Seismic Design Recommendations

Liquefaction of Ponded Ash

Field and Laboratory Characterization

Recommendations to Evaluate Embankment Stability for Seismic Loads

William Wolfe – The Ohio State University

Robert Bachus – Geosyntec Consultants

Welcome….Lovers of Fly Ash

http://jonvilma.com/band-of-brothers.html

We are a Band of Brothers (and Sisters) who share a passion (or at least an interest) in fly ash or CCRs

However, for the last 10 years, we have also been jumping over hurdles and beating our heads against the wall as we try to understand how to best close CCR ponds

http://www.alamy.com/stock-photo

https://bashny.net/t/en/6016

Welcome….Lovers of Fly Ash

Why, the frustration? Could be tricky material or tricky regulations, as we try to separate the realities from perceptions of CCRs

http://lmc123.com/en/news-room/195-when-business-perception-is-business-reality

And through it all, we often feel what Hester Prynne must have felt … eternally branded with a Scarlett Letter

Our goal over the next 50 minutes is to try in some measure to address the perception and demonstrate the reality of CCRs and seismic liquefaction

www.wikipedia.org

Liquefaction of Ponded Ash

- Liquefaction occurs when stresses and deformation in the ground caused by earthquake shaking disturb the soil structure.
- Water in the pore spaces will resist the natural tendency of the soils to consolidate into a denser and more stable arrangement during shaking.
- Because the soil cannot change in volume until water is drained from the pore spaces during the earthquake, porewater pressure will rise, soil particles may lose contact with each other, and the soil mass may lose much of its strength.

Why Is Liquefaction Important when We Consider Ponded Ash?

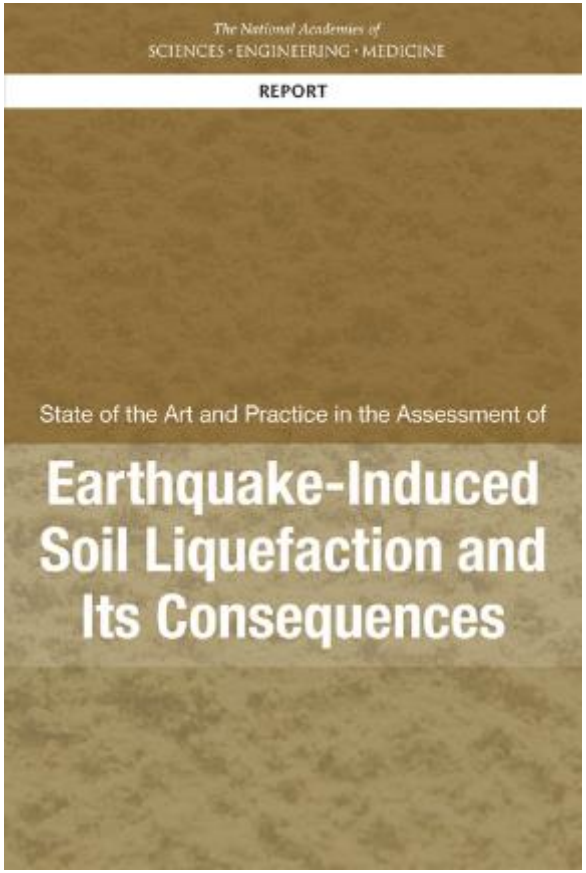
Earthquake induced liquefaction is a leading cause of earthquake damage worldwide

But before we discuss liquefaction and seismic design of CCR ponds, we need to understand some of the basic characteristics and realities of ponded ash

Suggested References

1998 NCEER/NSF Liquefaction Resistance of Soils: Summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils.
(Journal of Geotechnical and Geoenvironmental Engineering 127 (10), 817–833)

State of the Art and Practice in the Assessment of Earthquake-induced Soil Liquefaction and Its Consequences
(National Academies of Science, Engineering, Medicine, 2016)



Material Characterization

Field Methods

- Standard Penetration Test (SPT)
- Cone Penetration Tests (CPTu)
- Geophysical Test for Shear Wave Velocity (V_s)

Laboratory Methods

- Cyclic Triaxial Shear (CyTXC)
- Cyclic Direct Simple Shear (CyDSS)

We will discuss some of these methods to characterize the properties of ponded fly ash

Presentation Outline

- Basic Material Characterization
- Laboratory Strength Characterization
  - Static and Dynamic
- Field Characterization
- Seismic Design Recommendations

Acknowledgements

This work would not be possible without the encouragement, collaborative, and financial support from a number of different organizations and individuals.

Ken Ladwig – Electric Power Research Institute (EPRI)

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Mehedy Amin – The Ohio State University

Carlos Santamarina – Georgia Institute of Technology (now KAUST)

Greg Hebeler – Golder Associates

Kula Kulasingam – AECOM

Ken Daly – AMEC Foster Wheeler

Students at Ohio State and Georgia Tech who performed the tests cited in this presentation

Basic Material Characterization

Material Characterization and Properties

Material Characterization

- Material chemistry
- Particle size
- Specific gravity
- Particle shape
- Plasticity
- Pore fluid-solid interaction

Engineering Properties

- Realizable density
- Sample preparation
- In-pond layering
- Compressibility
- Drained strength
- Undrained strength
- Static liquefaction
- Seismic liquefaction
- Flow potential

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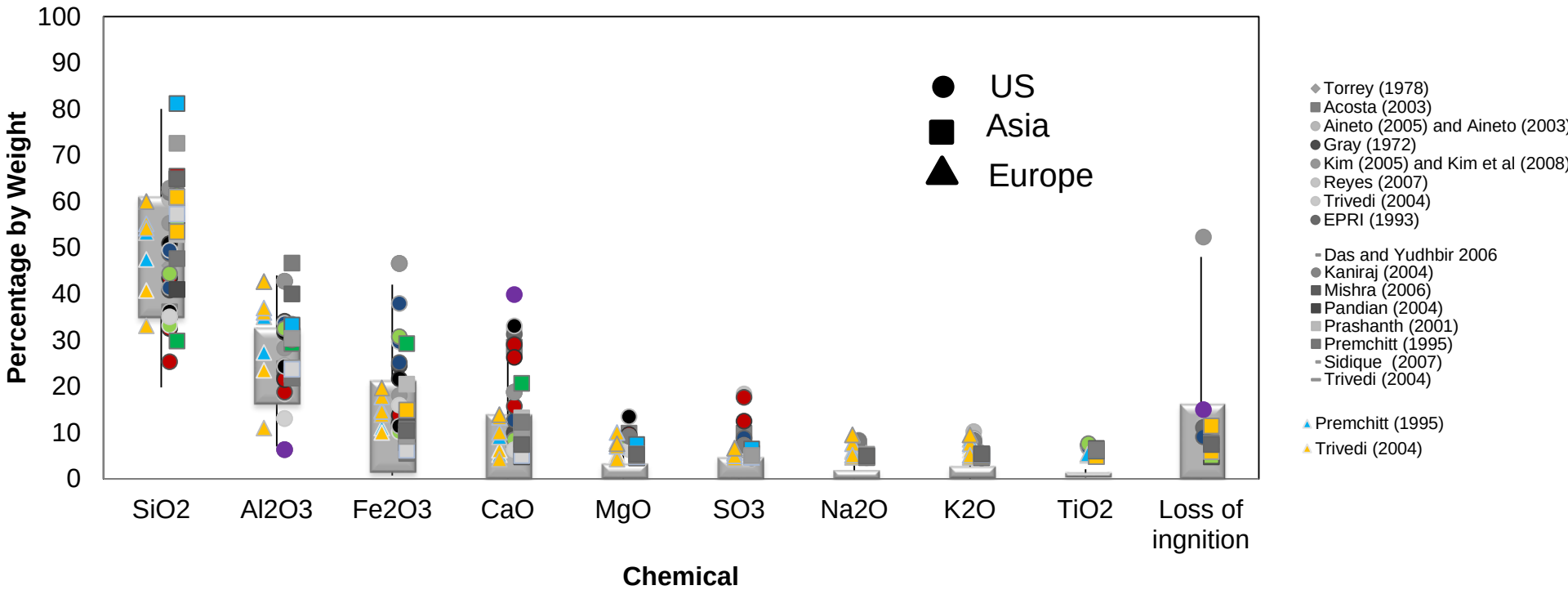
Chemical Composition



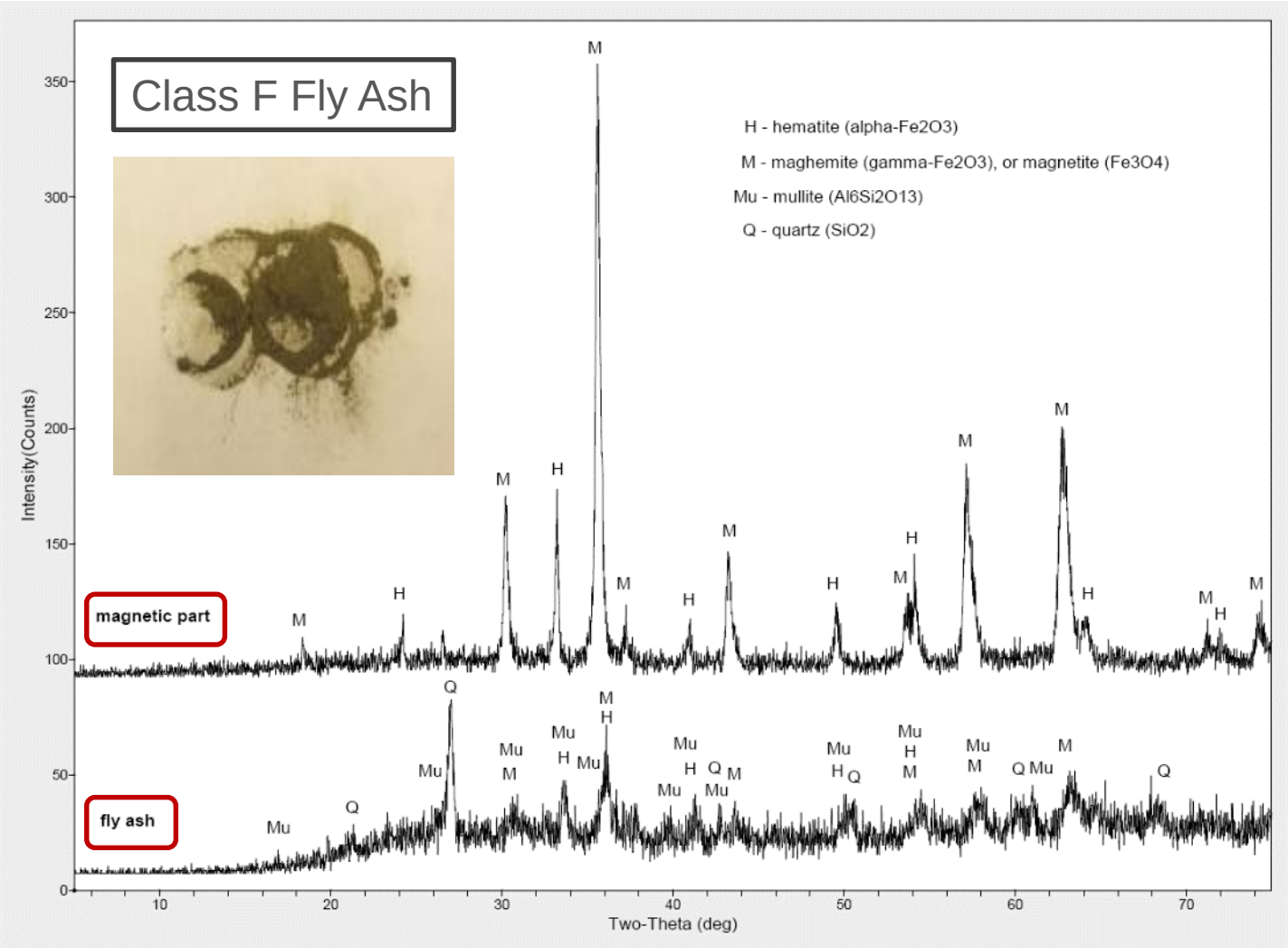
Notes:

Height of the box = 2 times standard deviation

Length of black lines: from maximum to minimum value found in literature

THE OHIO STATE UNIVERSITY

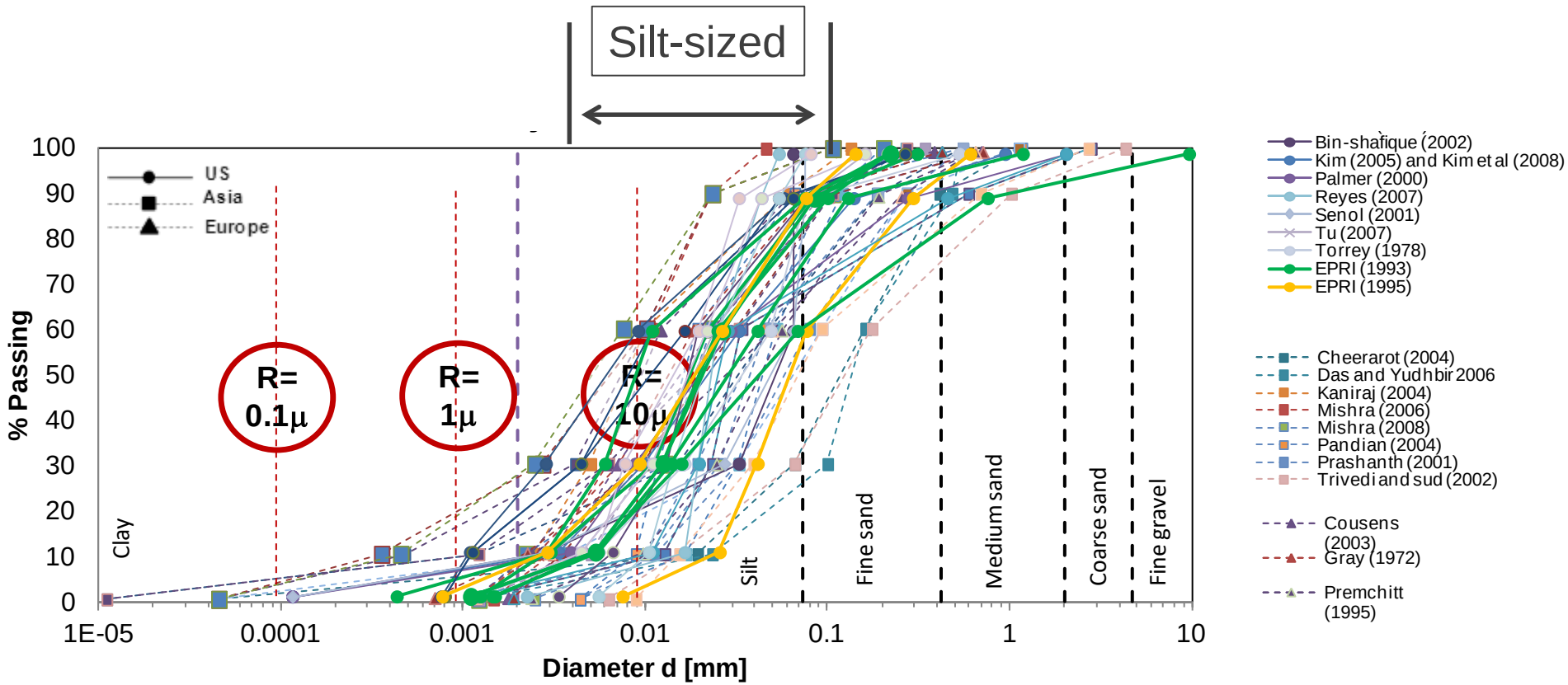
Evidence of Iron Particles



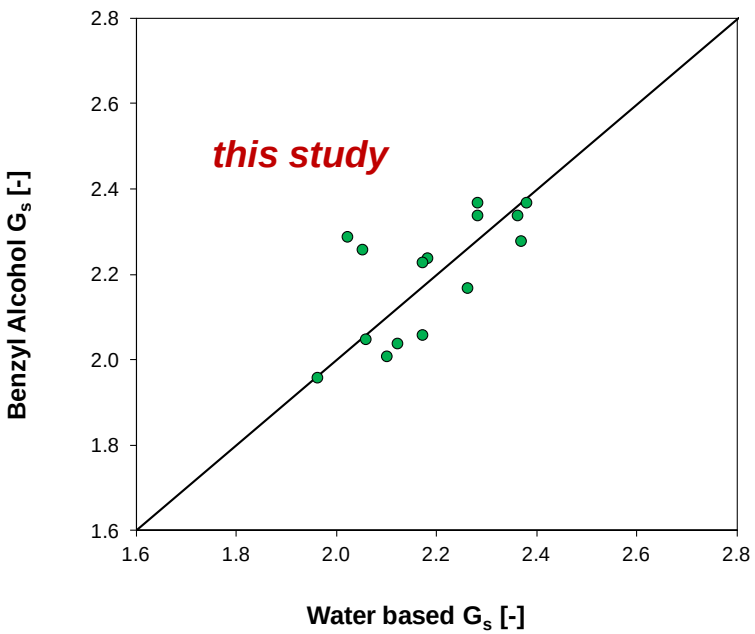
Magnetically separated fraction:

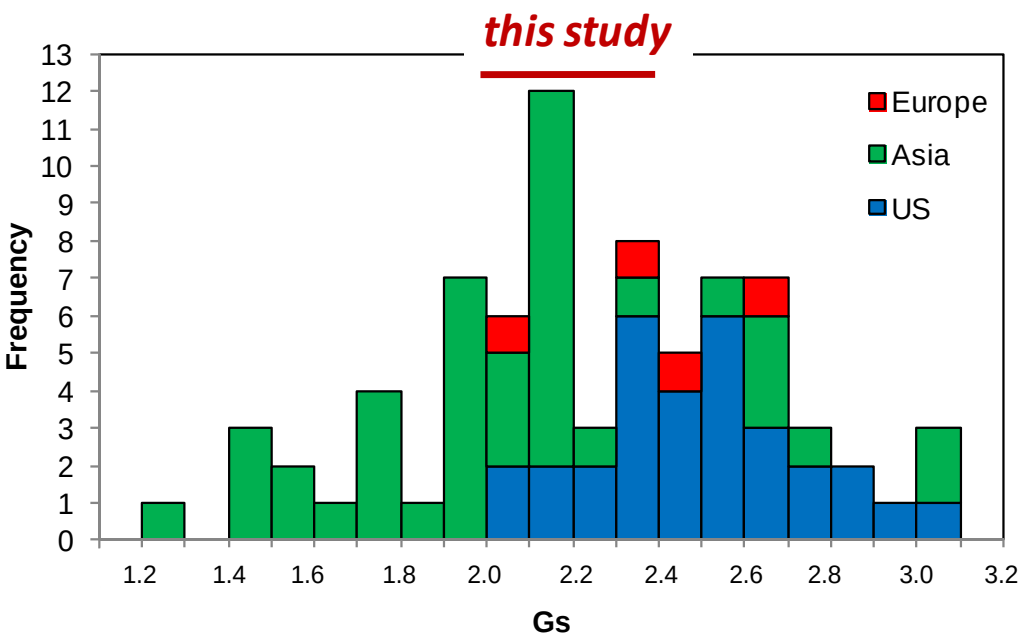
Hematite Fe_2O_3 (weakly magnetic), Magnetite Fe_3O_4 and Maghemite Fe_2O_3 (both strongly magnetic).

