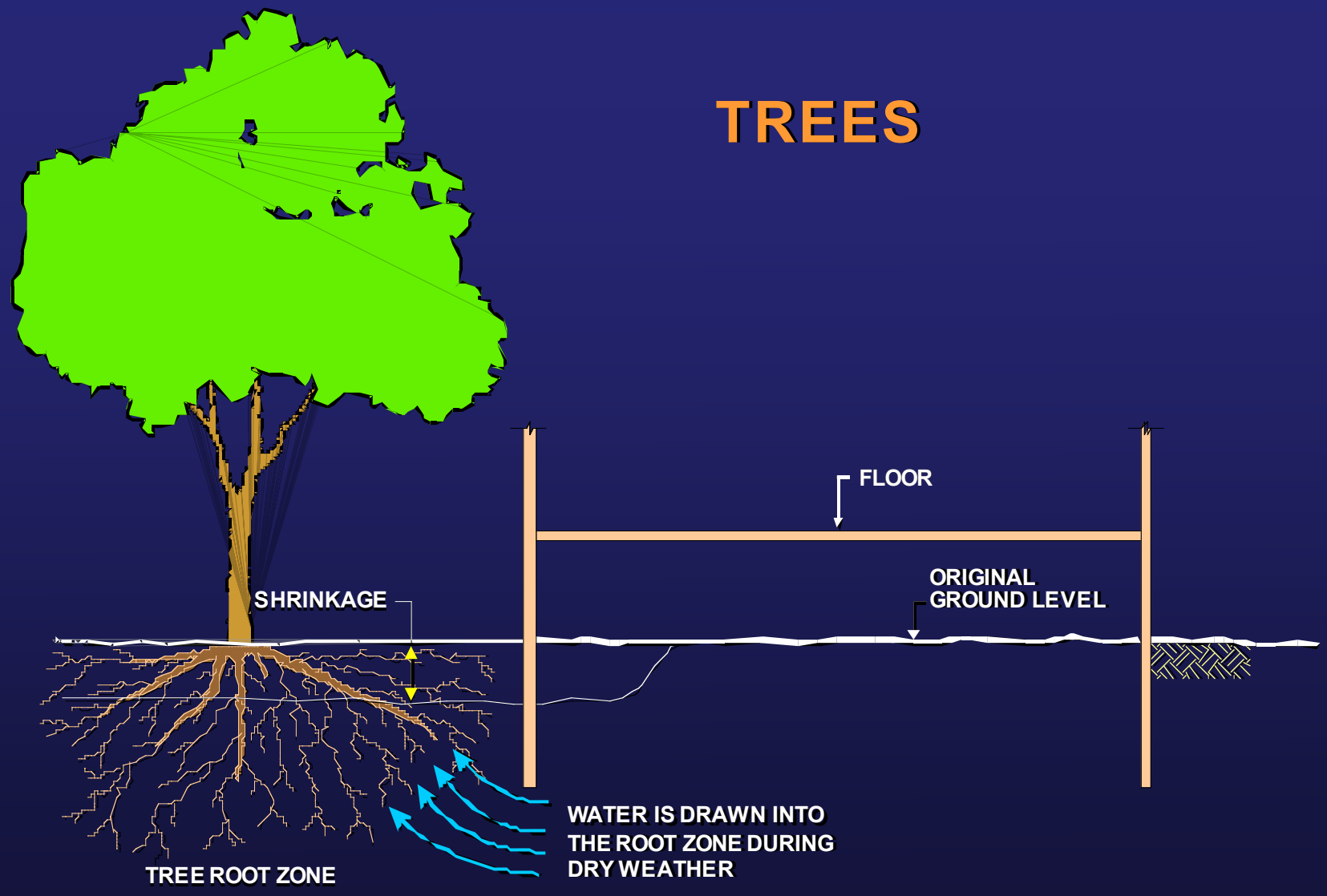
OUTSIDE WET	pF
FLOWER BED	2.9
LAWN WATER	3.0
TREE	4.5

pF DRY BENEATH	R.H.,%
6.50	**10**
6.35	**20**
6.22	**30**
6.10	**40**
5.98	**50**


Suction, pF vs Relative Humidity, %
Suction, pF
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
70
80
90
100
Relative Humidity, %

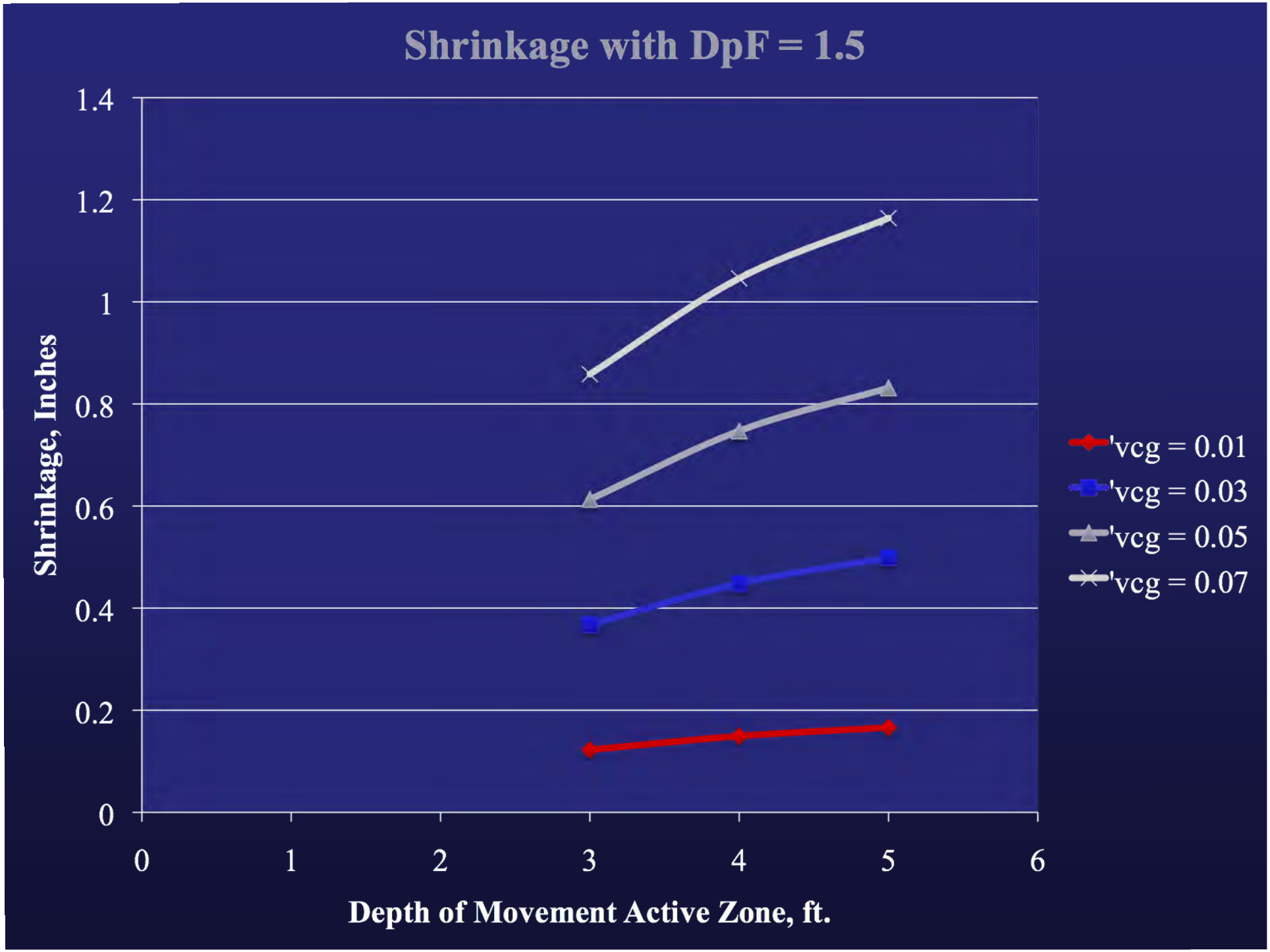

Shrinkage, in. vs Depth of Active Zone, ft.
Shrinkage, Inches
3
2
1
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Depth of Movement Active Zone, ft.
'vcg = 0.01'
'vcg = 0.03
'vcg = 0.05
'vcg = 0.07

TREES



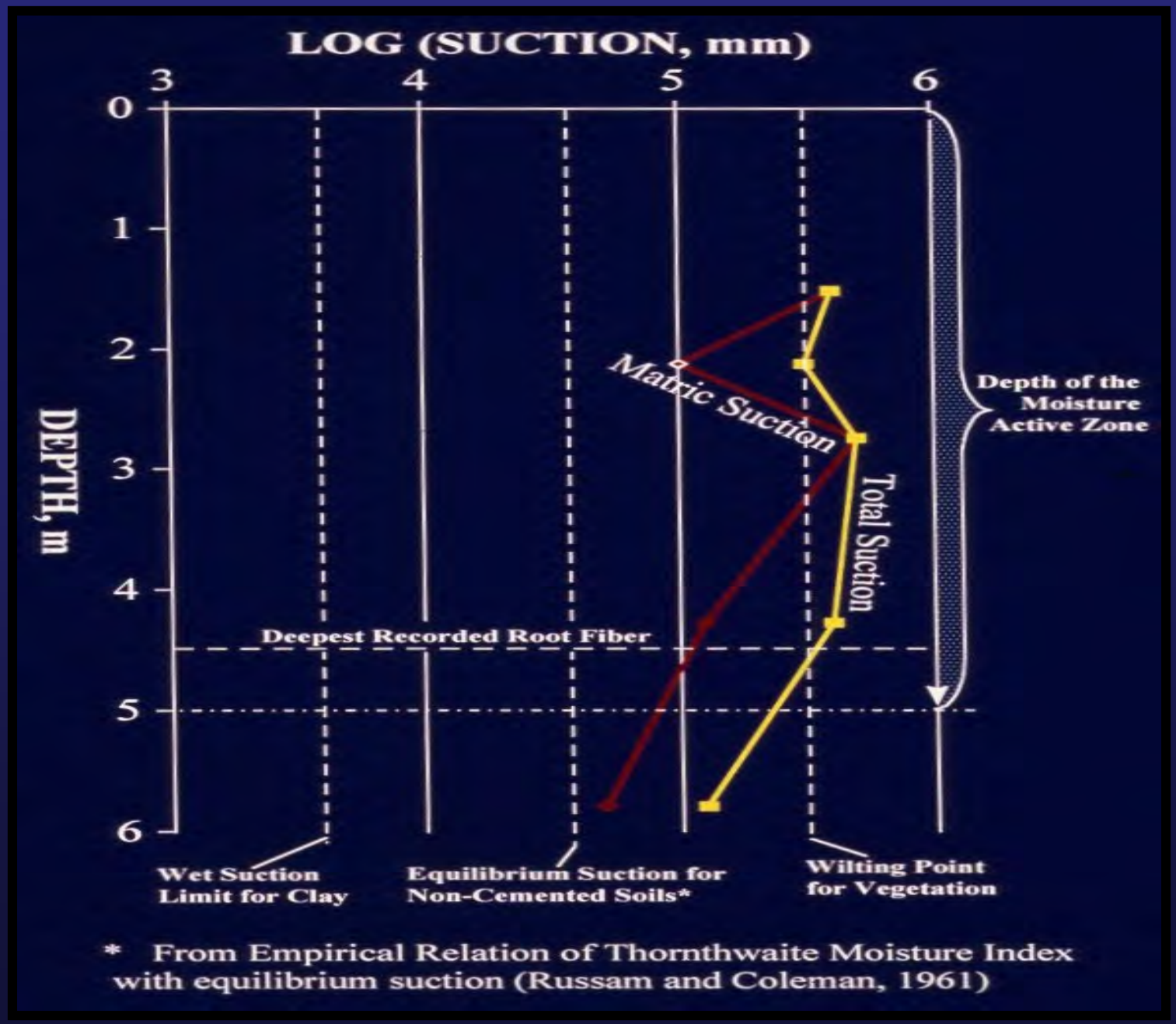
NOTE

AMOUNT OF SHRINKAGE DEPENDS ON THE DEPTH OF THE TREE ROOT ZONE, HOW FAR THE ROOTS PENETRATE BENEATH THE BUILDING, AND THE TYPE OF SOIL.


