Environmental Effects on Pavement Design

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ICAO South American Regional Office

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Ira A. Fulton Schools of Engineering

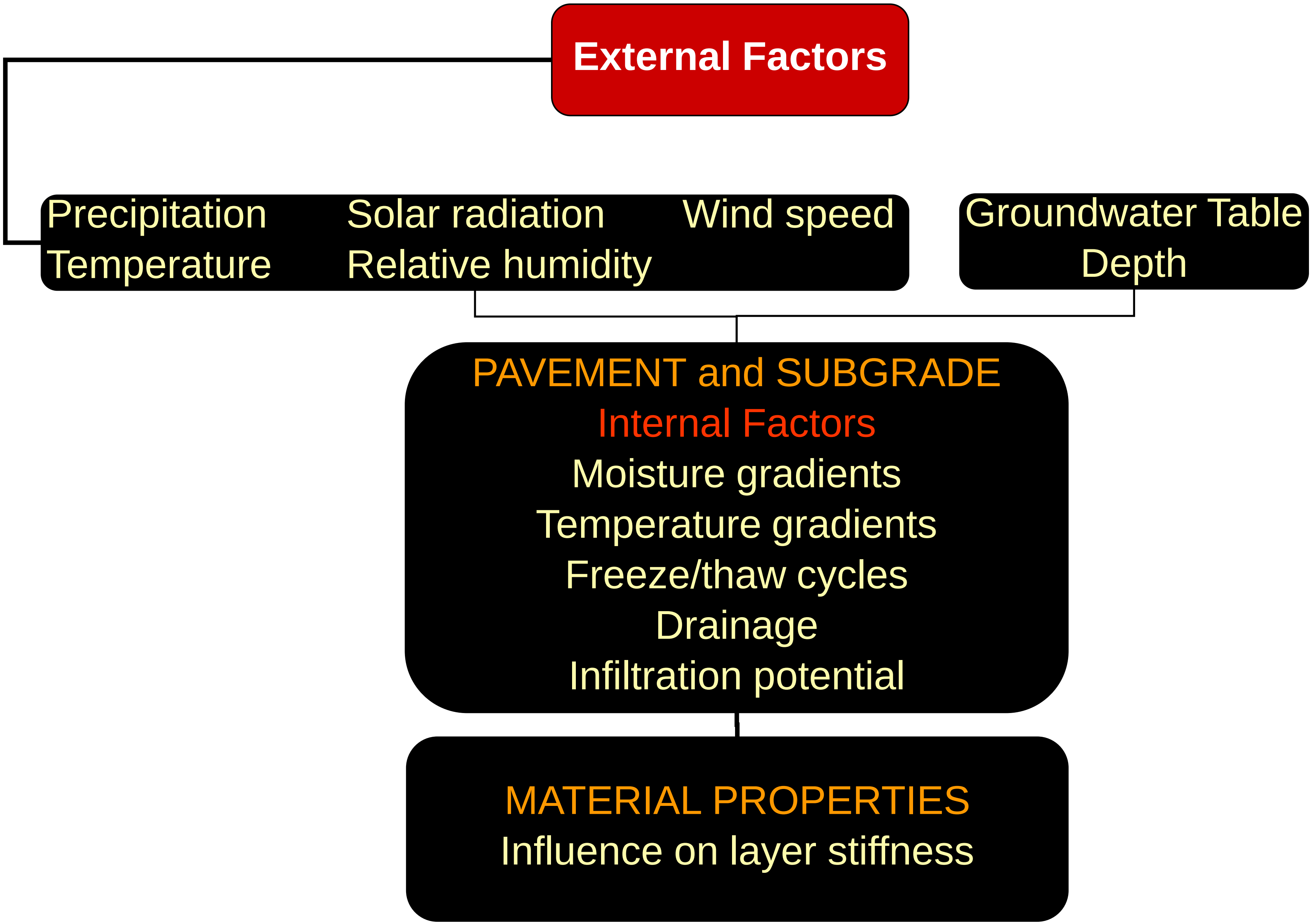
ARIZONA STATE UNIVERSITY

Agenda

- Introduction
- Moisture effects
- Temperature effects
- Environmental effect in pavement life
- Drainage considerations

part I: introduction

Environmental Conditions



Environmental Conditions

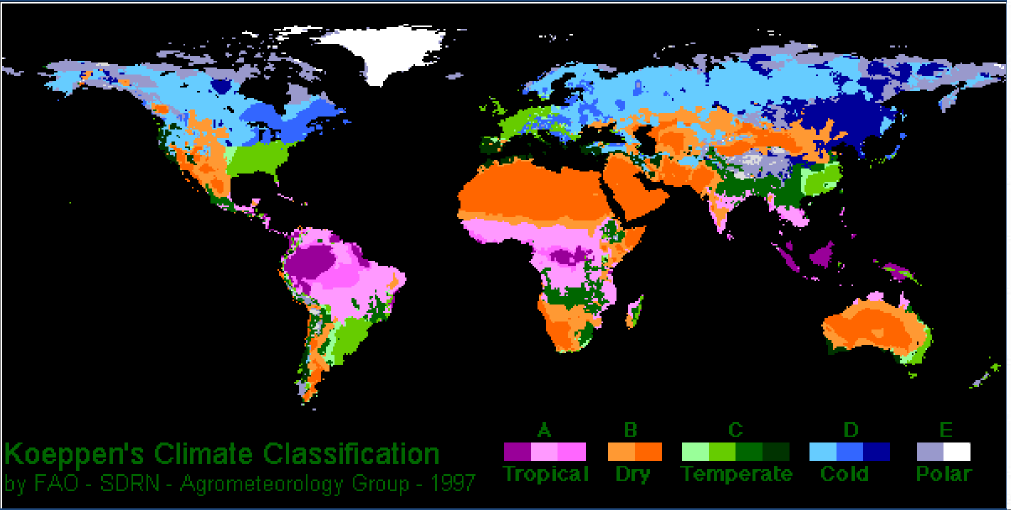
MECHANISTIC ANALYSIS

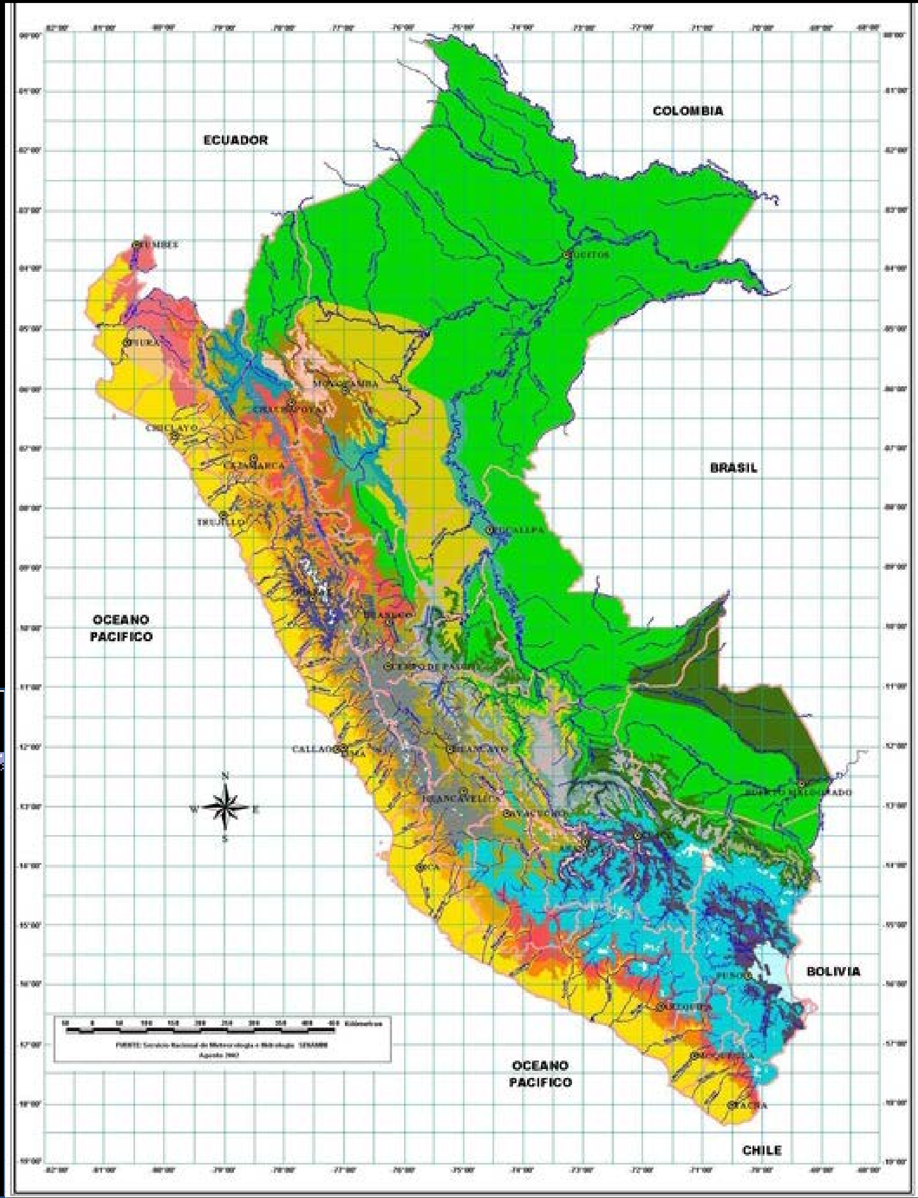
- **FLEXIBLE**
  - Fatigue cracking
  - Thermal cracking
  - Permanent deformations
  - IRI factor
- **RIGID**
  - JPCP faulting and fatigue cracking
  - Curling and warping
  - Drying shrinkage
  - CRCP punchouts
  - IRI factor
  - CRCP initial crack width

part II: moisture effects

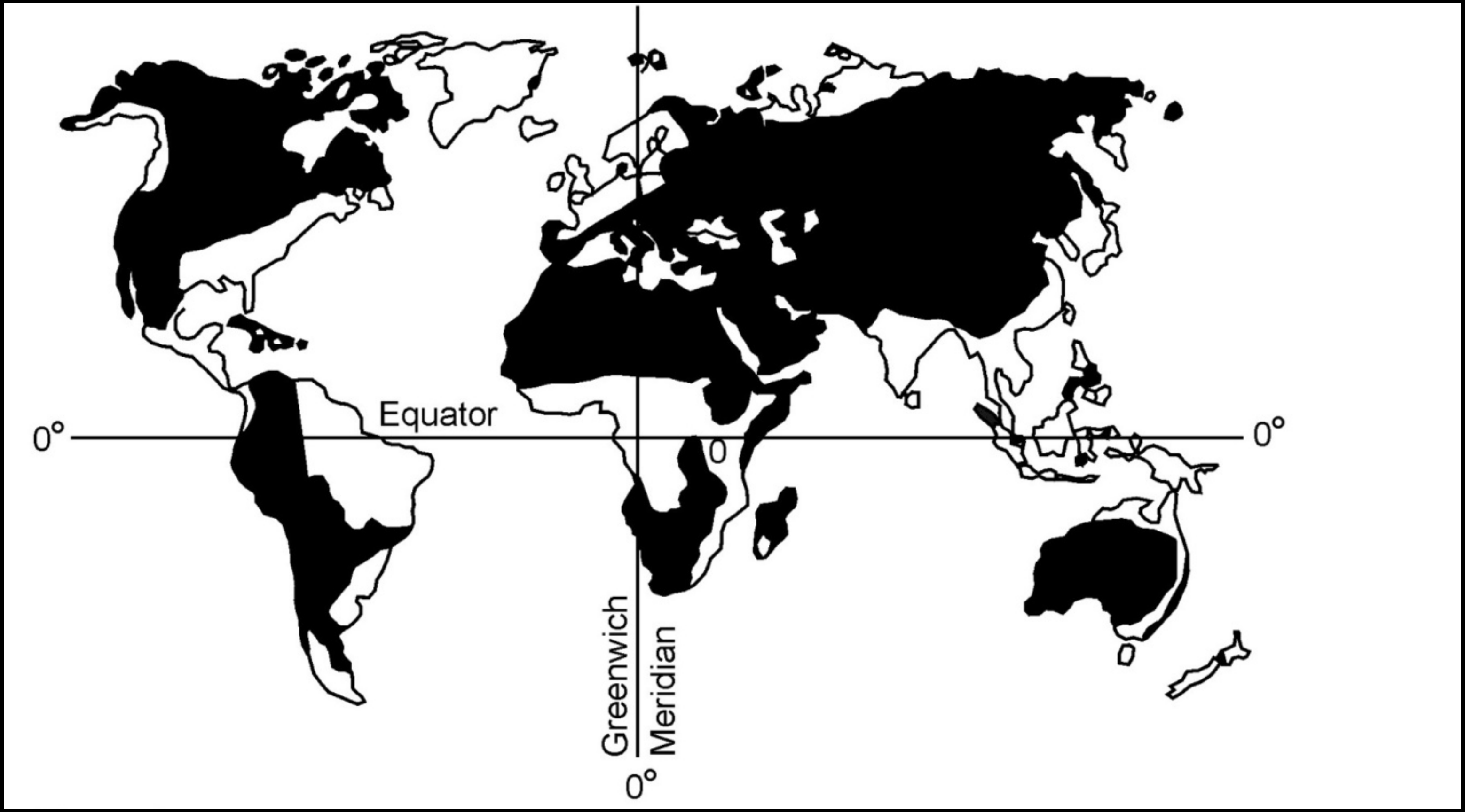
Unsaturated soils

- One-third of earth's surface is arid and semi arid
- Unbound materials under pavements are generally unsaturated





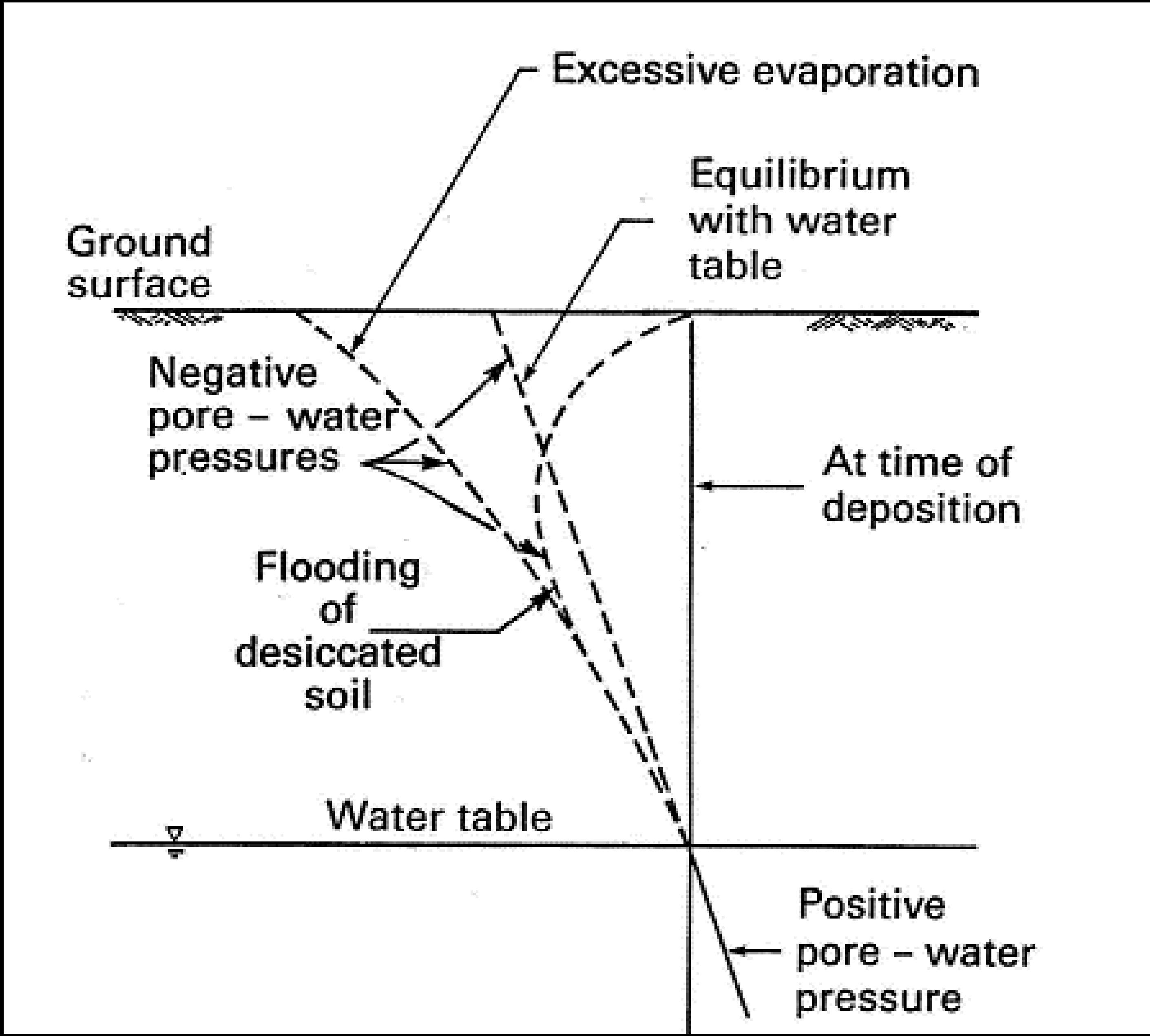
Seasonal Water Deficient Area – 65% !!



By definition, in a water deficient climate, the monthly evaporation from a free water surface exceeds the monthly rainfall throughout the year

- After decades of focus on saturated soils, the Geotech profession has begun to turn its attention to unsaturated soils
- Construction in unsaturated soils is preferred when practical, due to reduced costs and effort
- Research community has made substantial advances in understanding fundamental aspects of unsaturated soil behavior

Typical Pore Water Pressure Profile

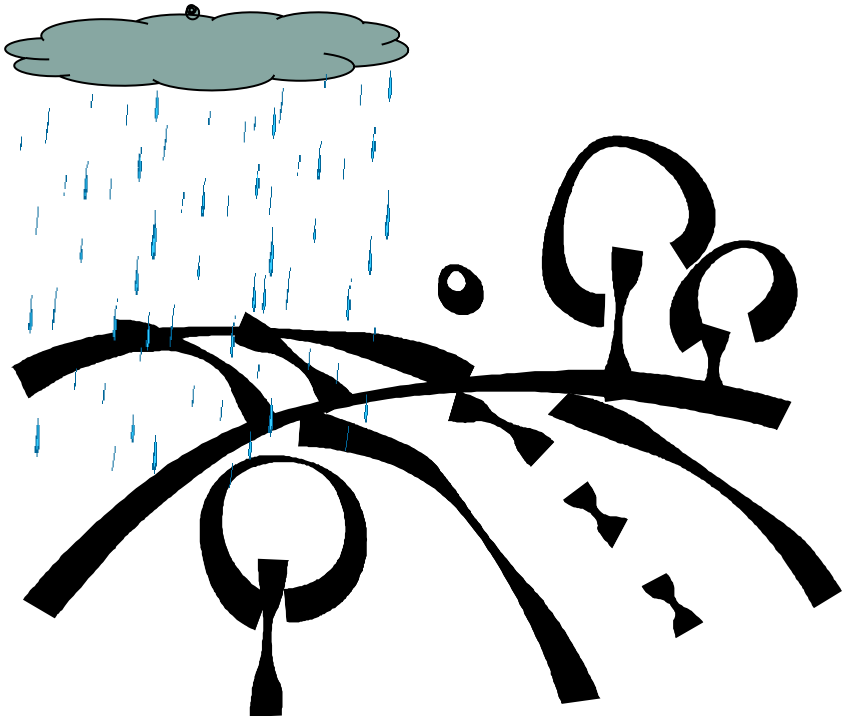


Pavements are constructed primarily in soils that exhibit continuous moisture changes

part IIa:
Thornthwaite moisture index

Thornthwaite Moisture Index (TMI)

Balance between Rainfall and Potential Evapo-transpiration (PE), which determines the amount of water available in the soil



$$TMI = 75\left(\frac{P}{PE} - 1\right) + 10$$

P = Annual Precipitation

PE = Evapotranspiration

f **(temperature)**

Thornthwaite Moisture Index

- TMI is an index that indicates the relative aridity or humidity of a given soil-climate system

- Factors included in TMI are:

  - Precipitation
  - Storage and runoff (soil type)
  - Air temperature
  - Evapotranspiration
  - Solar radiation

