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Case Studies of Problematic Expansive Soils: Characterization Challenges, Innovative Stabilization Designs, and Novel Monitoring Methods

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2020 Ralph B. Peck Lecture Geo-Congress 2020

Case Studies on Problematic Soils: Characterization Challenges, Innovative Solutions, and Novel Monitoring Methods

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Texas A & M University, College Station, Texas, USA &
Former Distinguished University Professor of Civil Engineering, The University of Texas at Arlington

Abbett Distinguished Seminar, June 2, 2021
Center for Intelligent Infrastructure
Missouri University of Science and Technology

Meeting Prof. Peck

Prof. Ralph B. Peck at ADSC Professor Training Class, Fort Collins, Colorado, 2000

Prof. Ralph B. Peck at ASCE Geo Congress 2007, Denver, Colorado, (February 18-21, 2007)

Introduction to the 21st Ralph B. Peck Award Lecture

Rodrigo Salgado, Ph.D., F.ASCE[1]

Abstract: Dr. Anand Puppala delivered the 21st Ralph B. Peck Award Lecture on February 28, 2020, at the ASCE GeoCongress event held in Minneapolis, Minnesota. This introduction briefly reviews Dr. Puppala's contributions to geotechnical engineering and discusses some of the highlights of the corresponding paper. **DOI: 10.1061/(ASCE)GT.1943-5606.0002519.** *© 2021 American Society of Civil Engineers.*

Dr. Anand Puppala delivered the 21st Ralph B. Peck Award Lecture on February 28, 2020, at the ASCE GeoCongress event held in Minneapolis, Minnesota. The conference was sponsored by the ASCE Geo-Institute. Dr. Puppala submitted the corresponding paper for publication in the ASCE *Journal of Geotechnical and Geoenvironmental Engineering*, and we are delighted to see to its publication together with this brief introduction.

Dr. Anand Puppala is presently the A. P. Wiley and Florence Chair of Zachry Civil and Environmental Engineering department at Texas A&M University (TAMU) and is also an Associate Director of the Center for Infrastructure Renewal (CIR). Before joining TAMU, he also served as Associate Dean for Research and was a Distinguished Scholar Professor in the Civil Engineering Department at the University of Texas at Arlington (UTA). Dr. Puppala received his bachelor's and master's in Civil Engineering from Andhra University and Indian Institute of Technology, Madras, and his Ph.D. in Civil Engineering from Louisiana State University, Baton Rouge, under the supervision of Professor Mehmet Tumay and the late Professor Yalcin Acar.

Dr. Puppala has taken on several leadership roles in geotechnical engineering, including serving as President of the United States Universities Council on Geotechnical Education and Research (USUCGER) from 2007 to 2009, Chair of the Soil Mechanics section (AFS00) of the Transportation Research Board (TRB) from 2014 to 2020, and Co-Chair of the newly formed Geology and Geotechnical Engineering section, also at TRB. He has participated consistently and extensively in ASCE technical committee activities.

Dr. Puppala's research has included topics in transportation geotechnics such as stabilization of expansive soils, the use of unmanned aerial vehicles (UAVs) for transportation infrastructure monitoring and infrastructure surveying, and asset management studies. He has also done research on dam and embankment slope treatment studies, in situ intrusive methods for site characterization and visualization, and infrastructure resilience, among others topics. Dr. Puppala has been a recipient of many research grants from federal, state, and local government agencies and industries and he serves as director of the National Science Foundation's (NSF's) Industry University Cooperative Research Center Site on Composites in Civil Infrastructure (CICI) at TAMU, College Station, Texas, with a focus on geosynthetics and polymer additive treatment studies.

Dr. Puppala has published more than 450 papers, over 200 of which in journals. He has supervised 35 doctoral and 52 master's thesis students and is currently advising several doctoral students. Dr. Puppala is an editorial member of the ASCE *Journal of Geotechnical and Geoenvironmental Engineering* and several others. He is a registered professional engineer in Louisiana, an ASCE Fellow and Institute of Civil Engineers (UK) Fellow, and a Diplomate of the ASCE Academy of Geo-Professionals. Dr. Puppala received many awards including the 2019 Fredlund Paper Award from the *Canadian Geotechnical Journal*, 2013 UTA Distinguished Researcher award, 2010 UT System's Regents Teaching Award, and 2017 TRB Best Paper Awards in Geotechnical and Geoenvironmental Engineering sections.

Dr. Puppala's paper, "Performance Evaluation of Infrastructure on Problematic Expansive Soils: Characterization Challenges, Innovative Stabilization Designs, and Monitoring Methods," addresses practical studies with a focus on ground improvement technologies of problematic expansive soils. For the past three decades, Dr. Puppala and his research group have been working on problematic expansive soil issues related to characterization challenges, sulfate-rich soils and their stabilization methods, innovative tools and technologies for better visualization of subsurface characteristics, and the health monitoring of civil infrastructure built on problematic soils.

The paper begins with a review of expansive soil characterization and their limitations, followed by the presentation of research results dealing with advanced expansive soil characterization models using clay mineralogy, pore void distribution, and unsaturated soil mechanics. Three case studies are presented, in which advanced soil stabilization and screening tools are used to design pavements on expansive soils with or without sulfates and strengthen earthen dams with stronger surficial slopes. The last two sections cover innovations in subsurface site characterization and health monitoring of infrastructure using kriging-based analyses of seismic cone penetration studies and unmanned aerial platforms.

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Note. This manuscript was submitted on December 2, 2020; approved on January 20, 2021; published online on May 17, 2021. Discussion period open until October 17, 2021; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Geotechnical and Geoenvironmental Engineering***, © ASCE, ISSN 1090-0241.

J. Geotech. Geoenviron. Eng., 2021, 147(8): 04021052

Performance Evaluation of Infrastructure on Problematic Expansive Soils: Characterization Challenges, Innovative Stabilization Designs, and Monitoring Methods

Anand J. Puppala, Ph.D., P.E., D.GE, F.ASCE[1]

Abstract: This paper describes key research on expansive soils and the methods employed to characterize them; fallacies in the current characterization of expansive soils are also explained. Novel swell characterization models that account for hydro, chemical, and mechanical behaviors of soils are introduced and used to demonstrate in case studies to improve expansive soil stabilization practices. The first two case studies present the results of expansive soils stabilized by incorporating clay mineralogy and soluble soil sulfate measurements. An innovative design method for successful stabilization of expansive soil is introduced in the first case study, which incorporated both basic clay mineralogy and unsaturated soil behaviors as well as performance-based durability studies. Sulfate soil stabilization works on medium-to-high sulfate soils, including rigorous laboratory and field validation studies, are presented in the second case study. The third case study, which involves a steep earthen embankment built with expansive clayey soils and experiencing recurring surficial slope failures and maintenance issues, is also discussed. Forensic studies explaining the causes of slope failures and their mitigation methods are also included. All case studies reveal the need for detailed data about soil chemistry, including clay mineralogy and sulfate studies, to improve the current field stabilization and infrastructure design on expansive soils. The last section summarizes recent innovations for better health monitoring and management of civil infrastructure built on expansive soils using unmanned aerial vehicle platforms and visualization tools, which will be valuable for validating the application of new materials, designs, and construction processes. **DOI: 10.1061/(ASCE)GT.1943-5606.0002518.** *© 2021 American Society of Civil Engineers.*

Author keywords: Expansive soil; Swelling; Montmorillonite; Slopes; Visualization; Geostatistics.

Introduction and Background

Expansive and unsaturated soil also referred to in the literature as swelling soil, is a problematic soil that has severely distressed civil infrastructure for decades. Expansive soils are primarily controlled by their soil chemistry; in particular, clay mineralogy and clay-water interactions (Chittoori et al. 2018; Puppala and Pedarla 2017). Most expansive soils contain smectite minerals (predominantly dioctahedral Montmorillonite minerals), which are prone to swelling when subjected to hydration and undergo shrinkage cracking during dry conditions. The volumetric strains of these soils are larger than 10%, and such large volume changes induce differential movements that cause surface cracking distress to infrastructures, especially to lightweight infrastructures such as highway infrastructures and residential single-story dwellings. Annual repairs to address the infrastructure distresses cost billions of dollars, and hence they are regarded as a worldwide problem, as expansive soils are distributed across most continents (Puppala and Cerato 2009).

This paper describes key research works on expansive soils, novel characterization methods, stabilization practices, and field implementation studies as well as innovative health monitoring of civil infrastructure built on challenging soil conditions. The first section of this paper addresses practical challenges and fallacies of current expansive soil characterization practices, and this is followed by a description of newer methods that employ clay mineralogy and unsaturated soil property concepts. Professor Peck espoused that "In soil mechanics, no evidence can be considered reasonably adequate until there is sufficient field experience to determine whether the phenomena observed in the laboratory are indeed the same as those that are encountered in the field." Accordingly, three case studies of expansive soils for which stabilization methods were implemented to reduce shrink-swell movements of expansive soils and fills are described.

These case studies cover the stabilization design of expansive soils, with an emphasis on soil chemistry, unsaturated soil mechanics, and macroengineering behaviors to enhance the performance of transportation and civil infrastructure, including pavements, highway embankments, dam slopes, and others. An anthropogenic expansive soil problem, known in the literature as calcium-based, additive-treated sulfate soils, is then briefly presented. Field instrumentation and data collected were used to address the efficacy of field stabilization methodologies in reducing both natural and manufactured heaving issues. Lessons learned from these case studies are briefly presented.

The paper ends with a section that highlights Professor Peck's vision and his insights into the observational approach as a way to better understand the performance of civil infrastructures built on challenging expansive soil conditions. Infrastructure monitoring using a rich visual format that employs new and innovative technologies, from unmanned drone technologies to geospatial kriging models is discussed in detail (Congress et al. 2018;

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My Presentation Outline

I. Introduction to Problematic soils

- ✓ Expansive soils – Natural and Man-Made Soils

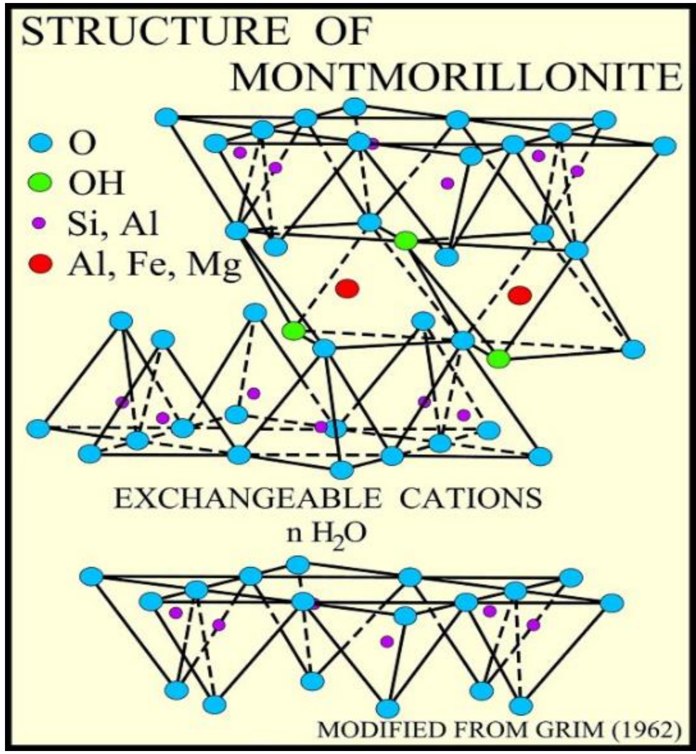
> *"In soil mechanics, no evidence can be considered reasonably adequate until there is sufficient field experience to determine whether the phenomena observed in the laboratory are indeed the same as those that encountered in the field"*
>
> **– Prof. Ralph B. Peck**

IV. Visualization – Novel Monitoring Methods

V. Summary

Problematic Soils: Expansive Soils

- $Billions$ of dollars of infrastructure damages caused by natural expansive soils
  - ✓ Pavements, Dams, and Embankments
  - ✓ Residential and Industrial Dwellings
- Montmorillonite-rich clays, over-consolidated clays, shales
- Simple Plasticity Index (PI) based characterization – Still current practice
- Clay mineralogy (less focus) – Montmorillonite (MM)
  - ✓ Smectite group
  - ✓ Specific surface area – 600 to 800 m^2/g
  - ✓ Cation Exchange Capacity (CEC) – 47 to 162 meq/100g



MODIFIED FROM GRIM (1962)

I. Introduction

Natural Expansive Soil: Infrastructure Distress

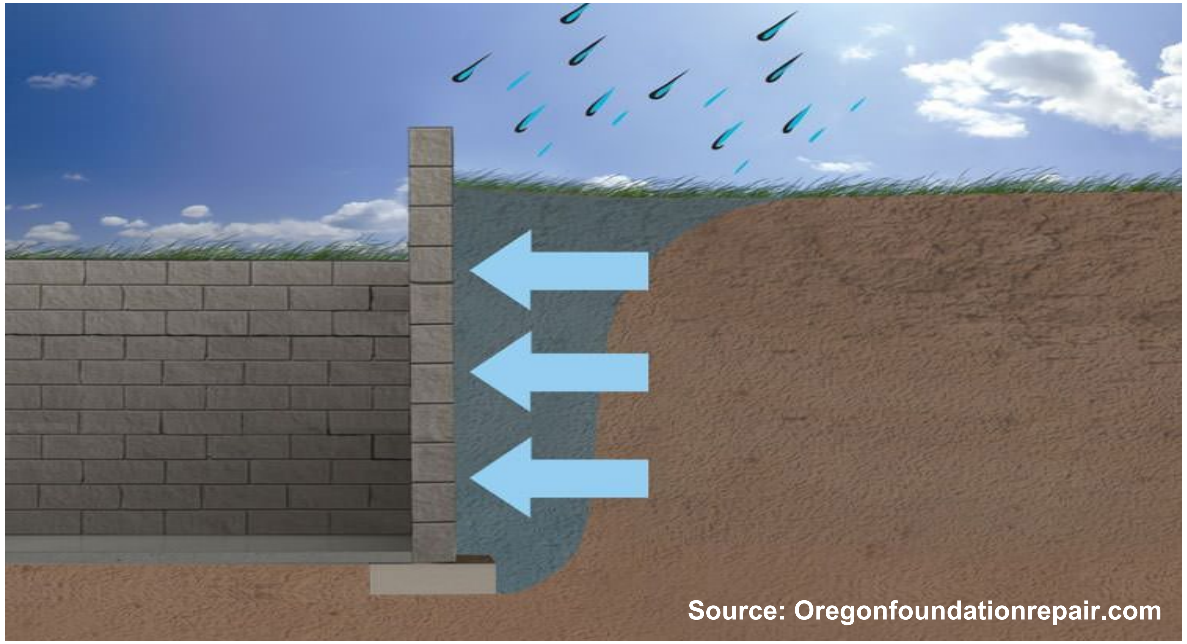
Longitudinal Cracking

Paris District, TX

Source: Oregonfoundationrepair.com

Source: FHWA Report

Natural Expansive Soil: Infrastructure Distress


Source: Oregonfoundationrepair.com

I. Introduction

Natural Expansive Soil: Infrastructure Distress

Grapevine Dam, Texas

Joe Pool Dam, Texas

Service Road along US 75

Joe Pool Dam Crest

(Source: Les Perrin, USACE)

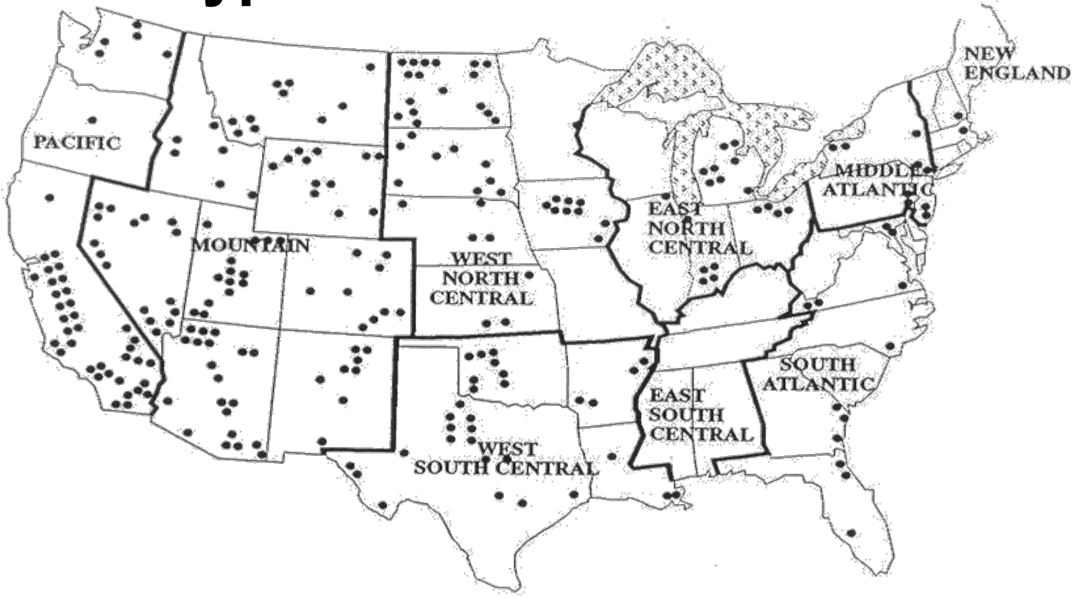
I. Introduction

Man-Made Expansive Soil – Sulfate Laden Soil

- **Sources of Sulfates in Soil**
  - ✓ Gypsum ($CaSO_4.2H_2O$)
  - ✓ Sodium Sulfate (Na_2SO_4)
  - ✓ Magnesium Sulfate ($MgSO_4$)

Gypsum in Natural Soils

Distribution of
Gypsum Rich Soils in USA



Calcium Based Treatments of Sulfate Soils: Sulfate-induced Heave - Ettringite Formation (Mitchell, Hunter, Little and Many Other Researchers)

Sulfate Soils: Infrastructure Distress

Heaving on Joe Pool Lake Road, Grand Prairie, Texas

Source: Les Perrin, USACE

Joe Pool Lake (Les Perrin, USACE)

Heaving on US 67, Midlothian, Texas

Source: Wimsatt, 1999

Subsoils Near DFW Airport Sulfate Contents > 30,000 ppm

Characterization Challenges with Expansive Soils

Soil Characterization Issues ~ Soils with similar PI are not the same type of expansive soil!

Soil Source	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
Bryan	45	14	31
Fort Worth	61	32	29
Paris	60	24	36
Pharr-B	56	19	37

Need For Improved Soil Characterization

Premature Failures

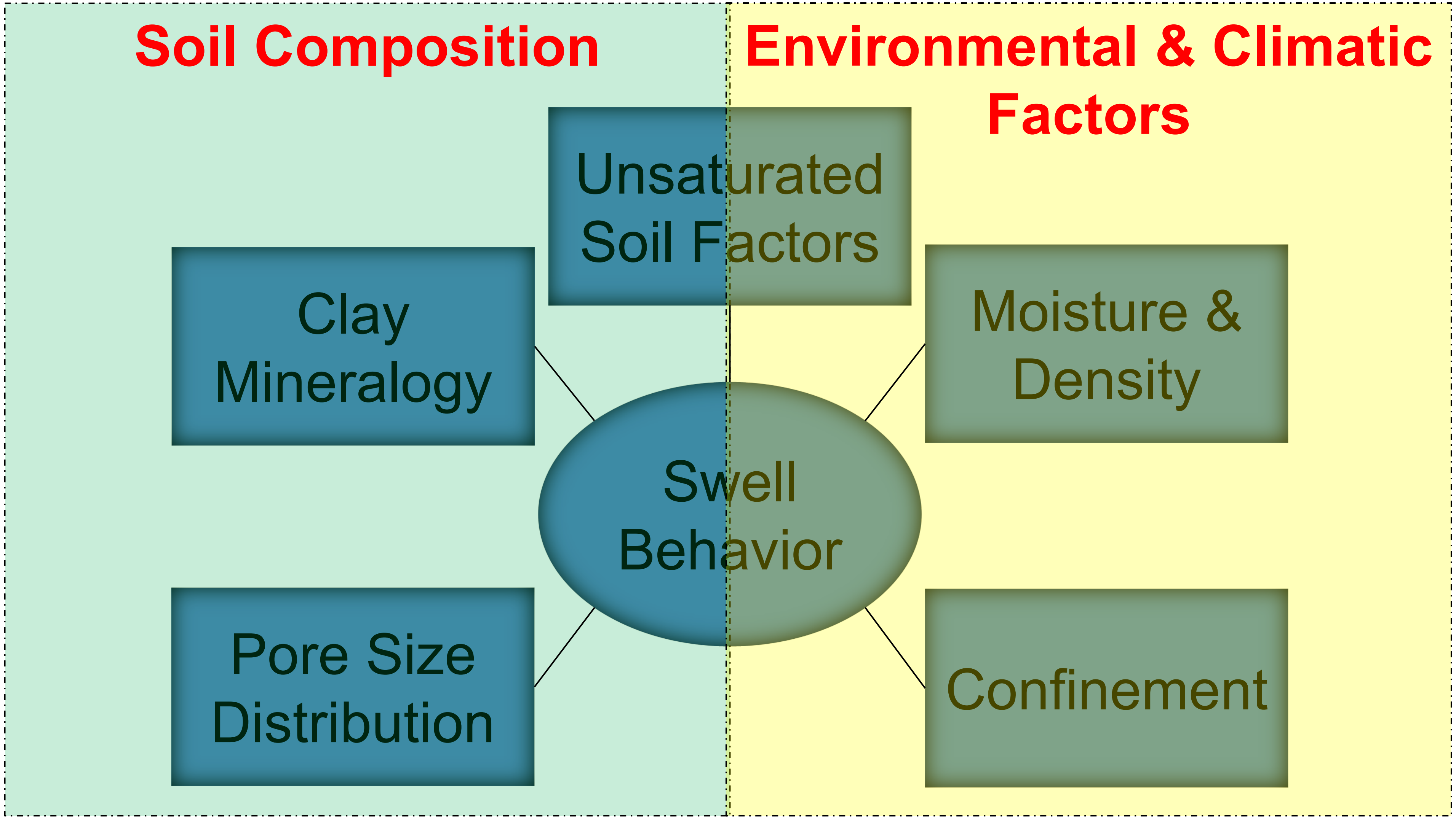
*Chittoori, B.S., and Puppala, A.J. "Quantification of Clay Mineralogy" *ASCE, Journal of Geotechnical and Geoenvironmental Engineering*, 2011, Vol.137, No.11, pp 997-1008.