Shrinkage with DpF = 1.5
Shrinkage, Inches
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
Depth of Movement Active Zone, ft.
'vcg = 0.01
'vcg = 0.03
'vcg = 0.05
'vcg = 0.07

Laboratory Tests

- Atterberg limits
- Hydrometer
- Water content
- Dry density
- Sieve analysis


LOG (SUCTION, mm)
3
4
5
6
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)

Web Soil Survey - Windows Internet Explorer

http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx

File Edit View Favorites Tools Help

Web Soil Survey

YaA	Yahola fine sandy loam, 0 to 1 percent slopes, rarely flooded	858.7	0.2%
ZaB	Zack fine sandy loam, 1 to 5 percent slopes	11,763.7	3.1%
ZaC2	Zack fine sandy loam, 2 to 5 percent slopes, eroded	1,729.5	0.5%
ZaD	Zack fine sandy loam, 5 to 8 percent slopes	3,194.0	0.8%
ZaE3	Zack fine sandy loam, 8 to 25 percent slopes, severely eroded	269.9	0.1%
ZcB	Zack-Urban land complex, 1 to 5 percent slopes	7,841.9	2.1%
ZcD	Zack-Urban land complex, 5 to 8 percent slopes	547.6	0.1%
ZuB	Zulch fine sandy loam, 1 to 3 percent slopes	11,440.6	3.0%
Totals for Area of Interest		**377,977.9**	**100.0%**

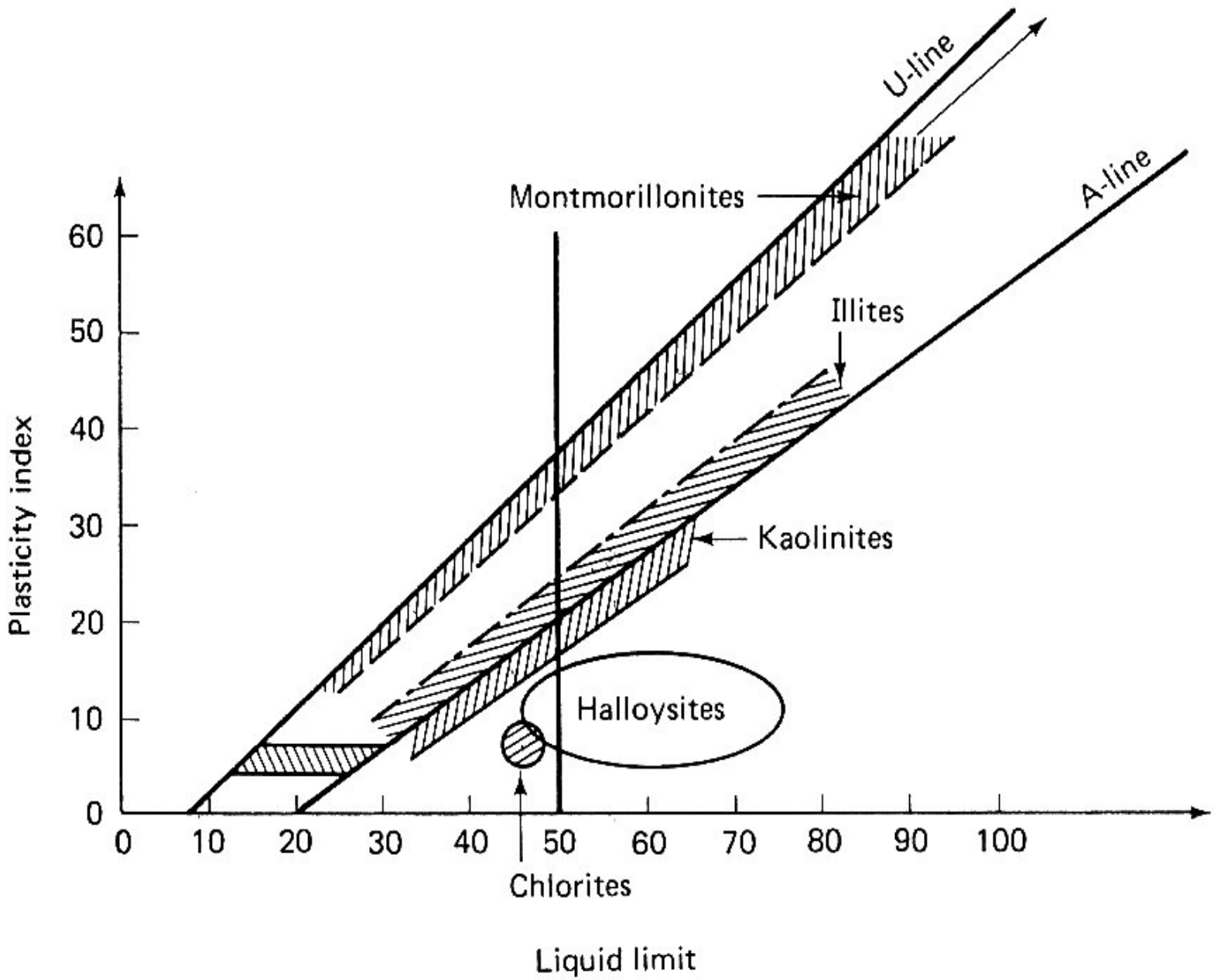
Warning: Soil Map may not be valid at this scale.

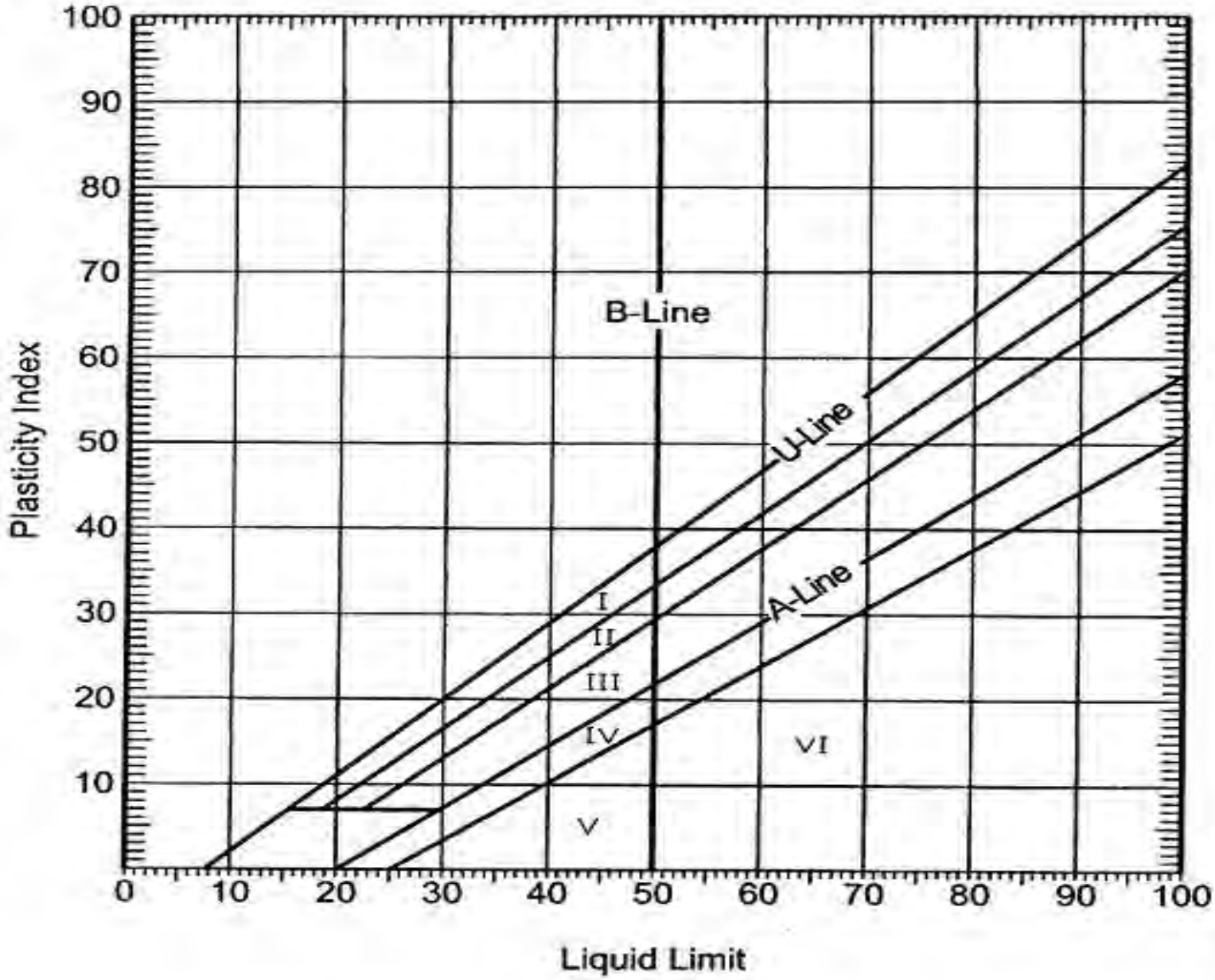
You have zoomed in beyond the scale at which the soil map for this area is intended to be used. Mapping of soils is done at a particular scale. The soil surveys that comprise your AOI were mapped at 1:20,000. The design of map units and the level of detail shown in the resulting soil map are dependent on that map scale.

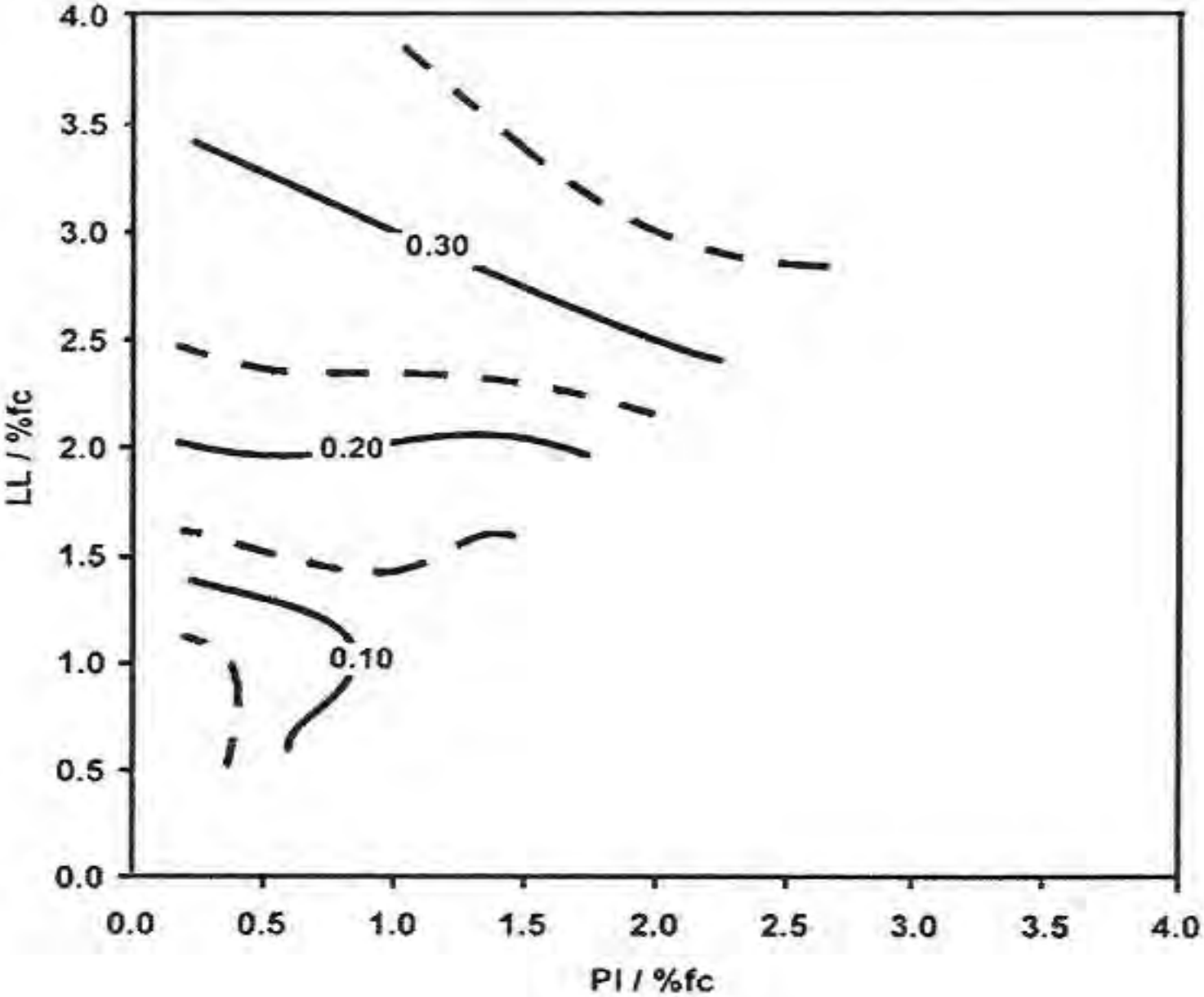
Enlargement of maps beyond the scale of mapping can cause misunderstanding of the detail of mapping and accuracy of soil line placement. The maps do not show the small areas of contrasting soils that could have been shown at a more detailed scale.

