PEER Workshop *on* Liquefaction Susceptibility

APPENDIX E

Session 1 Presentations

K. Önder Çetin: ***Probabilistic Models for Seismic Soil Liquefaction Susceptibility***

Thomas Weaver: ***Evaluating Liquefaction Susceptibility for Nuclear Power Plant Sites***

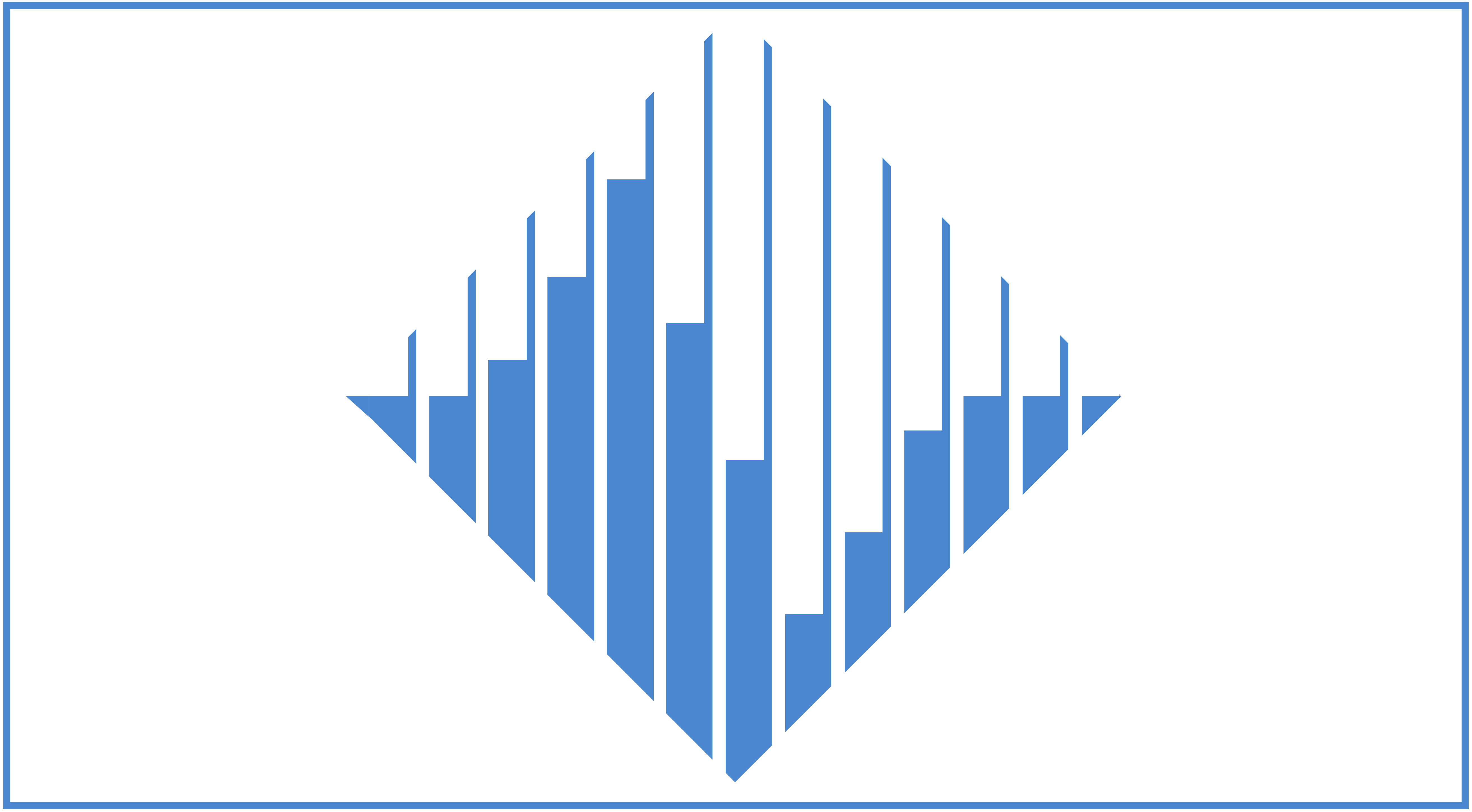
Erik Malvick: ***Challenges of Liquefaction Assessment at California's Dams***

Pedro Espinosa: ***Dynamic Behavior of the Treasure Island Natural Shoals***

Sam Sideras: ***Liquefaction Susceptibility of a Low Plasticity Silty Soil Utilizing Cyclic Direct Simple Shear Testing***

Matt Gibson: ***Liquefaction Susceptibility of Grays Harbor Silts***

Brice Exley: ***The Impacts of Analyzing Deep Sand and Transitional Soil Profiles with State of the Practice Methods***



PROBABILISTIC MODELS FOR SEISMIC SOIL LIQUEFACTION SUSCEPTIBILITY

September 08, 2022

Prof. Dr. K. Onder Cetin

Middle East Technical University, Turkey

Contributors

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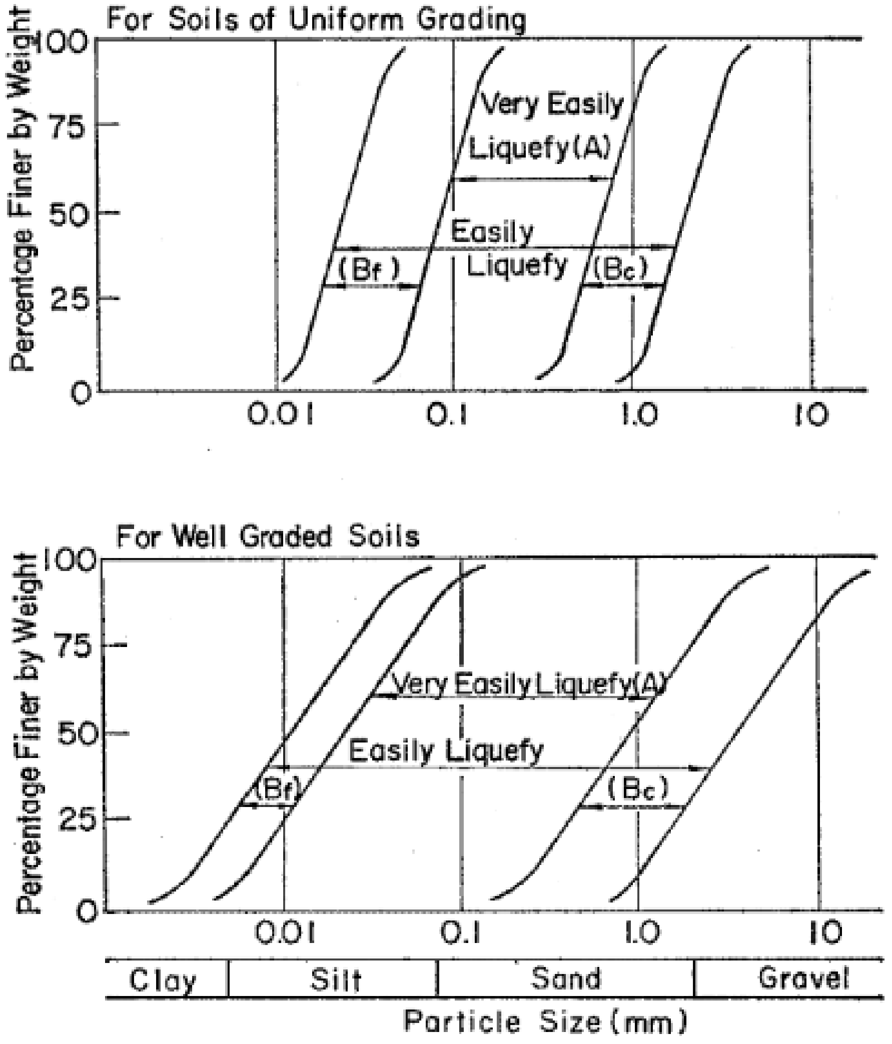
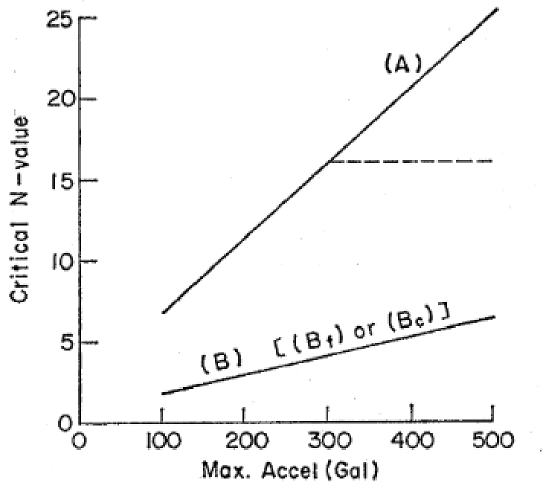




‘Field performance data obtained near the strong ground motion earthquake observation station’

1964 Niigata EQ, Akita Port, 1975 Miyagi-ken-oki,

1983 Nihonkai-Chubu

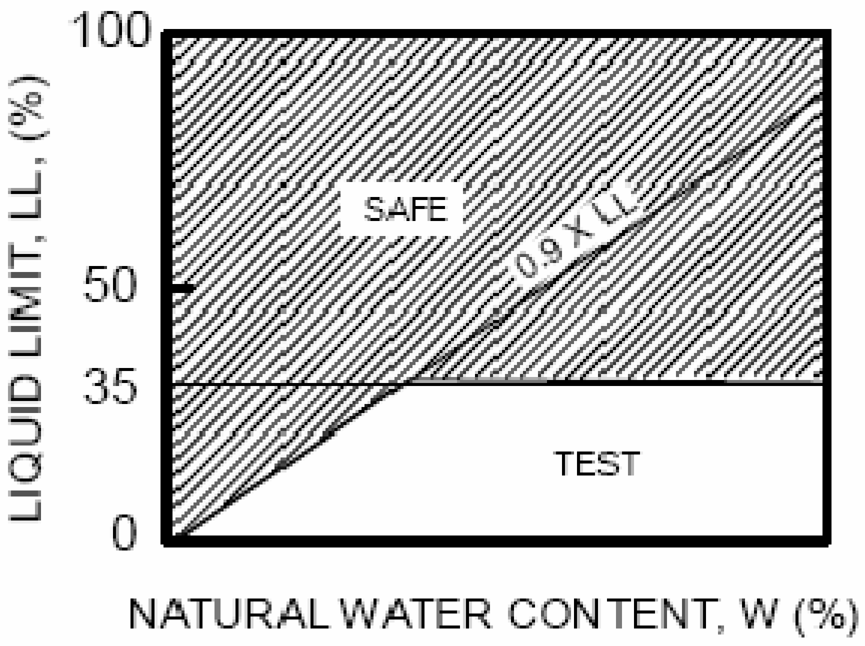
AVAILABLE SUSCEPTIBILITY ASSESSMENTS

Tsuchida (1970), Iai et al. (1986, 1989)

AVAILABLE SUSCEPTIBILITY ASSESSMENTS

Chinese Criteria, Wang (1979)

1. Percent Finer than 0.005mm ≤ 15%
2. Liquid Limit (LL) ≤ 35%
3. Water Content (W) ≥ 0.9 x LL



‘Chinese EQ field performance data

Clay < 5 microns

LL by fall cone as opposed to Casagrande percussion method

	Liquid Limit < 32 (1)	Liquid Limit ≥ 32
Clay Content < 10% (2)	Susceptible	Further Studies Required *(Considering plastic non-clay sized grains - such as Mica)*
Clay Content ≥ 10%	Further Studies Required *(Considering non-plastic clay sized grains – such as mine and quarry tailings)*	Not Susceptible

Notes:

1. Liquid Limit determined by Casagrande-type percussion apparatus
2. Clay defined as grains finer than 0.002mm

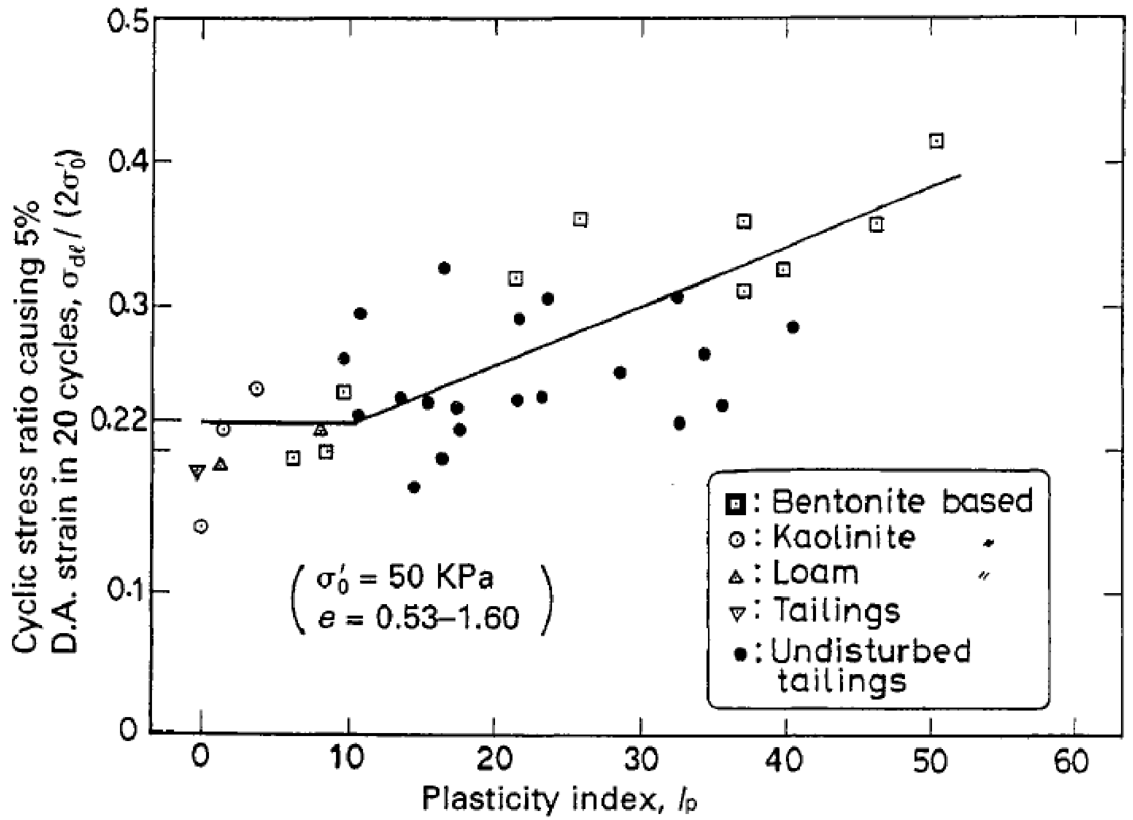
‘Standard definitions and procedures’

Modified Chinese Criteria

wc/LL > 0.9 eliminated

AVAILABLE SUSCEPTIBILITY ASSESSMENTS

Andrews and Martin (2000)

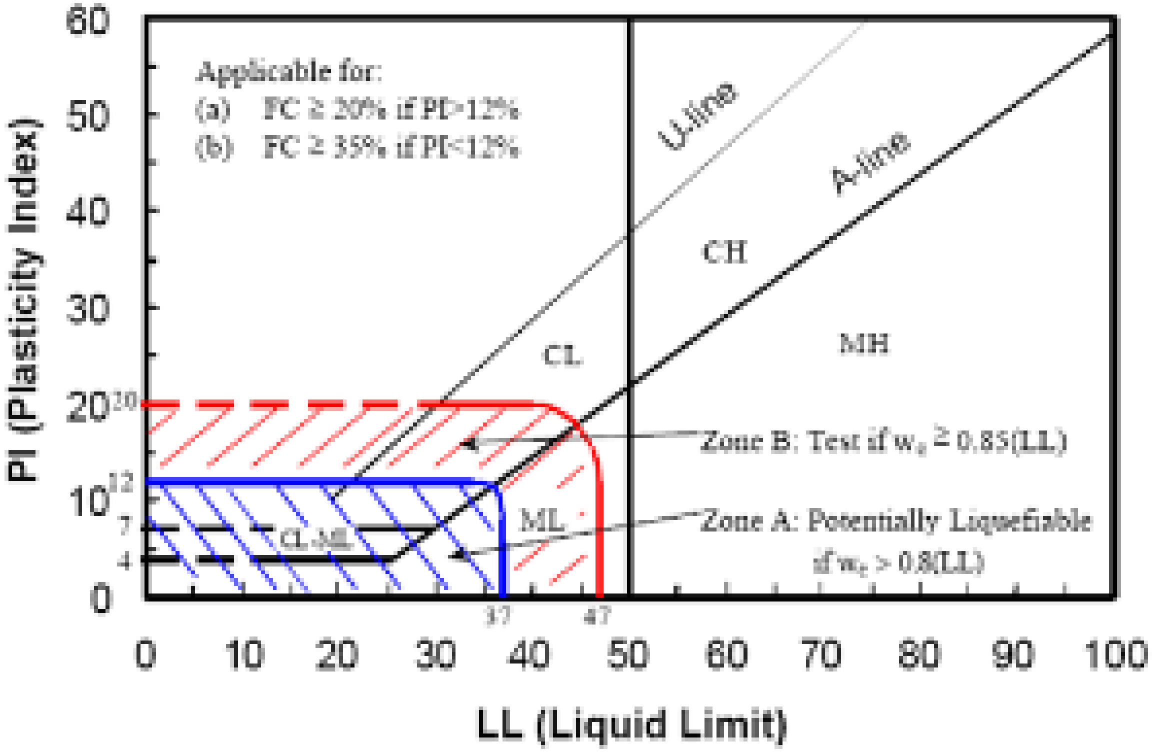


Cyclic Triaxial Tests,

5 % Double Amplitude Axial Strain in 20 cycles

AVAILABLE SUSCEPTIBILITY ASSESSMENTS

Ishihara (1996)



Adapazari silty-clayey sands, 1999 Kocaeli Earthquake,

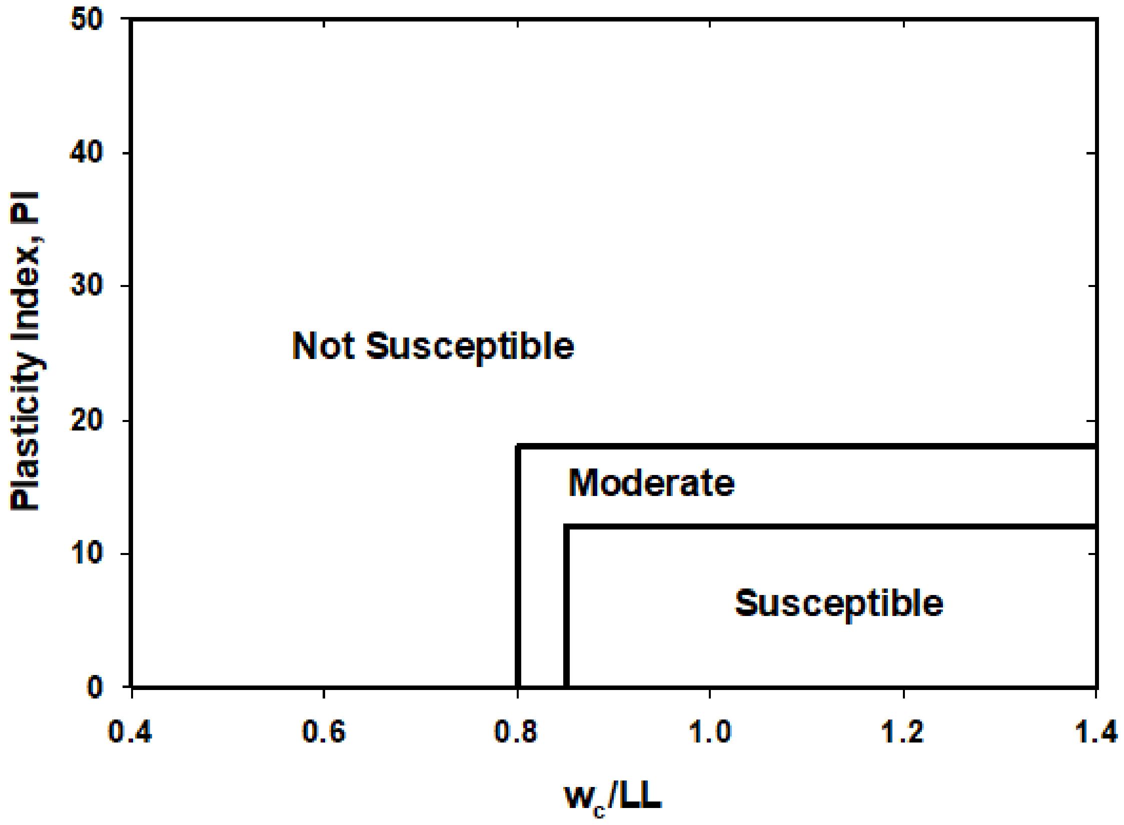
Cyclic Triaxial Tests,

CSR= 0.3, 0.4, 0.5

3 % Single Amplitude Axial Strain

AVAILABLE SUSCEPTIBILITY ASSESSMENTS

Seed et al. (2003)