Particle Size Distribution



Specific Gravity of Solids





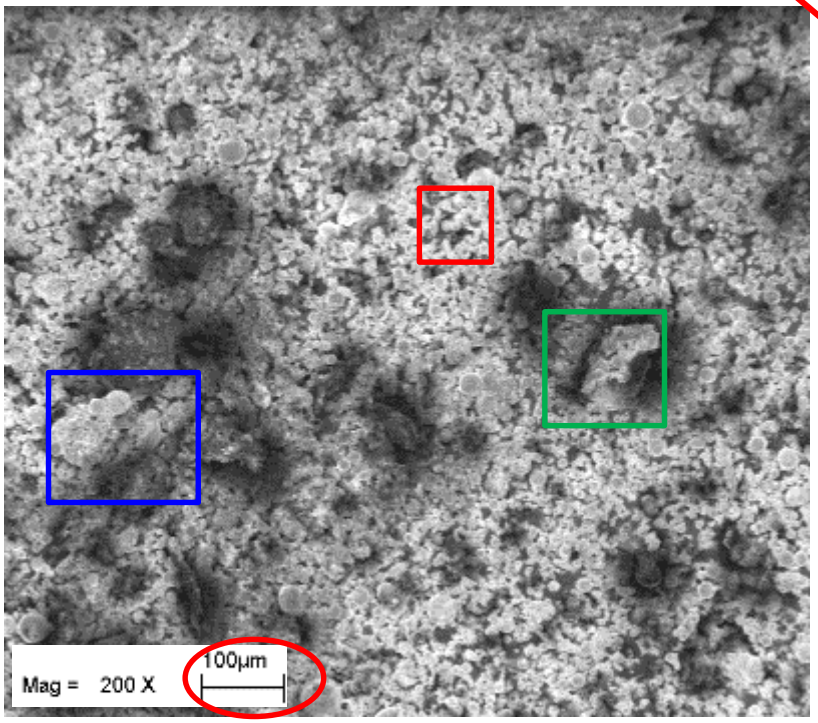
Acosta (2003)
Gray (1972)
Kim et al. (2008)
Pandian (2004)
Senol (2001)

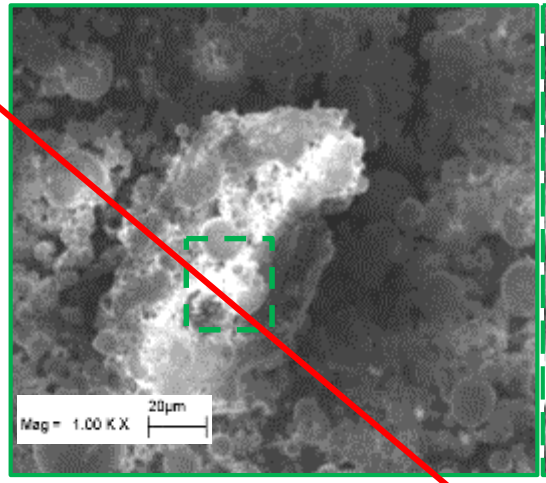
Das and Yudhbir (2006)
Kaniraj (2004)
Mishra (2006)
Premchitt (1995)
Trivedi & Sud (2002/4/7)

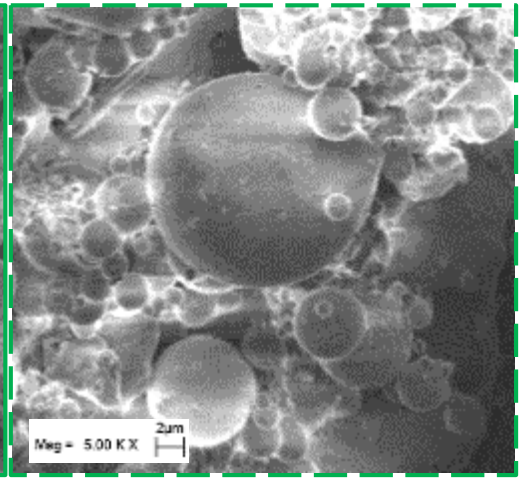
EPRI (1993/5)
Kim (2005)
Mishra (2008)
Reyes (2007)
Torrey (1978)

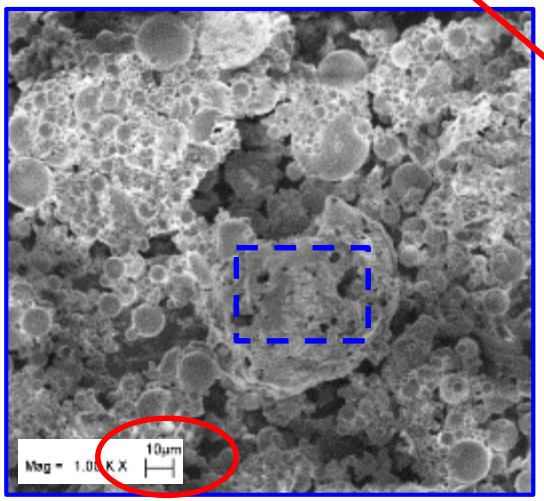
Particle Shape

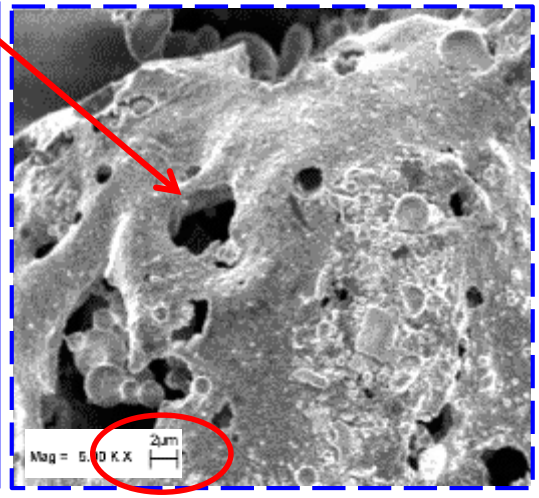
Note shape and size of “holes” (recall clay-sized = 2µm)



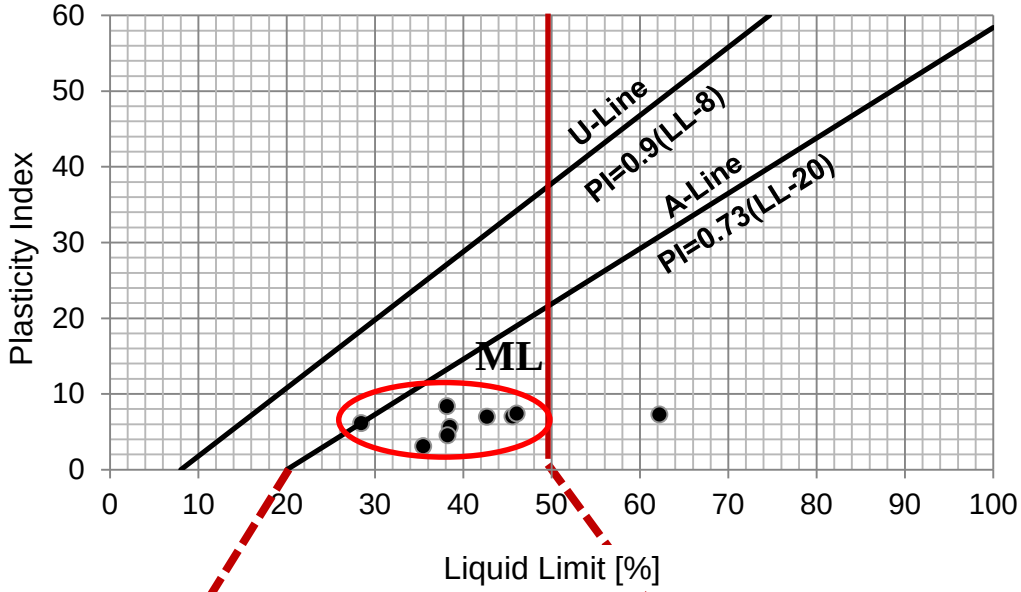


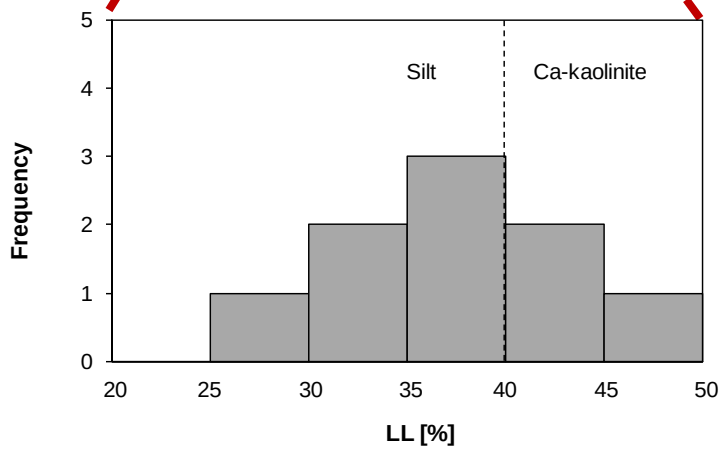






Atterberg Limits - Plasticity

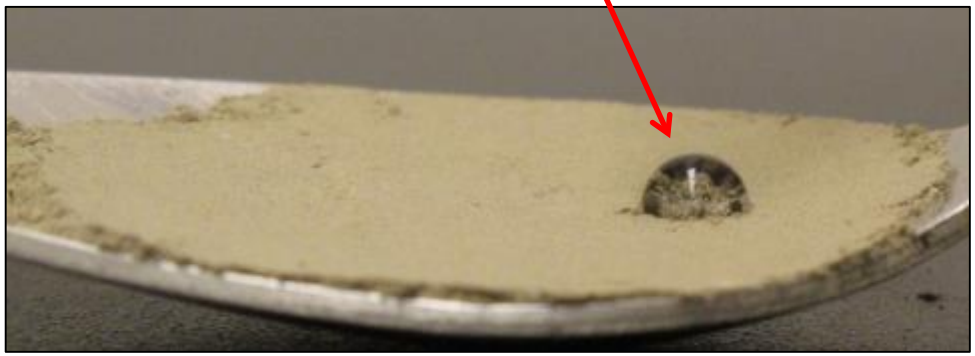


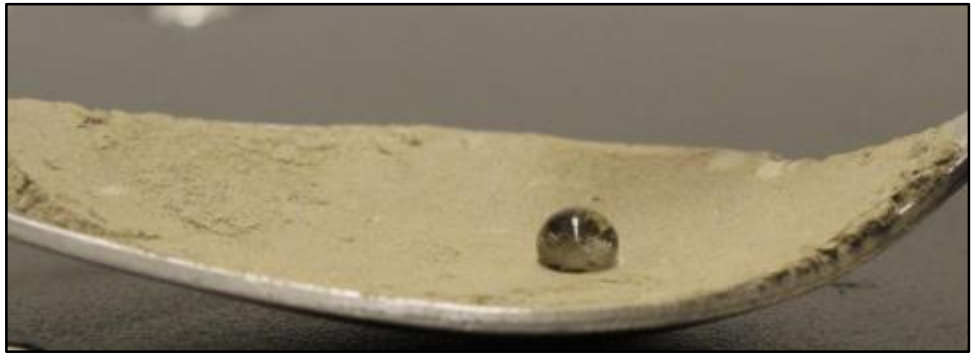


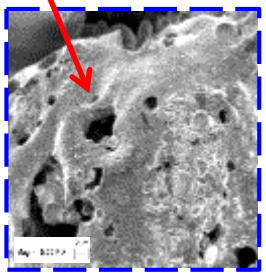
Soil-Water Interaction

How to fit 3,000µm **drop** in a 2µm **hole**??

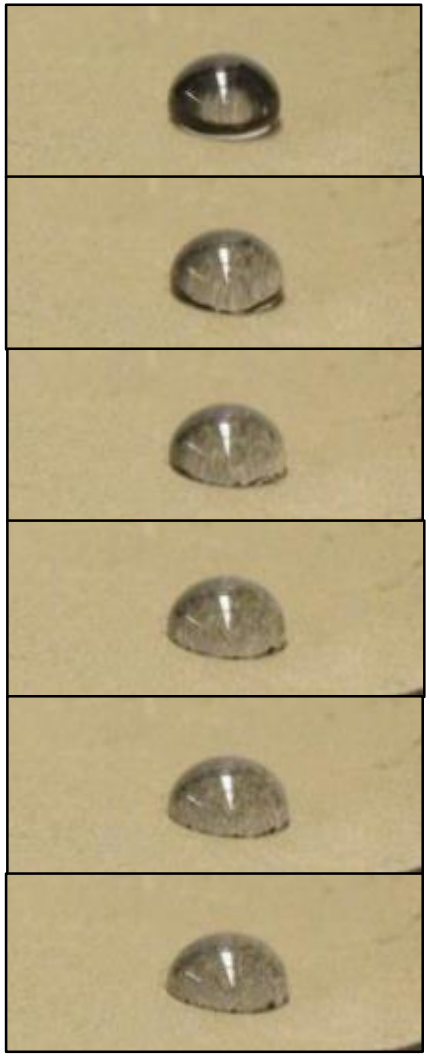
Water







Oil



Water drop = 1/8 inch = 3,000µm

Material Characterization and Properties

Material Characterization

- Material chemistry
- Particle size
- Specific gravity
- Particle shape
- Plasticity
- Pore fluid-solid interaction

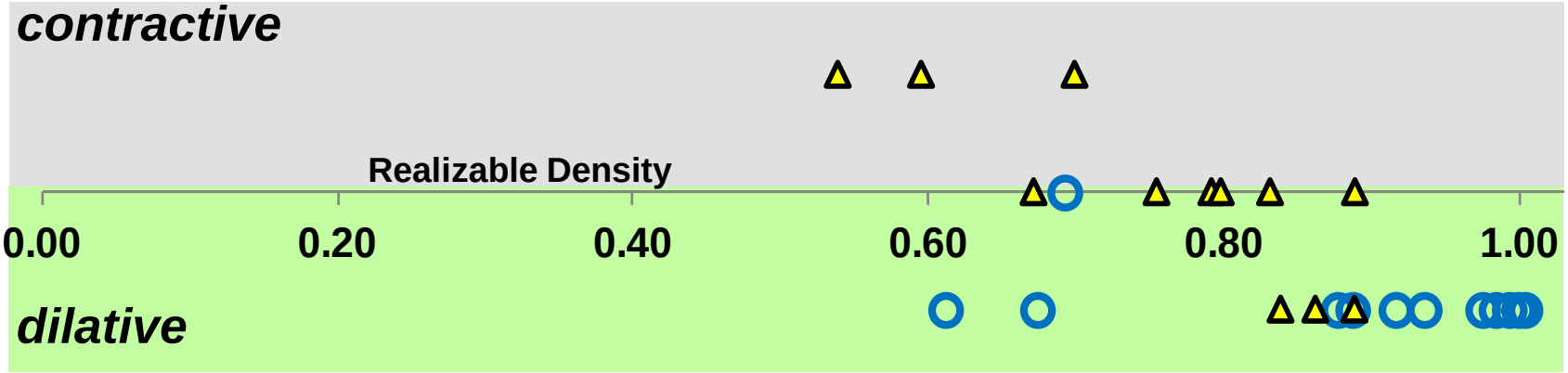
Engineering Properties

- **Realizable density**
- **Sample preparation**
- **In-pond layering**
- **Compressibility**
- **Drained strength**
- **Undrained strength**
- **Static liquefaction**
- **Seismic liquefaction**
- **Flow potential**

Realizable Density Concept

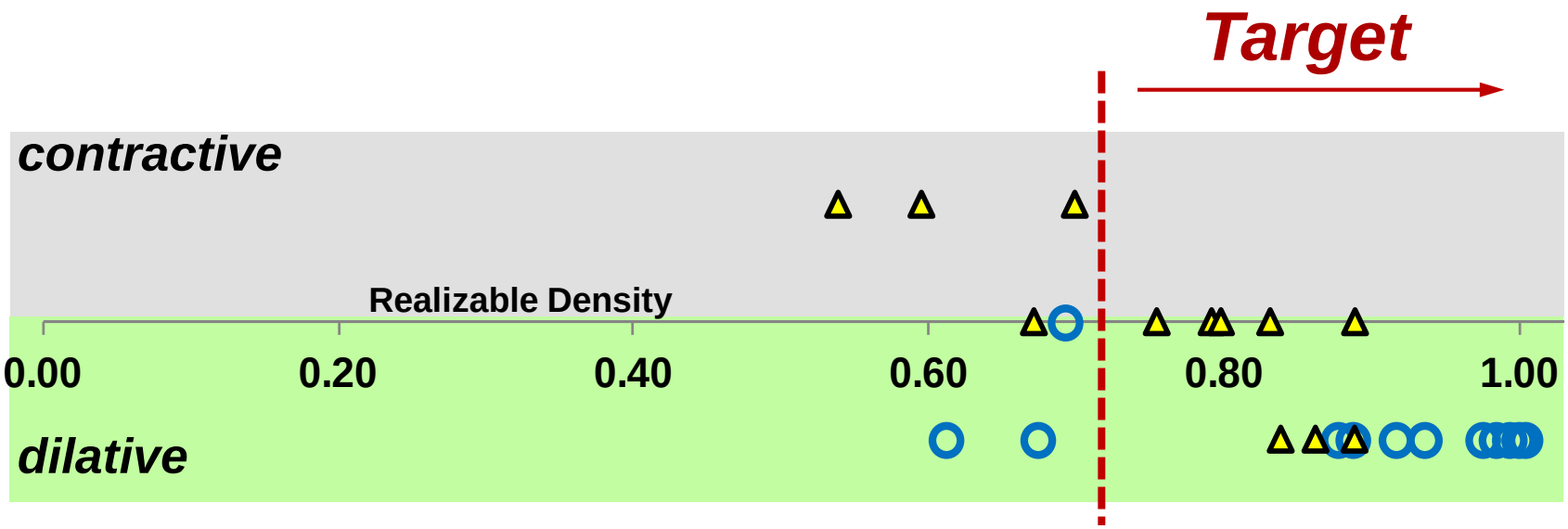
Methods	Dry Density					
	G_S: 2.26	G_S: 2.28	G_S: 2.05	G_s: 2.28	G_S: 2.36	G_S: 2.28
Formation under shear	880	1099	605	943	1061	559
Suspension settlement	924	1130	603	864	1126	853
Water pluviation with a sieve	1034	1182	688	--	1071	946
Free fall through a funnel	1111	1145	626	945	1084	639
Tapping compaction	1133	1312	767	1211	1290	908
Standard compaction test	1285	1442	950	1250	1508	1233

