Stability of Slopes and Earth Structures Constructed of High Plasticity Clays

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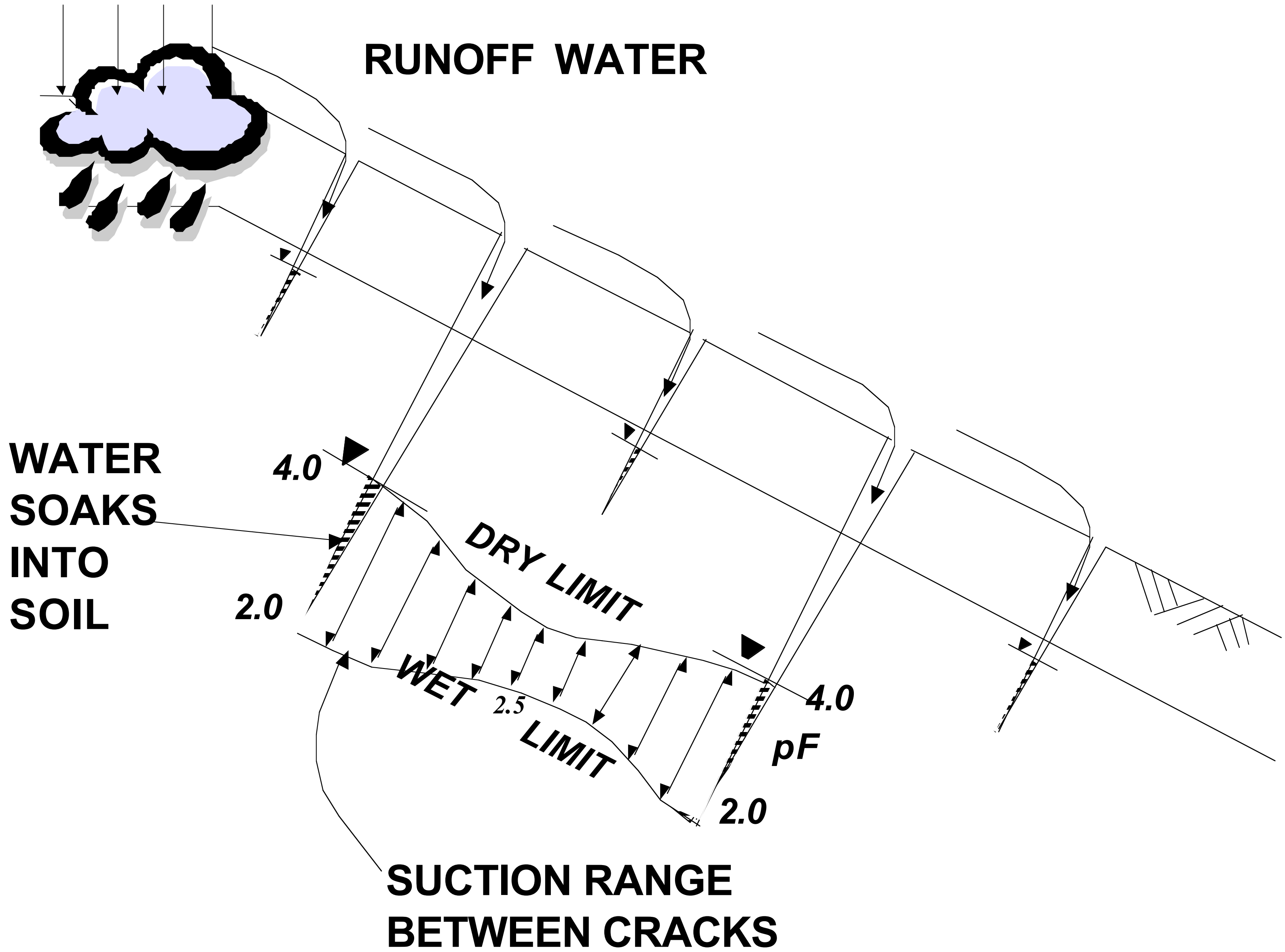
Outline

- The Problem
- Model for Slope Failures
- Soil Suction
- Case Histories
- Cracking
- Moisture Diffusion
- Suction-Soil Strength Relationship
- Other Earth Structures

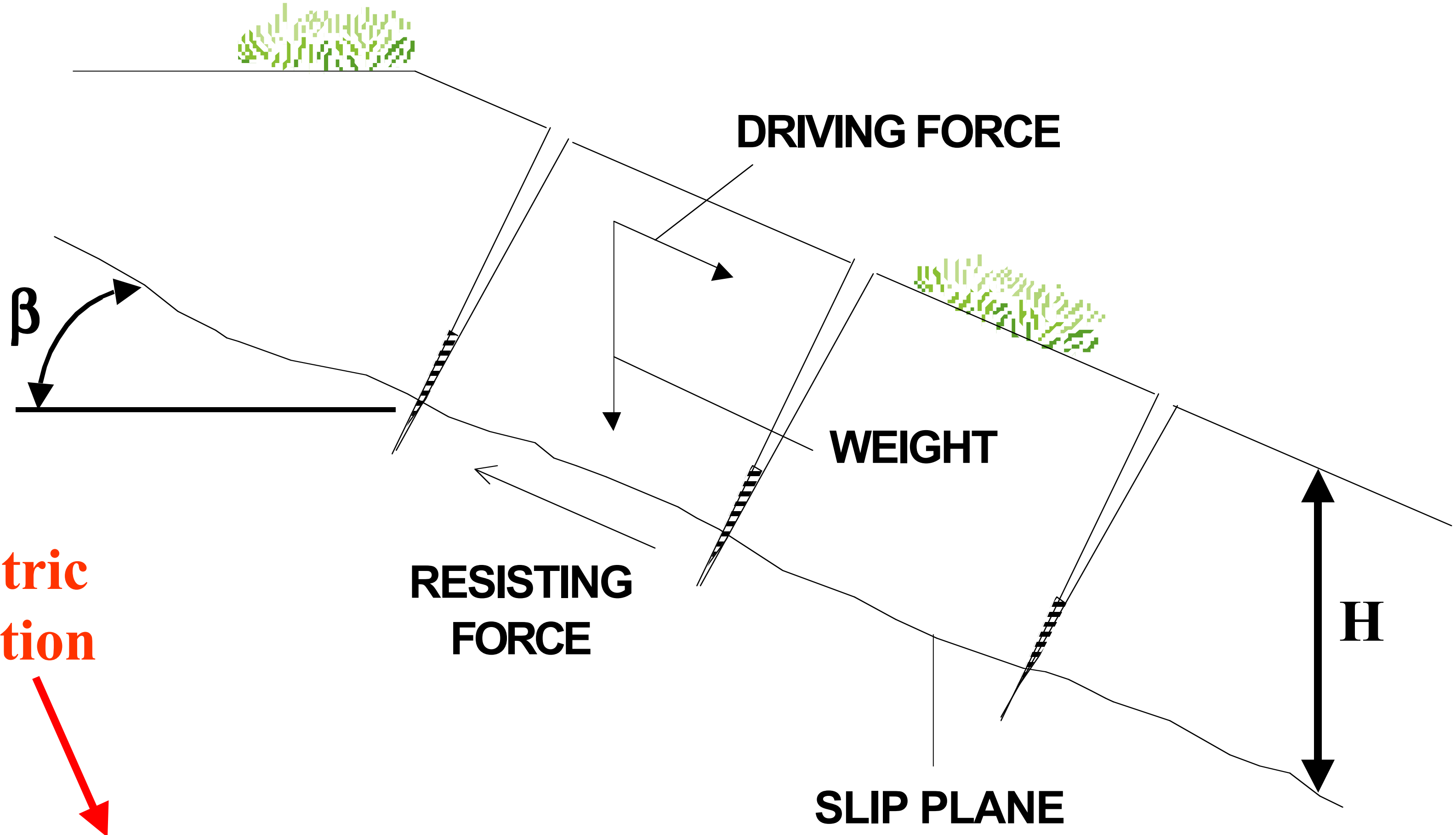
Issues

(TxDOT Project 2000-2002)

- **Mechanism of Slope Failures**
- **Evaluation of Relevant Soil Properties**
- **Analytical Models of Strength Degradation**
- **Expected Strength Loss over Time and Location**


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

MECHANISM OF SHALLOW SLOPE FAILURE



Matric Suction

$$FS = h_m f \Theta \sin \phi' / \gamma H \cos \beta \sin \beta (1+\sin \phi')$$

Soil Suction

$$h_t = h_m + \pi$$

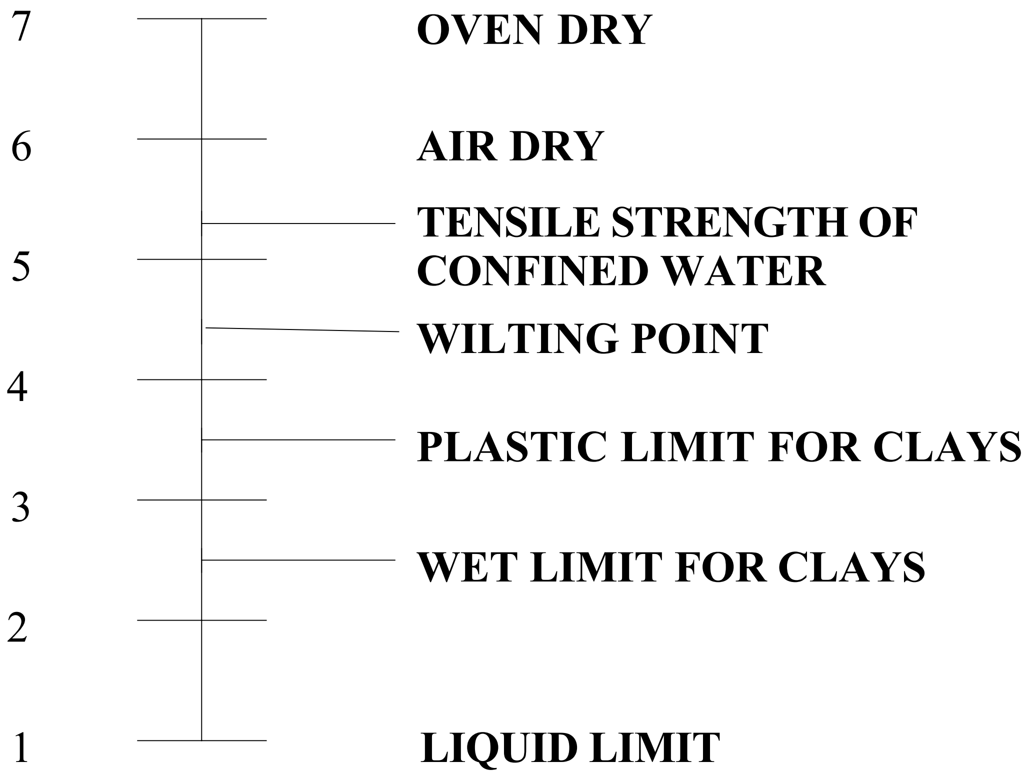
Total
Controls Flow
Through Soil

Matric
Controls
Soil Strength,
Volume Change

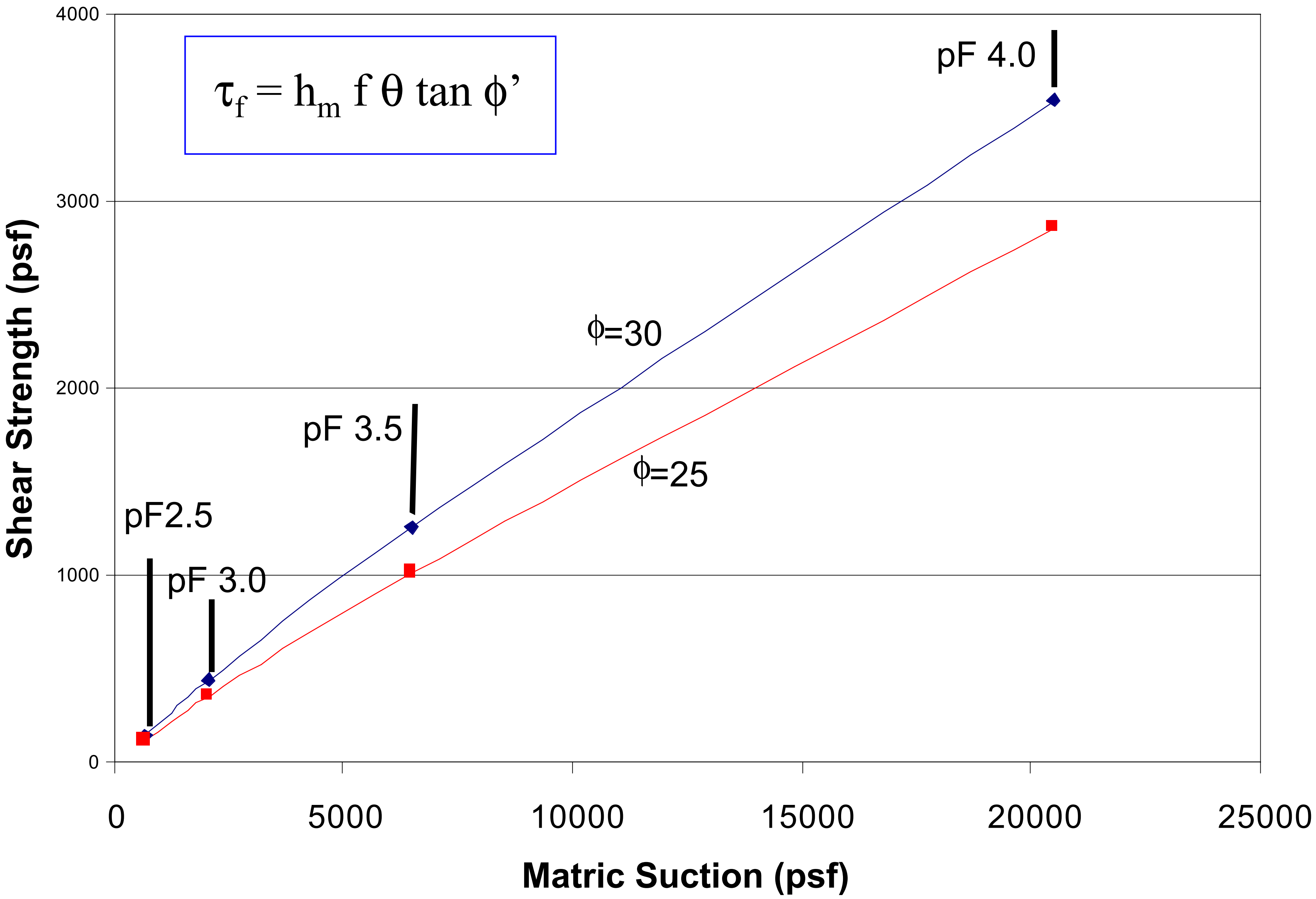
Osmotic
f (pore salts)

pF SUCTION SCALE

$$pF = \log_{10} \{h\ (\mathrm{cm})\}$$



Typical Strength vs Suction



Case Histories

Data Source: Kayyal & Wright, 1991

- **Paris Clays - 16 failures**
- **Beaumont Clays - 18 failures**

TAMU Interpretation: Aubeny & Lytton

- **Infinite Slope Analysis**
- **Soil Strength Derived from Suction**
- **c'=0**

$$FS = h_m f \Theta \sin \phi' / \gamma H \cos \beta \sin \beta (1+\sin \phi')$$

Paris Clays

- **16 failed slopes**
- **LL = 80, PL = 22**
- **Depth of failure mass: 2-10 ft**
- **Slope: 2.3-3.0 Horizontal to 1 Vertical**