Linking Micro to Macro Scale Properties: Understanding Swell Behavior

- ☐ **Micro-scale measurements with macro-scale properties**
  - **Clay Mineralogy**
  - **MIP – Porosimetry**
  - **Soil Water Characteristic Curve**
  - **Swell Properties**

- ☐ **Models based on unsaturated soil mechanics principles facilitate better simulation of heave behavior of expansive soils**

Swell Characterization Models



Soil Composition

Environmental & Climatic Factors

Unsaturated Soil Factors

Clay Mineralogy

Moisture & Density

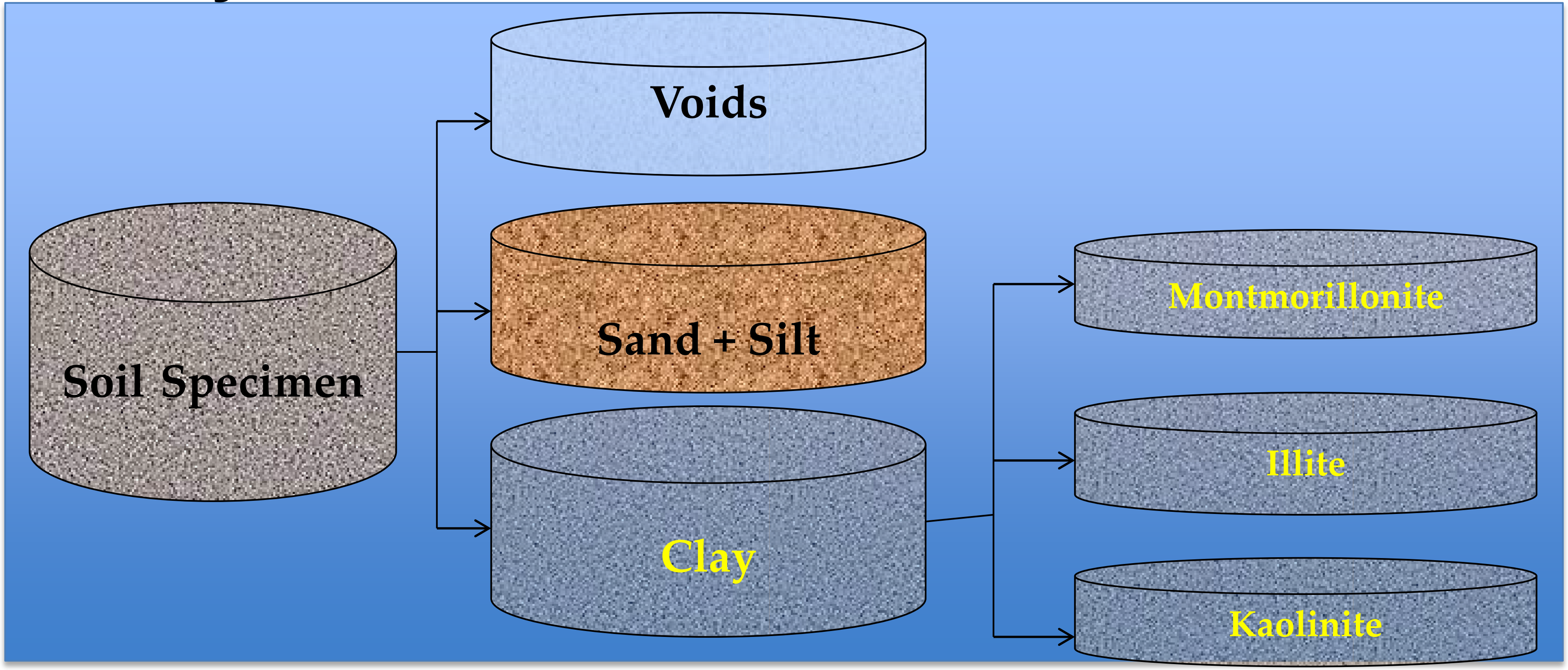
Swell Behavior

Pore Size Distribution

Confinement

Expansive Soil Composition

- ❑ <u>Strong basis</u> for the understanding of swell behavior of a clay specimen
  - Clay Mineralogy
  - High Affinity for Water



Quantifying Clay Mineralogy

Mineral Type	Cation Exchange Capacity (CEC), meq/100gm	Specific Surface Area (SSA), m^2/gm	Total Potassium (TP), %
Illite (I)	15-50	80-120	6
Kaolinite (K)	1-6	5-55	0
Montmorillonite (M)	80-150	600-800	0

The final chemical compositions of different soils can be related to their mineral percentages by the following three equations:

$$\%M \times CEC_M + \%K \times CEC_K + \%I \times CEC_I = CEC_{soil} \quad (1)$$

$$\%M \times SSA_M + \%K \times SSA_K + \%I \times SSA_I = SSA_{soil} \quad (2)$$

$$\%M \times TP_M + \%K \times TP_K + \%I \times TP_I = TP_{soil} \quad (3)$$

Approximate Mineral Percentages ~ obtained by solving three equations

*Chittoori, B.S., and Puppala, A.J. "Quantification of Clay Mineralogy" *ASCE, Journal of Geotechnical and Geoenvironmental Engineering*, 2011, Vol.137, No.11, pp 997-1008.

NSF Study: Swell Prediction Model I

☐ **Chemical Mineralogy Related Parameter (C_p)**

$$Cp = CF \times \sum_{i=1}^{n} SF * f_i$$

Where CF is Clay-size Fraction; f_i is the mineral content in the clay fraction; and SF is Swell Factor (Montmorillonite – 90, Illite – 9, Kaolinite – 1)

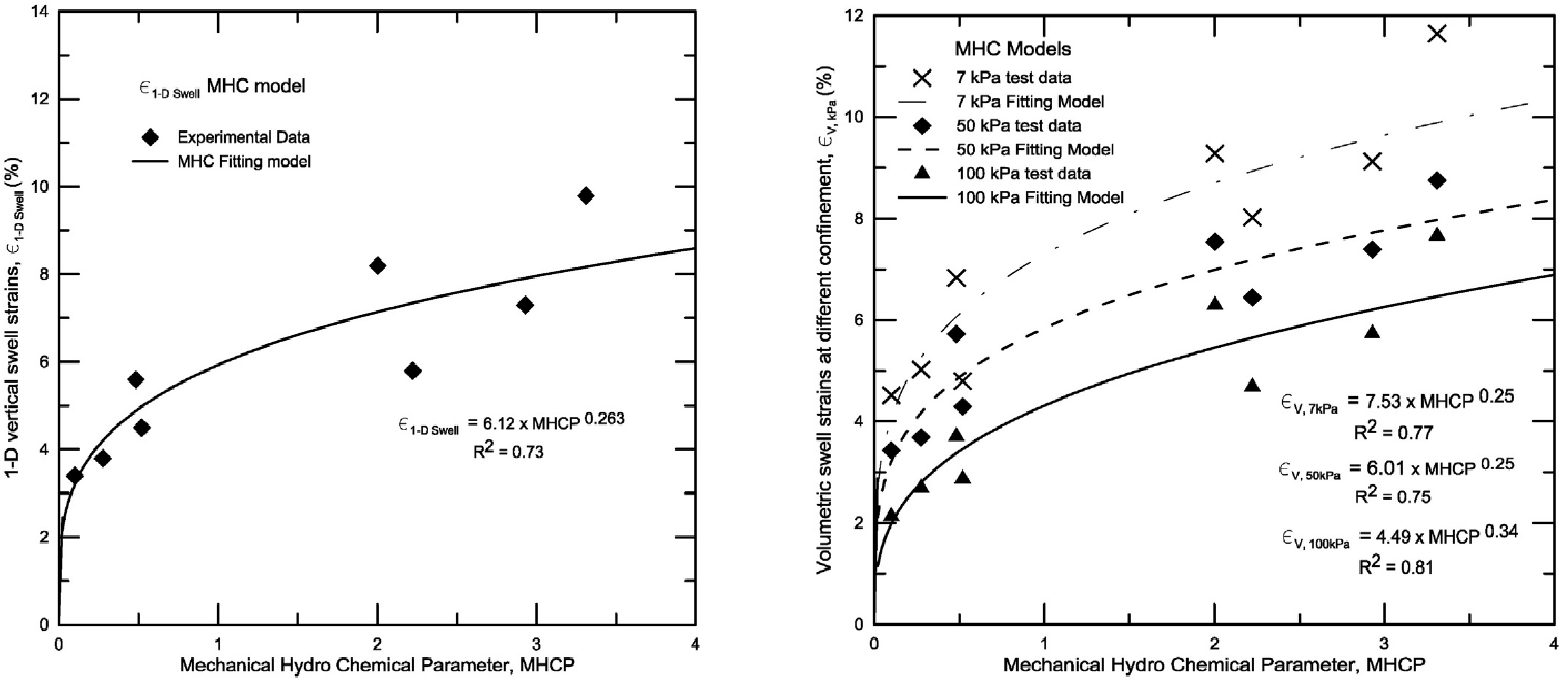
☐ **Mechanical/Hydro Parameter (α)**

$$\propto = \frac{(e_f - e_i)}{(\log(\psi_{final}) - \log(\psi_{initial}))}$$

☐ **Mechanico-hydro-chemical parameter (MHCP)**

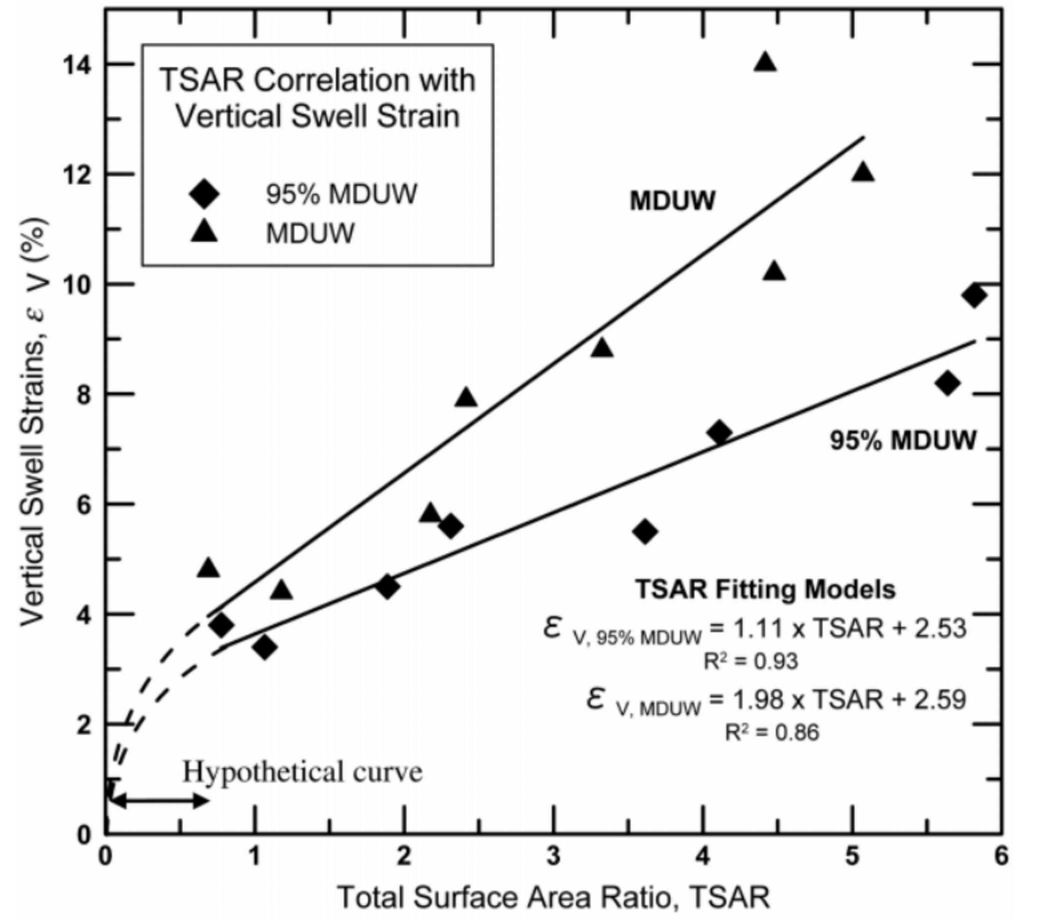
$$MHCP = \pi(\alpha, C) = \alpha \, X \, C_p$$

NSF Study: Swell Prediction Model I



Puppala et al. (2016). A semi-empirical swell prediction model formulated from 'clay mineralogy and unsaturated soil properties. Engineering geology, 200, 114-121.

NSF Study: Swell Prediction Model II



MDUW – Max Dry Unit Weight – Wet of Optimum

Pedarla, A., Puppala, A.J., Hoyos, L.R., and Chittoori, B. (2015) “Evaluation of Swell Behavior of Expansive clays from Internal Specific Surface and Pore Size Distribution”, ASCE Journal of Geotechnical and Geoenvironmental Engineering, Nov 2015. Vol. 142 (2).

II. Characterization

Better swell characterization models are possible...

However, their application into real practice is still a challenge!

> ***"Translating the findings of our research into simple concepts and procedures for the guidance of the practicing engineer is, in my opinion, a duty and worthy activity of our profession…"***
>
> **– Prof. Ralph B. Peck**

III. Case Studies

Innovative infrastructure design by integrating soil characterization:

Three case studies – involving expansive soils

Two on pavements and one on embankment slopes

> ***"The most fruitful research grows out of practical problems"***
>
> ***"No theory can be considered satisfactory until it has been adequately checked by actual observations"***
>
> **– Prof. Ralph B. Peck**

III. Case Study 1

Pavements built on Expansive Soils

Current Practices

- ☐ Remove and replace the top-soil
- ☐ Mix with chemicals
  - **Lime**
  - **Cement**
  - **Chemical Stabilizer**
- ☐ Application of **Geosynthetics**

Geosynthetics

Lime Stabilization

Source: http://www.ecslimited.com

Chemical Stabilization

Source: http://www.esslsoils.com

Test Soils: Clay Mineralogy

Soil Stabilization Design Incorporating Clay Mineralogy

Soil	%Illite	%Kaolinite	%Montmorillonite
Austin	29	18	53
Bryan	23	40	37
El Paso	63	14	23
Fort Worth	16	23	60
Keller	18	62	20
Paris	13	17	70
Pharr A	26	26	48
Pharr B	28	54	18

Characterization Challenges with Expansive Soils

Soil Characterization Issues ~ Soils with similar PI are not the same type of expansive soil!

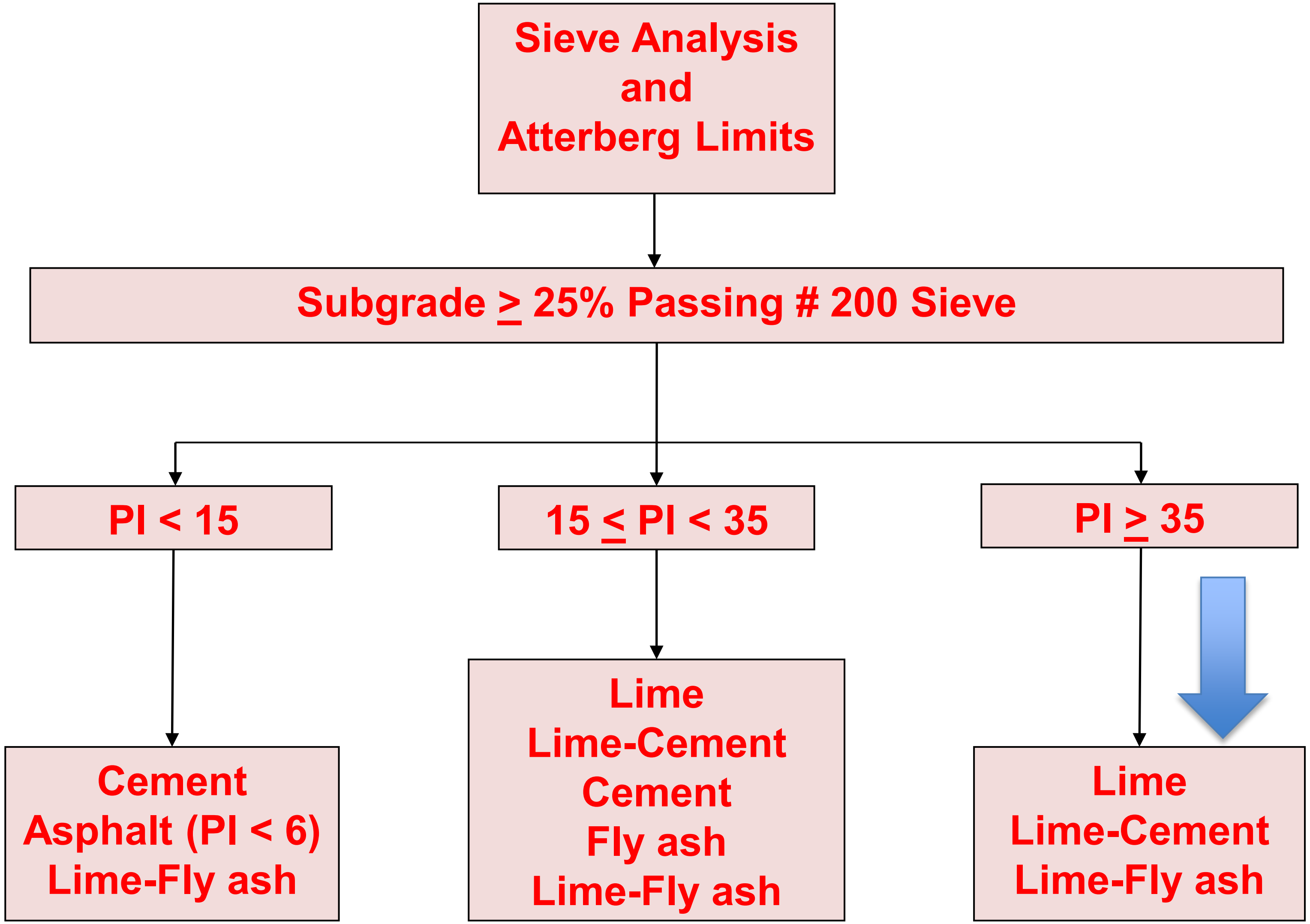
Soil Source	Liquid Limit (%)	Plasticity Index (%)	Dominant Mineral
Bryan	45	31	**Kaolinite**
Fort Worth	61	29	**MM**
Paris	60	36	**MM**
Pharr-B	56	37	**Kaolinite**

Note: MM - Montmorillonite

Premature Failures

III. Case Study 1

Stabilization Design Guideline



Sieve Analysis and Atterberg Limits

Subgrade ≥ 25% Passing # 200 Sieve

PI < 15
- Cement
- Asphalt (PI < 6)
- Lime-Fly ash

15 ≤ PI < 35
- Lime
- Lime-Cement
- Cement
- Fly ash
- Lime-Fly ash

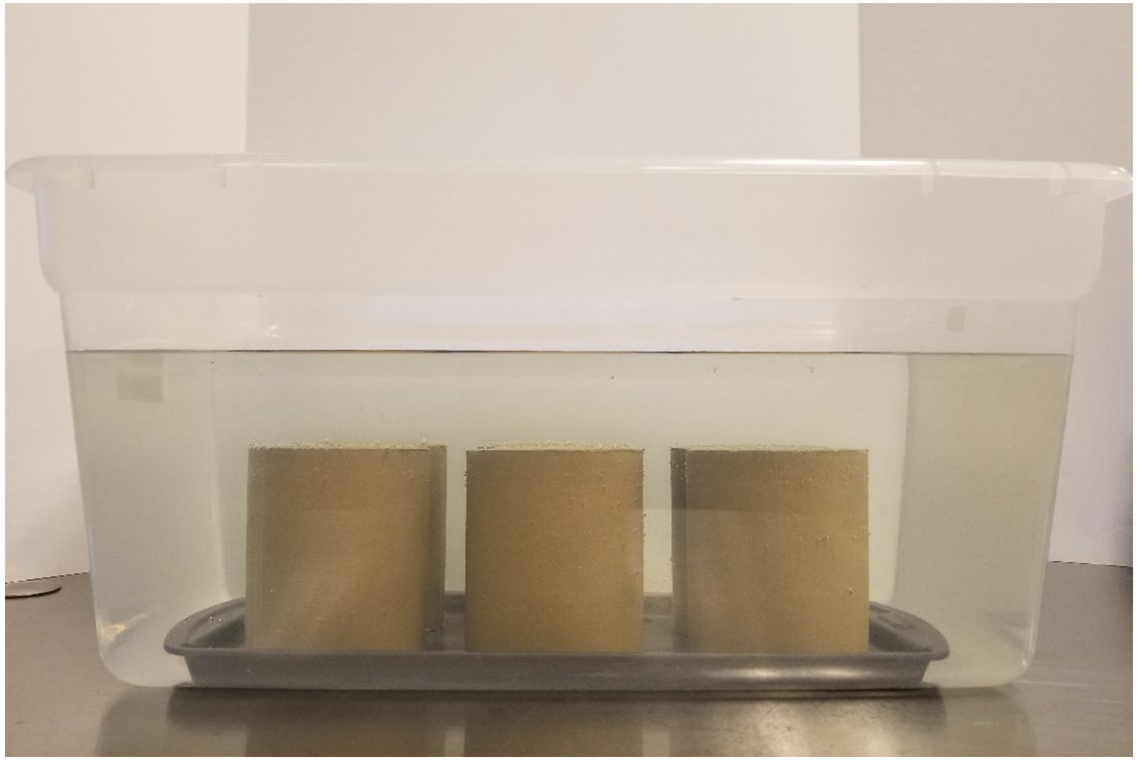
PI ≥ 35
- Lime
- Lime-Cement
- Lime-Fly ash

TxDOT: Additive Selection Criteria for Subgrades
Lime Treatment – 6 to 8% Selected