Application of Realizable Density



circles: undrained
triangles: drained

Application of Realizable Density



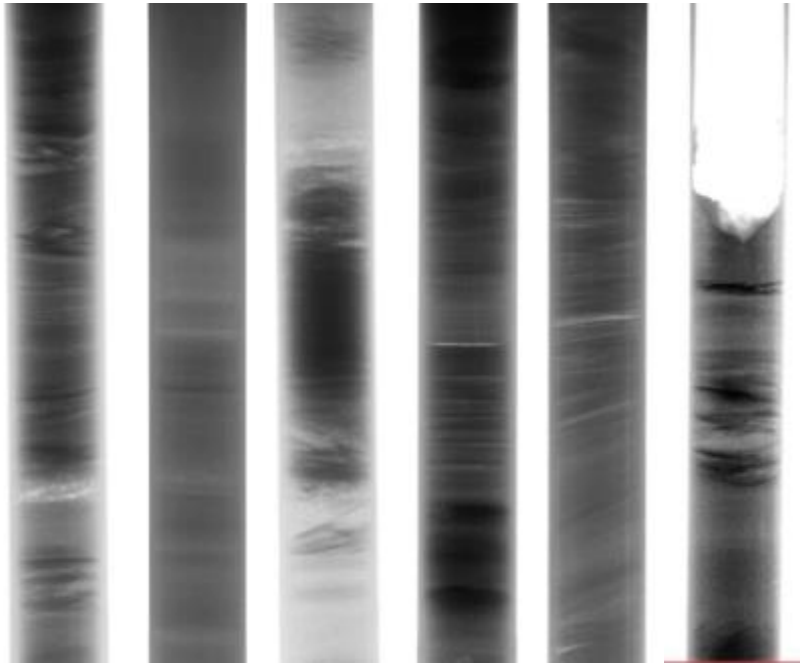
circles: undrained
triangles: drained

Inherent Layering

Laboratory Sedimentation - Photograph

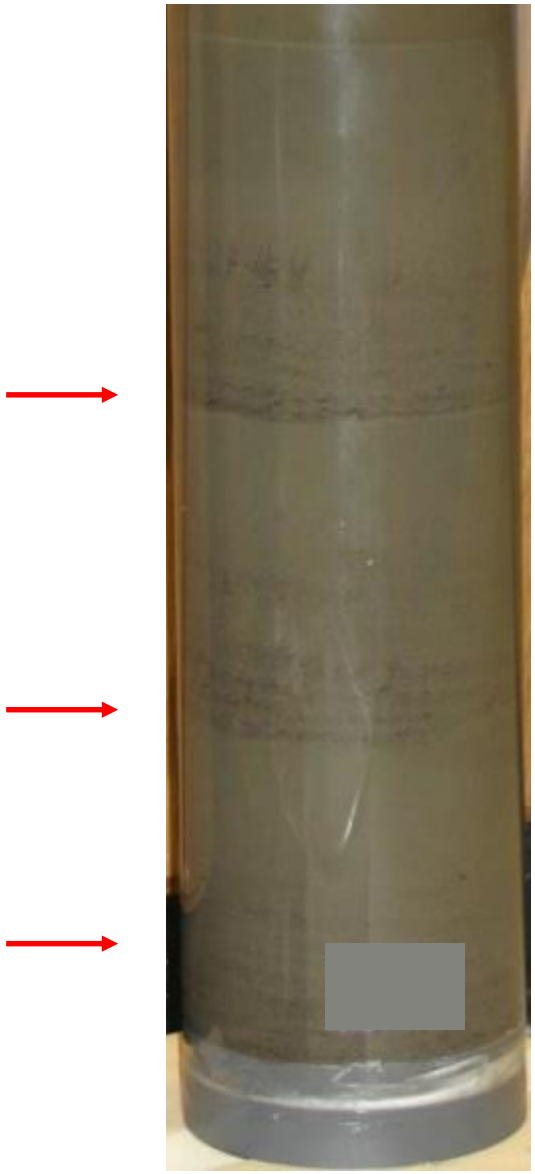
1 2 3

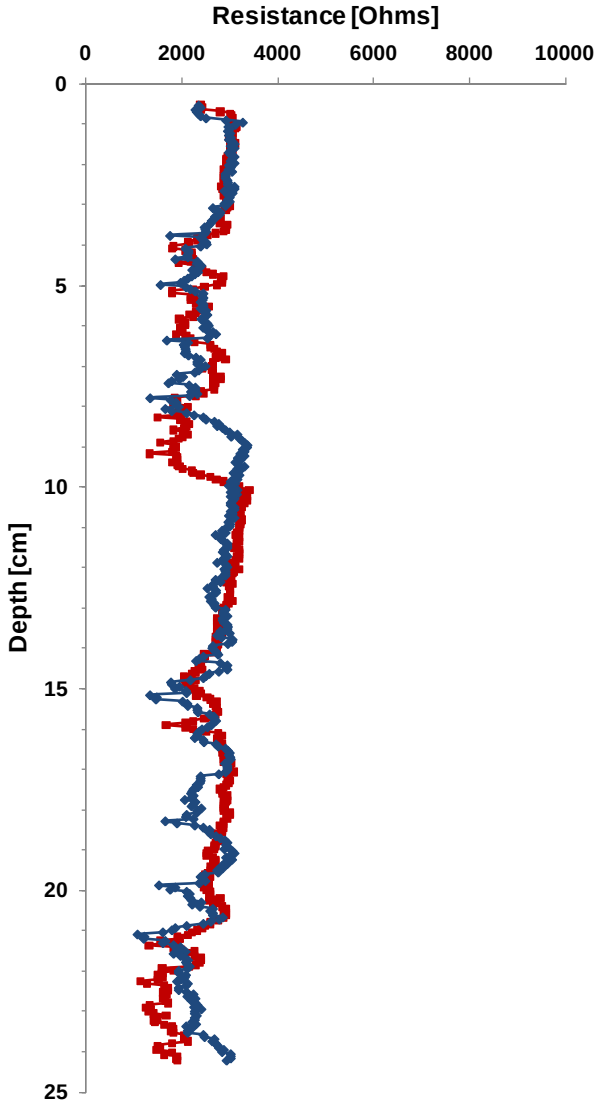
Field Sedimentation - Radiograph



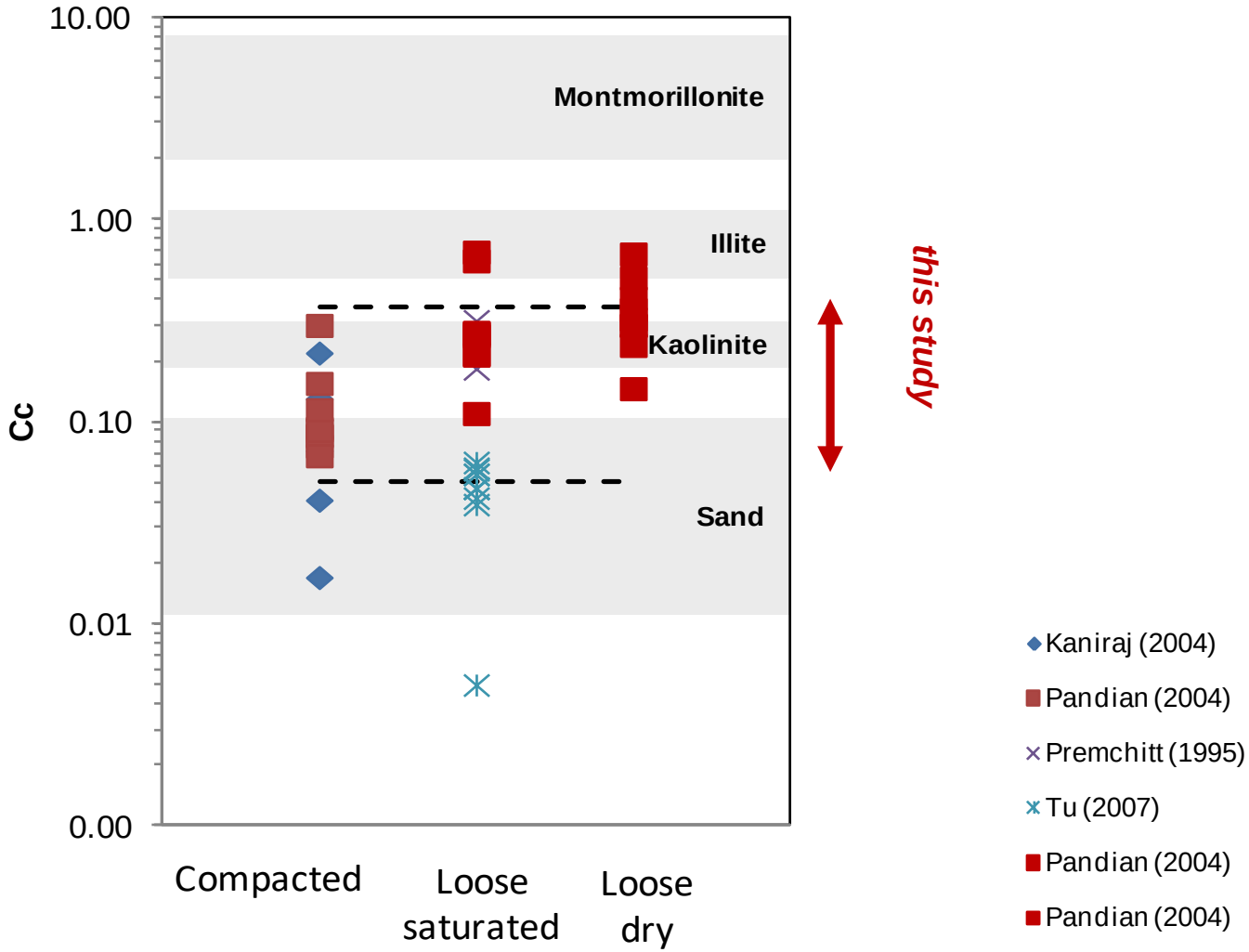
1 2 3 4 5 6

Evidence of Layering - Laboratory





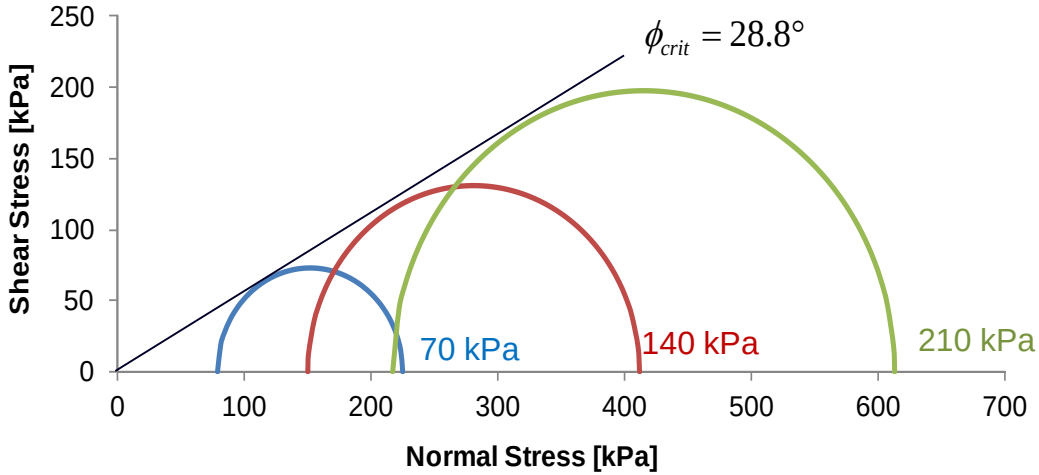
Compressibility



Laboratory Strength Characterization Static

Drained Triaxial Strength

Critical state



Peak state

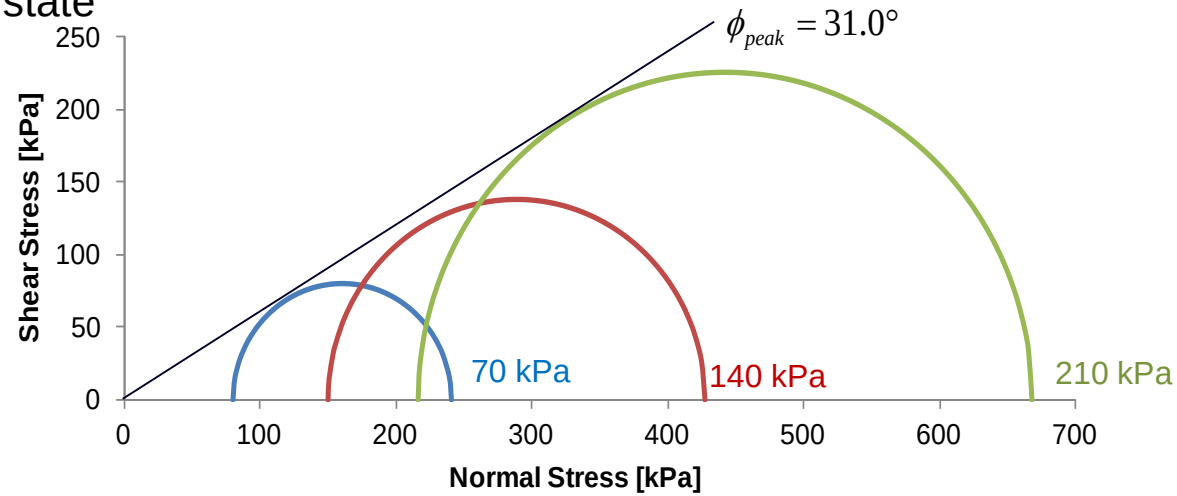
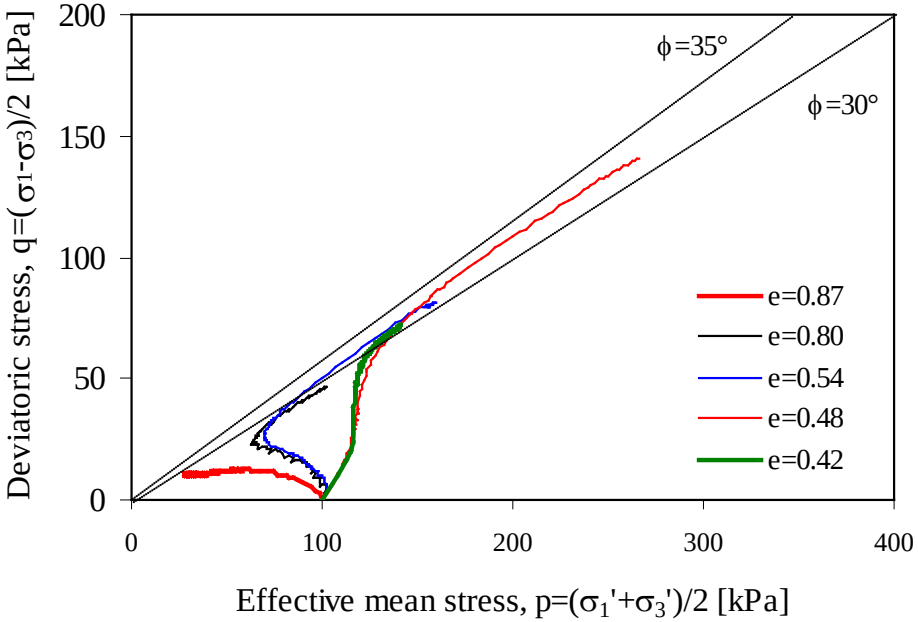


Table 4.1 Representative Values of ϕ_d for Sands and Silts

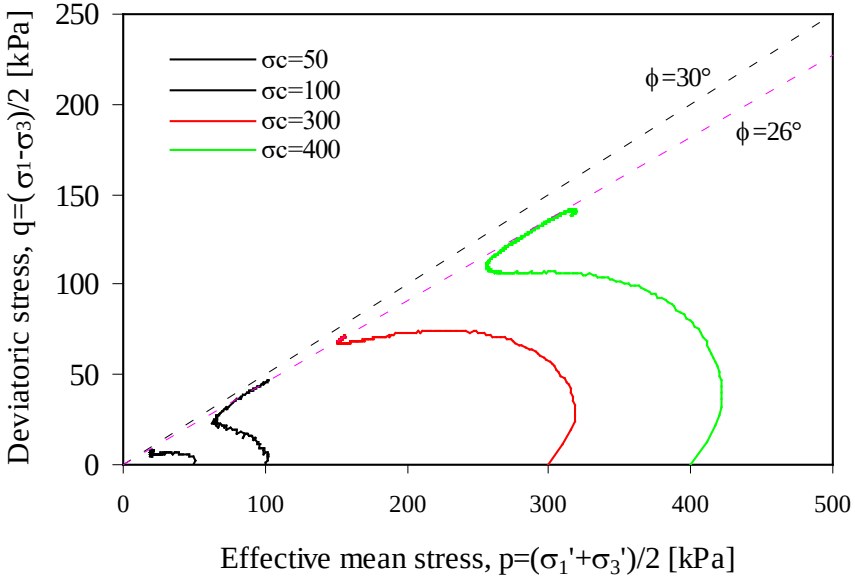
Material	Degrees	
	Loose	Dense
Sand, round grains, uniform	27.5	34
Sand, angular grains, well graded	33	45
Sandy gravel	35	50
Silty sand	27–33	30–35
Inorganic silt	27–30	30–34

(after Peck, Hanson, and Thornburn, 1953)

Undrained Triaxial Strength

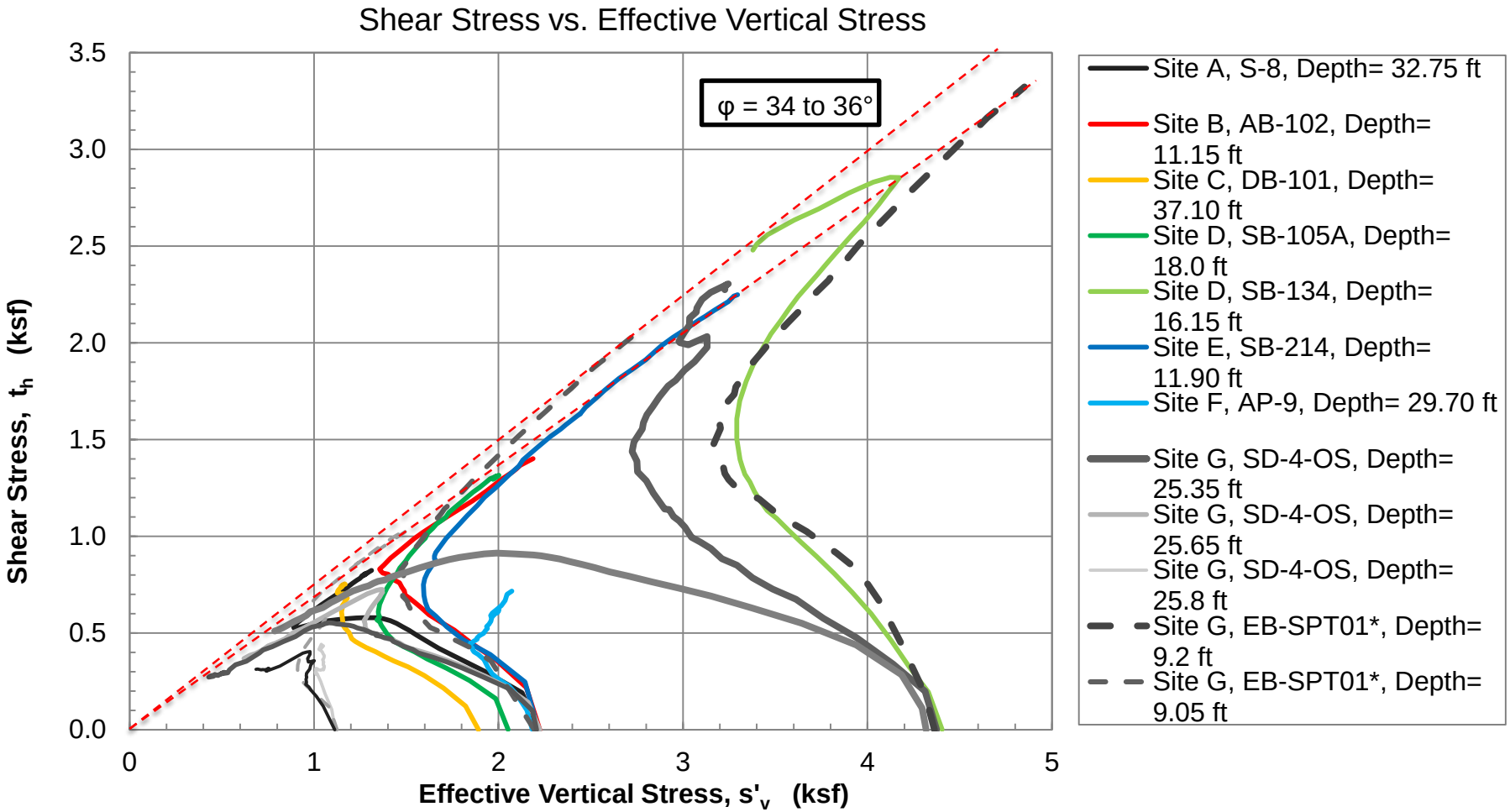


Constant Initial Consolidation Pressure



Constant Unit Weight

Undrained Triaxial Strength



(after AECOM, 2016)

Laboratory Strength Characterization Dynamic

Cyclic Triaxial Test Program

The Ohio State University has been actively involved for the past several years to develop a large database of dynamic triaxial test results on behalf of the American Electric Power Company (AEP)

Objectives of Laboratory Study

- Develop sample preparation techniques to mimic the field sedimentation process of a ponded fly ash
- Conceptually, this implies that the specimens are formed by when saturated ash is deposited under water. The process is termed “wet pluviation.”
- Develop, refine, and document a specimen preparation process that produces repeatable specimen characteristics at target realizable density.
- Perform a series of undrained cyclic triaxial tests on a wide range of fly ashes from across the AEP portfolio
- Compile and synthesize the test results

Specimen Preparation Process

Split mold (2.8” x 6”)
Latex membrane (0.012-in. thick)
Vacuum applied to stretch membrane
Mold filled with water