- **Back-calculated *matric* suction at failure:**
  pF 2.23+/- 0.18

Beaumont Clays

- **18 failed slopes**
- **LL = 73, PL = 21**
- **Depth of failure mass: 2.4-5 ft**
- **Slope: 2.5-3.1 Horizontal to 1 Vertical**

- **Back-calculated *matric* suction at failure:**

  <u>pF 2.05+/- 0.14</u>

Chronology of Slope Failure

- **Post-Construction: pF ~ 4, high strength**

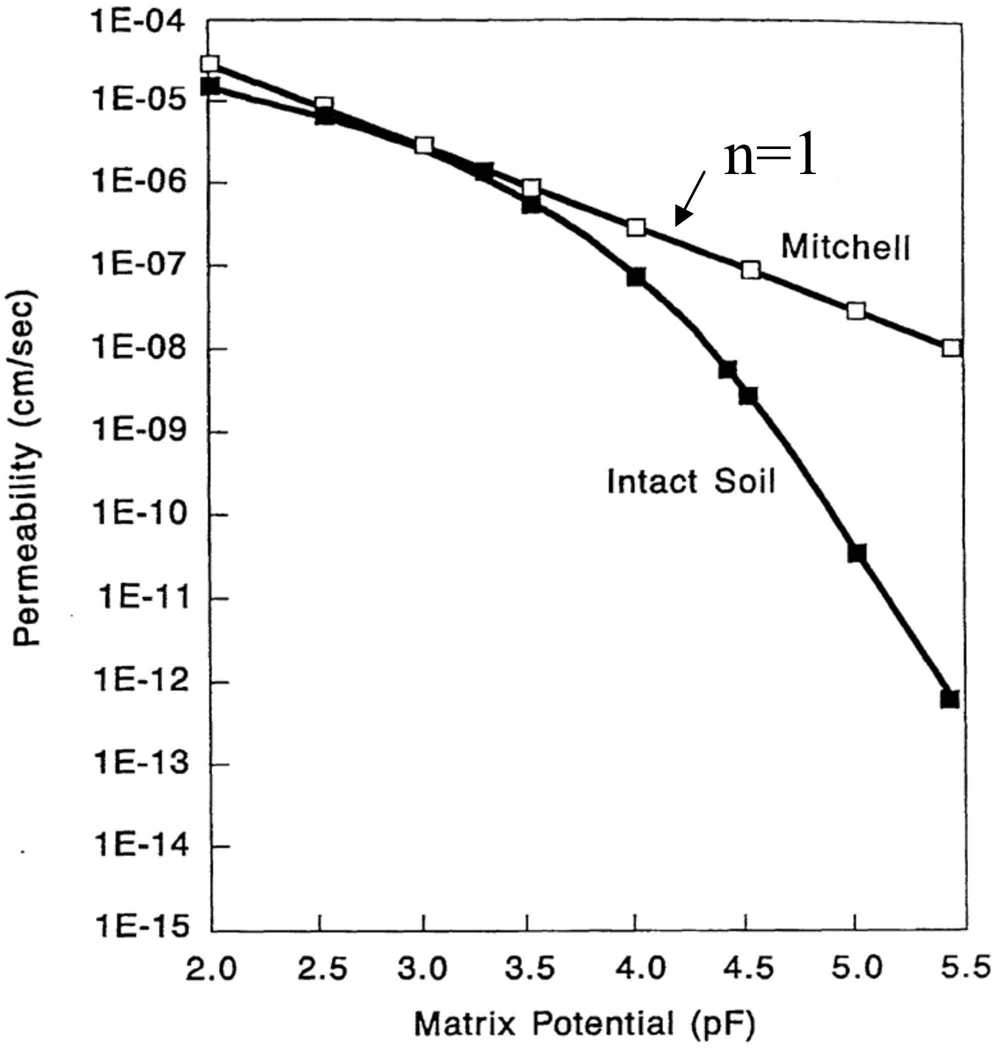
- **Surface Cracks**
  f (root depth, climate, soil)

- **Moisture Infiltration into Soil**
  f (crack depth, climate, soil α)

- **Suction Reduction / Strength Loss**
  f (suction, time, friction ϕ')

Moisture Diffusion through Unsaturated Soil

- **Mitchell's Formulation**
- **Diffusion Coefficient, α**
- **Generalized Formulation**
- **Analytical/Numerical Solutions**



$$k = k_0 (h_0/h)^n$$

k_0 = saturated k (pF=2)

h_0 = reference h (pF=2)

n = material constant

Permeability versus Suction

Flow Through Partly Saturated Soil

Mitchell Assumption, n=1

$$k = k_0 \left(\frac{h_o}{h_t} \right)^n \qquad u(pF) = \log_{10} h_t (cm)$$

Darcy's Law:

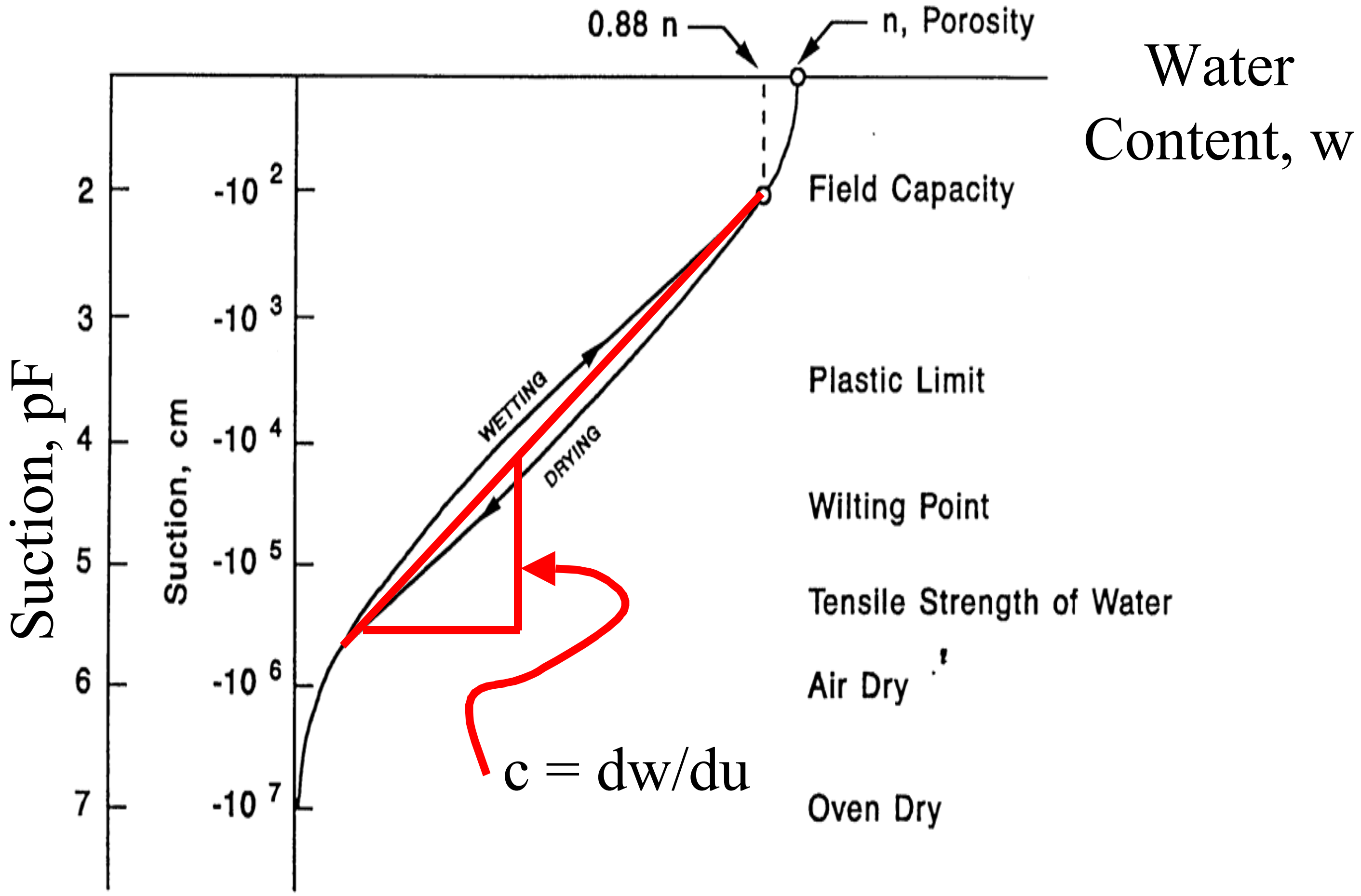
$$V = -k \frac{dh_t}{dx} = -k_0\, h_0 \frac{dh_t / h_t}{dx} = \frac{-k_0\, h_0}{0.434} \frac{d \log_{10} h_t}{dx}$$

$$\boxed{V = -\left\{ \frac{k_0 h_0}{0.434} \right\} \frac{du}{dx} = p \frac{du}{dx}}$$

Equation Linear in u(pF)

=> flow nets apply

=> analytical solutions apply



Suction versus Water Content

Fluid Flow Through Soil
(after Mitchell, 1980)

Unsaturated

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

$\alpha = p / \gamma_d c$

= Diffusion Coefficient

$u = \log h_t$

Saturated

(Terzaghi)

$$\boxed{c_v \frac{\partial^2 h}{\partial x^2} = \frac{\partial h}{\partial t}}$$

$c_v = k / m_v \gamma_w$

= Consolidation Coefficient

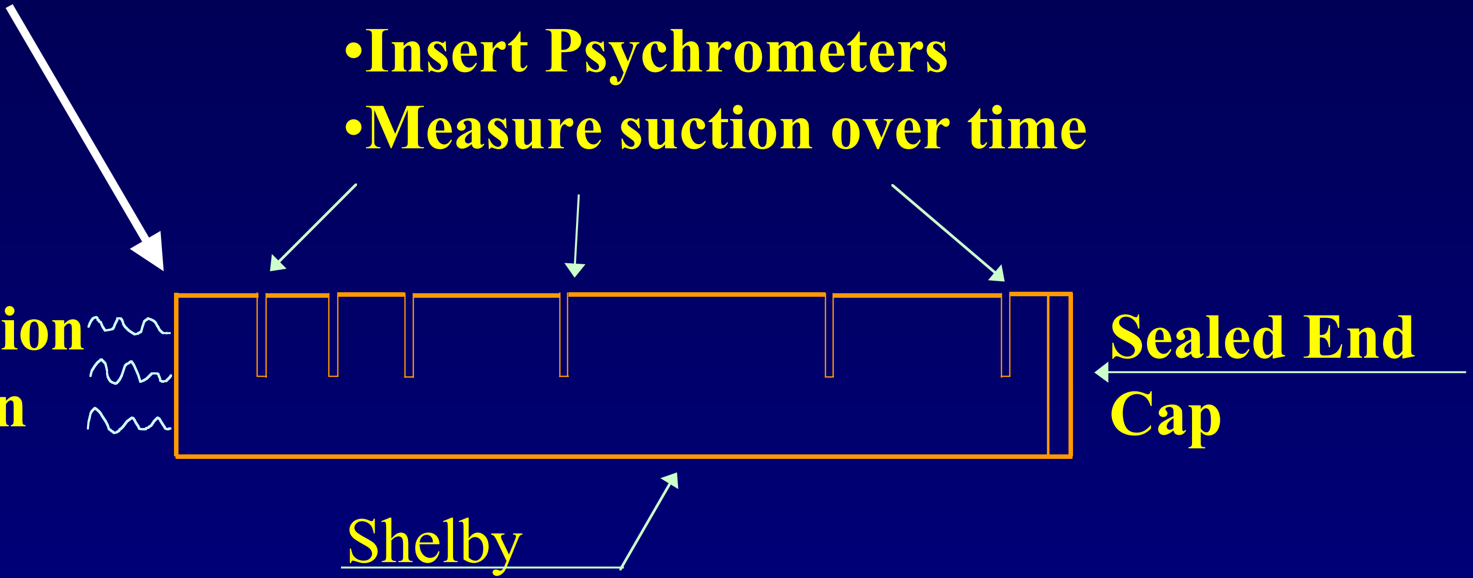
h = total head

Advantages of Mitchell's Formulation

1. **Closed-form solutions possible**
2. **Graphical solutions (flow nets) possible**
3. **Simple FEM analysis for complex geometry**
4. **Straight-forward evaluation of material properties (α)**