Adapazari silty-clayey sands, 1999 Kocaeli Earthquake,

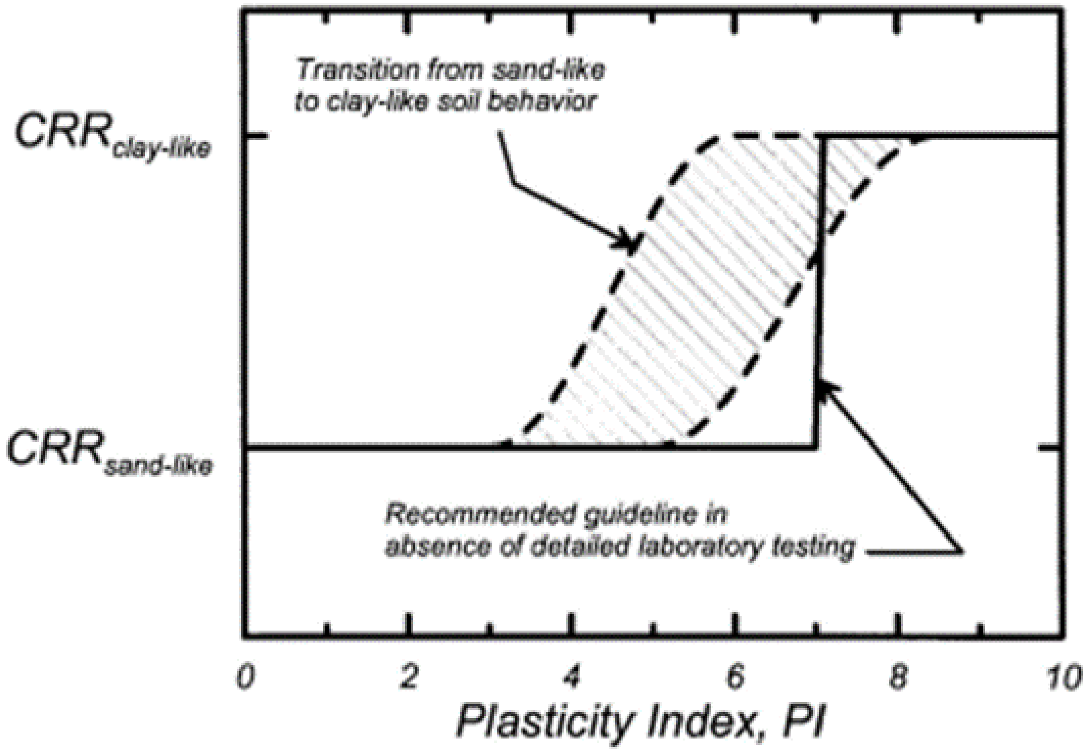
Cyclic Triaxial Tests,

CSR= 0.3, 0.4, 0.5

3 % Single Amplitude Axial Strain

AVAILABLE SUSCEPTIBILITY ASSESSMENTS

Bray and Sancio (2006)



Sand-like vs. Clay-like

Sand-like soils can be assessed with simplified liquefaction triggering assessment methods

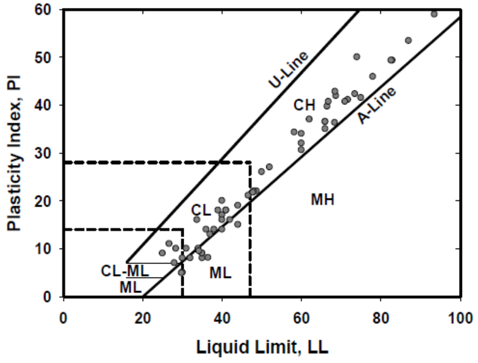
AVAILABLE SUSCEPTIBILITY ASSESSMENTS

Boulanger and Idriss (2006)

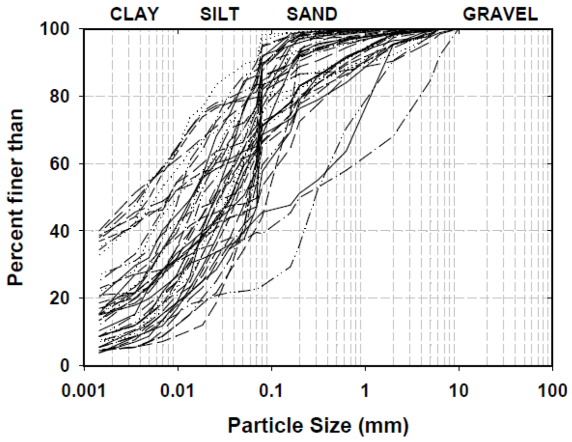
AVAILABLE SUSCEPTIBILITY ASSESSMENTS

Cetin and Bilge (2014)

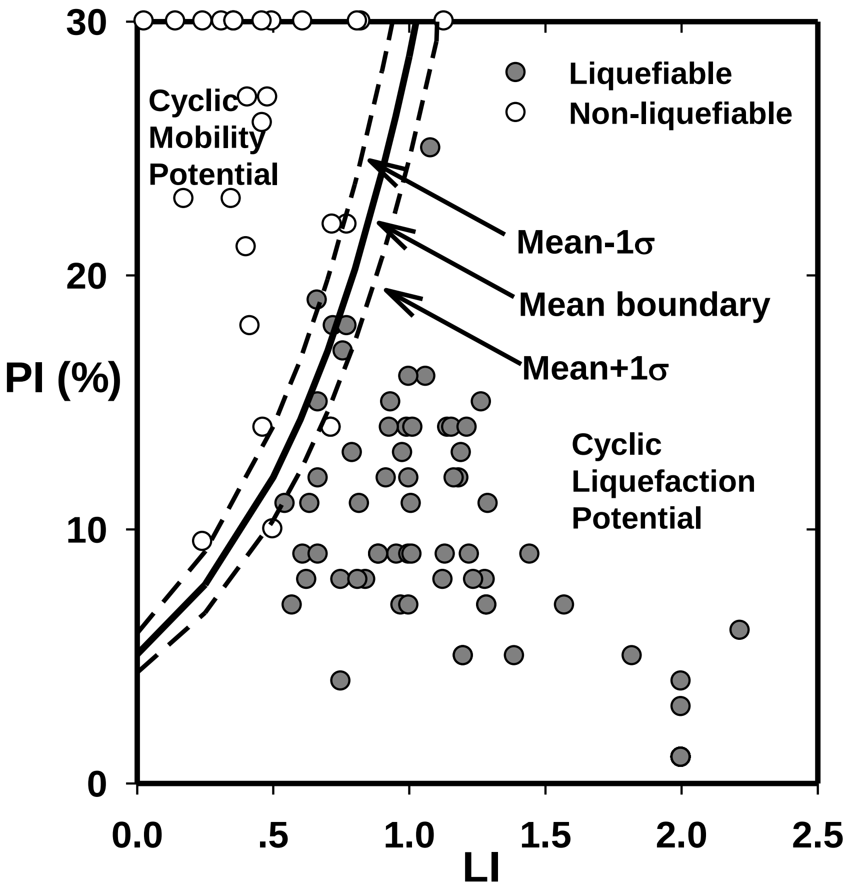
Bilge (2010)



Samples tested



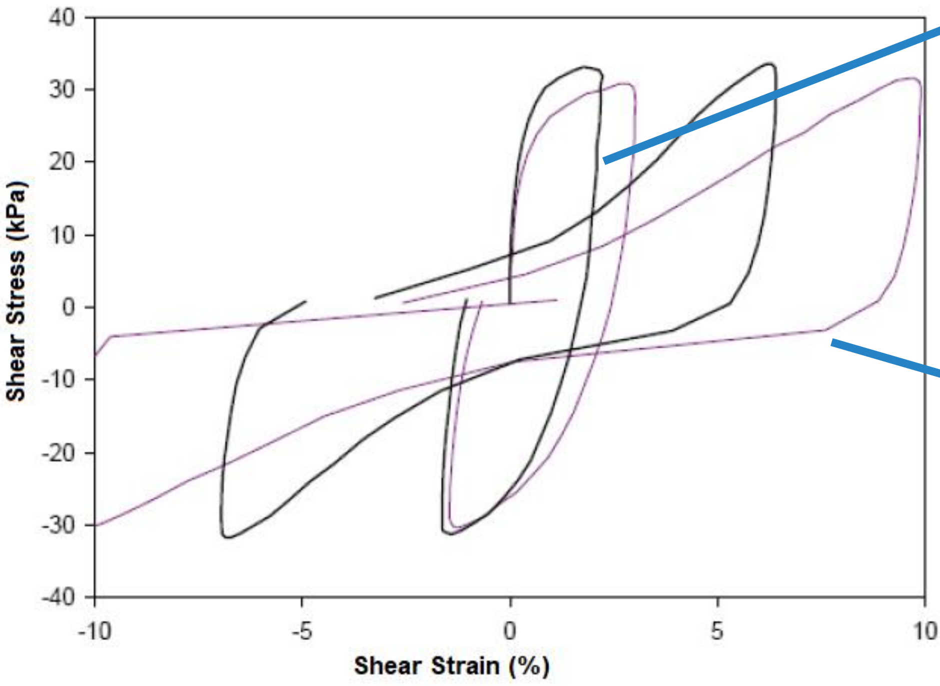
Grain size distribution



Cetin and Bilge (2014)

a probability-based susceptibility criterion

$$P[Liq - \ susceptibility] = \Phi\left[\frac{LI - 0.578 \cdot ln(PI) + 0.940}{0.101}\right]$$



Cyclic Mobility

Cylic Liquefaction

Cetin and Bilge (2014)

a probability-based susceptibility criterion

$$P[Liq - \ susceptibility] = \Phi\left[\frac{LI - 0.578 \cdot ln(PI) + 0.940}{0.101}\right]$$

AVAILABLE SUSCEPTIBILITY ASSESSMENTS

Cetin and Bilge (2014)

Ideal liquefaction susceptibility assessment framework

i) depends on intrinsic characteristics of soils (grain size, shape, grading, consistency, etc.)

ii) independent of liquefaction triggering parameters (i.e.: independent of intensity of shaking, duration, relative density state, etc.),

iii) address the uncertain nature of susceptibility assessments (i.e.: probability-based),

iv) benefit from both laboratory and field case history data (i.e.: a verified and calibrated model).

With the aim of fulfilling these requirements, **SPT and CPT-based liquefaction triggering case histories**, documented **as part of Next Generation Liquefaction database** (https://nextgenerationliquefaction.org/) were studied.

RELIABILITY-BASED SUSCEPTIBILITY MODELS

SPT-based liquefaction triggering case histories

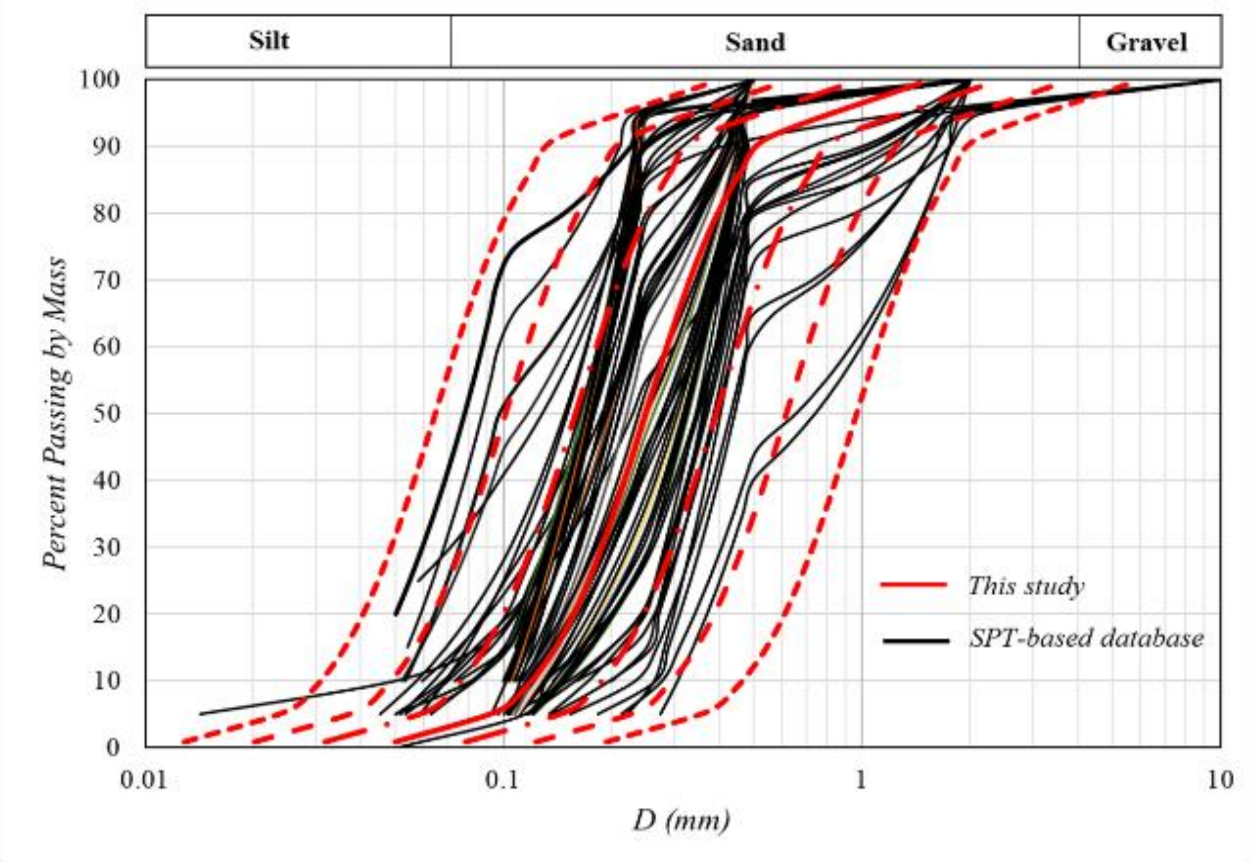


Figure 2. a) Grain size distribution curves of susceptible, coarse-grained soils from SPT database

RELIABILITY-BASED SUSCEPTIBILITY MODELS

SPT-based liquefaction triggering case histories

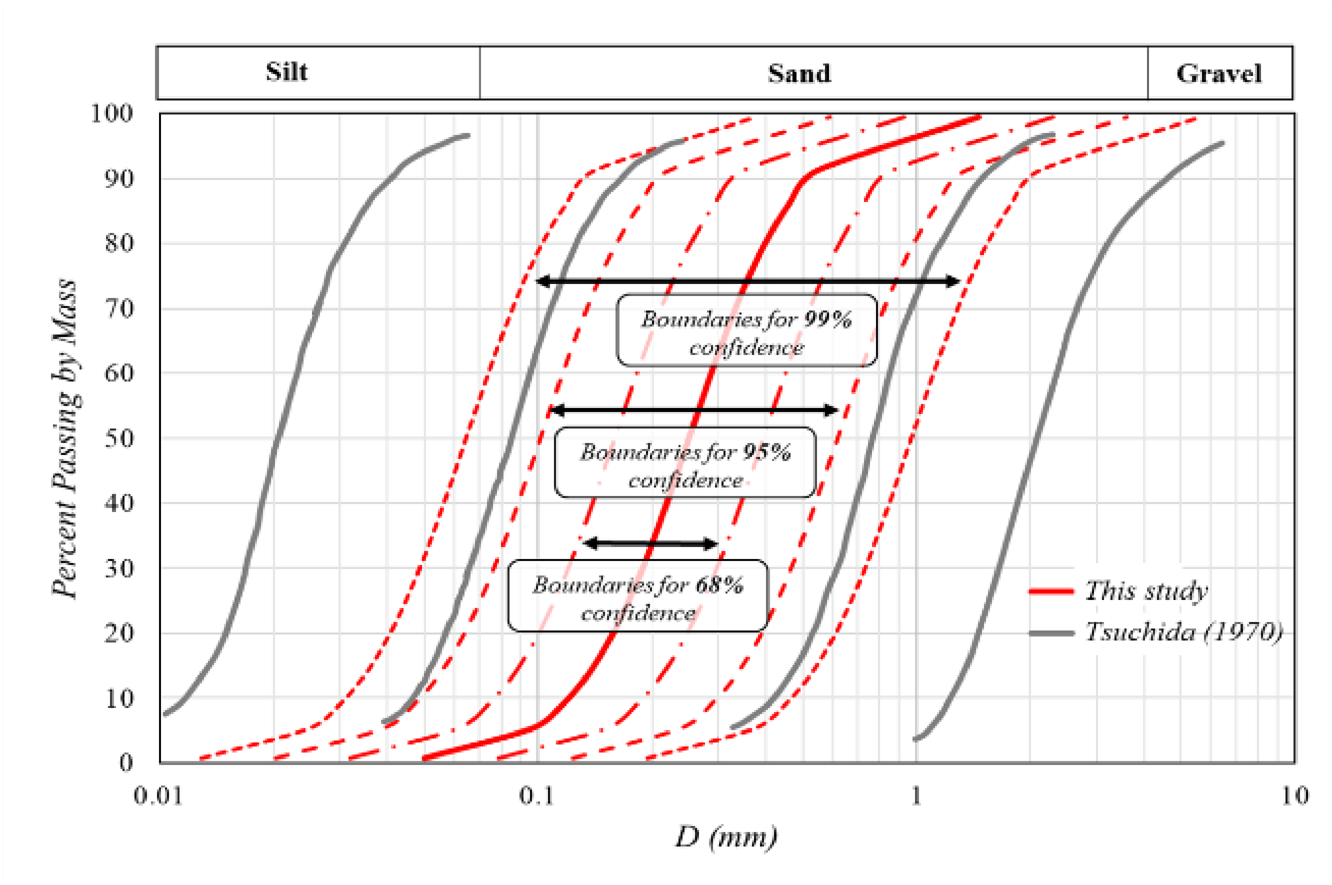


Figure 2. b) the proposed probabilistic boundaries for susceptibility assessments.

RELIABILITY-BASED SUSCEPTIBILITY MODELS

CPT-based liquefaction triggering case histories

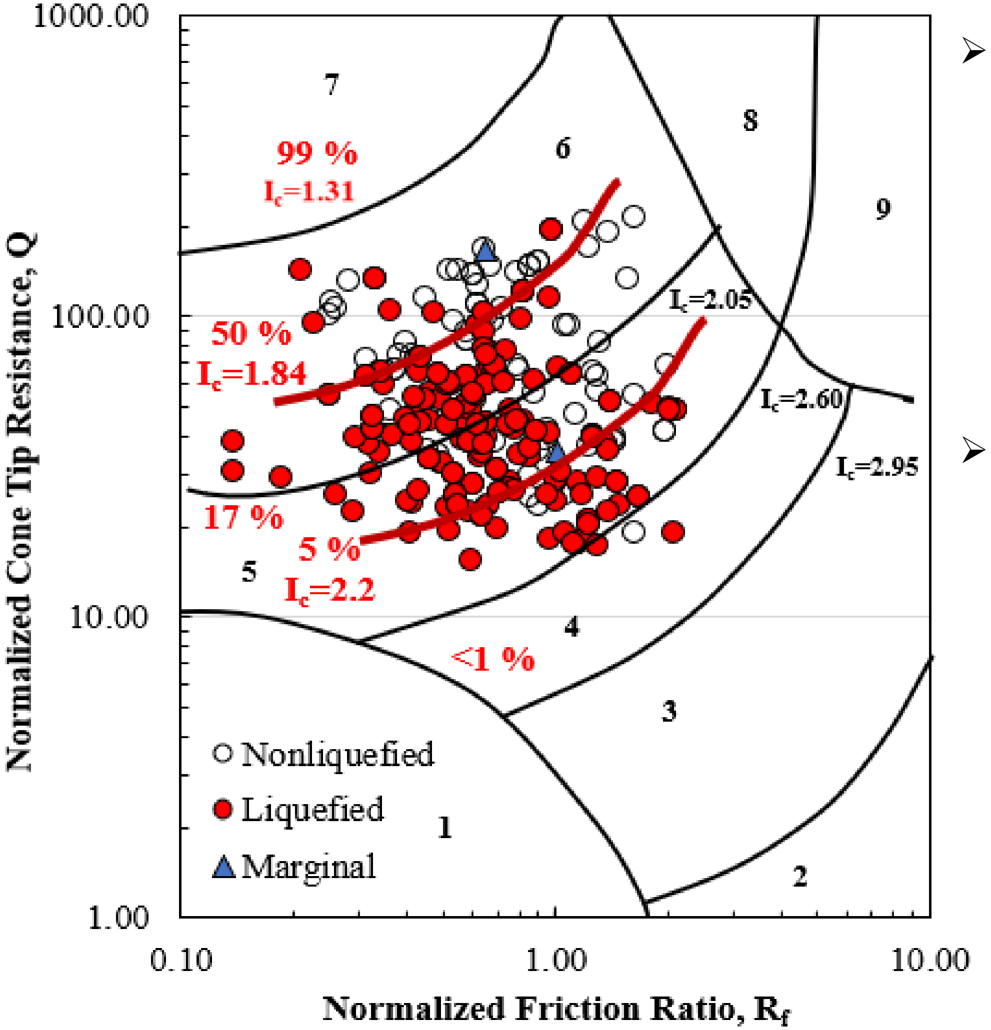


Figure 3. CPT-soil classification-based liquefaction susceptibility boundary curves.