Done Internet 100%

start Inbox - Microsoft Out... C:\Documents and Se... Web Soil Survey - Wi... SoilDataAvailabilityMa... CVEN 646 Materials 6:29 PM

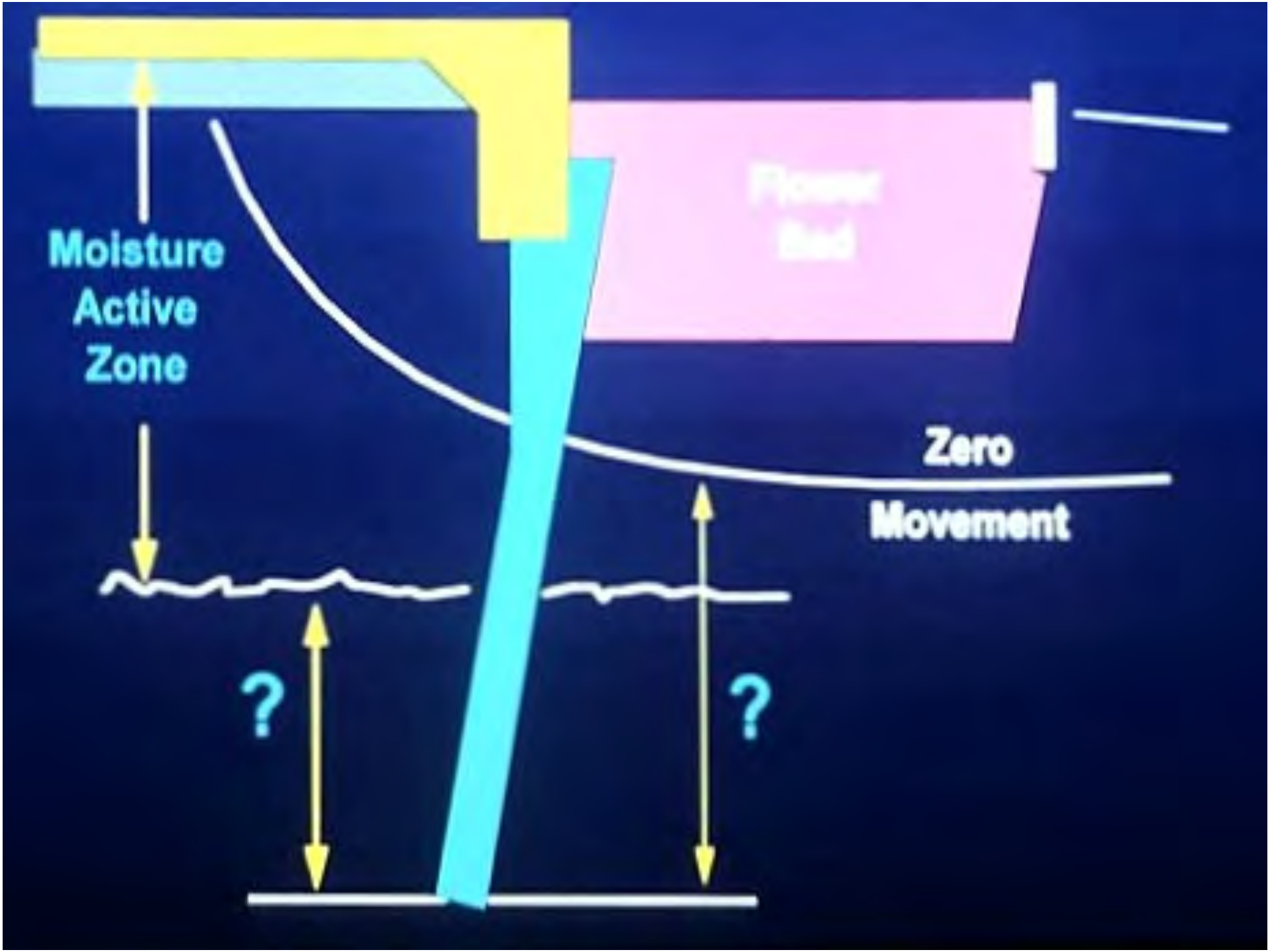

U-line
A-line
Montmorillonites
Illites
Kaolinites
Halloysites
Chlorites
Plasticity index
Liquid limit
0
10
20
30
40
50
60
70
80
90
100

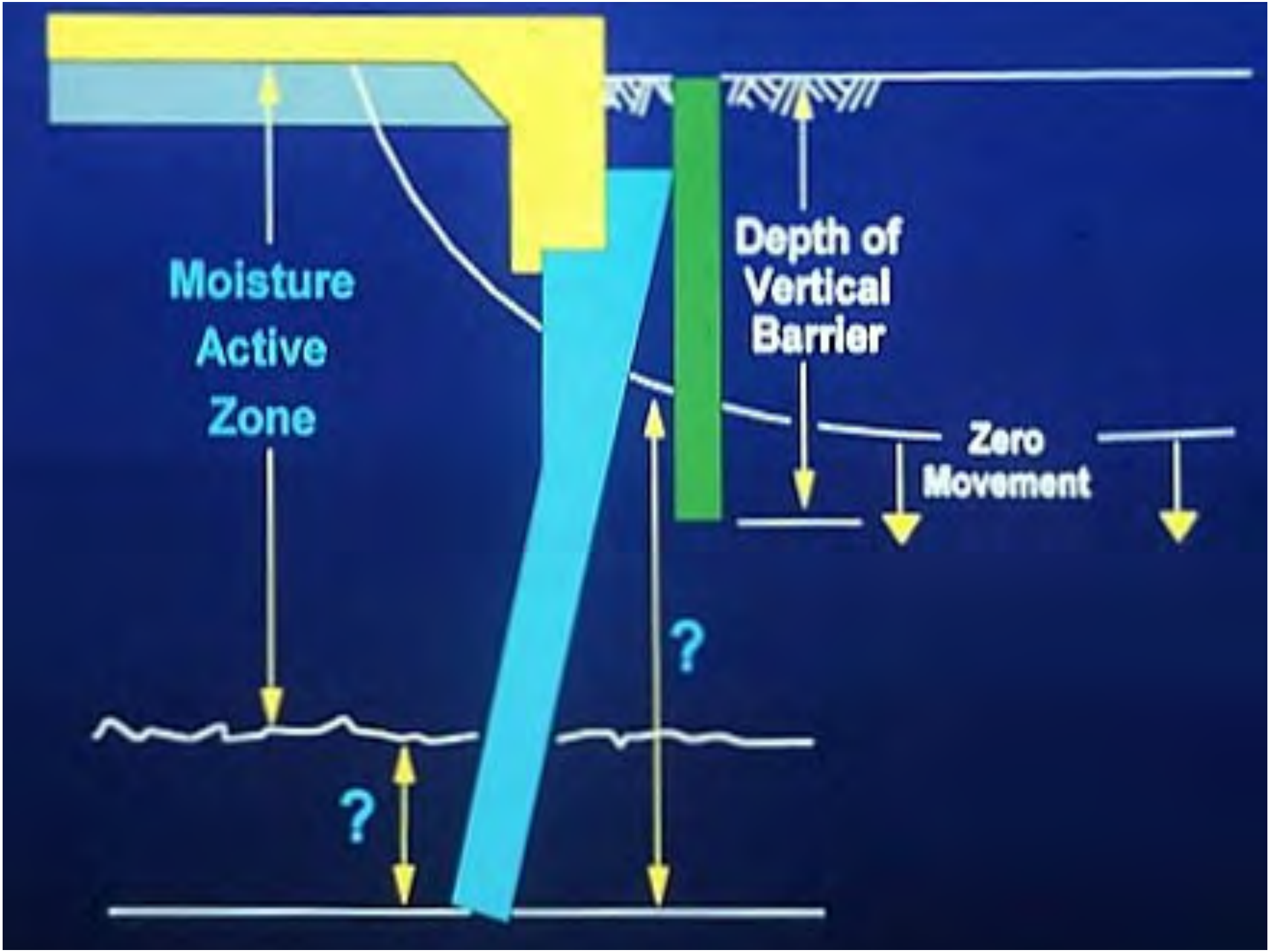

Plasticity Index
Liquid Limit
B-Line
U-Line
A-Line
I
II
III
IV
V
VI
0
10
20
30
40
50
60
70
80
90
100


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

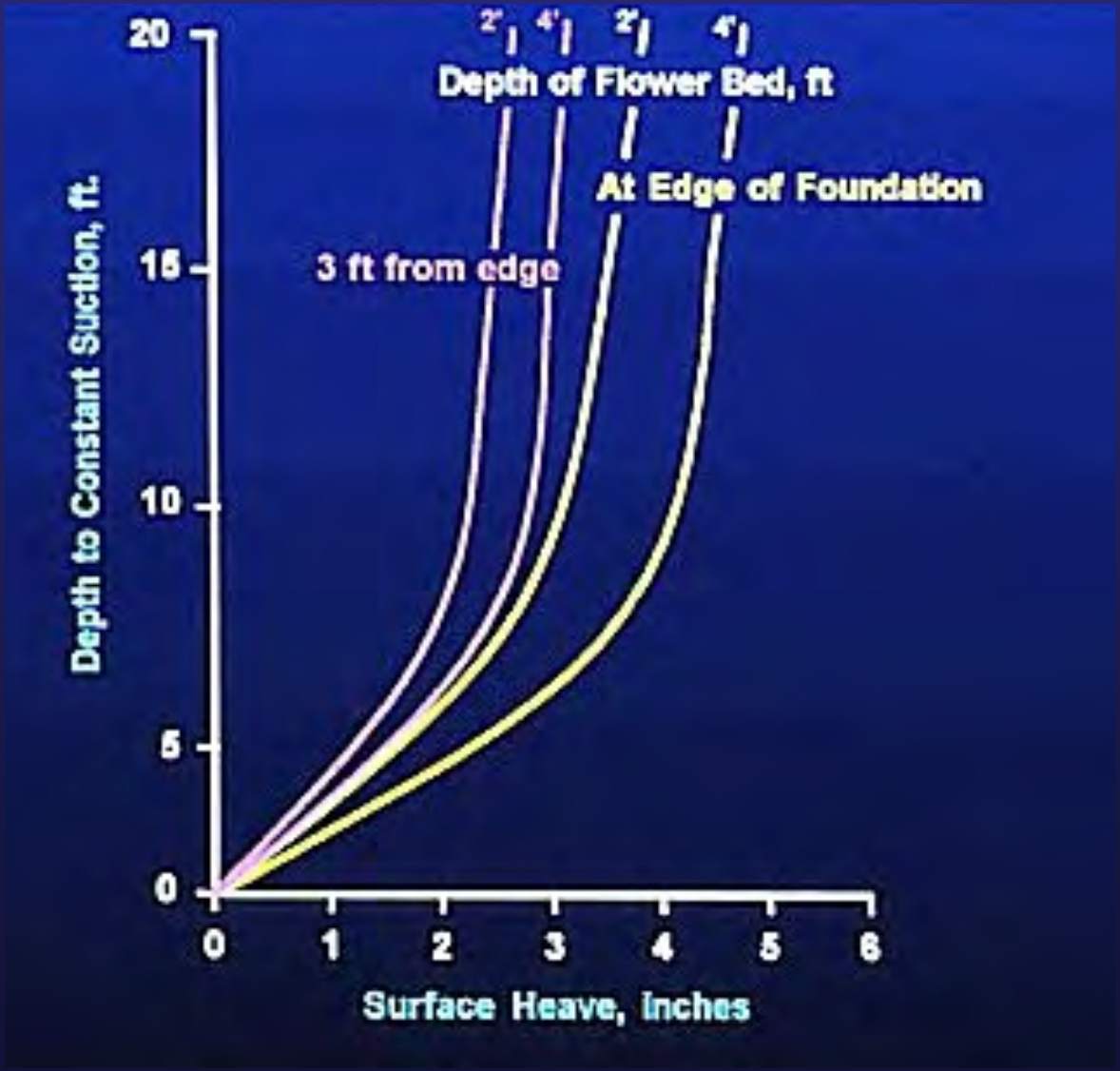
Typical Clay Properties

Property	Range	Example
Liquid Limit	55-90	86
Plasticity	30-60	59
Plastic Limit	25-30	27
Percent Passing #200	80-99	97
Percent Passing 0.002mm	-	65