Shelby Tube Sample

OPEN END – DIFFUSION TEST



Boundary suction function of relative humidity in air

- **Drill Holes**
- **Insert Psychrometers**
- **Measure suction over time**

Evaporation from open end

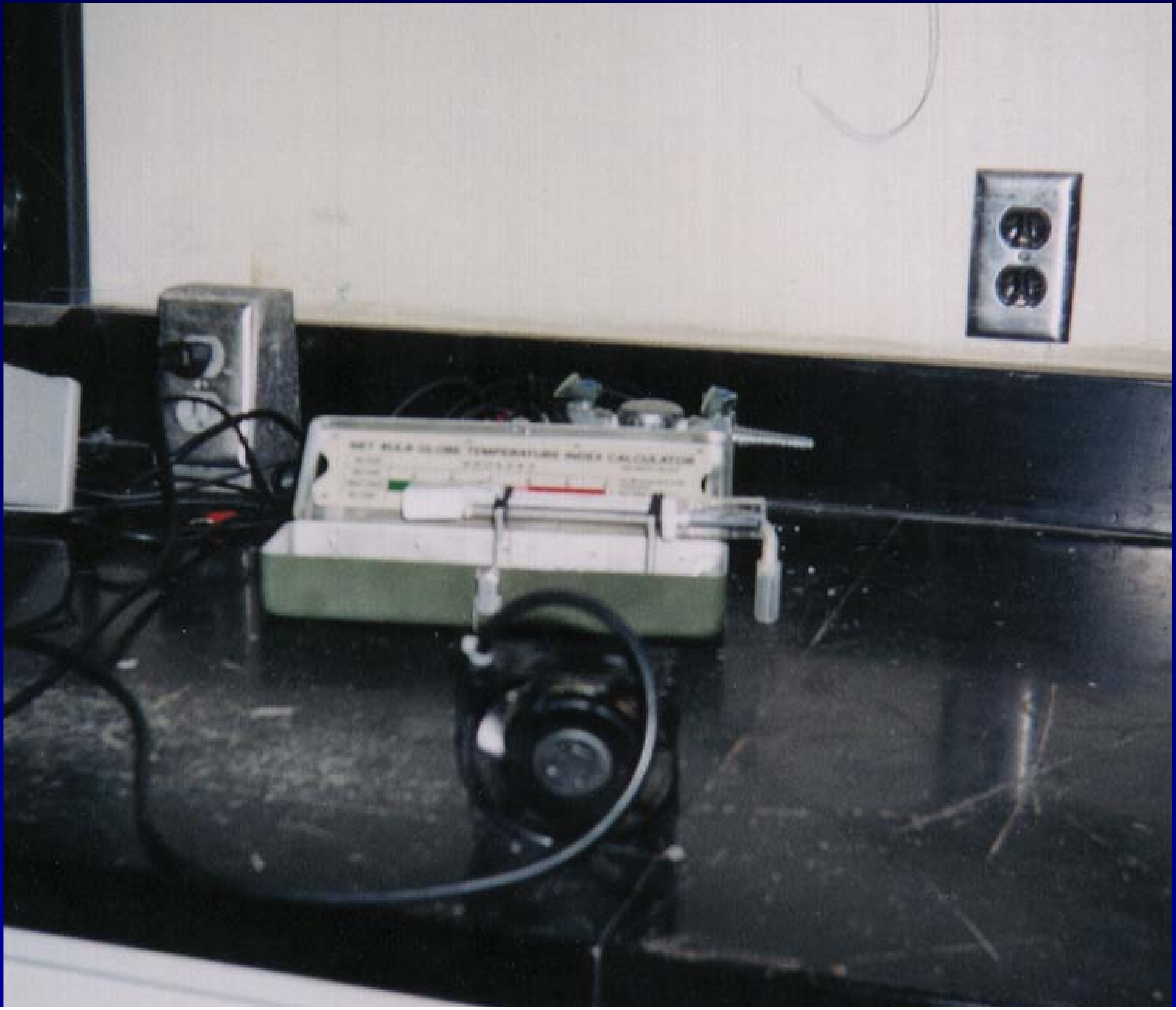
Sealed End Cap

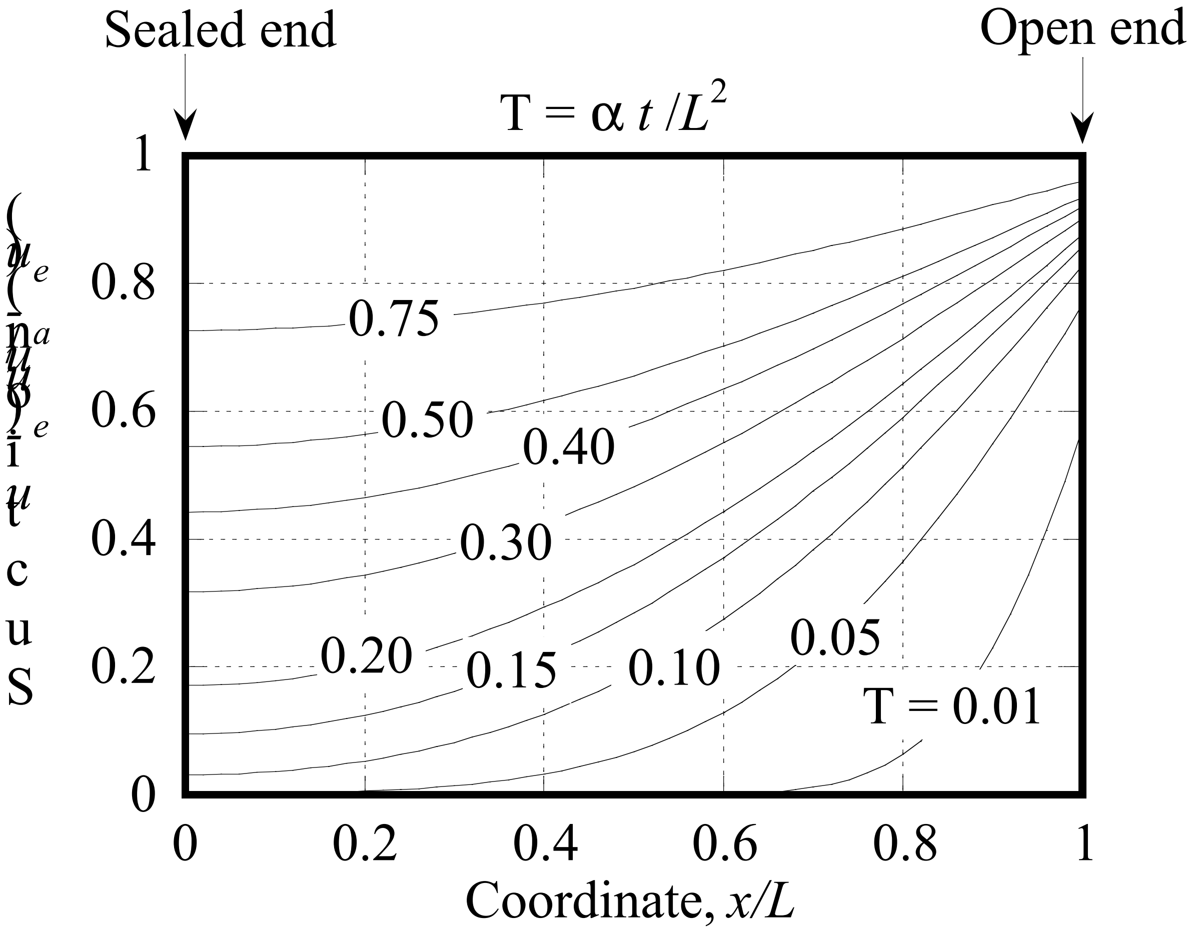
Shelby Tube

Shelby Tube and Psychrometers

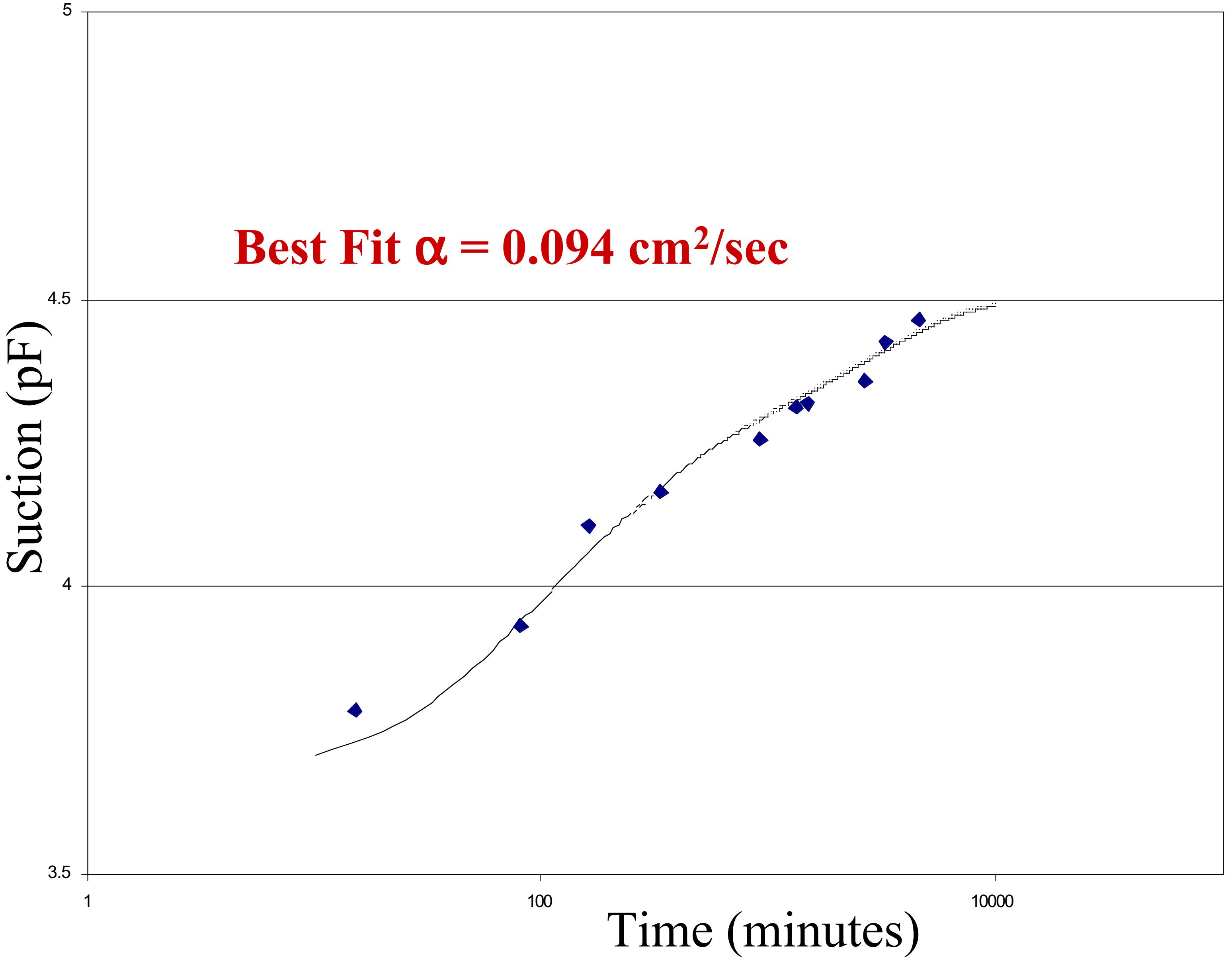
Assembled Diffusion Test

Bulb Humidity Equipment

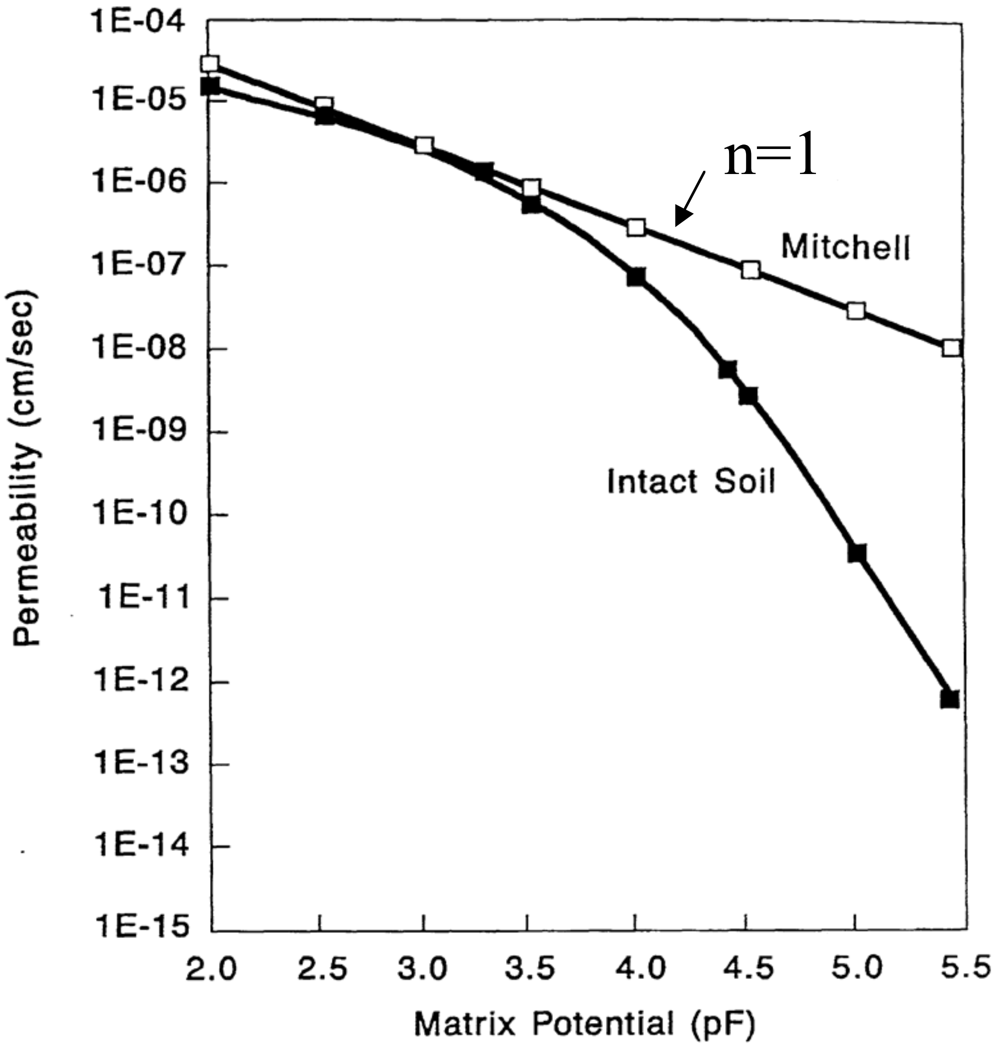



Sealed end
Open end
T = α t /L²
Suction
1
0.8
0.6
0.4
0.2
0
0.75
0.50
0.40
0.30
0.20
0.15
0.10
0.05
T = 0.01
0
0.2
0.4
0.6
0.8
1
Coordinate, x/L