- The median soil behavior index I_c, along with its standard deviation were probabilistically assessed benefitting from the **maximum likelihood framework.**
- The resulting database and the **I_c boundaries corresponding to different confidence levels** are also comparatively shown with CPT-based soil classification boundaries of **Robertson (2010), and Cetin and Ozan (2009).**

RELIABILITY-BASED SUSCEPTIBILITY MODELS

CPT-based liquefaction triggering case histories

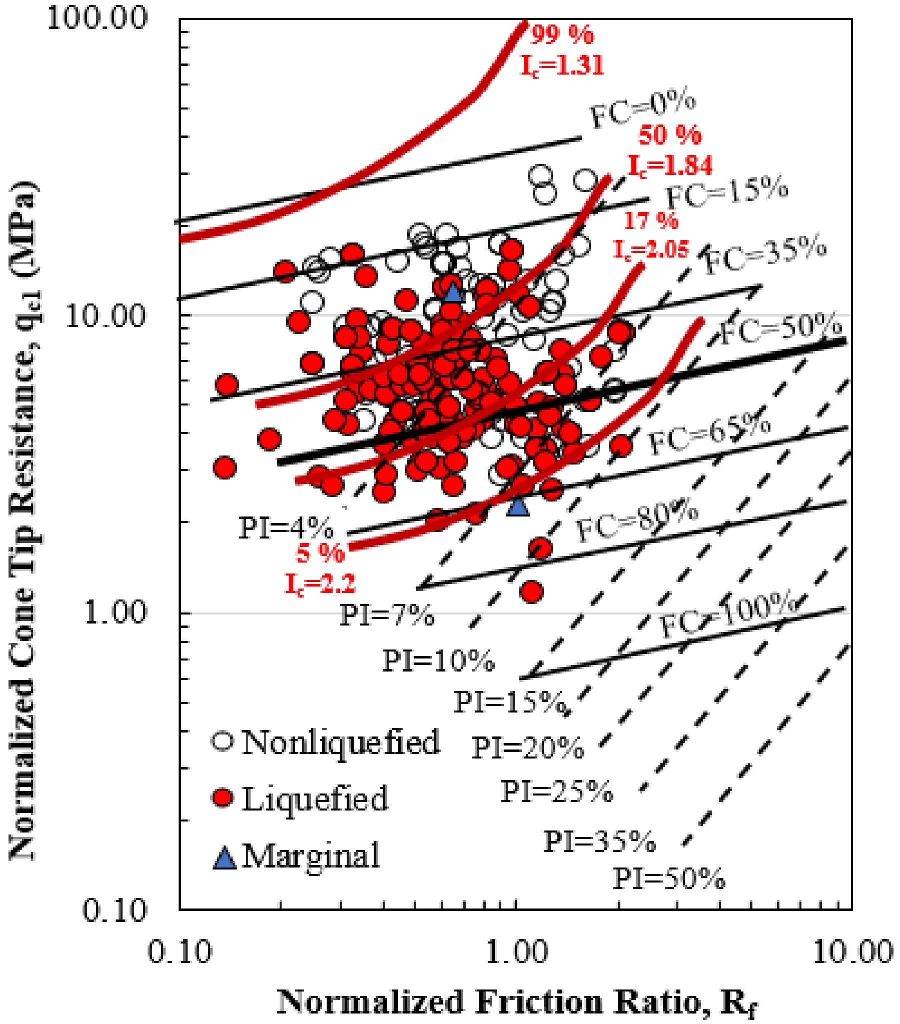


Figure 3. CPT-soil classification-based liquefaction susceptibility boundary curves.

RELIABILITY-BASED SUSCEPTIBILITY MODELS

Cetin and Ozan (2009)

CONCLUDING REMARKS AND RECOMMENDATIONS

- Currently available liquefaction susceptibility boundaries were **subjectively and deterministically defined**, with limited to **no reference to confidence levels** of the proposed boundaries.

- Also, some of them **refer to triggering parameters (e.g. CRR)**; hence, better to be called as **screening criteria**, which combine both susceptibility and triggering assessments.

CONCLUDING REMARKS AND RECOMMENDATIONS

- A set of probability-based screening boundaries were recommended for coarse- and fine-grained soils.

- The recommended probabilistic boundaries were expressed as probabilistic confidence intervals

  - % fines by mass vs. particle size (D), and CPT q vs R_f domains.

- **Fine grained soils with I_c>2.6** are concluded to be **not susceptible** to soil liquefaction with **more than 99 %** confidence.

- **Fine grained soils with PI > 12%** were judged to be again **not susceptible to liquefaction** with **confidence levels of 99 %**.

Special Thanks to our Sponsors…

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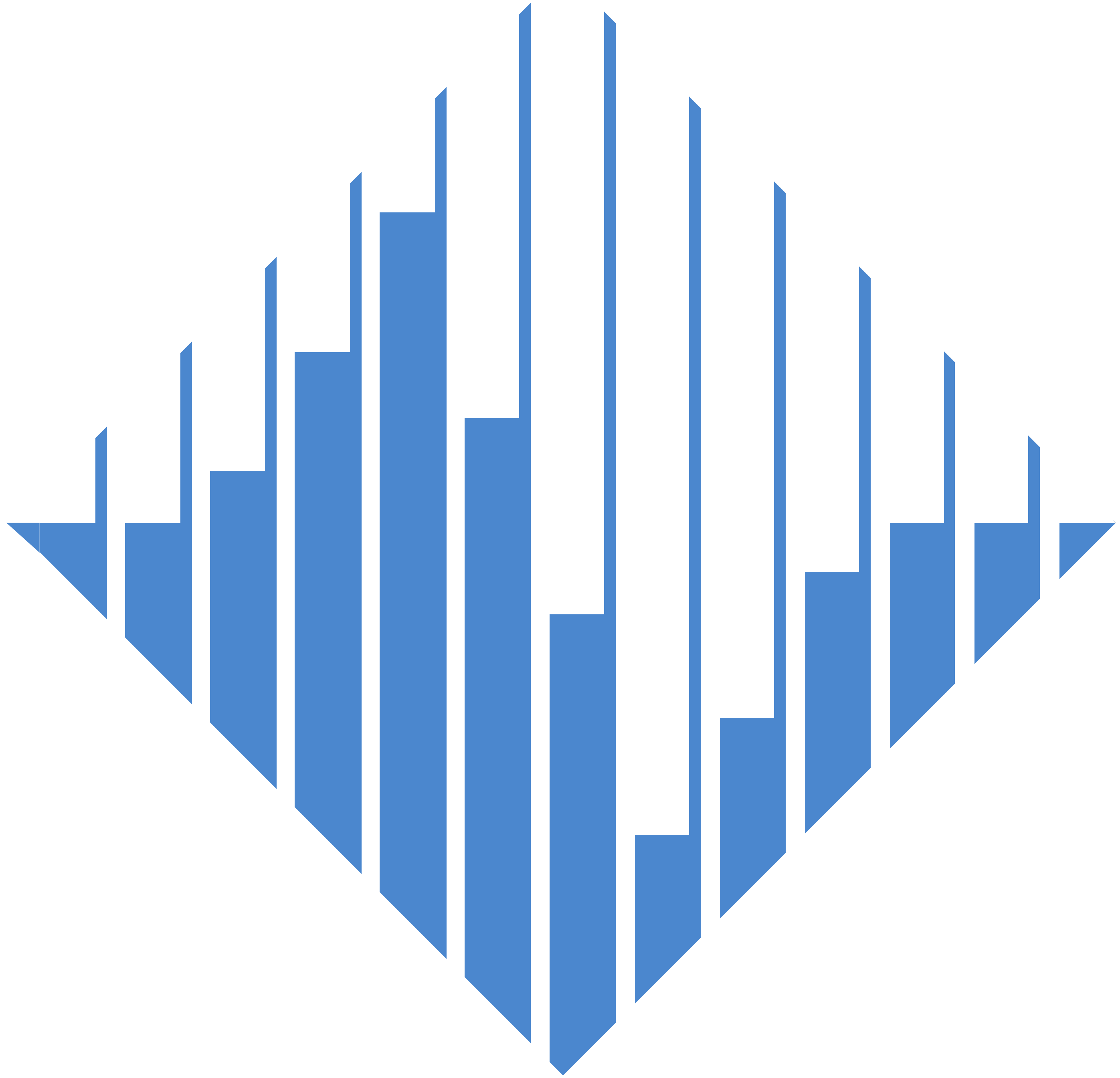
NGL
NEXT GENERATION LIQUEFACTION



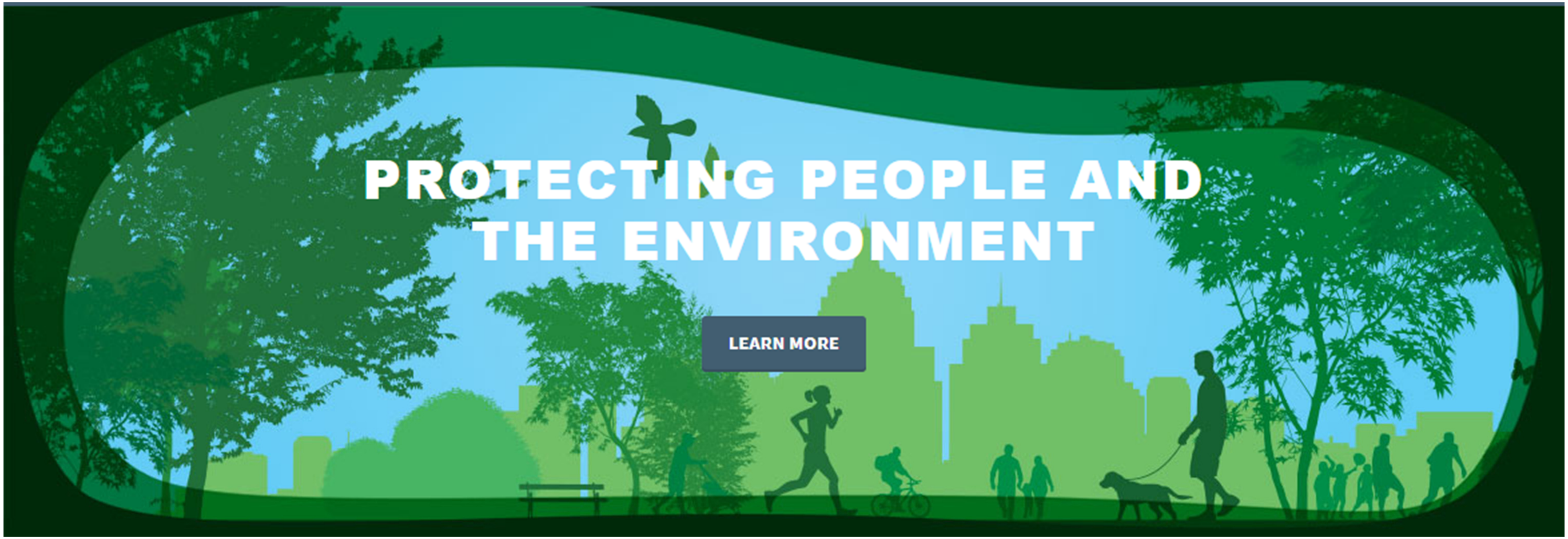
Evaluating Liquefaction Susceptibility for Nuclear Power Plant Sites

Thomas Weaver, PhD, PE

U.S.NRC

United States Nuclear Regulatory Commission

Protecting People and the Environment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October 2021

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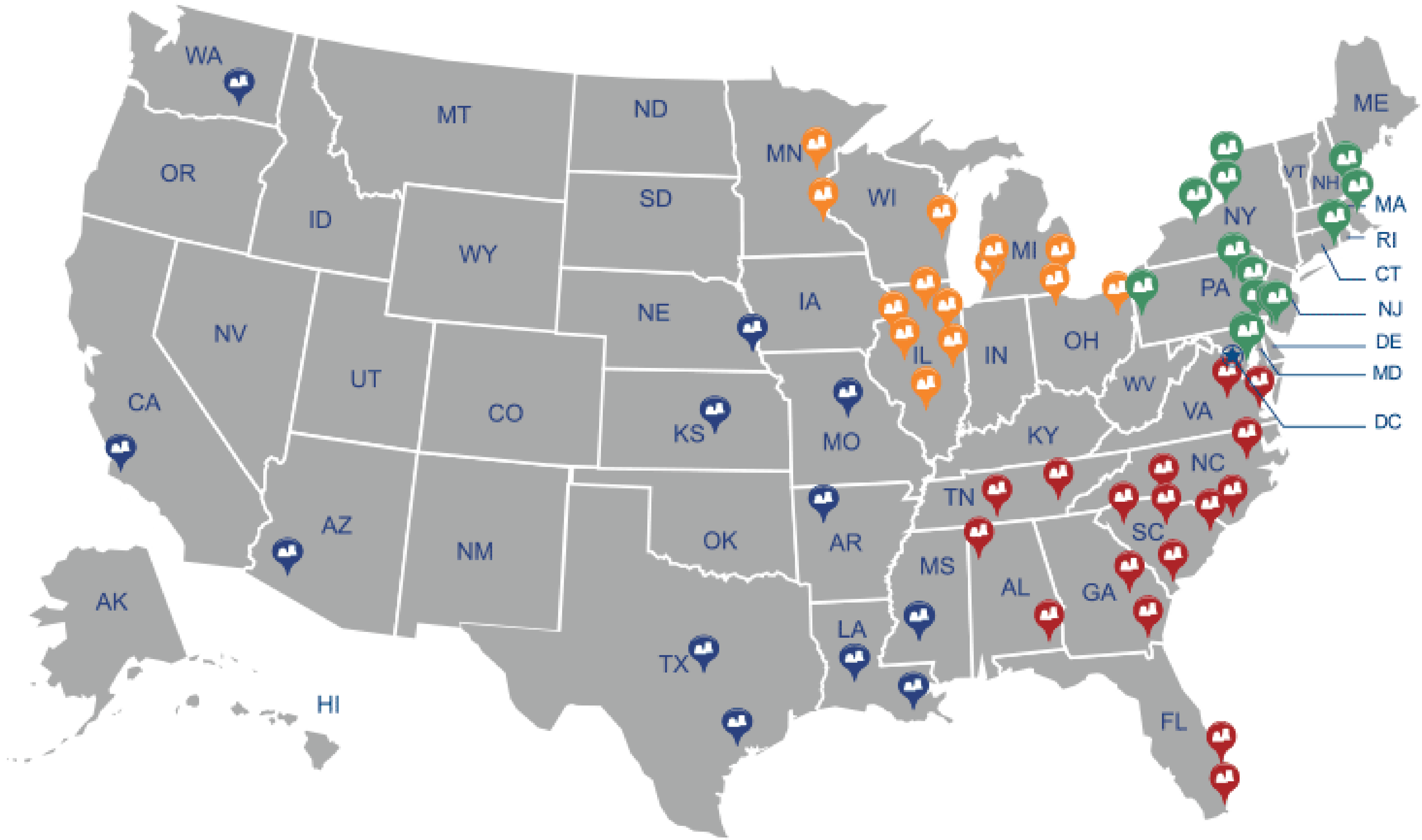


CODE OF FEDERAL REGULATIONS

CFR

10 Energy

Parts 51 to 199

OFFICE OF THE FEDERAL REGISTRAR

U.S. NUCLEAR REGULATORY COMMISSION November 2003

REGULATORY GUIDE

OFFICE OF NUCLEAR REGULATORY RESEARCH

REGULATORY GUIDE 1.198

(Draft was issued as DG-1105)

PROCEDURES AND CRITERIA FOR ASSESSING SEISMIC SOIL LIQUEFACTION AT NUCLEAR POWER PLANT SITES

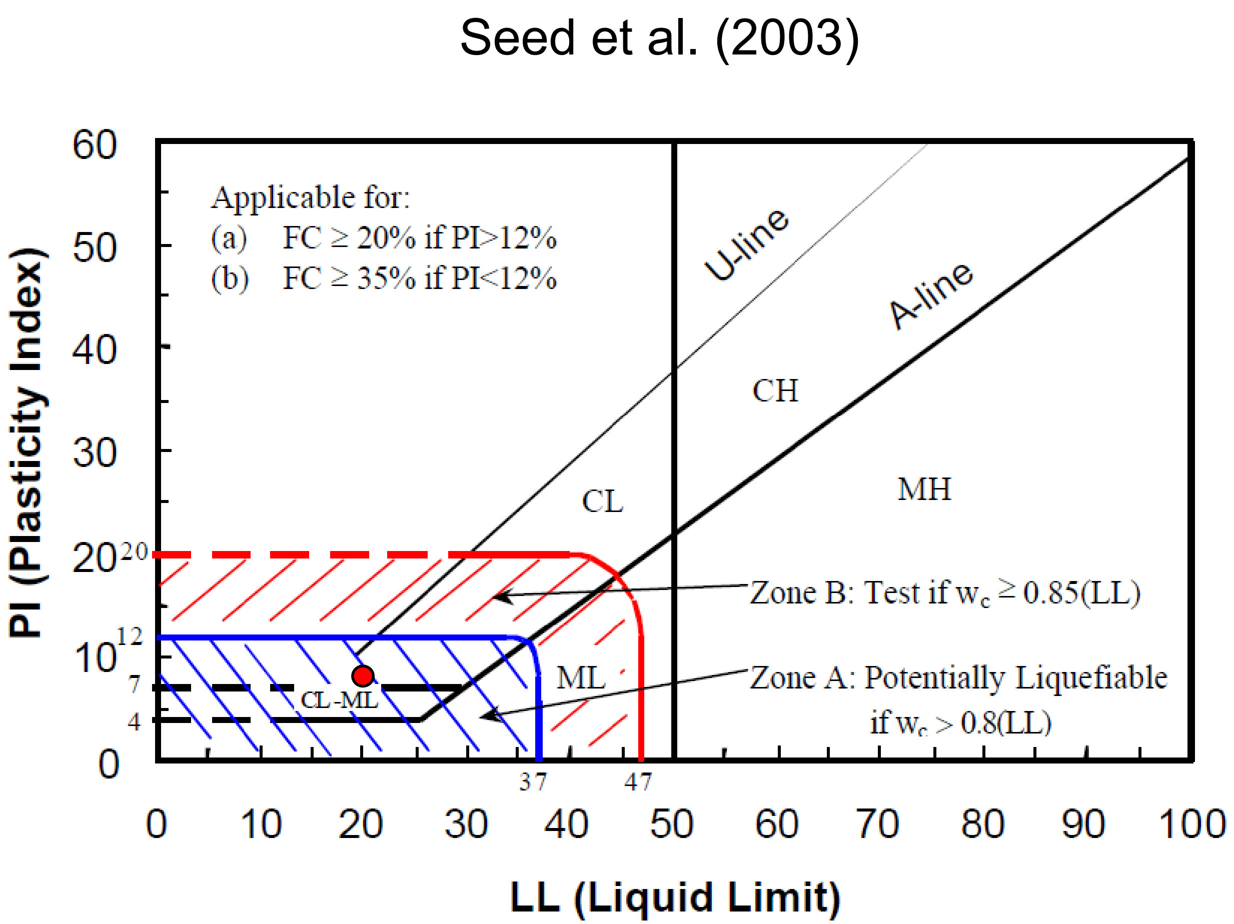
Susceptibility Criteria
Regulatory Guide 1.198