Durability Studies

Wetting/Drying Studies: ASTM D 596

- **Wetting Cycle - 5 hours**
- **Drying Cycle - 42 hours in an oven**



Wetting Cycle

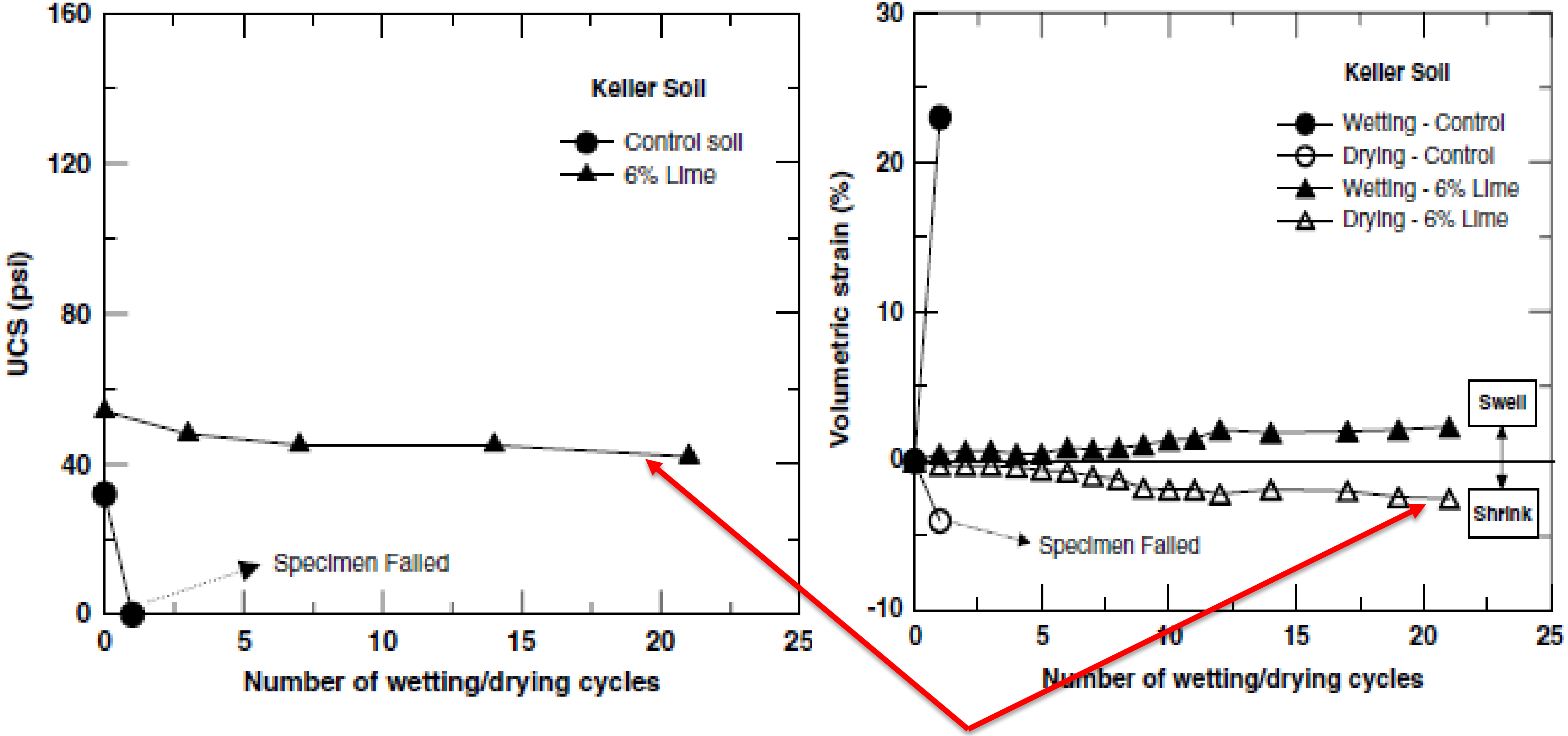
Drying Cycle

Durability Studies – Untreated and Treated Fort Worth Clay

Soil Name	Liquid Limit	Plastic Limit	Plasticity Index	Dominant Clay Mineral
Fort Worth	61	32	29	Montmorillonite

III. Case Study 1

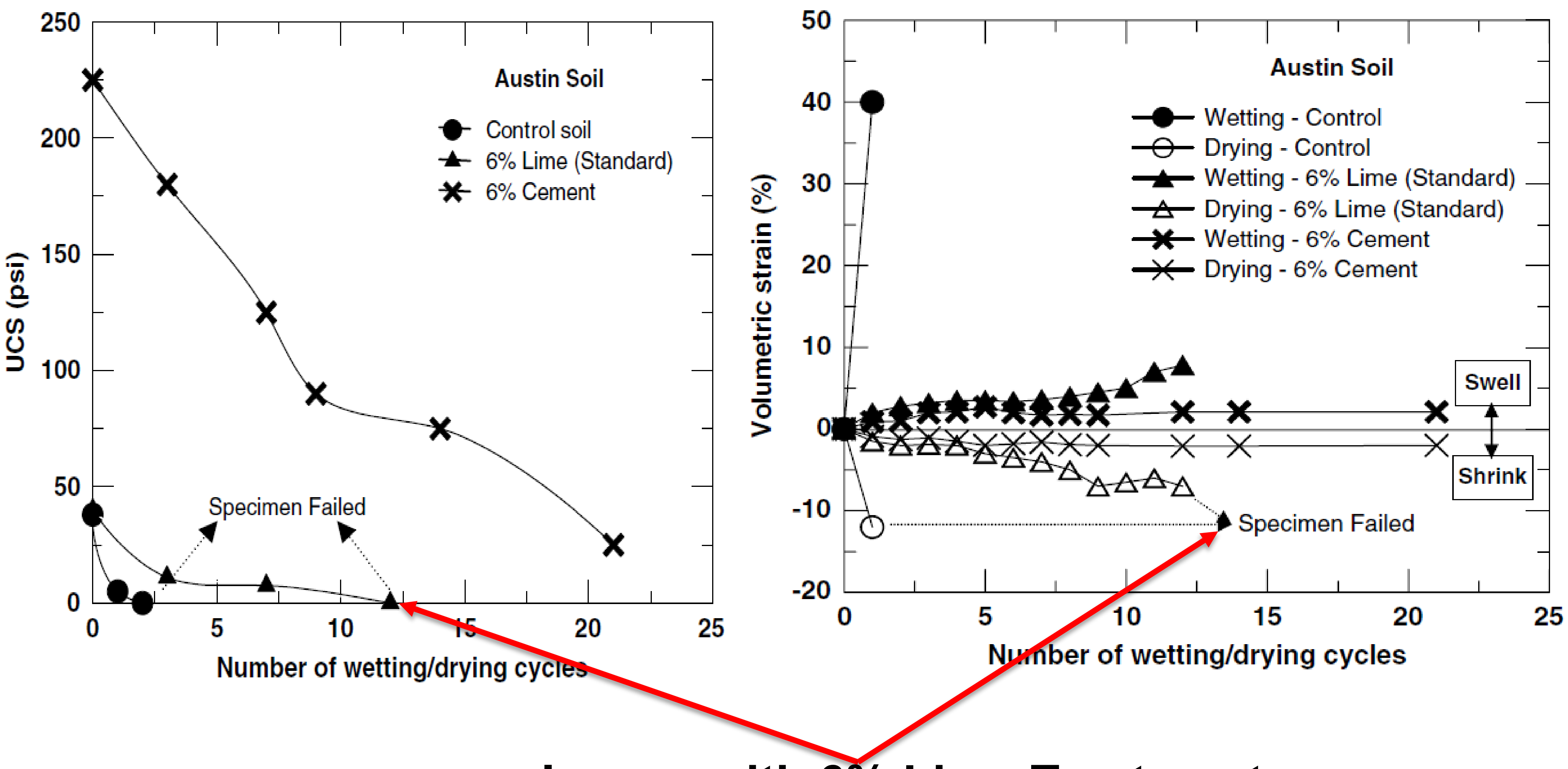
Durability Studies: Keller Soil (Kaolinite Dominant)



No Issues with 6% Lime Treatment

III. Case Study 1

Durability Studies:
Austin Soil (Montmorillonite Dominant)



Issues with 6% Lime Treatment

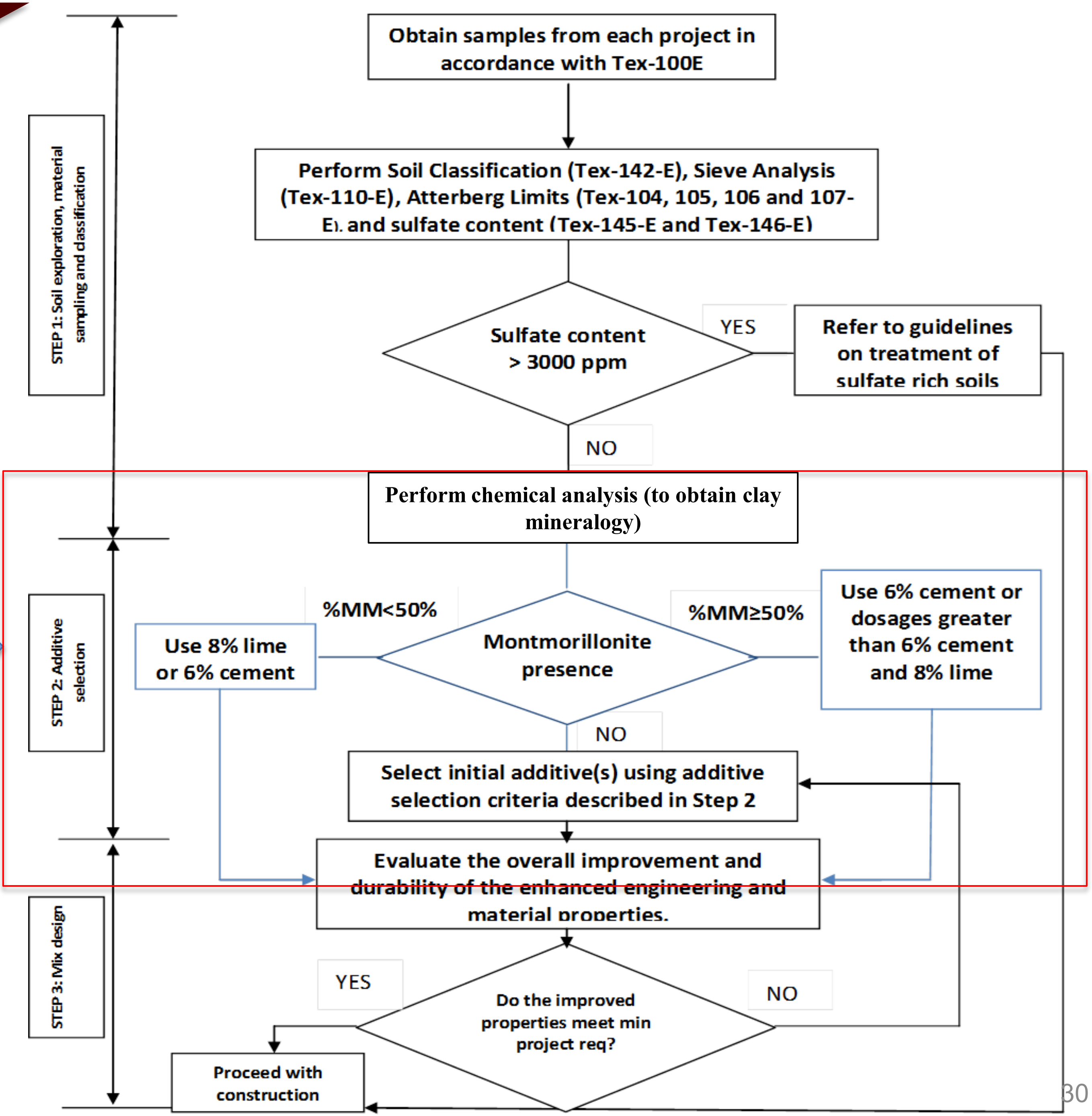
Summary of Durability Studies: Lime Stabilizer Dosages

Soil Source	Dominating clay mineral	Amount of additive, (% by weight)	# of cycles sample survived	Volumetric strain (%)	Retained strength (%)
Austin	Montmorillonite	6%	12	15	0
Fort Worth	Montmorillonite	6%	10	15	0
Paris	Montmorillonite	8%	7	15	0
Pharr-A	Montmorillonite	4%	4	30	0
Bryan	Kaolinite	8%	21*	6	93
Keller	Kaolinite	6%	21*	5	80
Pharr-B	Kaolinite	3%	8	18	0
El Paso	Illite	8%	21*	12	80

*** - Maximum cycles tested is equal to 21**

III. Case Study 1

Recommended modifications in stabilization chart



STEP 1: Soil exploration, material sampling and classification

STEP 2: Additive selection

STEP 3: Mix design

Obtain samples from each project in accordance with Tex-100E

Perform Soil Classification (Tex-142-E), Sieve Analysis (Tex-110-E), Atterberg Limits (Tex-104, 105, 106 and 107-E). and sulfate content (Tex-145-E and Tex-146-E)

Sulfate content > 3000 ppm

YES

Refer to guidelines on treatment of sulfate rich soils

NO

Perform chemical analysis (to obtain clay mineralogy)

%MM<50%

%MM≥50%

Montmorillonite presence

Use 8% lime or 6% cement

Use 6% cement or dosages greater than 6% cement and 8% lime

NO

Select initial additive(s) using additive selection criteria described in Step 2

Evaluate the overall improvement and durability of the enhanced engineering and material properties.

YES

NO

Do the improved properties meet min project req?

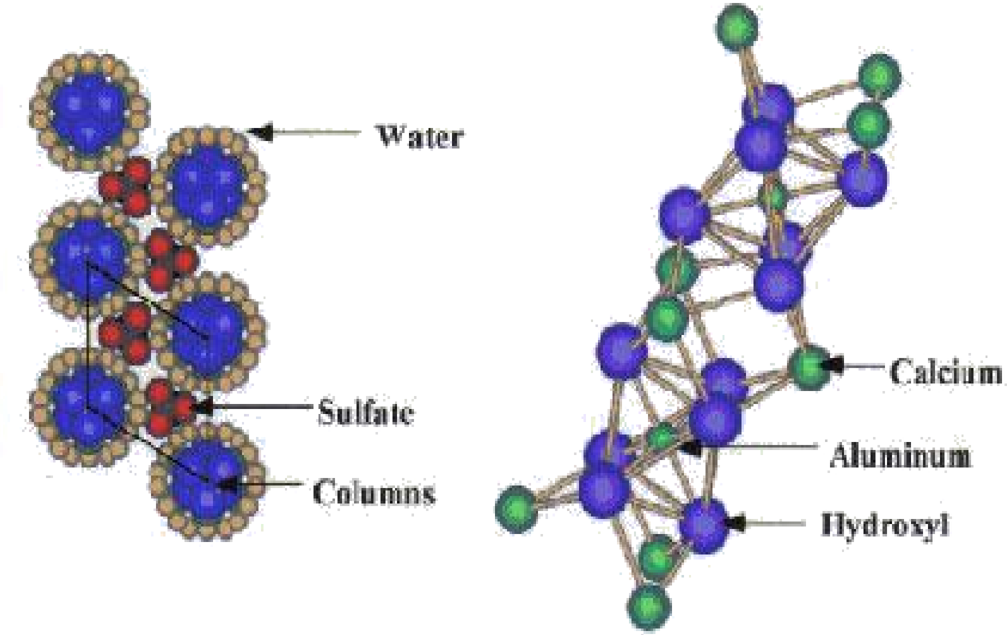
Proceed with construction

%MM – Percent Montmorillonite

III. Case Study 2

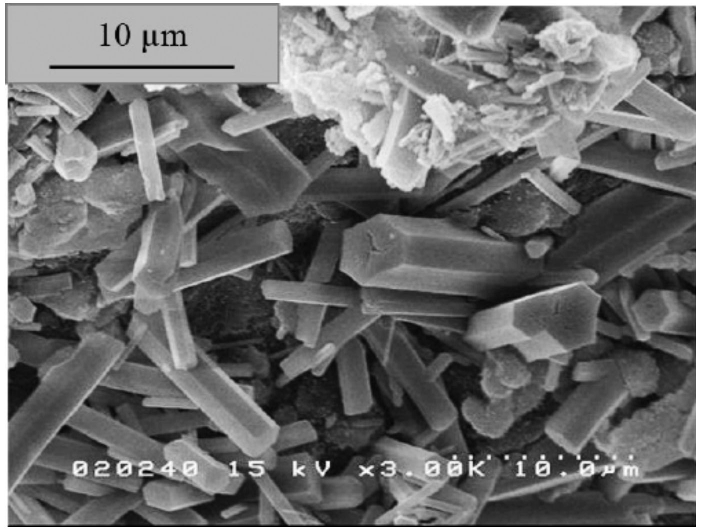
Sulfate Heaving: Man-Made Expansive Soil

- ❑ **High sulfate soil when treated with calcium-based stabilizers by Mitchell (1986) and Hunter (1988):**
  - **Soil Distress**
  - **Heaving**



geoweb.princeton.edu

Source: https://alchetron.com/Ettringite

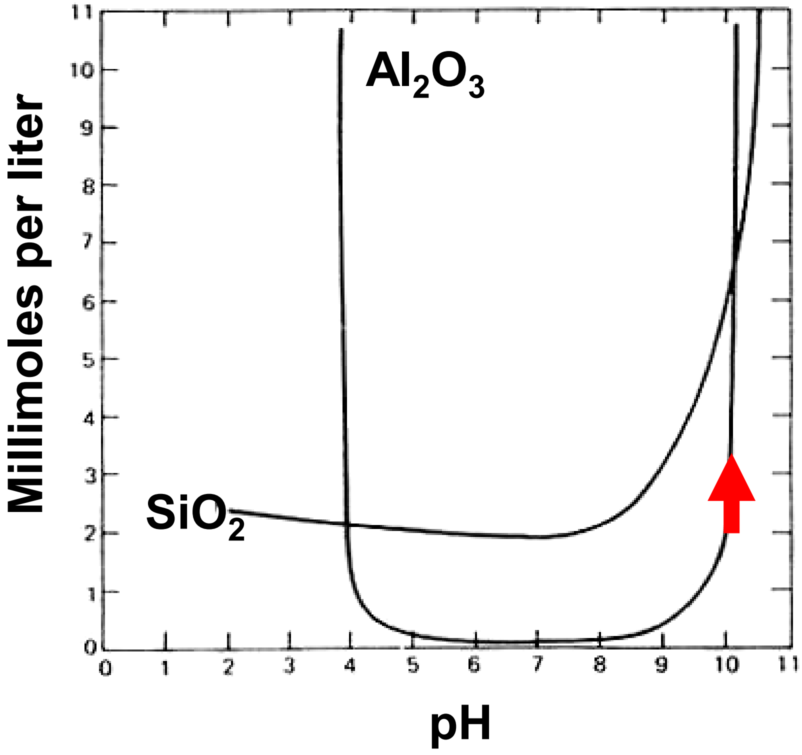


Jewell et al. (2014)

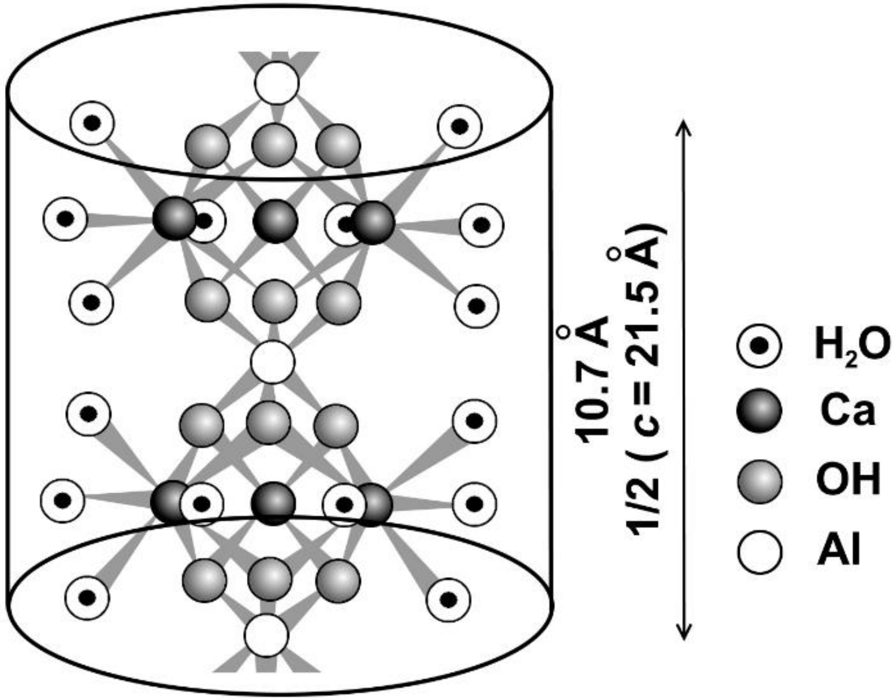
Chemical interaction between calcium and aluminum existing within the soil mineralogy in the presence of soluble sulfate and water produces **Ettringite**

III. Case Study 2

Gypsum or Sulfate Rich Soils



Lime – High pH



$$CaO + H_2O \rightarrow Ca^{2+} + 2OH^-$$

(Hydration of Lime – Free Calcium)

$$Al_2Si_4O_{10}(OH)_2{\bullet}nH_2O + 2(OH)^- + 10H_2O \rightarrow 2Al(OH)_4^- + 4H_4SiO_4 + nH_2O$$

(Dissolution of clay mineral at pH>10.5, Free Alumina)

$$6Ca^+ + 2Al(OH)_4^- + 4OH^- + 3(SO_4)^{2-} + 26H_2O \rightarrow Ca_6[Al(OH)_6]_2{\bullet}(SO_4)_3{\bullet}26H_2O$$

(Formation of Ettringite, expansive mineral)

III. Case Study 2

Sulfate-induced Heave - Literature

Location	Soil Type	Reaction products	Lime(L)/ Cement(C) %	Sulfate Content (mg/kg)	Heave Appearance after Construction
Parking Lots, Kansas, Southern California	N/A	Ettringite	NA	NA	NA
Stewart Avenue, Las Vegas, Nevada	Silty clay	Ettringite and Thaumasite	4.5% (L)	43,500	6 months
Lloyd Park, Joe Pool Lake, Dallas, Texas	OC Clays	Ettringite	5% (L)	2,000 – 9,000	Immediately
Auxiliary Runway, Laughlin AFB, Spofford, Texas	Clays	Ettringite	6-9% (L)	14,000 – 25,000	2 months
Cedar Hill State Park, Joe Pool Lake, Dallas, Texas	Highly plastic residual clays	Ettringite	6% (L)	21,200	2 months
Denver International Airport, Denver, Colorado	Expansive Clays	Ettringite	NA (L)	2,775	NA
SH-118, Alpine & SH-161, Dallas	Clayey Subgrades	Ettringite	4% (C) 6-7%(L)	>12,000	6 to 18 months
Dallas – Fort Worth International Airport, Irving, Texas	Clay	Ettringite	5% (L)	320 – 13,000	3 months
Near Shreveport, Louisiana	Aggregates	Ettringite	NA	NA	NA
Holloman Air Force Base, NM	Crushed Concrete	Ettringite	NA	NA	Several years
U.S.82,TX	N/A	Ettringite	6%(L)	100-27800	Immediately
Baylor Creek Bridge, Childress, TX	All soils	Ettringite	5%(L); 3%(C)	6800-35000	Several years
Western Oklahoma	Clays	Ettringite	0-5%(L)	194-84000	NA

Problematic Sulfate Levels - Research

- **Sulfate Levels < 8000 ppm ***
  - ✓ **Low Risk: < 3000**
  - ✓ **Medium Risk: 3000 to 5000ppm**
  - ✓ **Moderate to High Risk: 5000-8000ppm**
- **Sulfate Levels > 8000ppm**
  - ✓ **<u>High Sulfate Soil</u>: Severe Concern**
  - ✓ **Lime/Cement Stabilization to be Avoided**
  - ✓ **Remove and Replace Sulfate Soils or Blend in Non-Plastic Soils**
    - ➢ ***Economic and Sustainability Impacts***
    - ➢ **<u>High Sulfate Soils – TxDOT Research</u>**