Premeasured amount of fly ash placed in flask

Flask then filled with water

Specimen Preparation Process

Wet pluviation from flask to split mold

Vibrate flask to prevent clogging

Near the end of wet pluviation

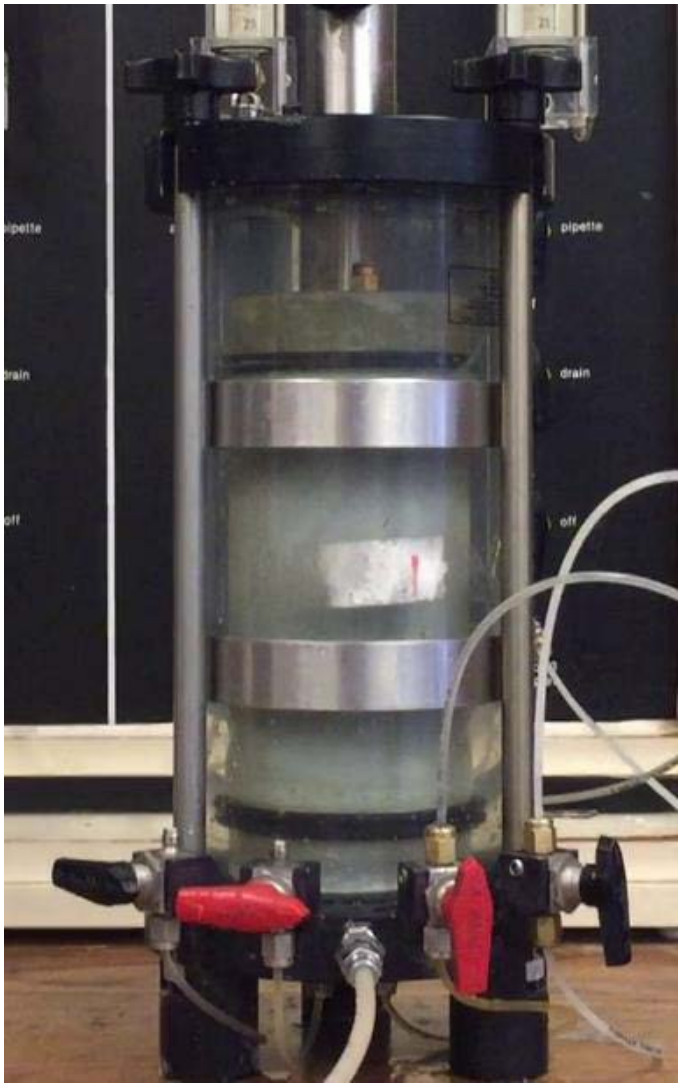
Specimen Preparation Process

Specimen after removal of flask

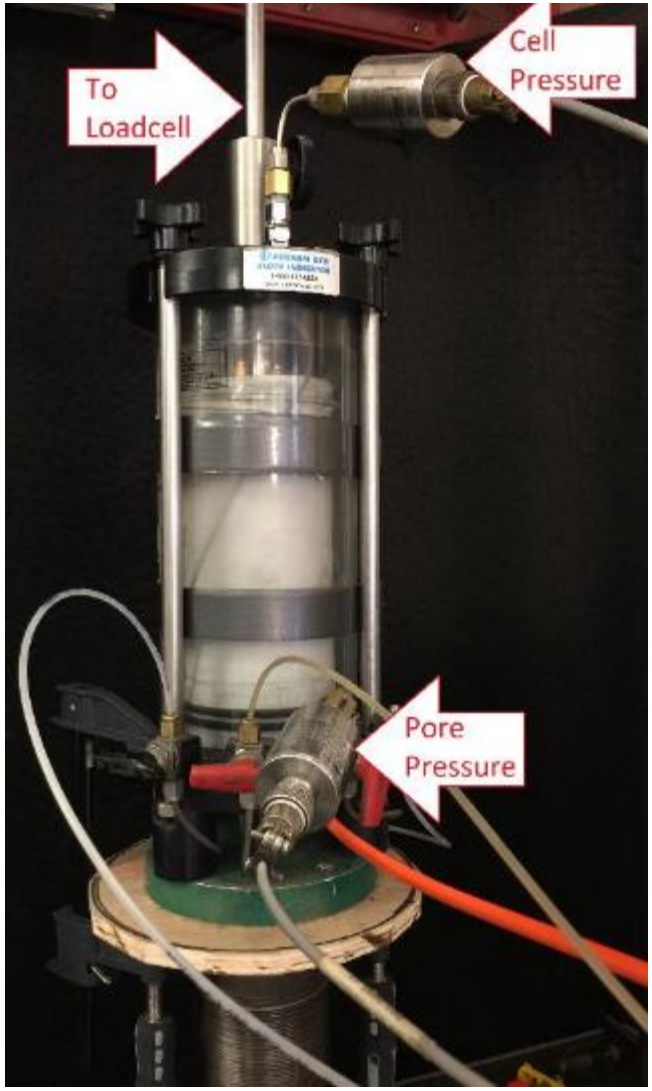
Apply vacuum to specimen

Specimen after removal of split mold

CyTXC Specimen Testing



Specimen in triaxial chamber for consolidation



Cyclic testing of consolidated specimen

Results of Specimen Preparation

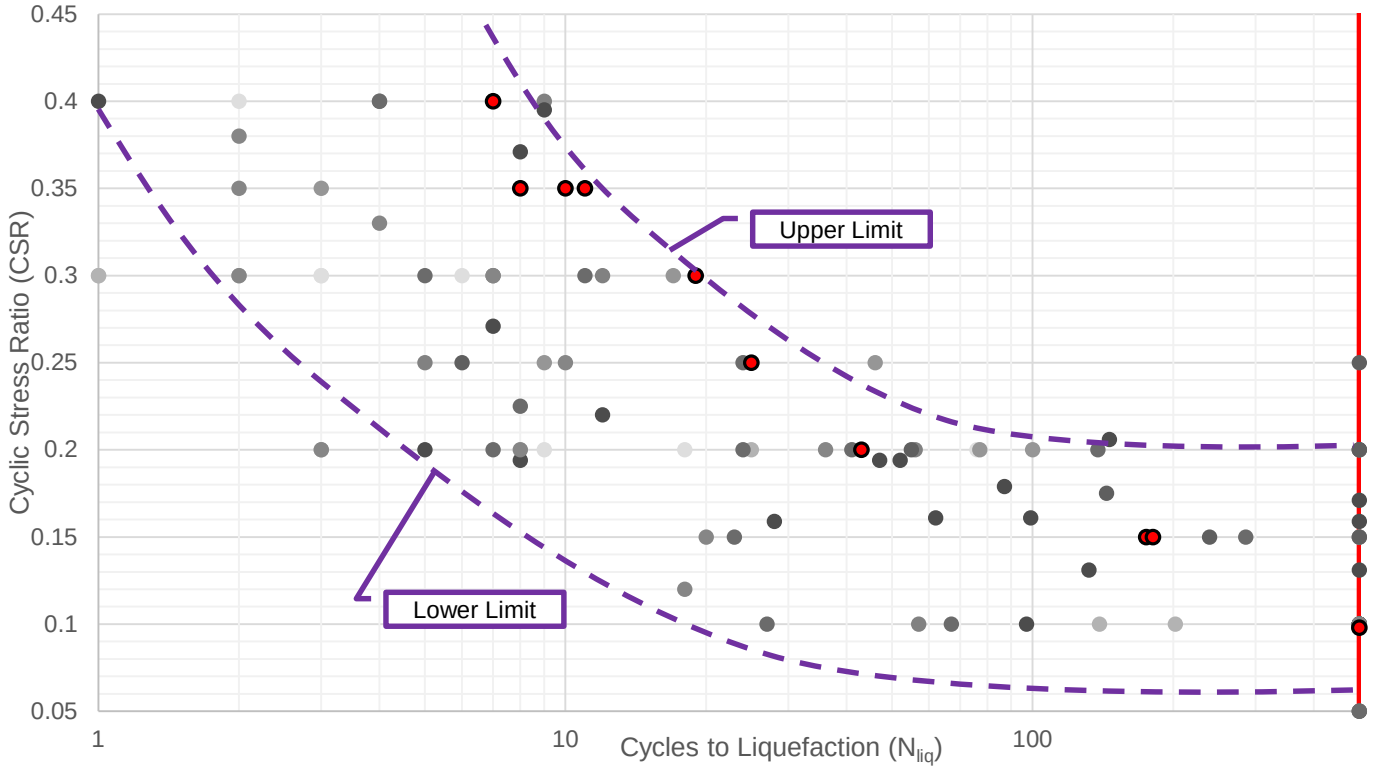
Realizable Density

Site ID	Realizable Density		Specimen Density, $\gamma d_{specimen}$		
	Minimum γd_{min} (pcf)	Maximum γd_{max} (pcf)	Dr 40% (pcf)	Dr 60% (pcf)	Dr 65% (pcf)
GL	45.2	61.2	51.6	54.8	55.6
AS	70.1	86.0	76.5	79.6	80.4
SE	58.2	85.5	69.1	74.6	75.9
BY	69.1	96.2	79.9	85.4	86.7

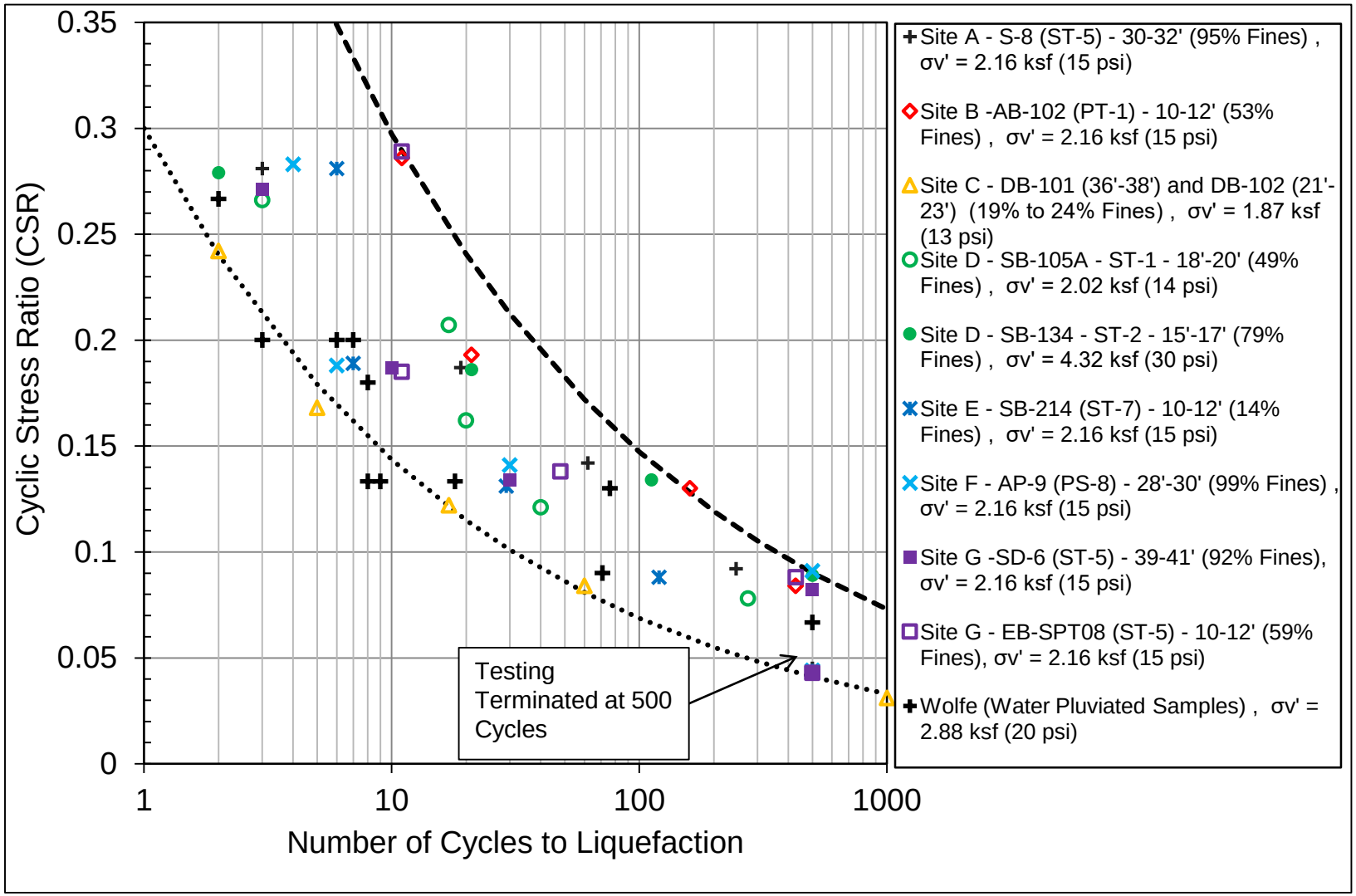
$$Realizable\ Density, D_r(\%) = \frac{\gamma d_{specimen} - \gamma d_{min}}{\gamma d_{max} - \gamma d_{min}} \times 100$$

Minimum realizable density after EPRI (2012)
Maximum realizable density after ASTM D698-12

Cyclic Liquefaction Test Results

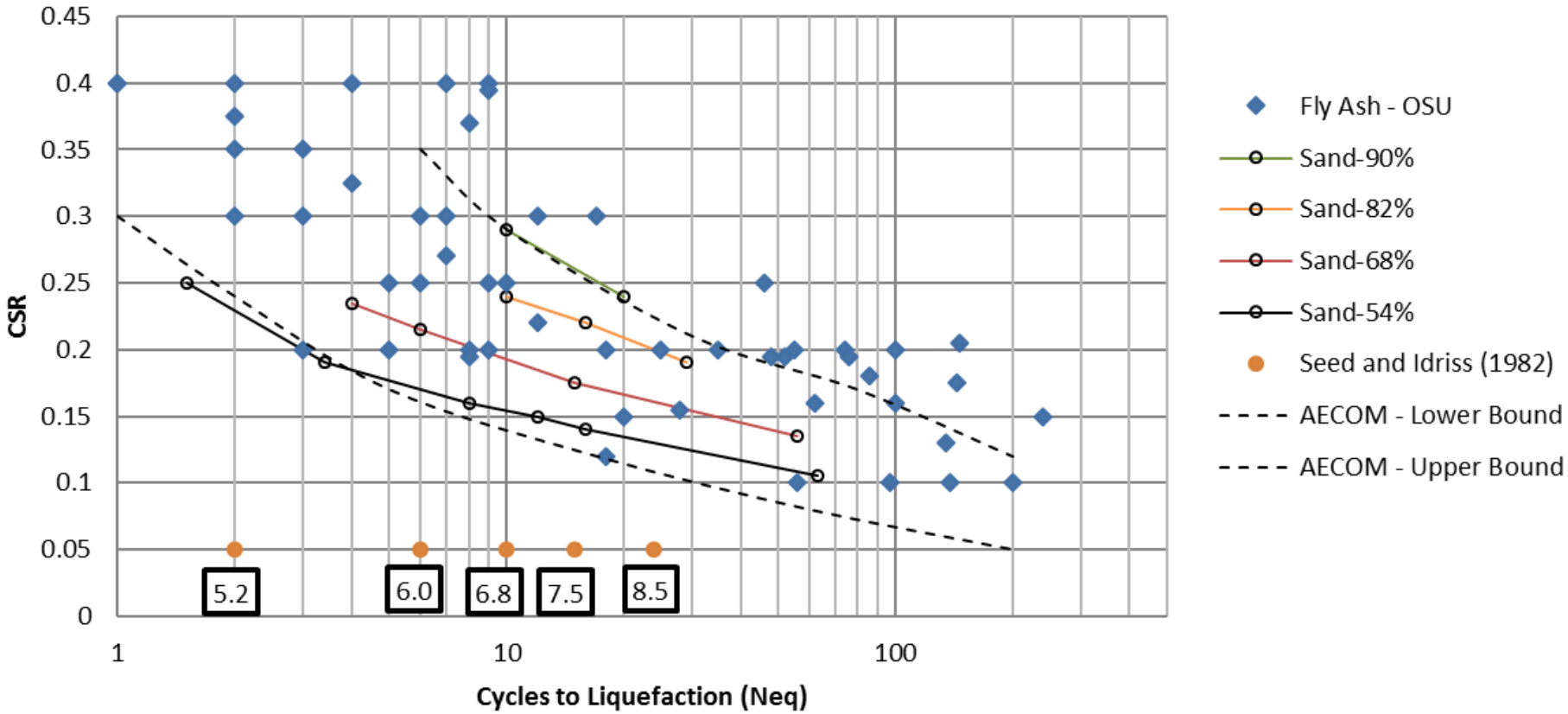


Direct Simple Shear (DSS) Response



(after AECOM, 2016)

Dynamic Undrained Results Triaxial and DSS

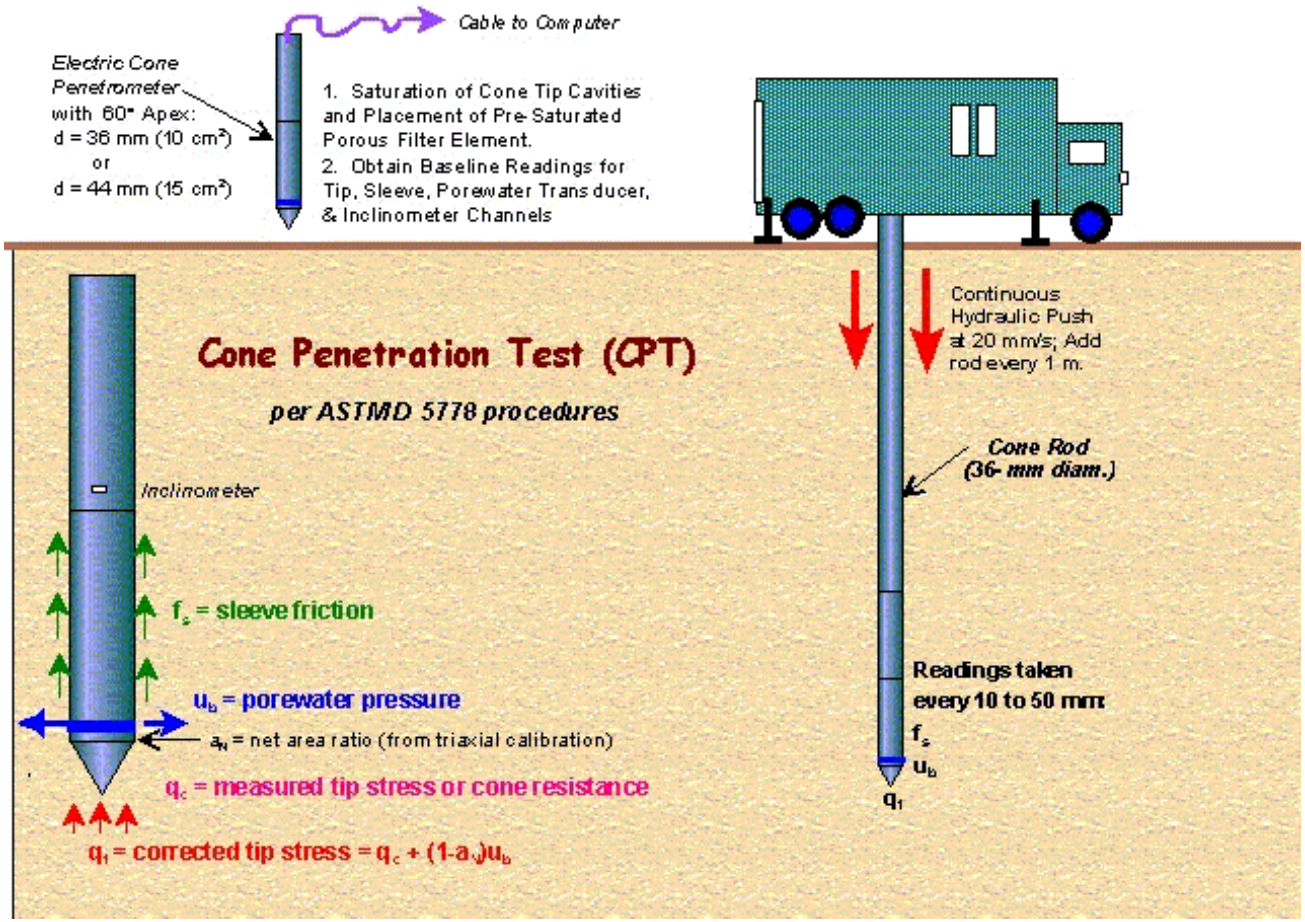


Source:
Wolfe (2016) - fly ash
deAlba (1976) - sand

Field Characterization

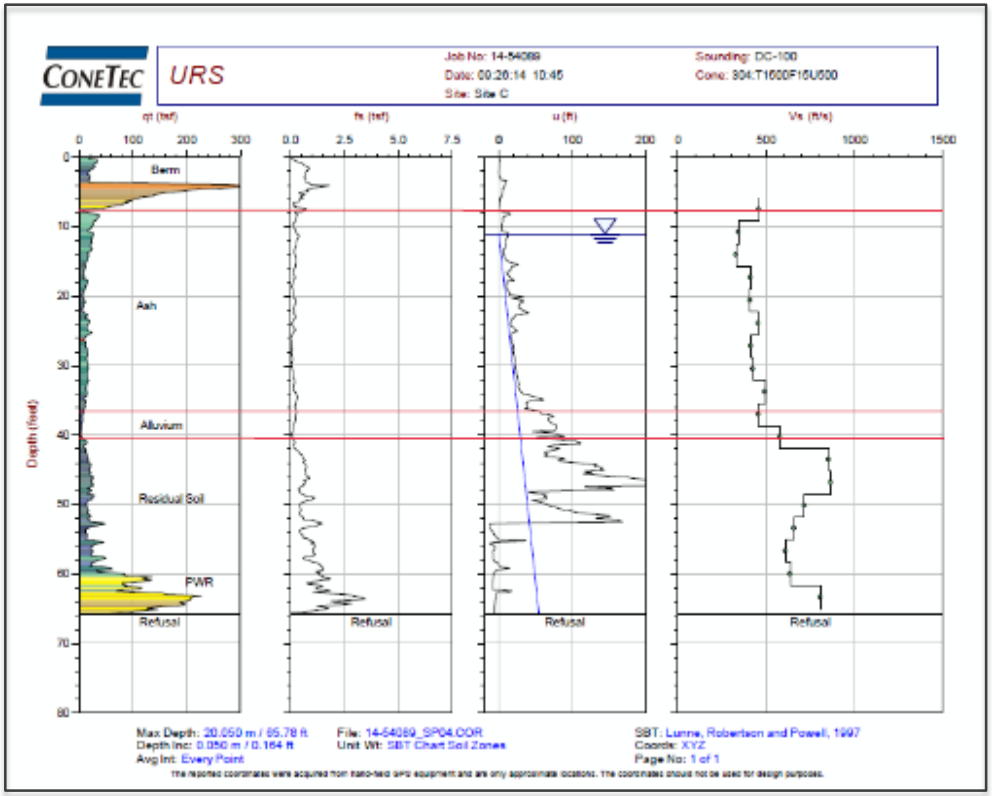
Cone Penetration Test (CPTu)