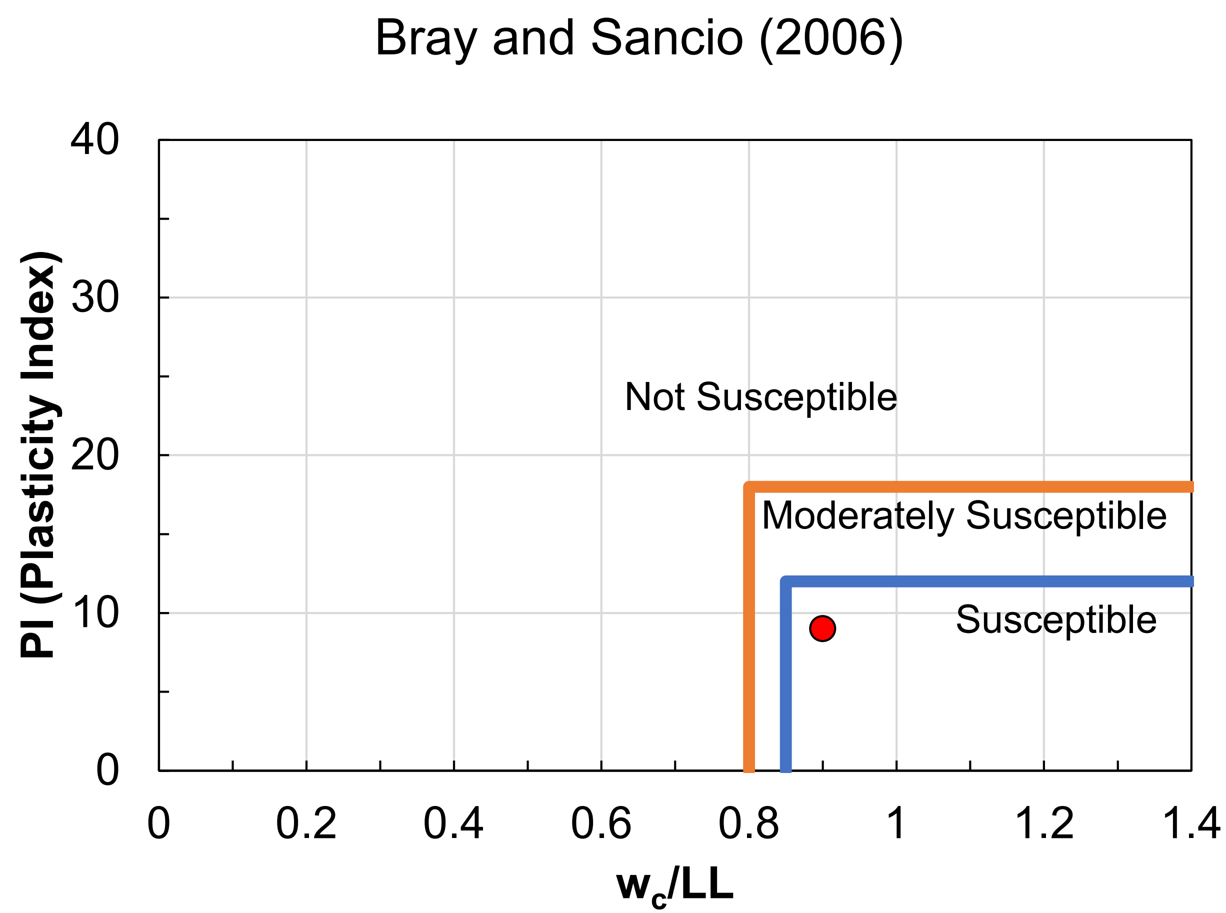
❌ Soils with FC > 30% and fines either:
1. Classified as clay, or
2. PI > 30

❌ Clay content > 15%, and
LL > 35, and
w_c < 90%

✅ Coarse grained soils with dual classification (e.g. SM-SC)

Criteria for Fine-Grained Soils





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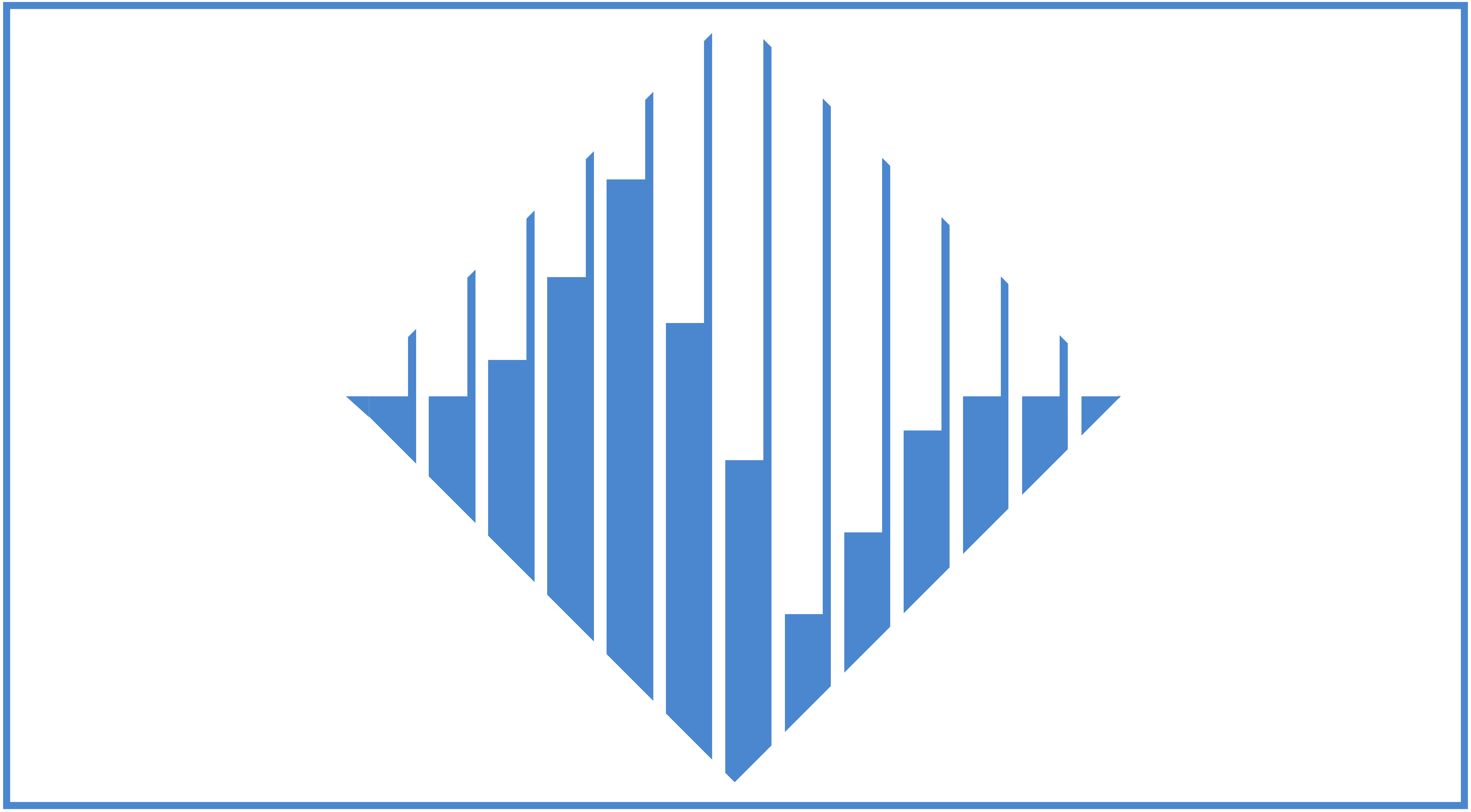
NEXT GENERATION LIQUEFACTION

Research Grants

- University Nuclear Leadership Program in October 2022
  - Scholarship and Fellowship Grant
- Grants.gov in February 2023
  - Award ceiling of $500,000 and 3 year period of performance
  - U.S. public or private higher education institutions
  - Must meet U.S. citizenship requirements



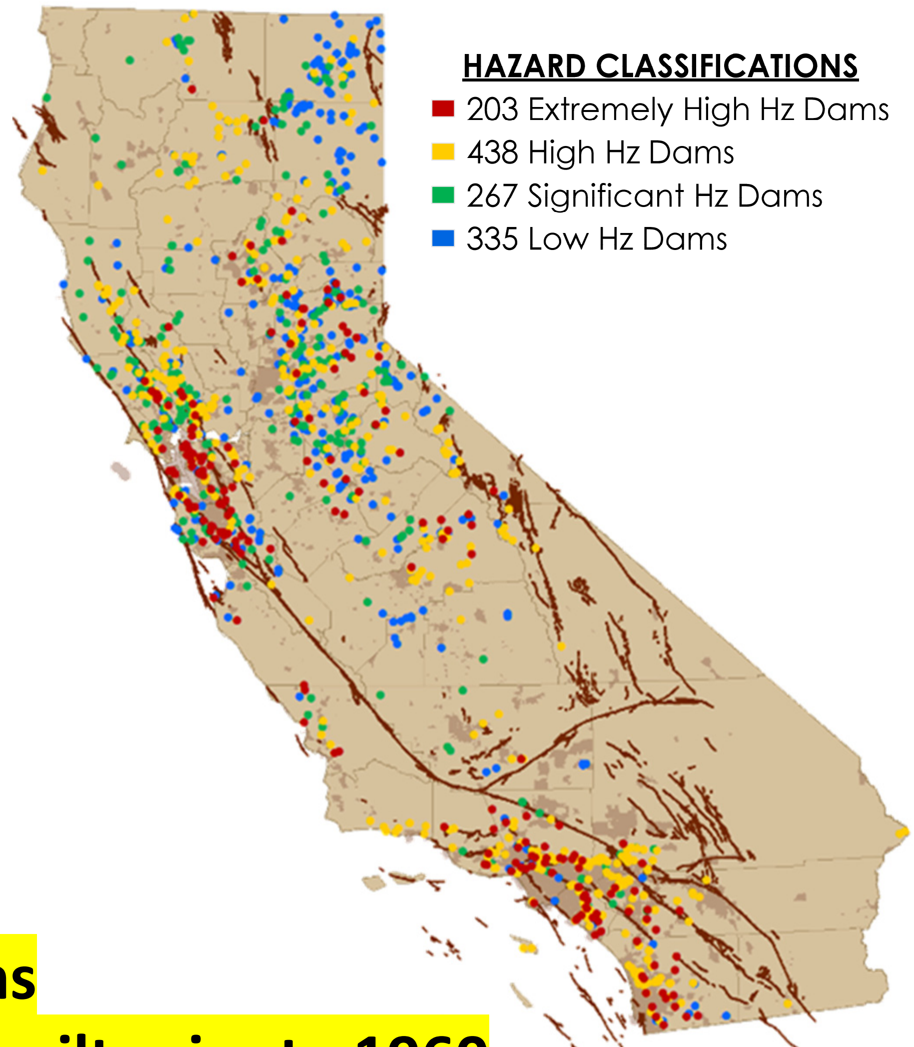
Challenges in Assessing Liquefaction Susceptibility at California's Dams

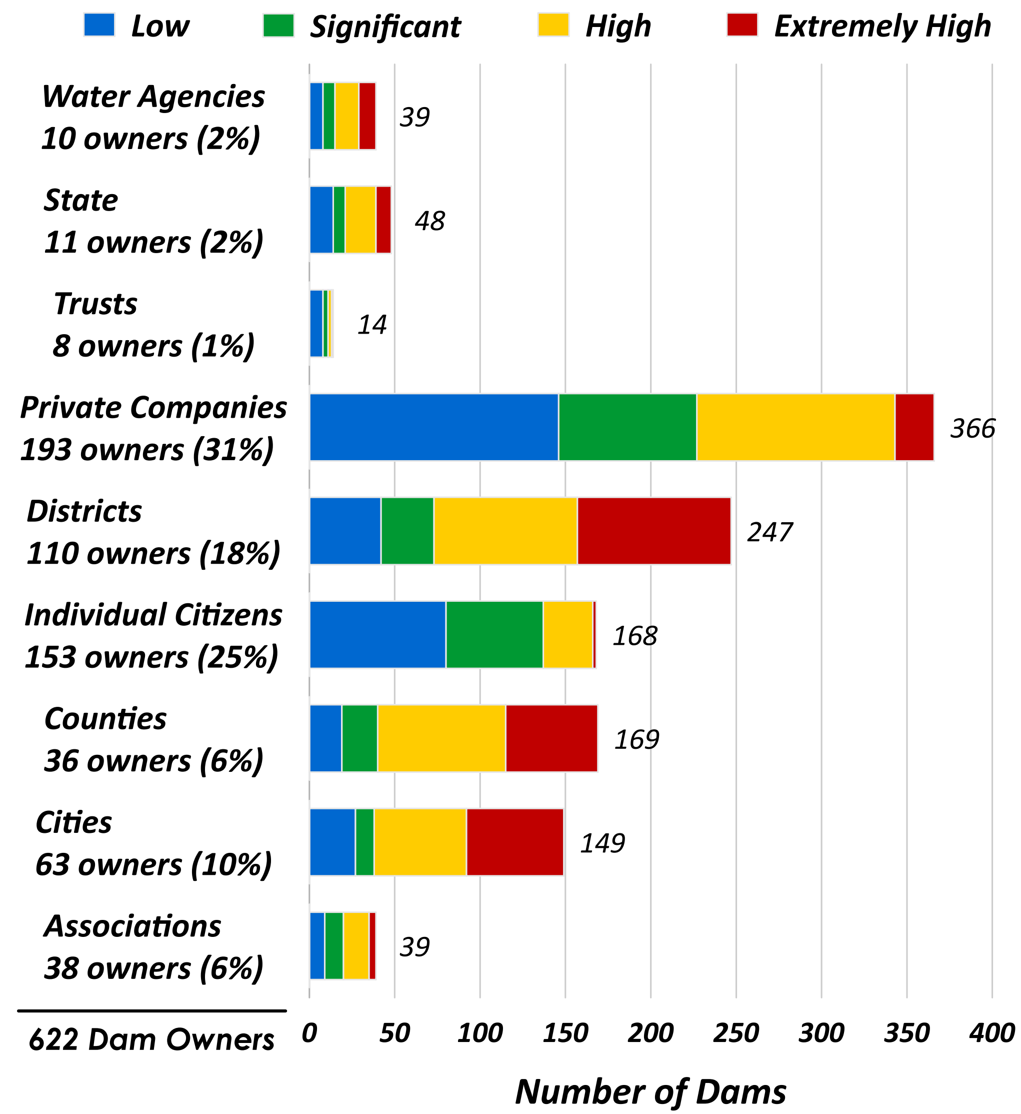
Erik Malvick, Ph.D., P.E., G.E.
Design Engineering Branch Manager

September 2022

CALIFORNIA DEPARTMENT OF WATER RESOURCES
DIVISION OF SAFETY OF DAMS

CA Dam Safety Program (DSOD) Jurisdiction





~1240 dams

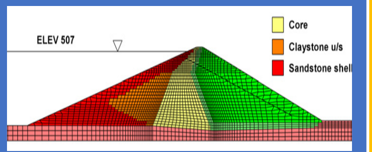
600 dams built prior to 1960

CALIFORNIA DEPARTMENT OF WATER RESOURCES
DIVISION OF SAFETY OF DAMS

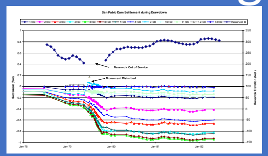
CA Dam Safety Program

Design Review & Construction Supervision

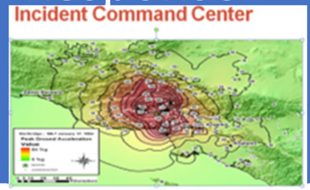
Re-evaluations



Surveillance Monitoring

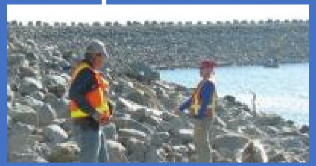


Emergency Response

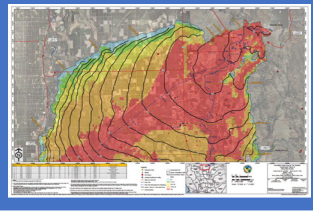


Bolsteed

Maintenance Inspections



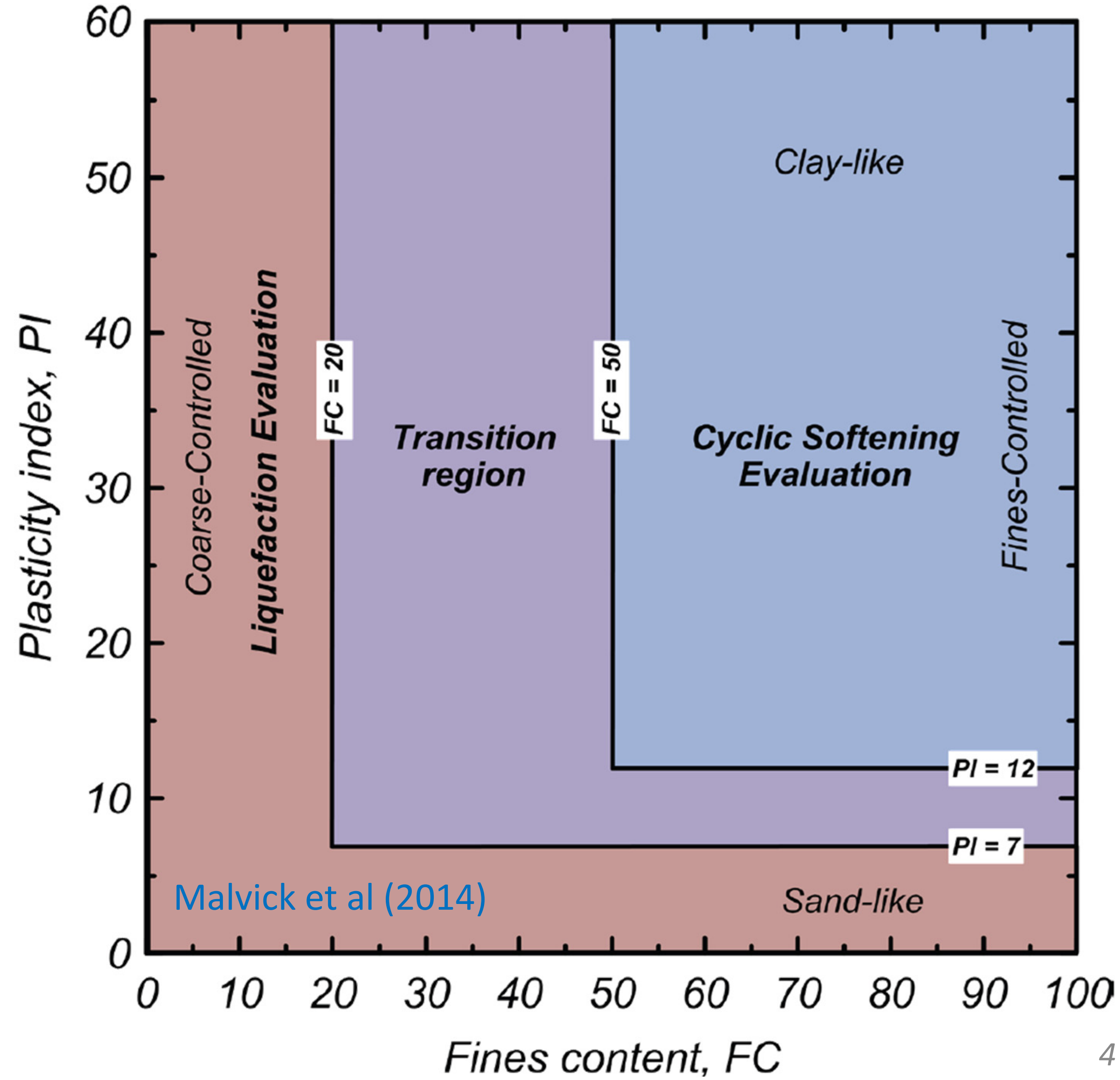
Inundation Maps



Dam Safety

DSOD Review of Susceptibility

- Transition Region
  - Cyclic Testing?
    - YES: use results
    - NO: assume susceptible to liquefaction
- Challenges
  - Sample availability / quality
    - Gravels
    - Recovery
    - Site accessibility
  - Costs / owner resources