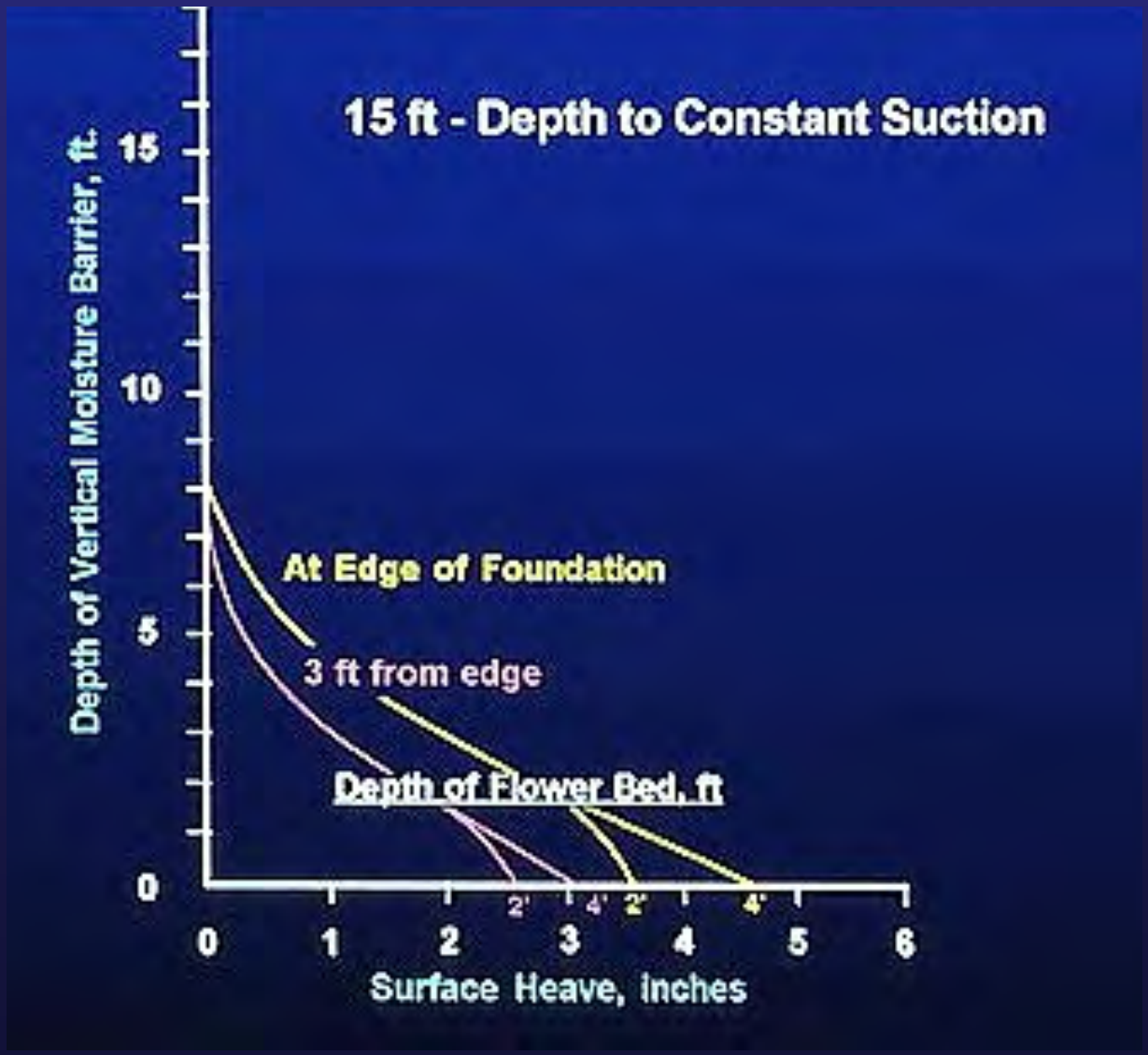

Moisture
Active
Zone
Zero
Movement
?
?


Moisture
Active
Zone
Depth of
Vertical
Barrier
Zero
Movement
?
?