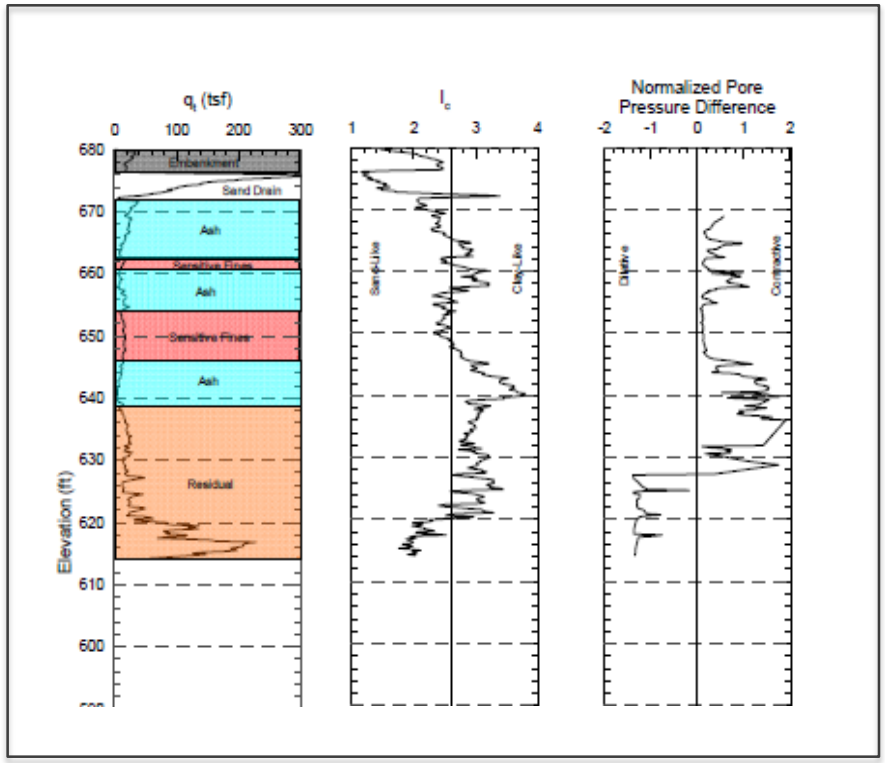
www.lankelma.co.uk



http://www.geotechdata.info/geotest/cone-penetration-test.html

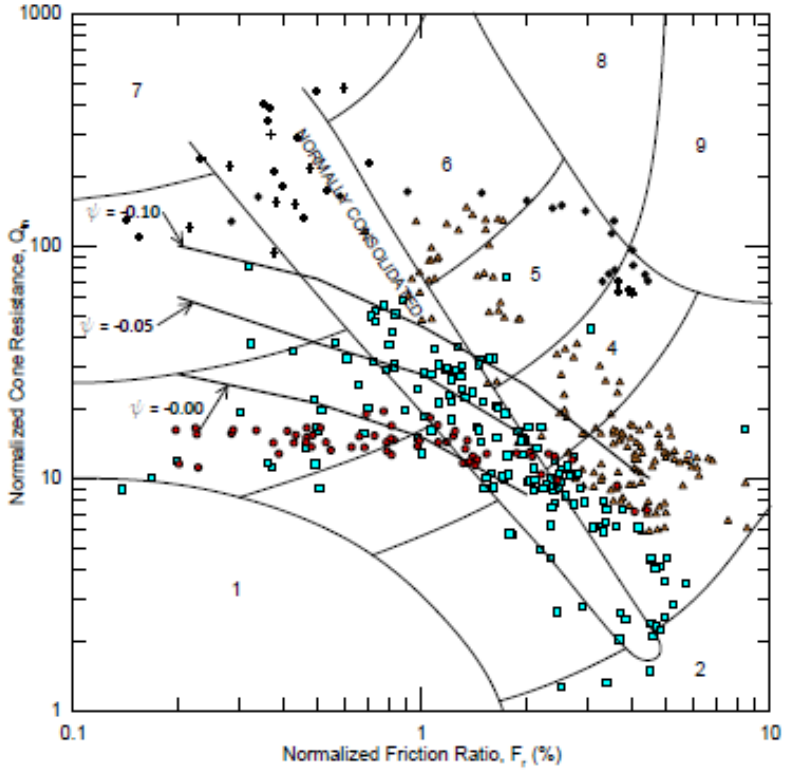
CPTu Test Results





(after AECOM, 2016)

CPTu Test Interpretation

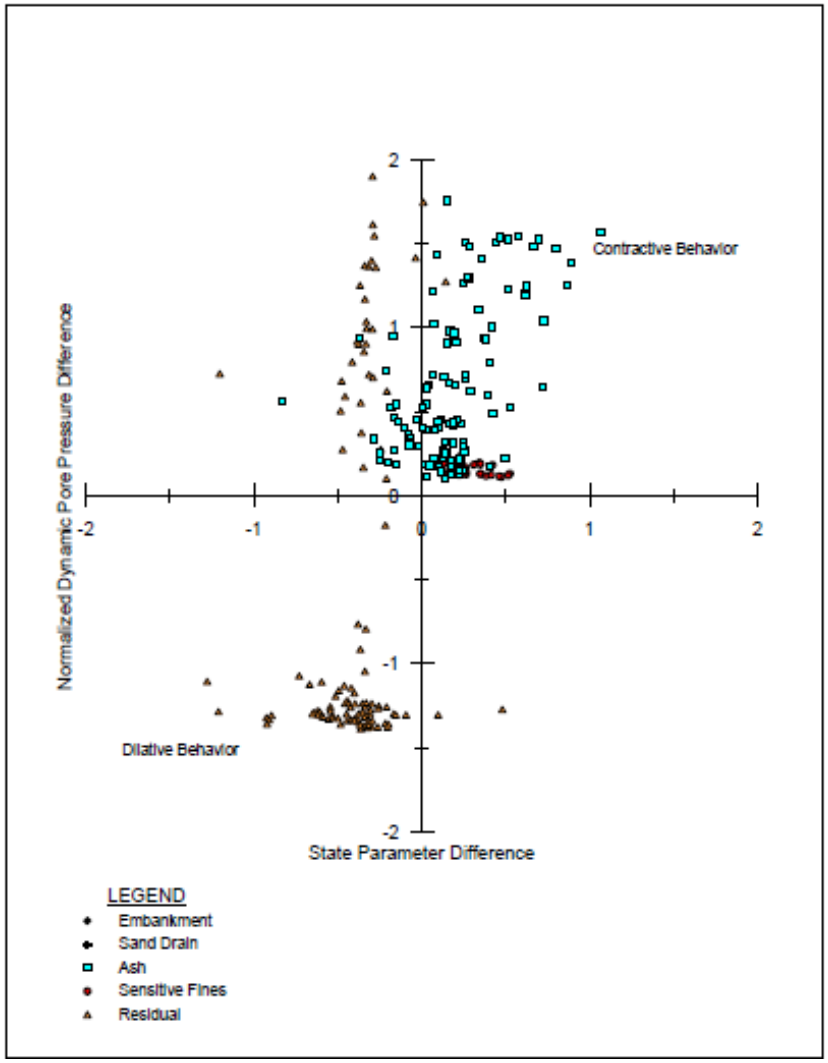


Zone	Soil Behavior Type	Ic
1	Sensitive, fine grained	N/A
2	Organic soils peats	>3.6
3	Clays-silty clay to clay	2.95-3.6
4	Silt mixtures-clayey silt to silty clay	2.6-2.95
5	Sand mixtures-silty sand to sandy silt	2.05-2.6
6	Sands-clean sand to silty sand	1.31-2.05
7	Gravelly sand to dense sand	<1.31
8	Very stiff sand to clayey sand*	N/A
9	Very stiff, fine grained*	N/A

*Heavily overconsolidated or cemented

LEGEND
- Embankment
- Sand Drain
- Ash
- Sensitive Fines
- Residual

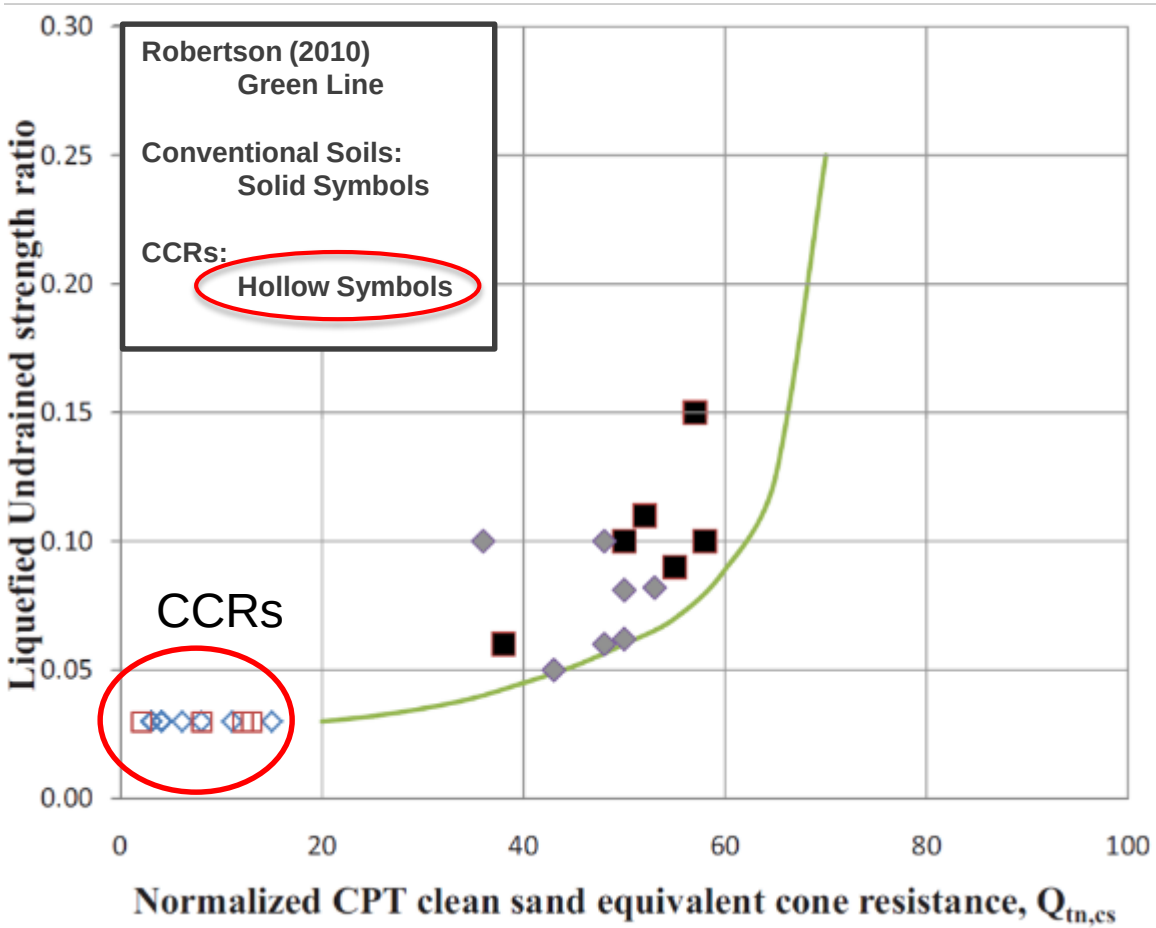
PROJECT NO.	Duke Energy Site C	CPT- DC-100 Approximate Boundary Between Dilative and Contractive Soil Response Using Normalized CPT and Pore Pressure Parameters	FIGURE
	AECOM		



(after AECOM, 2016)

CPTu Test Interpretation

- Current SOP for soils
  - Based on Robertson (2010)
  - Converts q_t to $Q_{tn,cs}$
  - Estimate strengths using case histories
- Potentially too conservative for CCRs?



(after Golder, 2017)

Vane Shear Test - VST

Field Vane Shear Test (VST) deployed at depth

http://www.greggdrilling.com/canada/services/cFQUY/vane-shear-testing

http://geonor.no/en/soil-testingmed-vingebor/

(after discussion with Golder, 2017)

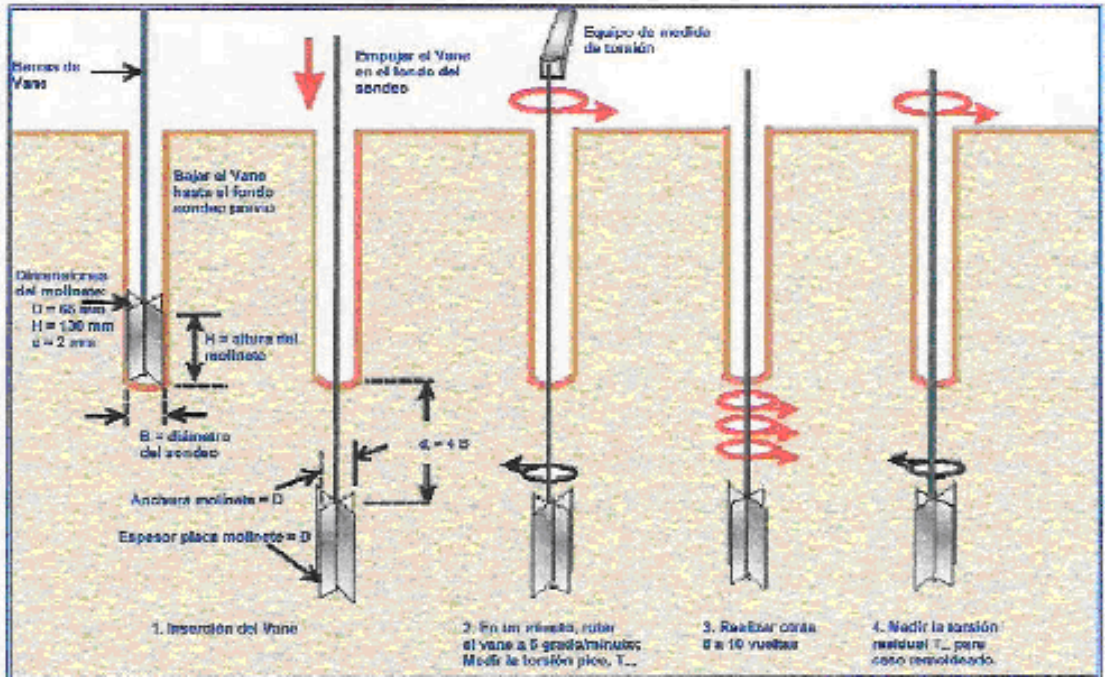
Portable VST deployed at Shallow Depth

www.itlneels.com

(after discussion with CALM, 2016)

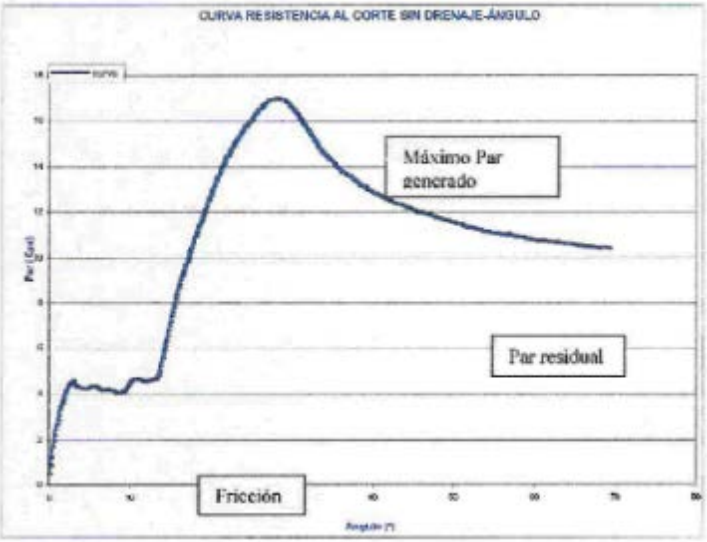
Vane Shear Test - VST

Field Vane Shear Test (VST) deployed at depth



http://english.geocpt.es/Vane_Test.html

Typical VST Results



Vane Shear Test Interpretation

Stacked Ash

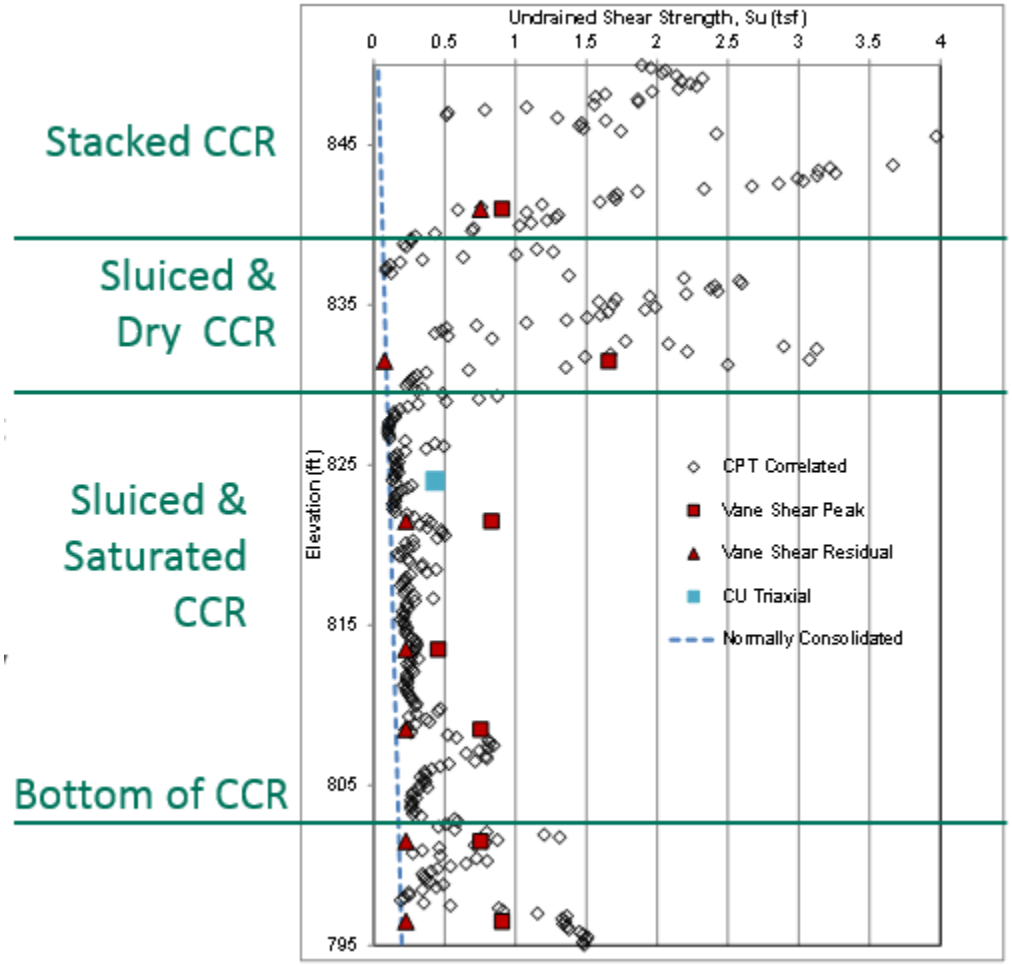
Generally achieves good strengths & is not prone to liquefaction