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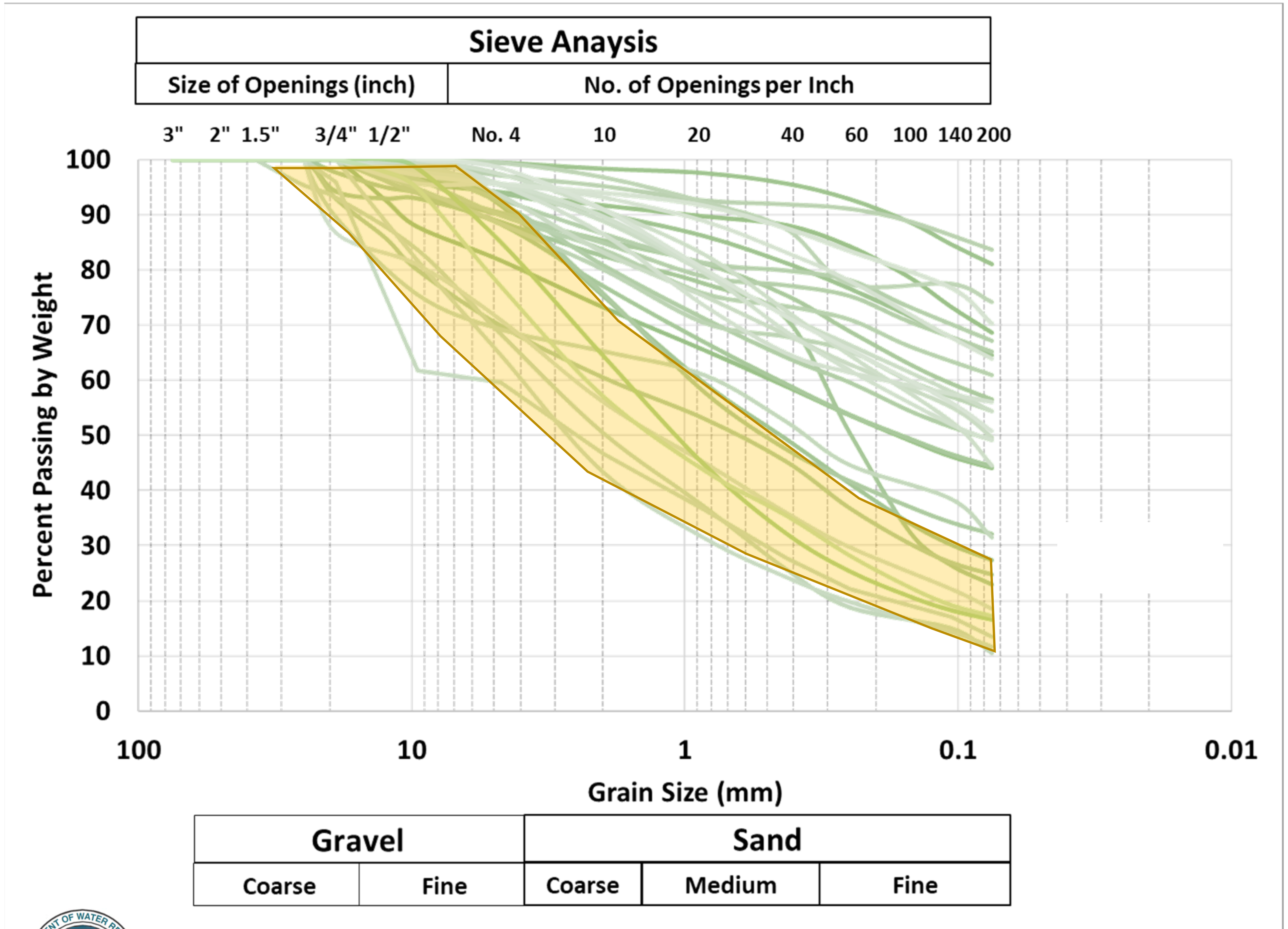
DIVISION OF SAFETY OF DAMS

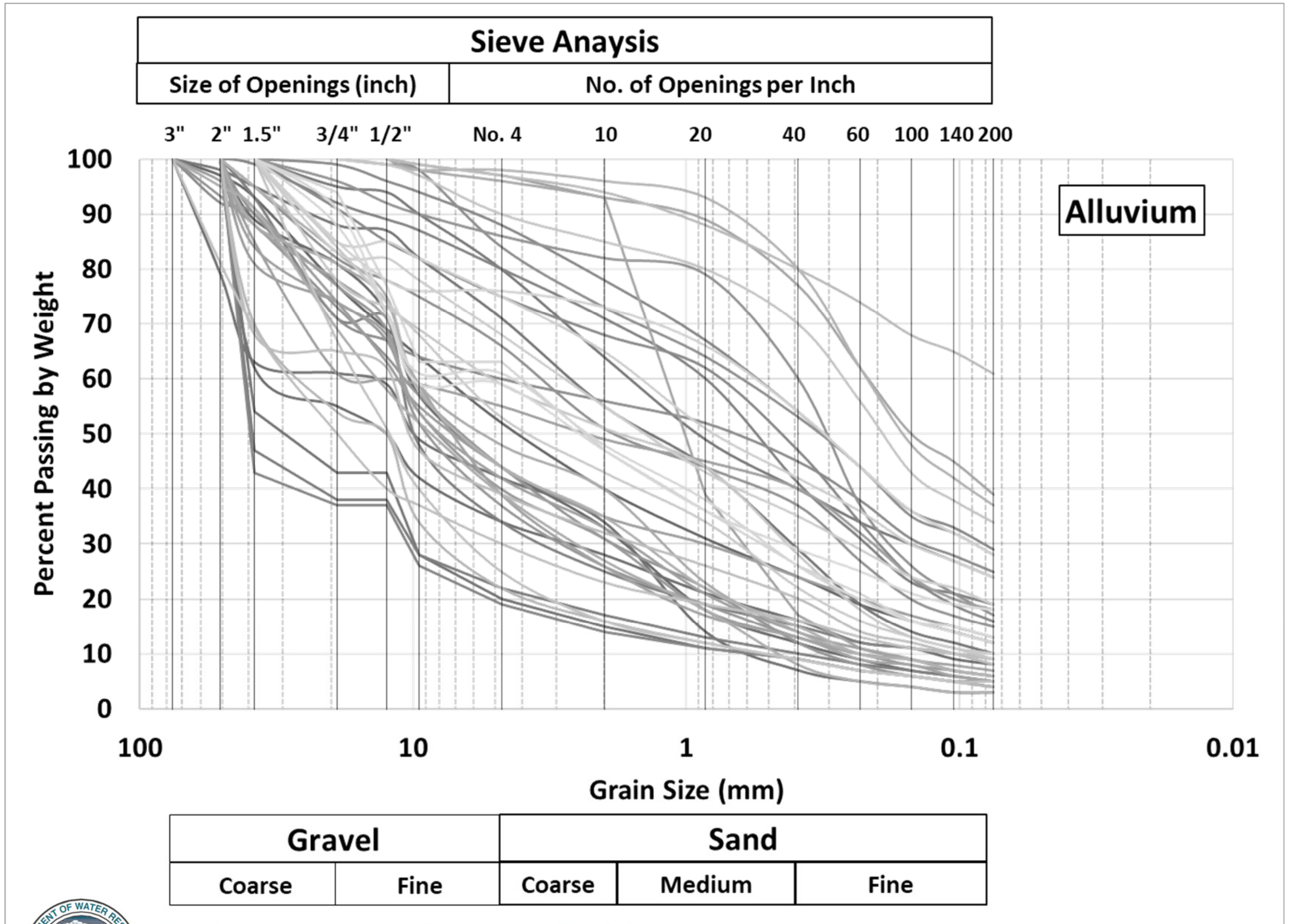
Example Dam 1 (coast)



- Gravels = 5 to 40%
- Fines = 10 to 30%
- Sand = 50 to 65%
- C_u = > 10 (about 80 for greatest)

- Most samples with F > 50% were CL but not measurable for gravel samples

Example Dam 2 (Sierras)



- Glacial Deposit
- Gravel everywhere
- Most samples scalped with low recovery
- Larger equipment inaccessible

- Gravel = 5 to 80%
- Fines = 3 to 40% (one outlier)
- C_u = 3 to 100 (median about 10)
- No PI data

Challenges with Gravel

- Sampling
  - Limited recovery
  - Site accessibility
  - Sample Quality

- Susceptibility and Gravel
  - What materials control behavior
  - Gravels vs. Sands
  - Other: C_u , permeability, geology

Other Challenges and Observation

- Expertise: Retirees, high demand, knowledge transfer need
- 95% of dam owners lack resources
  - Budgets and rules often limit them to lower quality consultants
  - Cost of exploration becomes prohibitive
  - Cyclic testing has limited commercial feasibility, especially with gravels
- Trends towards statistical models
  - Tied into the above issues, it is easy to get “lots” of data and use statistics without considering data quality, or material origin (geology, engineered fills, etc.)
- Result = Assumption that most materials of questionable susceptibility are susceptible

DSOD challenges and goal

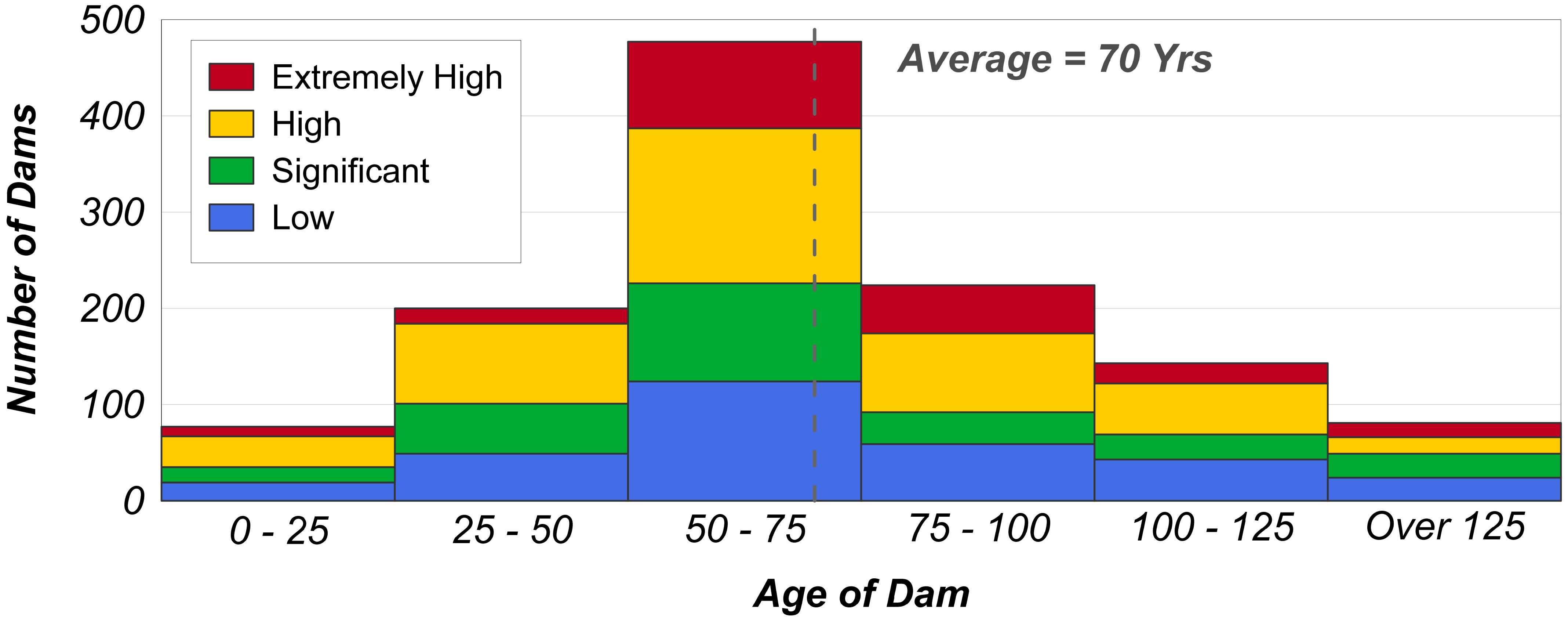
- Heightened public focus, extreme consequences,
  - Real materials rarely fall into bins currently shown in literature (nor do they have clear cut boundaries)
  - Conservatism on transitional materials or gravels
- Resources
  - Broad expectation comprehensive evaluation of all 700 high hazard dams on a 10-year cycle
  - Most projects lack data beyond basic gradation and maybe plasticity
- Goals
  - Clearer guidelines on susceptibility including materials that can be clearly excluded will help everyone
  - Need clear consensus as state-of-the-art develops to implement

Thank You

erik.malvick@water.ca.gov

courtesy Edison International

Age of Dams by Hazard Potential

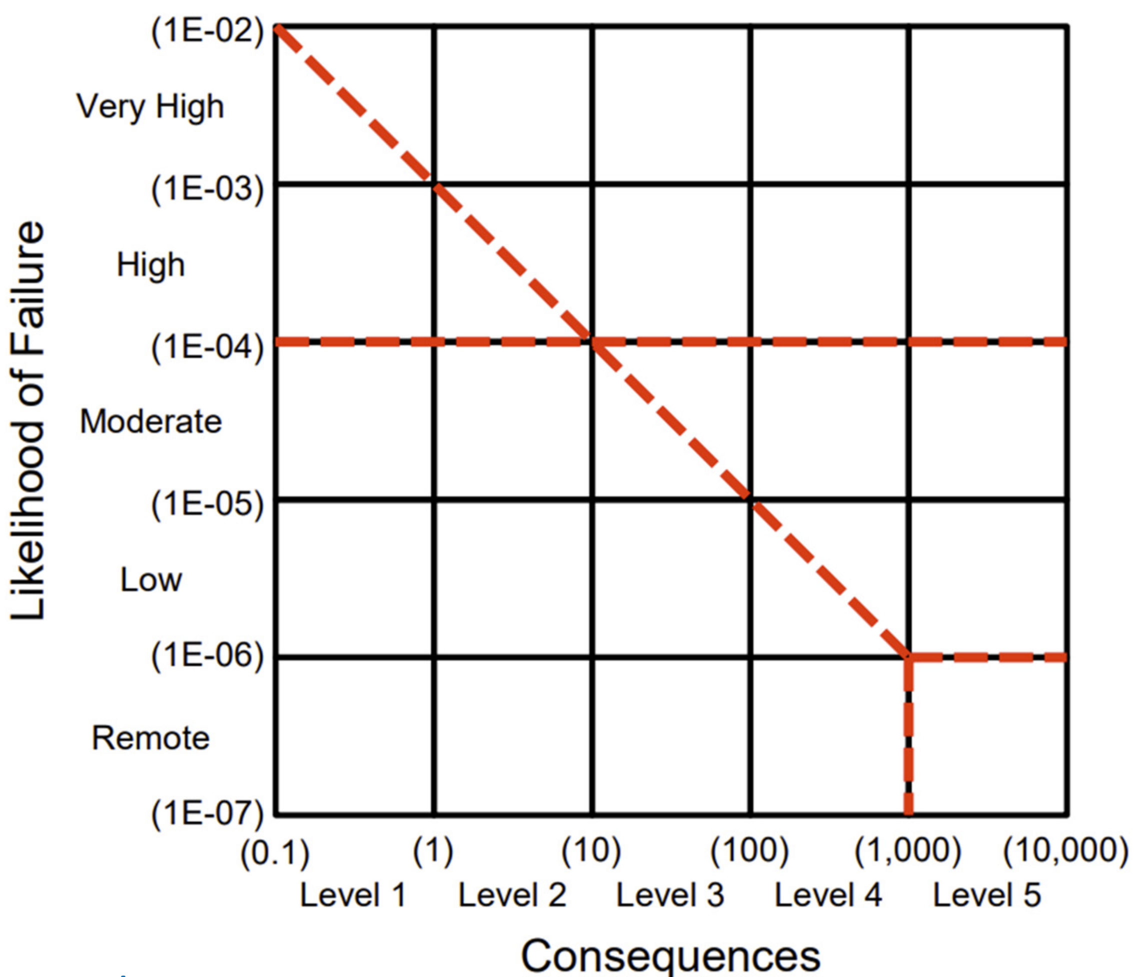


General Program Features

- Design Review
  - Independent evaluation and analyses
  - Plan and specification review
- Reevaluations
  - Focused or comprehensive analyses
- Field Review
  - Annual inspections of all dams
  - Surveillance and monitoring
  - Construction inspections
- Geology Review
  - Site investigation
  - Geologic hazards assessment
  - Ground motion hazard development
- Emergency Response

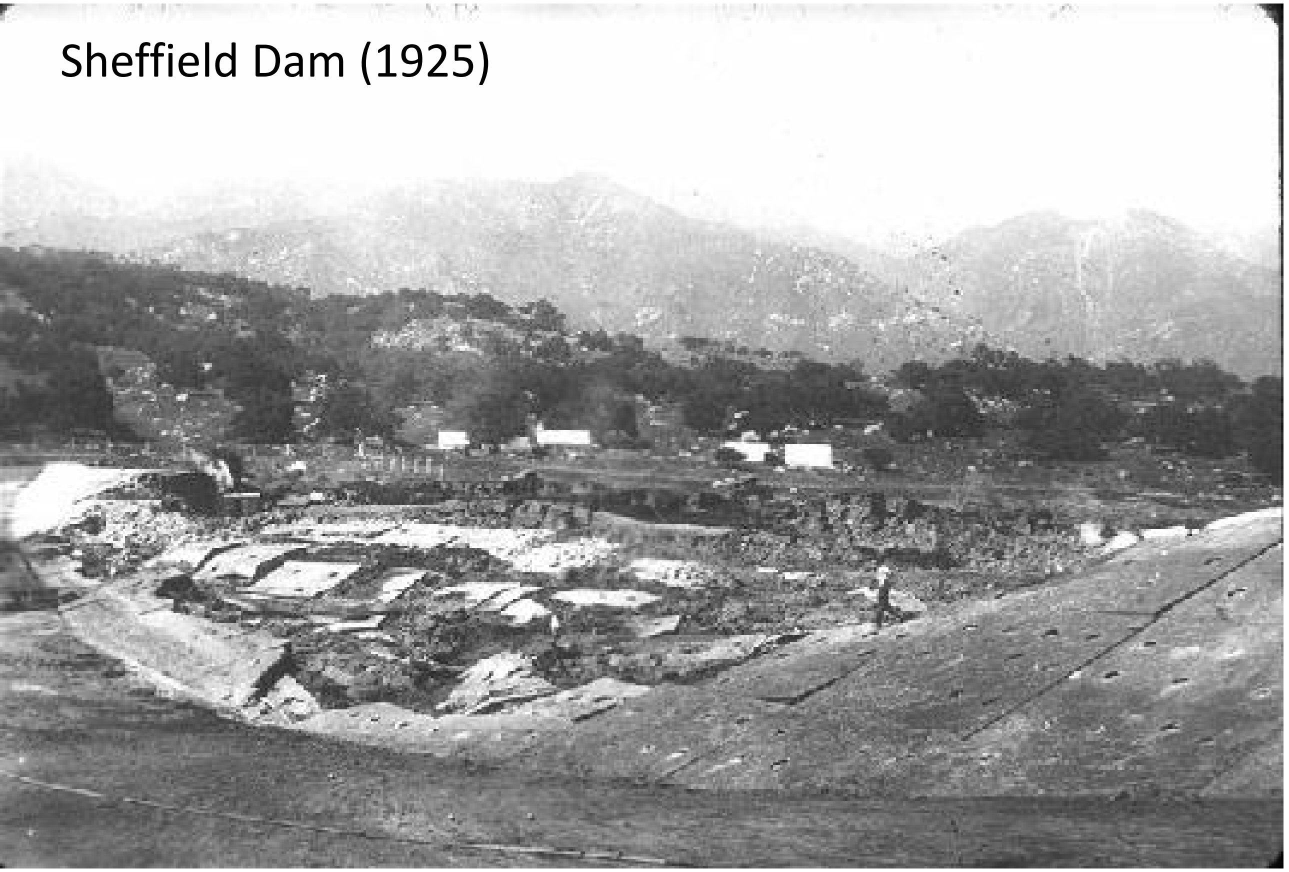
Dam Safety Program (Design and Reevaluations)