Thornthwaite Moisture Index

- **Potential Evapotranspiration**

$$PE_i = 1.6\left(\frac{10t_i}{H_y}\right)^a$$

H_y = annual heat index for year *y*
t_i = mean monthly temperature in ºC

- **Annual Heat Index**

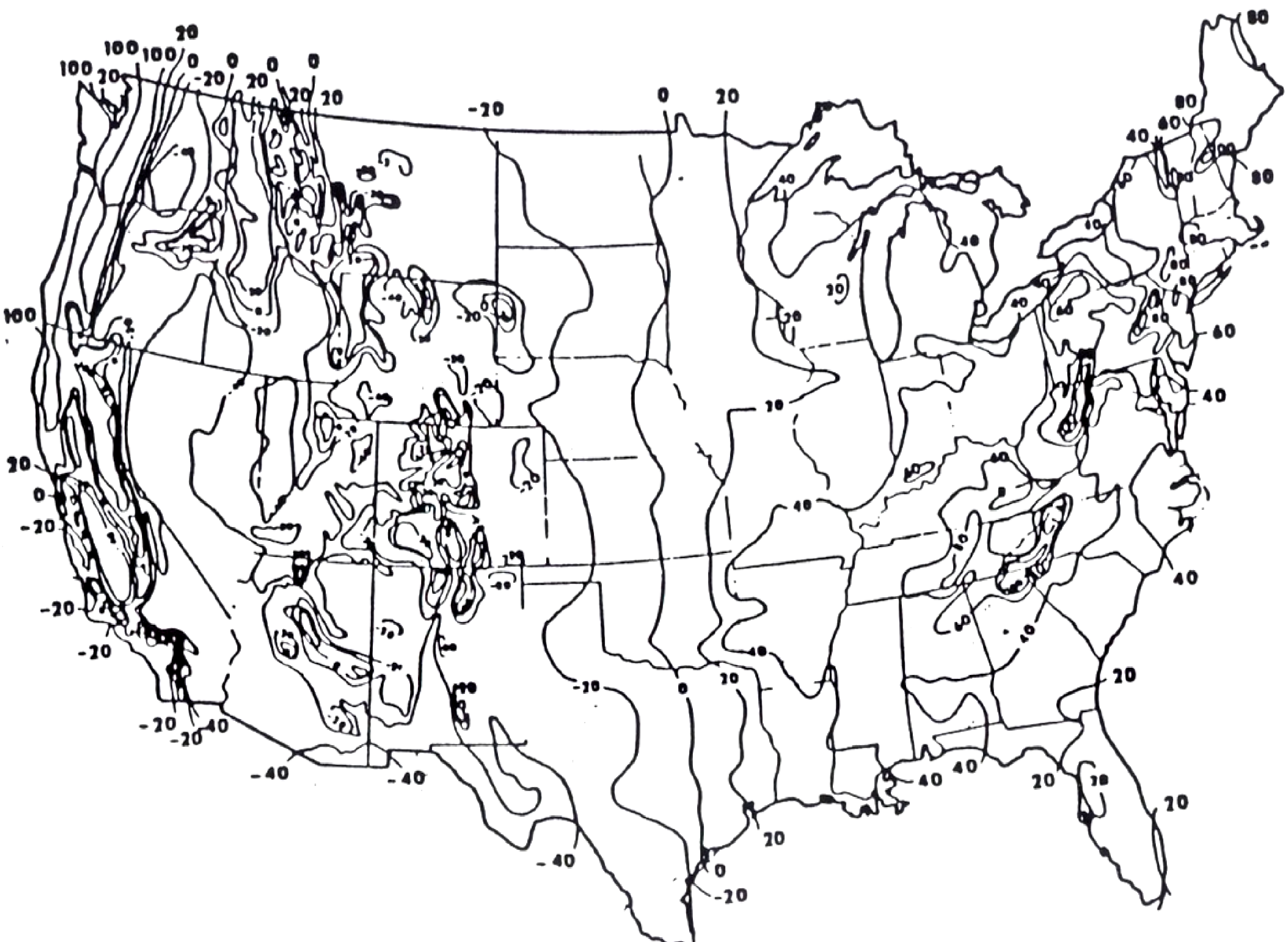
$$H_y = \sum_{i=1}^{12} h_i$$

$$h_i = (0.2t_i)^{1.514}$$

$$PE_i' = PE_i \frac{D_i N_i}{30}$$

D_i = day length correction based on latitude and sunshine

Thornthwaite Moisture Index



Thornthwaite Moisture Index

Phoenix,AZ
TMI_1 =-55

Los Angeles,CA
TMI_2 =-32

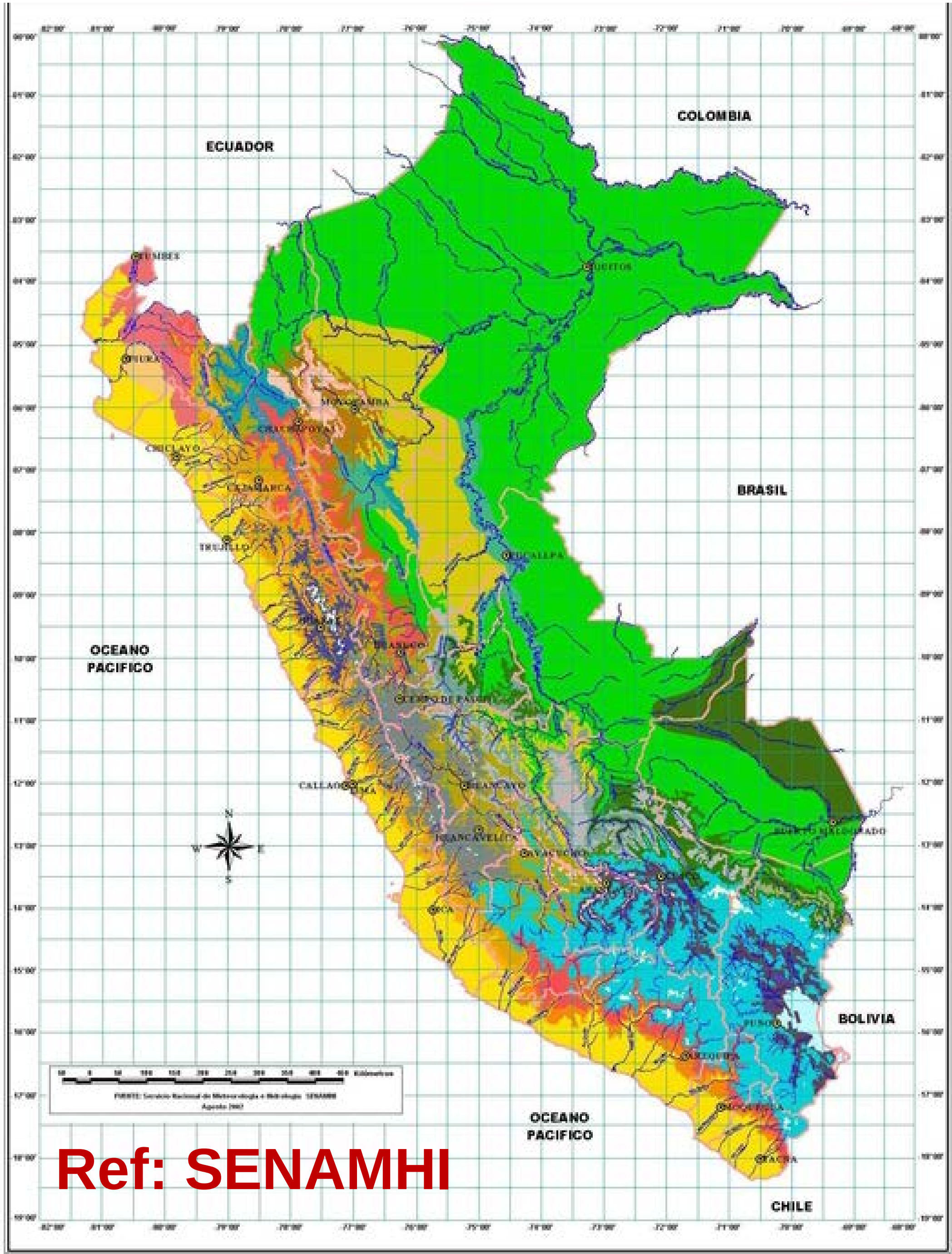
Dallas,TX
TMI_2 =-2

Miami, FL
TMI_2 =17

Athens,GA
TMI_2 =33

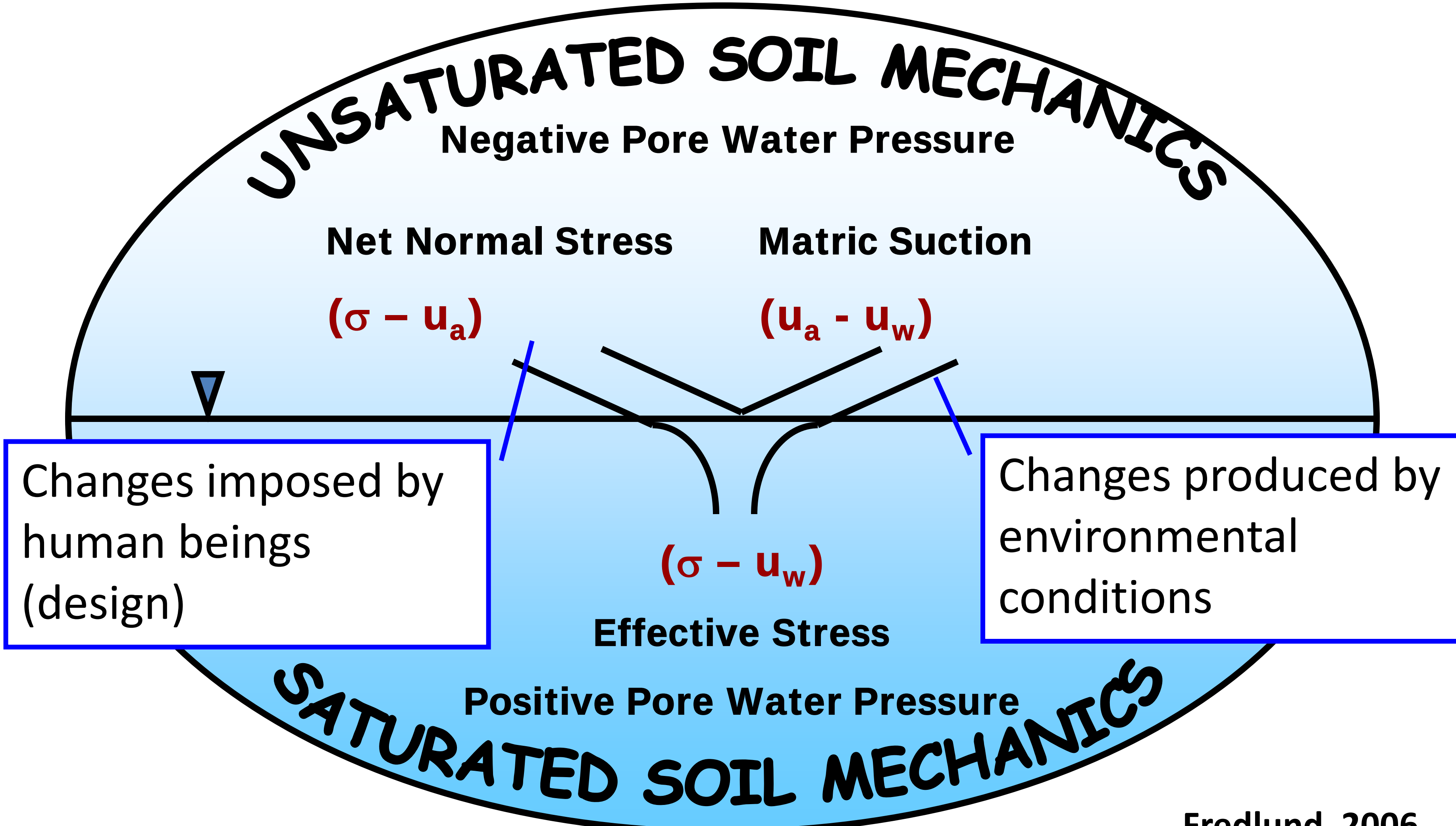
Lima TMI ≈ -30

- Luke-warm (semi-calido)
- Desert climate
- Rainfall deficiency during all weather stations
- RH = Humid



part IIb: soil matric suction

Most Accepted Stress State Variables



Fredlund, 2006

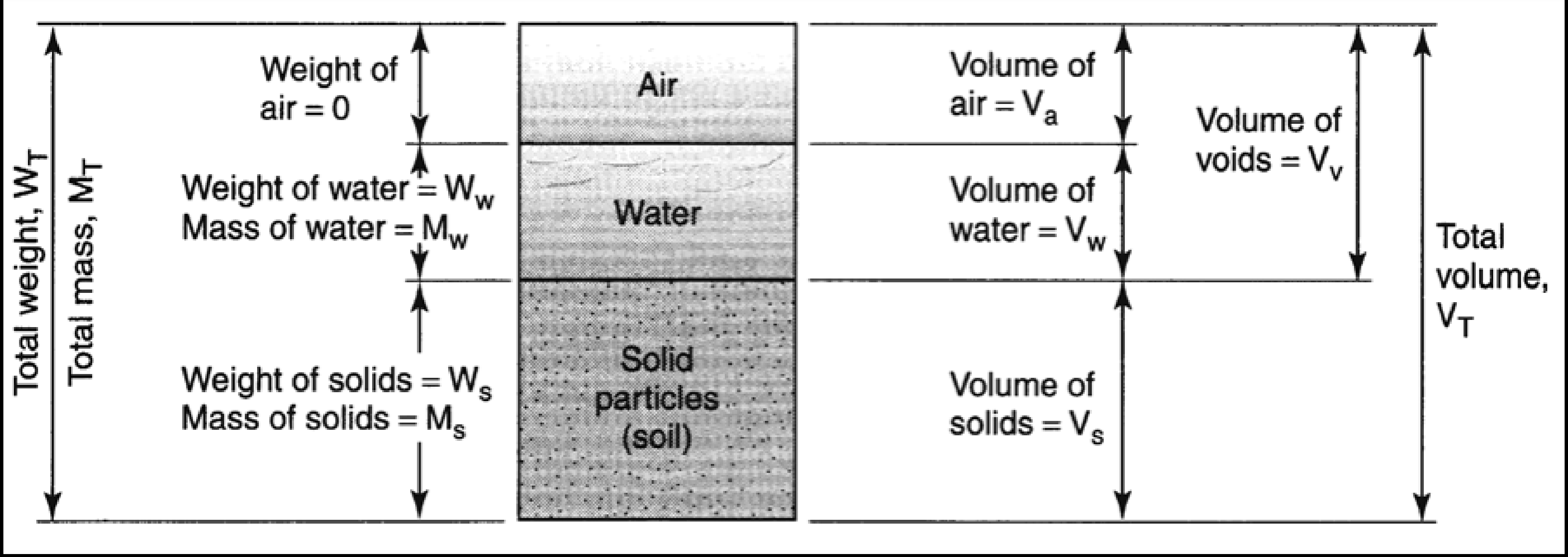
Stress State for Unsaturated Soils in a Nutshell

In general, soil has three (3) phases:

- Solid soil particles
- Water
- Air

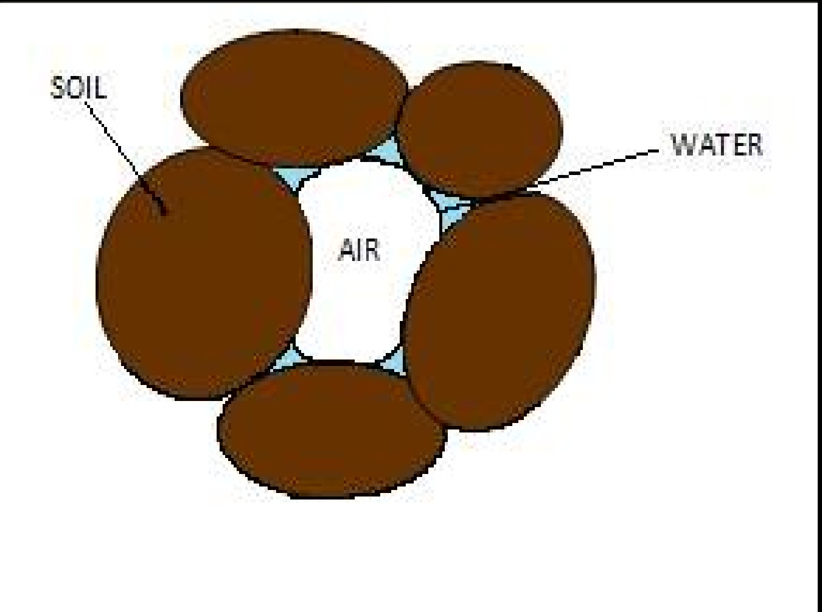
Recall the mass-volume phase relationships

Stress State for unsaturated Soils in a Nutshell



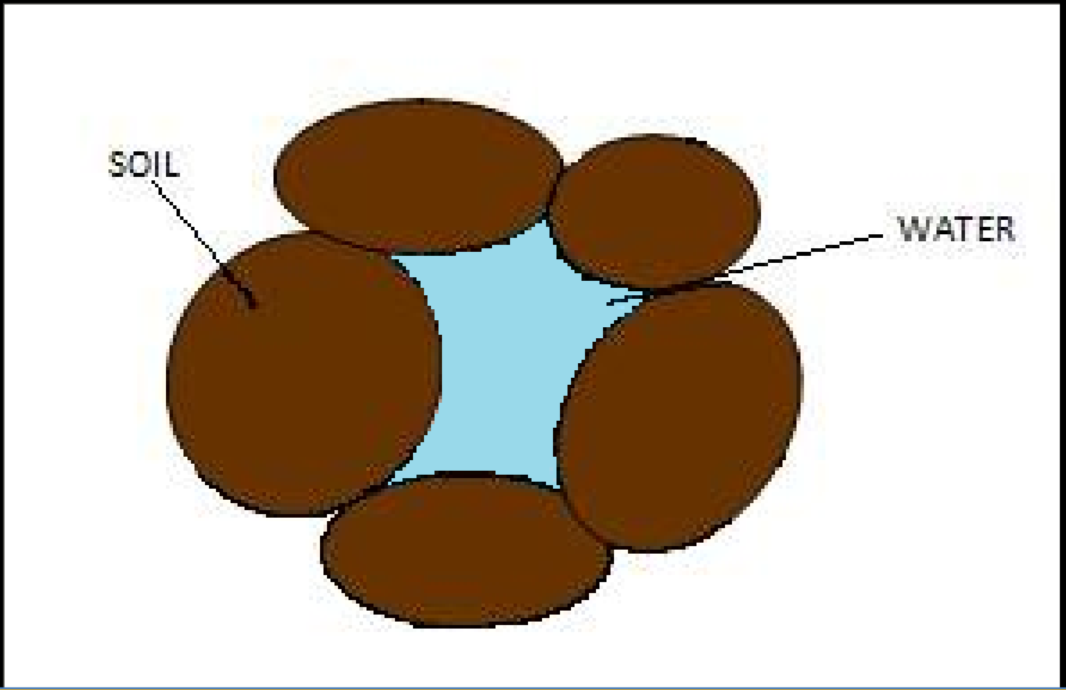
Stress State for unsaturated Soils in a Nutshell

When both air and water occupy the void space between particles, the soil is called Unsaturated.



Stress State for unsaturated Soils in a Nutshell

When the void space is filled with water the soil is called Saturated.



Saturated soil is just a special case of Unsaturated soil

What Stresses Act on Soil?

Because soil is, in general, a three-phase medium (air, water, and solid), there are three stresses that must be considered in describing the overall state of soil stress:

What Stresses Act on Soil?

- Total stress (σ):

  Normally compressive

- Pore air pressure (u_a)

  Normally positive

- Pore water pressure (u_w)

  Can be positive or negative, but is normally negative when the soil is unsaturated and all three phases are present

What Stresses Act on Soil?

- We can combine these three stresses into two measurable "net" stress state variables, both of which tend to keep the grains together when the soil is unsaturated:

- The "net" total stress: $(\sigma - u_a)$
- The matric suction: $(u_a - u_w)$

A simple example of how matric suction pulls grains together follows.

When building a sand castle, it is the matric suction (water in tension) that tends to pull grains of sand together, providing strength and stiffness.

Simplifications for Saturated Soil Conditions

When the soil void space is filled with water, and the soil is saturated, the stress state is represented by two stresses:

- Total Stress

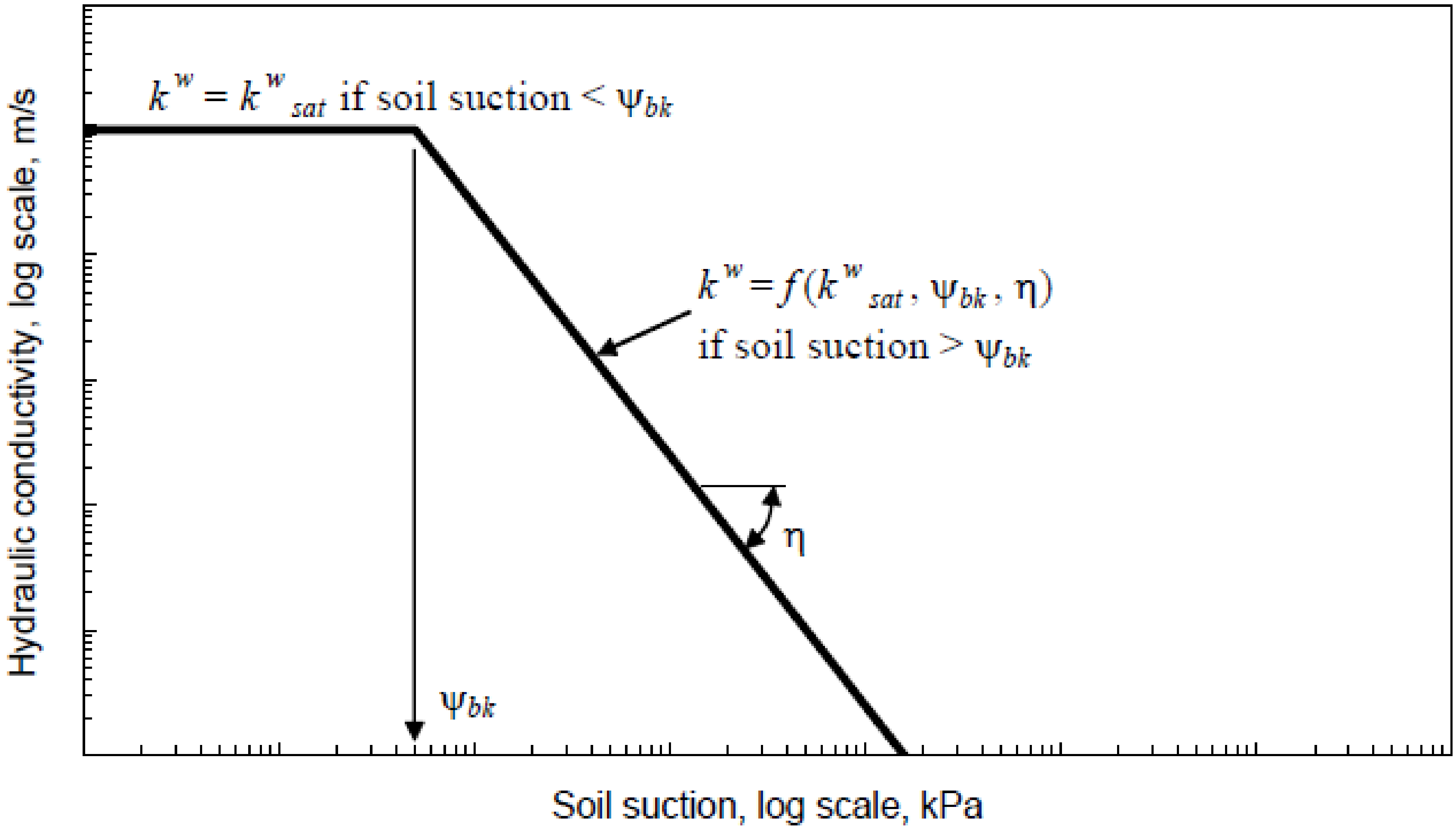
- Pore Water Pressure

When combined, the Effective Stress is the stress that controls the behavior of saturated soils