Sluiced Ash then dried

CRR that remains dry also exhibits significant peak strengths but maintains low residual & post liquefied strengths

Sluiced Ash but still wet

CCR typically exhibits residual strengths close to NC behavior and very small strength increases with depth (may form lightly cemented structure)



(after Golder, 2017)

Example Of Ponded Ash Excavation

Excavated and Dewatered Ash Stands in Vertical Sidewalls

After Transportation (i.e., Vibrations) Material Can Flow

(after Golder, 2017)

Flow/Slump Potential - Laboratory

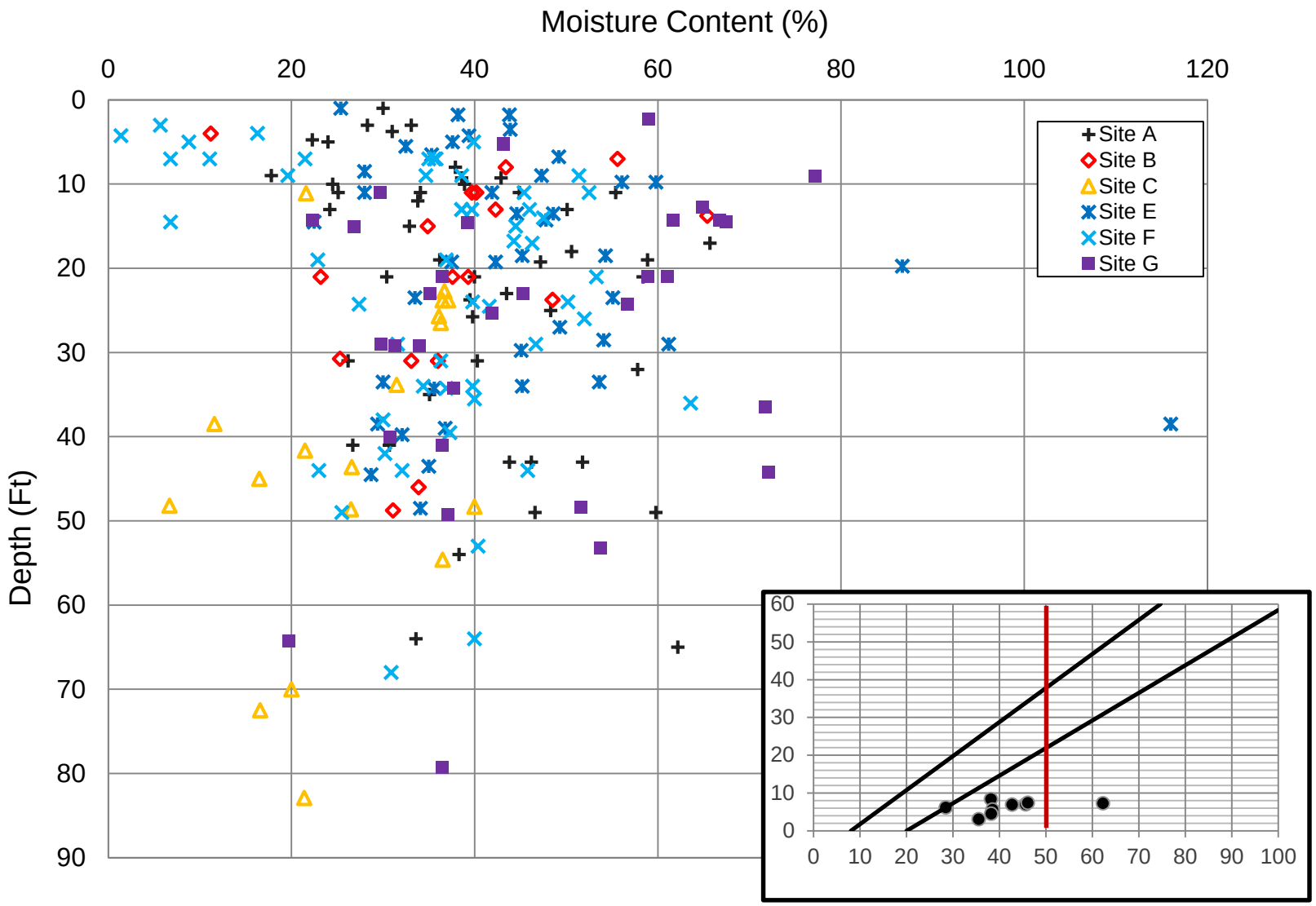
This is not That!

Flow/Slump Potential - Laboratory

No Free Water and Unsupported: Material will Slump

Vibration in Absence of Free Water: Material can Flow and Impact Workability

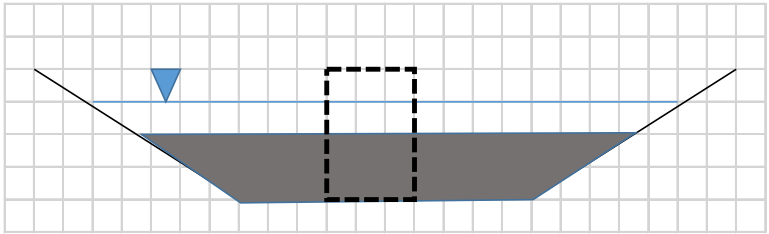
Importance of Eliminating Water

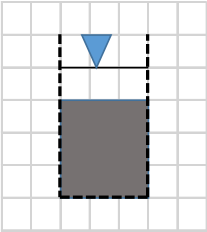


(after AECOM, 2016)

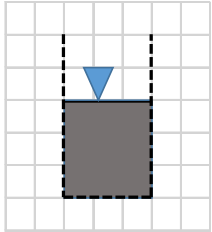
Importance of Pond Dewatering

Schematic of Ash Pond

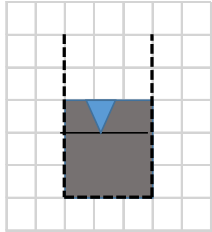




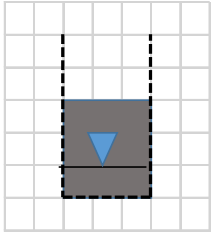
Initial Condition



Drained Pond



Near-surface Dewatering



Dewatered Pond

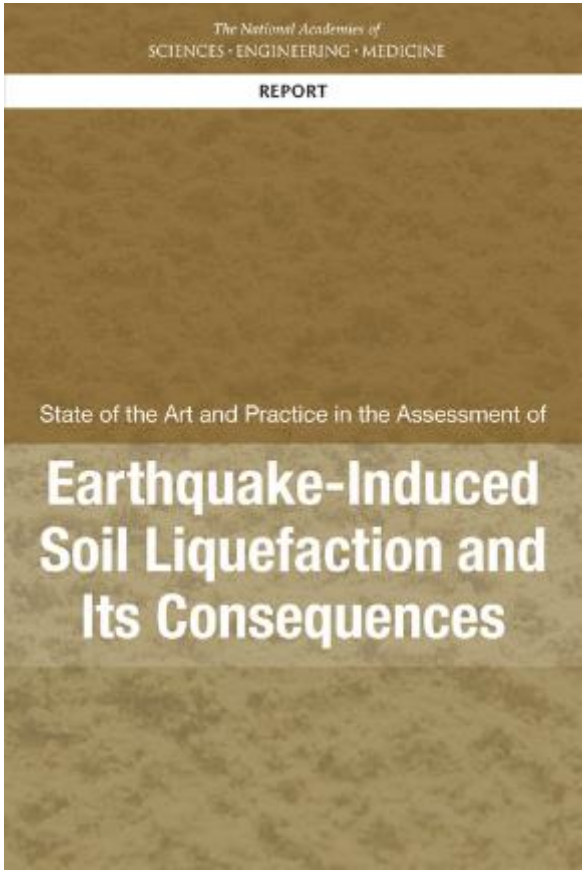
- Draining of free water is “easy” and yields large quantities of water.
- Eliminating free water is essential to reducing flow potential!
- Dewatering the ash may lower the phreatic surface, but may yield small amounts of water (e.g. < 10% to ~30% of ash volume) depending on the particle size of the ponded materials, especially when compared to the drained volume
- Dewatering the ash will not significantly (e.g., >10%) alter the “moisture content” of the ponded ash, but will likely be sufficient to allow vertical cuts for construction and benefit liquefaction potential
- Dewatering may NOT “dry” most CCRs to a level sufficient for compaction
- Important to express the goal of dewatering to manage expectations

Seismic Design Recommendations

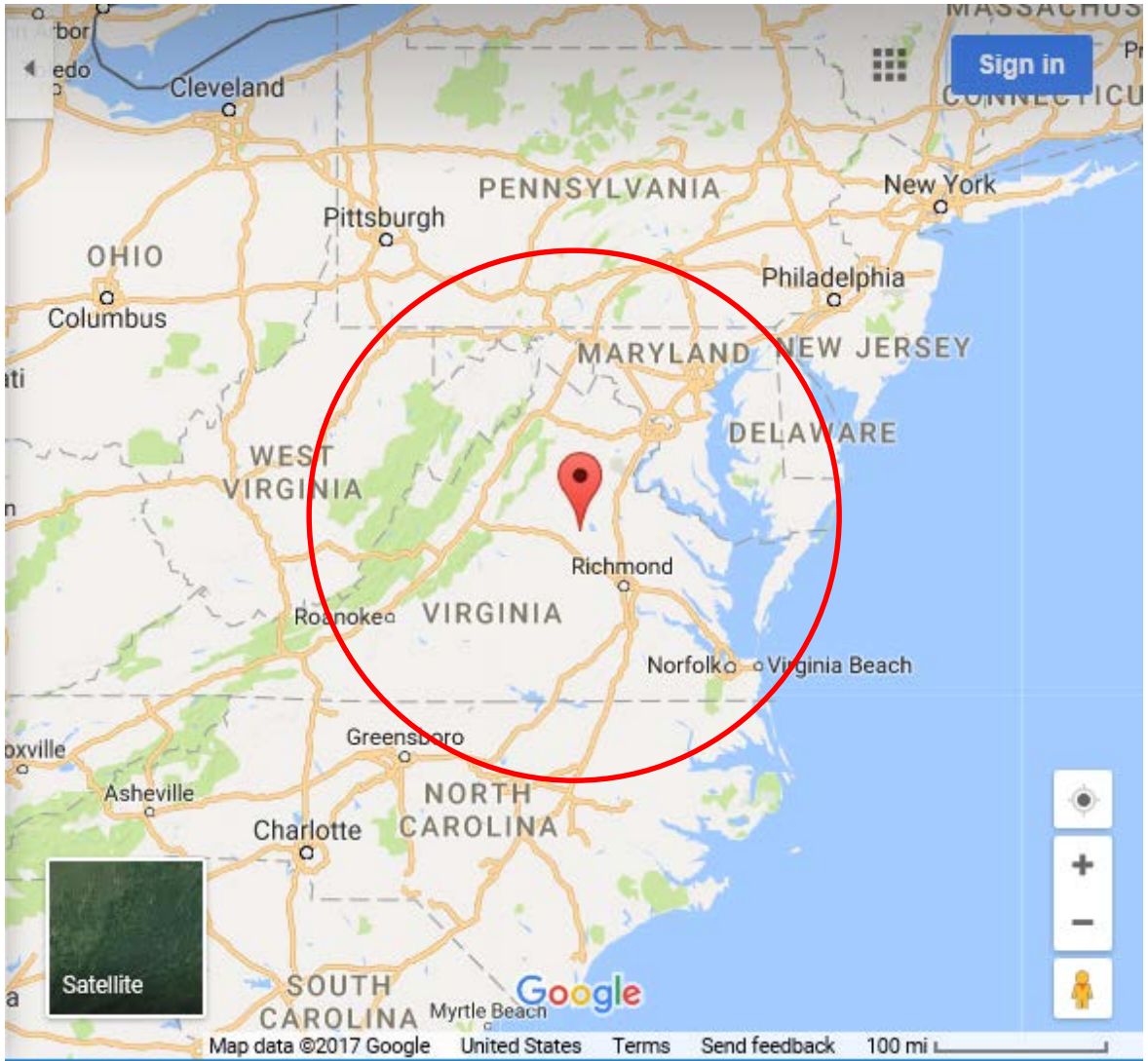
Evaluate Embankment Stability

1998 NCEER/NSF Liquefaction Resistance of Soils: Summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils.
(Journal of Geotechnical and Geoenvironmental Engineering 127 (10), 817–833)

State of the Art and Practice in the Assessment of Earthquake-induced Soil Liquefaction and Its Consequences
(National Academies of Science, Engineering, Medicine, 2016)



East Coast Seismicity
Mineral, VA Earthquake (23 August 2011)



Magnitude ~5.8

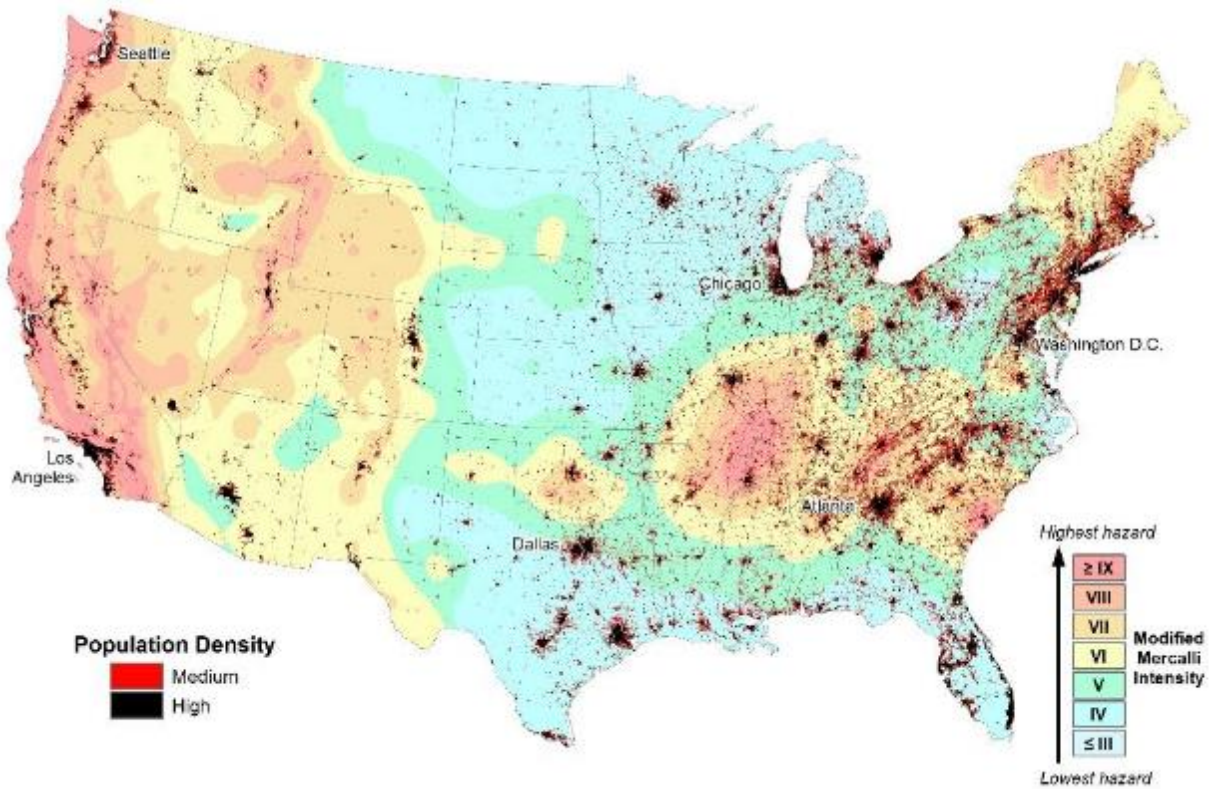
Landslides noted within 150 miles of epicenter

Evidence of liquefaction?

Liquefaction Potential Map

Map showing areas where there id 2% chance in 50 years that peak ground acceleration will attain or exceed 0.1g

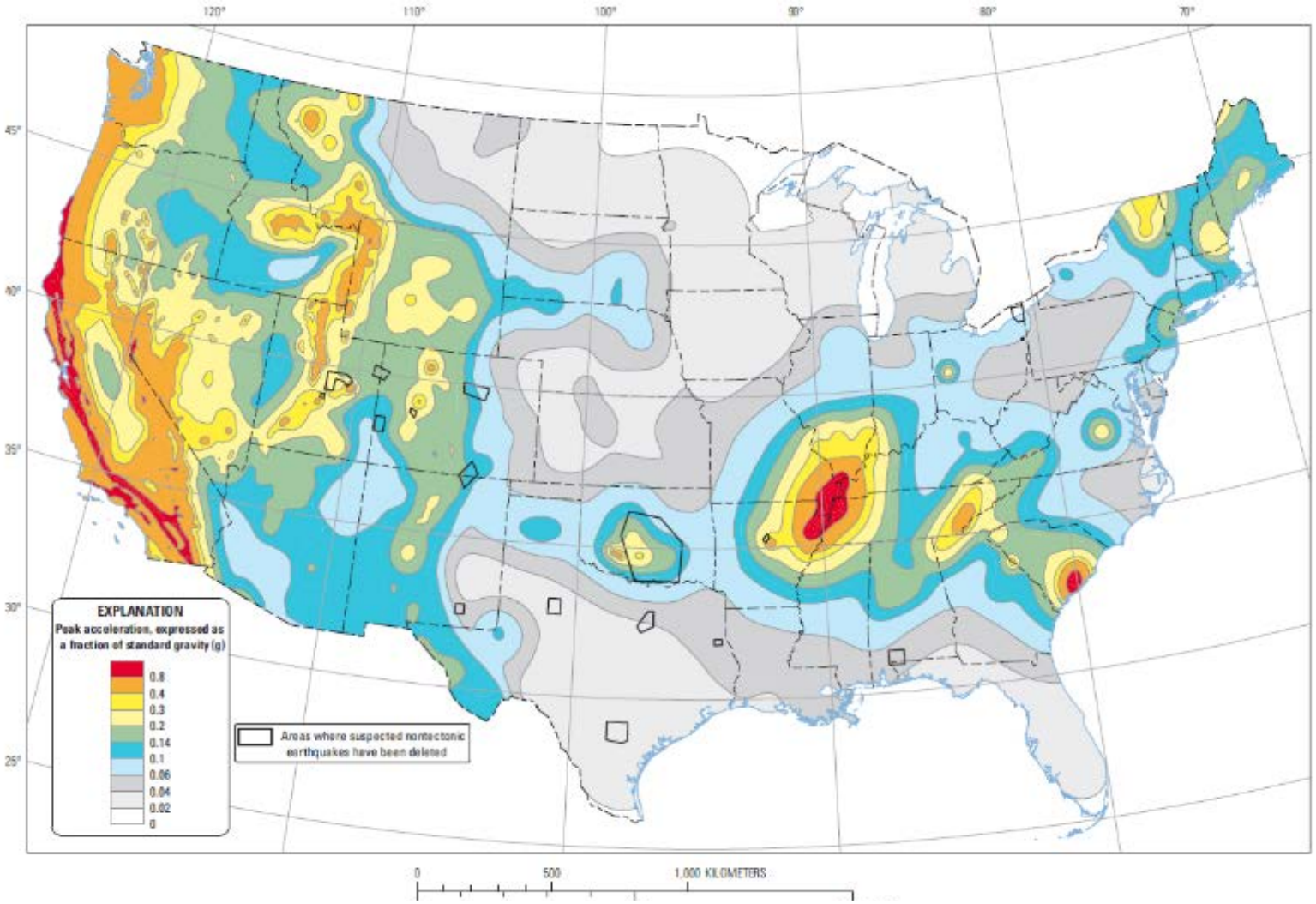
(modified from Petersen et al., 2014)



Ground shaking is presumed to be intense enough to cause liquefaction in water-saturated granular materials.