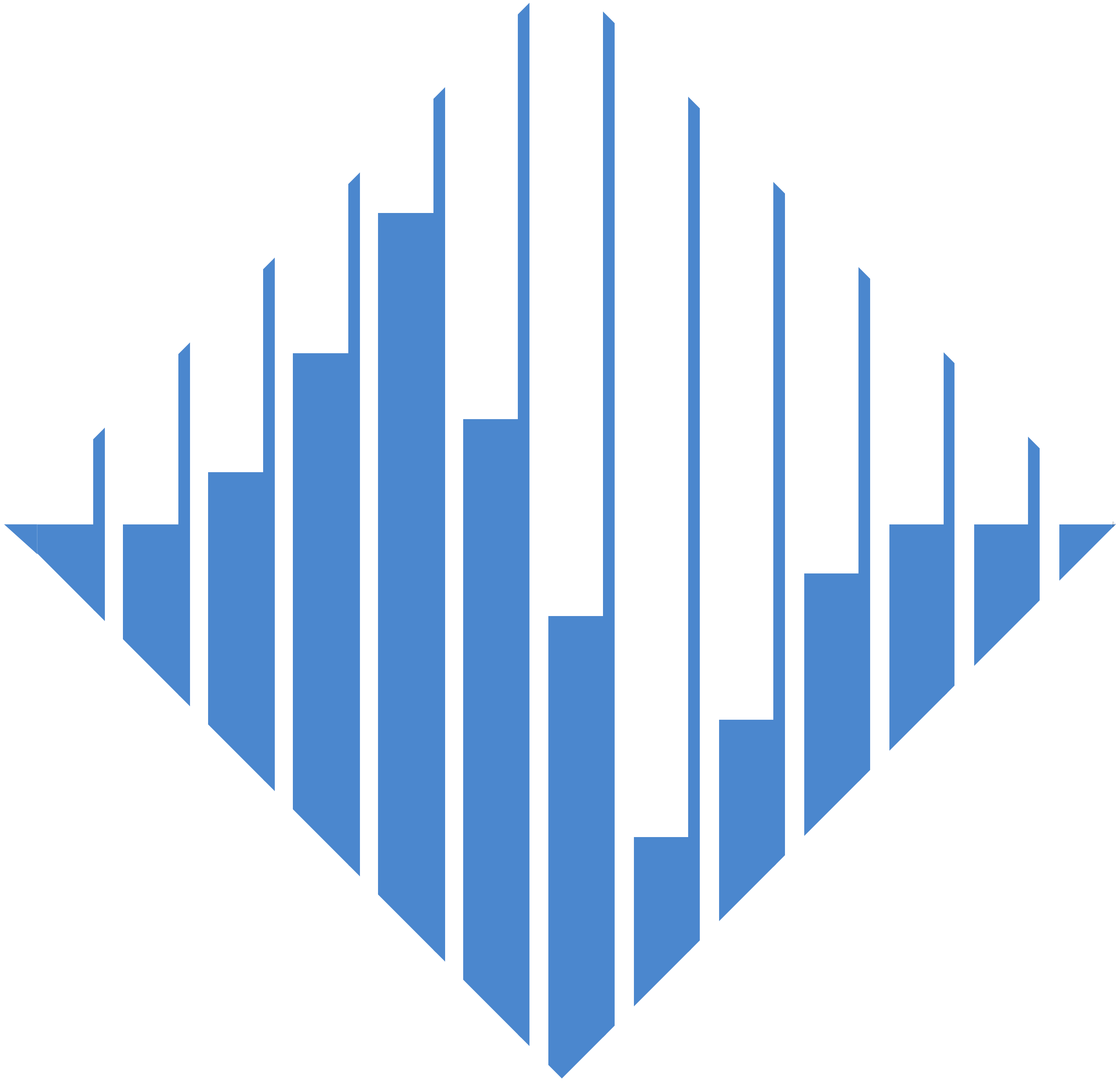
- Owners and consultants analyze their dams
- DSOD conducts independent evaluations
  - Provide feedback on site investigations
  - Geologic review of dam sites, seismicity
  - Site characterization
  - Liquefaction evaluation
  - Develop analytical model
- Use standard of practice methods with lean towards state-of-the-art techniques that are headed towards adoption



From USBR best practices

Liquefaction at California Dams





Dynamic Behavior of The Treasure Island Natural Shoals

Uri Eliahu, GE
Pedro Espinosa, GE

ENGEO
Expect Excellence

OUTLINE

- **Treasure Island Original Condition, Construction, and Development Plan**

- **Geotechnical Hazards, Mitigation Plan, Field Densification Test, and Study Motivation**

- **Comprehensive Field Study**
  - **Detailed Subsurface Geology Characterization**
  - **Laboratory Testing including Multiple Cyclic Simple Shears**
  - **Numerical Analysis (Plaxis and Flac)**
  - **Validation**

- **Conclusion**

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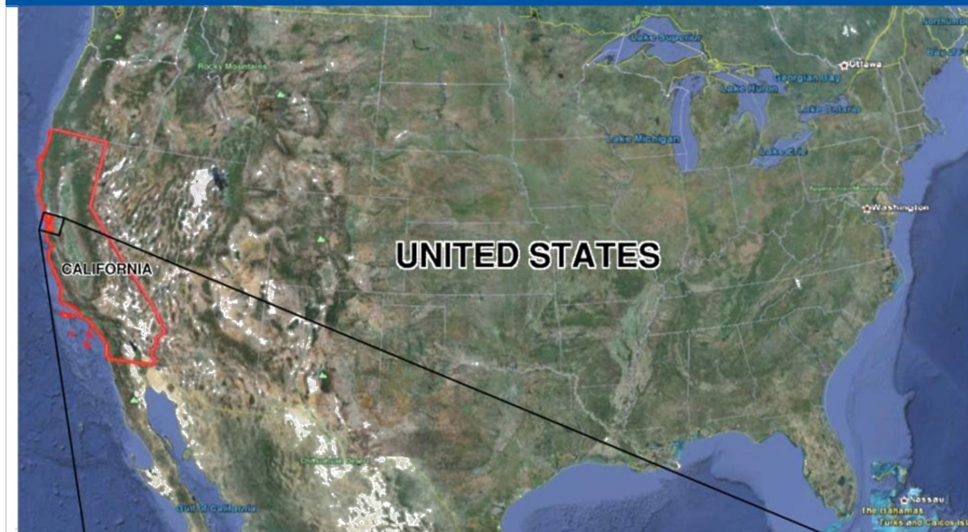
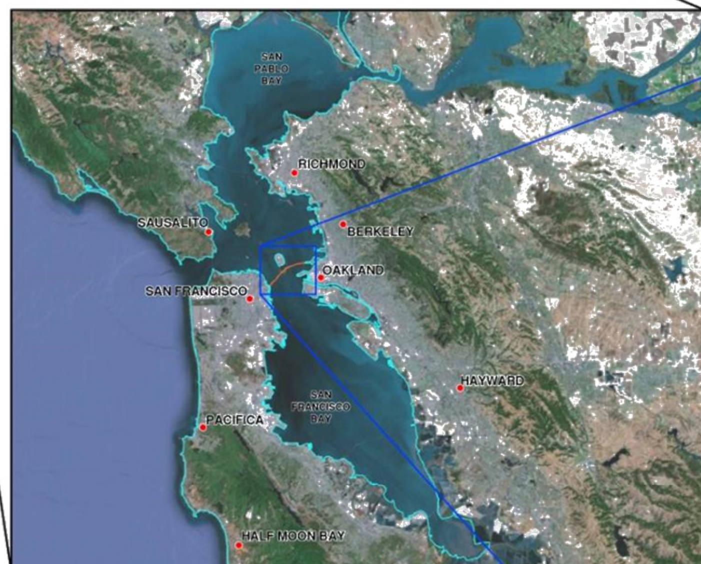
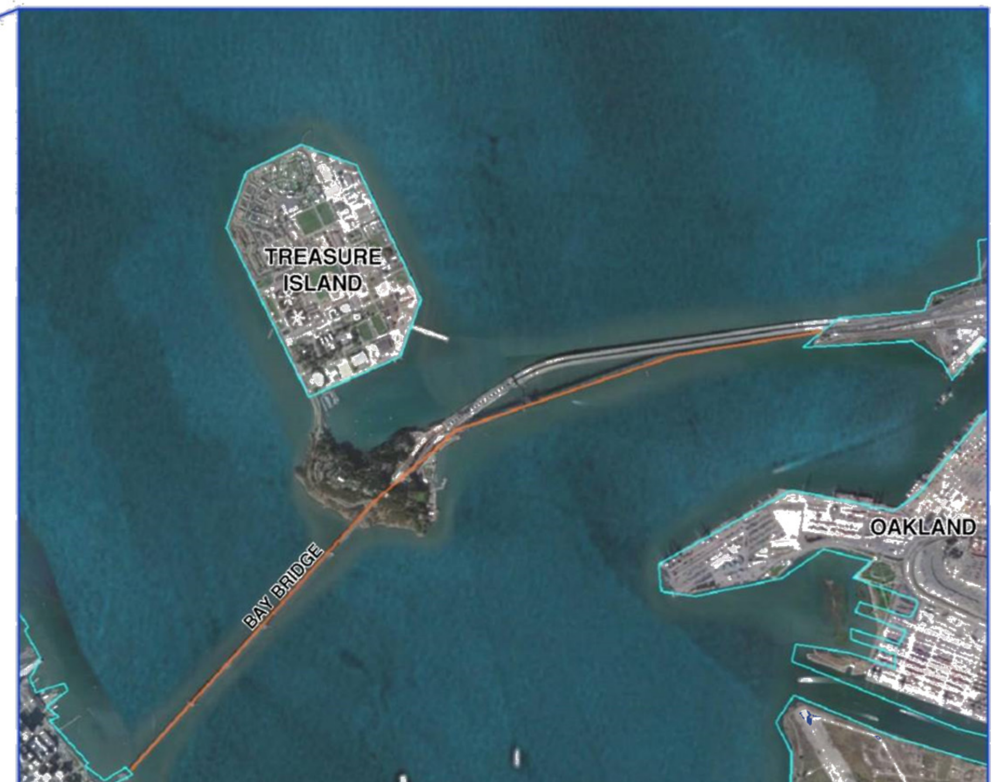
PROJECT LOCATION

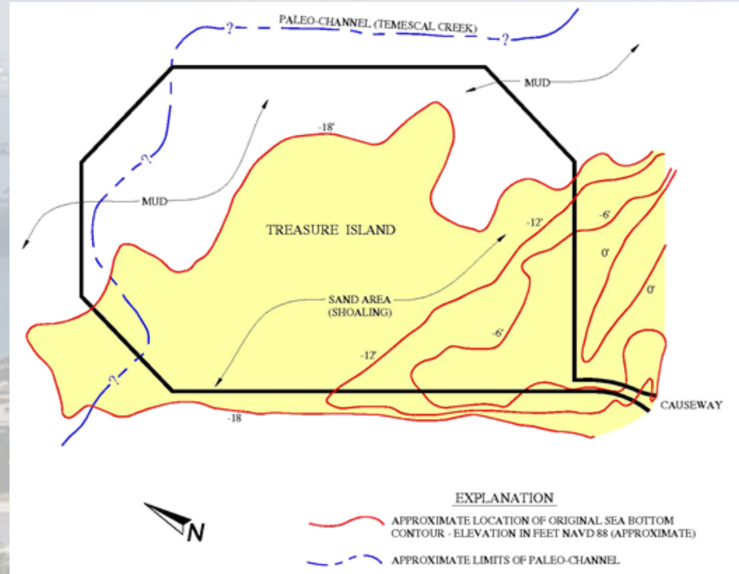
- Treasure Island is located within the San Francisco Bay in California in a seismically active region
- San Andreas fault is 17 km to the west
- Hayward fault is 11 km to the east of the island







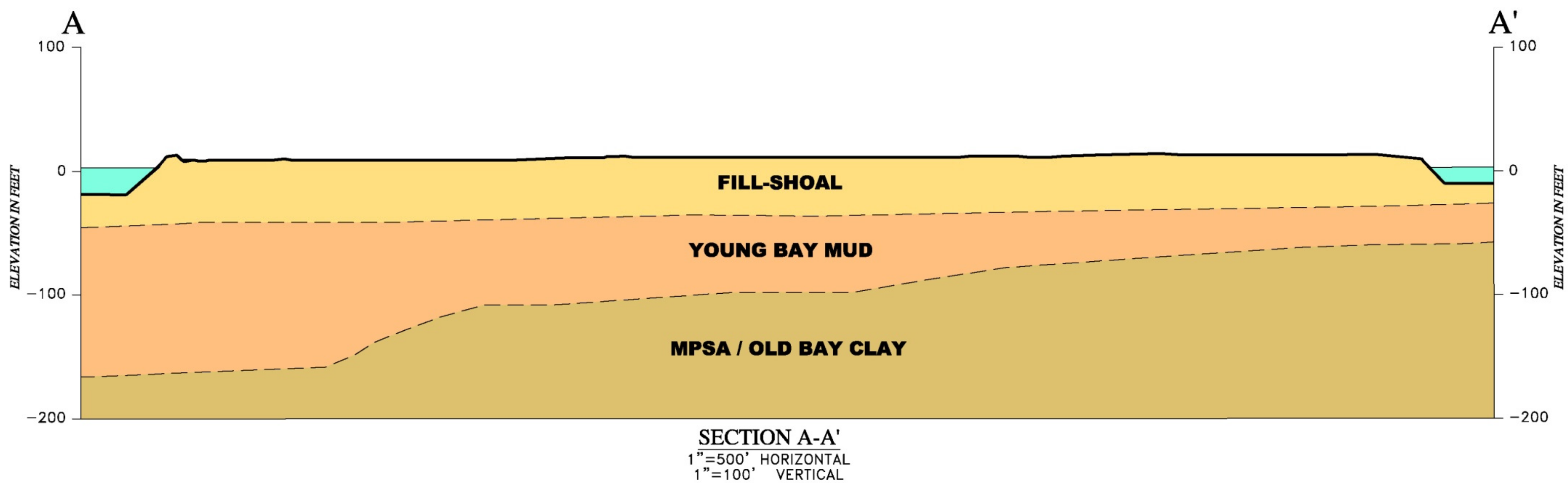
PRE-EXISTING CONDITION, CONSTRUCTION, AND REDEVELOPMENT PROGRAM



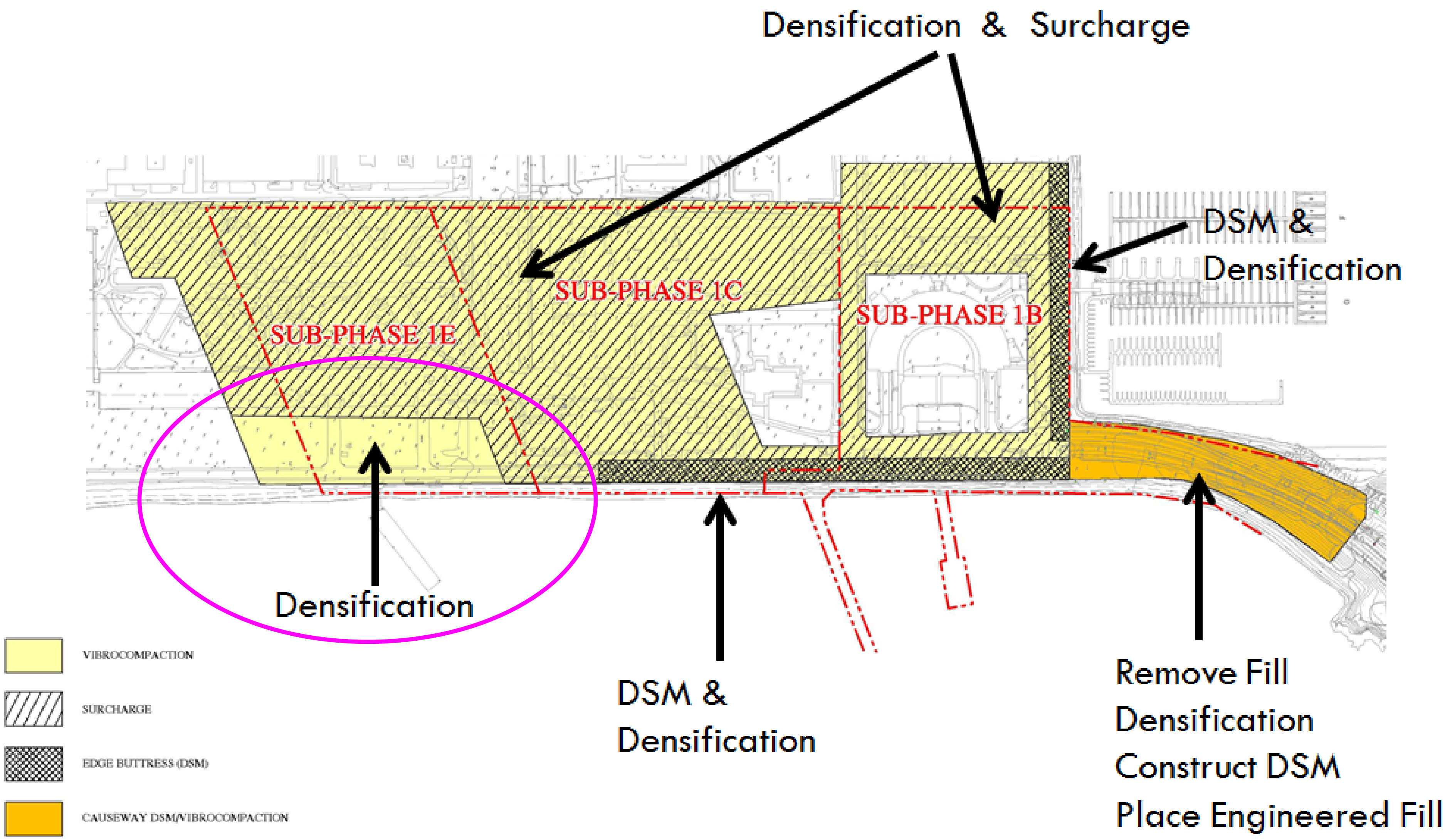
- Low-rise, Mid-rise, and High-rise Buildings – 8,000 units
- Hotel, Commercial, and Retail Uses
- 300 acres Open Space
- New Infrastructure and Transit Systems

GEOTECHNICAL HAZARDS

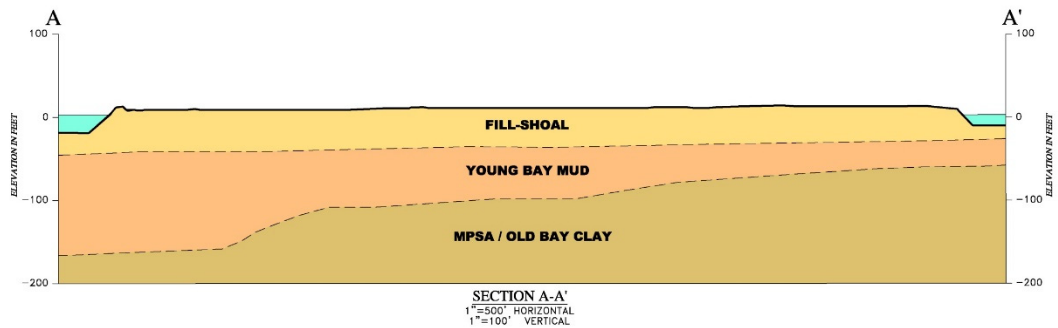
- Ground Shaking
- Liquefaction-Induced Settlement and Lateral Spreading Potential
- Shoreline and Causeway Seismic Slope Stability
- Consolidation Settlement of Young Bay Mud (YBM)
- Sea Level Rise