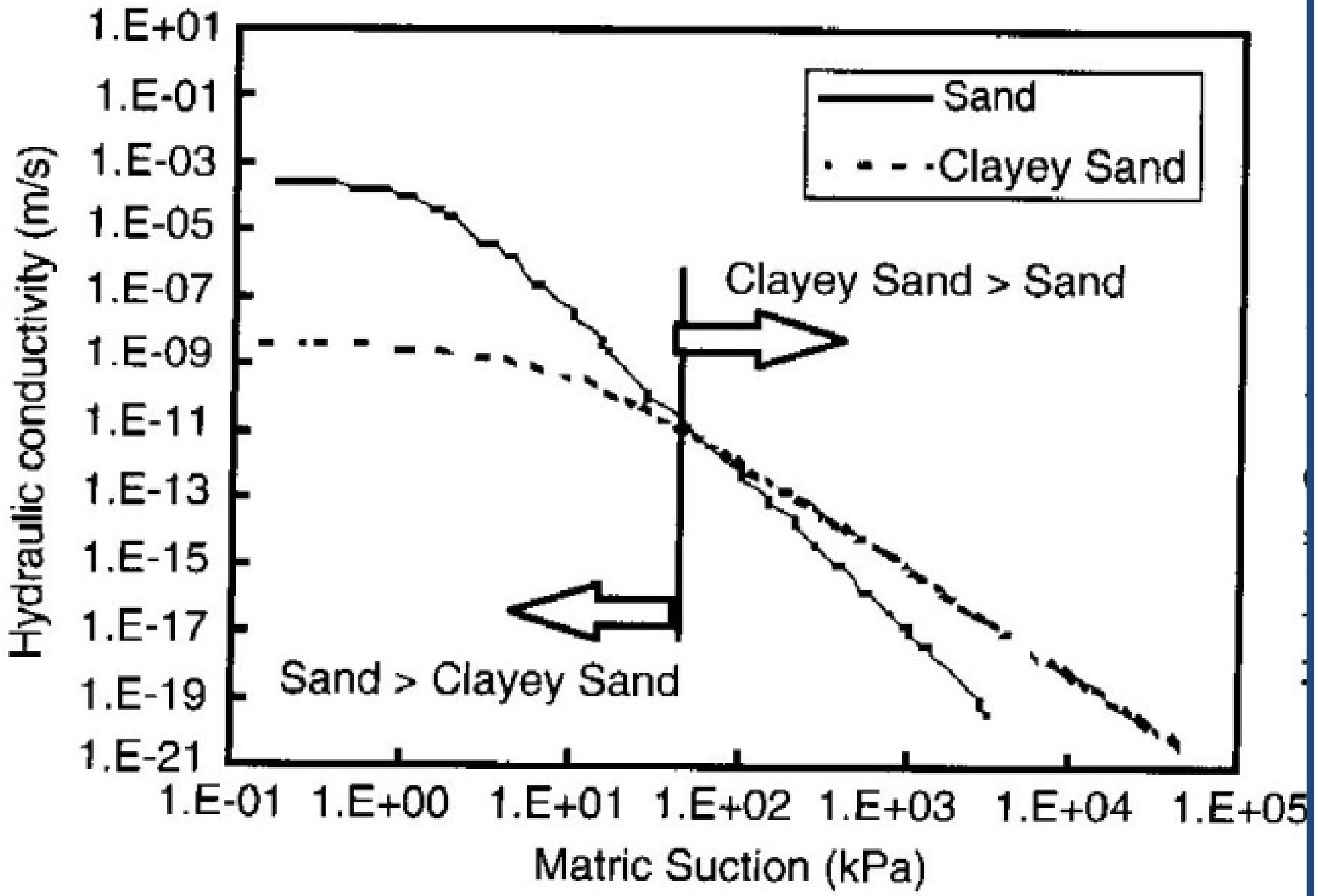
Soil Matric Suction

- Matric suction or negative pore water pressure is an independent stress state variable fundamental to the behavior unsaturated soils
  - Affects the total head for flow
  - Affects the hydraulic conductivity
  - Control soil moisture retention capabilities
- To consider the effect of moisture fluctuations on strength (modulus), one must characterize the soil in terms of its matric suction

Darcy's Law Gets a Bit Complicated when S < 100%



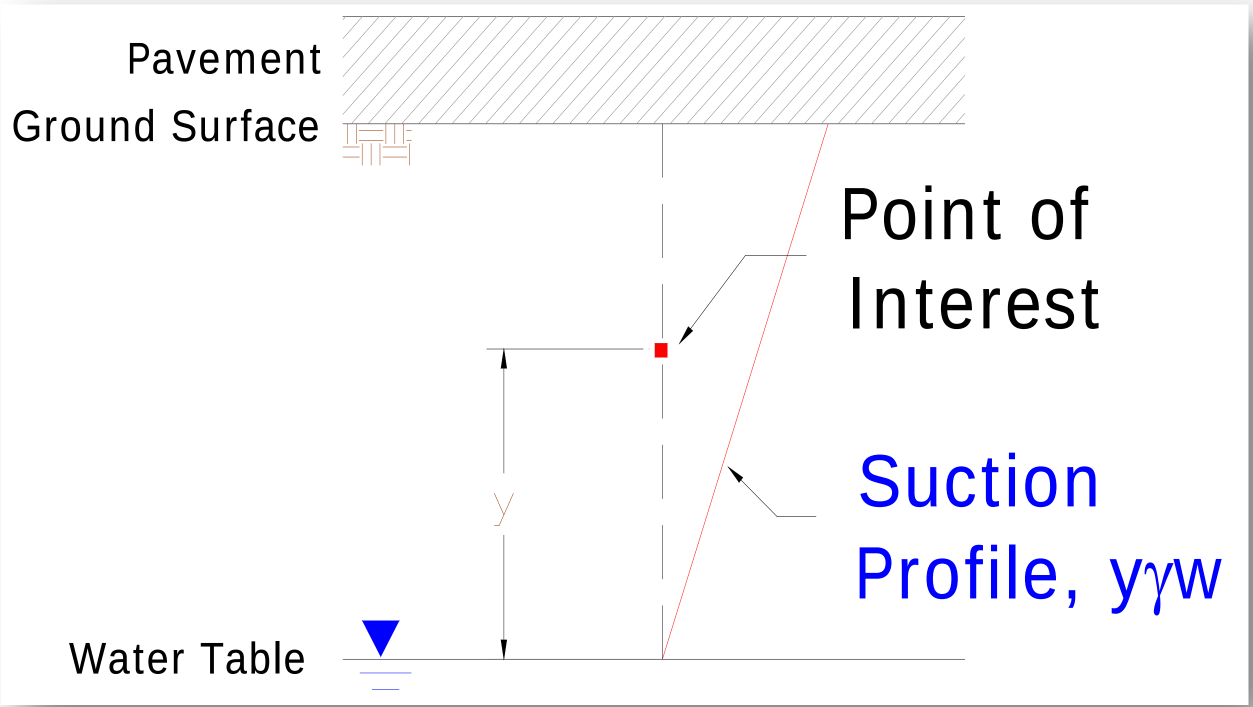
Hydraulic Conductivity Function



(a)

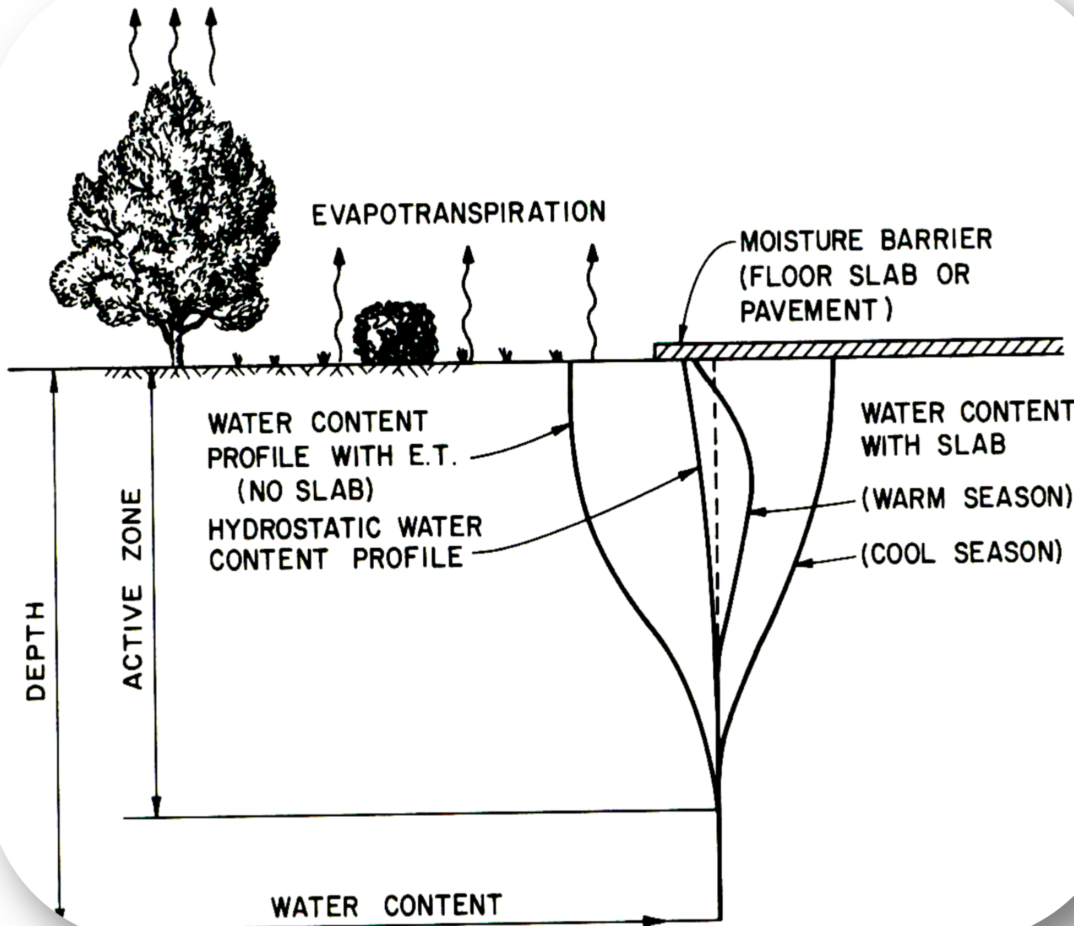
Conventional Assumption Used to Estimate Negative Pore Water Pressures

- For a relatively near-surface groundwater table, significant potential exists for **capillary rise** into subgrade soils



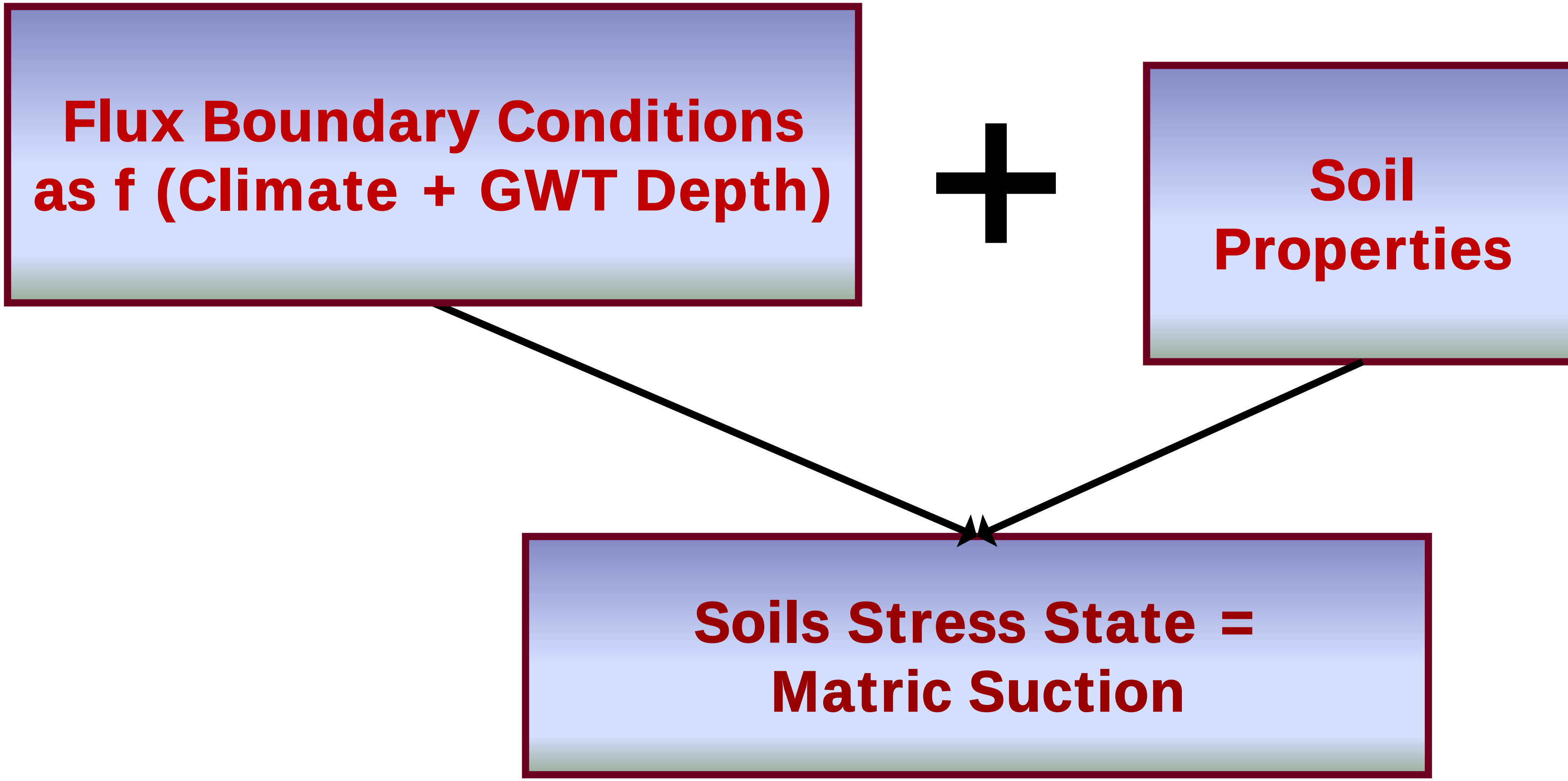
- Assumption appropriate when soils are wetted to a saturation of 85% or more

Flux Boundary Conditions



- Microclimate controls flux boundary conditions
  - **Lateral flow from shoulders**
  - **Vertical flow from cracks**
  - **Evapotranspiration**

Modeling Development



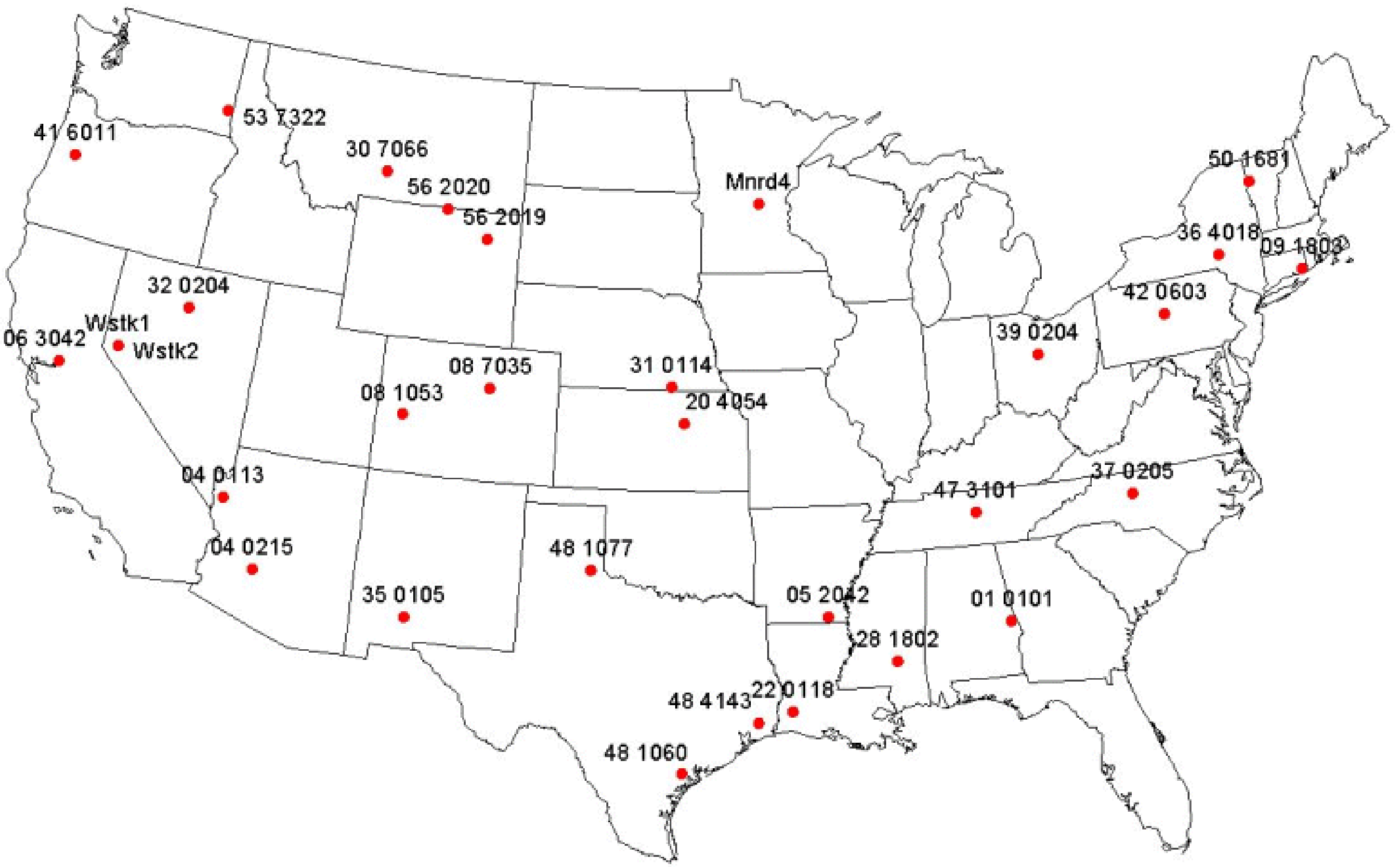
Climate Data

- Temperature
  - Sunrise/sunset time
  - Solar radiation
  - Air temperature
  - Percent sunshine
  - Wind speed
  - Longitude and latitude

- Moisture
  - Relative humidity
  - Precipitation
  - Groundwater table depth

Soils Data Collected to Calibrate Models

- 30 visited sites within the continental USA



Site Selection

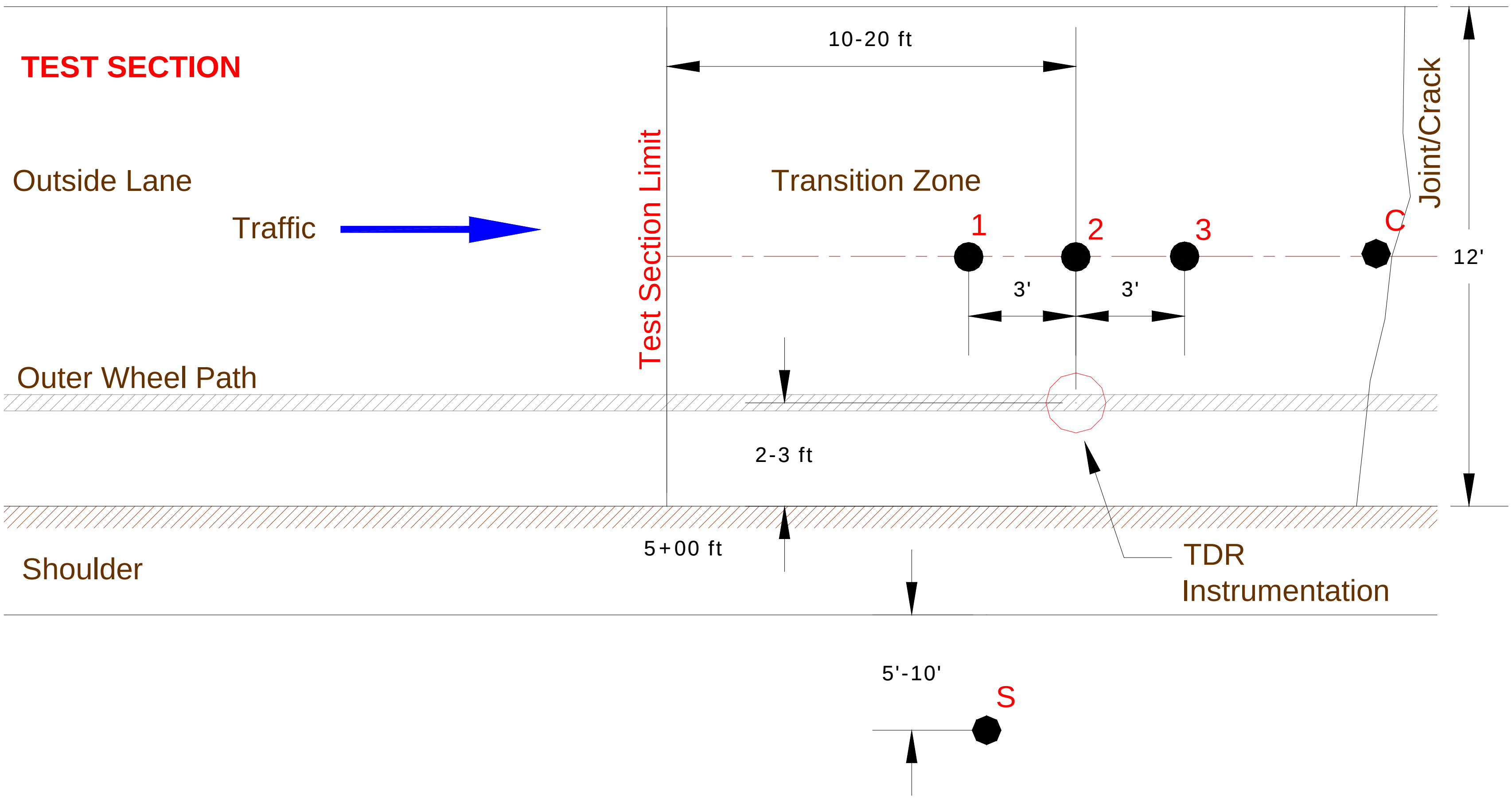
- Pavement Type
- Depth to Groundwater Table
- Mean Annual Air Temperature
- Precipitation
- Freezing Conditions
- Soil Type
- Pavement Cracking

Experiment Design – Field Data
30 Sites Visited

Calibration with Field Data					Pavement Type			
					AC		PCC	
					GWT depth			
					Deep	Shallow	Deep	Shallow
High Maat > 15°C	High Precipitation > 800 mm	Frozen	Coarse Sg					
			Fine Sg	High PI				
				Low PI				
		No freeze	Coarse Sg		1	1		
			Fine Sg	High PI	1	1	1	1
				Low PI		1		
	Low Precipitation < 800 mm	Frozen	Coarse Sg					
			Fine Sg	High PI				
				Low PI				
		No freeze	Coarse Sg		1		1	
			Fine Sg	High PI	1			
				Low PI		1		1
Low Maat < 15°C	High Precipitation > 800 mm	Frozen	Coarse Sg		1			1
			Fine Sg	High PI				
				Low PI				
		No freeze	Coarse Sg			1	1	
			Fine Sg	High PI	2			1
				Low PI				1
	Low Precipitation < 800 mm	Frozen	Coarse Sg		2			
			Fine Sg	High PI		1		
				Low PI	2	1		
		No freeze	Coarse Sg			1	1	
			Fine Sg	High PI	1	1		
				Low PI				