(after https://www.usgs.gov)

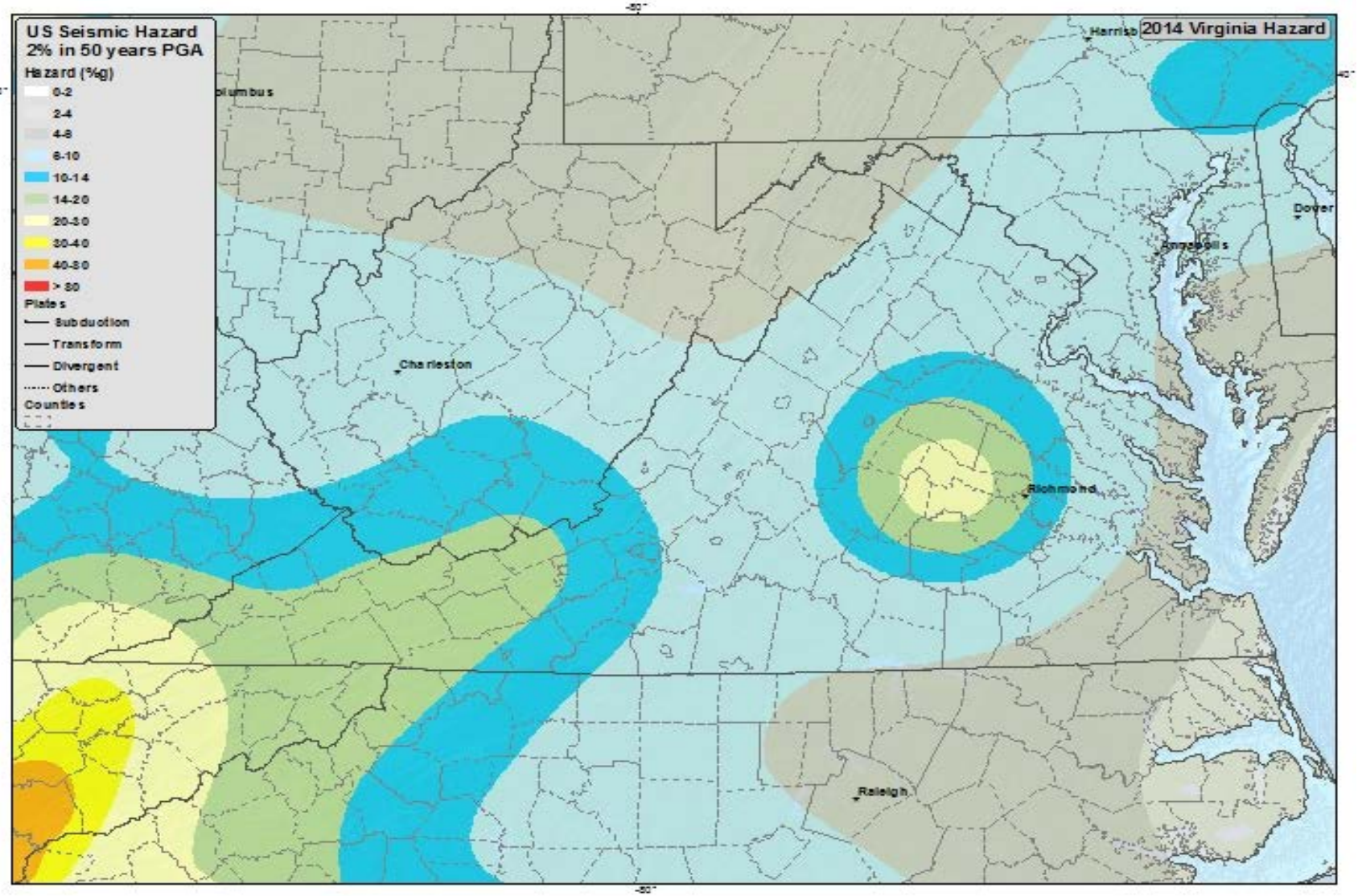
Peak Ground Acceleration Map



Two-percent probability of exceedance in 50 years map of peak ground acceleration

(after https://www.usgs.gov)

Regional Seismicity Map



(after https://www.usgs.gov)

Seismic Design Recommendations

Input Earthquake Motions: To commence a seismic design, one must first select a series of input ground motions that are “appropriate” for their site.

How to make this selection for East Coast seismic events where records for large events are often not available. This has been an age-old recognition, but one that we have found ways of resolving.

Analysis	Profile	Input Motion	Peak Acceleration (g)
A1	A-A’	1952 Taft	0.08
A2	A-A’	1952 Taft	0.15
A3	A-A’	1940 El Centro	0.08
A4	A-A’	1940 El Centro	0.15

We first identify a recurrence interval that we use for our design. This will define the peak ground acceleration (PGA) in bedrock that is used for design. We then find a suite of historic ground motions that exhibit the frequency content and scale these records to the design PGA.

Fly Ash Pond Example

Location of Site: Eastern U.S.

Depth of Ash in Pond: 158 ft

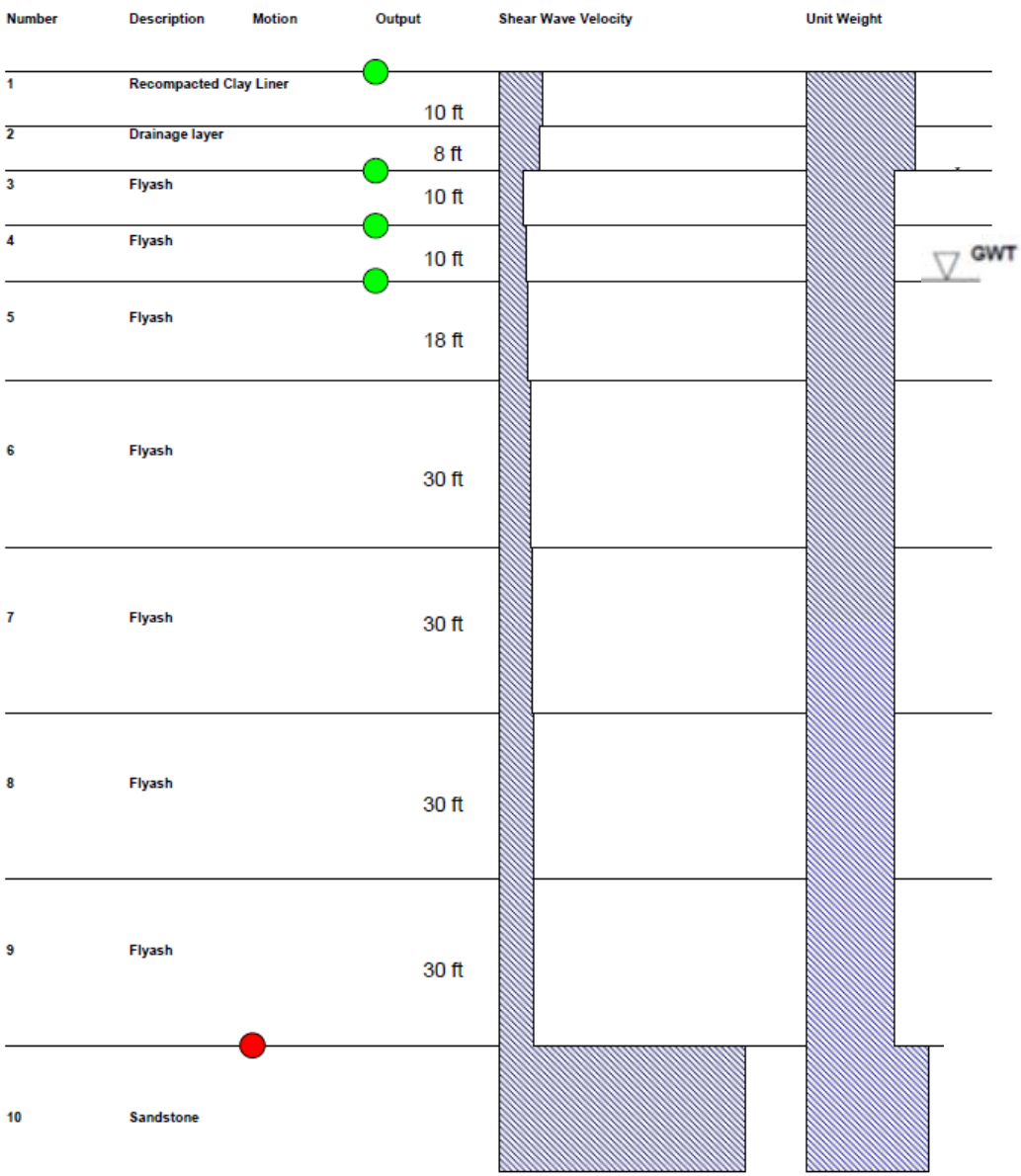
Clay Cover at Top of Profile: 10-ft thick

Drainage Layer below Clay Cover: 8-ft thick

Bedrock Layer at Base of Site: Sandstone Bedrock

Groundwater Table: 20 ft. below top of ash (z = 38 ft.)

Seismic Design Recommendations
Idealized Ash Pond Profile



Section A-A'

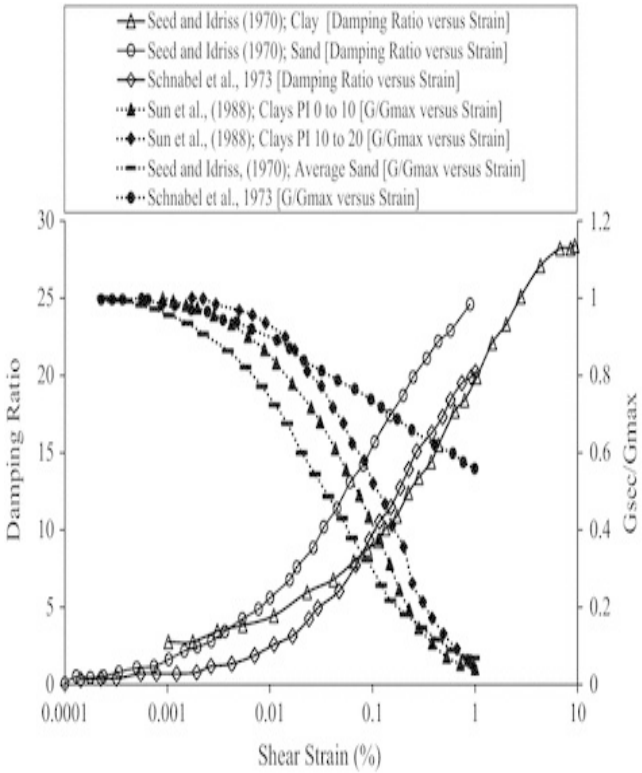
- Subdivide pond into discrete analysis layers (i.e., ten (10) layers in this example)
- Apply bedrock input motion at base of profile
- Propagate wave from the base through the ash column
- Calculate the response (i.e., shear stress) of the ash due to the propagation shear wave

Input Motion

Analysis Output

Seismic Design Recommendations Properties for Layers

Layer Number	Material Description	Thickness (ft)	Unit Weight (pcf)	Gmax (ksf)	Vs (ft/sec)	Modulus Reduction	Damping Curve
1	Recompacted Clay Liner	10	125	3,885	1,000	Clay (Seed and Sun 1989)	Clay (Idriss 1990)
2	Drainage layer	8	125	3,300	921	Sand (Seed & Idriss) - Average	Sand (Seed & Idriss) Average
3	Fly ash	10	100	1,000	567	Sand (Seed and Idriss 1970)	Sand (Idriss 1990)
4	Fly ash	10	100	1,200	621	Sand (Seed and Idriss 1970)	Sand (Idriss 1990)
5	Fly ash	18	100	1,400	671	Sand (Seed and Idriss 1970)	Sand (Idriss 1990)
6	Fly ash	30	100	1,600	717	Sand (Seed and Idriss 1970)	Sand (Idriss 1990)
7	Fly ash	30	100	1,800	761	Sand (Seed and Idriss 1970)	Sand (Idriss 1990)
8	Fly ash	30	100	1,900	781	Sand (Seed and Idriss 1970)	Sand (Idriss 1990)
9	Fly ash	30	100	2,000	802	Sand (Seed and Idriss 1970)	Sand (Idriss 1990)
10	Sandstone	Infinite	140	135,360	5,577	---	---



Seismic Design Recommendations
Propagation of Shear Wave (SHAKE)

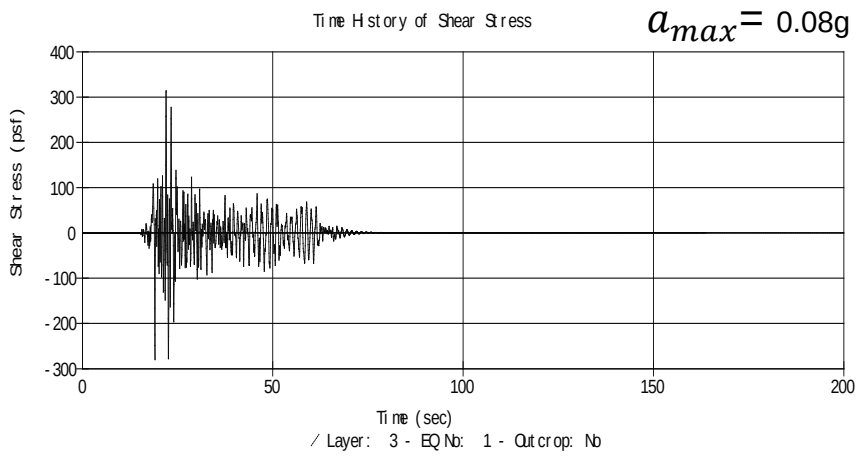
Propagation of shear wave from bedrock through the overlying saturated ash is calculated using established computer simulation programs. In this case, we will use the one-dimensional wave propagation program SHAKE. Other programs are now available as freeware (primarily developed by university faculty).

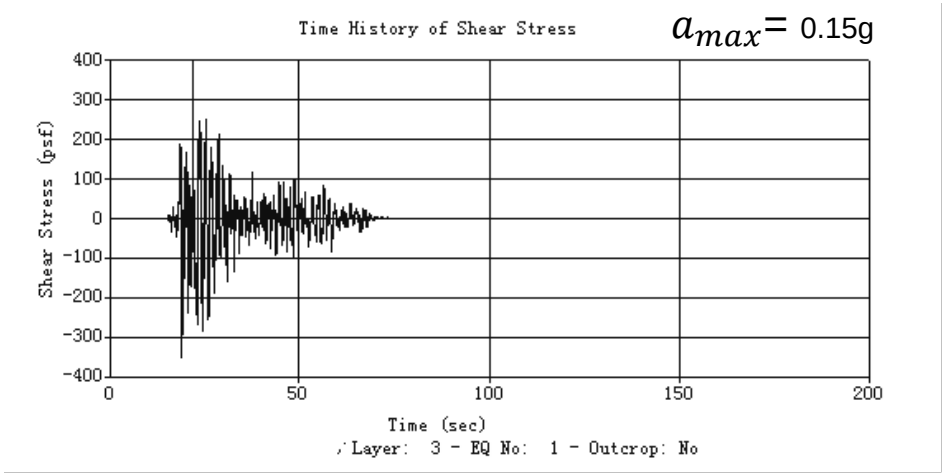
(Reference: P. B. Schnabel, J. Lysmer and H. B. Seed, "SHAKE - A Computer Program for Earthquake Response Analysis of Horizontally Layered Sites," Report No. EERC 72-12, Earthquake Engineering Research Center, University of California, Berkeley, 1972.)

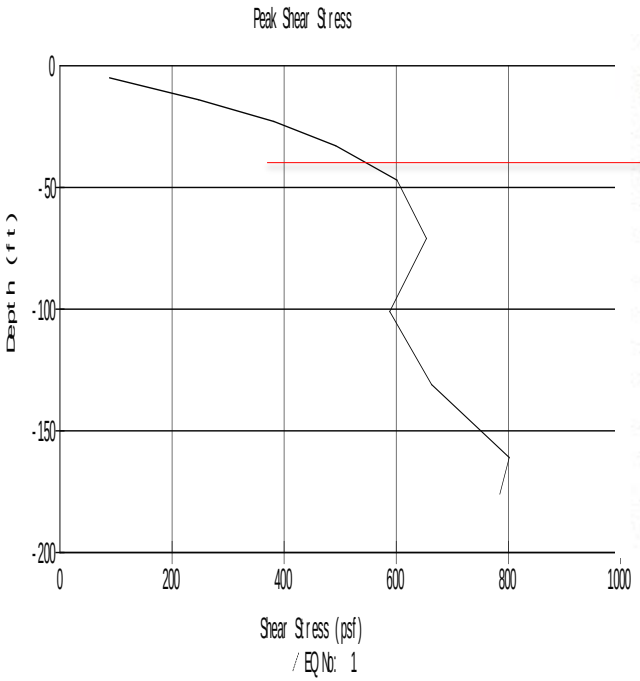
The following assumptions are implied in the analysis:

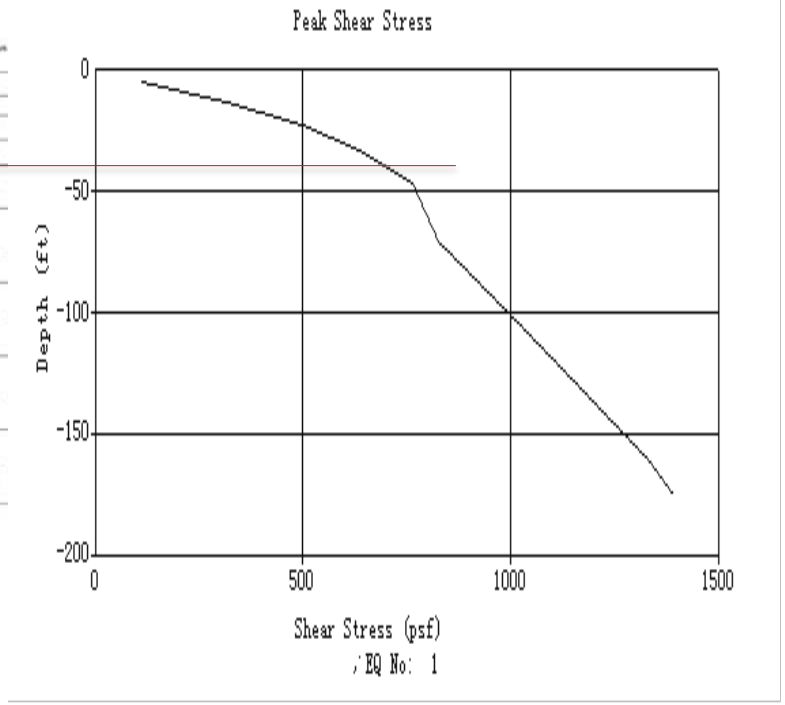
1. The soil system extends infinitely in the horizontal direction
2. Each layer in the system is completely defined by its value of shear modulus, critical damping ratio, density, and thickness. These values are independent of frequency.
3. The responses in the system are caused by the upward propagation of shear waves from the underlying rock formation.
4. The shear waves are given as acceleration values of equally spaced time intervals. Cyclic repetition of the acceleration time history is implied in the solution.
5. The strain dependence of modulus and damping is accounted for by an equivalent linear procedure based on an average effective strain level computed for each layer.
6. The program is able to handle systems with variation in both moduli and damping and takes into account the effect of the elastic base.
7. The motion used as a basis for the analysis, the object motion, can be given in any one layer in the system and new motions can be computed in any other layer.