Test 2 - Psychrometer 6



Best Fit α = 0.094 cm^2/sec



$k = k_0 (h_0/h)^n$

k_0 = saturated k (pF=2)
h_0 = reference h (pF=2)
n = material constant

Permeability versus Suction

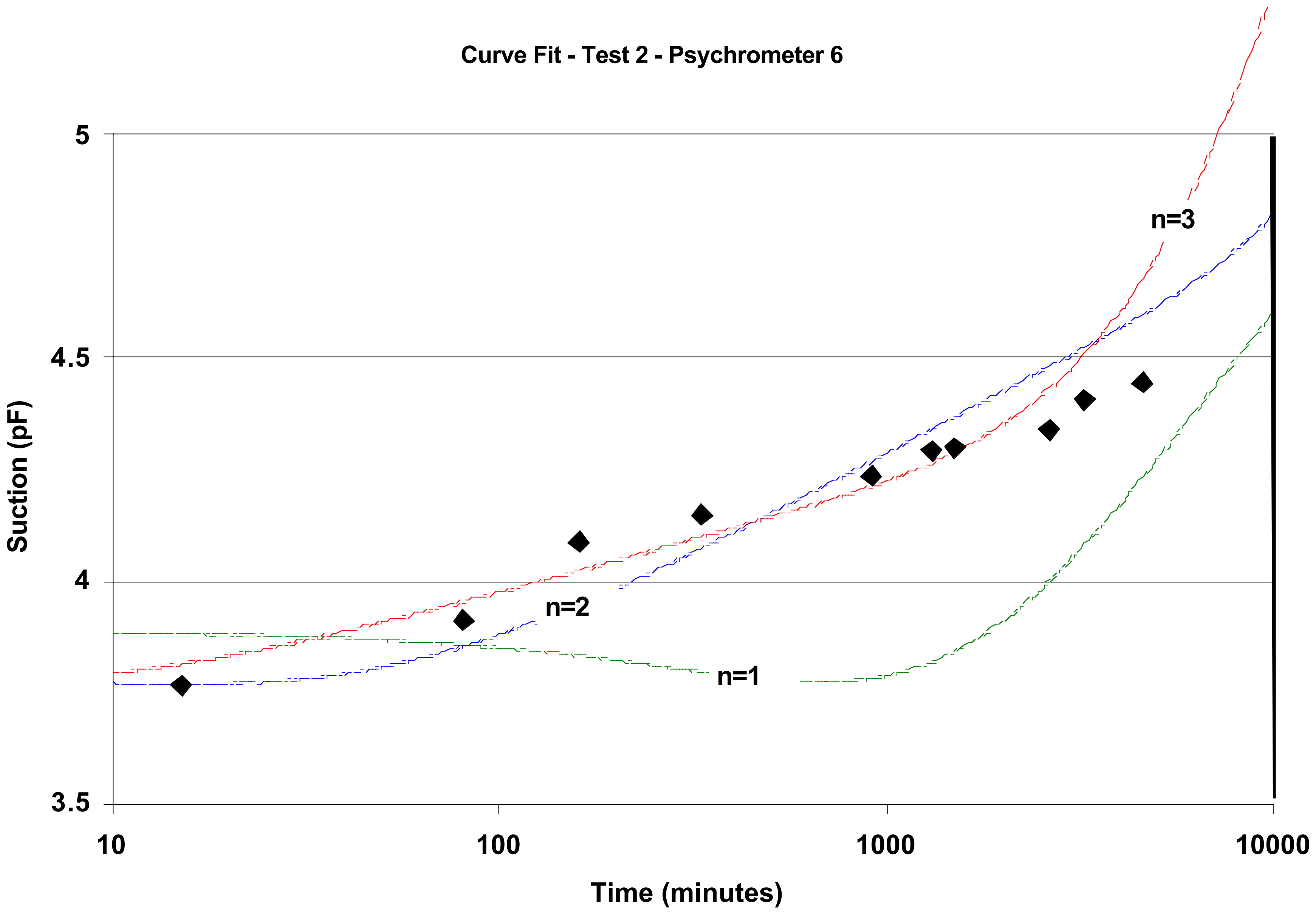
Generalization of Mitchell’s Formulation

(n not equal 1)

$$\acute{a}' \frac{\partial^2 \text{ø}}{\partial x^2} = \frac{\partial \text{ø}}{\partial t}$$

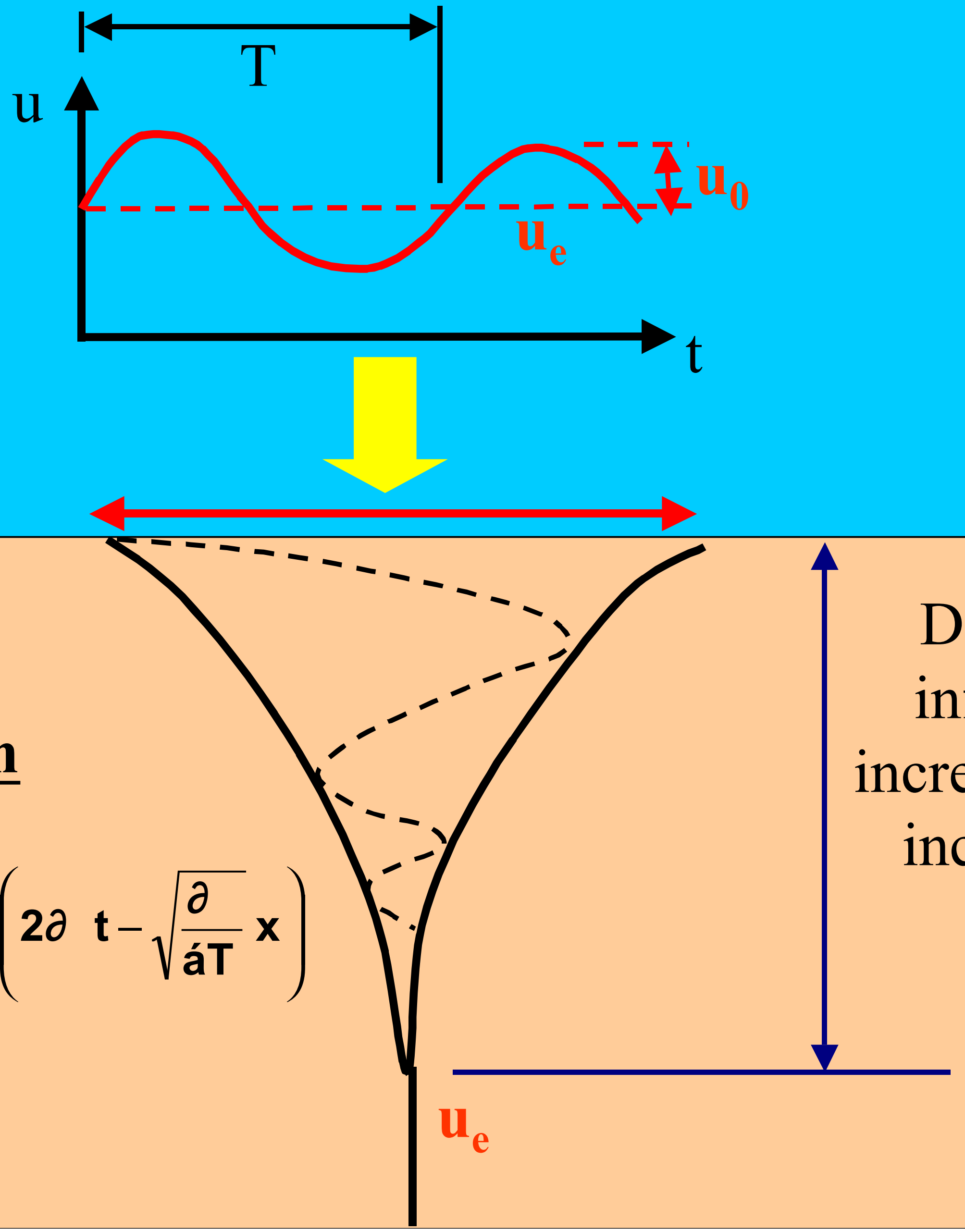
$$\text{ø} = \begin{cases} \log_e h & n = 1 \\ (1-n)\, h^{1-n} & n \neq 1 \end{cases}$$

- **Equation still linear**
- **2 Material Parameters, α’ and n**


Curve Fit - Test 2 - Psychrometer 6
Suction (pF)
5
4.5
4
3.5
10
100
1000
10000
Time (minutes)
n=3
n=2
n=1