Fieldwork in Groton, CT

Typical Sample Location Layout



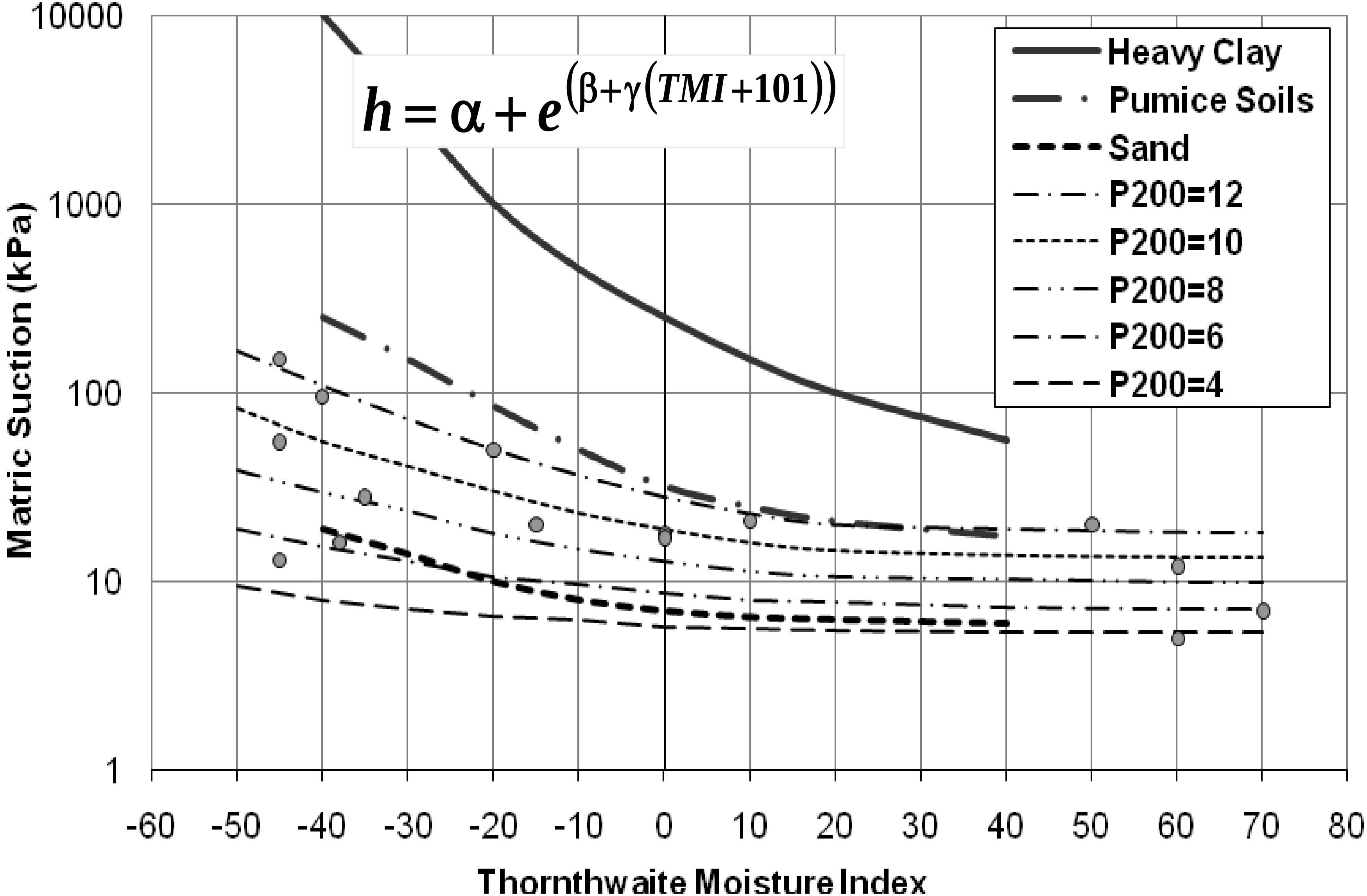
Laboratory Testing Completed

In-situ Moisture Content	257
In-situ Dry Density	251
Atterberg Limits	144
Grain Size Distribution	148
Specific Gravity of Solids	104
Soil-Water Characteristic Curves	94
Saturated Hydraulic Conductivity on Unbound Materials	64
Saturated Hydraulic Conductivity on Bound Materials	22

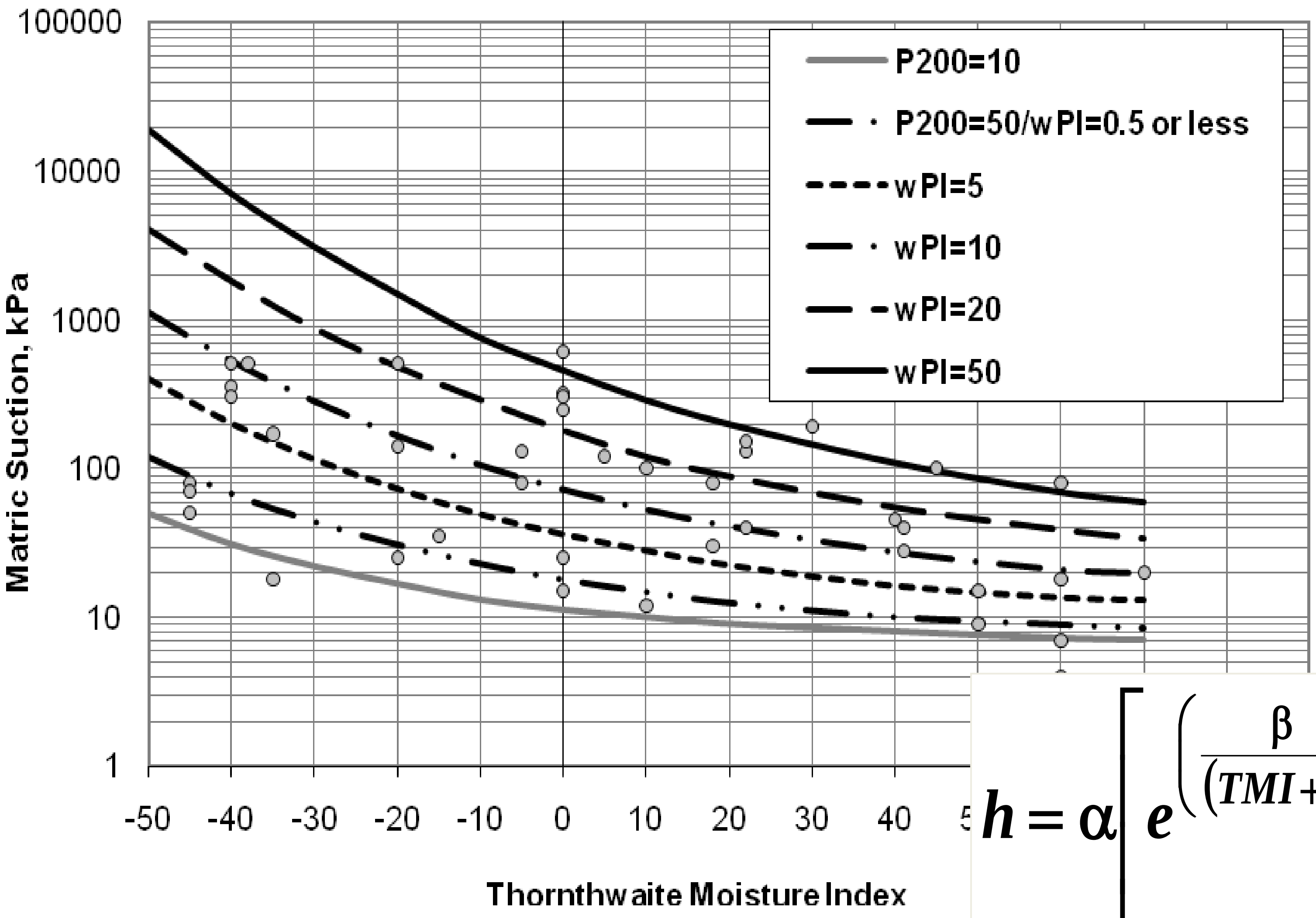
Parameters Considered for Correlation with Matric Suction

- Annual Mean Relative Humidity
- Annual Mean Precipitation
- Thornthwaite Moisture Index (TMI)
- Depth to Groundwater Table
- P_{200} and Plasticity Index
- and more …

TMI-P_{200} Model – Granular Bases



TMI-P_{200}/wPI Model – Subgrades



$$h = \alpha\left[e^{\left(\frac{\beta}{(TMI+\gamma)}\right)} + \delta\right]$$

Error Analysis
Comparison with $y\gamma_w$ Method

Error Analyzed	Model for Granular Material	Model for Plastic Material	$y\gamma_w$
Mean Absolute	9.5%	37.7%	267%
Mean Algebraic	2.1%	0.07%	-259%

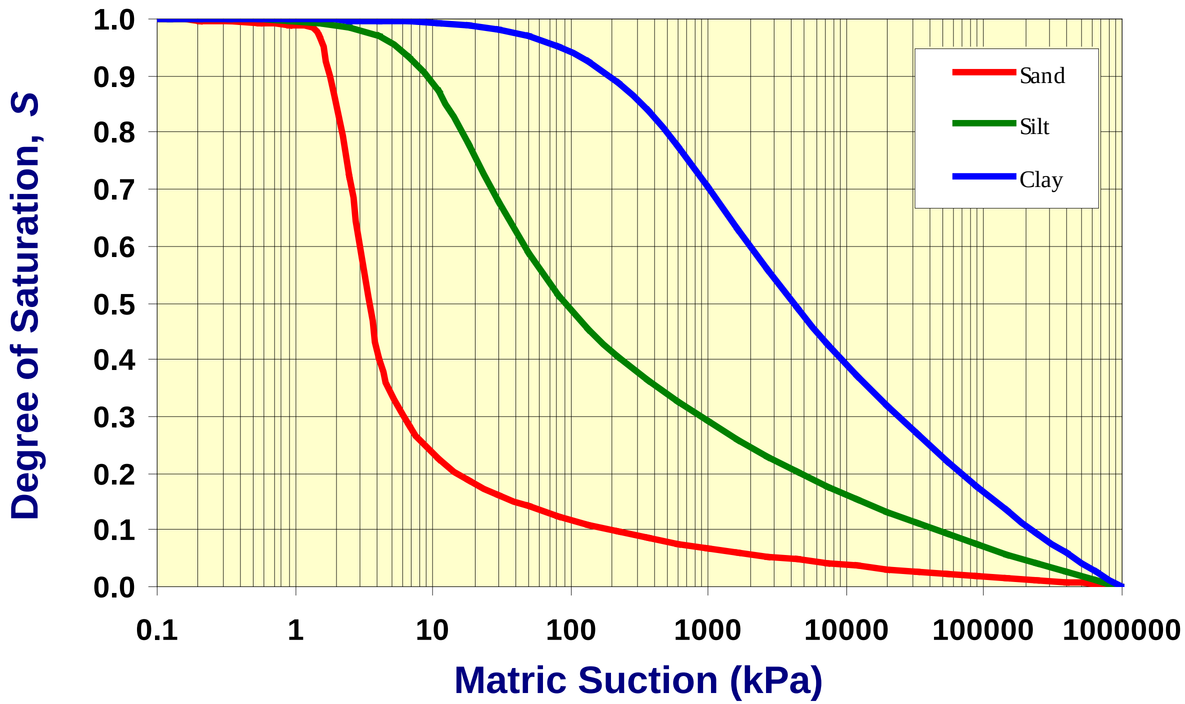
Conclusions

- TMI seems to quantify the environmental factors beneath a covered area (pavement) effectively
- Soil type can be effectively represented by Passing #200 and Plasticity Index
- Suction prediction based on TMI is far superior than the traditional upward extrapolation from groundwater table depths
- Models are easy to implement

part IIc: soil-water characteristic curve

Soil-Water Characteristic Curve

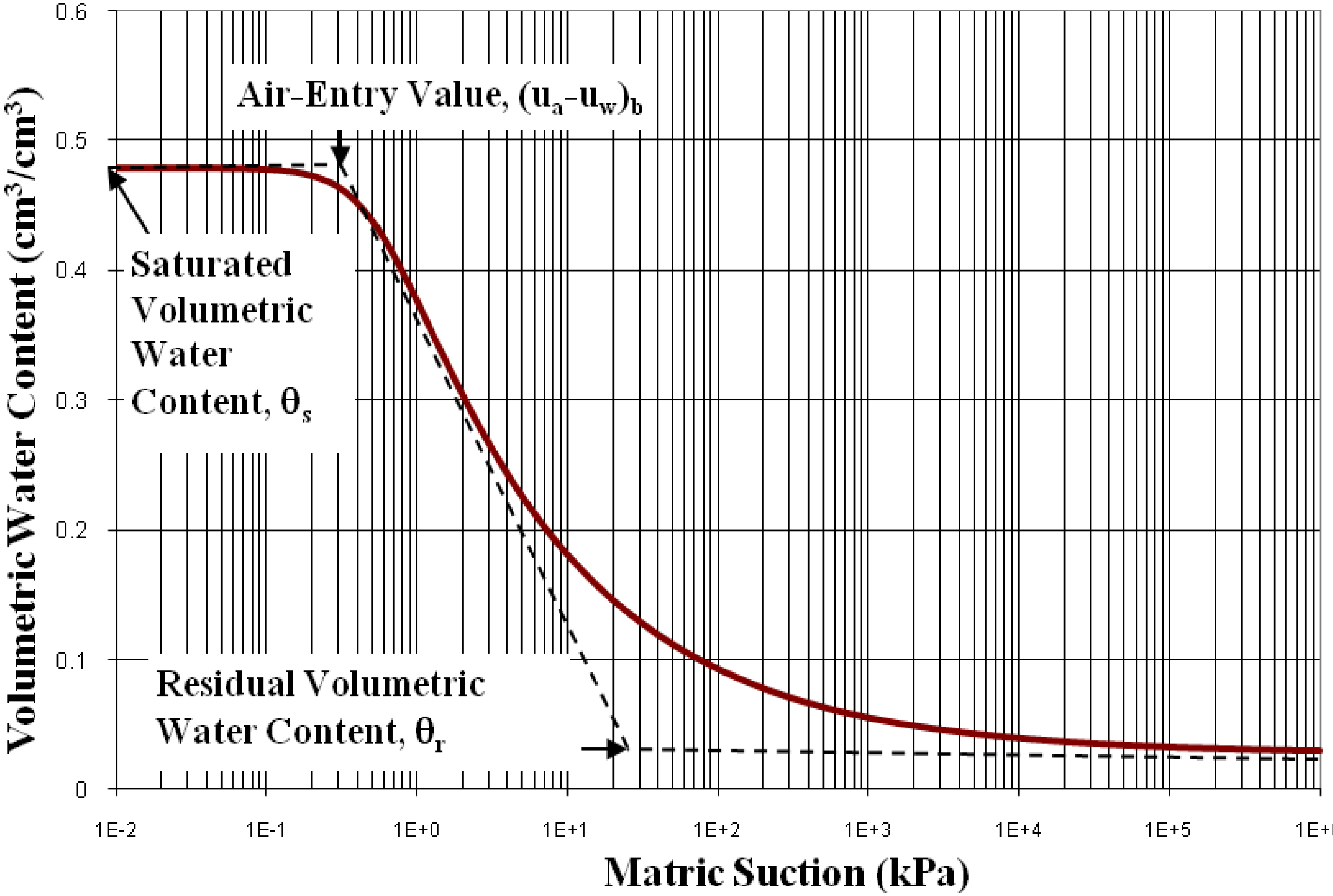
- Moisture content is directly related to **soil matric suction** by means of the soil-water characteristic curve



SWCC Parameters

- **The SWCC is the relationship between soil moisture content and the matric suction at equilibrium conditions**
- **Suction dictates the moisture retention or storage capacity of the soil**
- **Suction is perhaps the most important stress state in the gradient that causes fluid flow when the soil is not 100% saturated**

SWCC Descriptive Parameters



SWCC Models

Model	Equation
Brooks and Corey (1964)	$\Theta_d = 1$ $\Theta_d = (\psi / a_c)^{-n_c}$
Brutsaert (1966)	$\Theta_d = 1 / (1 + (\psi / a_r)^{n_r})$
McKee and Bumb 1984 (a Boltzman exponential form)	$\Theta_d = 1$ $\Theta_d = \exp((a_z - \psi) / n_z)$
McKee and Bumb 1987 (Fermi)	$\Theta_d = 1 / (1 + \exp((\psi - a_e) / n_e))$
Fredlund and Xing (1994)	$\Theta_d = (1 / \ln(e + (\psi / a_f)^{n_f}))^{m_f}$
Gardner (1956)	$\Theta_d = 1 / (1 + a_g \psi^{n_g})$
van Genuchten (1980)	$\Theta_d = (1 / (1 + (a_v \psi)^{n_v}))^{m_v}$
van Genuchten (1980) – Burdine (1953)	$\Theta_d = (1 / (1 + (a_b \psi)^{n_b}))^{(1 - 2 / n_b)}$
van Genuchten (1980) – Mualem (1976)	$\Theta_d = (1 / (1 + (a_m \psi)^{n_m}))^{(1 - 1 / n_m)}$
Normalized water content form	$\theta_n = \theta_r + (1 - \theta_r)(\theta_f(\psi))$
Fayer and Simmons (1995) correction	$\theta = \theta_a (1 - \ln(\psi) / \ln(1\,000\,000)) + (\theta_s - \theta_a (1 - \ln(\psi) / \ln(1\,000\,000)))(\theta_f(\psi))$
Fredlund and Xing (1994) correction	$\theta = (1 - \ln(1 + \psi / \psi_r) / (1 + 1\,000\,000/\psi_r))(\theta_f(\psi))$

SWCC Parameters

$$S = C(h) \times \left[\frac{1}{\left[\ln \left[\exp(1) + \left(\frac{h}{a_f} \right)^{b_f} \right] \right]^{c_f}} \right]$$

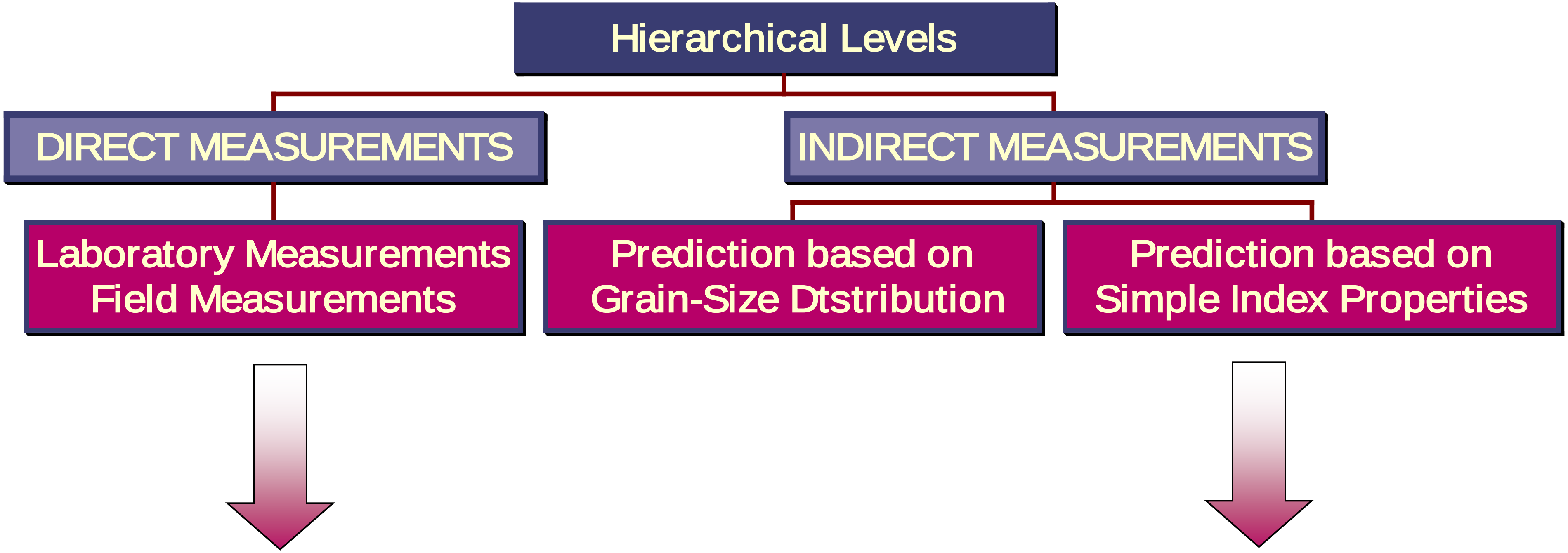
Degree of Saturation

Matric Suction

$$C(h) = \left[1 - \frac{\ln\left(1 + \frac{h}{h_r}\right)}{\ln\left(1 + \frac{10^6}{h_r}\right)} \right]$$

How to obtain the soil suction?

How to Obtain Soil Suction?



Most accurate

Sophisticated equipment

High cost

Higher uncertainty

Very low cost

Easier to implement

How to Obtain Matric Suction?

- Laboratory measurements
  - Pressure plates, pressure membranes
  - Filter paper method
- Field measurements
  - Thermal conductivity sensor
  - Tensiometers
- Concept and theories have been developed
- Routine testing implementation has proven difficult to achieve

SWCC Cells

Mounted and Unmounted Ceramic Disks

Difficulties when Measuring Suction (SWCC)

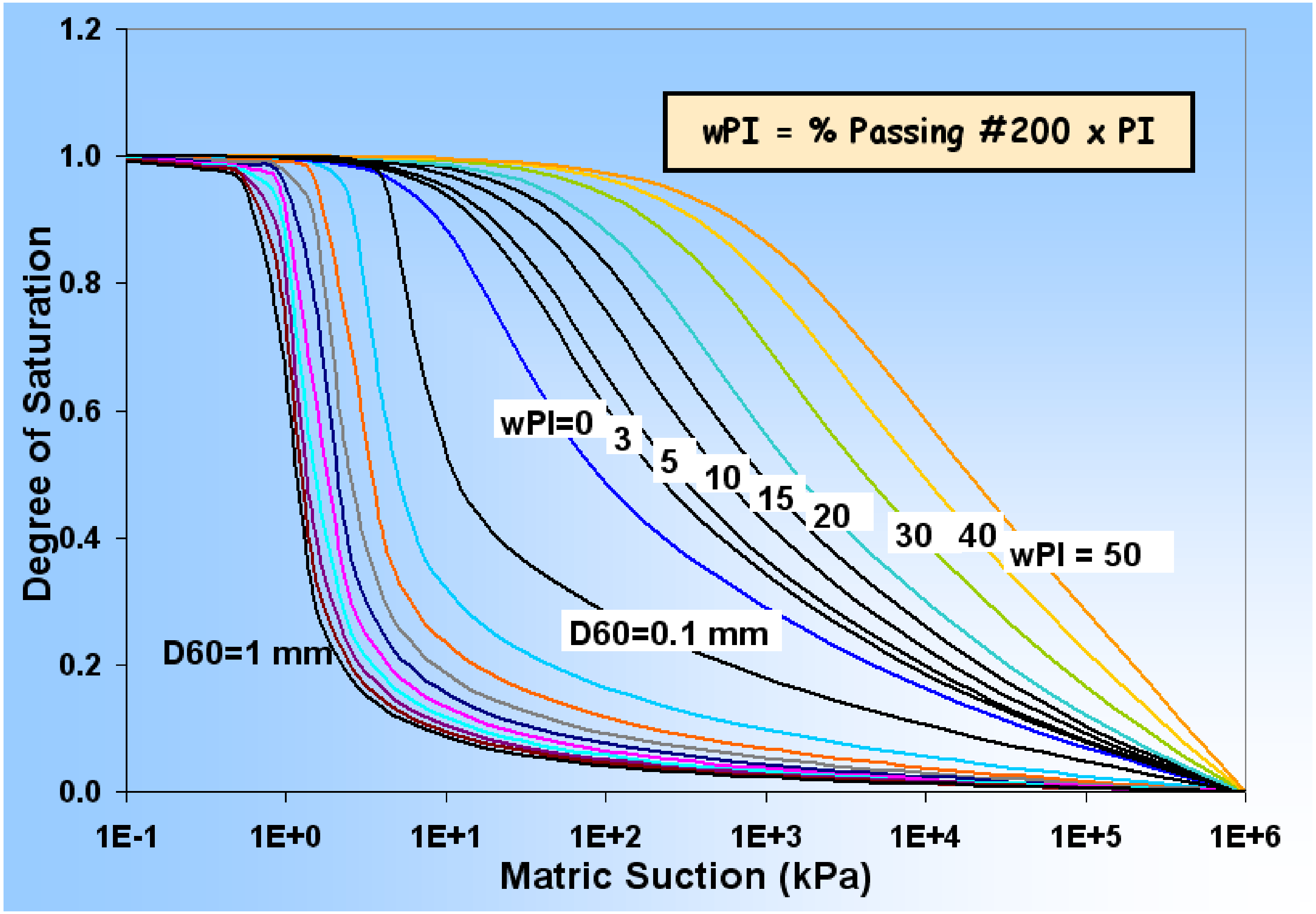
- Greater level of difficulty
  - Non-linear functions
- Time and cost associated with unsaturated soil characterization
- Variability associated with measured suction
- Practitioners have not fully adopted and/or accepted suction measurements as part of the regular laboratory soils testing programs
  - Reluctance to accept new practices