Taft EQ Input at Top of Rock

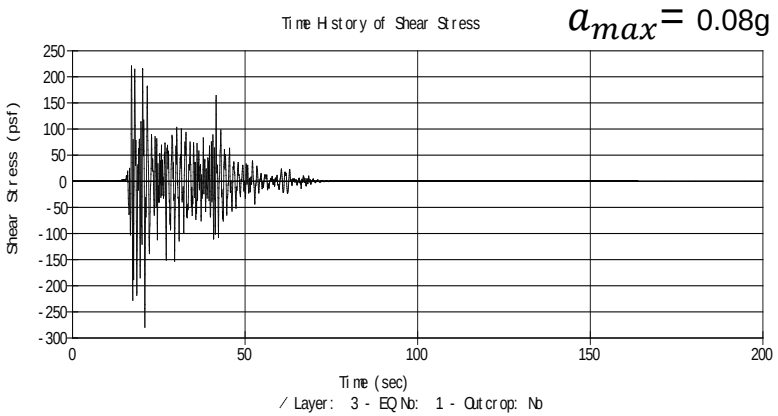


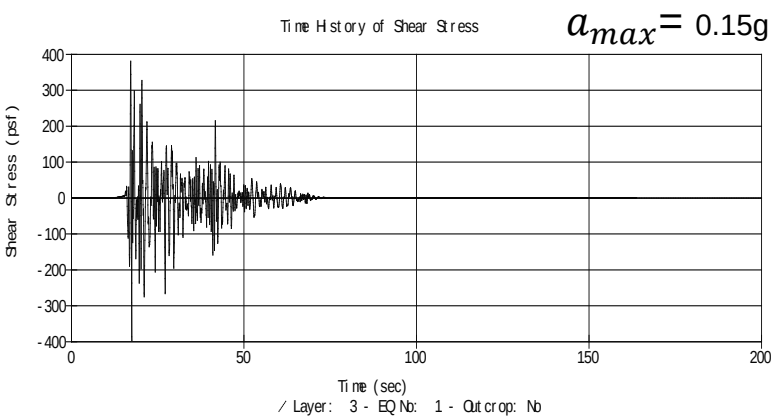


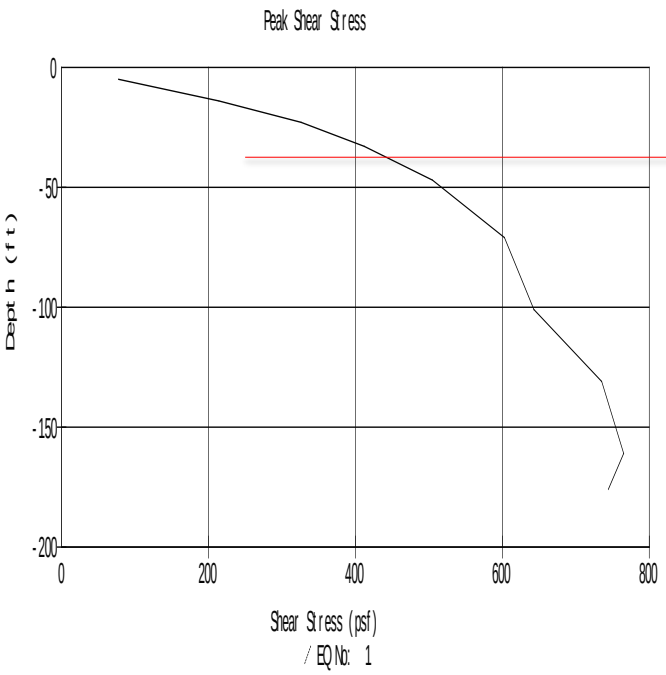


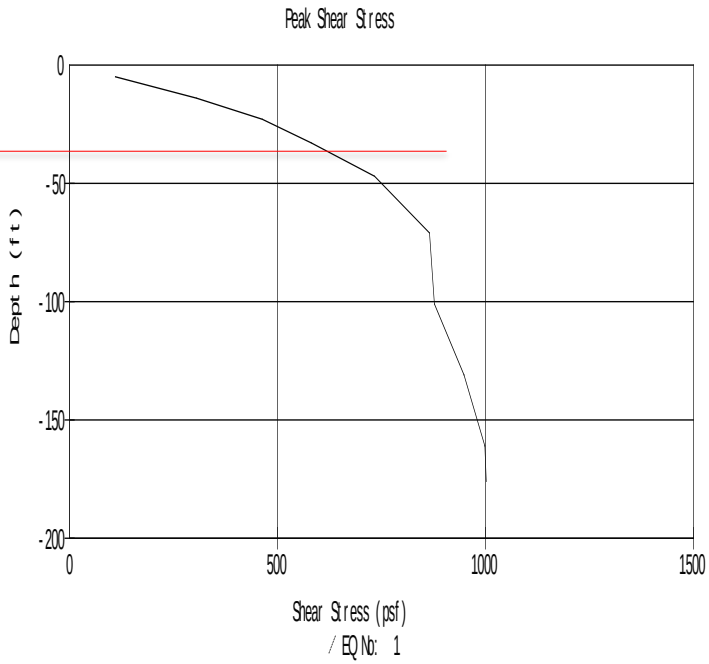


El Centro EQ Input at Top of Rock









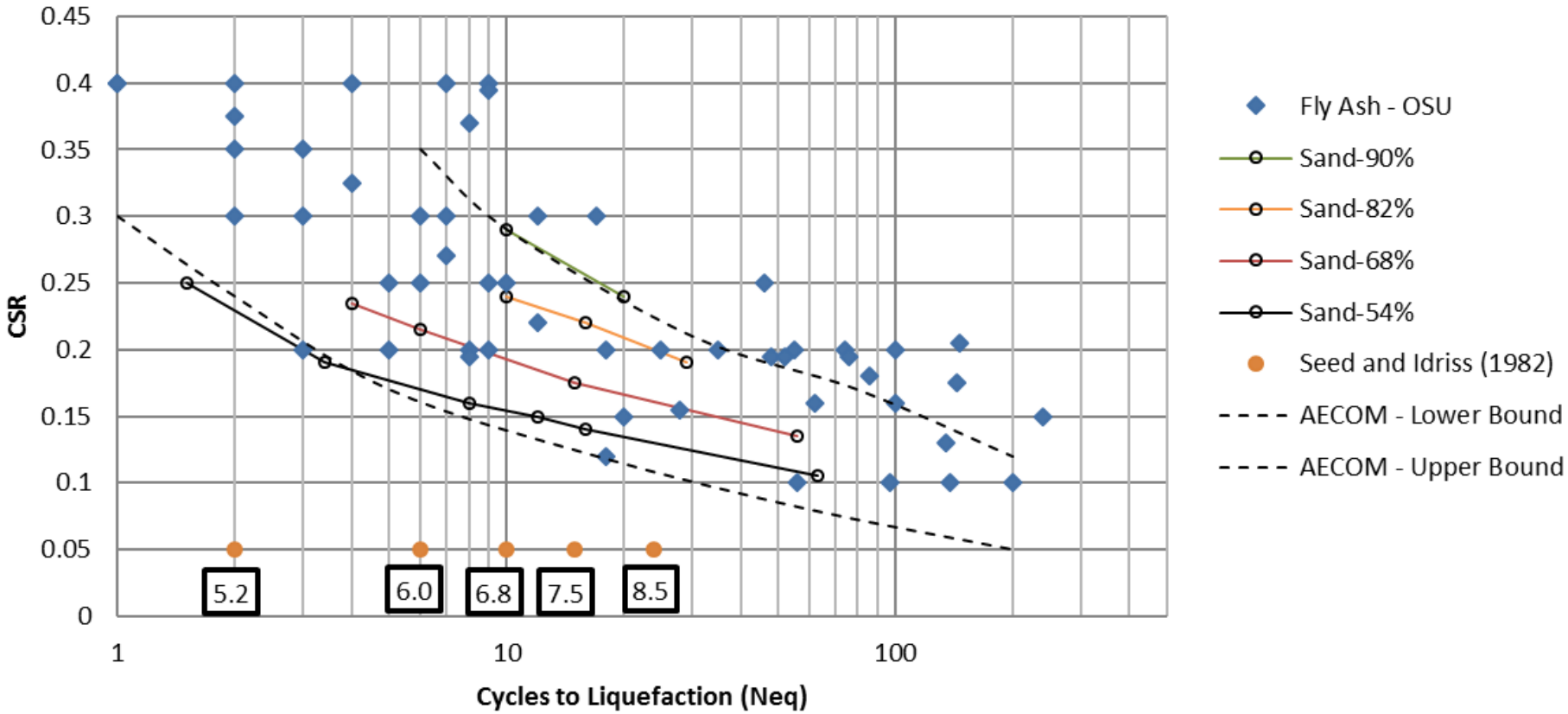
Results of Ground Response Analysis

Parameters	Layer #	Depth (ft)	σ_0' (psf)	τ_{max} (psf)	τ_{cyc} (psf)	N_{equ}	CSR_{field}	CSR_{lab}
A-A'	3	18	2250	310	202	4	0.09	0.10
Taft	4	28	3250	436	283	4	0.09	0.10
a_{max}=0.08g	5	38	4250	536	348	4	0.08	0.09
A-A'	3	18	2250	397	258	6	0.11	0.13
Taft	4	28	3250	556	361	6	0.11	0.12
a_{max}=0.15g	5	38	4250	682	443	6	0.10	0.12
A-A'	3	18	2250	279	181	8	0.08	0.09
El Centro	4	28	3250	382	248	8	0.08	0.09
a_{max}=0.08g	5	38	4250	458	298	8	0.07	0.08
A-A'	3	18	2250	386	251	6	0.11	0.12
El Centro	4	28	3250	536	348	6	0.11	0.12
a_{max}=0.15g	5	38	4250	655	426	6	0.10	0.11

Noted Modifications

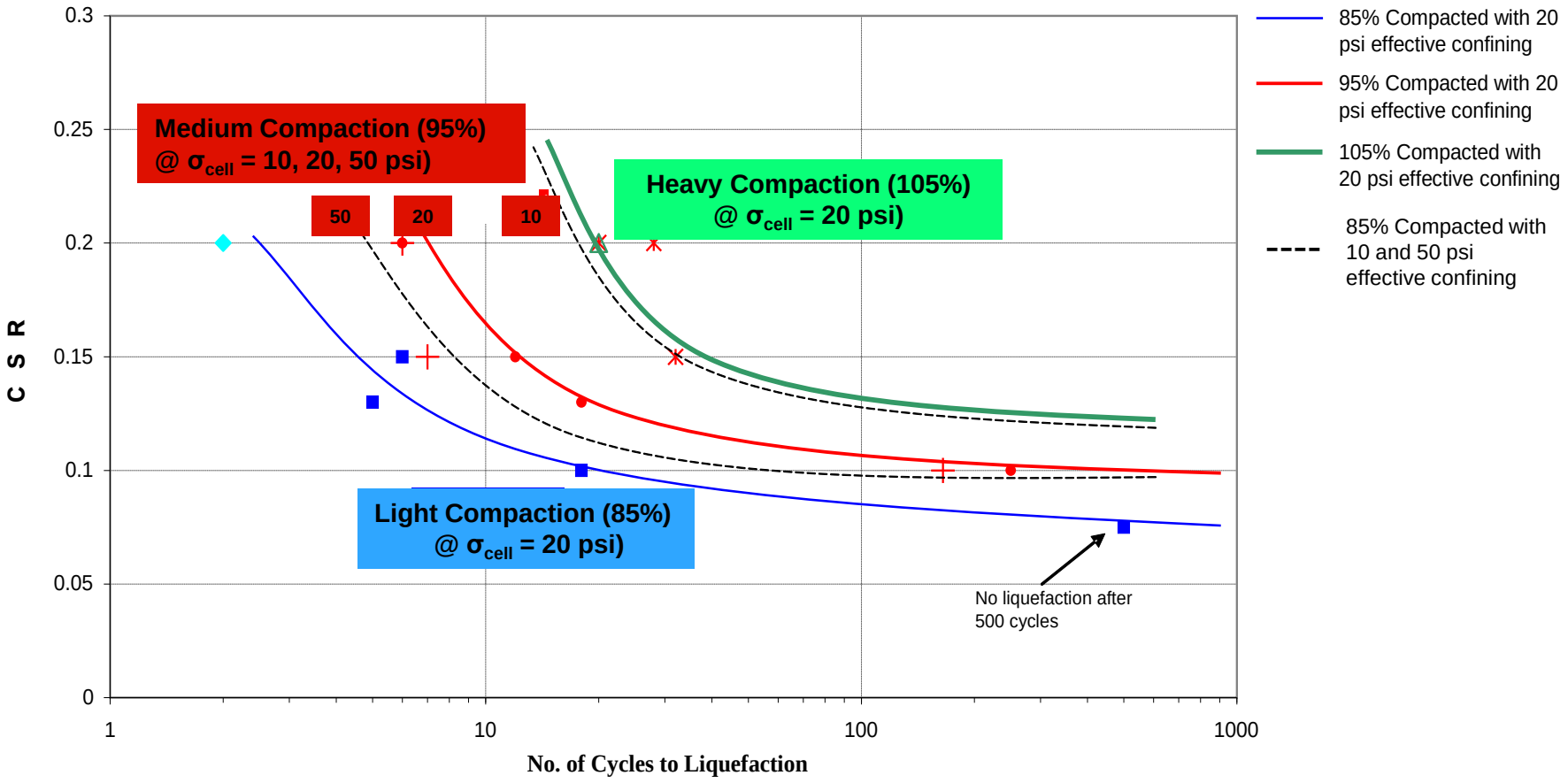
1. $\tau_{cyc} = \tau_{max}$
2. $(CSR)_{field} = 0.9\ (CSR)_{lab}$
3. $(CSR)_{DSS} = 0.65\ (CSR)_{TXC}$

Dynamic Undrained Results Triaxial and DSS

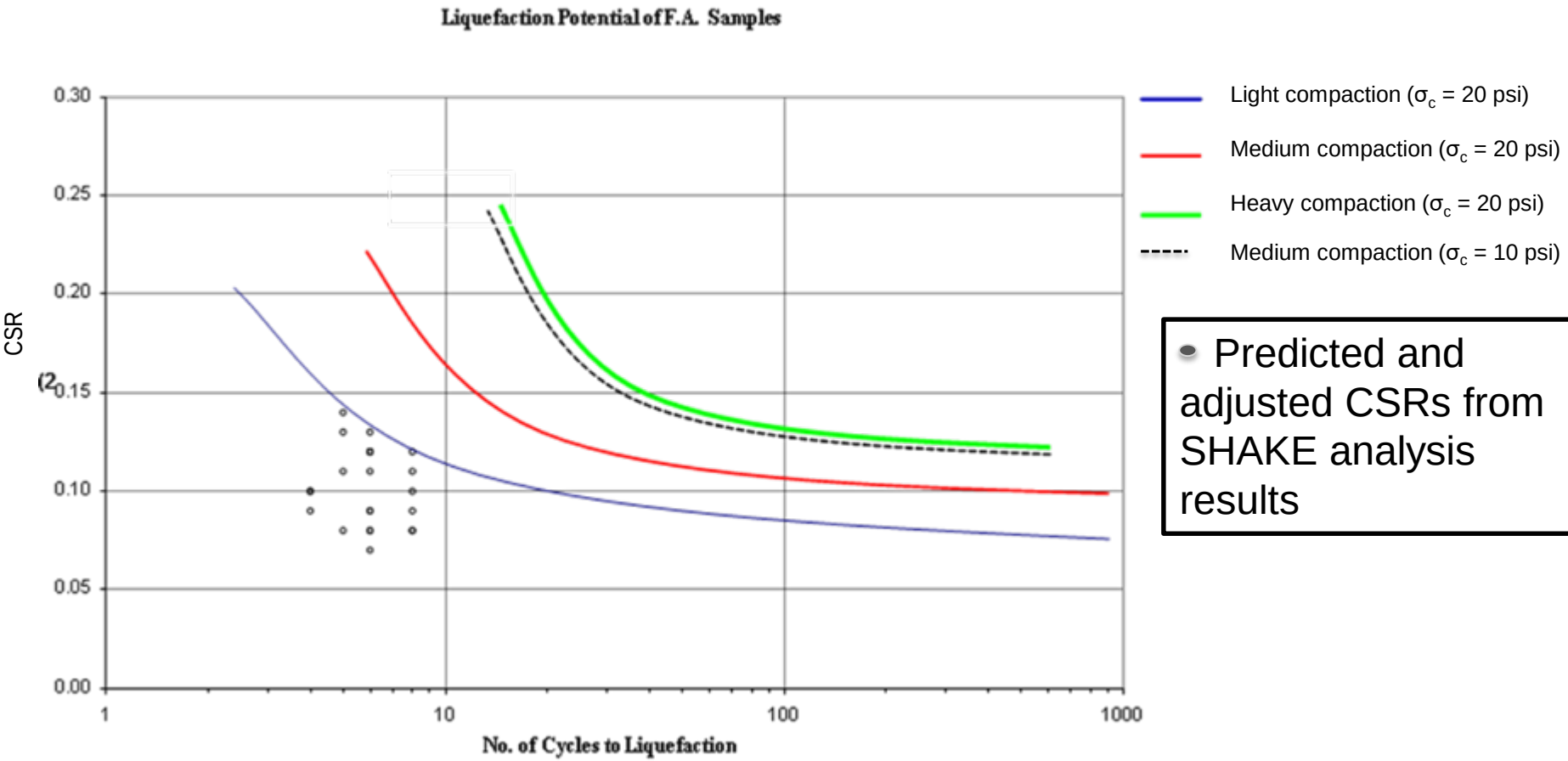


Source:
Wolfe (2016) - fly ash
deAlba (1976) - sand

Cyclic Triaxial Tests



SHAKE Analysis Results



- Predicted and adjusted CSRs from SHAKE analysis results

Observations

Overall Observations

- Fly ash under cyclic loads behaves similarly to natural granular fine grained soils.
  - For a given relative density, the number of loading cycles to produce liquefaction decreases with increasing shear stress ratio (CSR); and
  - For a given shear stress ratio (CSR), liquefaction resistance increases with increasing relative density

- Cyclic strength, expressed as CRR, falls within the range of strength values measured for fine sands and silts

- The factor of safety against liquefaction depends on the compactive effort, cyclic stress ratio, and initial confining pressure.

Specific Observations

- For the example problem, the measured cyclic strength (CRR) of the tested material was determined to be greater than the loading imposed by the two design earthquakes (CSR).

Presentation Outline

- Basic Material Characterization
- Laboratory Strength Characterization
  - Static and Dynamic
- Field Characterization
- Seismic Design Recommendations

Summary

Basic Material Characterization

- Ponded fly ash is characterized by a relatively consistent mineral chemistry that does not “react” chemically with water and unique particle shape
- Fly ash generally exhibits low specific gravity of solids relative to mineral soils, thus relatively low unit weight, and is best characterized as a well-graded silt
- Fly ash is typically low- to non-plastic and as such the properties are very sensitive to even subtle changes in moisture content
- Small particle size leads to large surface tension that “holds onto water” when partially saturated and controls the permeability
- Recognizing the concept of “realizable density” shows that wet pluviation (similar to the depositional conditions in an ash pond) does not results in an extremely loose structure, but does result in layering
- Because there is grain-to-grain contact, the ponded fly ash is only moderately compressible, and the permeability is relatively high
- Apparent “unusual” behavior of ponded fly ash is somewhat compounded by the fact that it is unusual to encounter thick strata of silt-sized particles in most geotechnical practices

Summary

Laboratory Strength Characterization

- Sample preparation is a key and must model the depositional process in the field to be used in design
- Static strength of ponded fly ash is consistent with that anticipated (and measured) for granular materials and generally indicates dilative behavior
- Cyclic response of ponded fly ash is consistent with the cyclic response of sands

Field Characterization

- Dewatered fly ash is NOT dry fly ash, due to the high capillary tension potential of the well-graded silty fly ash
- The layering of coarse and fine CCRs contribute beneficially to dewatering, but can contribute free water that can lead to rapid destabilization
- Standard penetration test (SPT) blow counts are very low and there are not any reliable “correlations” to engineering properties
- Cone penetration test (CPTu) profiling seems to be best technique for characterizing CCR ponds. We are still learning how to best utilize the correlations developed for “conventional” mineral soils
- Vane shear test (VST) assessment, while not typically used in silts, seems to provide better assessment of residual strengths relative to correlations from CPTU soundings

Summary

Seismic Design Recommendations

- Seismic design example to assess liquefaction resistance was developed and presented
- Techniques developed to assess liquefaction resistance for sands is believed to be appropriate for ponded fly ash
- There may be some inconsistent observations/conclusions when compared to CPTu correlations for liquefaction potential

Conclusions

http://jonvilma.com/band-of-brothers.html

Hopefully, this presentation will allow our Band of Brothers and Sisters to remain strong, informed, and vigilant….

… such that we can proudly wear the Scarlett Letter

Thank you for your interest and participation

www.wikipedia.org