<u>Treatments for Sulfate Soils</u>

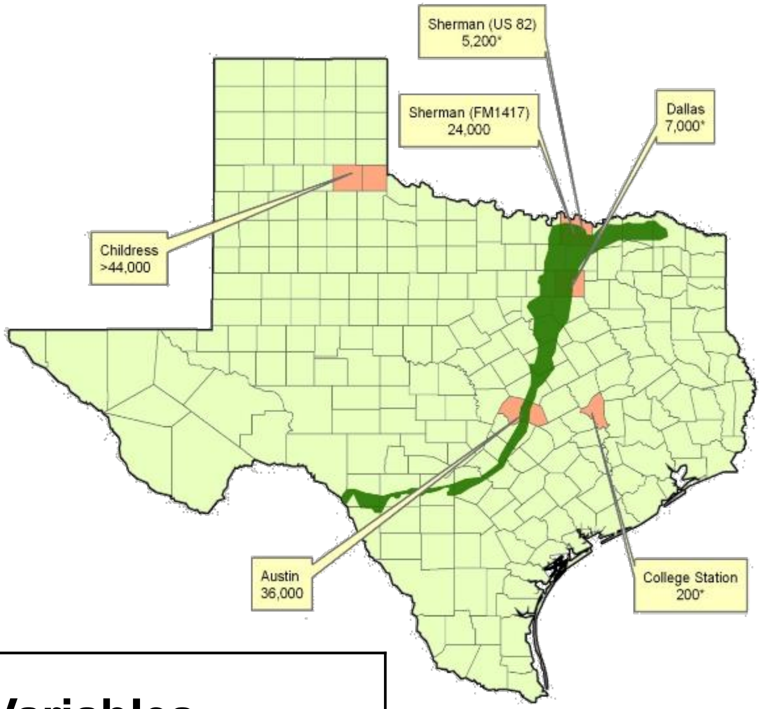
- **Ground Granulated Blast Furnace Slag (GGBFS)**
  - ✓ **Shown to be Successful in US and UK**
- **Sulfate Resistant Cements: Type II and Type V**
  - ✓ **Laboratory Results Show Successful Stabilization**
- **Class F Fly Ash – Co-additive**
- **Double Lime Treatment**
  - ✓ **Mixed results**
  - ✓ **Reappearance of Heave**
  - ✓ **Improved Tensile and Shear Strengths**

*** Sulfate Studies – NSF, US Army Corps of Engineers, NCHRP IDEA, USDOT - UTC, & Others**

III. Case Study 2

Sulfate Levels >8000 ppm

- **Lime Treatment: Extended Mellowing Period**
  - ✓ **Laboratory and Field Studies**



Soil Source	Atterberg's Limits %			USCS Classification	Soluble Sulfates, ppm
	LL	PL	PI		
Austin	76	25	51	CH	**36,000**
Childress	71	35	36	MH	**44,000**
Dallas	80	35	45	CH	7,000
Sherman	72	30	42	CH	24,000
Riverside	35	11	24	CL	200
US-82	75	25	50	CH	5,200

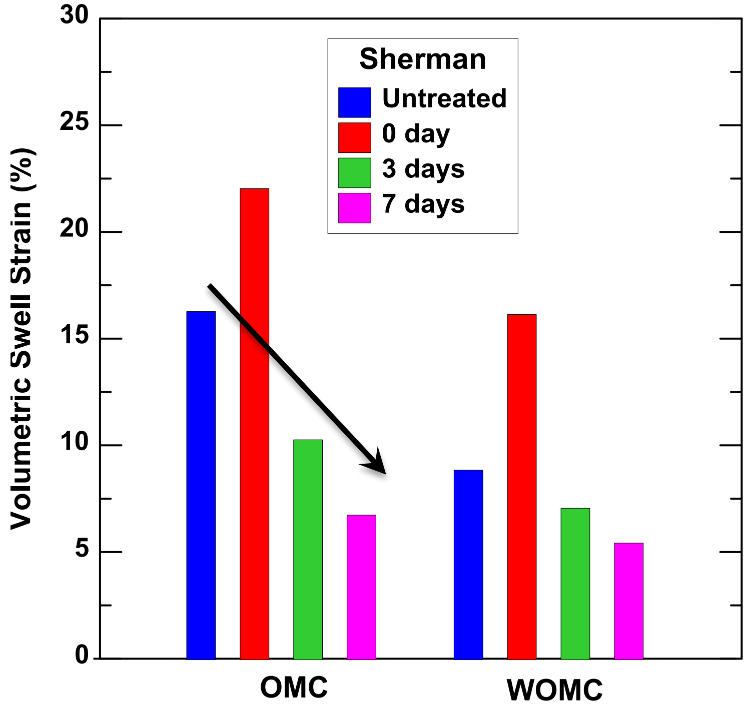
Description	Variables
Stabilizer	1 (Lime)
Dosage	1 (6%)
Compaction Moisture Contents	2 (Optimum-OMC and Wet of optimum-WOMC)
Mellowing Periods	3 (0, 3 and 7 days)

III. Case Study 2

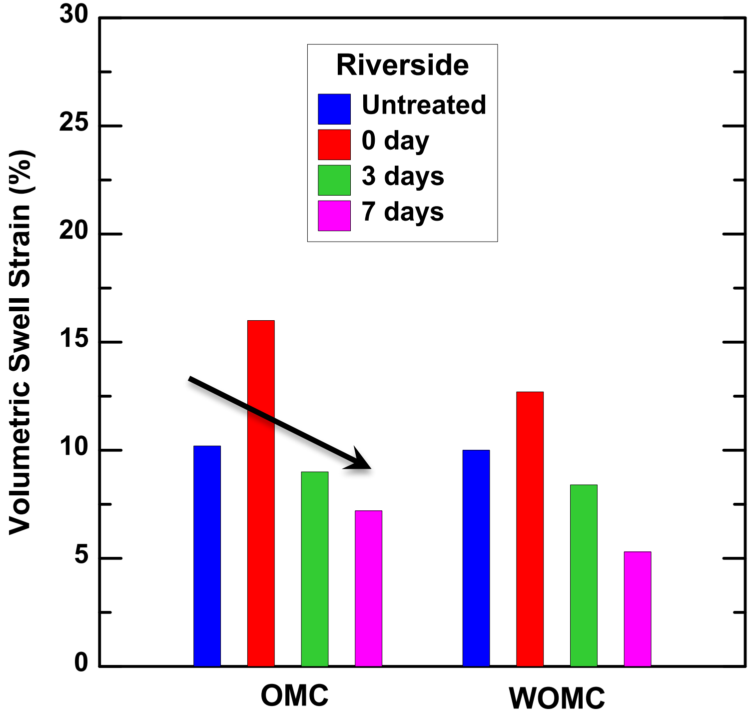
Sulfate Levels >8000 ppm

- **3D Volumetric Swell**

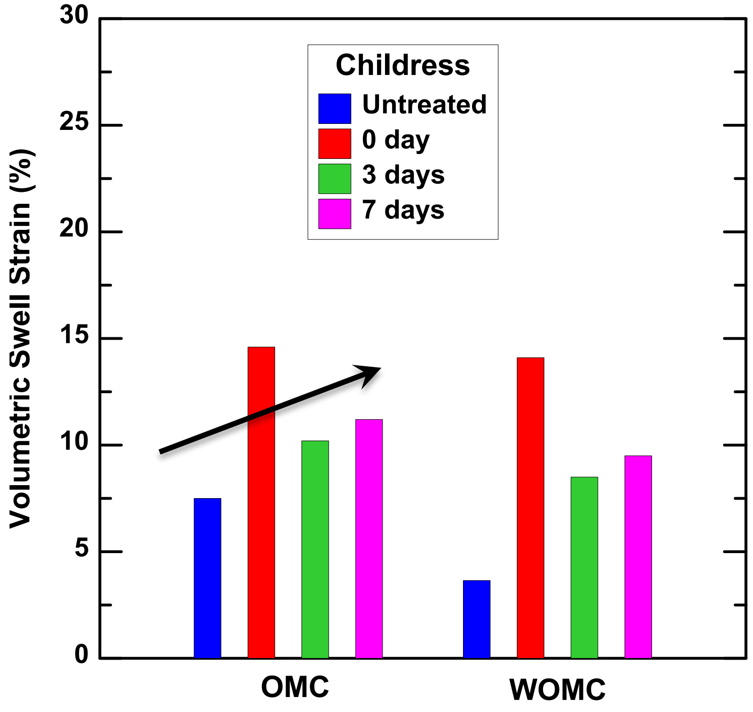
✓ **Volumetric Swell reduced with Mellowing in Treated Soils**



Sherman Soil
(‘CH’; 24,000 ppm sulfates)



Riverside Soil
(‘CL’, 20,000 ppm sulfates)



Childress Soil
(‘MH’; 44,000 ppm sulfates)

III. Case Study 2

Sulfate Levels >8000 ppm

- ☐ **Effects of Mellowing**
  - **Swell Behavior**
    - **Effective in <u>4 of 6 soils </u>(Dallas/Sherman/Riverside/US-82)**
    - **Reduced swell magnitudes at 3- and 7-days mellowing**
      - **All 4 soils have sulfates < 30,000ppm**
    - **Ineffective in Austin and Childress soils**
      - **Sulfate levels > 30,000ppm**
      - **Low reactive pozzolanic compounds**

- **Effect of Void Ratio**
  - **Low Void Ratios in Austin/Childress**
  - **Less space to Accommodate Ettringite**

III. Case Study 2

Sulfate Levels >8000 ppm

Reactive Alumina (Al) and Silica (Si) Measurements in ppm

Soil	Natural		0-day mellowing		3-day mellowing	
	Al	Si	Al	Si	Al	Si
Austin	**58.9**	**15.4**	22.8	6.1	18.9	5.1
Childress	**75.8**	**12.6**	28.1	5.9	32.2	7.2
Dallas	289.9	231.2	87.6	68.2	122.2	69.2
Sherman	279.2	137.3	115.9	47.1	131.9	50.3
Riverside	297	379.8	108.8	42.8	183.7	49.4
US-82	323.3	187.1	94.2	19.9	135.6	27.3

Compaction Void Ratios

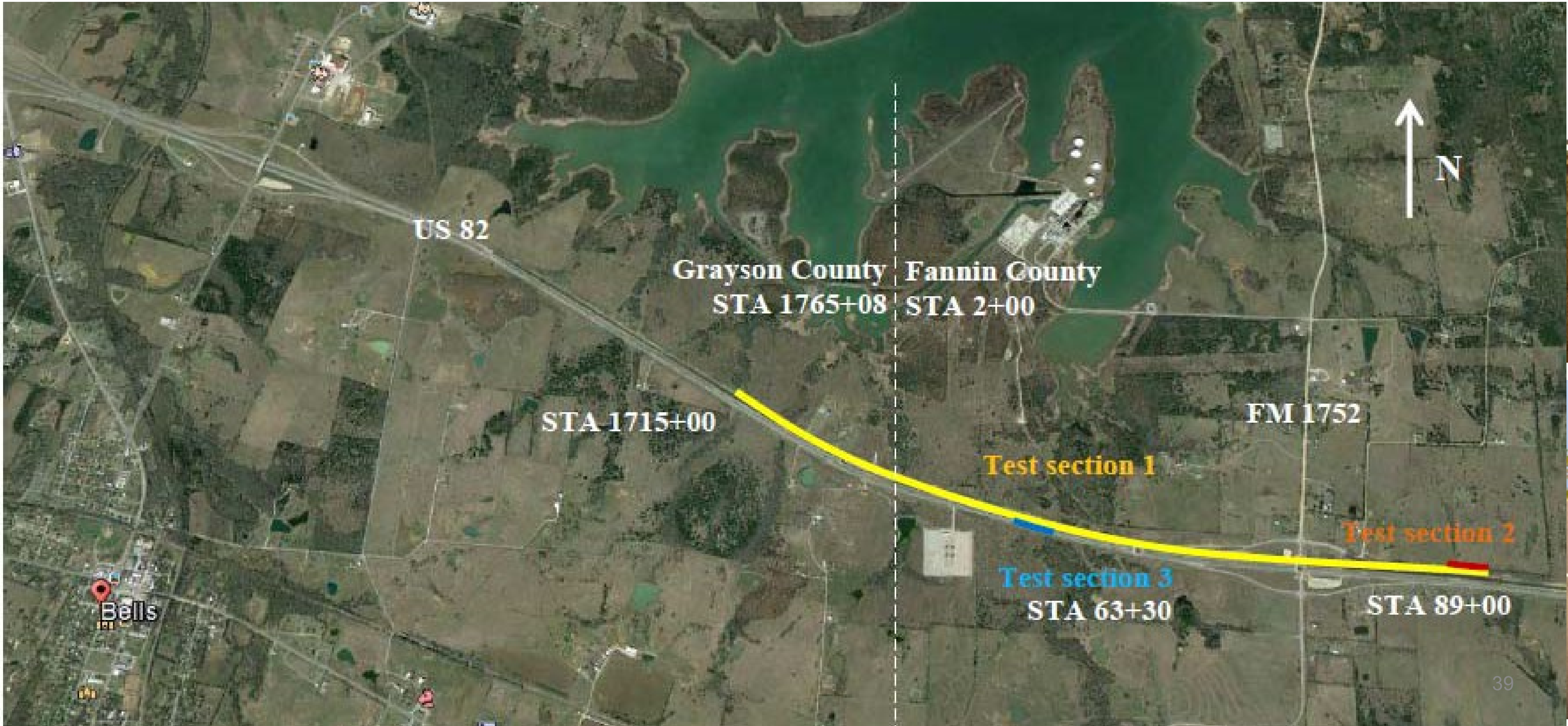
Soil Type	Sulfate Content, ppm	Void ratio, e @ OMC
Austin	**36,000**	**0.54**
Childress	**44,000**	**0.52**
Dallas	12,000	0.84
Sherman	24,000	0.86
Riverside	20,000	0.61
US-82	12,000	0.82

Relatively Lower Reactive Alumina/Silica in Austin and Childress Soils

Low Compaction Void Ratios – Less Space for Ettringite

III. Case Study 2

Field Validation Study

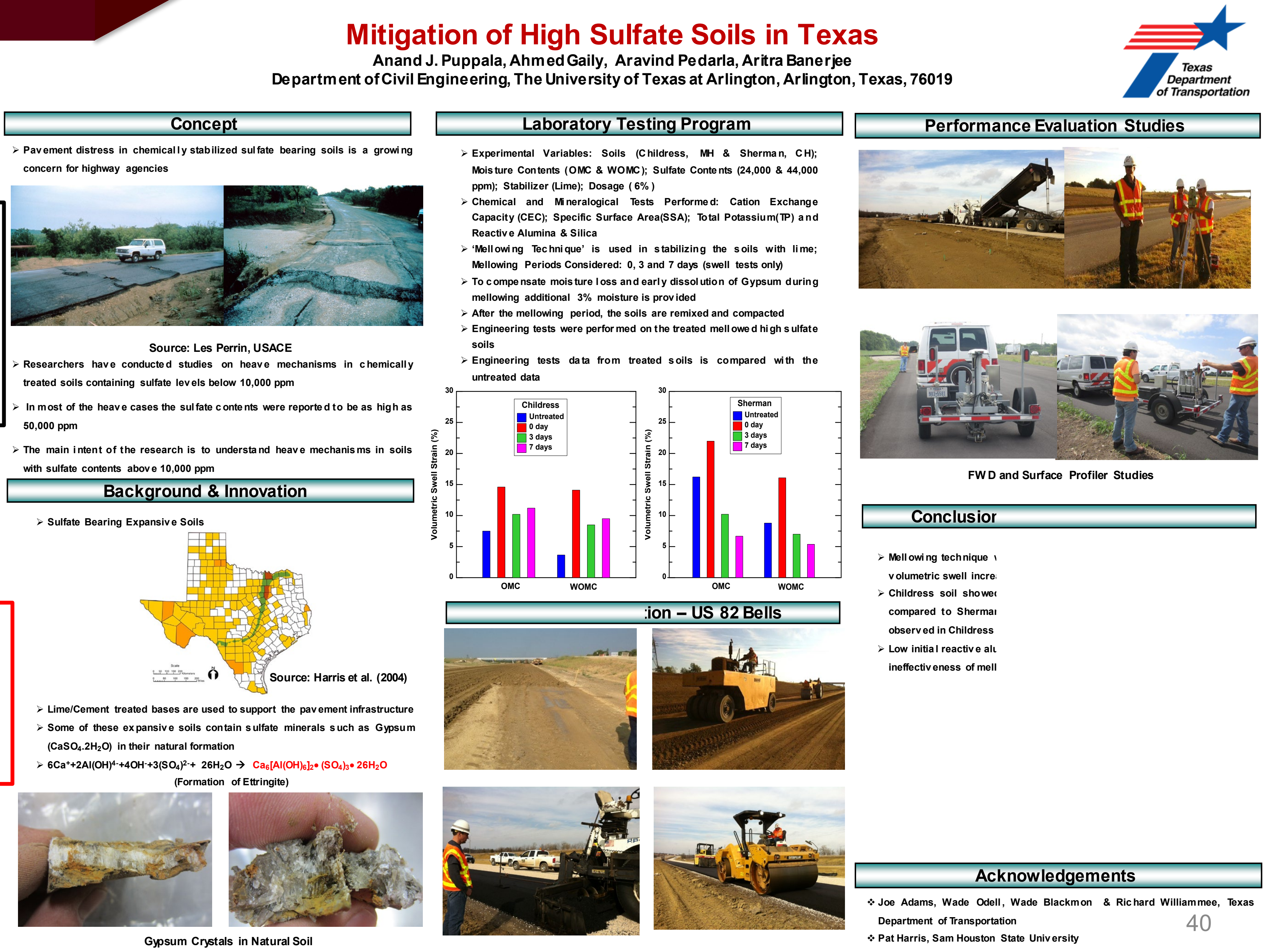


III. Case Study 2

AASHTO RAC Showcase Poster

Transportation Research Board Annual Meeting, Washington, DC, 2018

Recent Paper in ASCE JGGE 2020:
Talluri et al. 2020 – High Sulfate Soils



Mitigation of High Sulfate Soils in Texas

Anand J. Puppala, Ahmed Gaily, Aravind Pedarla, Aritra Banerjee
Department of Civil Engineering, The University of Texas at Arlington, Arlington, Texas, 76019

Texas Department of Transportation

Concept

- Pavement distress in chemically stabilized sulfate bearing soils is a growing concern for highway agencies

Source: Les Perrin, USACE

- Researchers have conducted studies on heave mechanisms in chemically treated soils containing sulfate levels below 10,000 ppm
- In most of the heave cases the sulfate contents were reported to be as high as 50,000 ppm
- The main intent of the research is to understand heave mechanisms in soils with sulfate contents above 10,000 ppm

Background & Innovation

- Sulfate Bearing Expansive Soils

Source: Harris et al. (2004)

- Lime/Cement treated bases are used to support the pavement infrastructure
- Some of these expansive soils contain sulfate minerals such as Gypsum ($CaSO_4.2H_2O$) in their natural formation
- $6Ca^{+}+2Al(OH)^{4-}+4OH^{-}+3(SO_4)^{2-}+ 26H_2O \rightarrow Ca_6[Al(OH)_6]_2\bullet (SO_4)_3\bullet 26H_2O$

(Formation of Ettringite)

Gypsum Crystals in Natural Soil

Laboratory Testing Program

- Experimental Variables: Soils (Childress, MH & Sherman, CH); Moisture Contents (OMC & WOMC); Sulfate Contents (24,000 & 44,000 ppm); Stabilizer (Lime); Dosage (6%)
- Chemical and Mineralogical Tests Performed: Cation Exchange Capacity (CEC); Specific Surface Area(SSA); Total Potassium(TP) and Reactive Alumina & Silica
- 'Mellowing Technique' is used in stabilizing the soils with lime; Mellowing Periods Considered: 0, 3 and 7 days (swell tests only)
- To compensate moisture loss and early dissolution of Gypsum during mellowing additional 3% moisture is provided
- After the mellowing period, the soils are remixed and compacted
- Engineering tests were performed on the treated mellowed high sulfate soils
- Engineering tests data from treated soils is compared with the untreated data

ion – US 82 Bells

Performance Evaluation Studies

FWD and Surface Profiler Studies

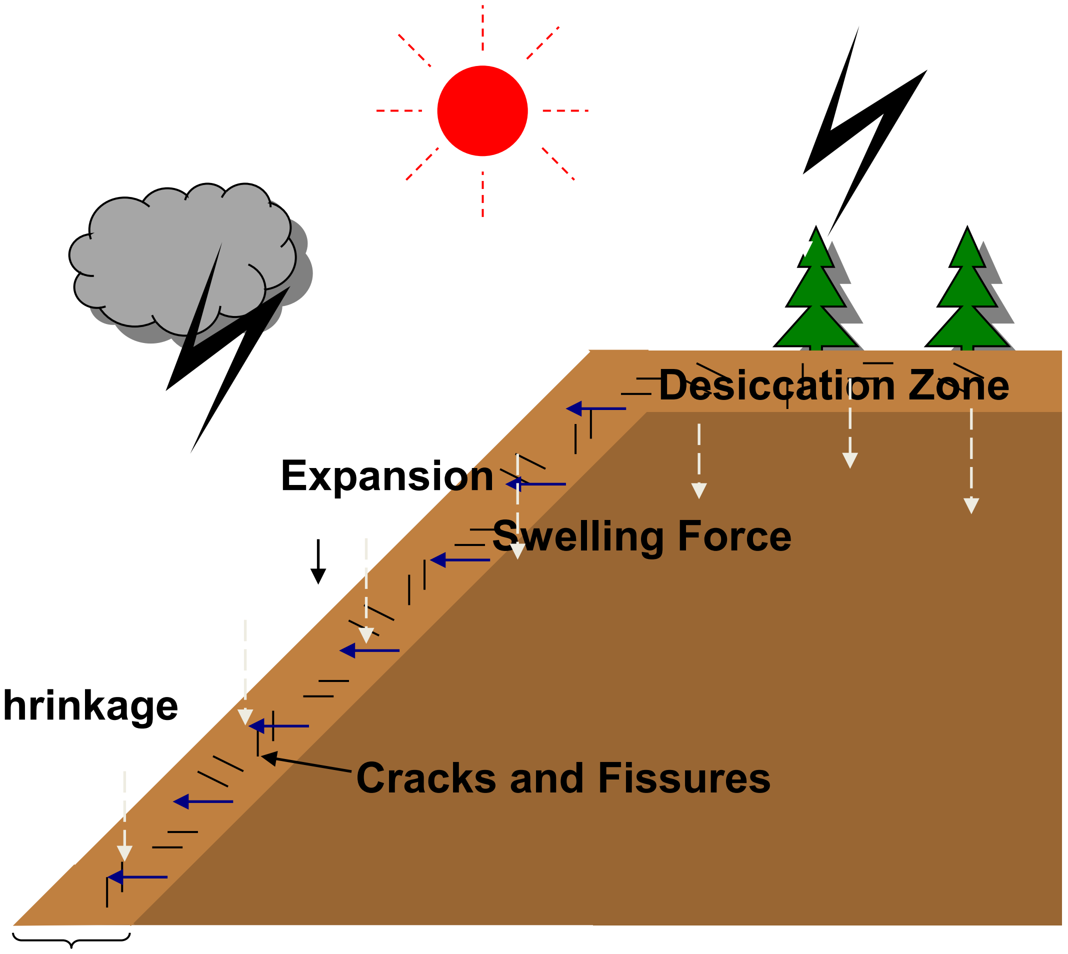
Conclusior

- Mellowing technique
volumetric swell incre
- Childress soil showe
compared to Sherma
observed in Childress
- Low initial reactive al
ineffectiveness of mell