SWCC prediction models

Predicting the SWCC

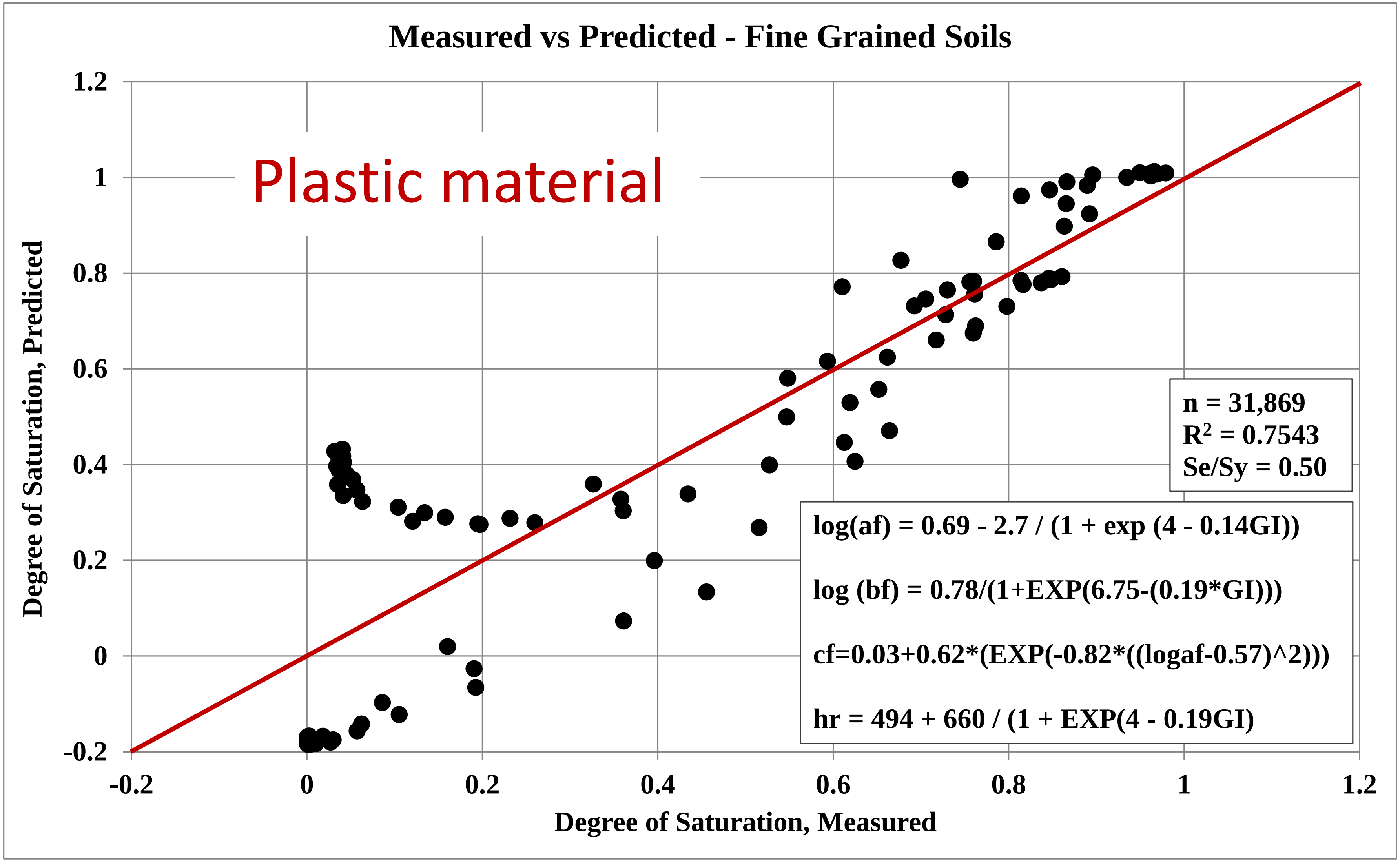
- Predictions of SWCC are based on:
  - Saturated soil properties
  - Grain size distribution
  - Soil index properties
    - Plasticity Index, *PI*

Estimating Suction based on Index Properties (Zapata, 1999)



New Model Available

Torres and Zapata, 2011

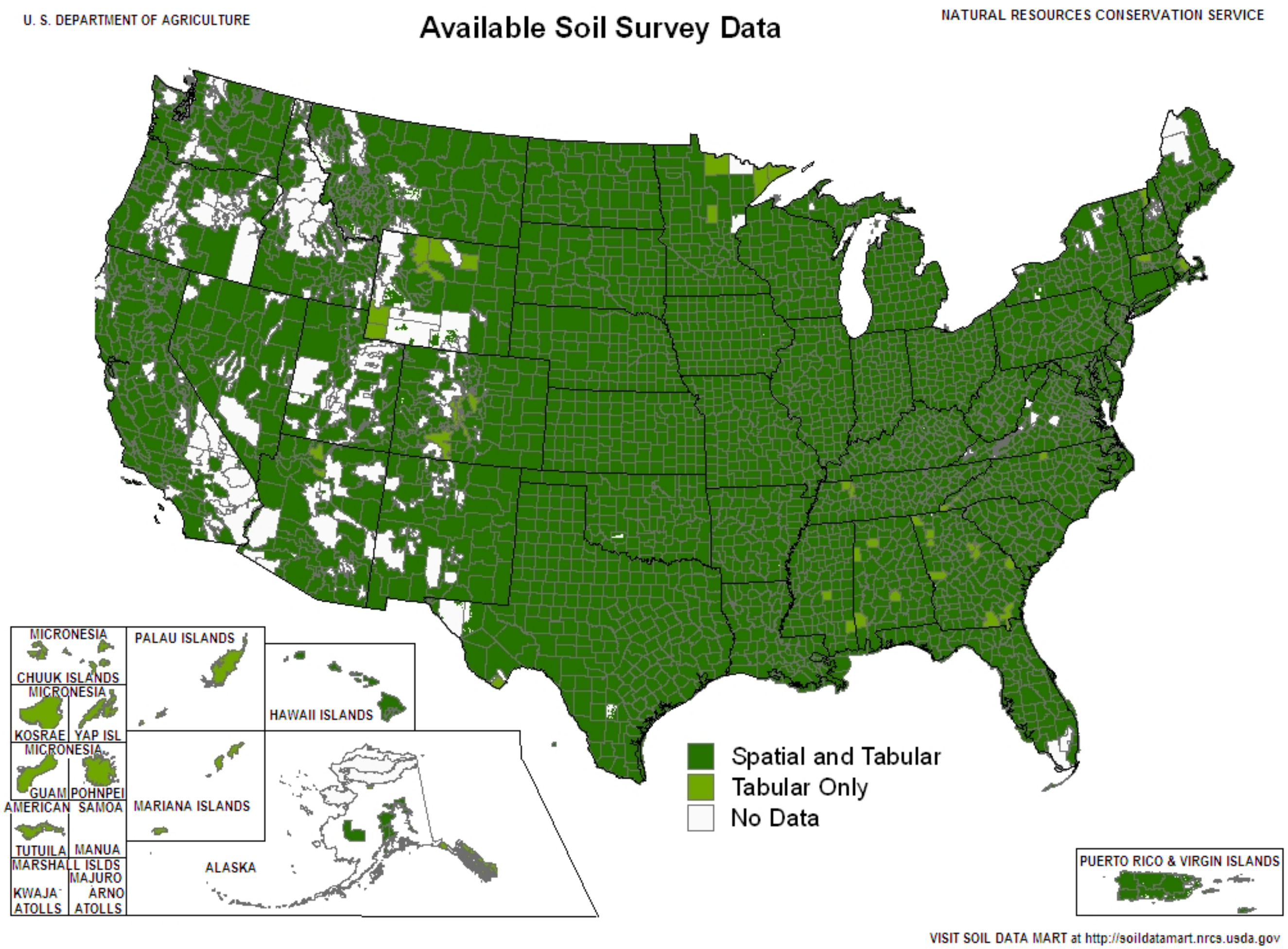


National catalogue for more than 31,000 soils

Origin of Database

- National Resources Conservation Service (NRCS) from the US Dept. of Agriculture (USDA) database
  - Initially intended for agricultural purposes
  - Key soil properties useful in highway/pavement engineering
  - Joint agreement with the then Bureau of Public Roads (BPR)
- Data is of public domain and available from the Soildatamart website
  - http://soildatamart.nrcs.usda.gov

Areas of Available Data



Properties Collected

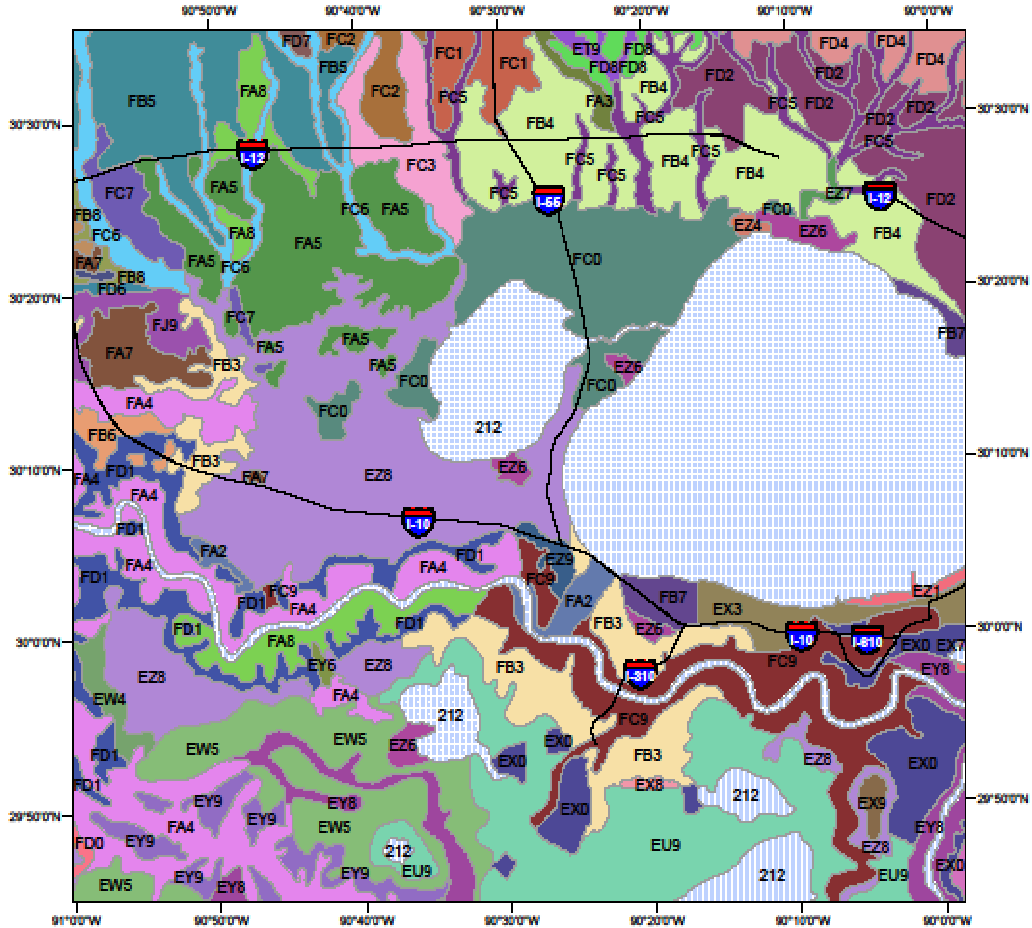
- Grain-size distribution (99%)
  - Passing #4, #10, #40, #200
  - Percentage of clay (> 0.002 mm) (4%)
- Atterberg limits
  - Liquid limit (88%)
  - Plasticity Index (99%)
- AASHTO soil classification (100%)
- Saturated hydraulic conductivity (100%)

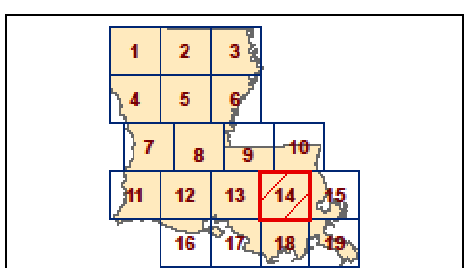
- Groundwater table depth
  - Annual average (32%)
  - Seasonal (29%)

Properties Estimated

- Enough data to estimate the Fredlund and Xing soil-water characteristic curve (SWCC) parameters (66%)
- AASHTO Group index
- CBR
  - From soil index properties
- Resilient modulus
  - From estimated CBR

Louisiana - Soil Unit Map 14





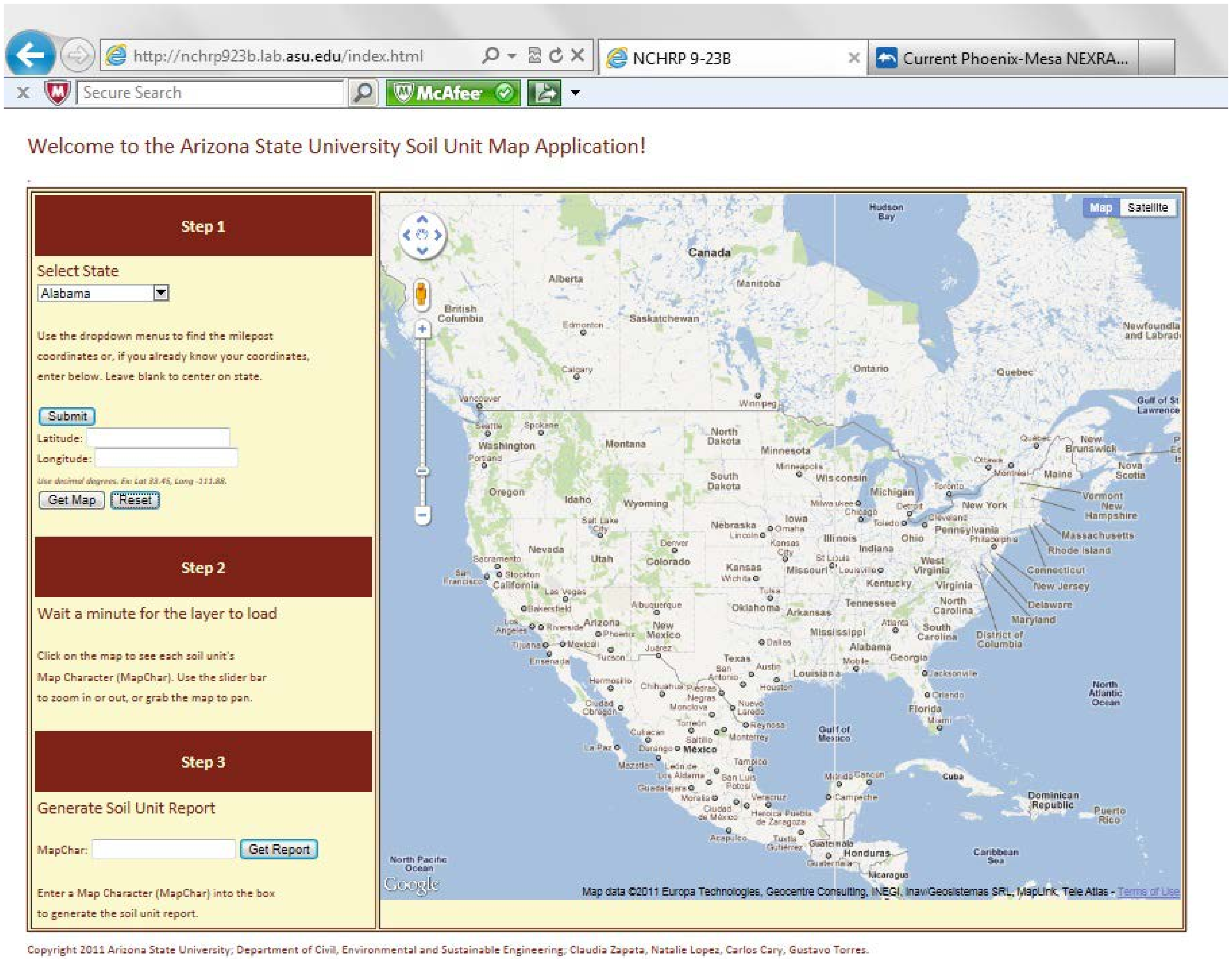
0 5 10 15 20 Miles

Created by: Natalie Lopez
Data by: Gustavo Torres, Claudia Zapata

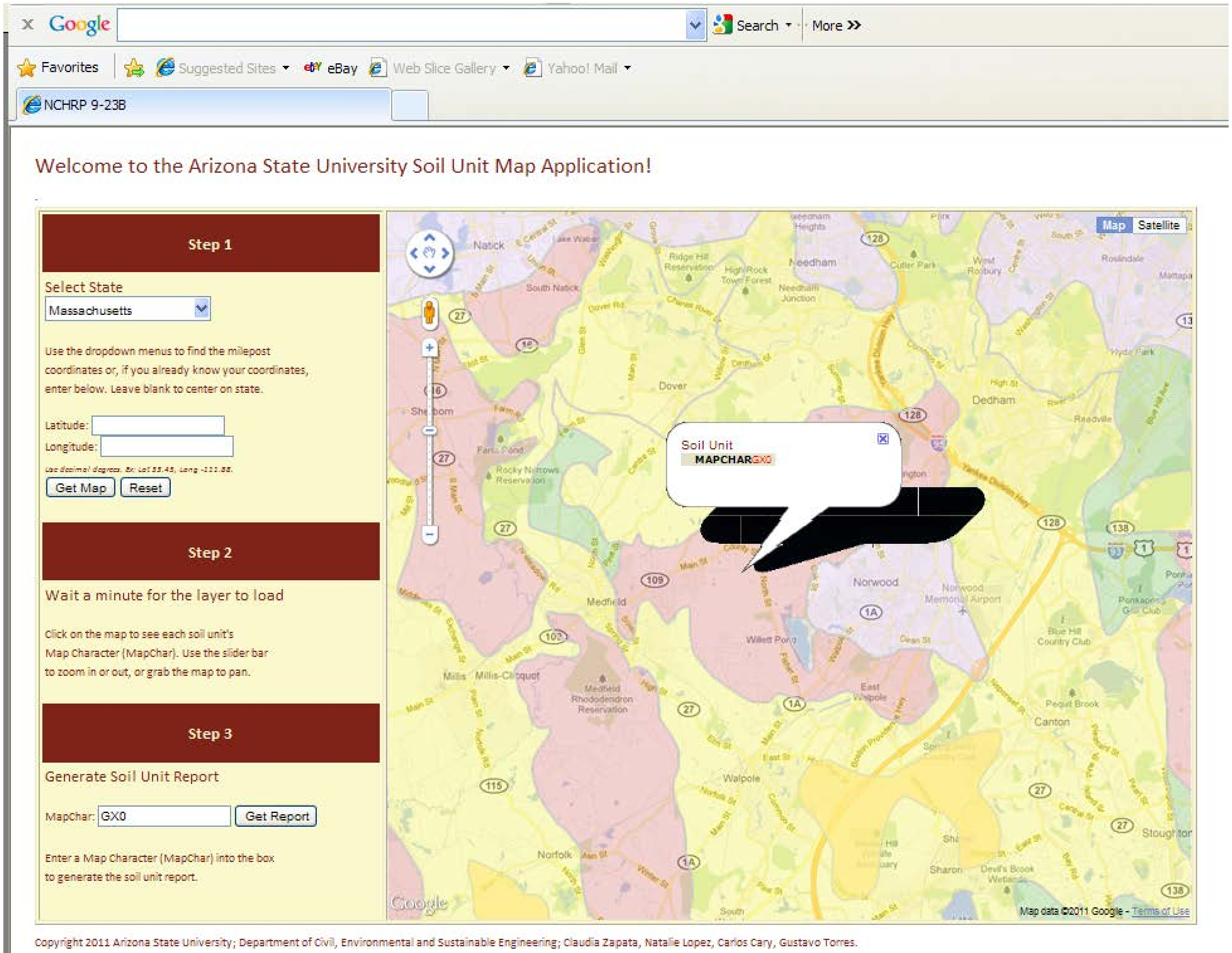
Date: 8/11/09
Projected Coordinate System: NAD 1983, State Plane, Louisiana North, FIPS 1701
Projection: Lambert Conformal Conic

This map was produced for the Department of Civil and Environmental Engineering at Arizona State University. Soil unit data was downloaded from the USDA NRCS. State boundaries and roads courtesy of the US Census.

Soil-Water Characteristic Parameters Database (NCHRP 923B Project)



Soil Units Available for the Whole USA



More Information Available

Integrating National Database of Subgrade Soil-Water Characteristic Curves and Soil Index Properties with Mechanistic-Empirical Pavement Design Guide
Claudia E. Zapata, Arizona State University
Carlos Ernesto Cary

Or

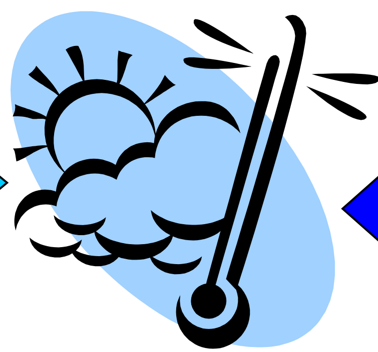
Zapata, C.E. (2010). *Research Results Digest 347: A National Catalog of Subgrade Soil-Water Characteristic Curves and Selected Soil Properties for Use with the MEPDG.* National Cooperative Highway Research Program, Transportation Research Board, of the National Academies. ISSN 0077-5614. ISBN: 978-0-309-09929-5. Library of Congress Control Number 2008924251. pp. 23.

part IId:
Environmental adjustment factors

How do we adjust the M_R due to environmental conditions?