Significance of α

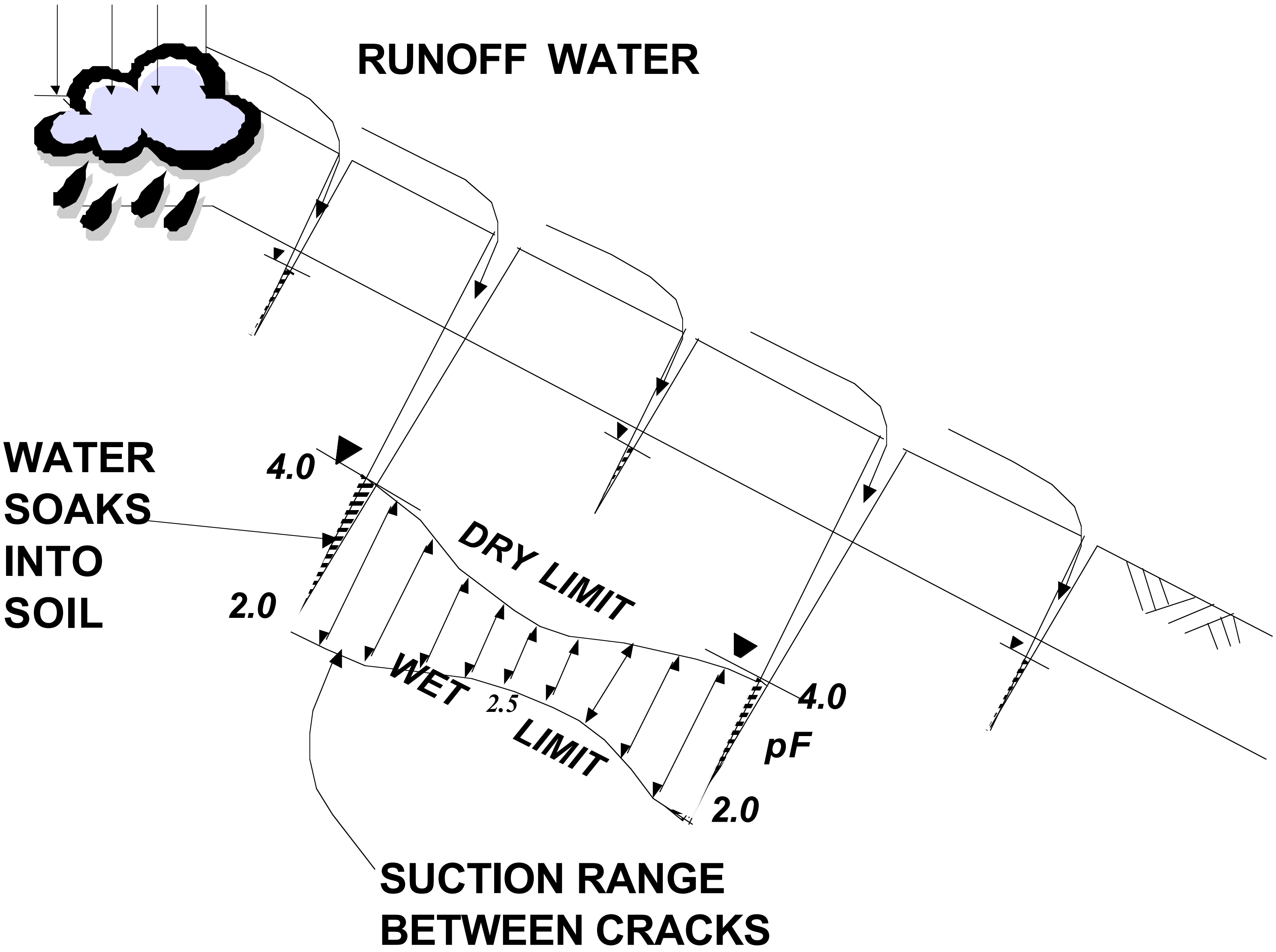
Variation in
Suction at Surface

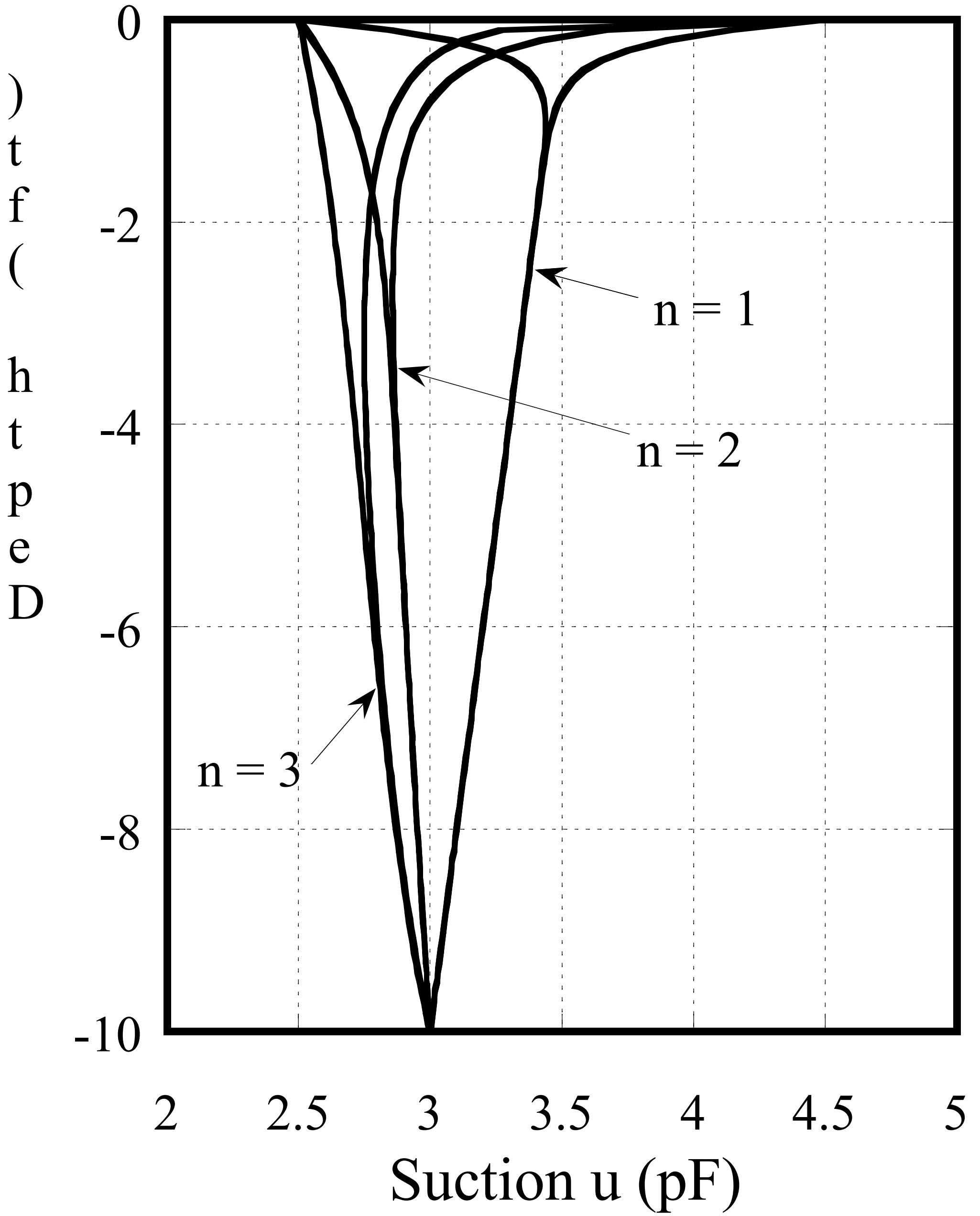


Depth of
influence
increases with
increasing
α, T

Analytical Solution

$$u = u_e + u_o \exp\left(-\sqrt{\frac{\partial}{\acute{a}T}}\,x\right)\cos\left(2\partial\ t - \sqrt{\frac{\partial}{\acute{a}T}}\,x\right)$$


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


0
-2
-4
-6
-8
-10
Depth (ft)
2
2.5
3
3.5
4
4.5
5
Suction u (pF)
n = 1
n = 2
n = 3

Suction-Strength Relationship

- Total Suction: $h(t)$ from moisture diffusion analysis

- Matric Suction: $h_m = h - \pi$

  π = Osmotic suction = f (pore water salts)

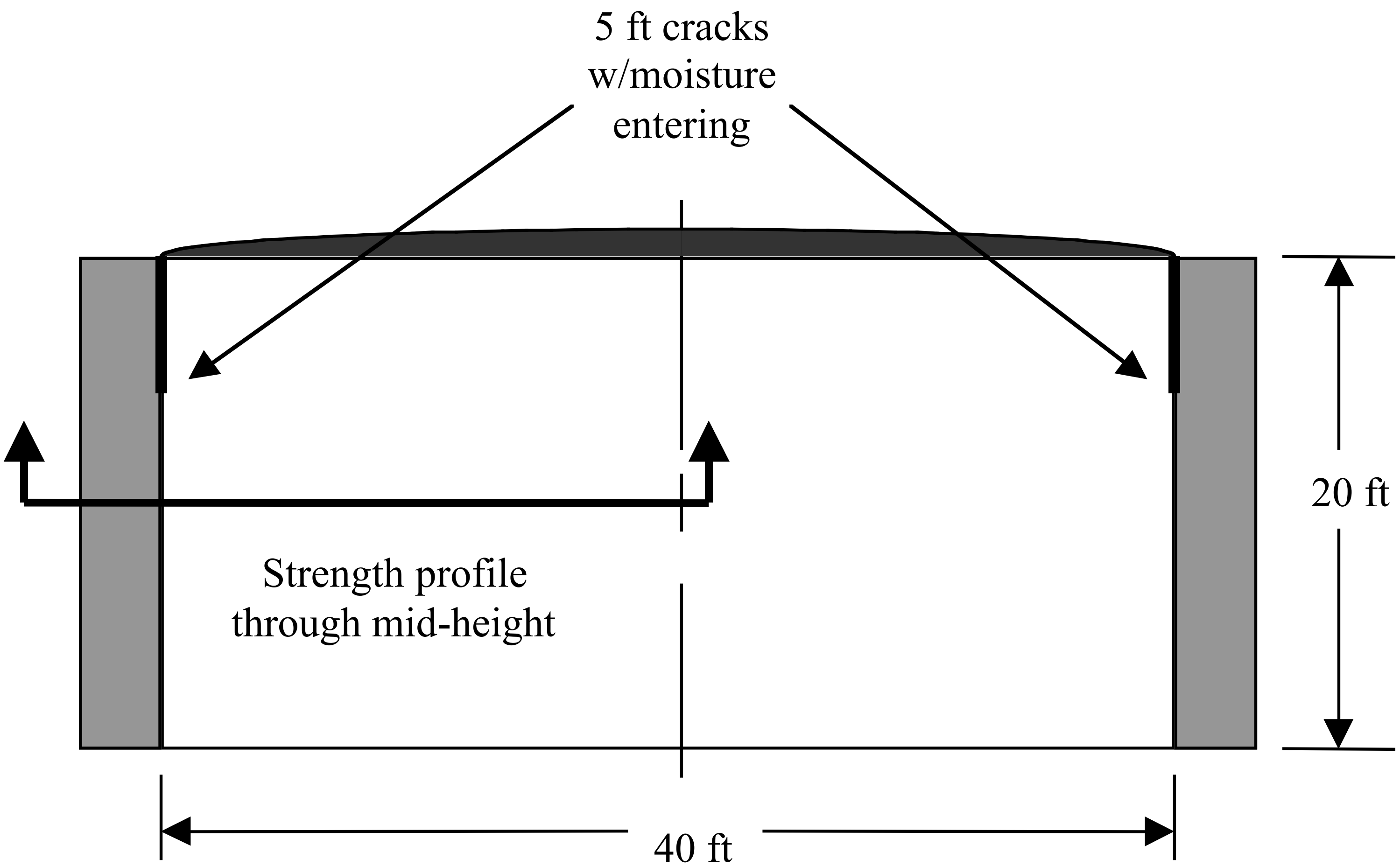
- 'Cohesive' Strength: $c_{app} = \theta f\, h_m \sin \phi' / (1 - \sin \phi')$

  θ = volumetric water content

  f varies from 1 to 1/ θ as full saturation approached

  ϕ' = friction angle

Other Earth Structures

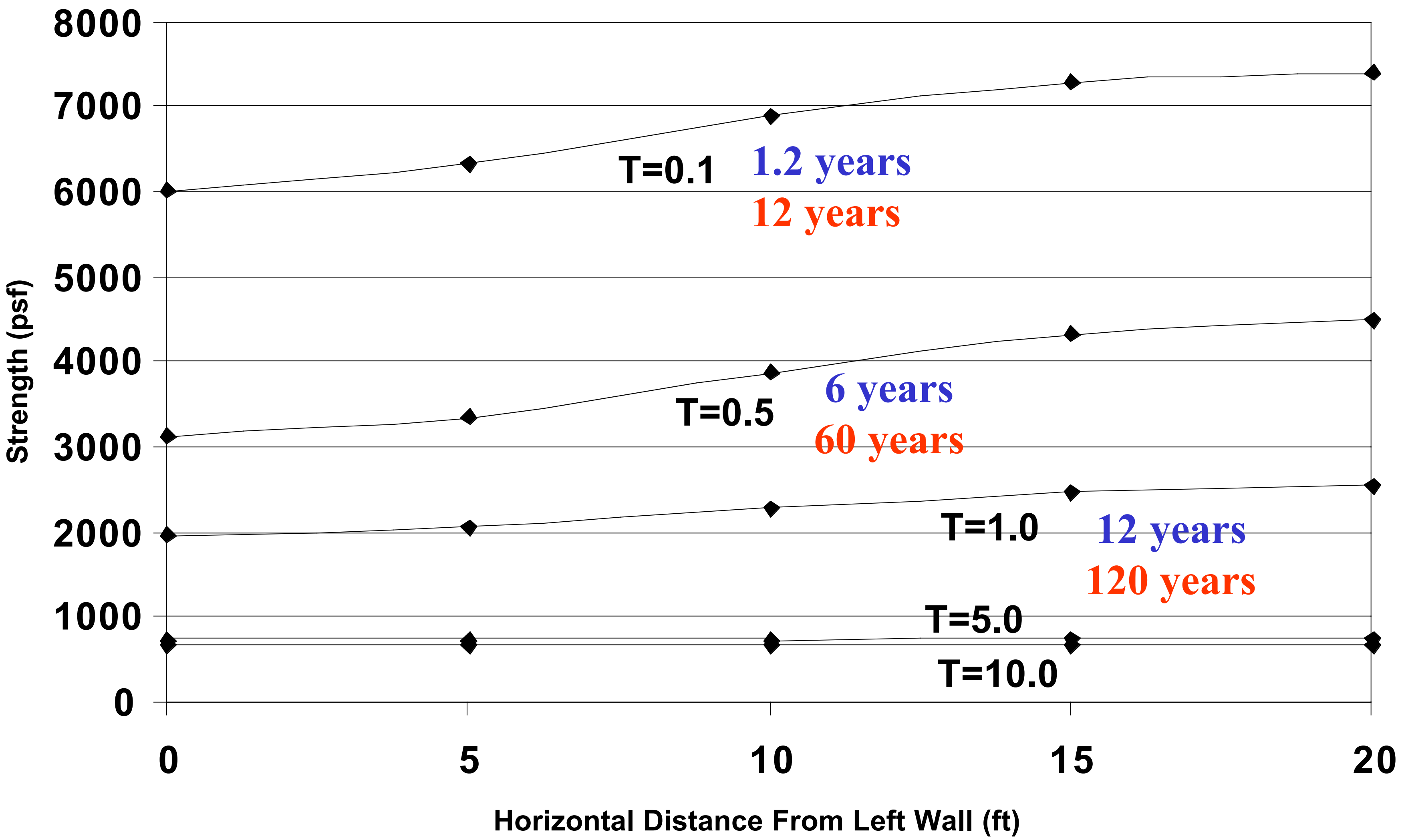


Definition Sketch

$\alpha = 10^{-3}\ \mathrm{cm^2/s}$

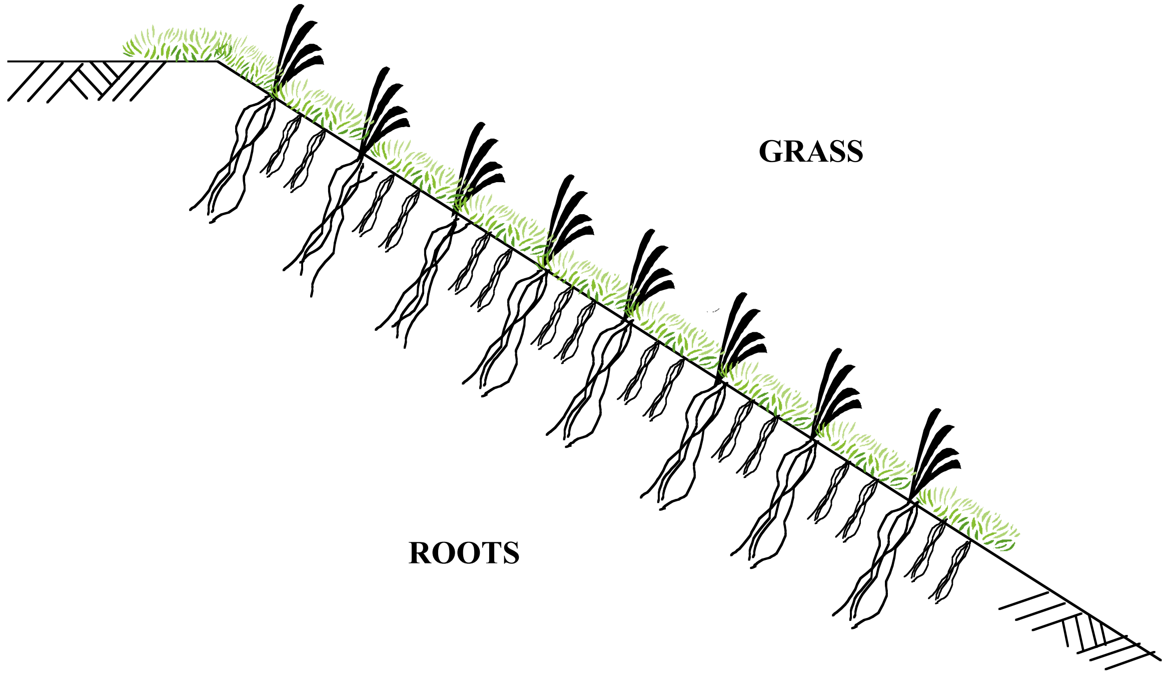
$\alpha = 10^{-4}\ \mathrm{cm^2/s}$

Strength Profile vs Time (mid-height of wall)