Acknowledgements

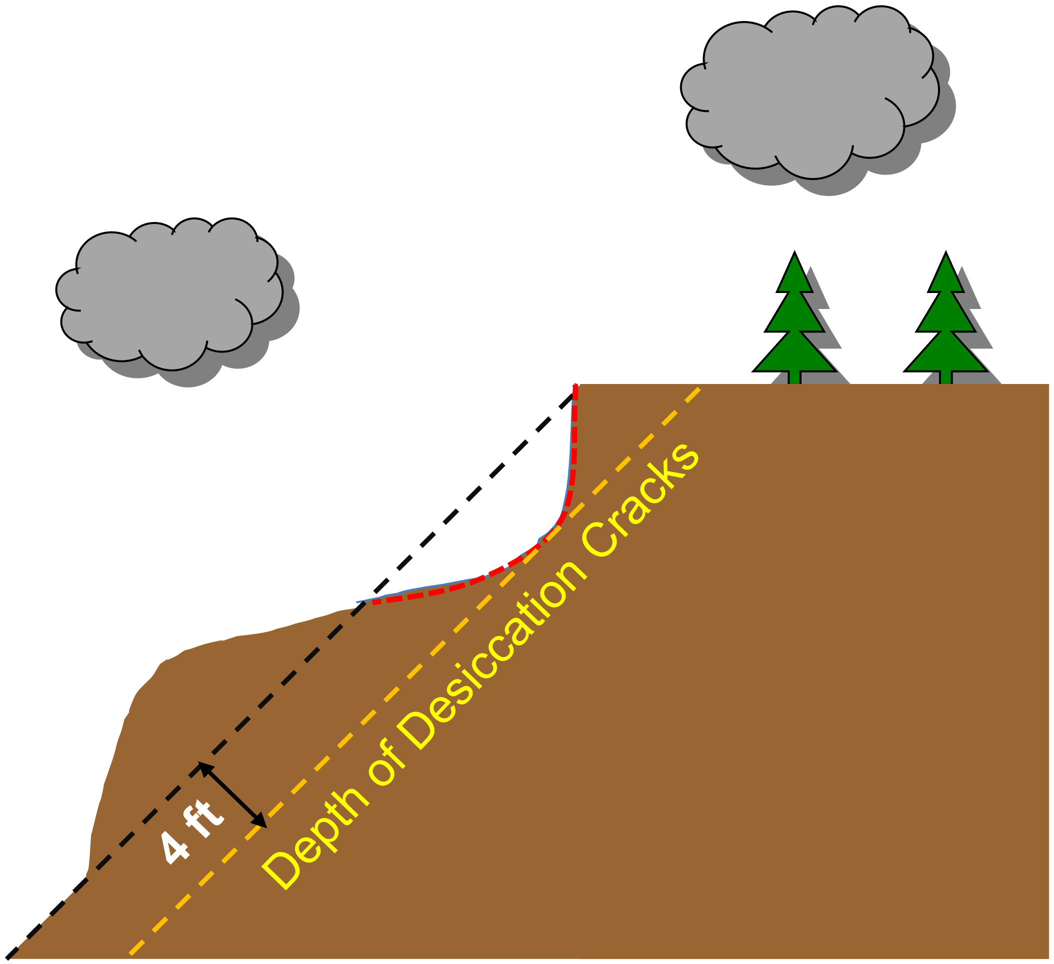
- Joe Adams, Wade Odell, Wade Blackmon & Richard Williammee, Texas Department of Transportation
- Pat Harris, Sam Houston State University

Surficial Slope Failures: Expansive Soils

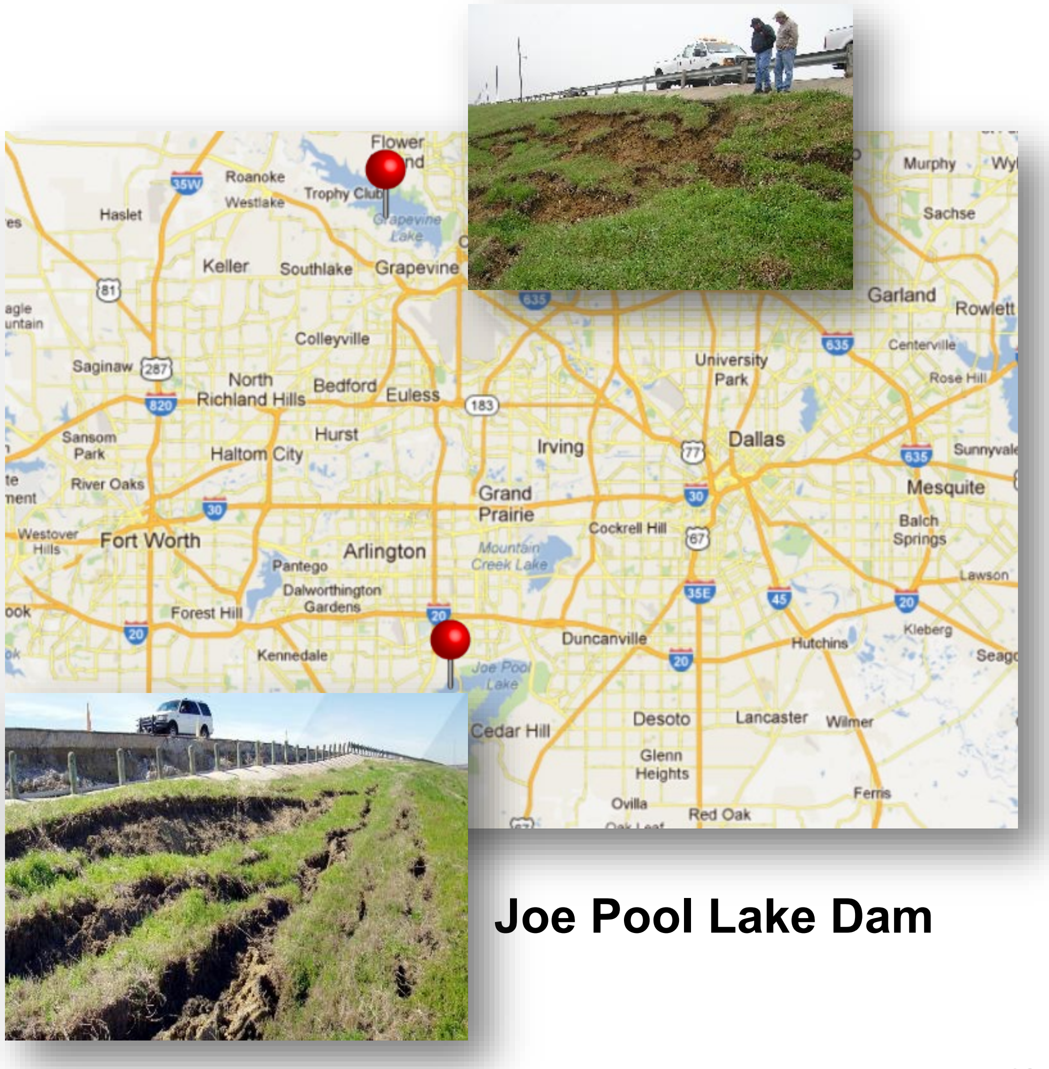


III. Case Study 3

Embankments, Dams and Slopes



Grapevine Dam

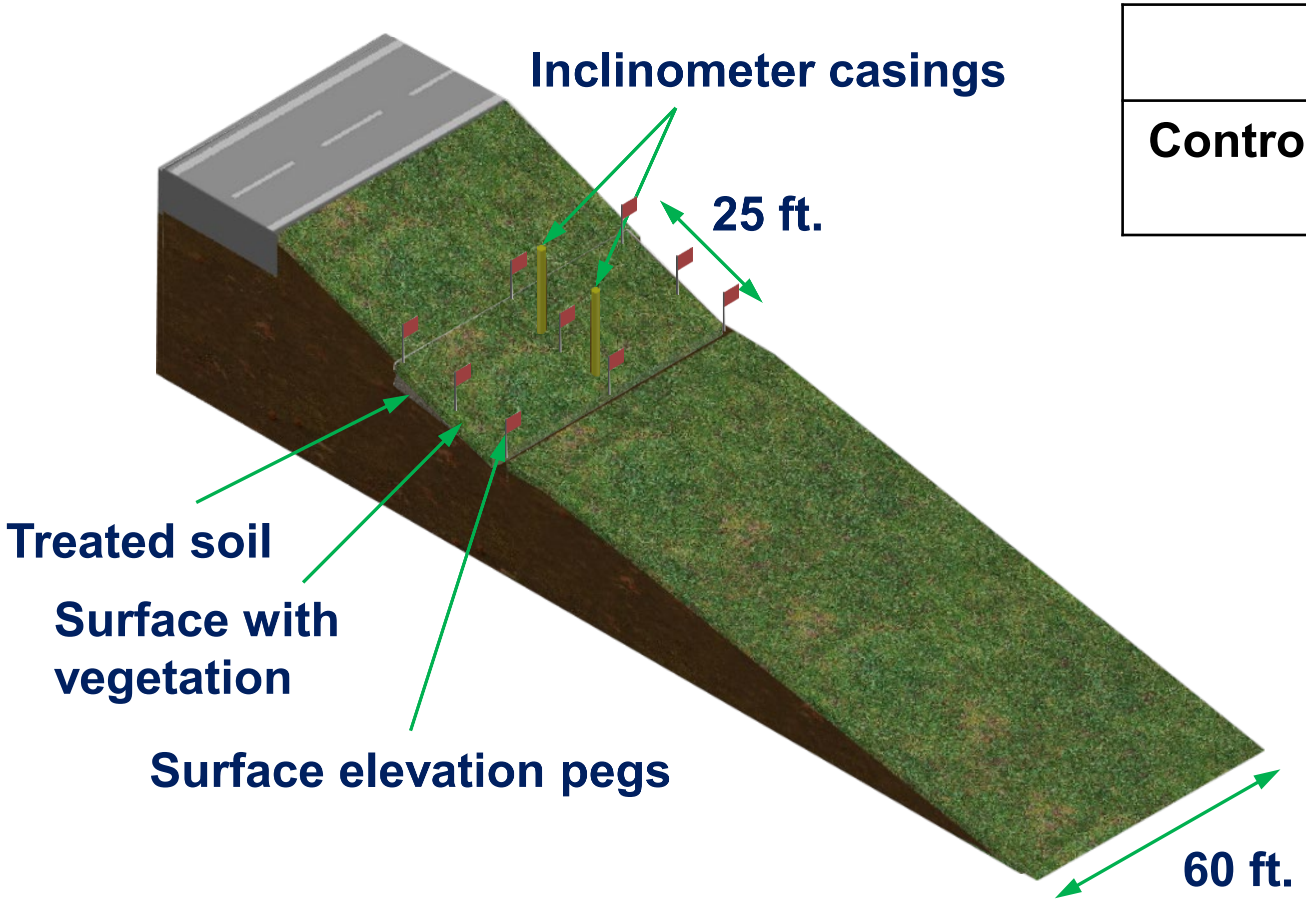


Joe Pool Lake Dam

III. Case Study 3

Embankments, Dams and Slopes

Typical section



Five Sections				
Control	20% compost	4%lime + 0.30%fibers	8%lime + 0.15%fibers	8% lime

Instrumentation

Moisture sensor

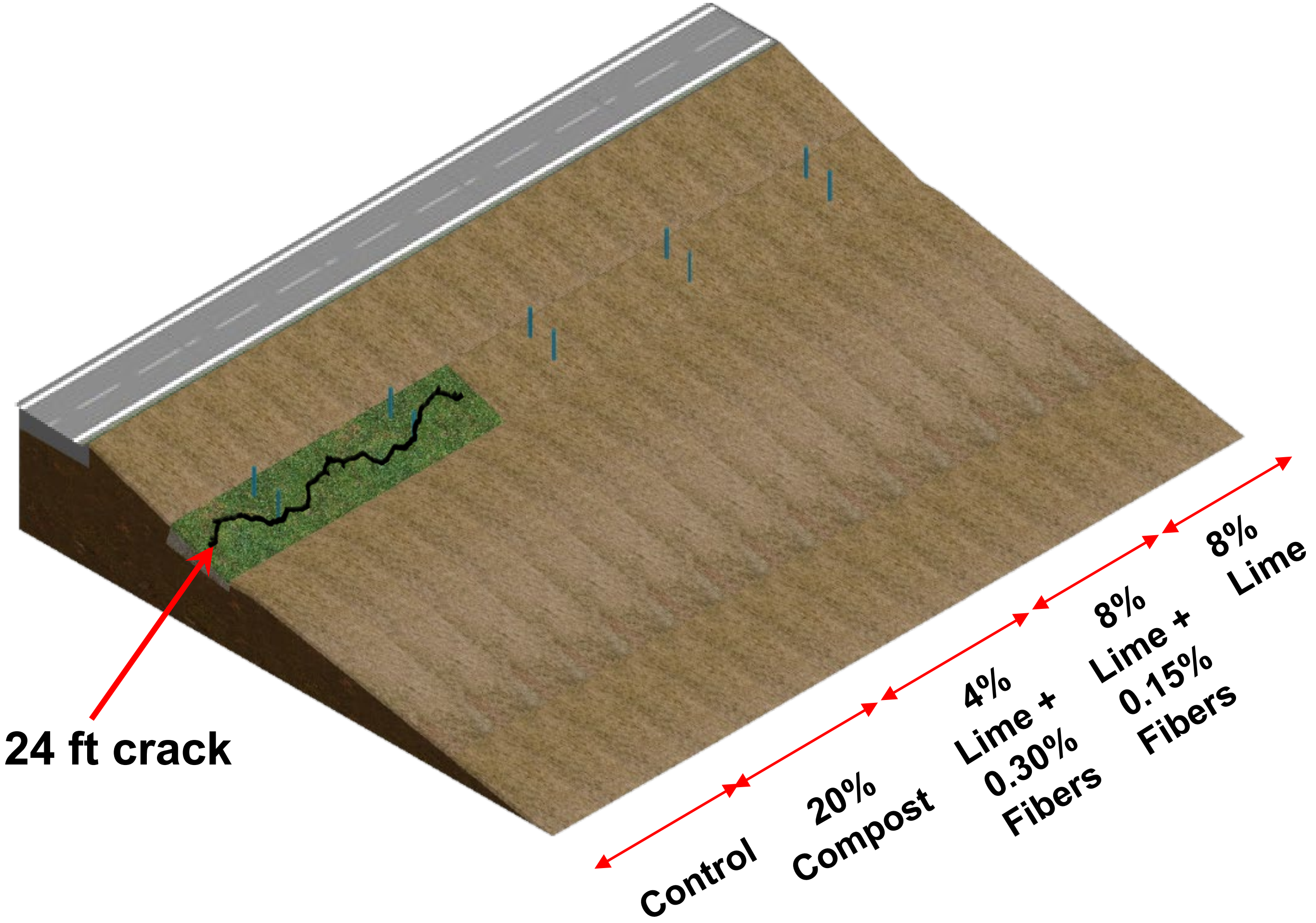
Total Station

Slope Indicator

III. Case Study 3

Embankments, Dams and Slopes

Joe Pool Dam

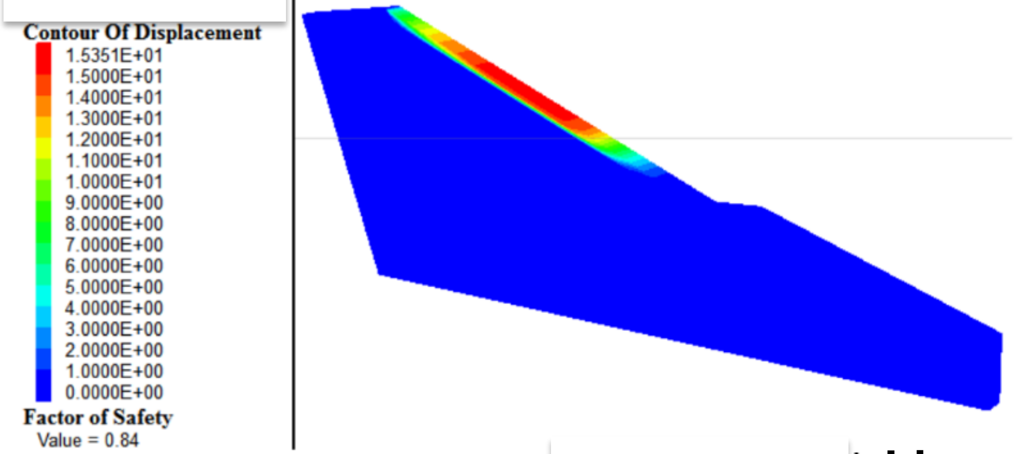



Control section

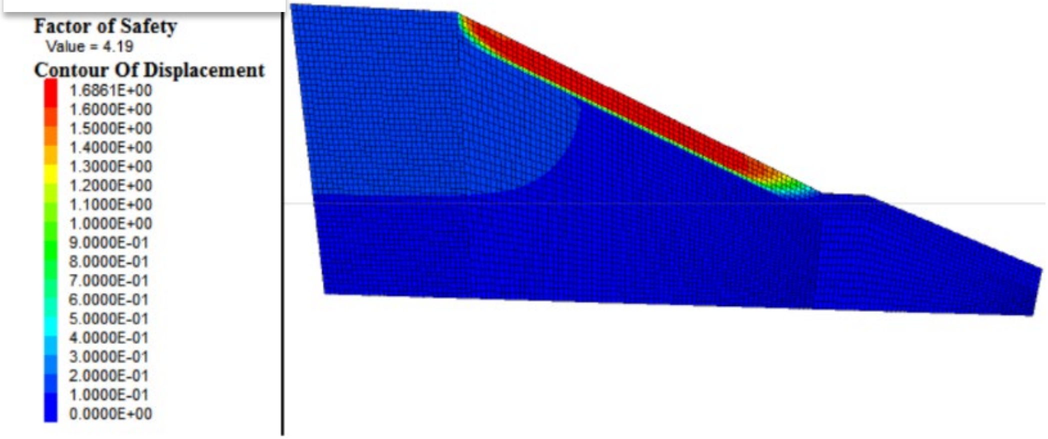

Desiccation Cracks

Slope Stability of Grapevine Dam- FOS

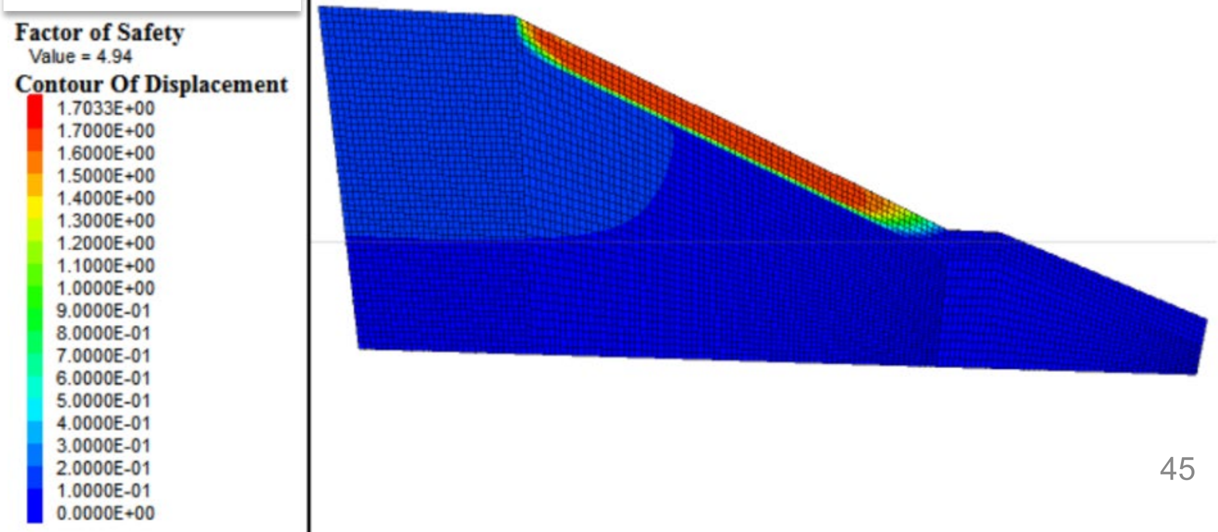
Control Section (FOS = 0.8)



Lime Treated (FOS = 4.2)

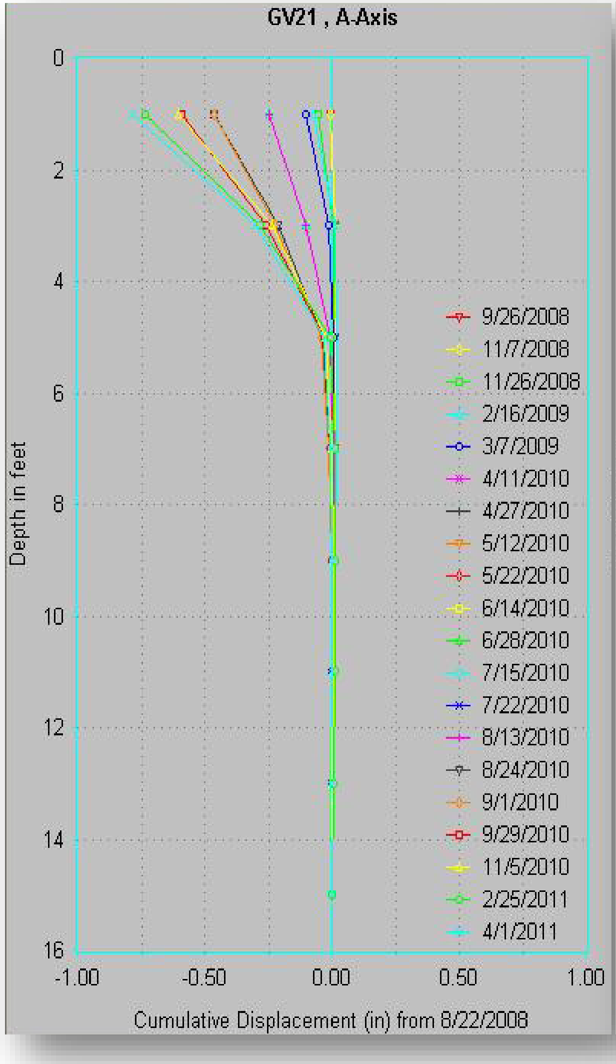


Lime + Fiber Treated (FOS = 4.9)