Moisture Adjustments

Freeze / Thaw Adjustments



Environmental Factor

$$M_r = F_{env} \times M_{r_{opt}}$$

Stiffness Adjustment

Environmental Factor

Triaxial Test

Stiffness Value Used in LEA

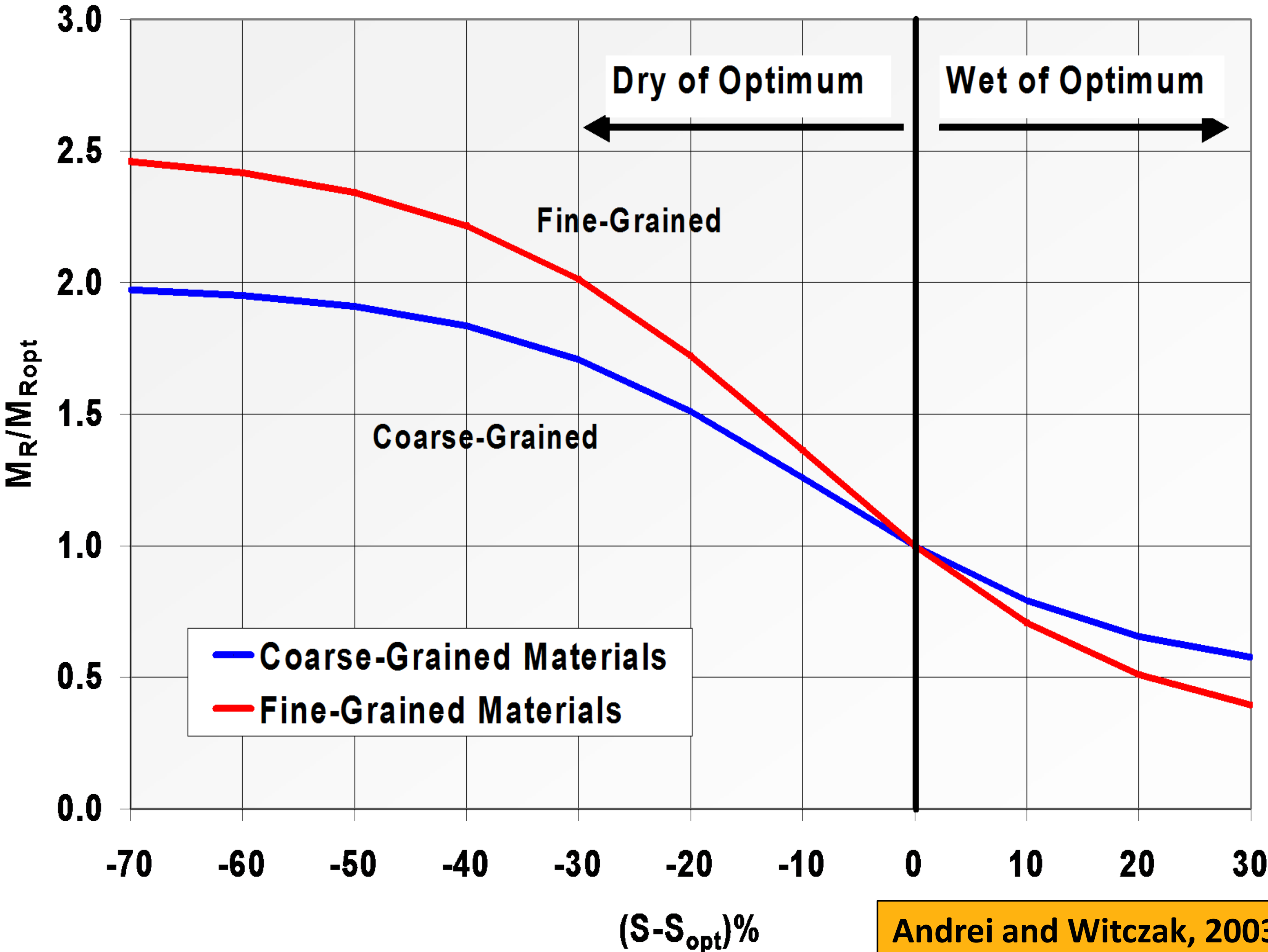
$$M_r = F_{env} \times M_{r\ opt}$$

EICM Model

Models by Andrei and Witczak, 2003

- **Normalize M_R, and S with respect to values at optimum and to plot *change* in M_R versus *change* in saturation**
- **Divide materials into:**
  - **Coarse-Grained and Fine-Grained**
- **Use sigmoid model form to fit the "data"**

Effect of Moisture on Modulus



Andrei and Witczak, 2003

M_R – Moisture Model

$$M_R = 10^{a + \frac{b-a}{1+EXP\left(\beta + k_m \cdot \left(S - S_{opt}\right)\right)}} \cdot M_{Ropt}$$

MOISTURE ADJUSTMENT FACTOR (F_U)

$M_R = F_U * M_{Ropt}$

M_R = Resilient Modulus at S

M_{Ropt} = Resilient modulus at S_{opt}

a, b, k_m = Regression parameters

$\beta = \ln_e(-b/a)$ from condition of (0,1) intercept

Resilient Modulus Adjustment Factor

F_{env}

$M_R = F_{env} \times M_{R\,opt}$

$$M_{R_{opt}} = k_1 \times p_a \times \left(\frac{\theta}{p_a} \right)^{k_2} \times \left(\frac{\tau_{oct}}{p_a} + 1 \right)^{k_3}$$

- **This form was implemented in the ME-PDG for "unfrozen" unbound materials**

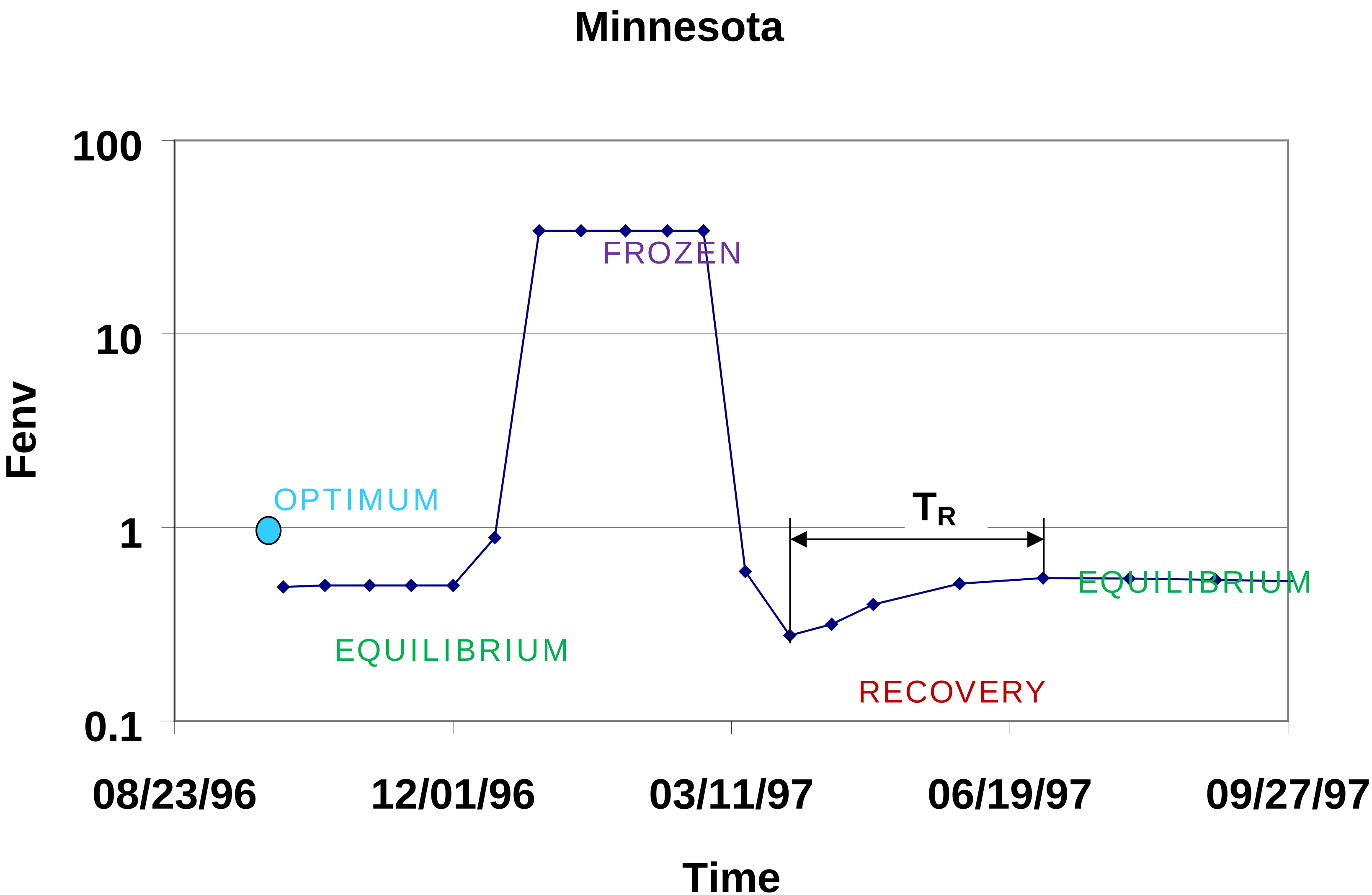
Freeze-Thaw Effects: Freezing

- **From Literature:**
  - M_R = 2,500,000 psi for non-plastic materials
  - M_R = 1,000,000 psi for plastic materials
- **Model Form:**
  - $M_R = F_F * M_{Ropt}$
- F_F = Adjustment factor for frozen materials

Freeze-Thaw Effects: Thawing

- **Modulus Reduction Factor**
  - **0.40 … 0.85 as a function of plasticity index and % fines (*wPI*)**
- **Recovery Period**
  - **90 … 150 days as a function of *wPI***
- **Model Form:**
  - $M_R = F_R * M_{Ropt}$
- **F_R = Adjustment factor for thawing (recovering) materials**

Example



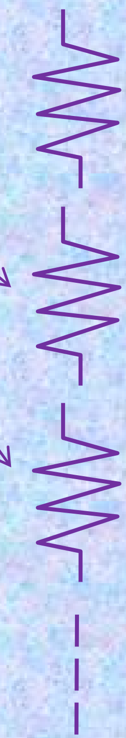
Minnesota
100
10
1
0.1
Fenv
OPTIMUM
FROZEN
EQUILIBRIUM
T R
EQUILIBRIUM
RECOVERY
08/23/96
12/01/96
03/11/97
06/19/97
09/27/97
Time

From NODE to LAYER …

Time (days)

Nodes	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Layer
1															AC
2															
3	F_F	F_F	F_F	F_F	F_F	F_F	F_F	F_F	F_R	F_R	F_R	F_R	F_R	F_R	BASE
4	F_F	F_F	F_F	F_F	F_F	F_F	F_F	F_F	F_R	F_R	F_R	F_R	F_R	F_R	
5	F_F	F_F	F_F	F_F	F_F	F_F	F_F	F_R	F_R	F_R	F_R	F_R	F_R	F_R	
6	F_F	F_F	F_F	F_F	F_F	F_F	F_F	F_R	F_R	F_R	F_R	F_R	F_R	F_R	
7	F_F	F_F	F_F	F_F	F_F	F_F	F_F	F_R	F_R	F_R	F_R	F_R	F_R	F_R	
8	F_F	F_F	F_F	F_F	F_F	F_F	F_F	F_R	F_R	F_R	F_R	F_R	F_R	F_R	
9	F_F	F_F	F_F	F_F	F_F	F_F	F_F	F_R	F_R	F_R	F_R	F_R	F_R	F_R	SUBBASE
10	F_F	F_F	F_F	F_F	F_F	F_F	F_F	F_R	F_R	F_R	F_R	F_R	F_R	F_R	
11	F_F	F_F	F_F	F_F	F_F	F_F	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	
12	F_F	F_F	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	
13	F_F	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	
14	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_U	F_U	F_U	
15	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_U	F_U	F_U	F_U	
16	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_R	F_U	F_U	F_U	F_U	F_U	F_U	
17	F_R	F_R	F_R	F_R	F_R	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	SUBGRADE
18	F_R	F_R	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	
19	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	
20	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	
21	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	
22	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	
23	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	
24	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	F_U	

SPRING ANALOGY



LEGEND:

- FROZEN
- RECOVERING
- UNFROZEN

F_{env} = Layer Adjustment Factor

Principle: Find F_{env} corresponding to an equivalent (composite) modulus that produces the same average displacement over the total thickness of the layer/sublayer for the considered analysis period (1 month or 2 weeks).

$$F_{env} = \frac{t_{total} \cdot h_{total}}{\sum_{t=1}^{t_{total}} \left(\sum_{node=1}^{n} \left(\frac{h_{node}}{F_{node,time}} \right) \right)}$$

- h_{node} = Length between mid-point nodes
- h_{total} = Total height of the considered layer/sublayer
- t_{total} = The desired time period (either a two-week period or a month period)
- $F_{node,t}$ = Adjustment factor at a given node and time increment which could be F_F, F_R, or F_U

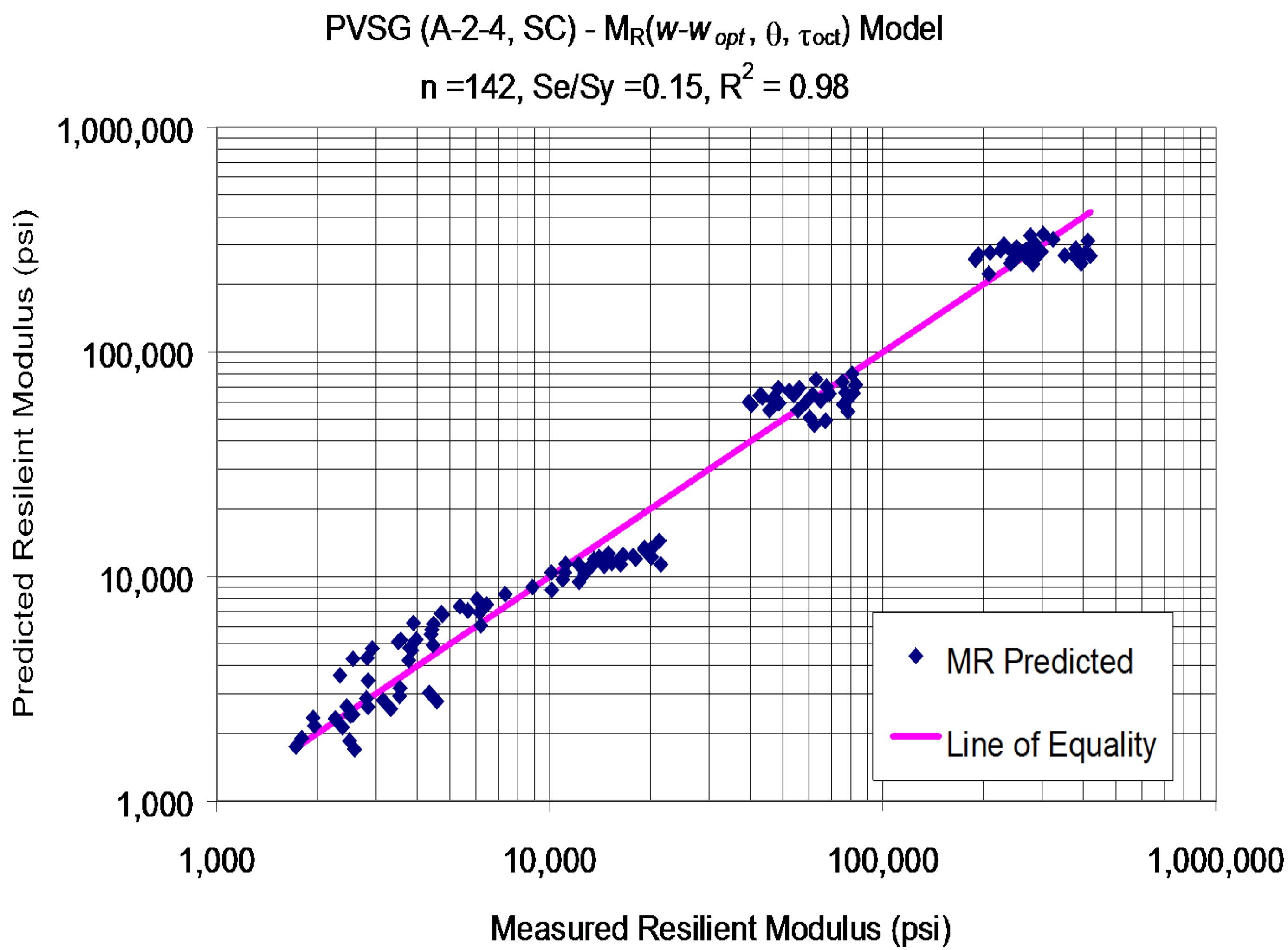
F_{env} Calculation Example

	Time (days)														
Nodes	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	
3	50	50	50	50	50	50	50	50	0.7	0.7	0.7	0.7	0.7	0.7	BASE
4	50	50	50	50	50	50	50	50	0.7	0.7	0.7	0.7	0.7	0.7	F_{env} = 1.45
5	50	50	50	50	50	50	50	0.7	0.7	0.7	0.7	0.7	0.7	0.7	
6	50	50	50	50	50	50	50	0.7	0.7	0.7	0.7	0.7	0.7	0.7	
7	50	50	50	50	50	50	50	0.7	0.7	0.7	0.7	0.7	0.7	0.7	
8	50	50	50	50	50	50	50	0.7	0.7	0.7	0.7	0.7	0.7	0.7	
9	75	75	75	75	75	75	75	0.6	0.6	0.6	0.6	0.6	0.6	0.6	SUBBASE
10	75	75	75	75	75	75	75	0.6	0.6	0.6	0.6	0.6	0.6	0.6	F_{env} = 0.92
11	75	75	75	75	75	75	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.7	
12	75	75	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.7	
13	75	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.7	
14	0.8	0.8	0.8	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	1	1	1	
15	0.8	0.8	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	1	1	1	1	
16	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	1	1	1	1	1	1	

LEGEND:

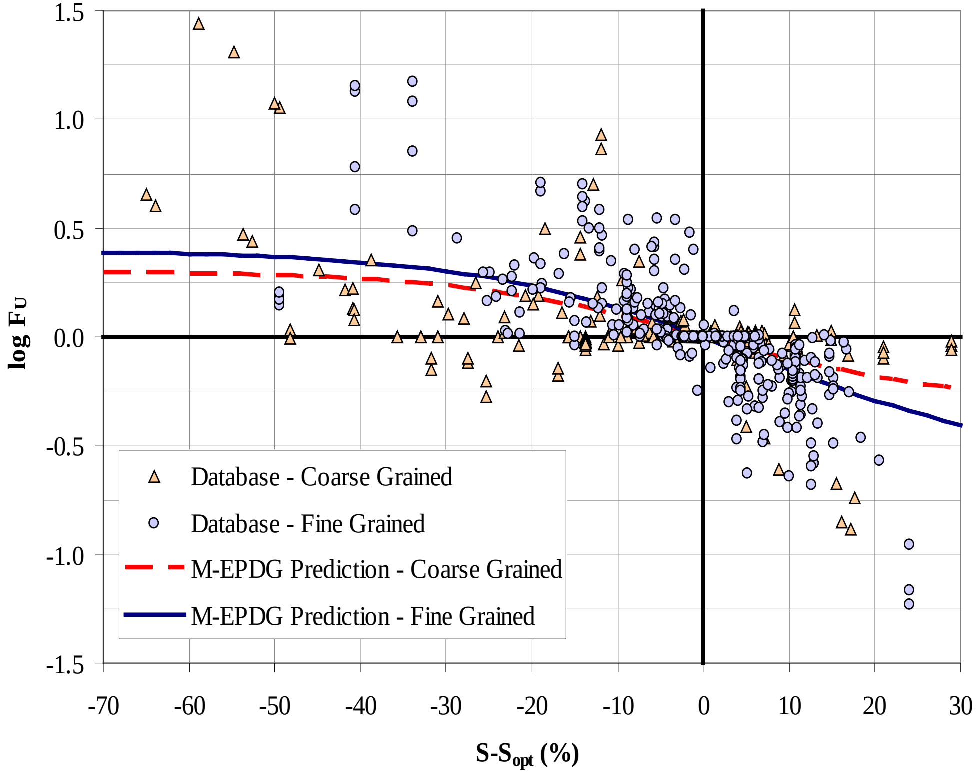
- FROZEN
- RECOVERING
- UNFROZEN

Goodness of Fit
Phoenix Valley Subgrade



part IIe: an improved environmental adjustment model

More data collected indicated…



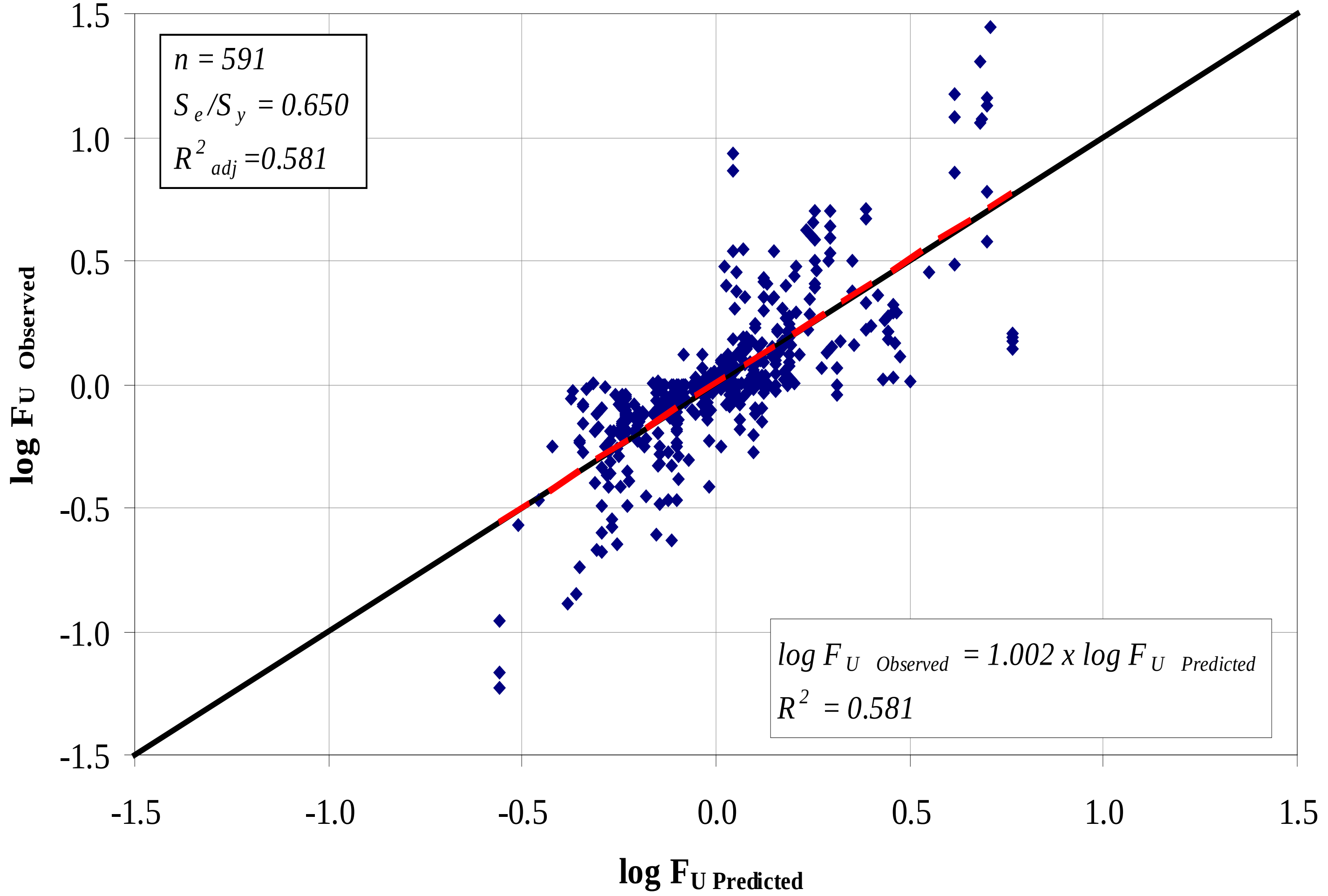
$$\log F_U = a + \frac{b-a}{1+e^{\left(\ln\frac{-b}{a}+k_m\cdot\left(S-S_{opt}\right)\right)}}$$