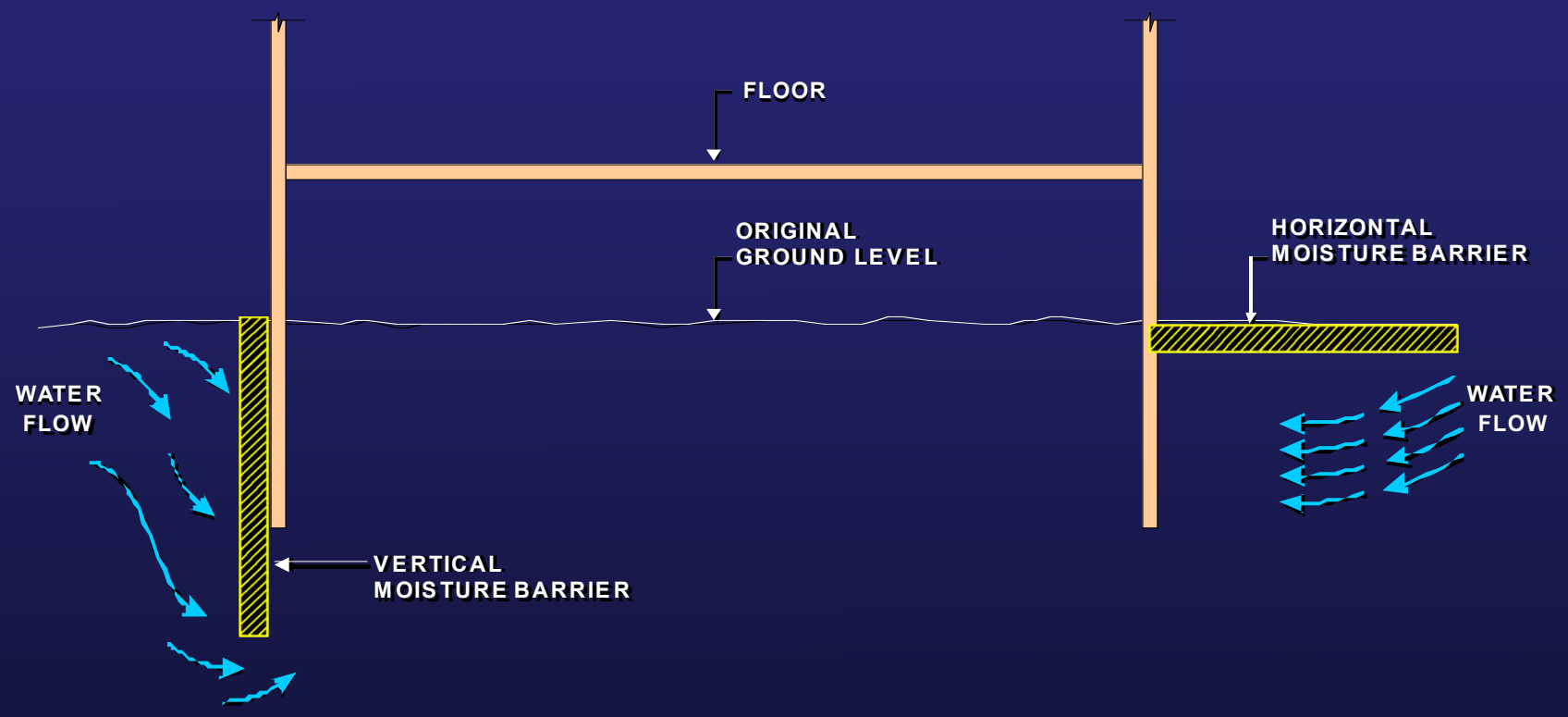
Effects of Flower Beds



Effects of Flower Beds

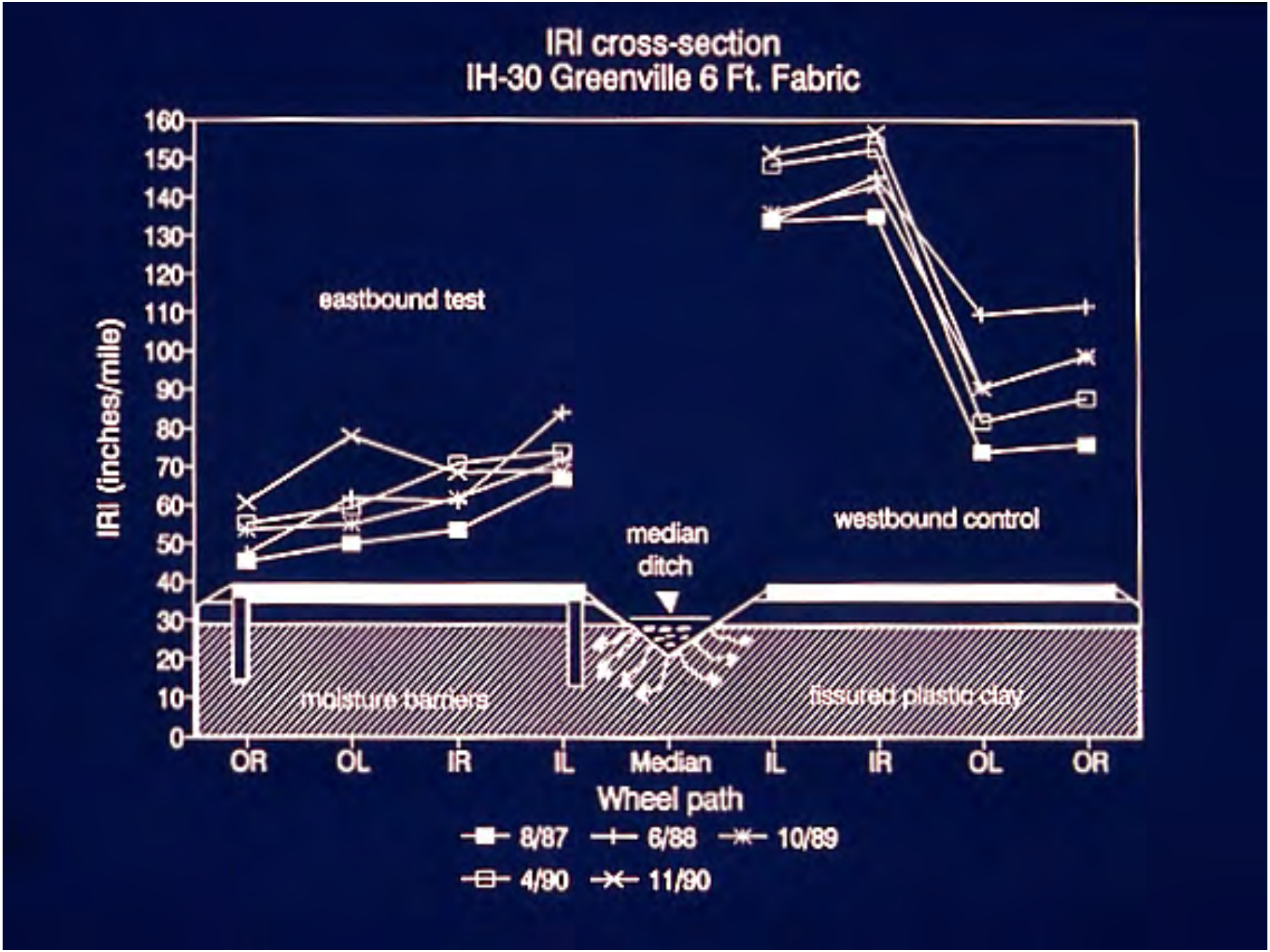


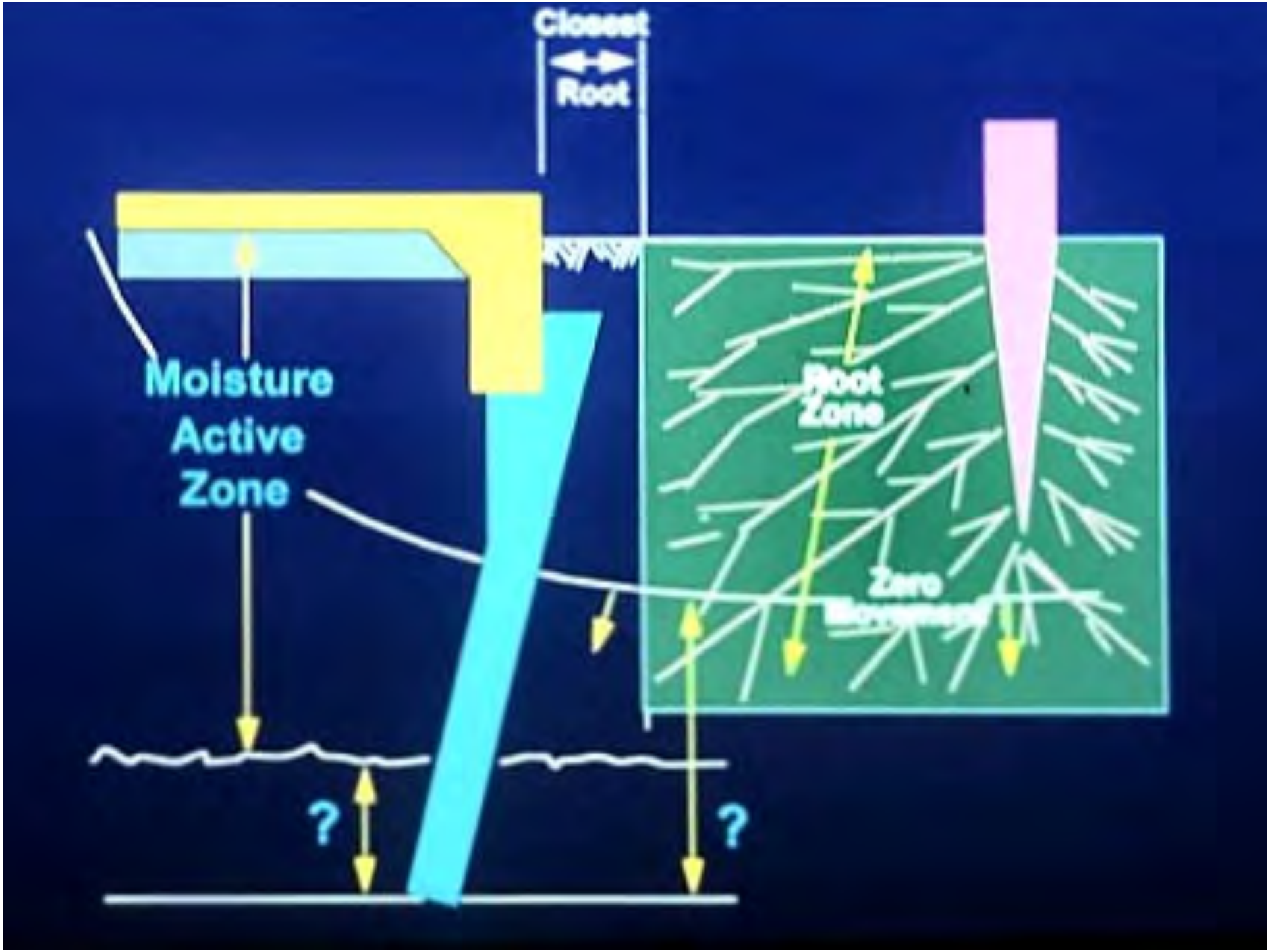
VERTICAL AND HORIZONTAL MOISTURE BARRIERS



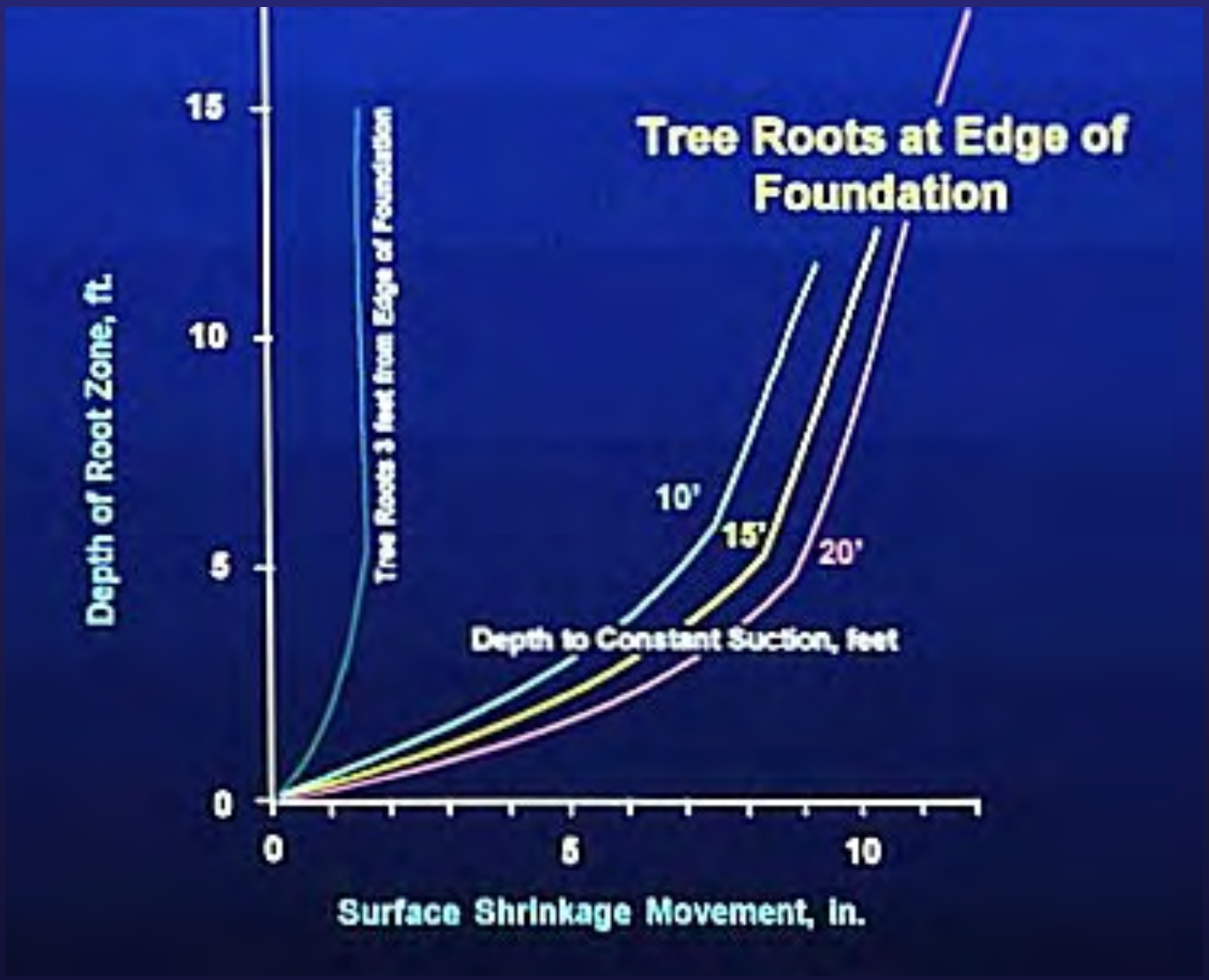
NOTE

VERTICAL AND HORIZONTAL MOISTURE BARRIERS DECREASE THE AMOUNT OF MOISTURE THAT GETS BENEATH THE WALLS OF THE BUILDING. EFFECTIVE DEPTHS OF VERTICAL MOISTURE BARRIERS ARE BETWEEN 2.5 AND 4 FEET. EFFECTIVE WIDTHS OF HORIZONTAL MOISTURE BARRIERS ARE BETWEEN 4 FEET AND em, THE EDGE MOISTURE VARIATION DISTANCE.

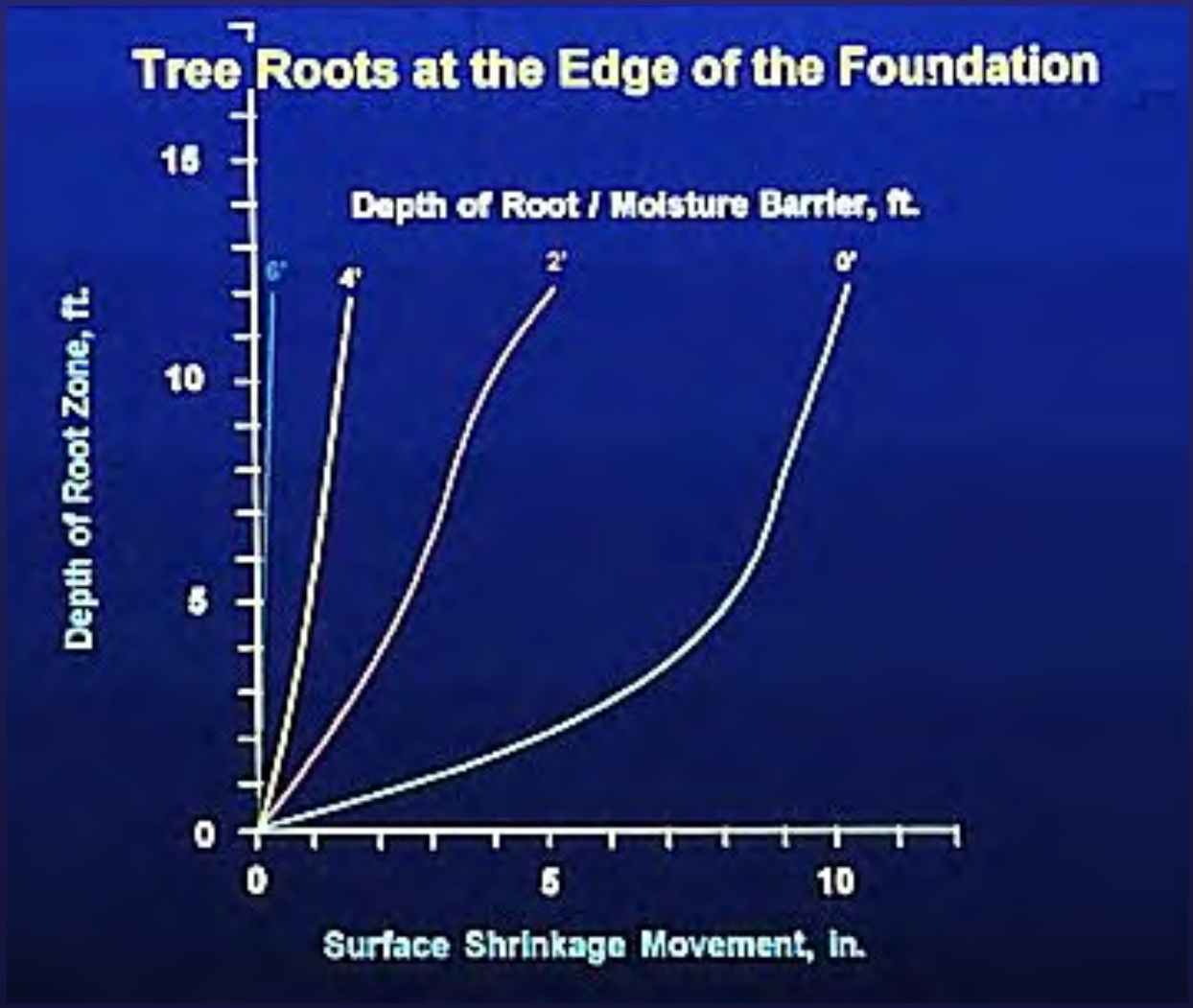

IRI cross-section
IH-30 Greenville 6 Ft. Fabric
IRI (inches/mile)
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
eastbound test
westbound control
median
ditch
moisture barriers
fissured plastic clay
OR
OL
IR
IL
Median
IL
IR
OL
OR
Wheel path
8/87
6/88
10/89
4/90
11/90


Closest
Root
Moisture
Active
Zone
Root
Zone
?
?