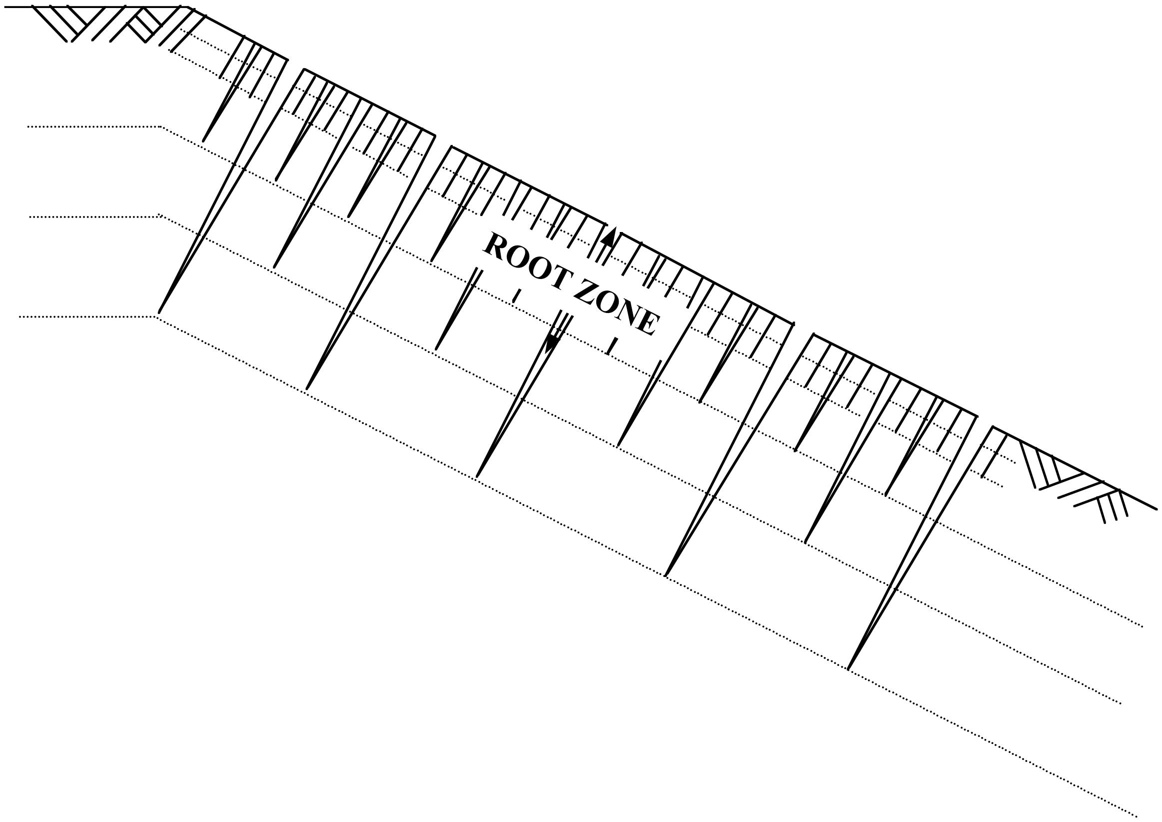


Model for Cracking

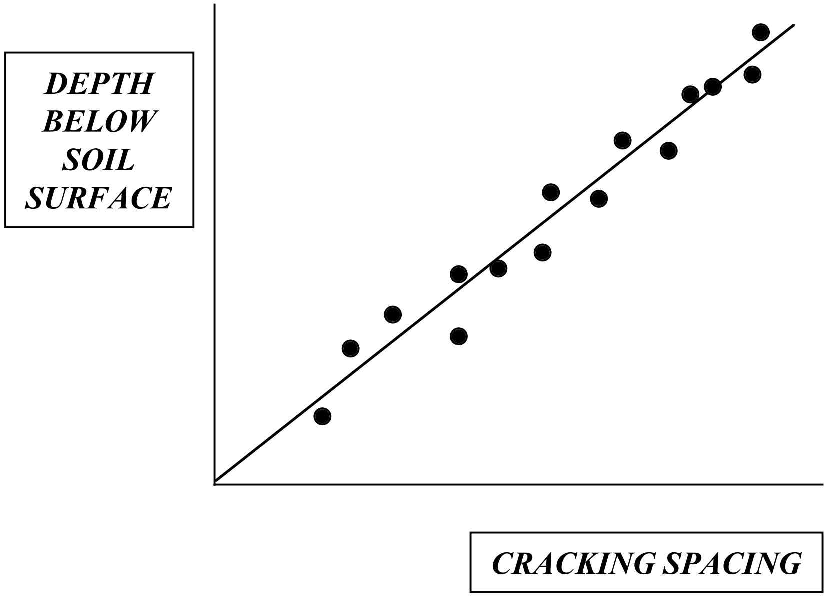
SHALLOW SLOPE FAILURE



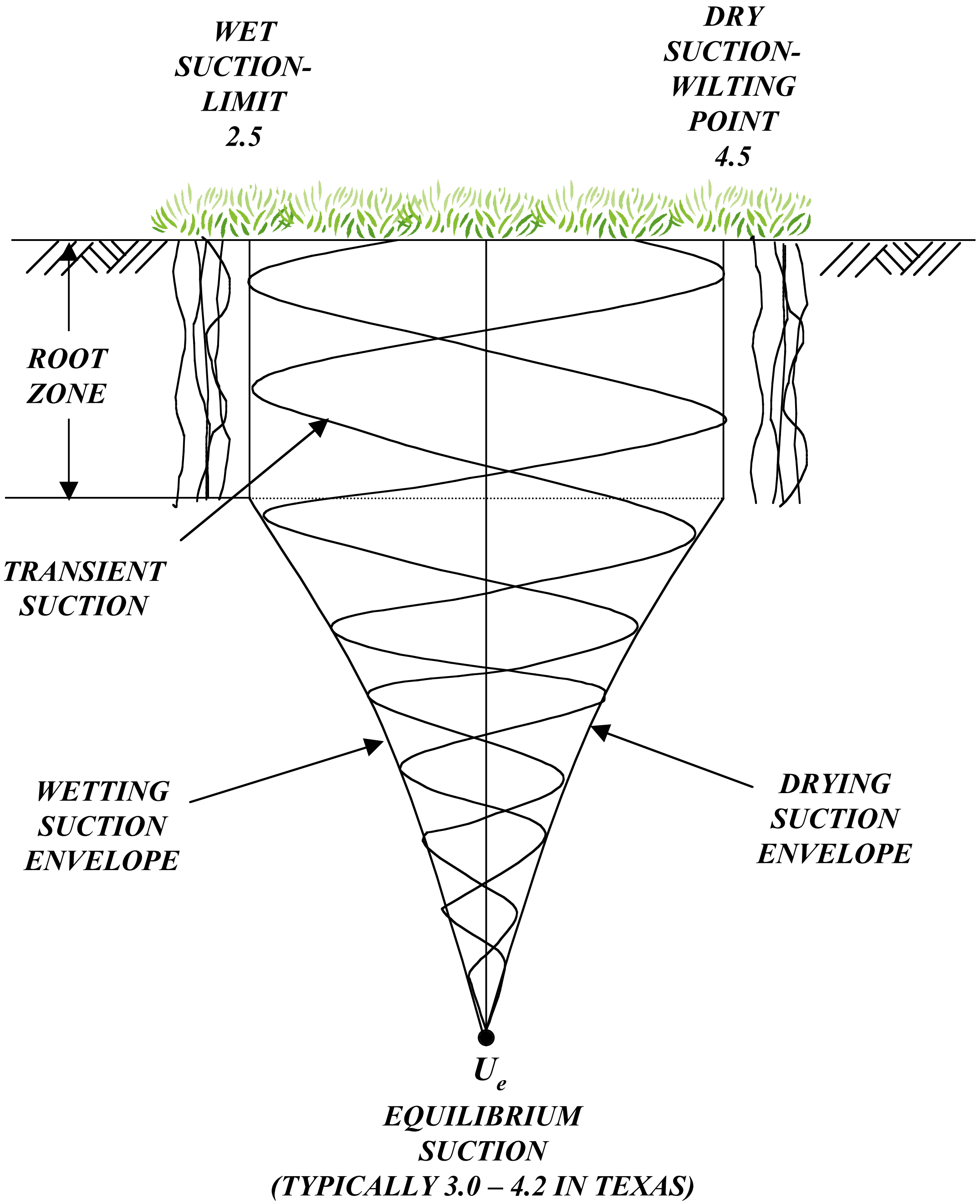
DURING DRY PERIODS ROOTS EXTRACT WATER
FROM THE SOIL AND CAUSE SHRINKAGE CRACKS

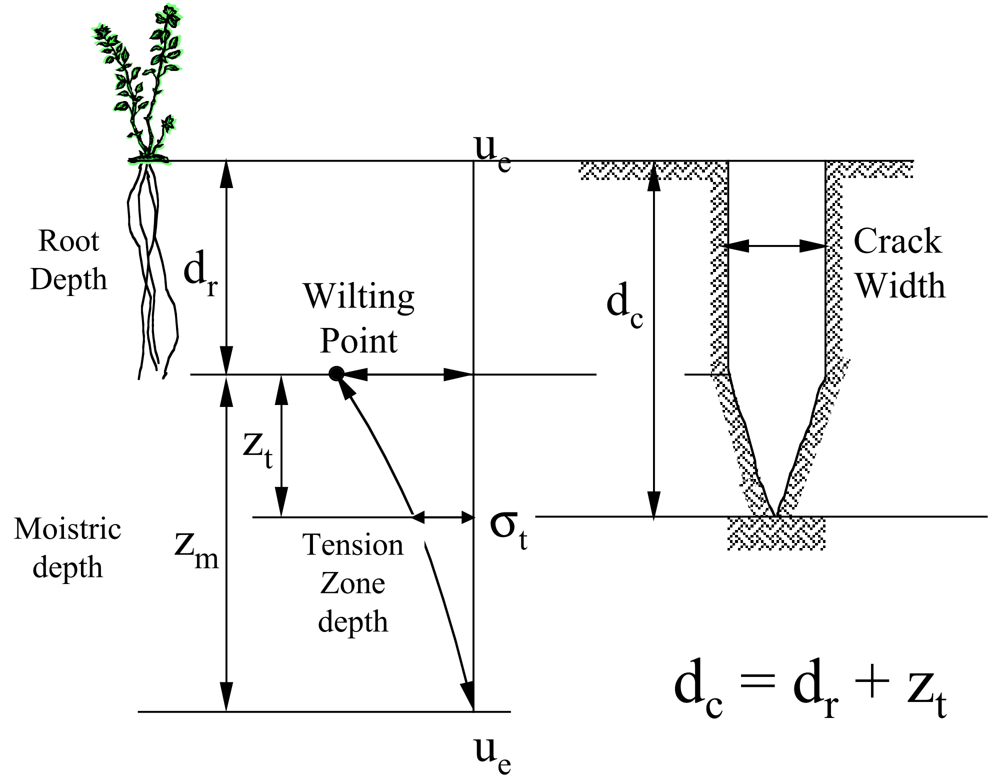


Crack Spacing Gets Larger with Depth

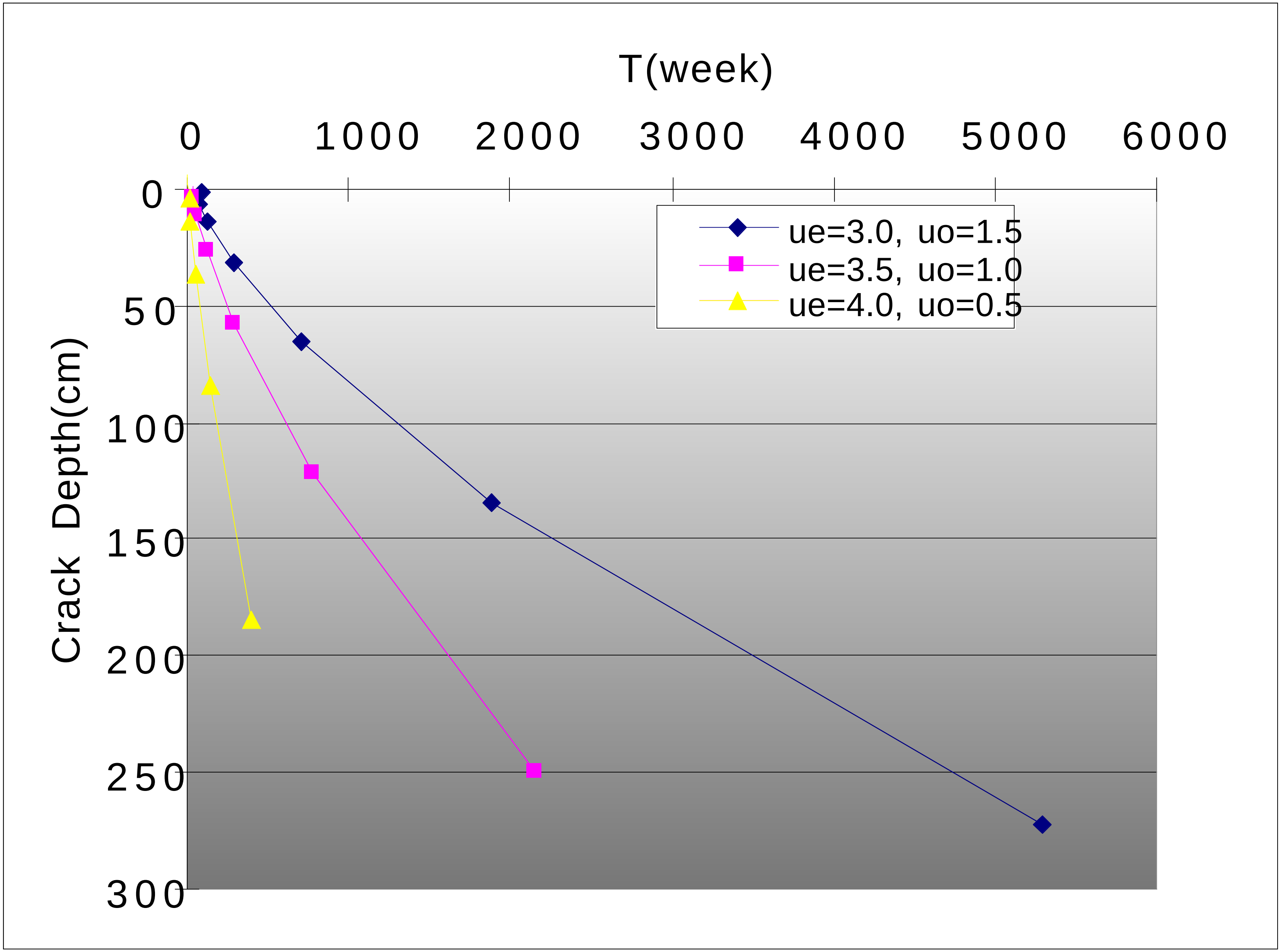


SOURCE : MICHAEL KNIGHT
PH. D. DISSERTATATION, GEOLOGY
UNIVERSITY OF MELBOURNE (AUSTRALIA)