- *EICM* → $F_U = M_R / M_{Ropt}$
- $a = \min F_U$
- $b = \max F_U$
- k_m = slope
- **F_U conservatively predicted**
- **F_U for fine grained materials underestimated at dry conditions**

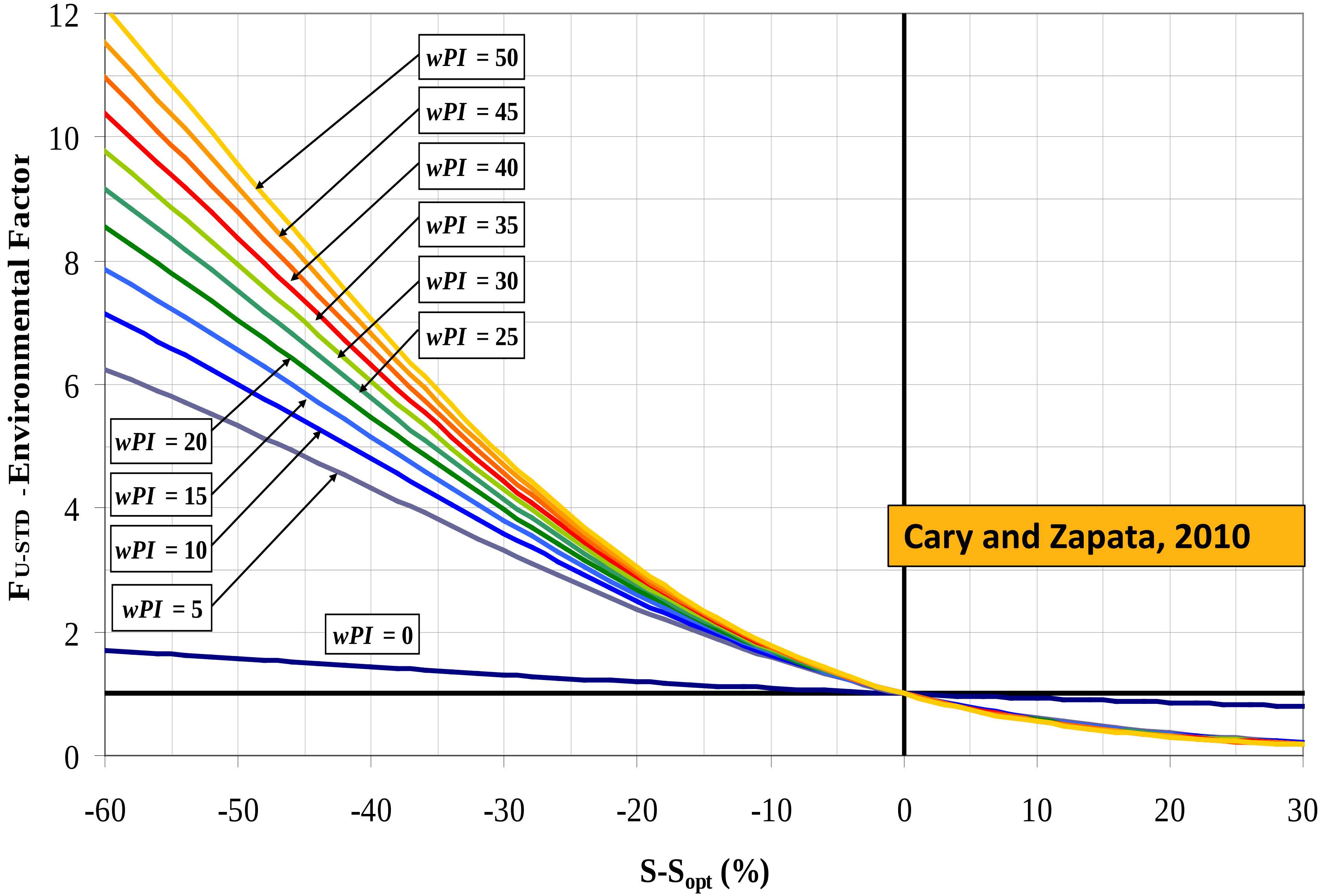
New Model as Function of Soil Type (Cary and Zapata, 2010)

$$\log F_U = \left(\alpha + \beta \cdot e^{-wPI}\right)^{-1} + \frac{(\delta + \gamma \cdot wPI^{0.5}) - (\alpha + \beta . e^{-wPI})^{-1}}{1 + e^{\left(\ln\left(\frac{-\left(\delta + \gamma \cdot wPI^{0.5}\right)}{\left(\alpha + \beta . e^{-wPI}\right)^{-1}} \right) + \left(\rho + \omega \cdot e^{-wPI}\right)^{0.5} \cdot \left(\frac{S - Sopt}{100} \right) \right)}}$$

Proposed Model as Function of Soil Type



Proposed Model as Function of Soil Type



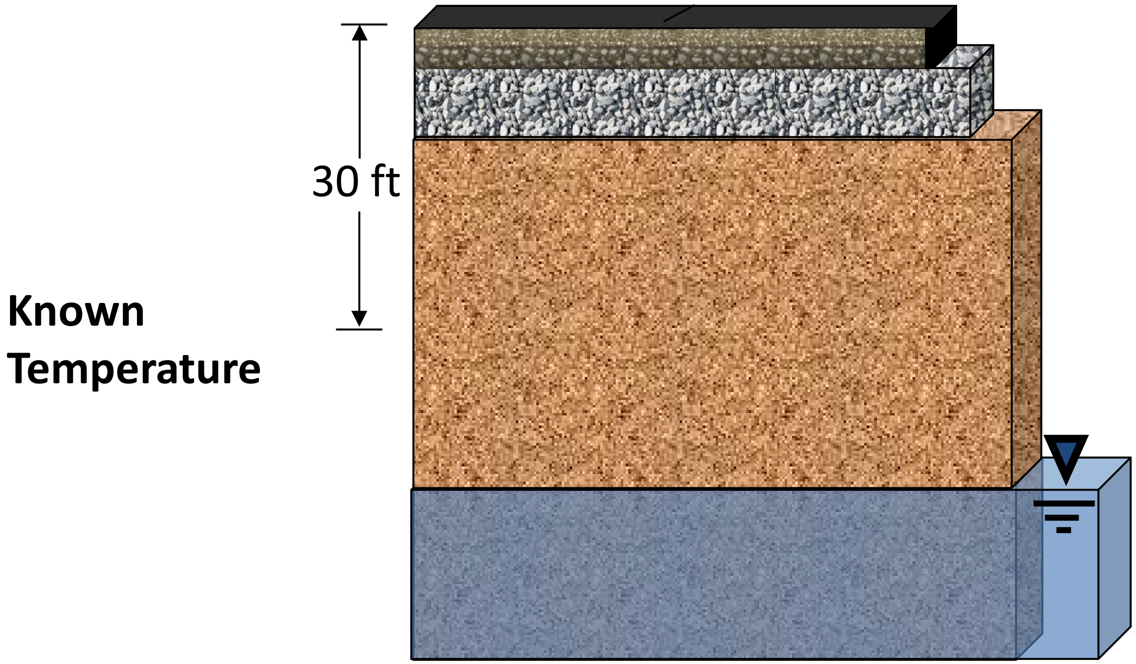
Conclusions

- A database comprising 96 soil types aimed at the enhancement of the environmental effects on Mr was developed.
- Current M-EPDG model predicts conservative estimates of the F_U, especially for plastic materials on the drier state
- Stress state level effects on F_U predictions were found to be no significant for the data collected
- Data for compaction energy effect evaluation (upon F_U) for subgrade material is hard to get and therefore, the model does not account for compaction effort for these materials
- The evaluation performed on granular materials was based on preliminary findings by Rada (1981)

part III: temperature effects

Temperature

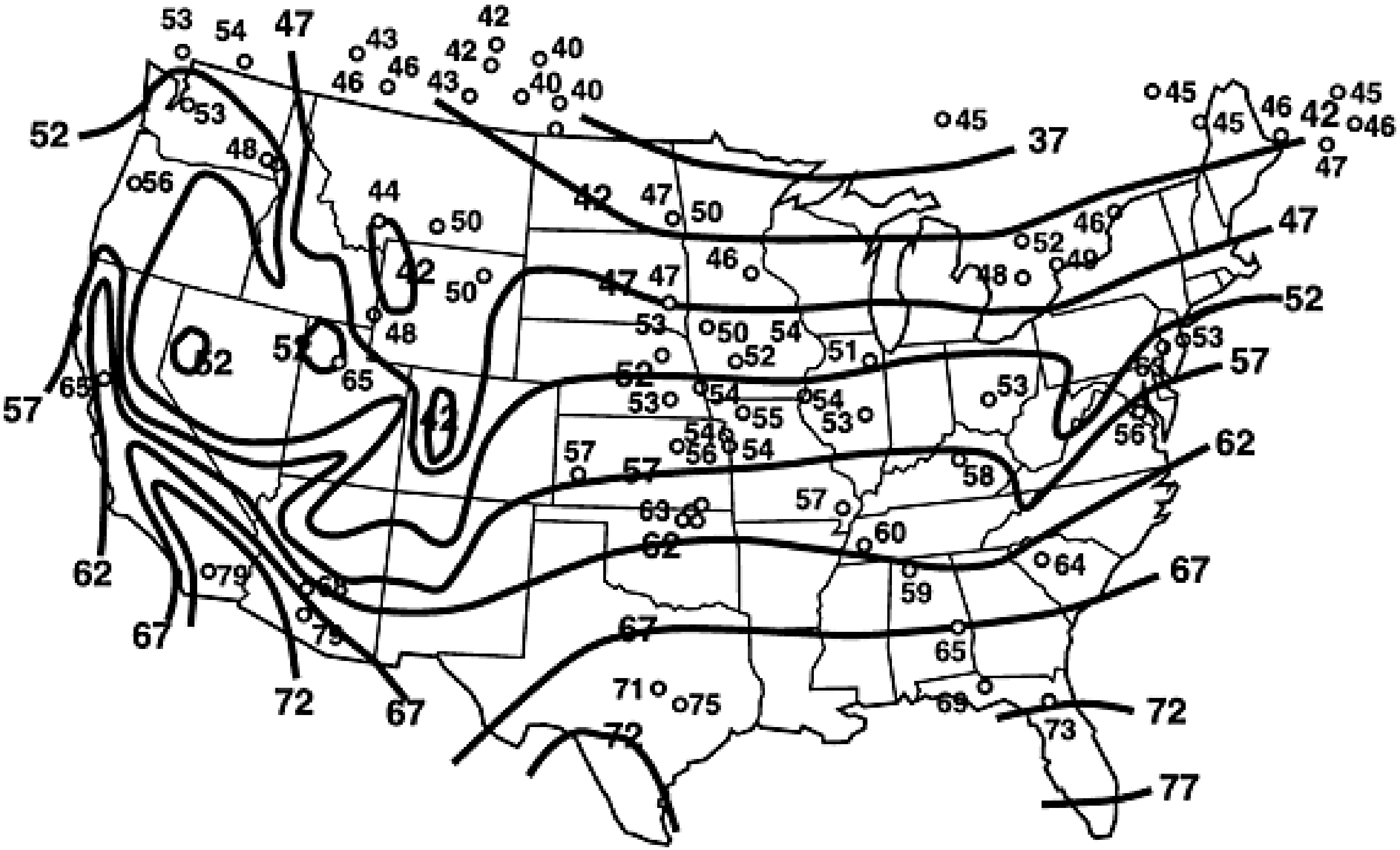
Boundary Conditions



Ground Temperature below 30' = MAAT

Temperature

Boundary Conditions



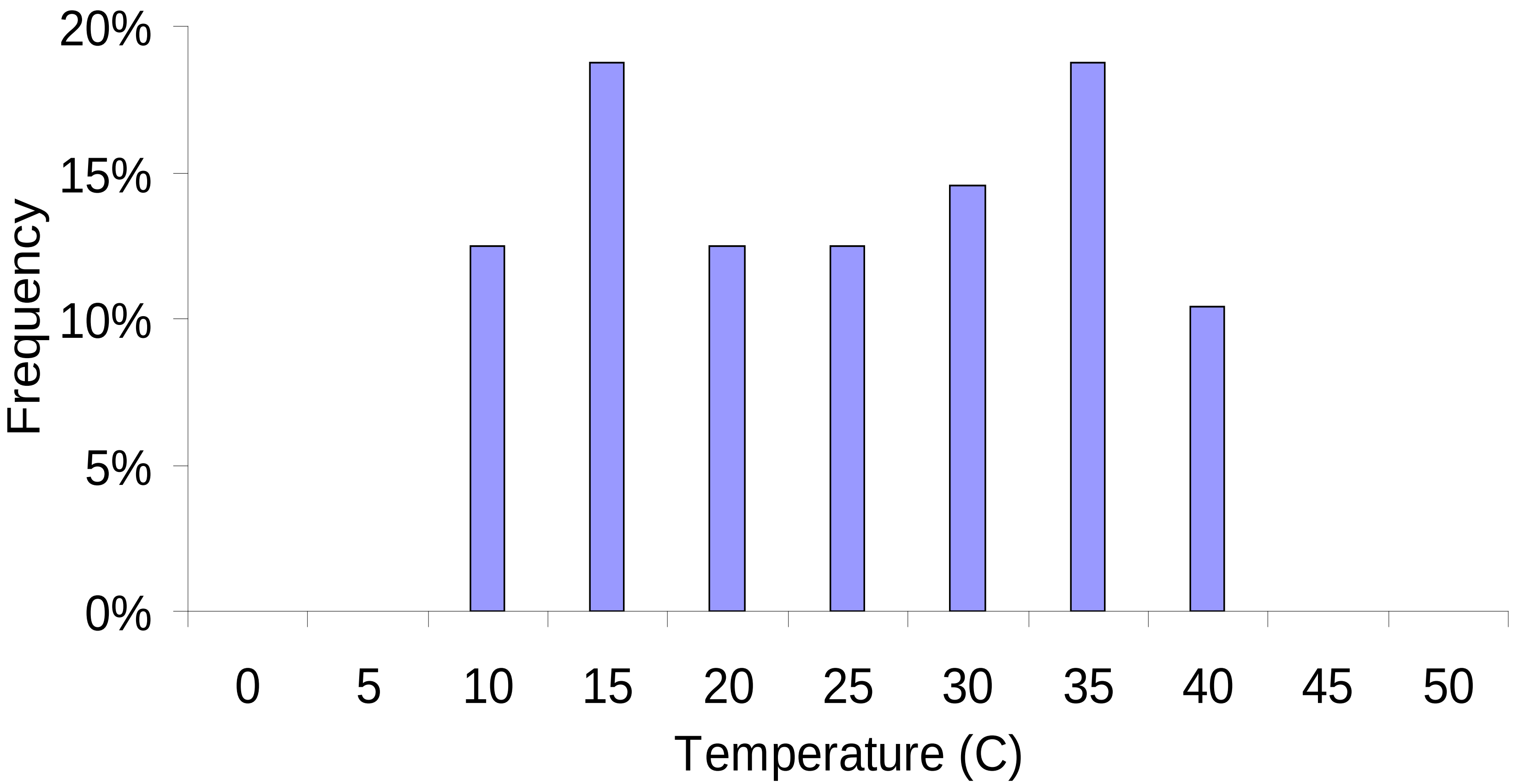
Isogeothermal Map: United States

FHWA-RD-90-033: Figure 8

Temperature Averaging

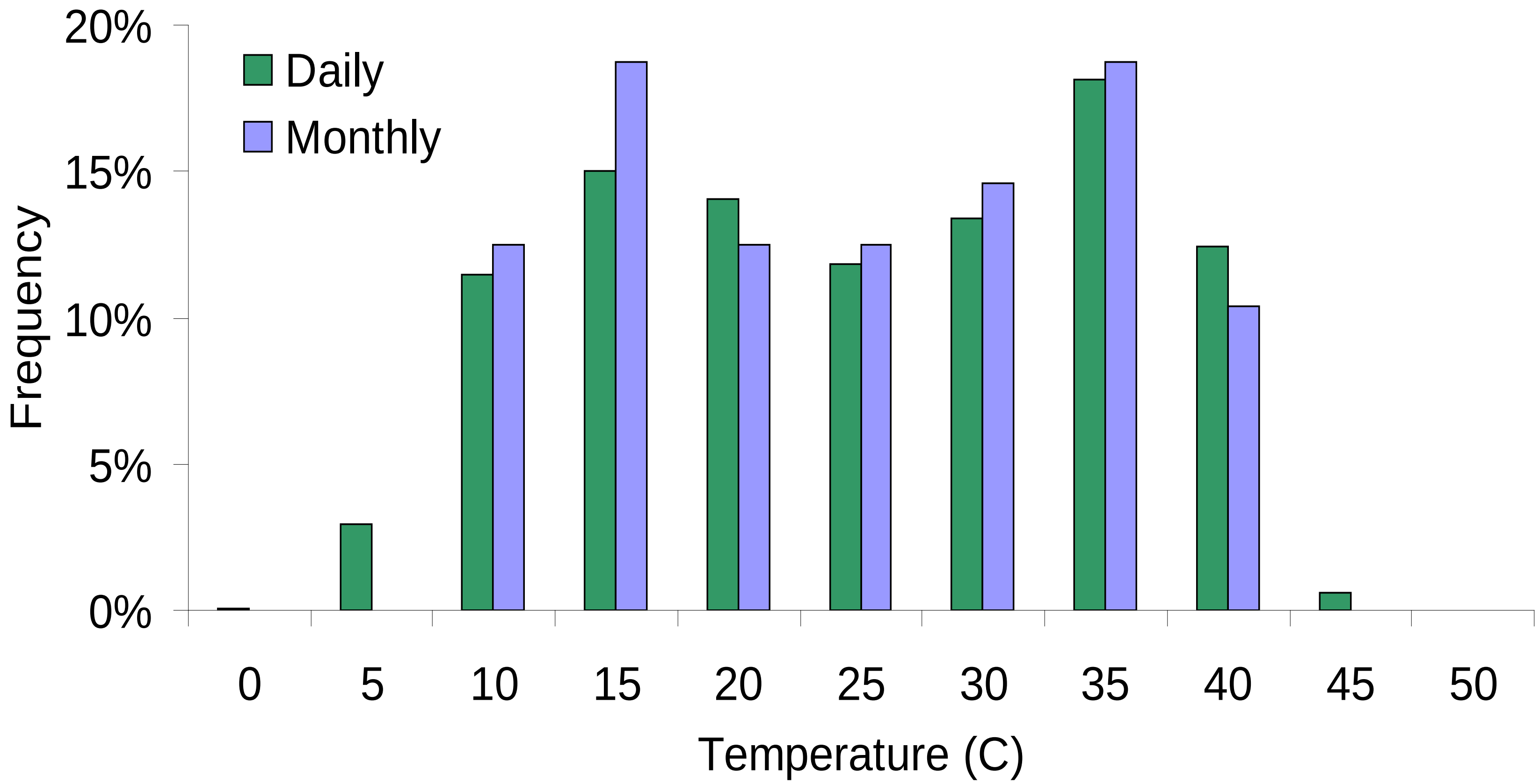
- AC stiffness varies with temperature
- AC stiffness affects the stiffness of underlying stress-dependent materials
- Pavement life estimates are based on the pavement stiffness and so can vary widely depending on AC temperature used in the analysis

Temperature Averaging: Monthly Data



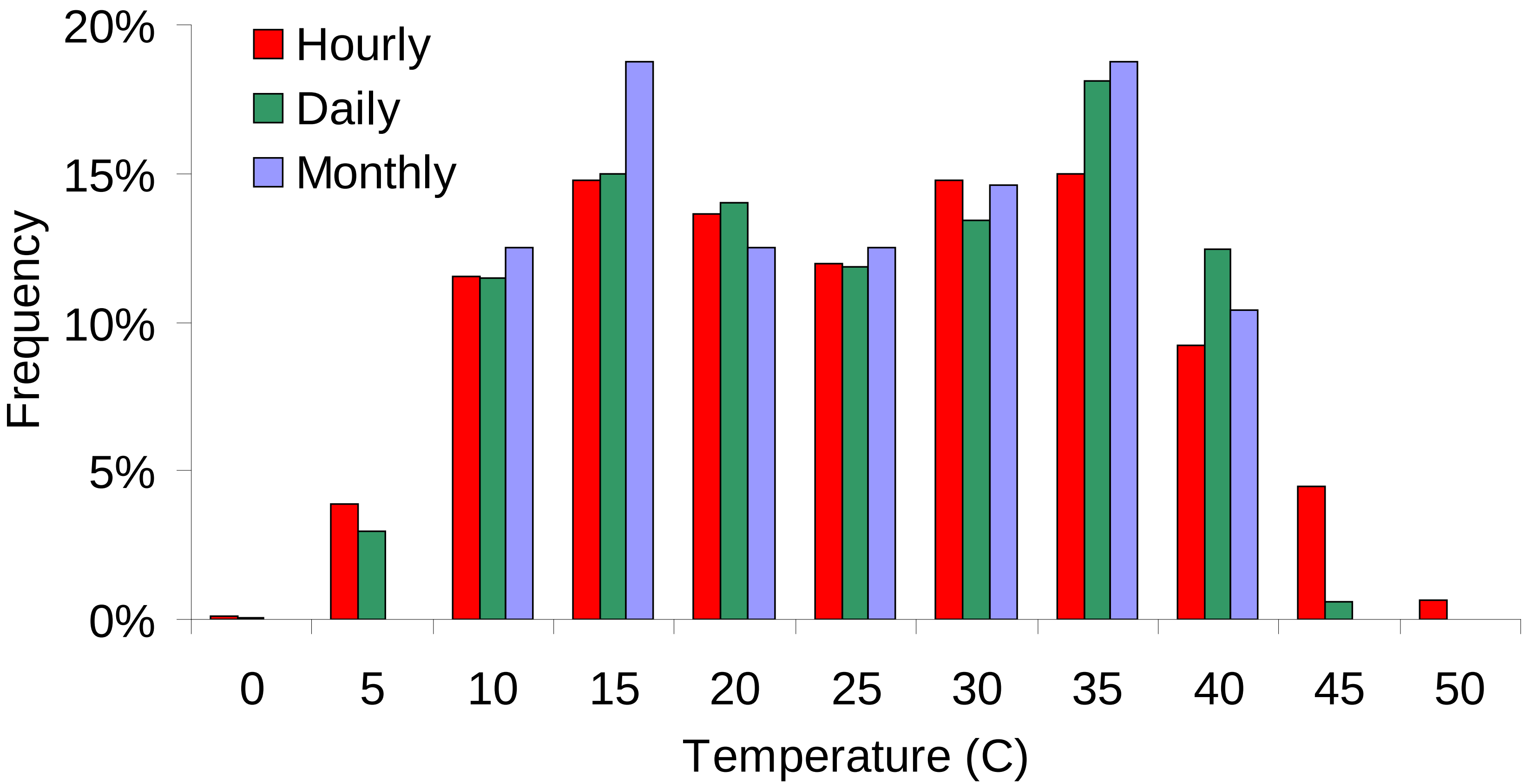
Temperature Averaging:

Monthly and Daily Data



Temperature Averaging:

Monthly, Daily, & Hourly Data



Temperature Averaging

- **What is the effect of the temperature averaging interval on computed design life if we assume a uniform distribution of traffic throughout the day?**

Temperature Averaging (Drumm)