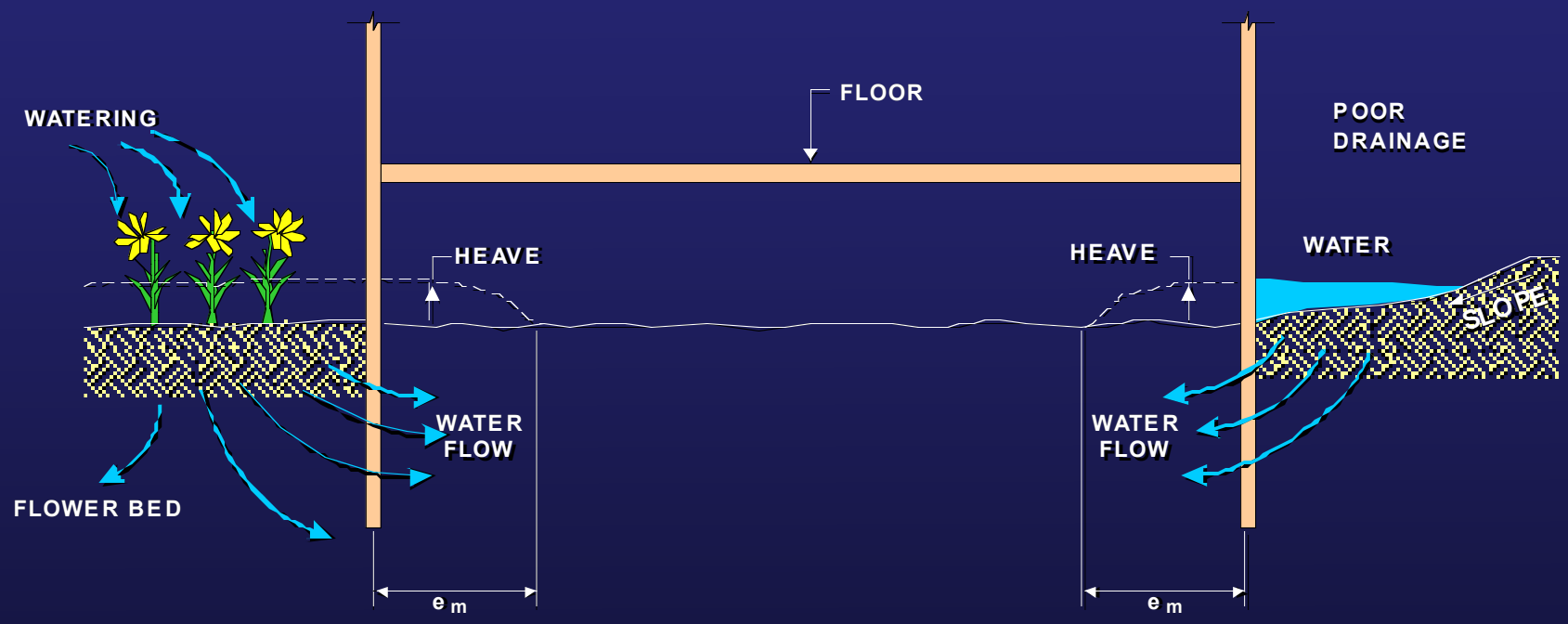
Effects of Trees



Effects of Trees



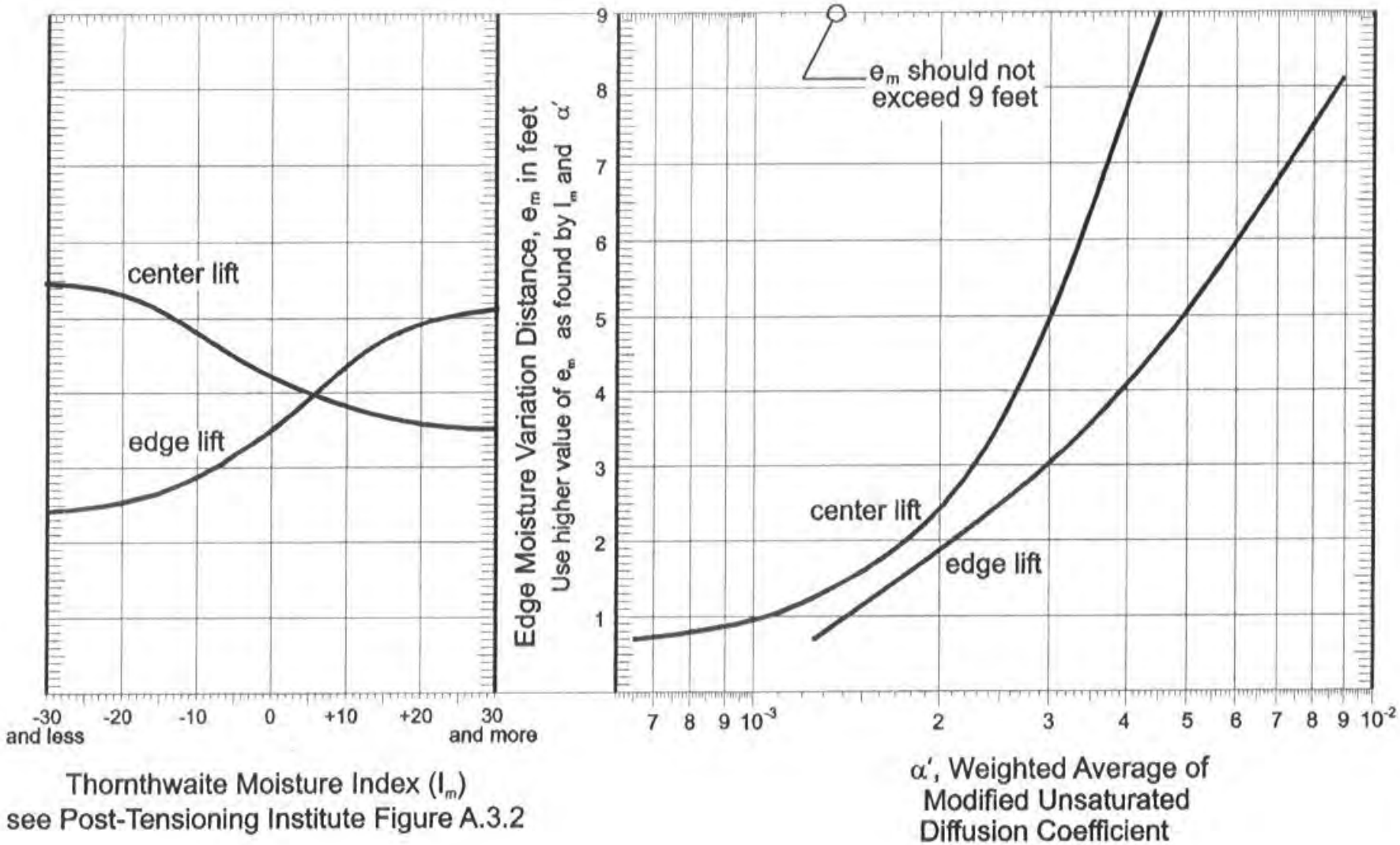
VERTICAL AND HORIZONTAL MOISTURE BARRIERS



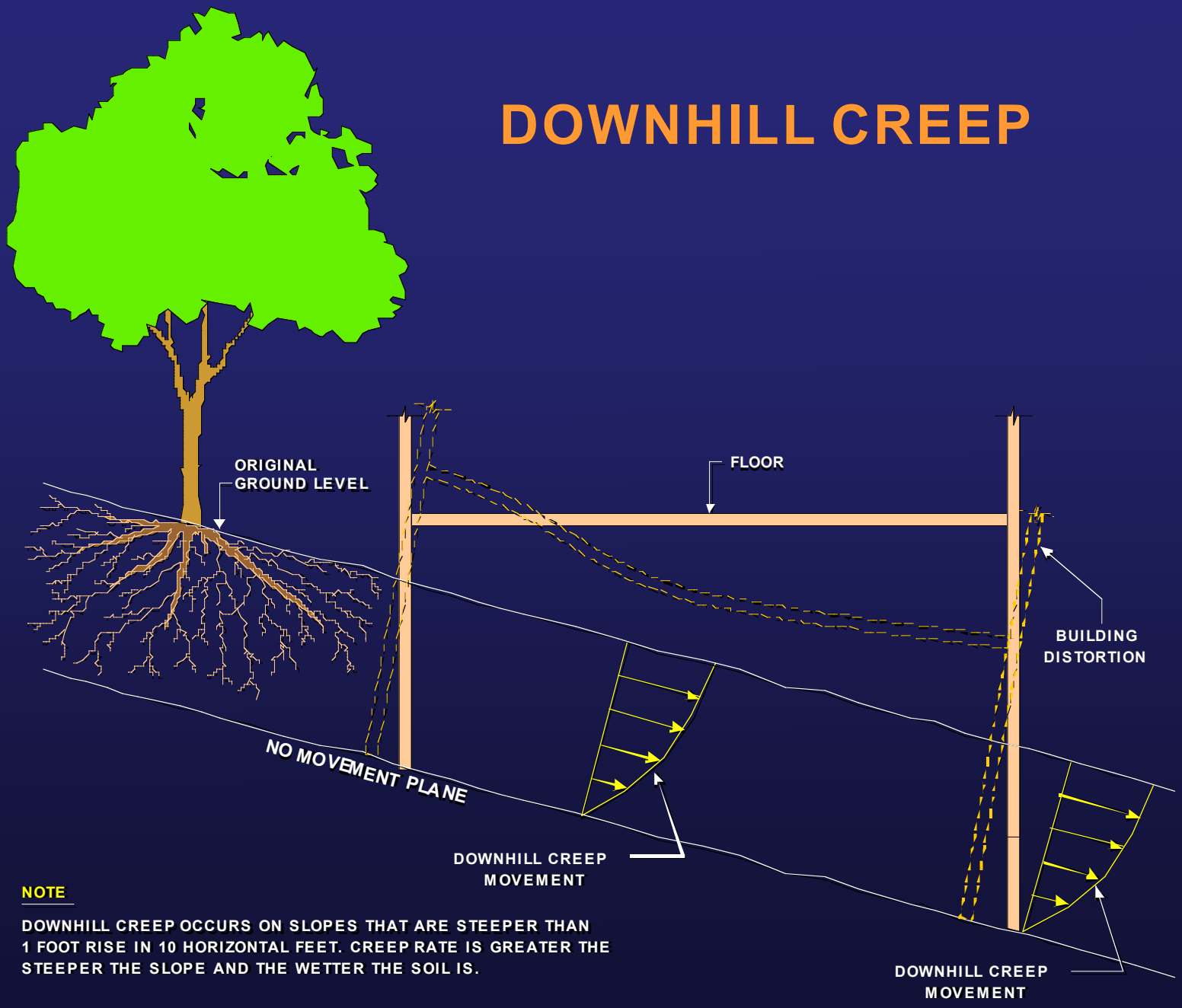
NOTE

AMOUNT OF HEAVE DEPENDS ON THE AMOUNT OF WATER THAT IS MADE AVAILABLE TO THE SOIL AT THE EDGE OF THE BUILDING AND THE TYPE OF SOIL. e_m IS THE EDGE MOISTURE VARIATION DISTANCE WHICH VARIES TYPICALLY BETWEEN 3 AND 9 FEET DEPENDING ON THE TYPE OF SOIL.