1972

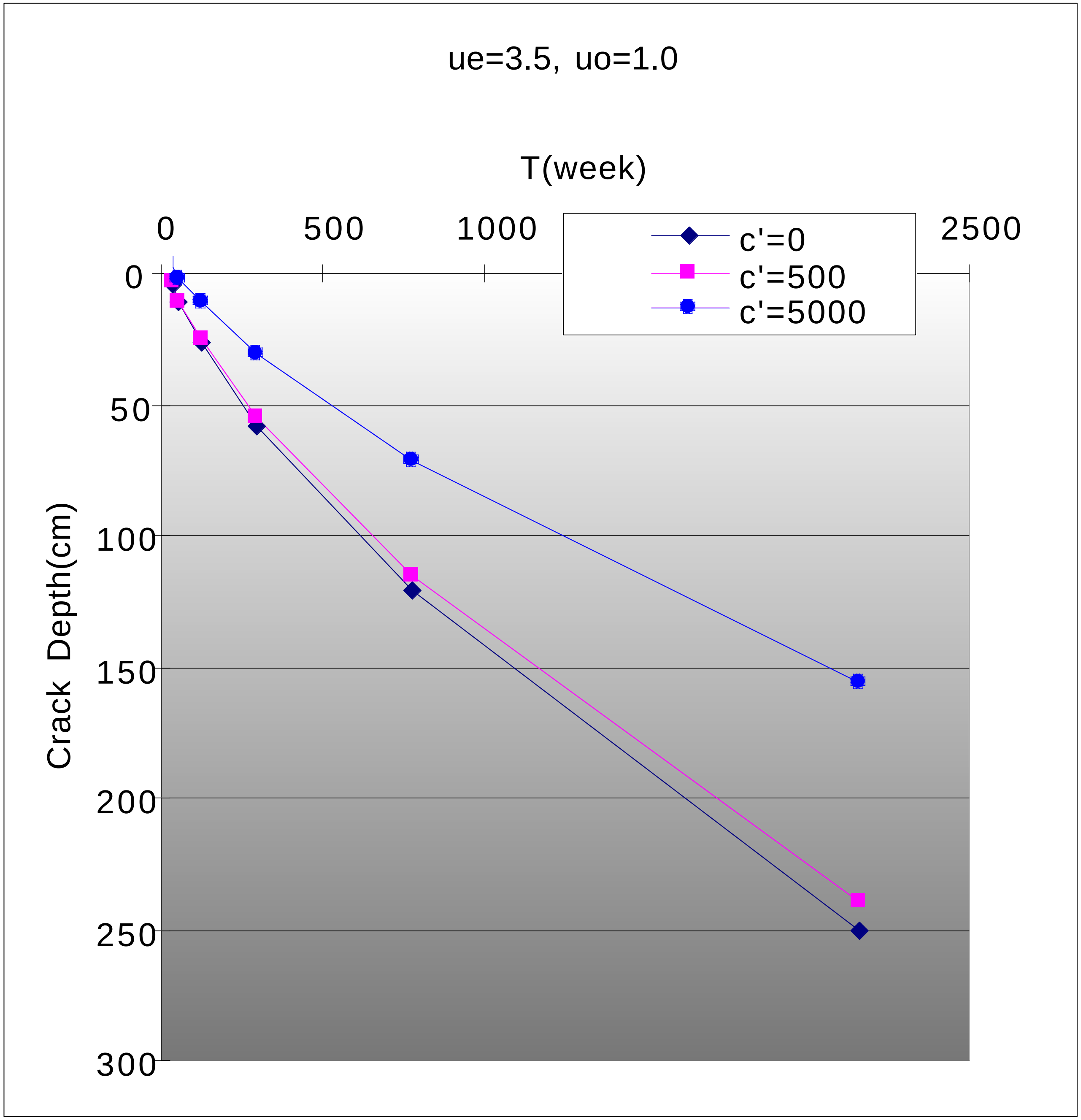

WET SUCTION-LIMIT 2.5
DRY SUCTION-WILTING POINT 4.5
ROOT ZONE
TRANSIENT SUCTION
WETTING SUCTION ENVELOPE
DRYING SUCTION ENVELOPE
U_e
EQUILIBRIUM SUCTION
(TYPICALLY 3.0 – 4.2 IN TEXAS)


u_e
Root Depth
d_r
Wilting Point
d_c
Crack Width
z_t
σ_t
Moistric depth
z_m
Tension Zone depth
u_e

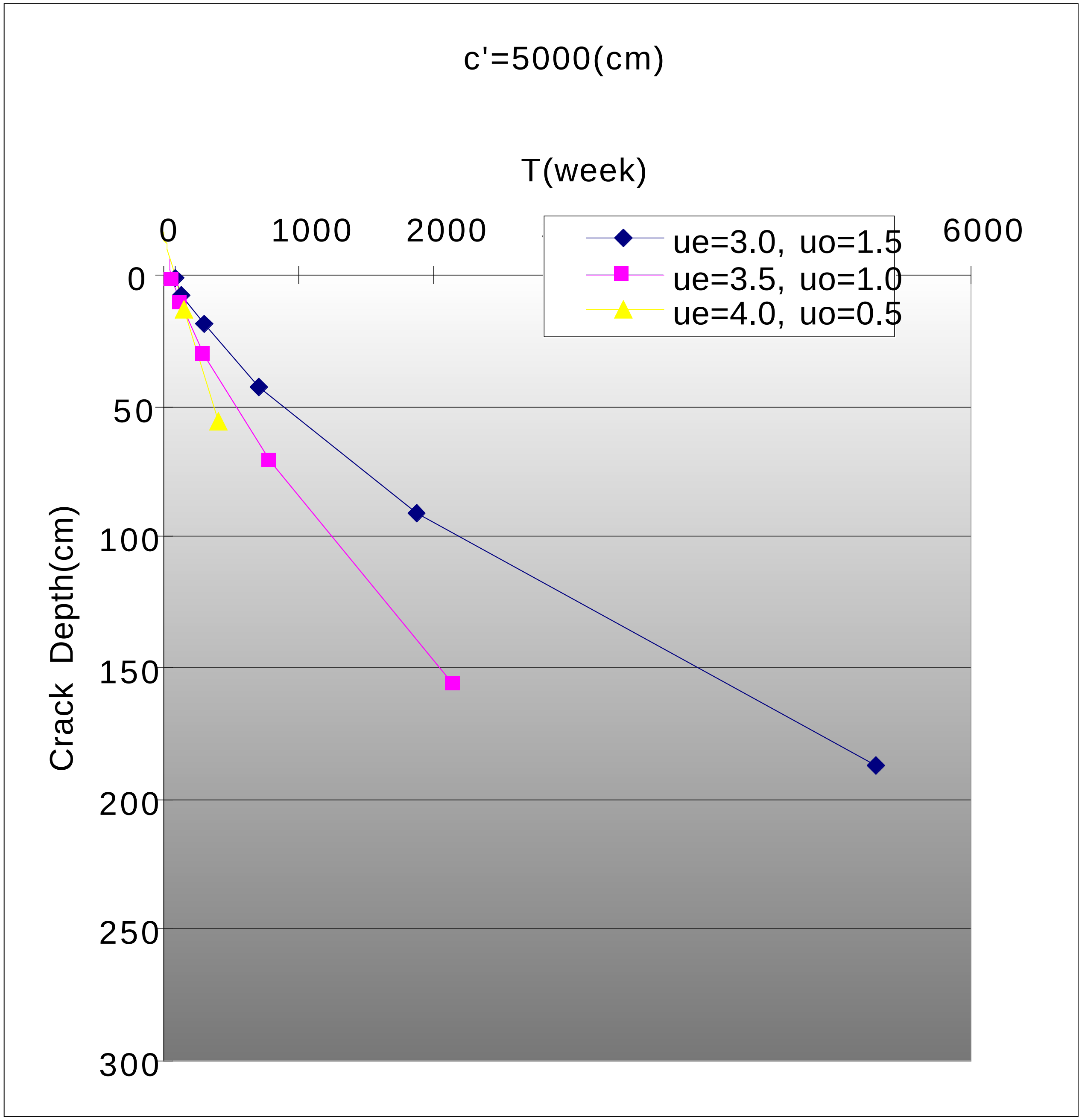
$$d_c = d_r + z_t$$



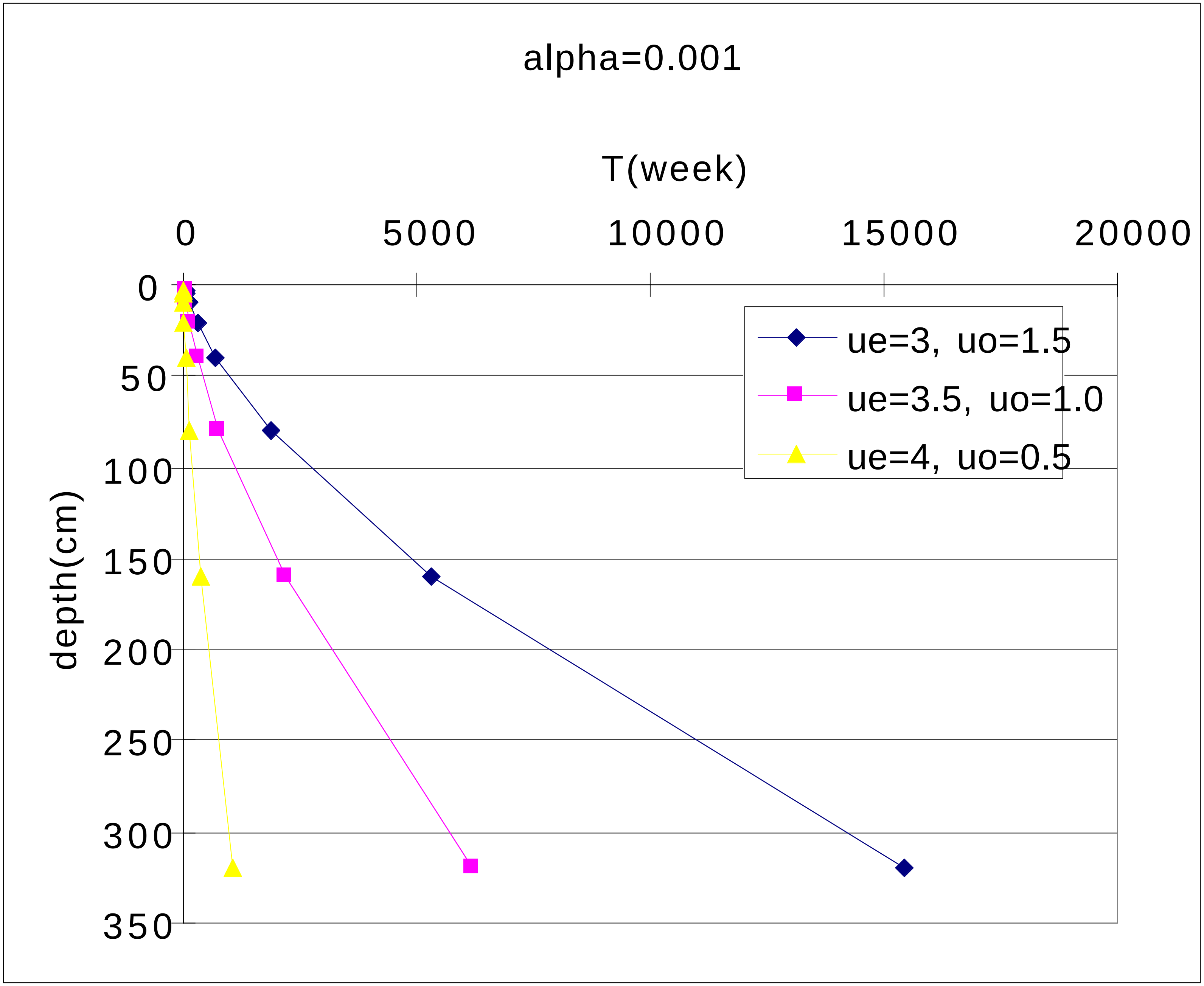
How deep do the cracks go?