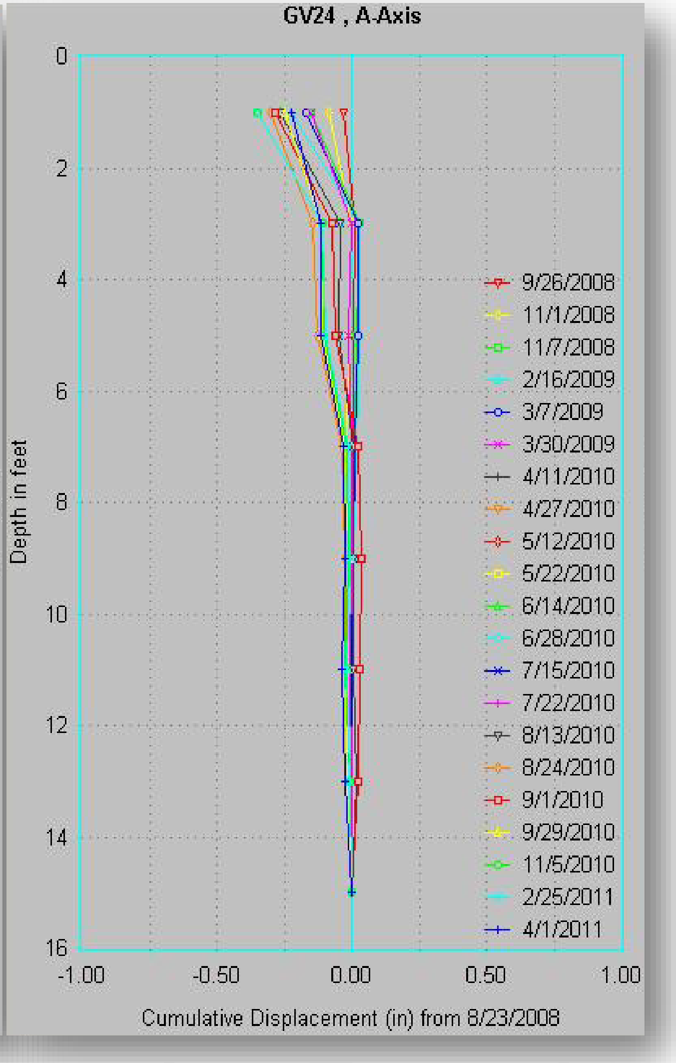


III. Case Study 3

Vertical Inclinometer Readings



Control



Lime Treated

Dam Safety Factsheet- USACE

CESWF Dam Safety Factsheet on
Embankment Stability Research and Development

U.S. ARMY CORPS OF ENGINEERS BUILDING STRONG®

Background and Overview:

Embankment Stability has historically been an issue for public infrastructure including dams, levees and highways that provide vast flood risk and transportation management benefits to the Nation. Joe Pool Dam suffered a stability failure during impoundment due to constructions defects with properly compacting the high placticity embankment soils. Joe Pool, Lewisville, Grapevine and several other dams, as well as levees, in the area have experienced an excessive number shallow instabilities, or surface slides, which only mildly threaten the integrity, but drive up O&M costs for monitoring and repairs. Floods in 2007 caused up to 20 slides along the Dallas Floodway and similar extreme storms in 2009 caused about 10 slides at Joe Pool that cost around $2M to monitor, repair and maintain.

Research Objectives and Conclusions:

Embankment Stability is currently under evaluation for Joe Pool and Grapevine Dams by the Fort Worth District in cooperation with the University of Texas at Arlington (UTA). Research efforts commenced in 2005-2008 by Mr. Kenneth McCleskey and Ms. Sarwenaj Ashraf of the Geotechnical Branch while in pursuit of thier Masters Degree in Civil Engineering. Research concluded that the regional soils were suseptible to shallow instabilities induced by volume changes due to seasonal moisture variations.

Additional field research was conducted by UTA graduate students in 2008-2014 the under direction of Dr. Anand Puppala to determine the Best Management Practices (BMPs) for repairing the induced slides using admixtures in the embankment soils; such as lime, composite fibers and compost to improve engineering properties for strength, durability, cracking and moisture control. Five test sections were prepared with different treatment methods and instrumentation was installed to monitor various properties that are known to affect the embankemnt stability. Instruments are read monthly and laboratory testing has been conducted to evaluate strength properties of the different treatments with respect to slope stability, as well as 2-dimensional modeling to analyse the Factor of Safety for a series of moisture conditions. This research has resulted in BMPs which have been used to improve repairs for more than five Fort Worth District dams as well as along the Dallas Floodway Levees.

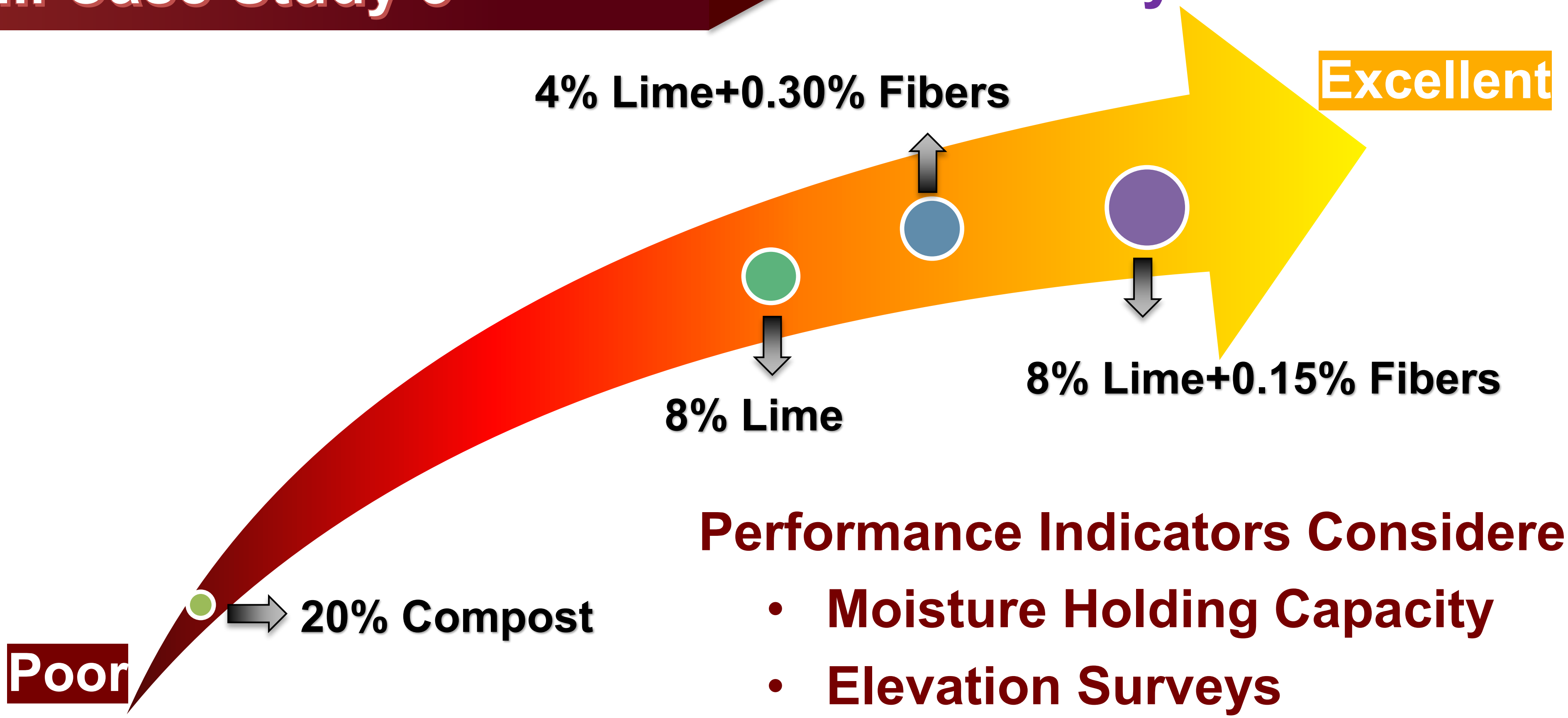
Joe Pool 2009

Joe Pool Test Section 2009

U.S. ARMY CORPS OF ENGINEERS – FORT WORTH DISTRICT, SOUTHWESTERN DIVISION
819 TAYLOR STREET, FORT WORTH, TX 76102
www.swf.usace.army.mil
March 04, 2013

III. Case Study 3

Summary of Stabilizers' Performance



Performance Indicators Considered

- Moisture Holding Capacity
- Elevation Surveys
- Inclinometer Surveys
- Desiccation Cracks
- Vegetation Growth
- Strength Properties
- Analytical Modeling

III. Case Study 3

Failed Highway Slope Section Details

Highway Embankment Slope Failure Along US75:
Texas DOT – Paris District

III. Case Study 3

Failed Highway Slope Section Details

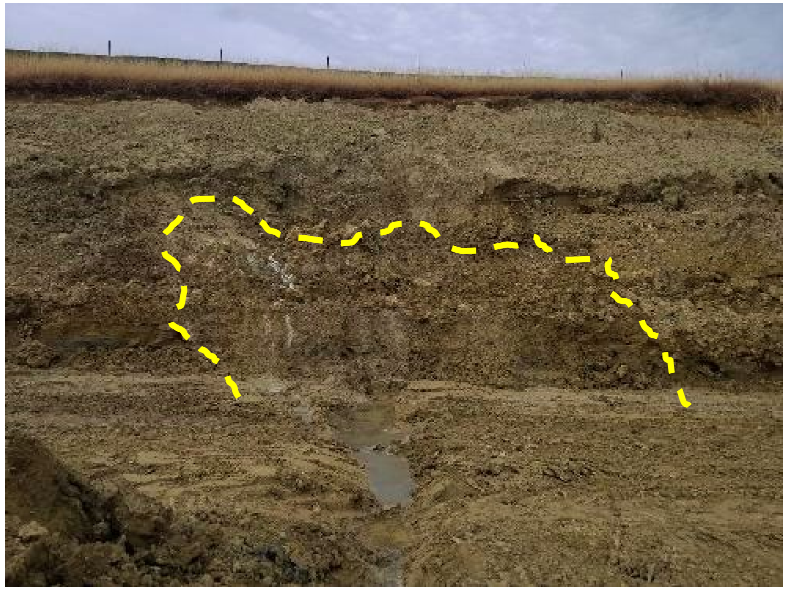
Randell lake

December 2017

December 2018

III. Case Study 3

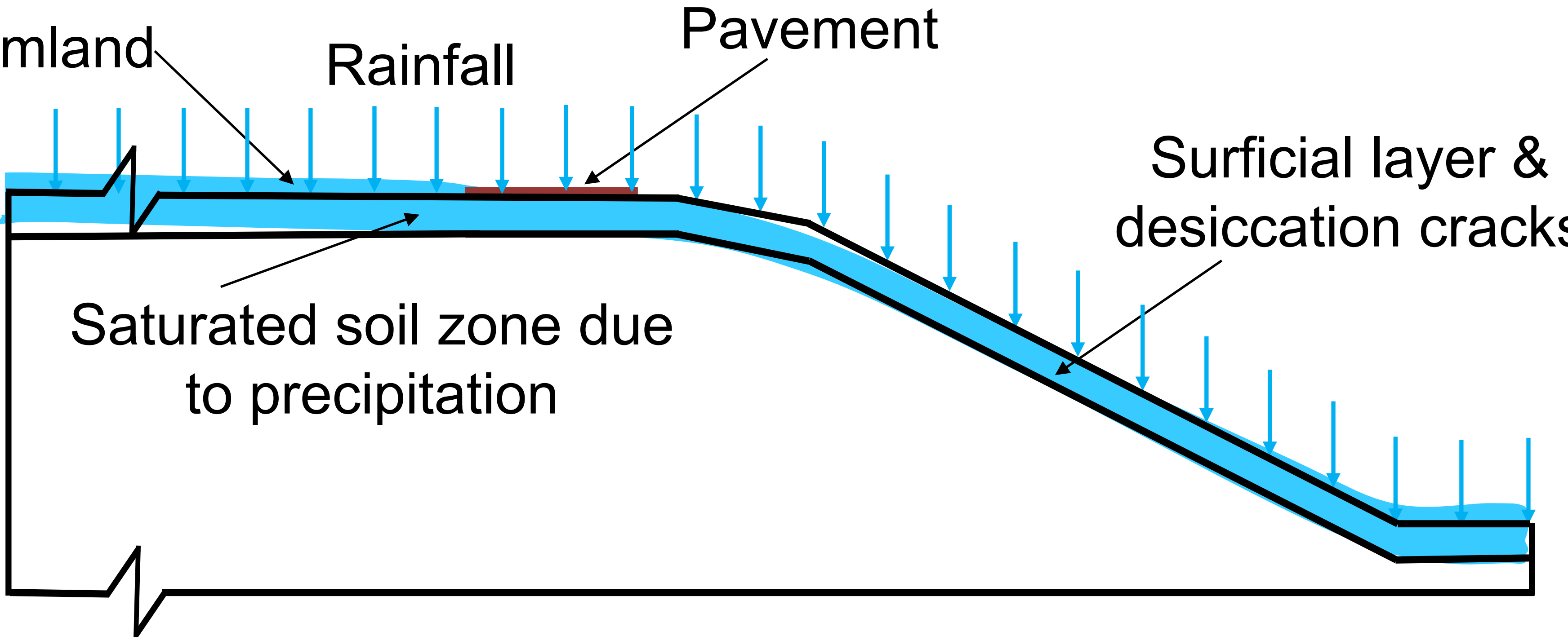
Failed Highway Embankment Details



III. Case Study 3

Failed Highway Embankment Details

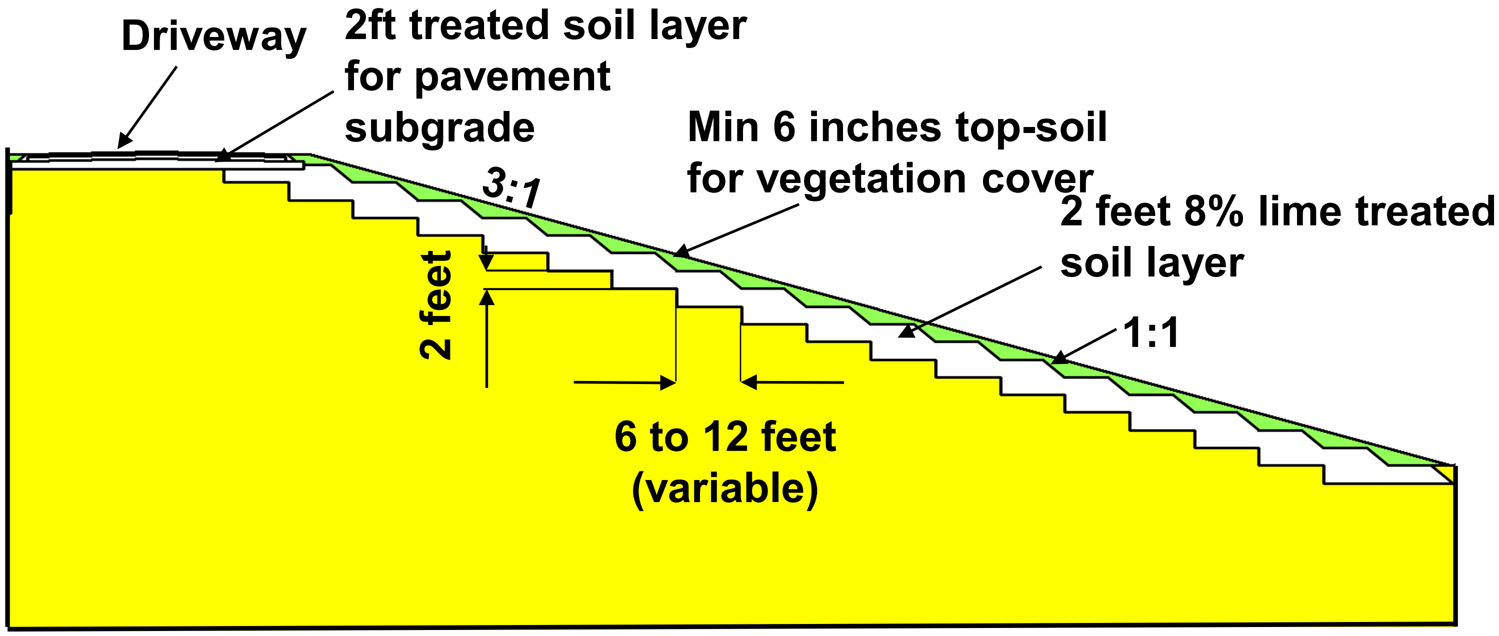
Stability Issues: Potential Moisture Movements

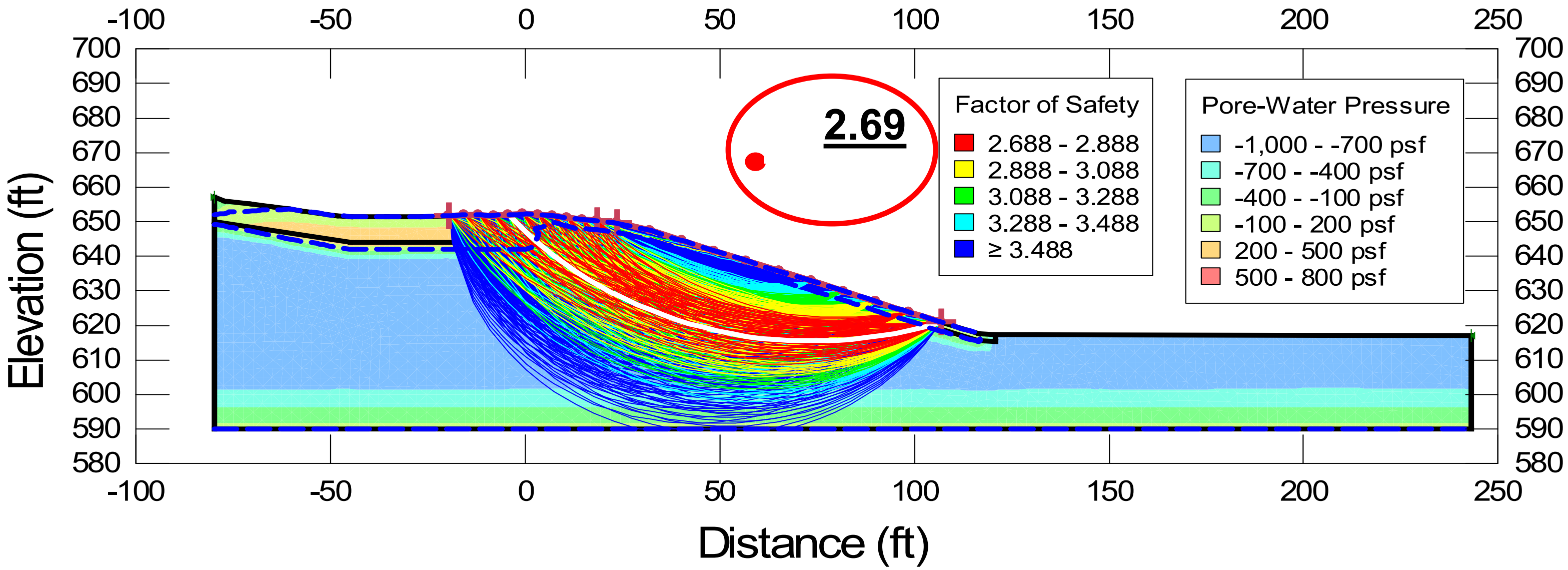


- **Coefficient of permeability of surficial layer ~ 10^{-1} to 10^{-3} cm/s**
- **Accumulated rainwater → Reduction in shear strength of soil**
- **Drainage is a problem**

III. Case Study 3

Highway Embankment Slope Modeling





Slope Stability: Lime Treated Section

Treated layer:

(8% Lime - 3 days cured)
c' = 89.8 psf
ϕ'= 29.0°
Fully Softened Strength

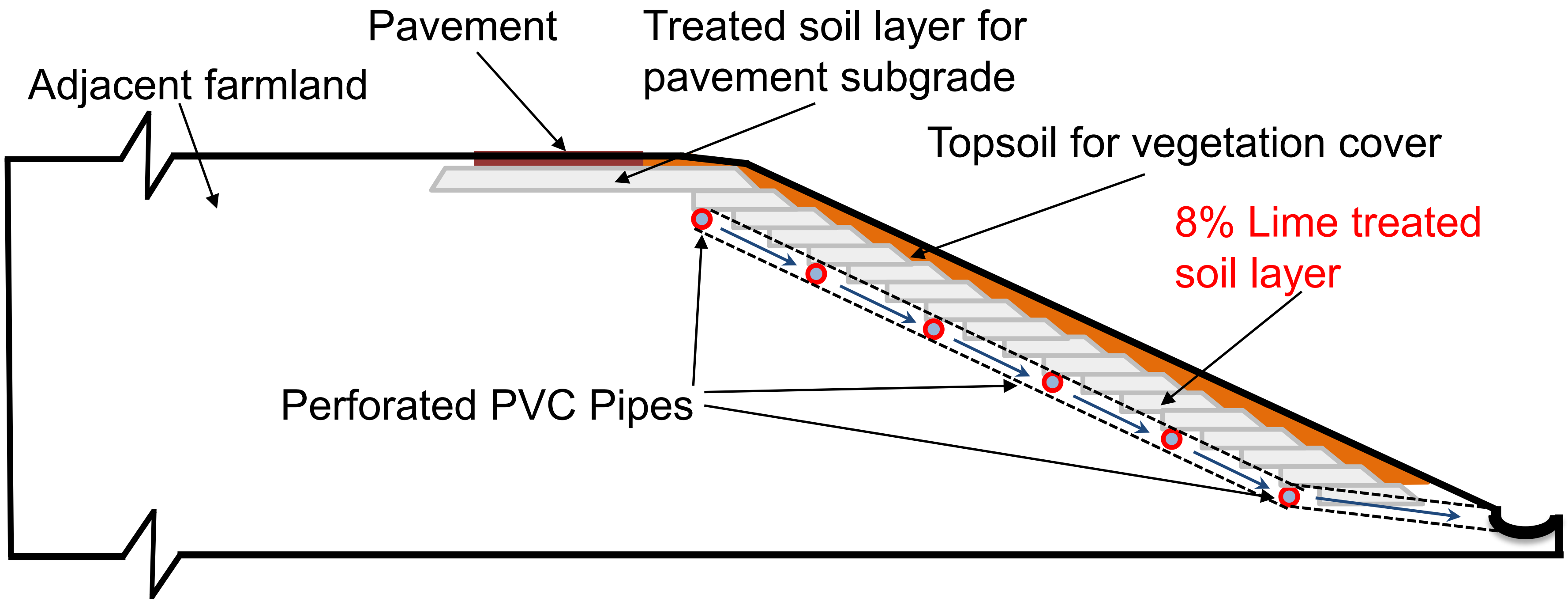
Deep layer:

c' = 280 psf
ϕ'= 23.6°
Peak Strength

- **2 ft - 8% Lime treated soil**
- **FOS > 1**
- **Safe**

III. Case Study 3

Embankment Reconstruction Details



Pavement

Adjacent farmland

Treated soil layer for pavement subgrade

Topsoil for vegetation cover

8% Lime treated soil layer

Perforated PVC Pipes

Purpose of Drains

- Prevent accumulation of rainwater
- Prevent reduction in shear strength

Purpose of Benching

- Ease of constructability
- Interface locking
- Prevent slickened slide plane

Visualization of Critical Infrastructure for Performance Monitoring

> ***"An instrument too often overlooked in our technical world is a human eye connected to the brain of an intelligent human being"***
>
> **– Prof. Ralph B. Peck**