Figure 8 - e_m Selection Chart



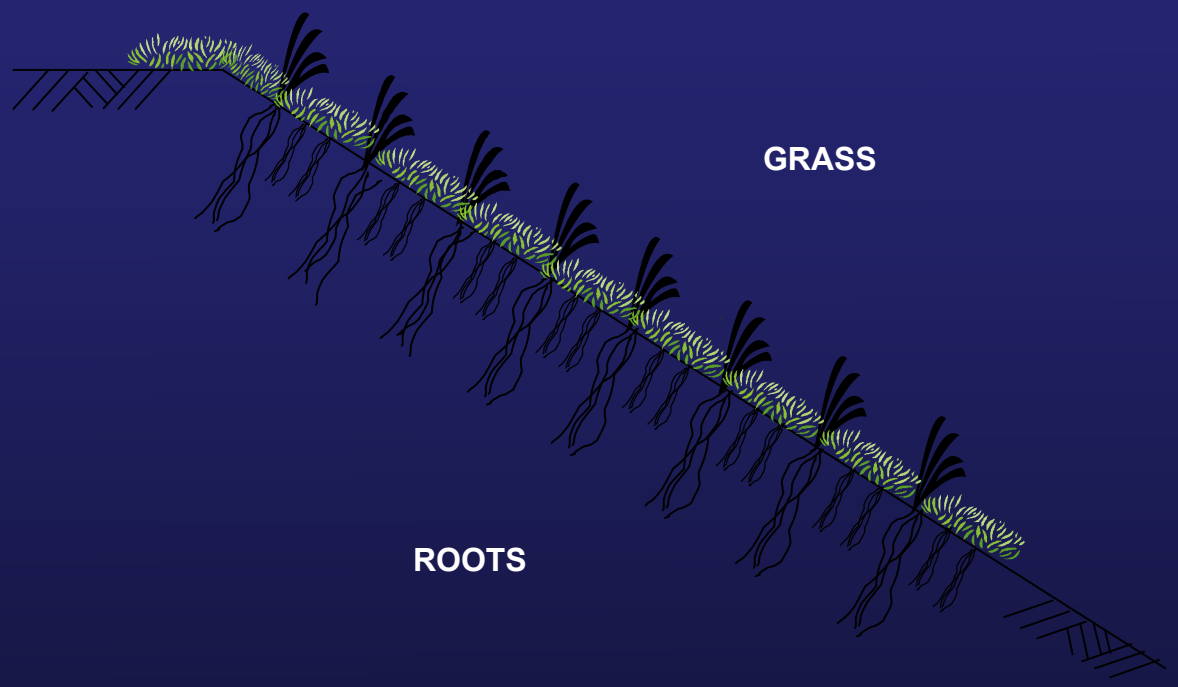
DOWNHILL CREEP



NOTE

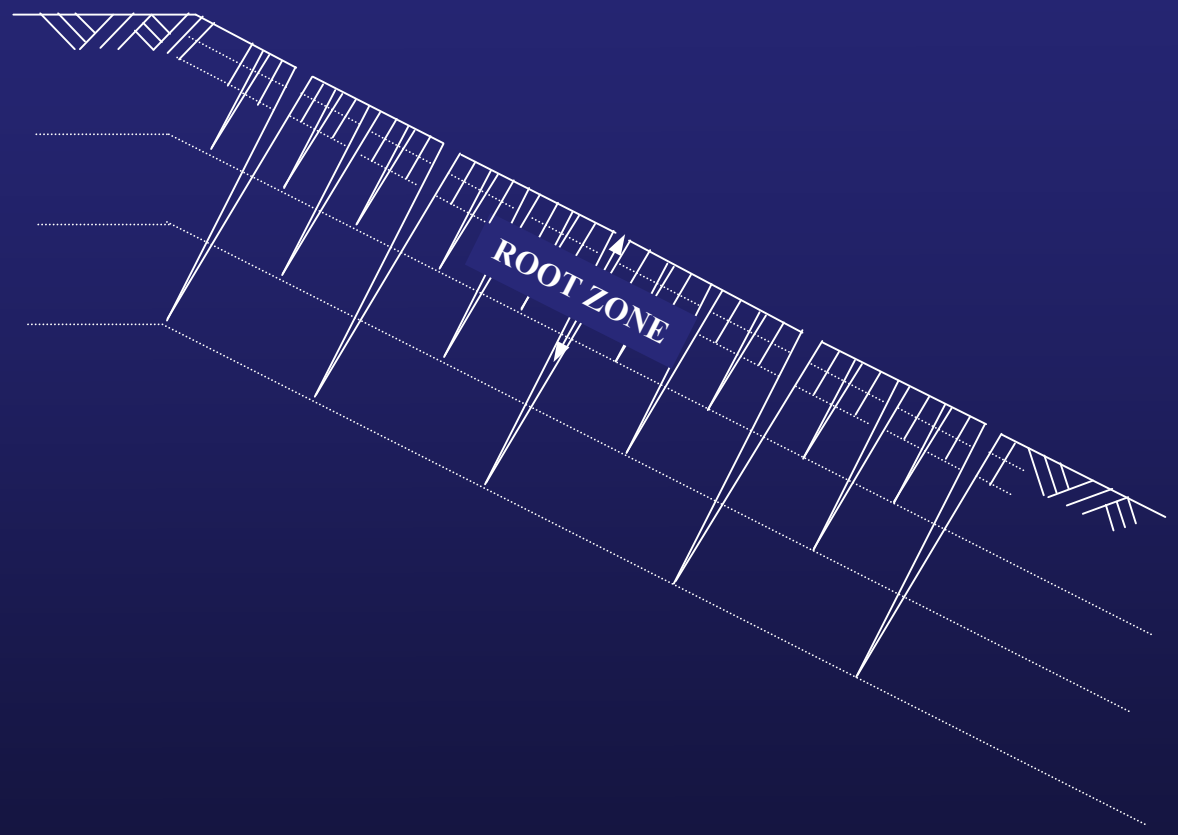
DOWNHILL CREEP OCCURS ON SLOPES THAT ARE STEEPER THAN 1 FOOT RISE IN 10 HORIZONTAL FEET. CREEP RATE IS GREATER THE STEEPER THE SLOPE AND THE WETTER THE SOIL IS.

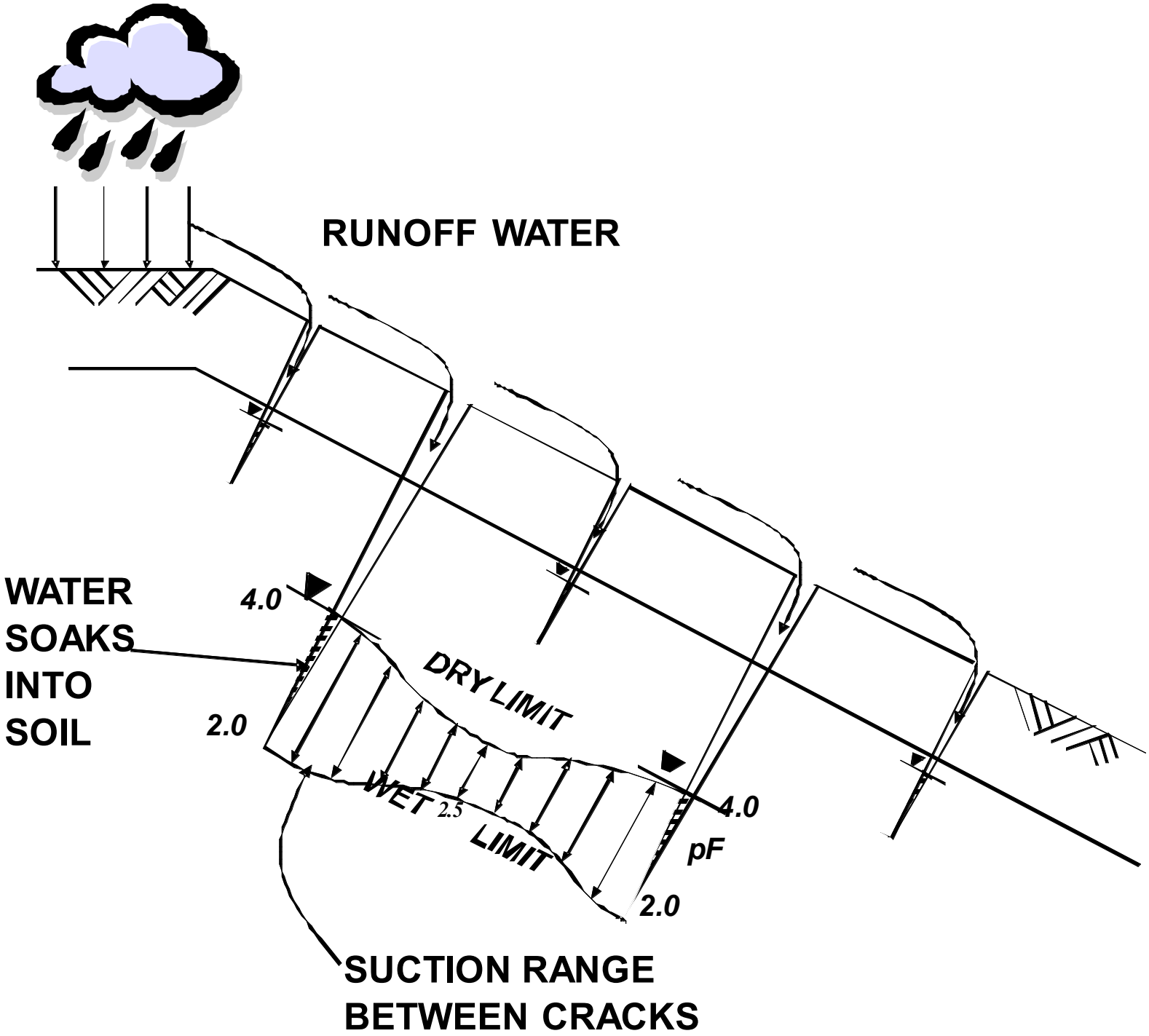
Shallow Slope Failure



During dry periods roots extract water From the soil and cause shrinkage cracks

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

Foundation soil properties

- Moisture Conditions
  - Beside Raised Floors
  - Beneath Raised Floors
- Differential Movements
- Soil Properties
- Site Investigation