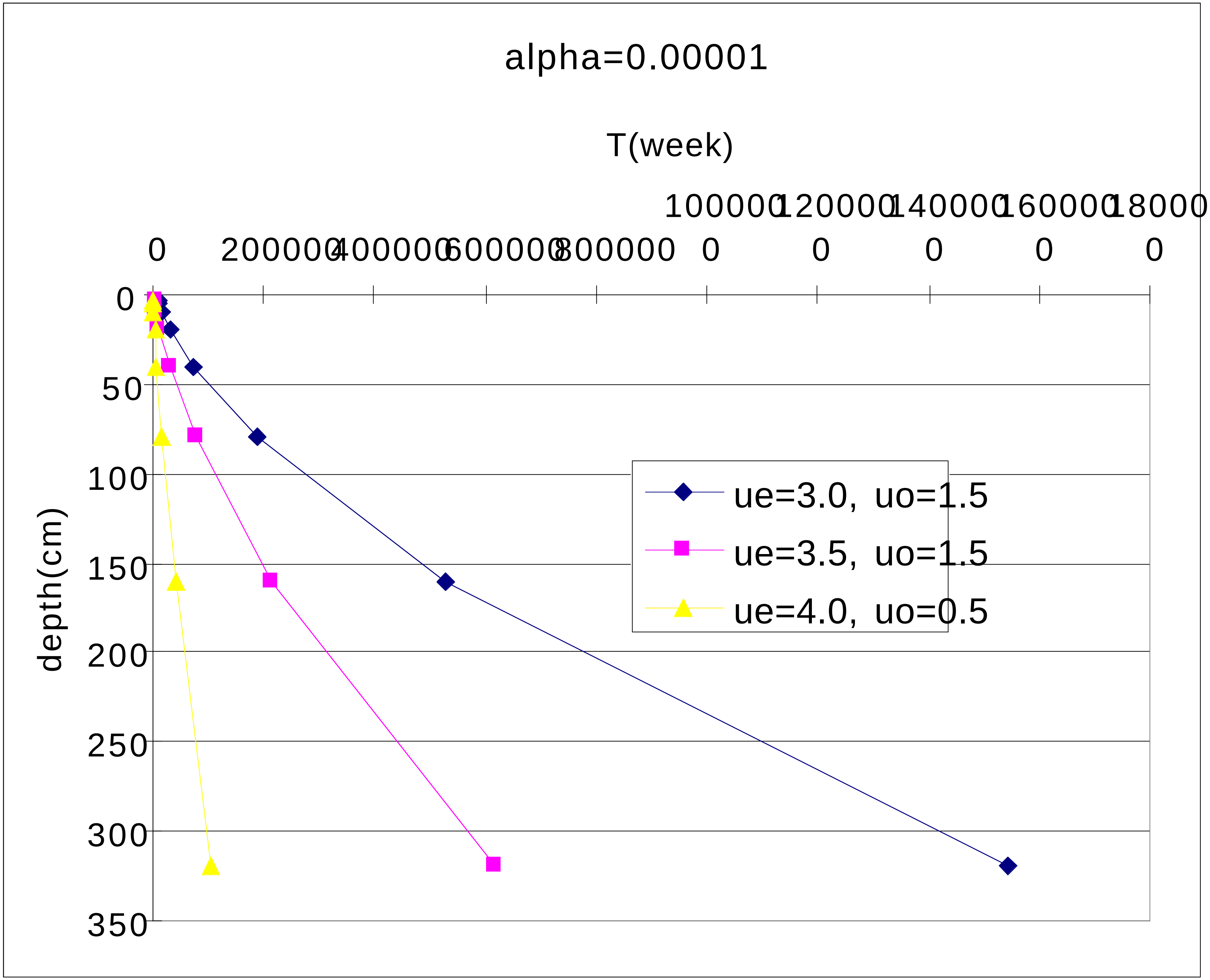


How does cementation affect the crack depth?



How do cemented soils behave in different climates?


alpha=0.001
T(week)
0
5000
10000
15000
20000
depth(cm)
0
50
100
150
200
250
300
350
◆ ue=3, uo=1.5
■ ue=3.5, uo=1.0
▲ ue=4, uo=0.5


alpha=0.00001
T(week)
0
200000
400000
600000
800000
100000
0
120000
0
140000
0
160000
0
18000
0
depth(cm)
0
50
100
150
200
250
300
350
ue=3.0, uo=1.5
ue=3.5, uo=1.5
ue=4.0, uo=0.5

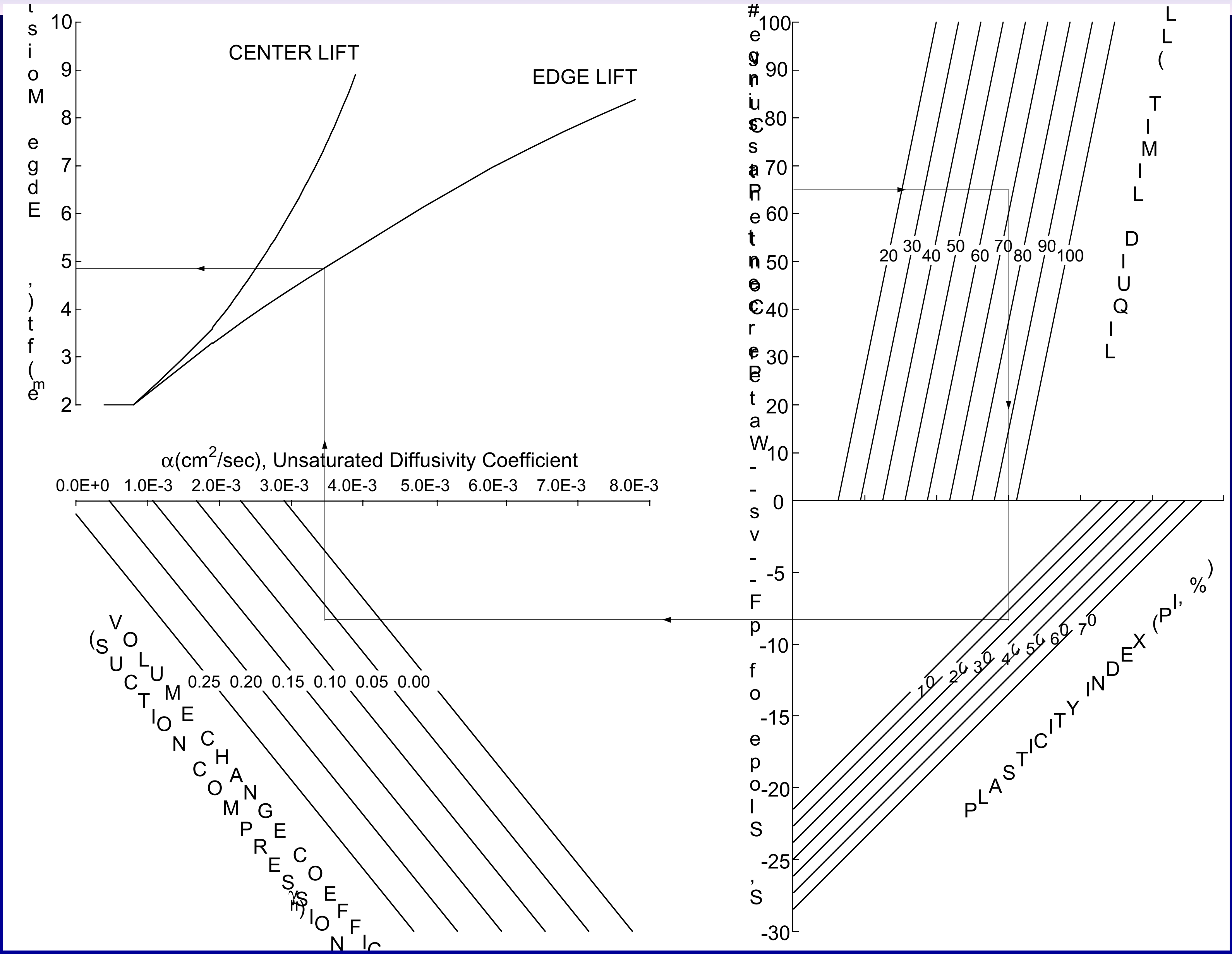
Conclusions

- **Decrease in suction related to slope failures**
- **Moisture diffusion controls rate of strength loss**
- **Critical parameters:**
  - Depth of root zone
  - Crack depth
  - Diffusion coefficient, α
  - Osmotic suction, π
  - Friction angle, ϕ'

Evaluation of Parameters

- Depth of root zone
  - field reconnaissance
- Crack depth
  - field reconnaissance, predictive model
- Diffusion coefficient, α
  - laboratory measurement, correlation to index properties
- Osmotic suction, π
  - laboratory measurement, regional databases
- Friction angle, ϕ'
  - laboratory measurement, correlation index properties

EDGE MOISTURE DISTANCE



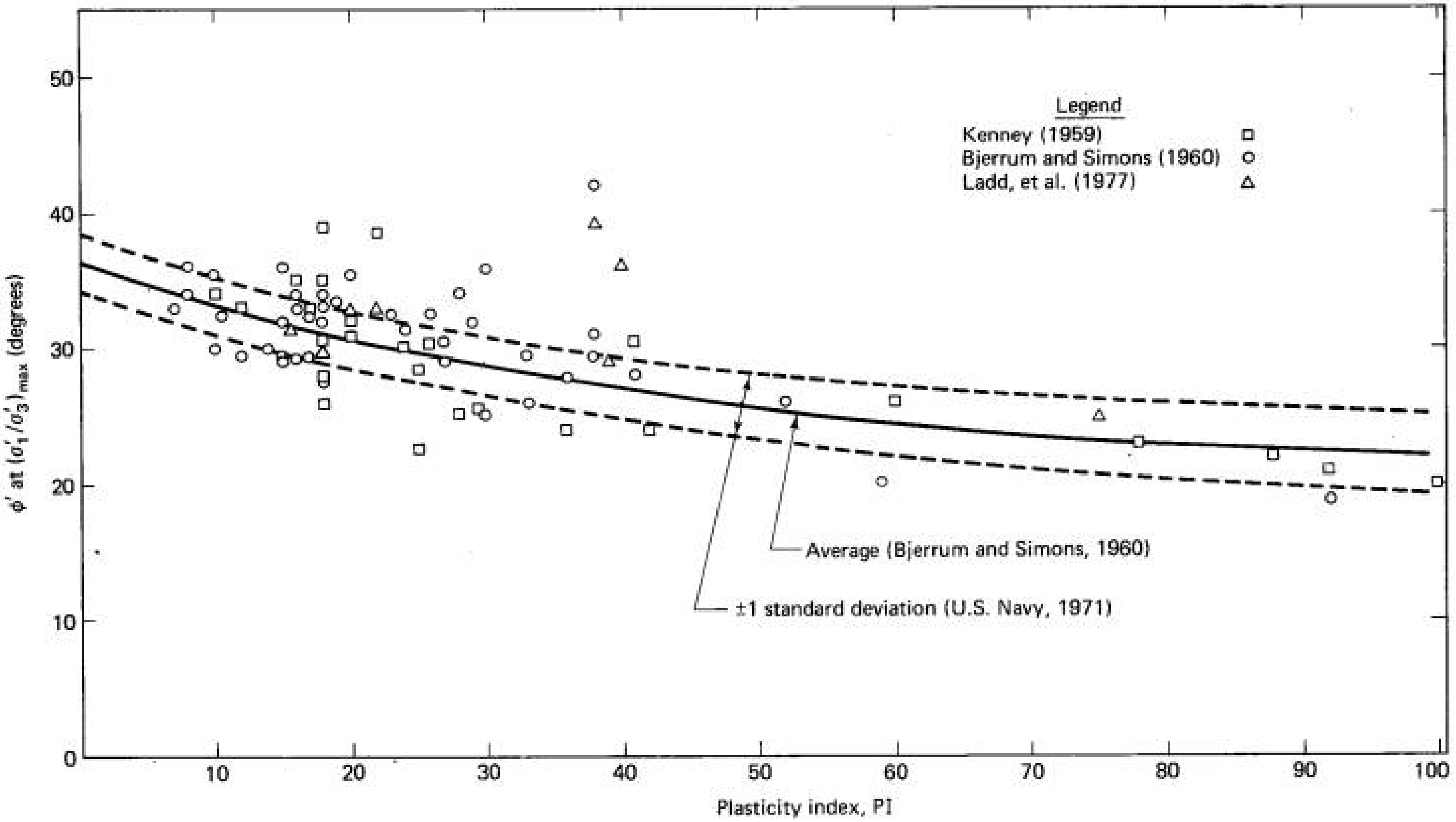


Fig. 11.27 Empirical correlation between φ' and PI from triaxial compression tests on normally consolidated undisturbed clays (after U.S. Navy, 1971, and Ladd, et al., 1977).