Introduction

<u>Visualization</u> in Geotechnical Engineering is primarily used for graphical presentation of geotechnical data

- **Provide insight into the nature of the problem**
  e.g. conceptualization, risk identification
- **To develop potential solutions to complex projects**
  e.g. ground improvement, reduce uncertainties

3D Visualization Geological Model

Source: Autodesk

Visualization of Critical Infrastructure

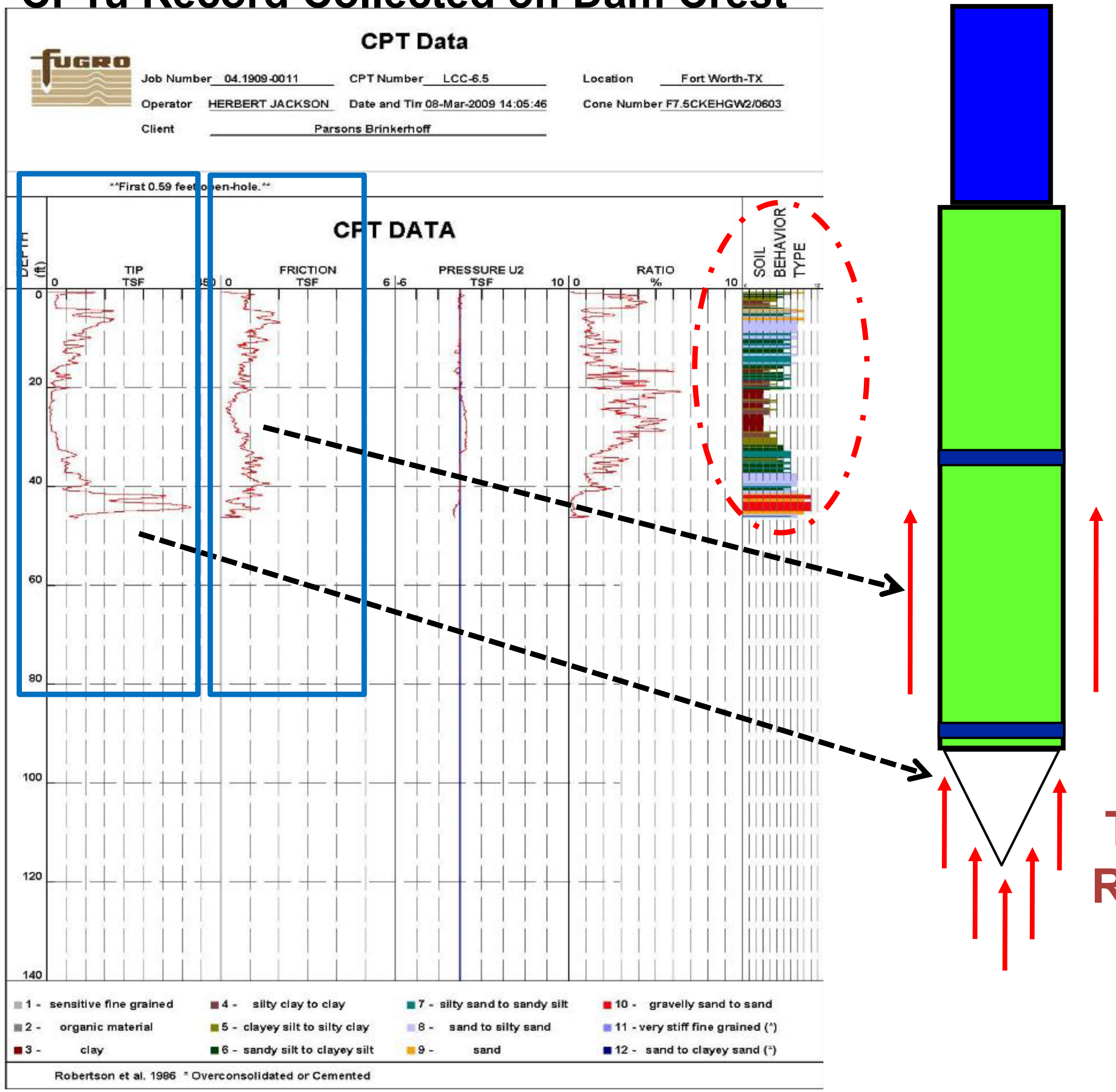
Vulnerability of Earthen Structures – Hydraulic Fill (HF) Dam Construction

Source: Hsu 1988

IV. Visualization

Typical CPTu Log along the Dam

CPTu Record Collected on Dam Crest



CPT Data

Job Number 04.1909-0011

CPT Number LCC-6.5

Location Fort Worth-TX

Operator HERBERT JACKSON

Date and Tir 08-Mar-2009 14:05:46

Cone Number F7.5CKEHGW2/0603

Client Parsons Brinkerhoff

First 0.59 feet open-hole.

CPT DATA

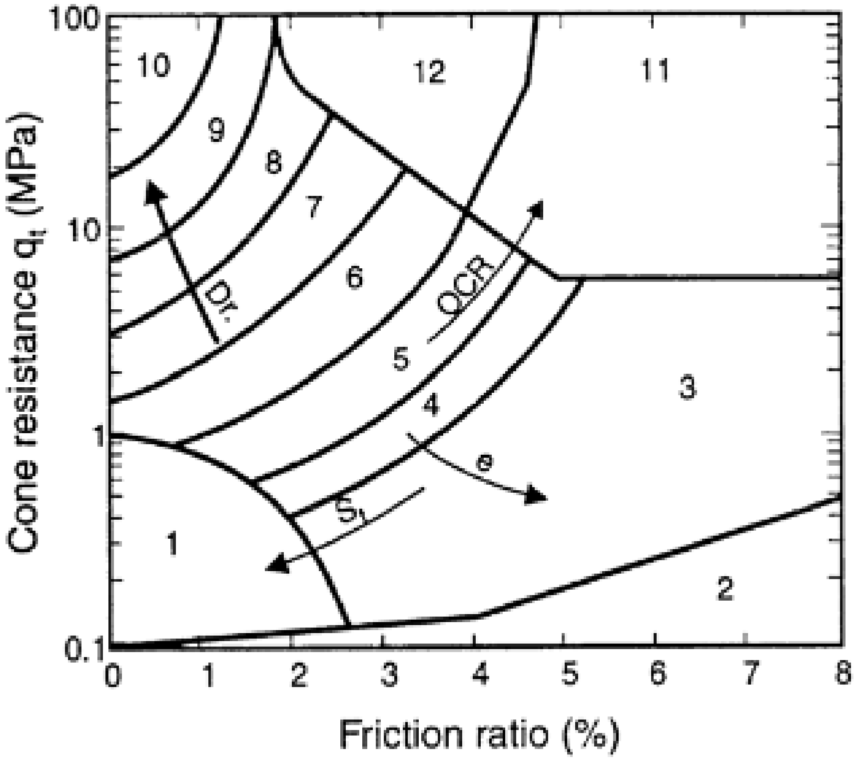
- 1 - sensitive fine grained
- 2 - organic material
- 3 - clay
- 4 - silty clay to clay
- 5 - clayey silt to silty clay
- 6 - sandy silt to clayey silt
- 7 - silty sand to sandy silt
- 8 - sand to silty sand
- 9 - sand
- 10 - gravelly sand to sand
- 11 - very stiff fine grained (*)
- 12 - sand to clayey sand (*)

Robertson et al. 1986 * Overconsolidated or Cemented

Sleeve Friction

Tip Resistance

Robertson (1986) Soil Behavior Type Chart

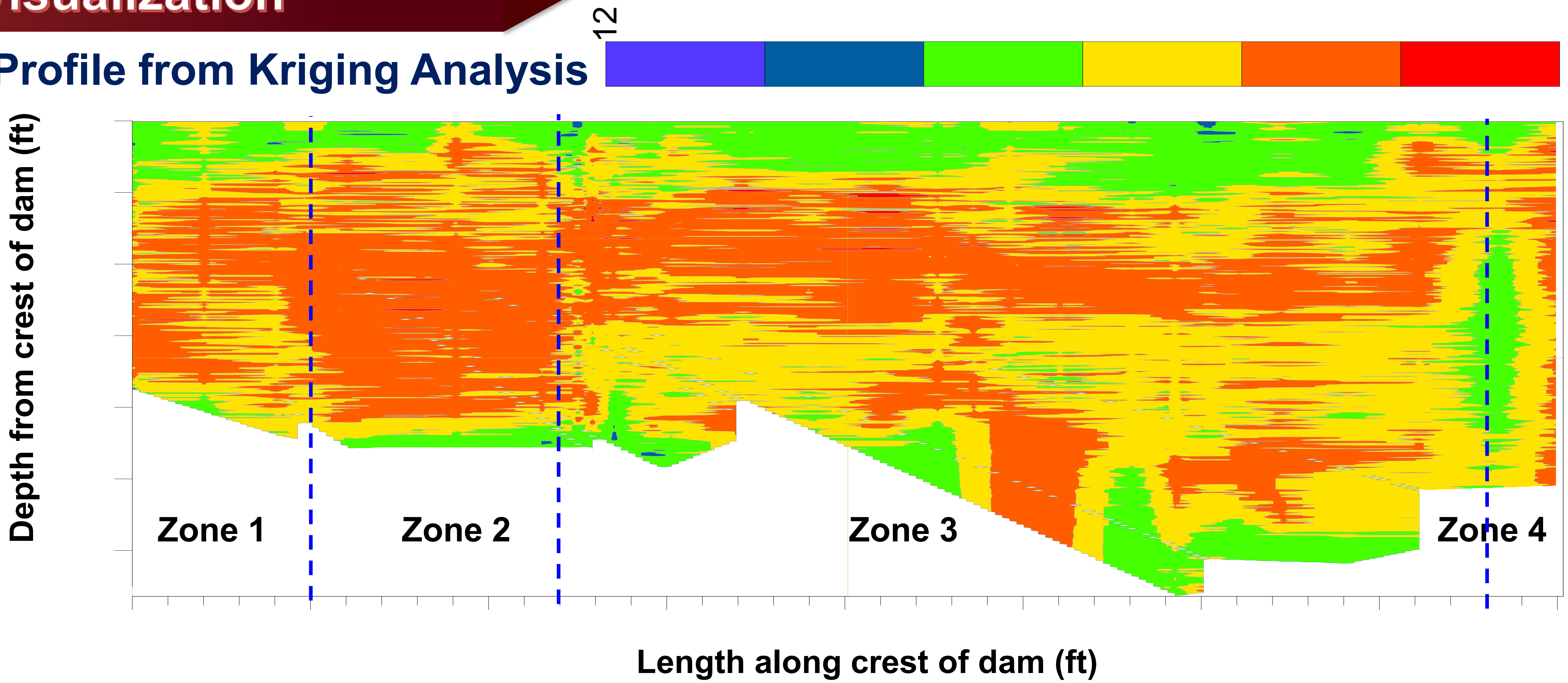


SBT Classification - **1:** sensitive fine grained; **2:** organic material; **3:** clay; **4:** silty clay to clay; **5:** clayey silt to silty clay; **6:** sandy silt to clayey silt; **7:** silty sand to sandy silt; **8:** sand to silty sand; **9:** sand; **10:** gravelly sand to sand; **11:** very stiff fine grained; **12:** sand to clayey sand

IV. Visualization

2-Dimensional Visualization of Dam

SBT Profile from Kriging Analysis

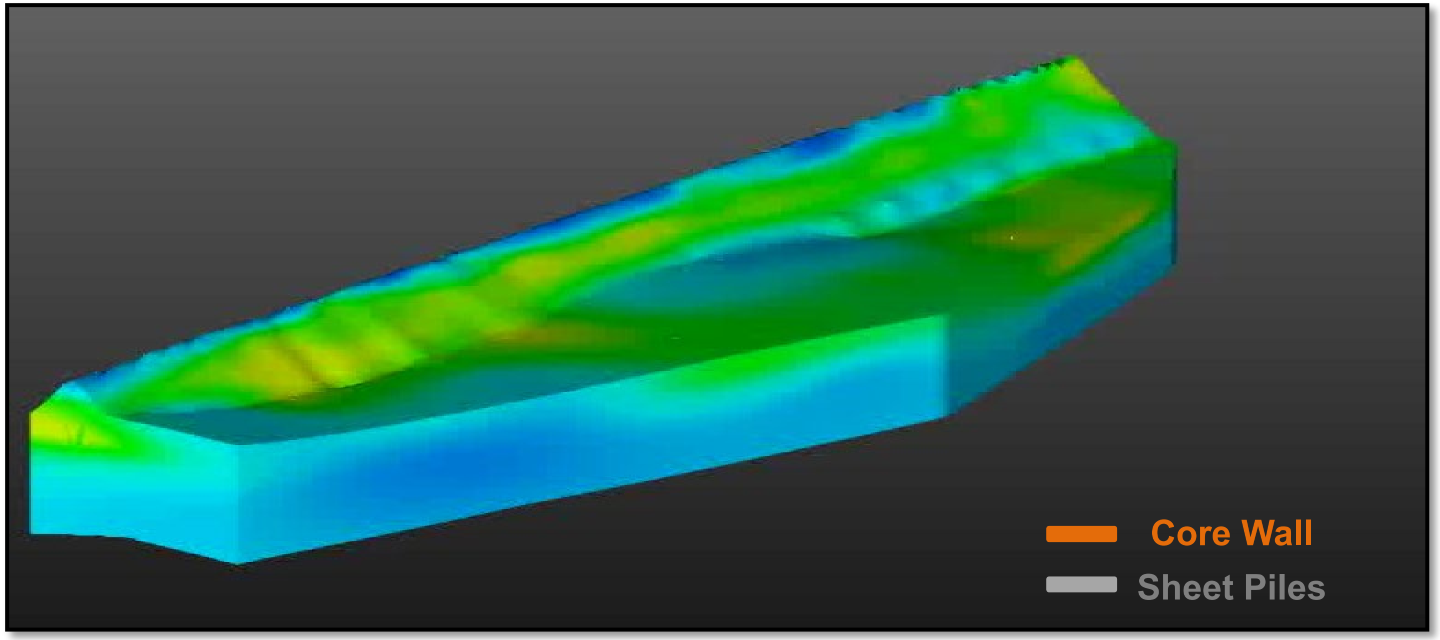


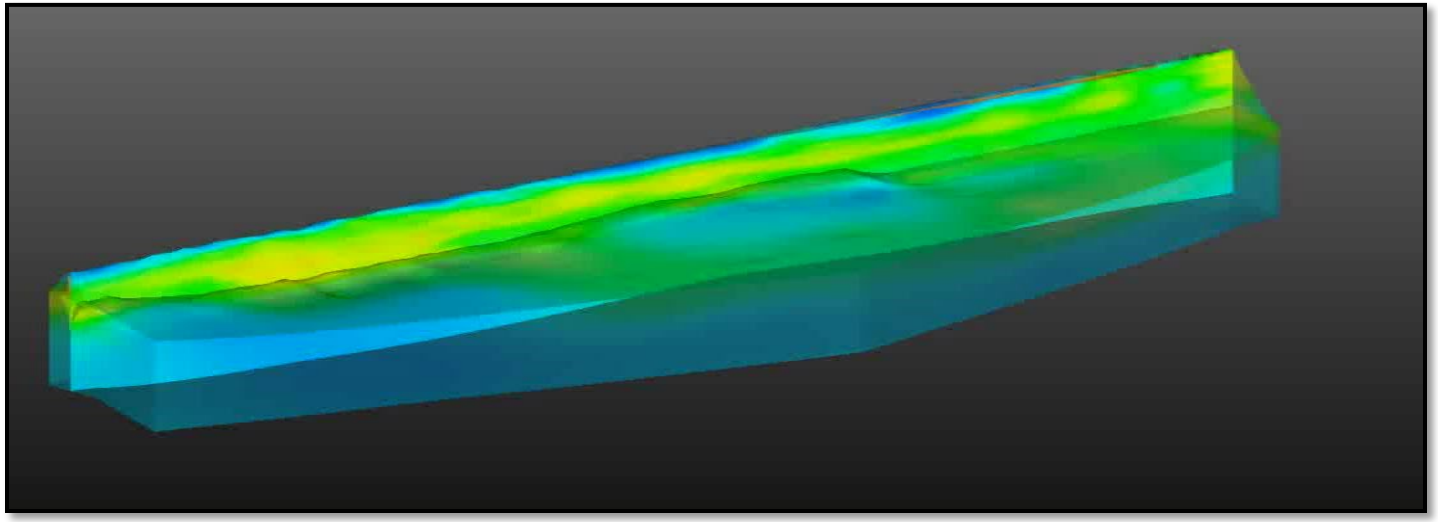
SBT classifications - **1:** sensitive fine grained; **2:** organic material; **3:** clay; **4:** silty clay to clay; **5:** clayey silt to silty clay; **6:** sandy silt to clayey silt; **7:** silty sand to sandy silt; **8:** sand to silty sand; **9:** sand; **10:** gravelly sand to sand; **11:** very stiff fine grained; **12:** sand to clayey sand

Key Observations: 4 zones

Along Dam's Crest: 0 to 500ft ; 500 to 1200ft; 1200 to 3800ft; 3800 to 4000ft

3-Dimensional Visualization of Dam





trwd
Tarrant
Regional
Water
District

Hydraulic fill → Material variability

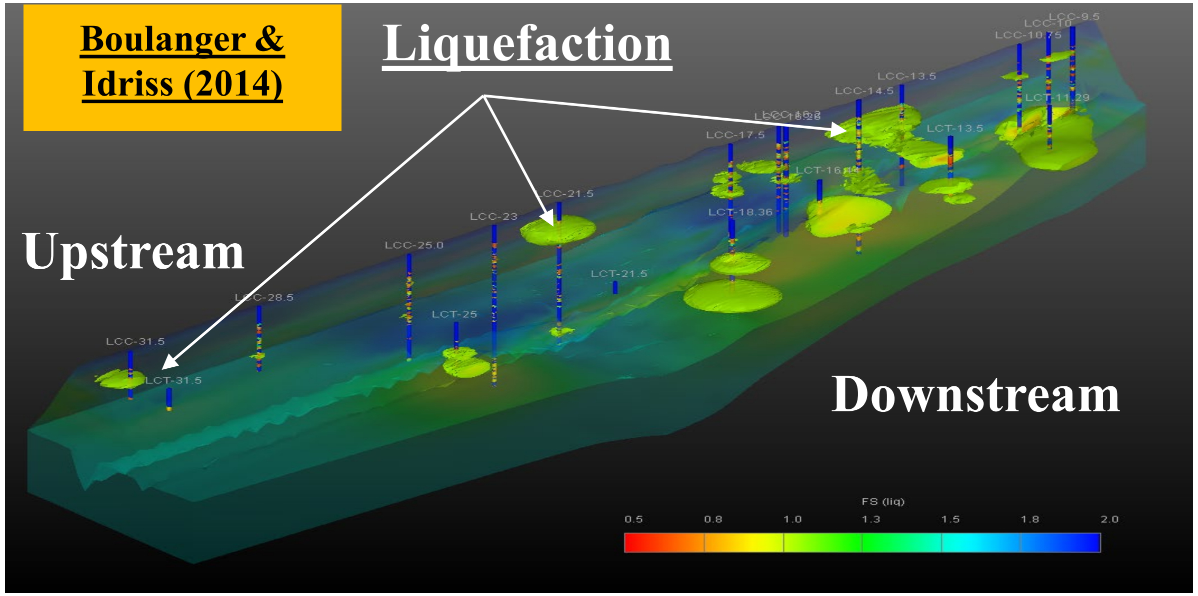
Identified the presence of clean sands in the core section (Zone 3). They can cause seepage problems or can be liquefied

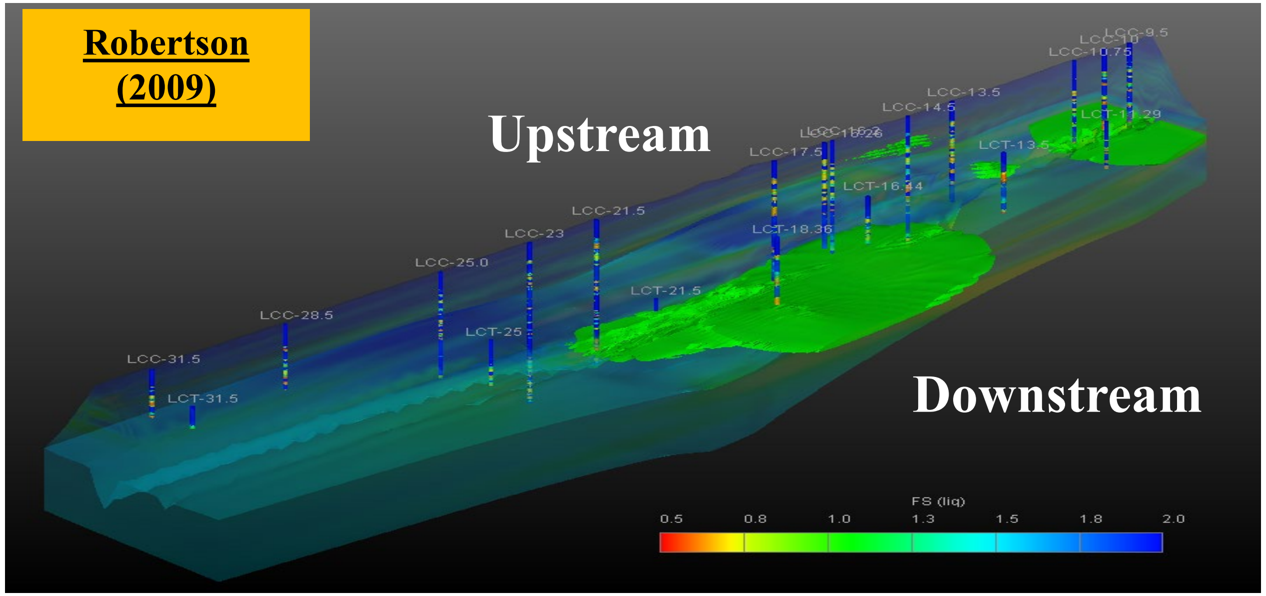
3-Dimensional Visualization of Dam

Seismic evaluation of dam (Hypothetical)