Raised Floor Foundation Boundary Conditions

OUTSIDE WET	pF
FLOWER BED	2.9
LAWN WATER	3.0
TREE	4.5

pF DRY BENEATH	R.H.,%
6.50	**10**
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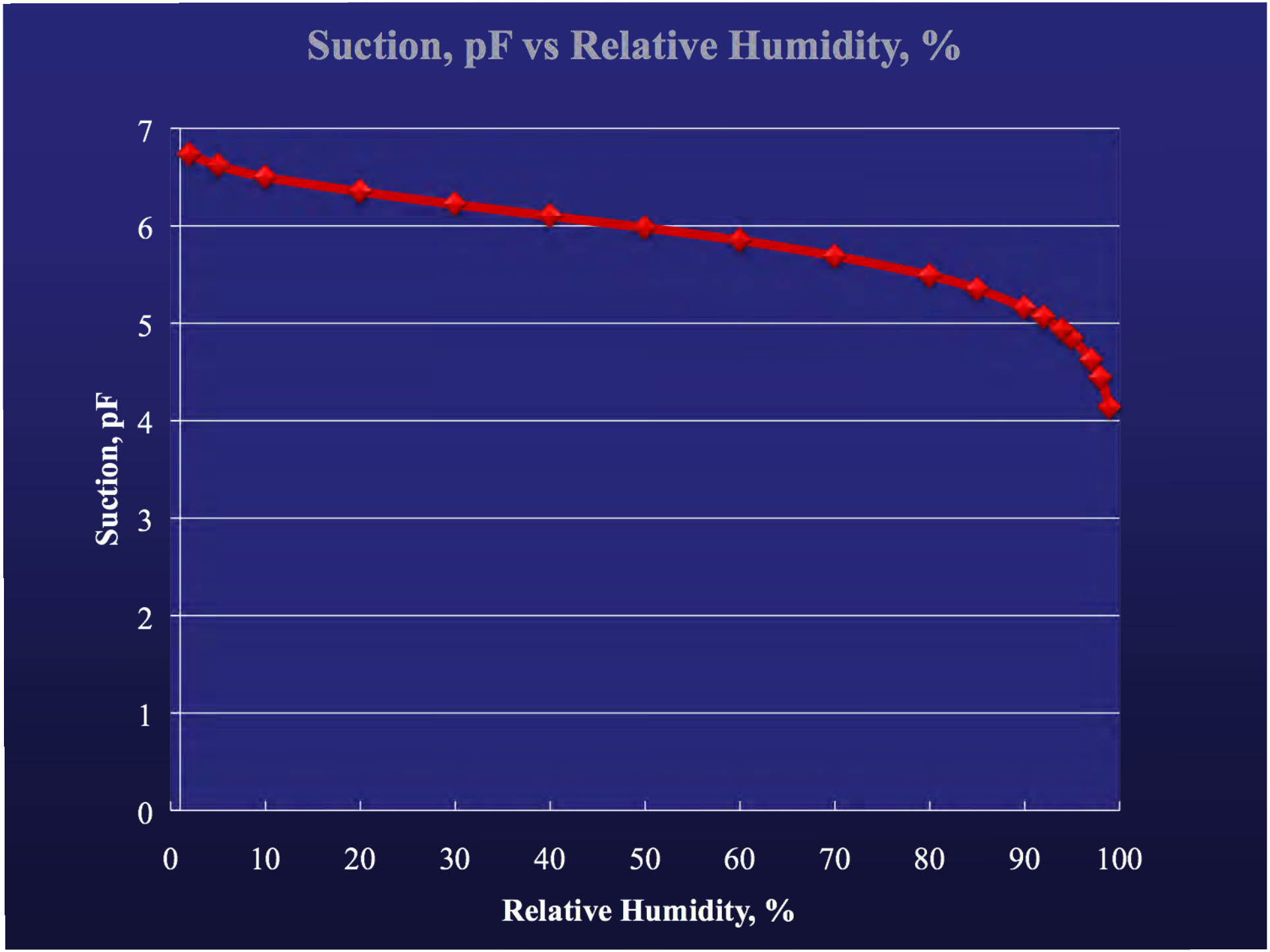
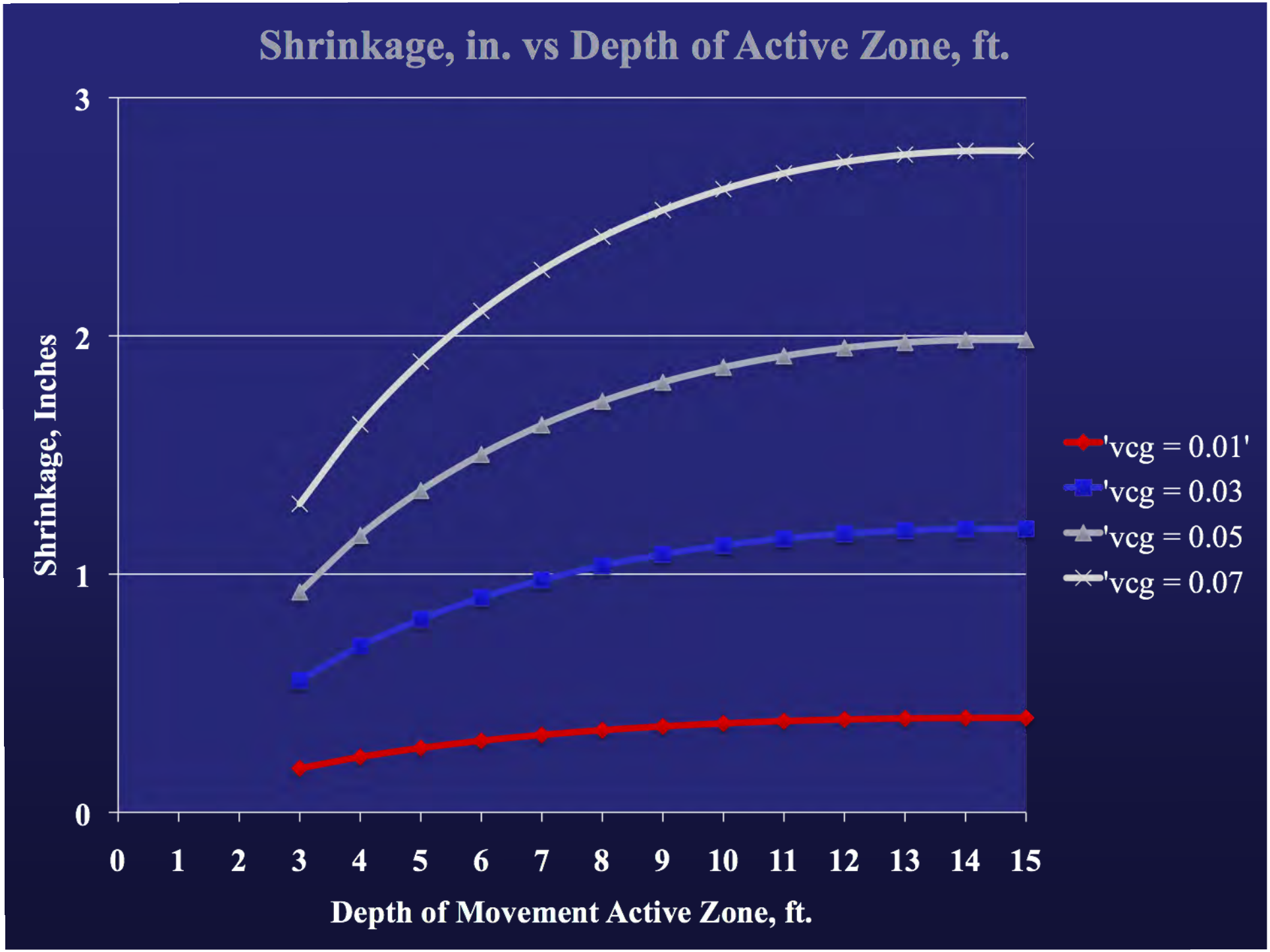

Suction, pF vs Relative Humidity, %
Suction, pF
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
70
80
90
100
Relative Humidity, %


Shrinkage, in. vs Depth of Active Zone, ft.
Shrinkage, Inches
3
2
1
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Depth of Movement Active Zone, ft.
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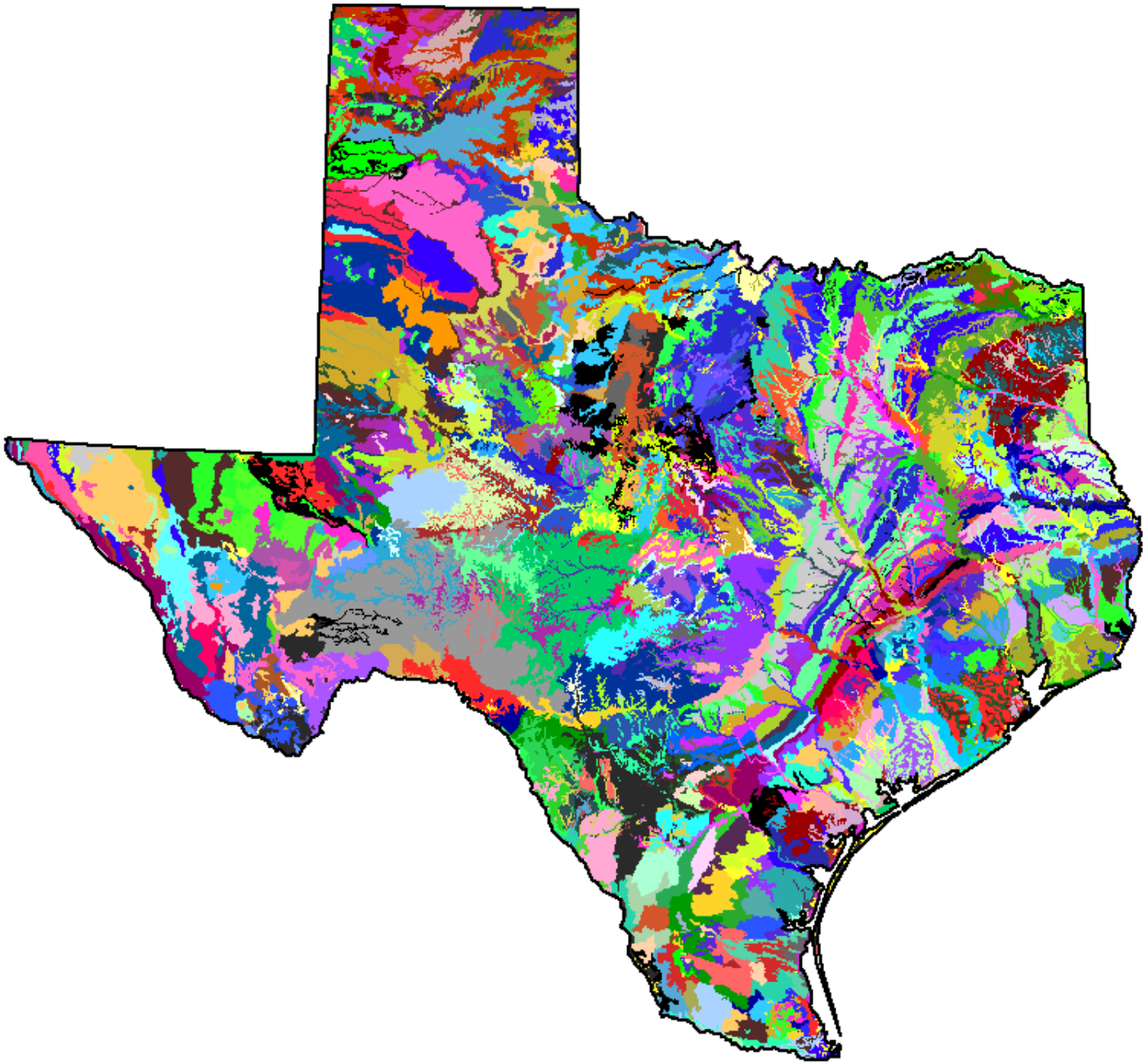
'vcg = 0.03
'vcg = 0.05
'vcg = 0.07



Web Soil Survey - Windows Internet Explorer

http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx

File Edit View Favorites Tools Help

Web Soil Survey

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ZaD	Zack fine sandy loam, 5 to 8 percent slopes	3,194.0	0.8%
ZaE3	Zack fine sandy loam, 8 to 25 percent slopes, severely eroded	269.9	0.1%
ZcB	Zack-Urban land complex, 1 to 5 percent slopes	7,841.9	2.1%
ZcD	Zack-Urban land complex, 5 to 8 percent slopes	547.6	0.1%
ZuB	Zulch fine sandy loam, 1 to 3 percent slopes	11,440.6	3.0%
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Done Internet 100%

start Inbox - Microsoft Out... C:\Documents and Se... Web Soil Survey - Wi... SoilDataAvailabilityMa... CVEN 646 Materials 6:29 PM

Outline

- Elements of design
- Site conditions
- Slabs-on-ground
- Raised floor foundations
- costs

Elements of Design

- Structural requirements
  - Moments
  - Shear
  - Deflection

  As determined by site conditions

- Costs

Site Conditions

- Soils
- Site hazards
  - Trees
  - Slopes
  - Drainage
- Building geometry

Contrasting Design Approaches for Slab-on-Ground and Raised Floor Foundations on Expansive Soils

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