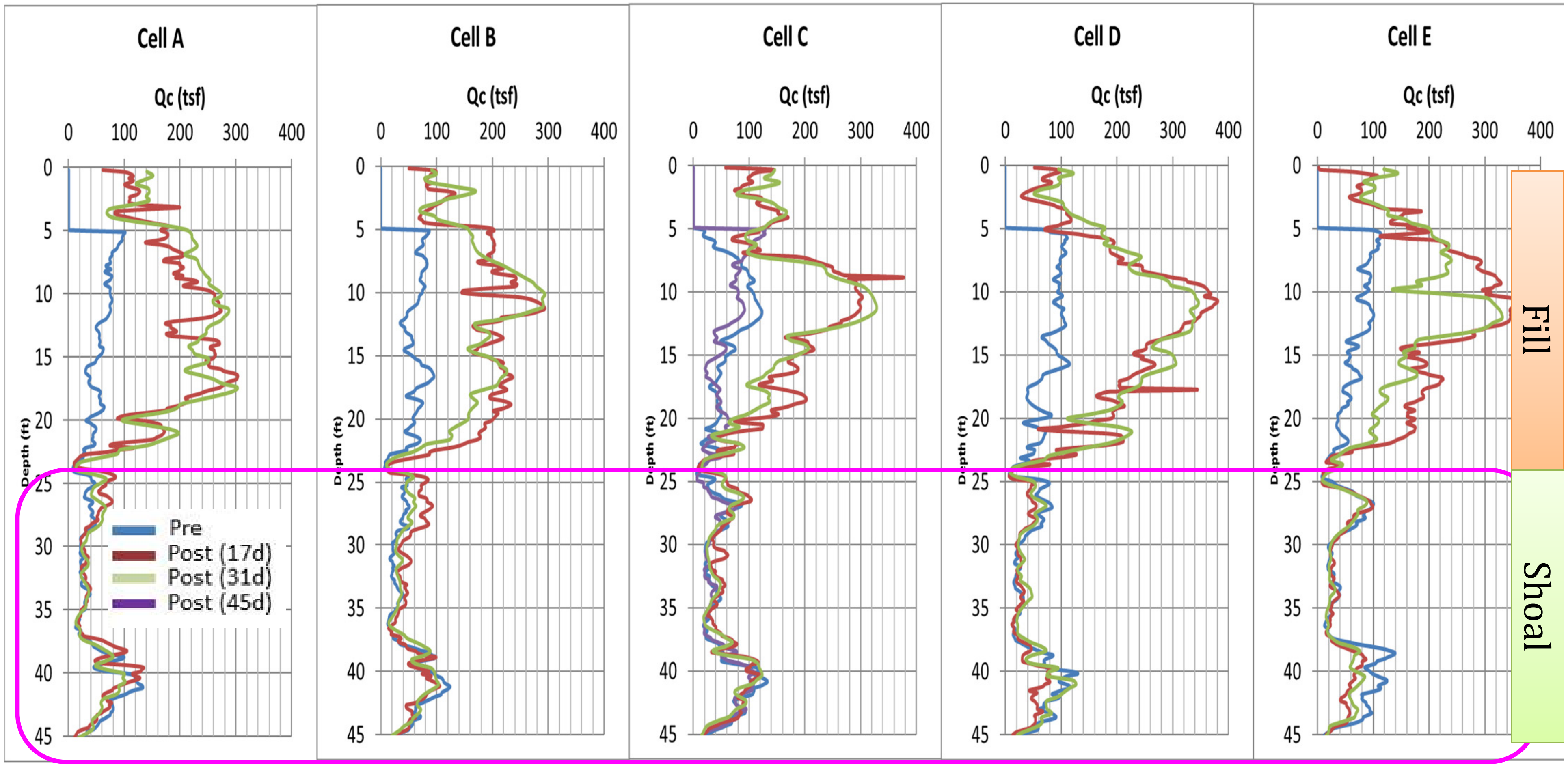
MITIGATION PLAN



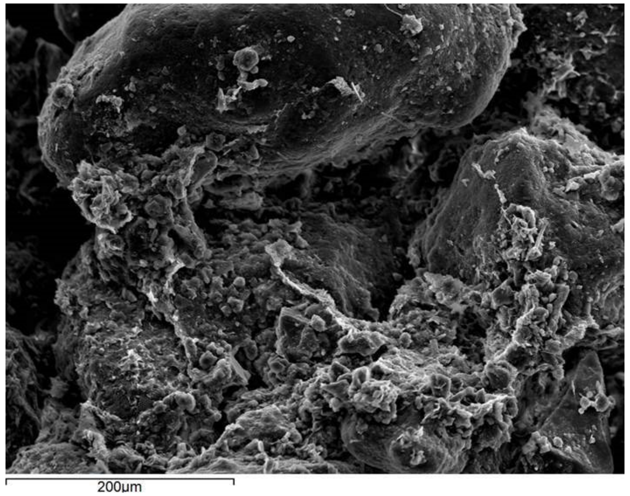
FULL-SCALE VIBRO-COMPACTION USING DPC

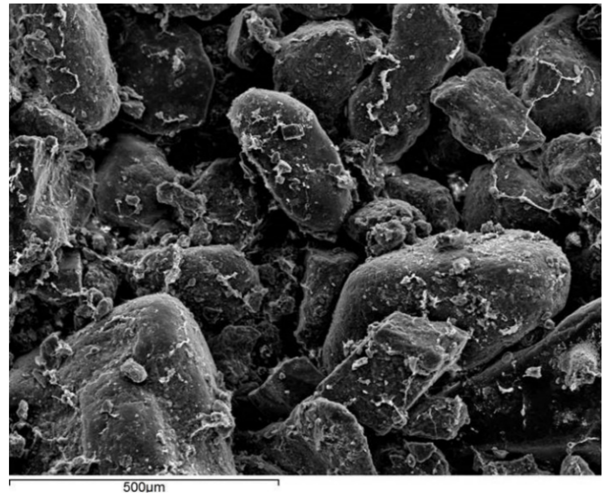


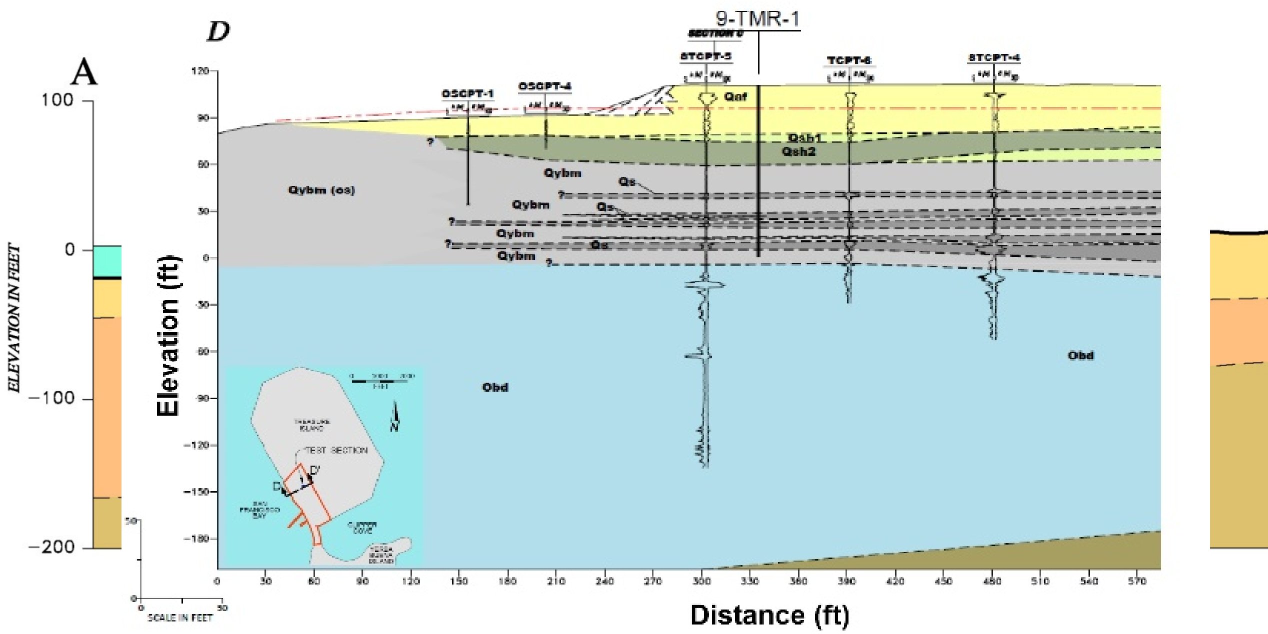
MOTIVATION: TEST PROGRAM CPT RESULTS



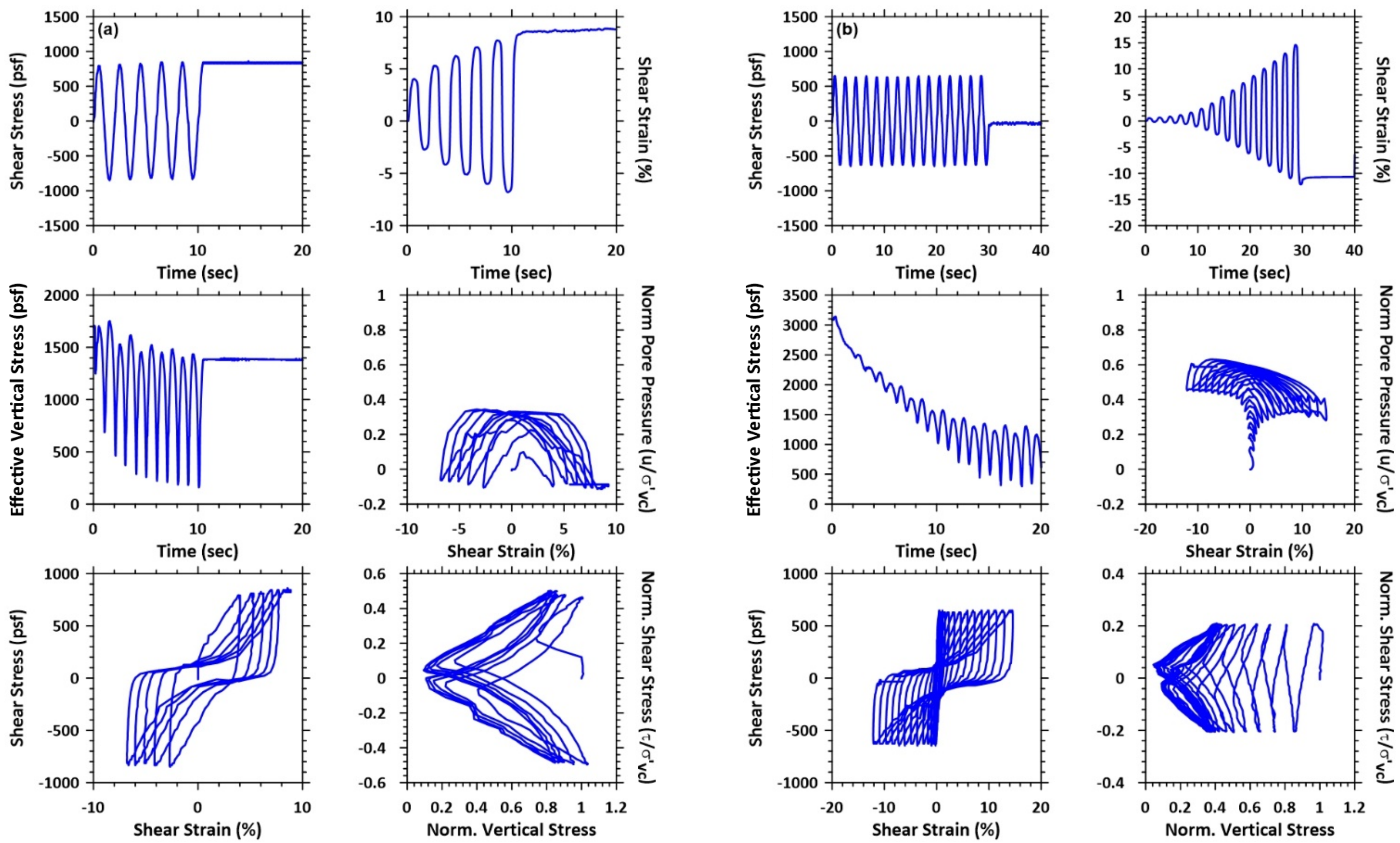
SUBSURFACE GEOLOGY







LABORATORY TESTING - Cyclic Simple Shear



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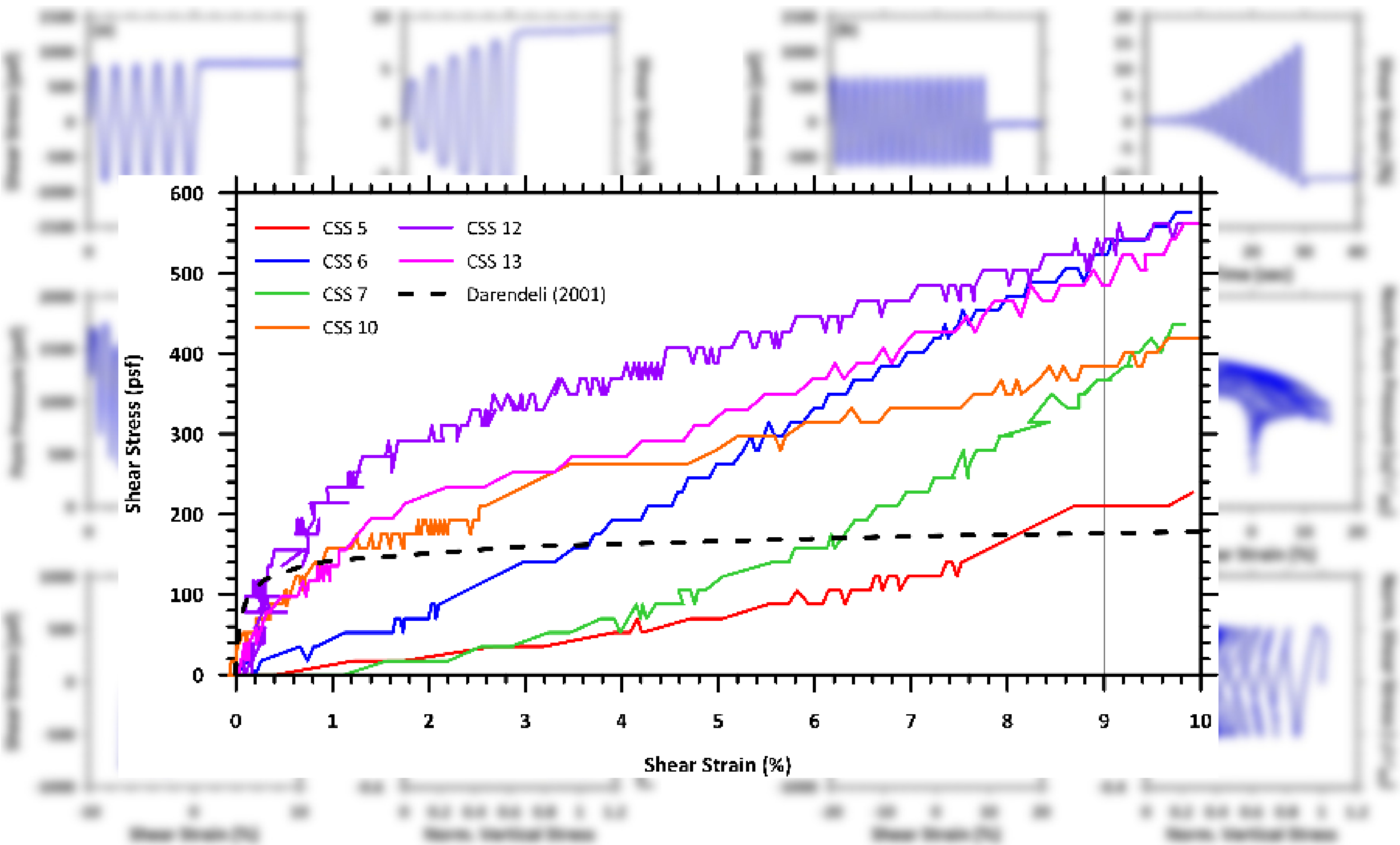
LABORATORY TESTING - Post-Cyclic Shear



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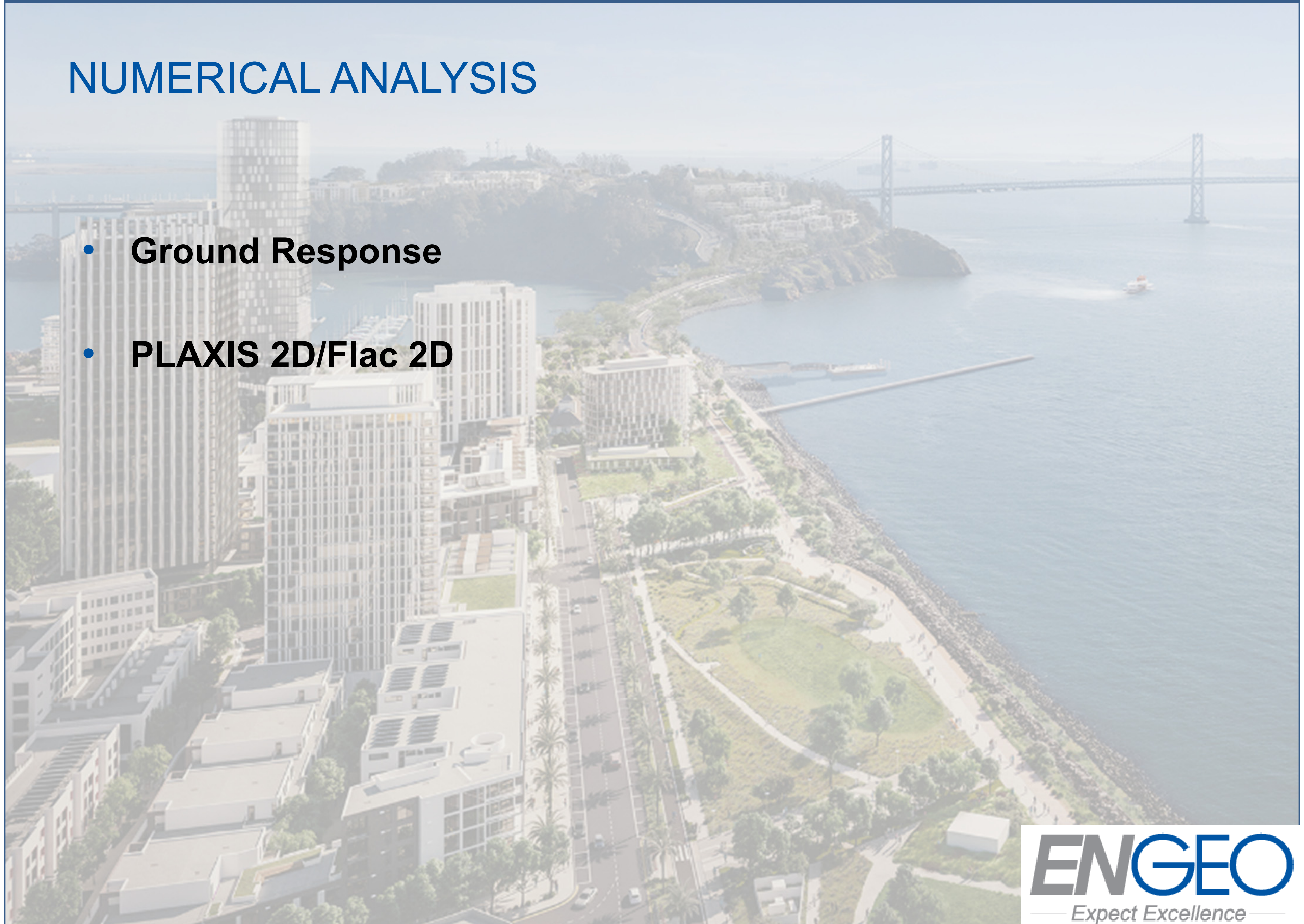
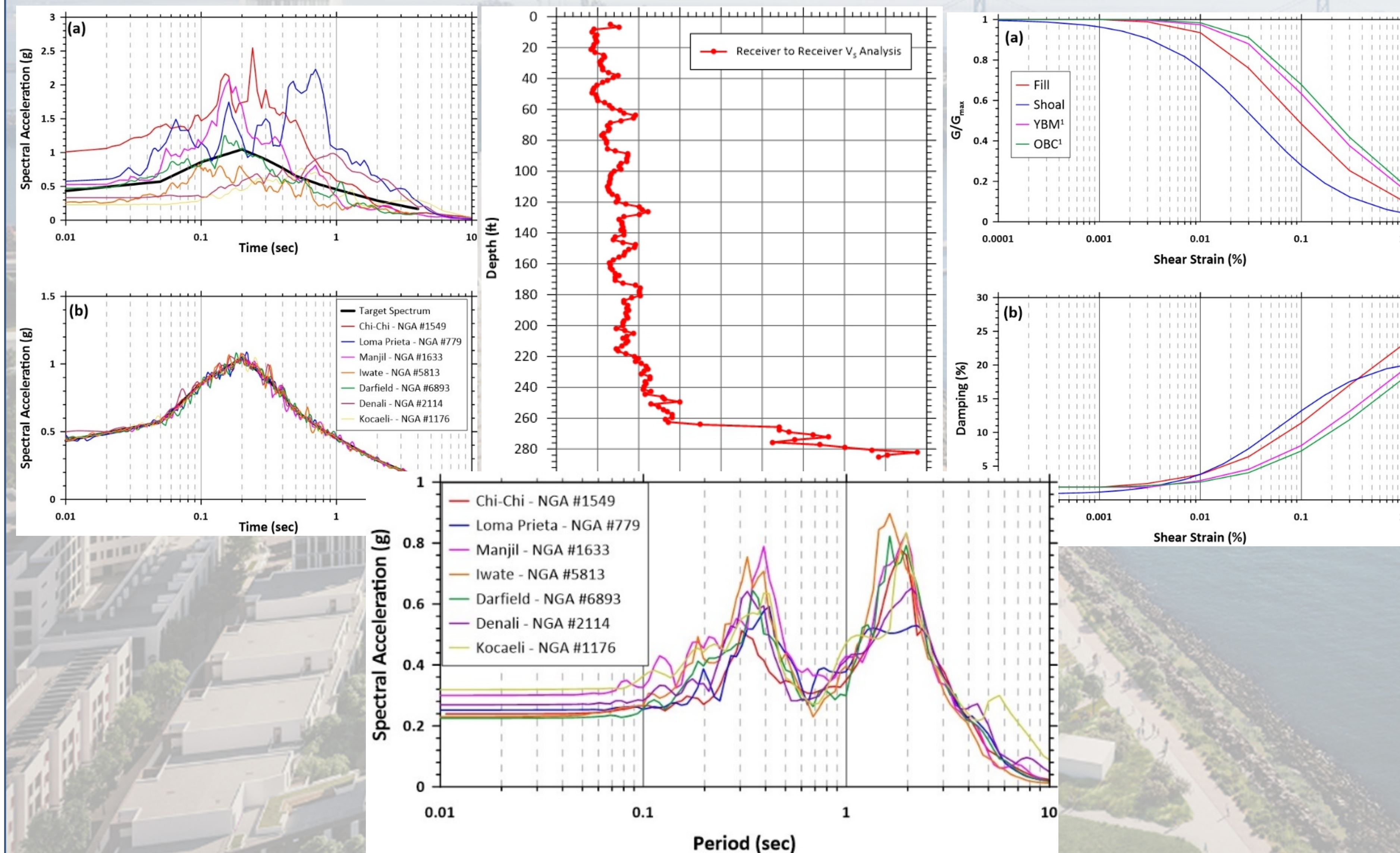
NUMERICAL ANALYSIS