- Sand – Cyclic Liquefaction
- Clay – Cyclic Mobility

a_{max}0.3g, Lake Level: El+672.0

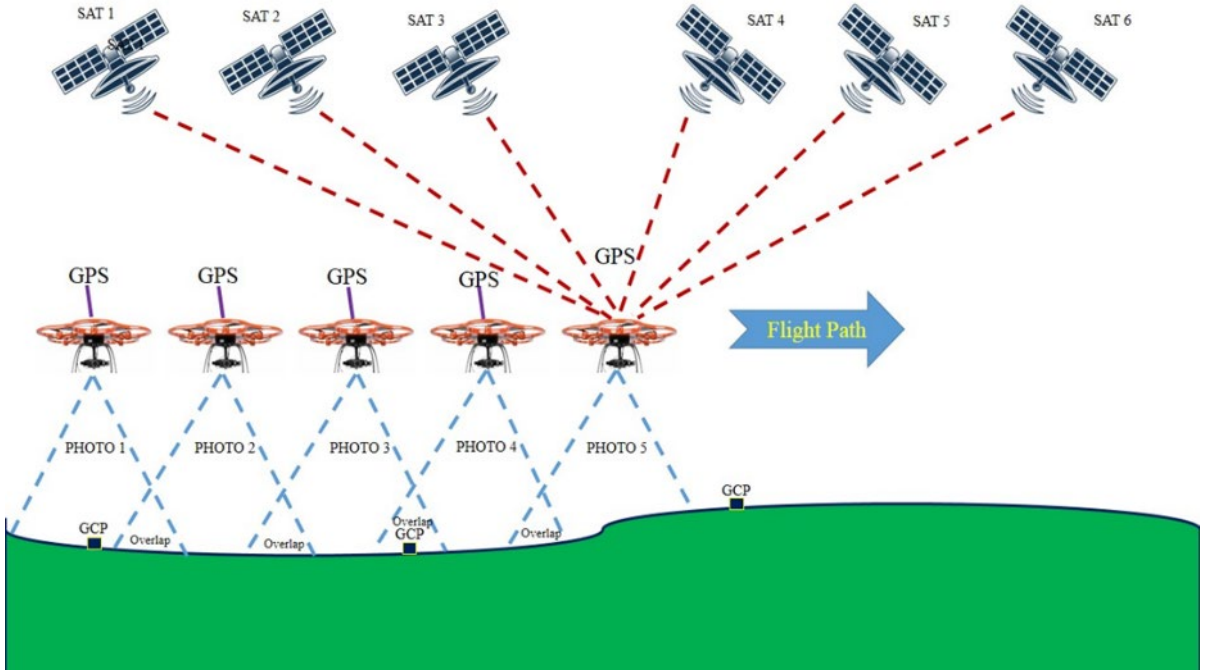




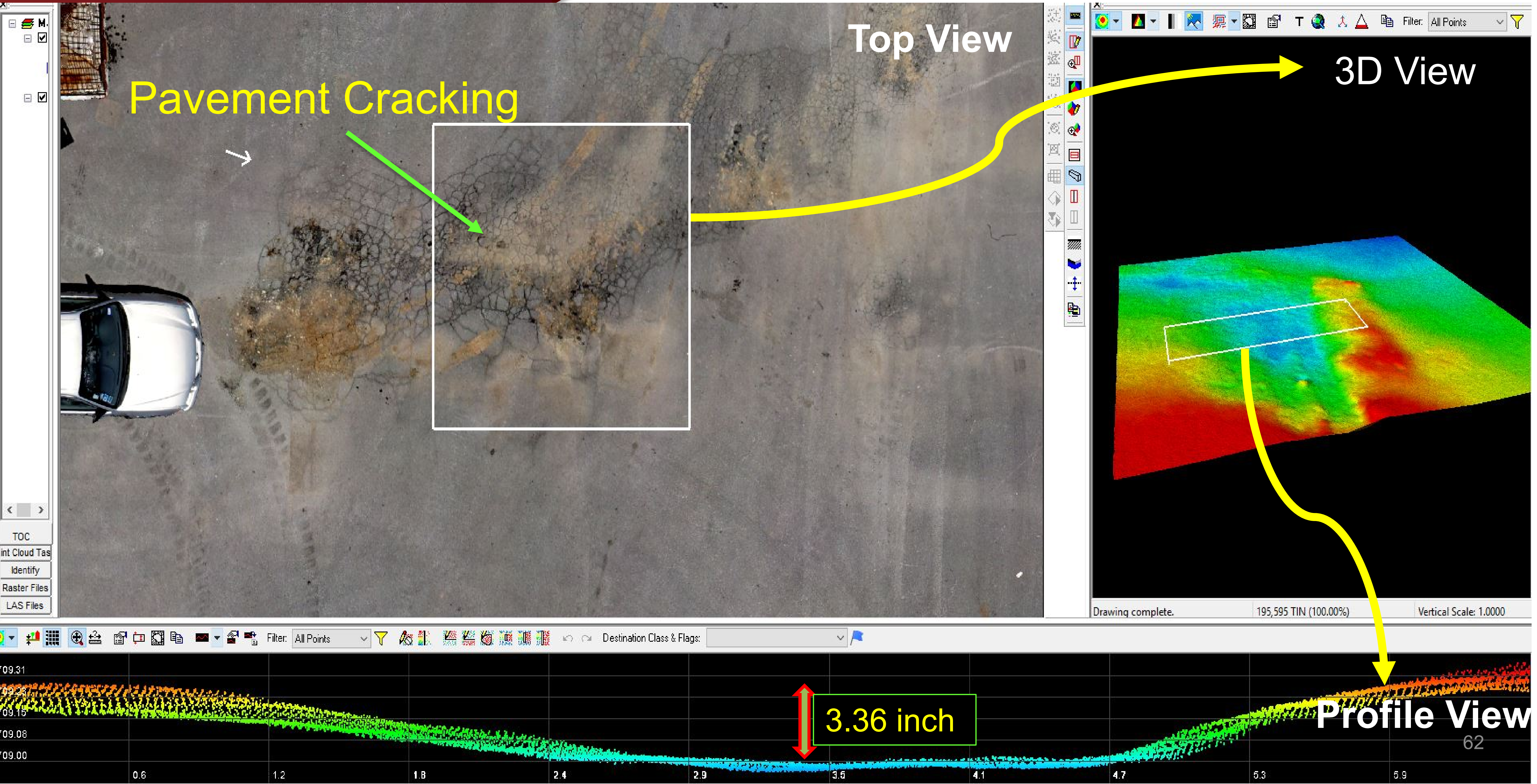
IV. Visualization

UAV-CRP Technology

No.	Type	Name	Latitude	Longitude	Altitude
1	Ⓠ	WP1	32.7848910	-97.2199521	30.00
2	Ⓠ	WP2	32.7848553	-97.2199255	30.00
3	Ⓠ	WP3	32.7848196	-97.2198989	30.00
4	Ⓠ	WP4	32.7847839	-97.2198723	30.00
5	Ⓠ	WP5	32.7847482	-97.2198457	30.00
6	Ⓠ	WP6	32.7847126	-97.2198191	30.00
7	Ⓠ	WP7	32.7846769	-97.2197924	30.00



Pavement Distress: Subgrade Failure



Filter: All Points

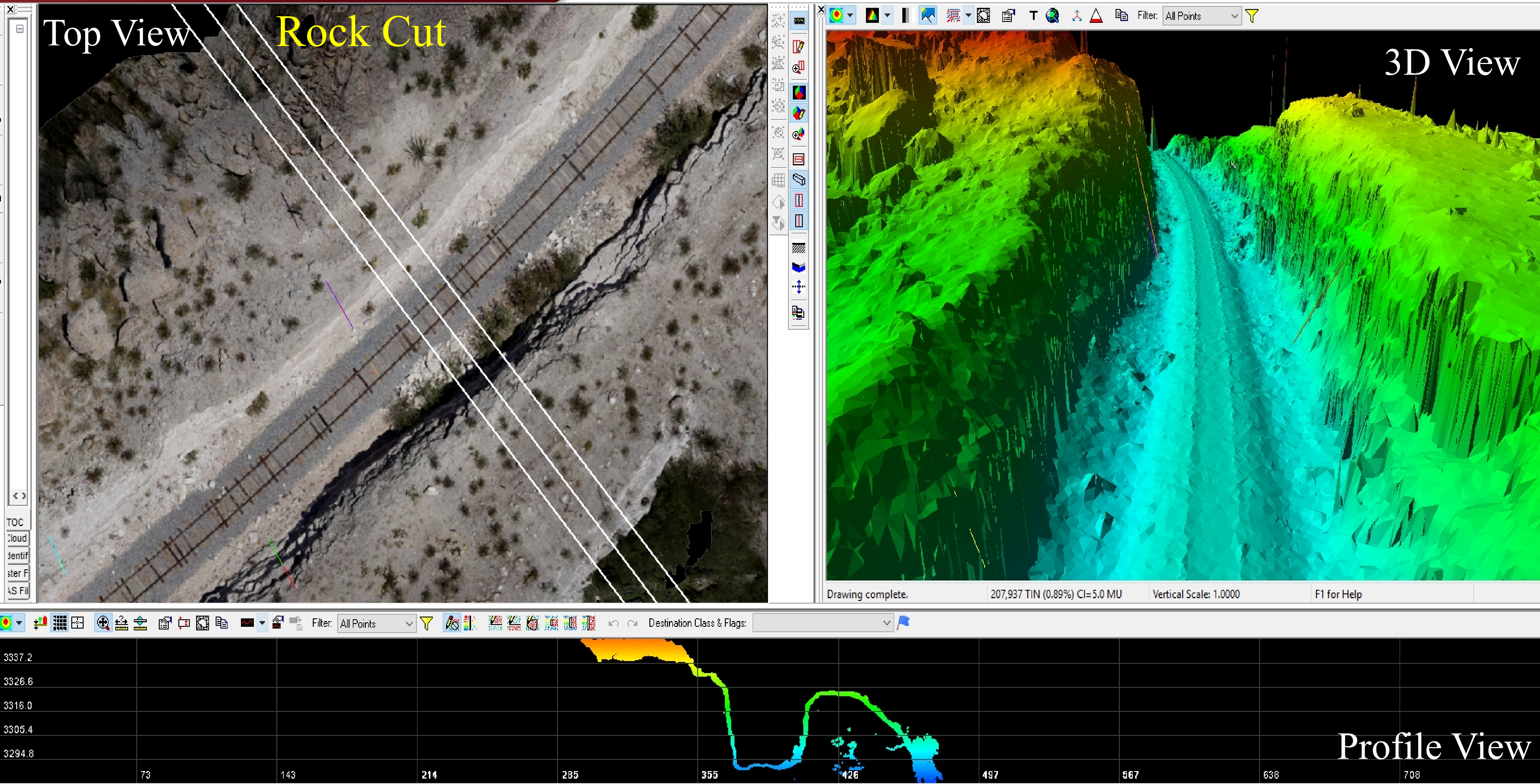
Drawing complete. 195,595 TIN (100.00%) Vertical Scale: 1.0000

Soil Erosion - Aerial Mapping

Source: Dr Puppala and MTRI

IV. Visualization

Rock Cut Monitoring and Data Analysis



Filter: All Points

Drawing complete.

207,937 TIN (0.89%) CI=5.0 MU

Vertical Scale: 1.0000

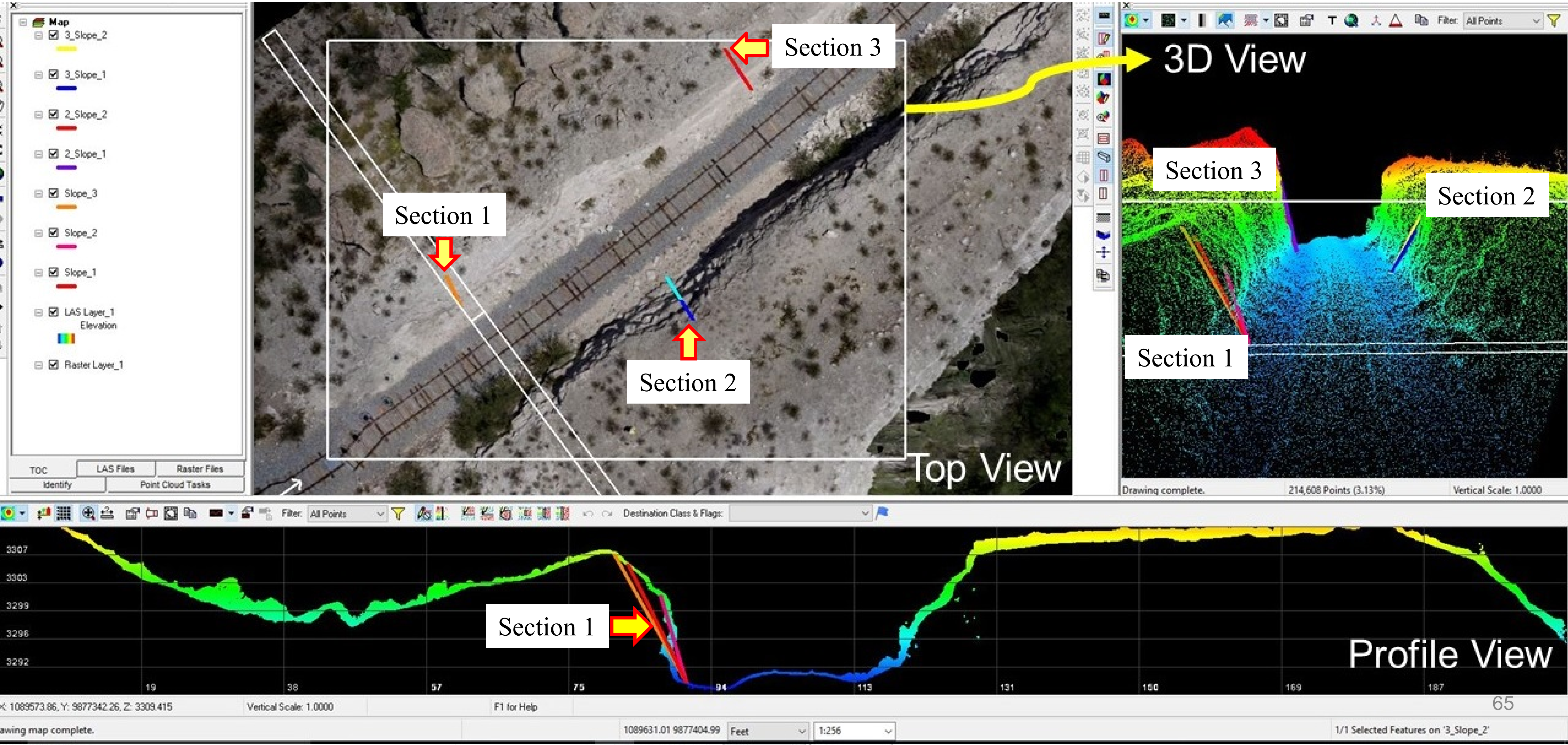
F1 for Help

Filter: All Points

Destination Class & Flags:

IV. Visualization

Rock Cut Area – 2D Slope Stability Analysis

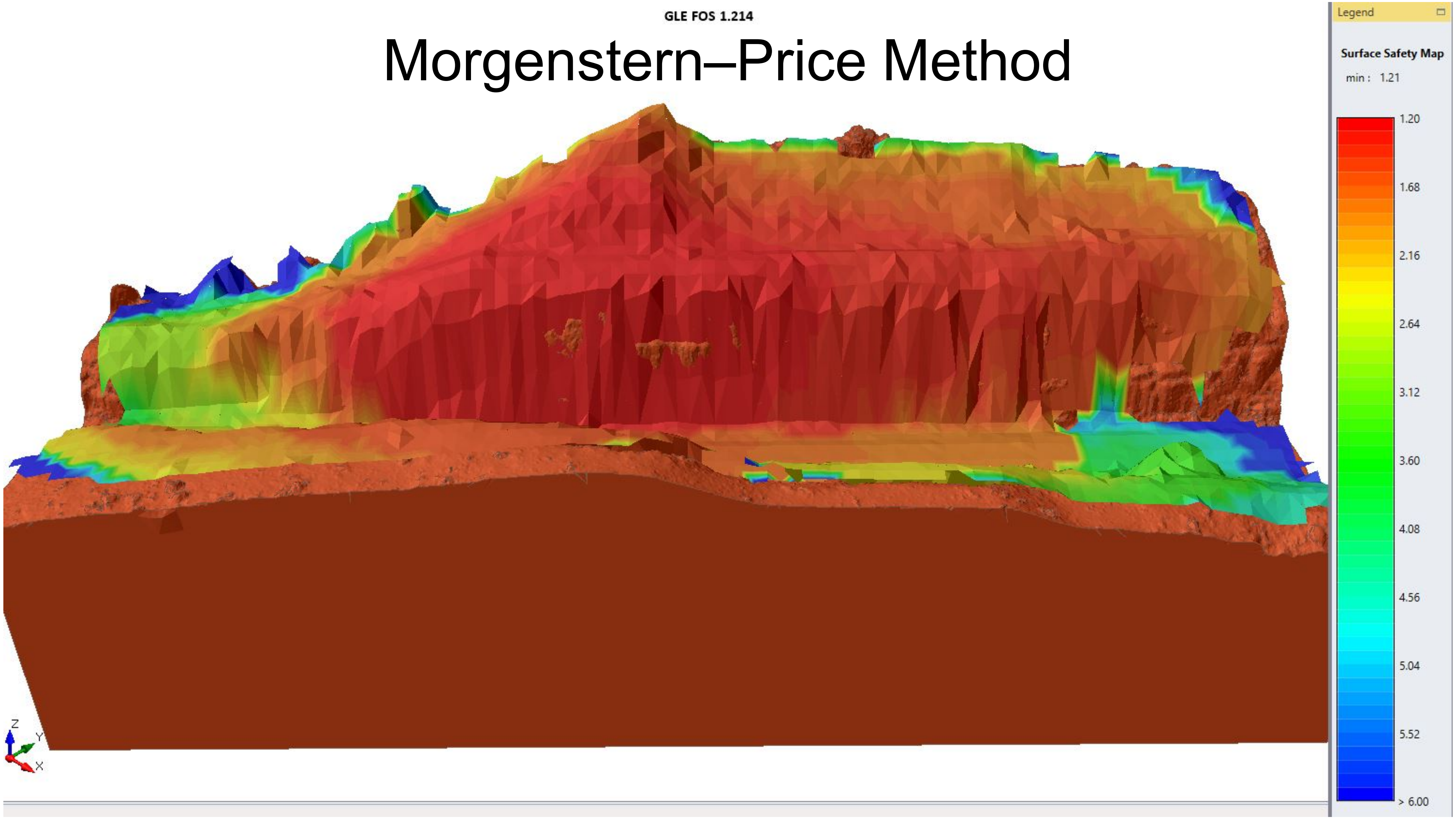


Drawing complete. 214,608 Points (3.13%) Vertical Scale: 1.0000

X: 1089573.86, Y: 9877342.26, Z: 3309.415 Vertical Scale: 1.0000 F1 for Help

awing map complete. 1089631.01 9877404.99 Feet 1:256 1/1 Selected Features on '3_Slope_2'

Rock Cut Area – 3D Slope Stability Analysis



Morgenstern–Price Method

Emergency Response

NSF Rapid – Data Fusion between Aerial and Social Media Technologies

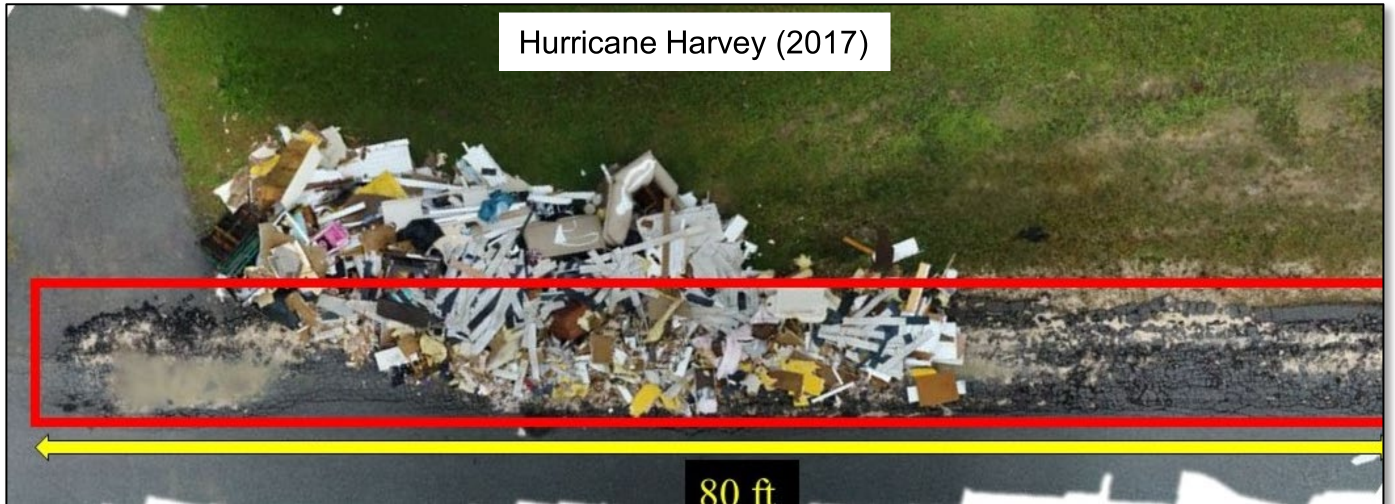
❑Emergency operation centers (EOCs) are tasked to

- Rapidly and accurately collect and process data
- To make informed decisions

❑Fusion between technologies is envisioned to Help EOCs

- Better preparedness
- Efficiently conducting tasks during natural disasters


Hurricane Barry (2019)


Hurricane Harvey (2017)

V. Peck Lecture: Summary

- Problematic expansive soils can be well characterized with more additional testing and better models, and this can be integrated into practice; Though field acceptance is slow for various reasons, but with time, this might become reality...

- Geotechnical case and validation studies are essential for evolution of best field practices…demonstrated with three case studies

- Visualization and Construction 4.0 – To Address Grand Challenges of Today's Engineering
  - UAVs, Sensors, Robotics, 3D Printers
  - Digitization and Automation
    - ✓ Enhance Virtual Reality
    - ✓ Restore Urban Structure
    - ✓ Artificial Intelligence and Machine Learning Modeling
  - ➢ Integration of Geotech & Technology – 'Ground' Breaking and Exciting!

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