Subgrade Stiffness	Pavement Life Overestimation Using Uniform Traffic and ...		
	Hourly Average Temps	Daily Average Temps	Monthly Average Temps
Very soft	11%		
Soft	10%		
Medium	10%		
Stiff	9%		

Temperature Averaging

Subgrade Stiffness	Pavement Life Overestimation Using Uniform Traffic and ...		
	Hourly Average Temps	Daily Average Temps	Monthly Average Temps
Very soft	11%	58%	
Soft	10%	54%	
Medium	10%	47%	
Stiff	9%	39%	

Temperature Averaging

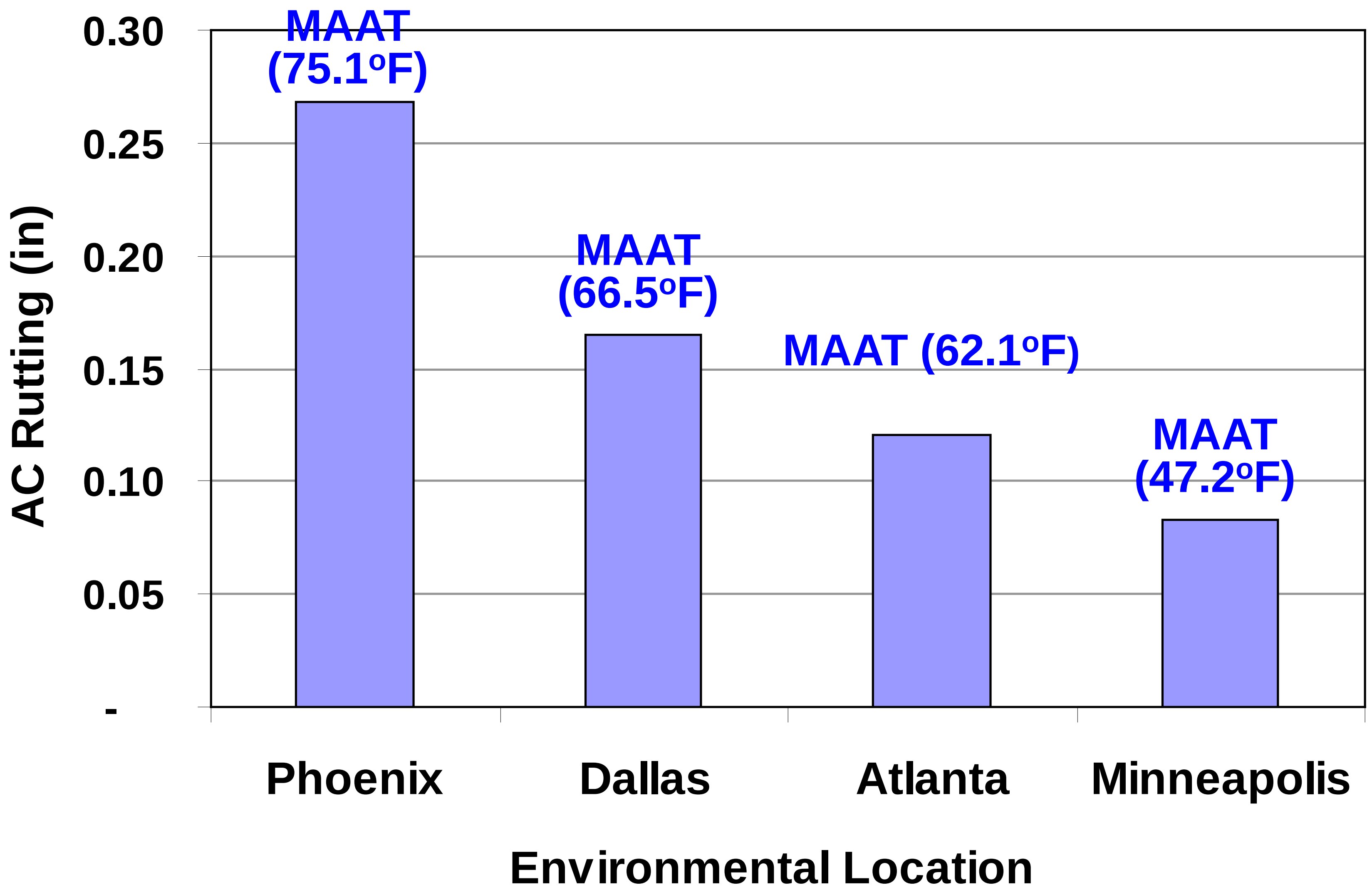
Subgrade Stiffness	Pavement Life Overestimation Using Uniform Traffic and ...		
	Hourly Average Temps	Daily Average Temps	Monthly Average Temps
Very soft	**11%**	**58%**	**76%**
Soft	**10%**	**54%**	**71%**
Medium	**10%**	**47%**	**62%**
Stiff	**9%**	**39%**	**52%**

part IV:
environmental effect in pavement life

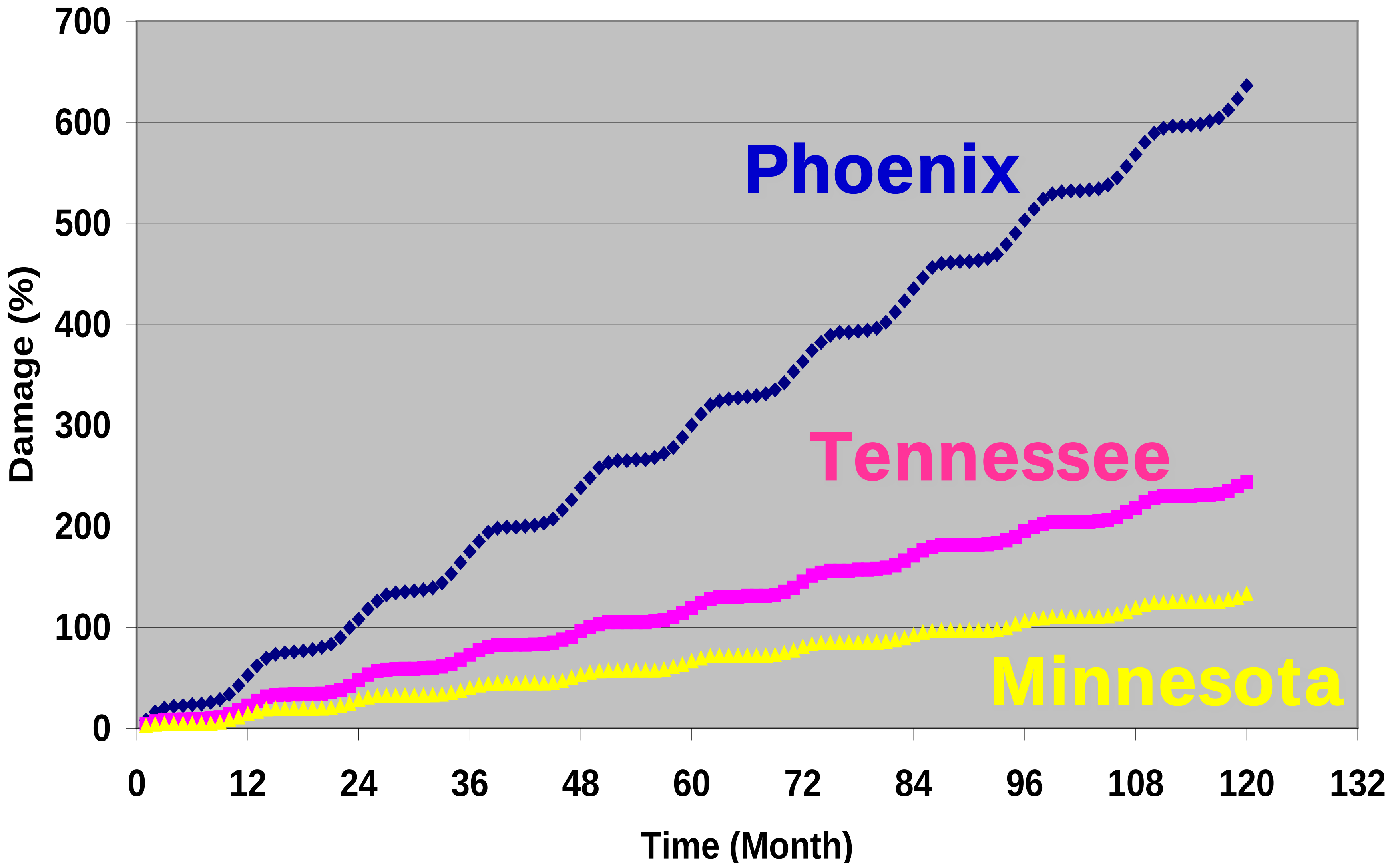
Environmental effect in pavement life

Environment effect in pavement life can be measured by the sensitivity of pavement distresses to environmental factors

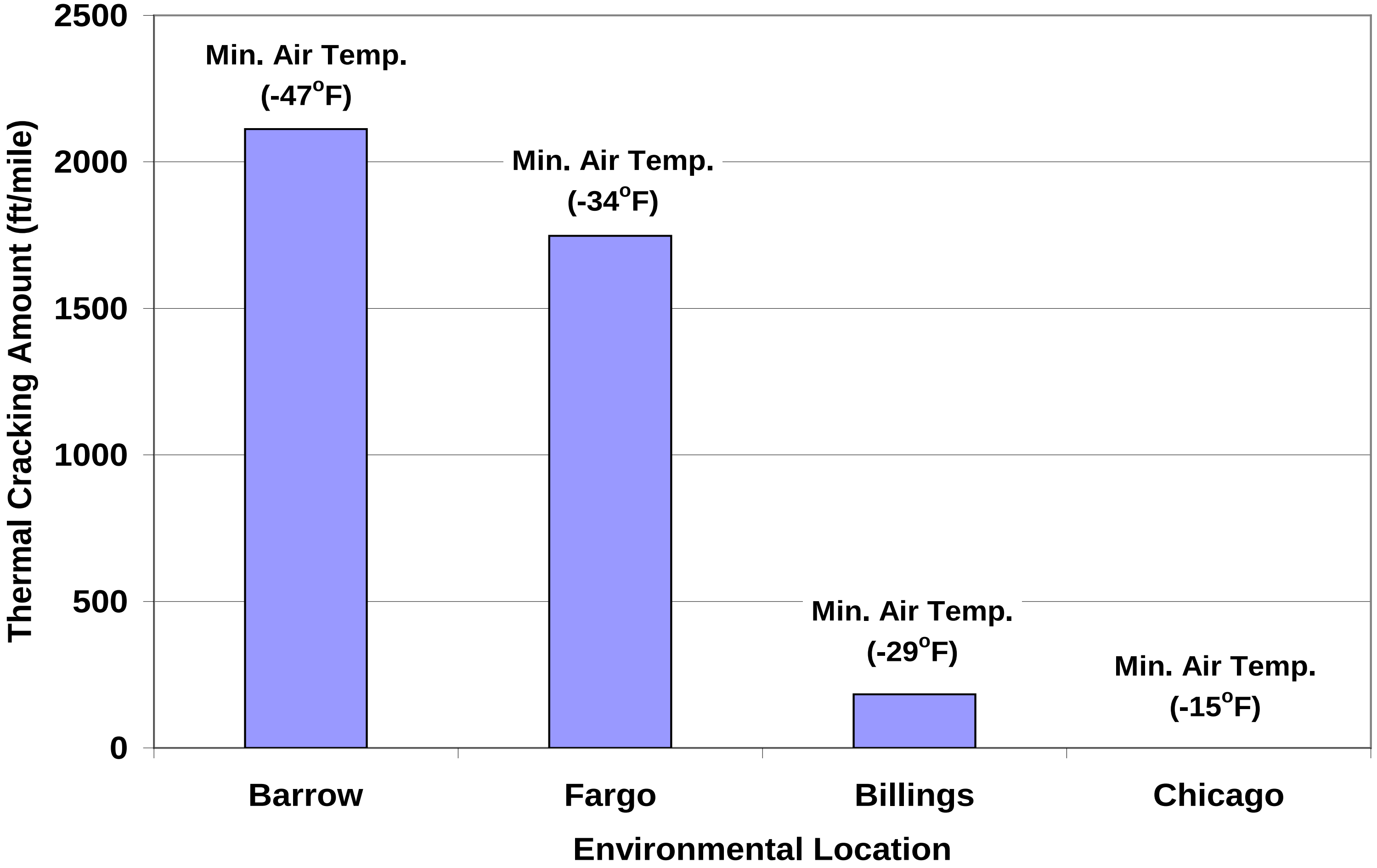
EFFECT OF ENVIRONMENTAL LOCATION (CLIMATE) UPON AC RUTTING



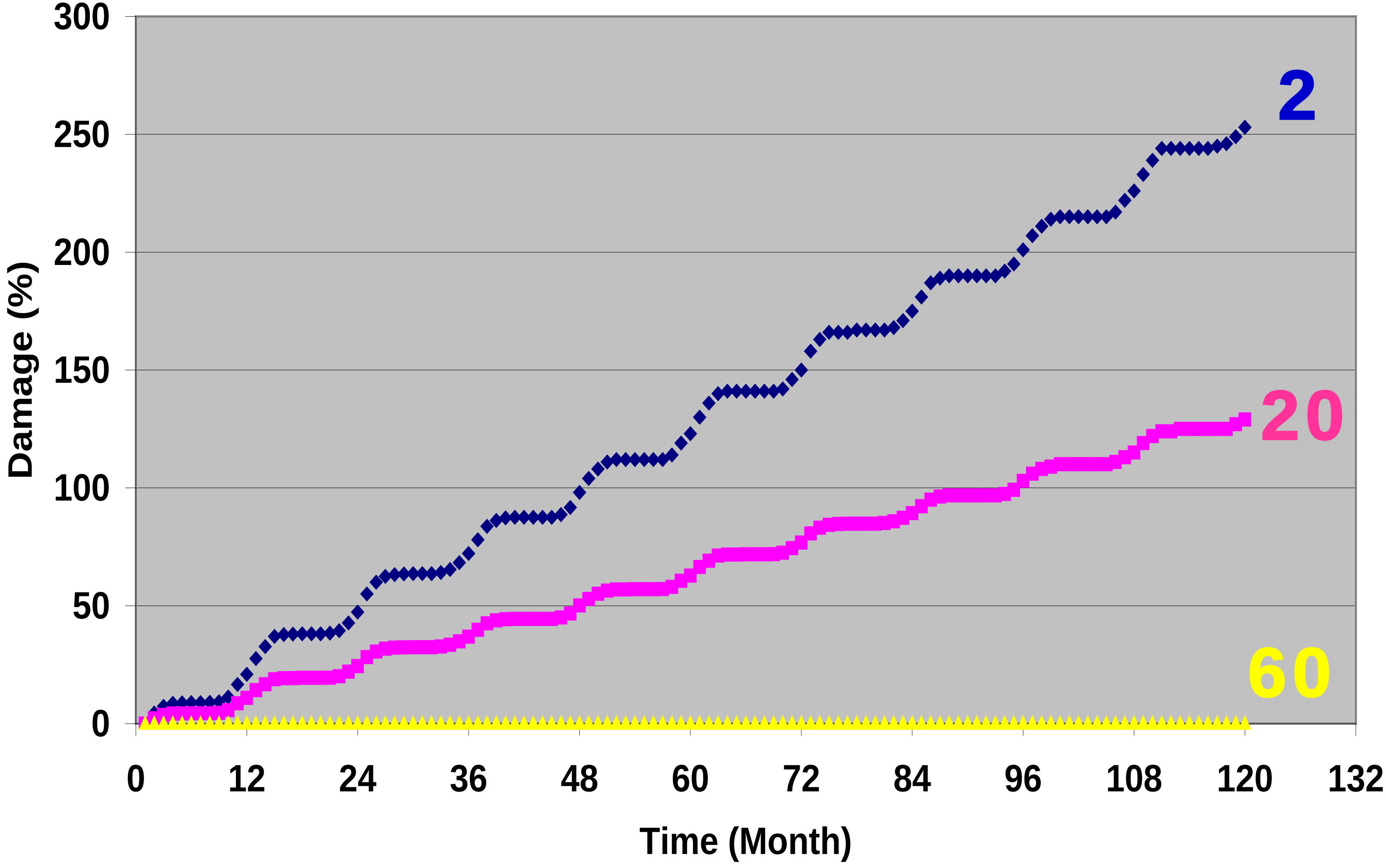
Effect of Climate on Cracking



EFFECT OF ENVIRONMENTAL LOCATION (CLIMATE) UPON AC THERMAL FRACTURE



Effect of Ground Water Table on Cracking



Depth to Ground Water Table, ft.

part V: drainage considerations

Effect moisture has on the characteristics of unbound road building material

All the research shows clearly that the bearing capacity of unbound granular materials (M_R and deformation properties) are affected by changes in the moisture content.

Effect moisture has on the characteristics of unbound road building material

- For coarse graded soils this effect is less significant.
- For dense graded materials and materials with a high content of fines the characteristics can change considerably.

Subsurface drainage systems are used for three basic reasons:

- **To lower the groundwater level**
- **To intercept lateral flow of subsurface water beneath the pavement structure**
- **To remove the water that infiltrates the pavement’s surface**

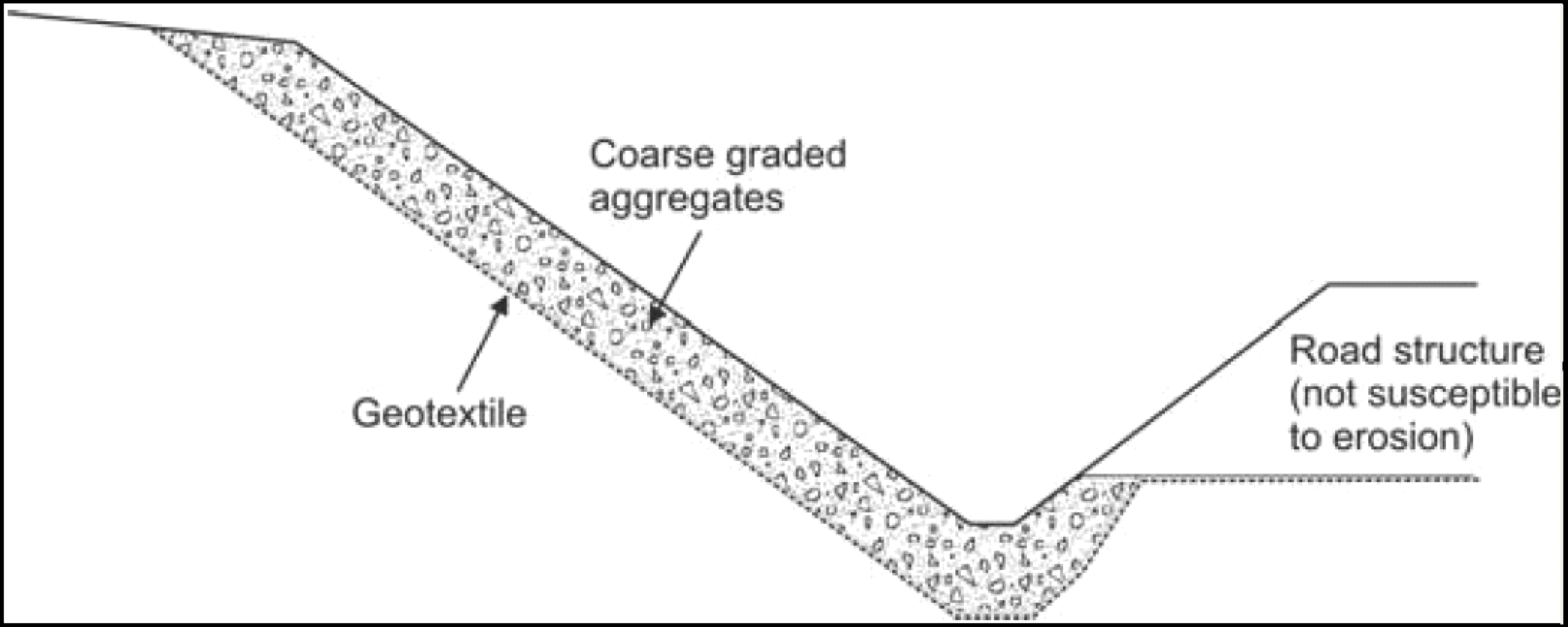
Typical drainage problems

- The biggest problems are in road sections located on sloping hills.

Berntsen and Saarenketo, 2005

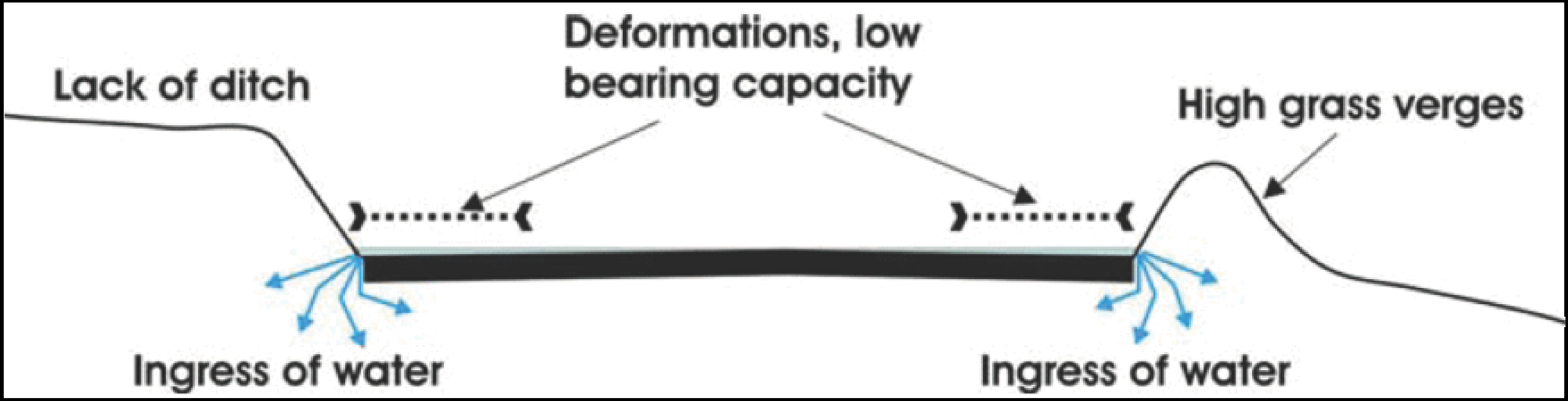
Protecting ditch slopes

- Stops falling of material into ditch
- Aids clearance.



Roads must have a ditch

- If ditch missing, pavement will be damaged



Typical drainage problems and proposed solutions

- Handout extracted from "DRAINAGE ON LOW TRAFFIC VOLUME ROADS" from Berntsen and Saarenketo, Norwegian Public Roads Administration, 2005

Modeling drainage benefit

- Berntsen & Saarenketo (2005)

$$N = a\left(\frac{1}{\varepsilon_v}\right)^b$$

- Hence, they reasoned

$$\frac{N_{undrained}}{N_{drained}} = a\left(\frac{1}{\varepsilon_{v-undrained}}\right)^b \Big/ a\left(\frac{1}{\varepsilon_{v-drained}}\right)^b = \left(\frac{\varepsilon_{v-drained}}{\varepsilon_{v-undrained}}\right)^b$$

- ε_v can be computed from any stress/strain analysis program
- Improvement easily computed

Maintaining and improving the drainage system is perhaps the most cost effective measure on paved fields where inadequate drainage is the main cause of deterioration.

part VI: gracias!