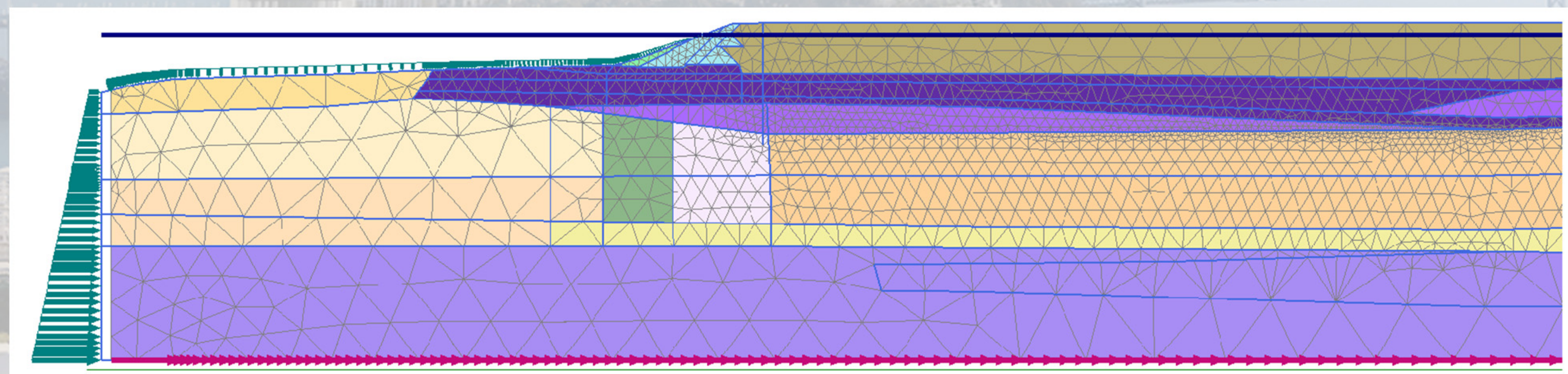


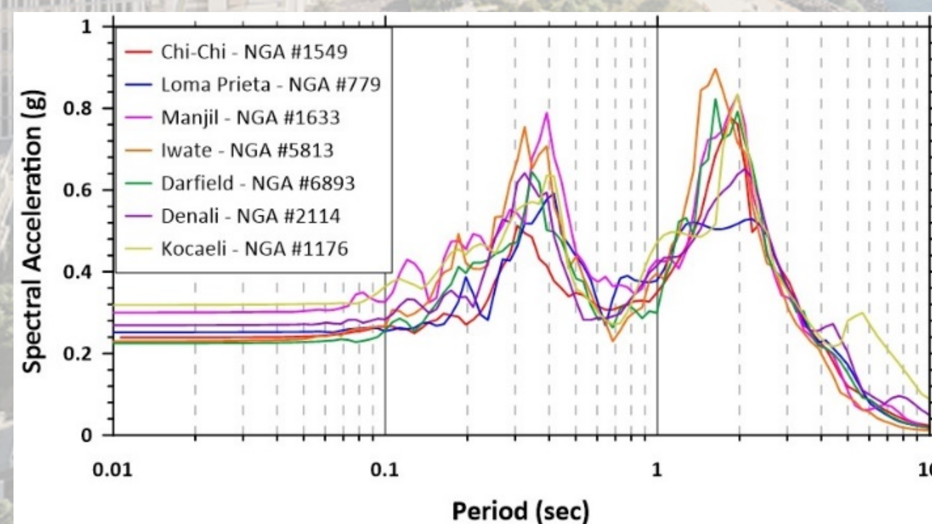
- **Ground Response**
- **PLAXIS 2D/Flac 2D**

NUMERICAL ANALYSIS



NUMERICAL ANALYSIS





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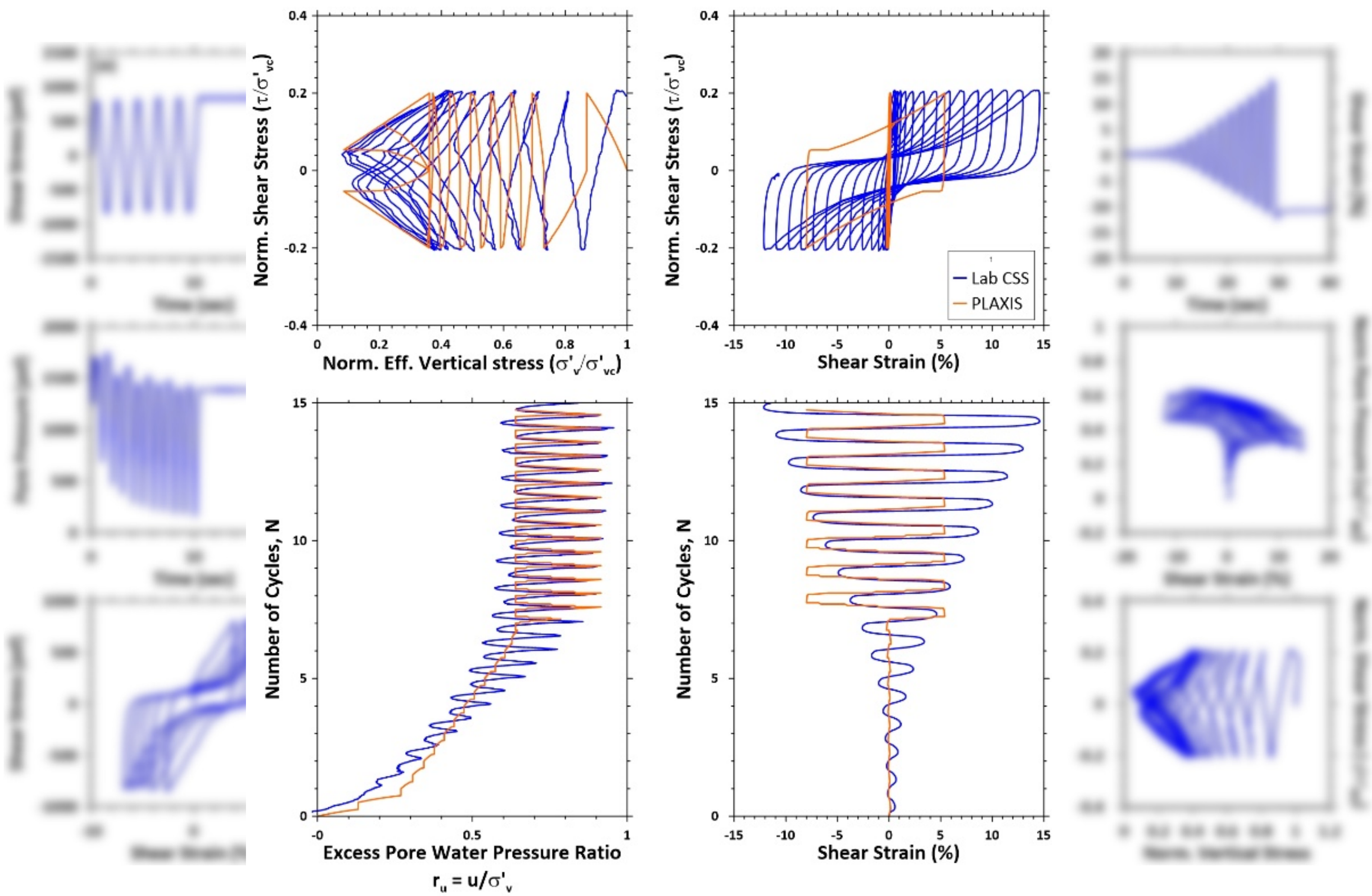
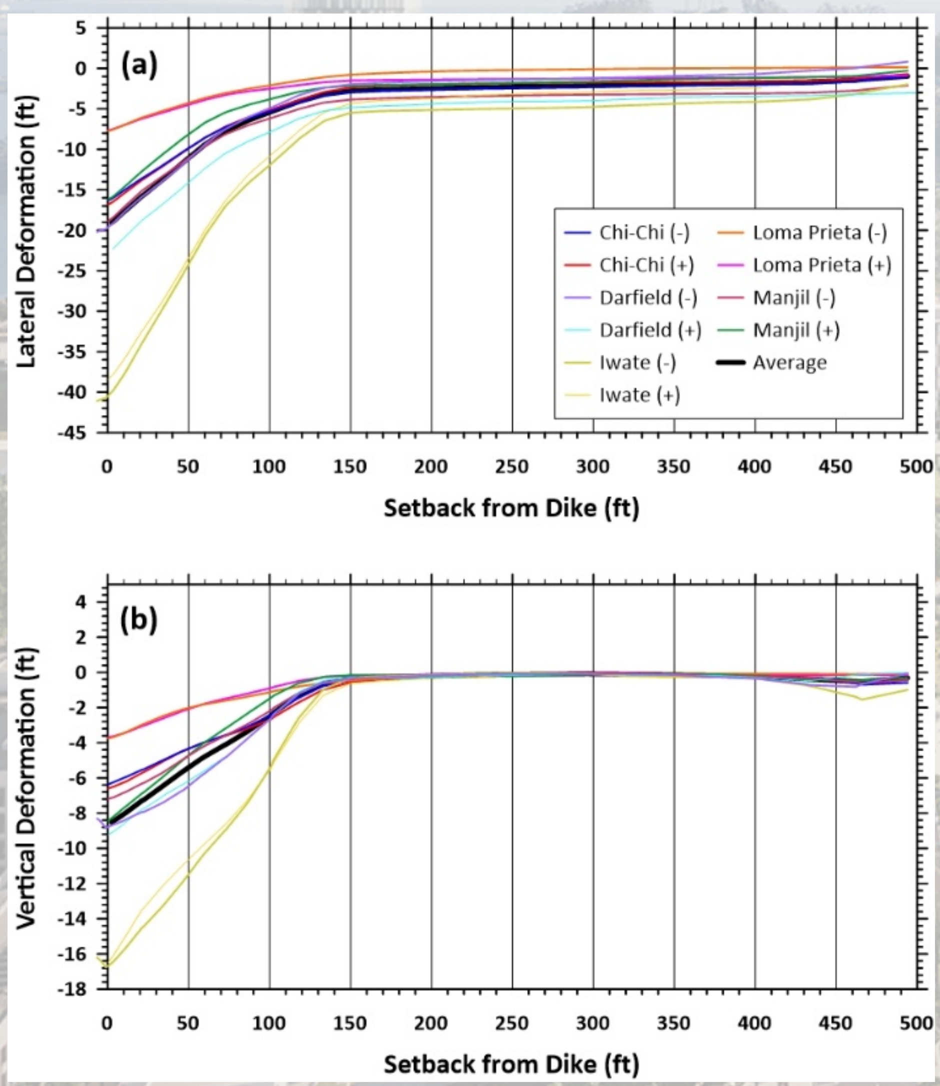
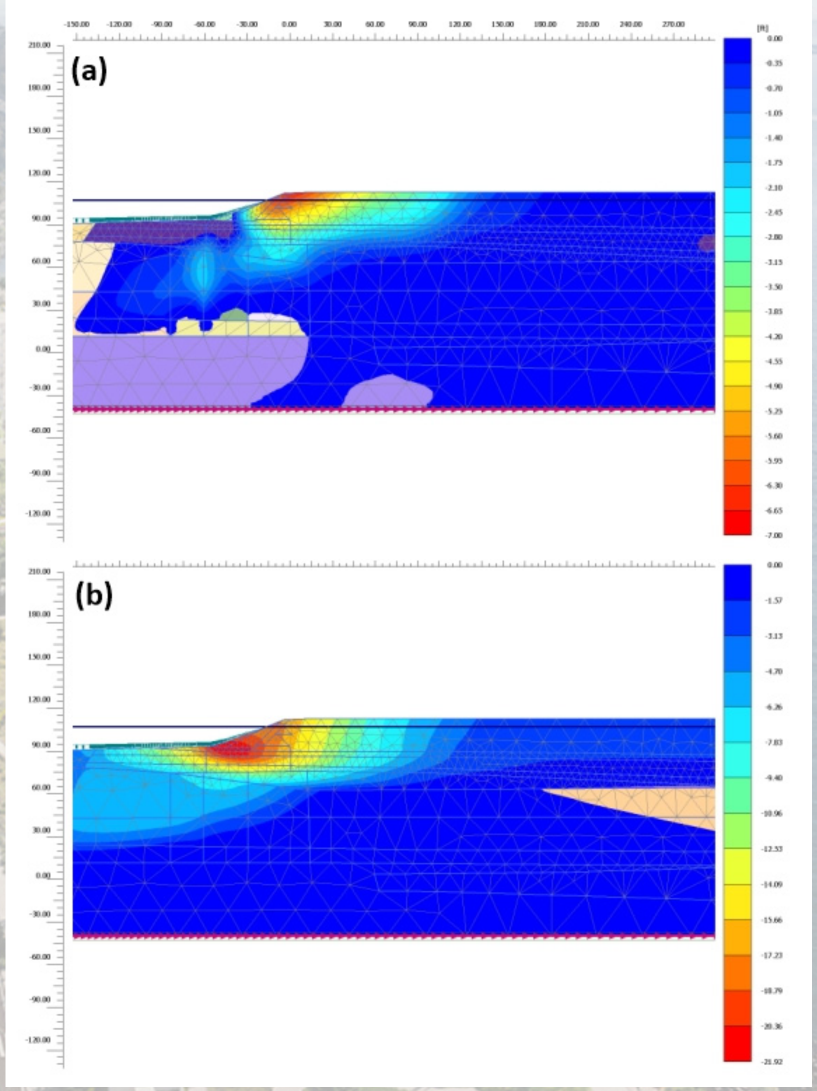
UBC SAND MODEL CALIBRATION

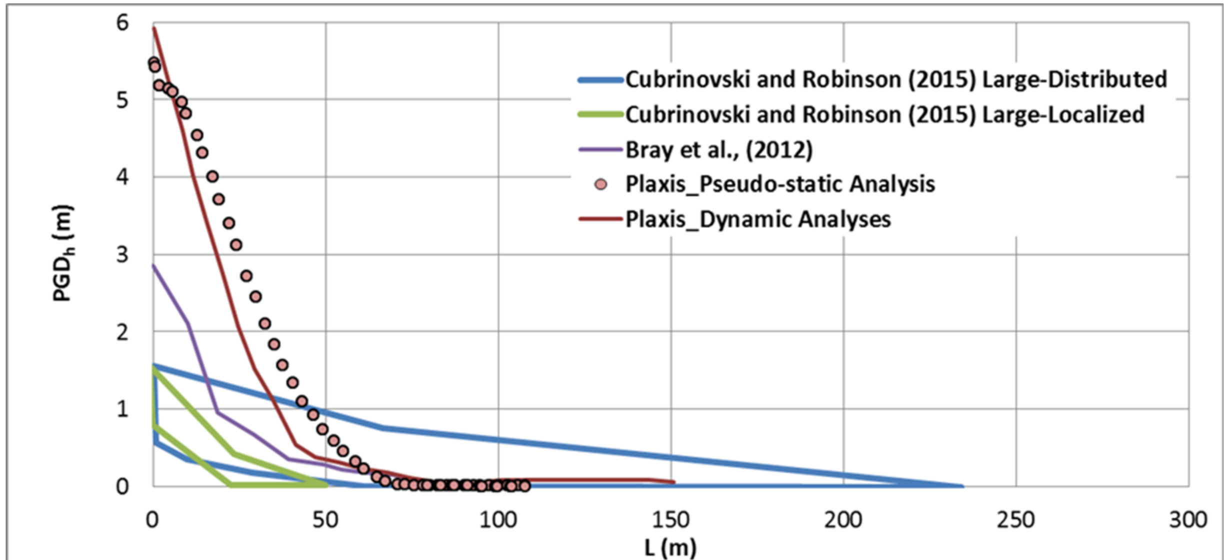


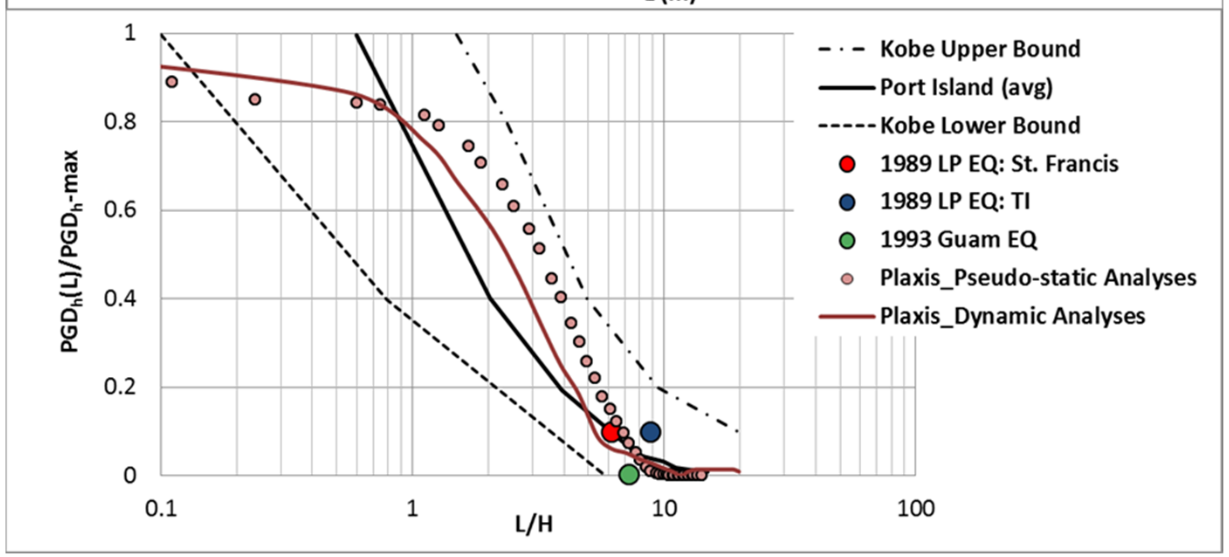
ANALYSIS RESULTS





ANALYSIS RESULTS VALIDATION

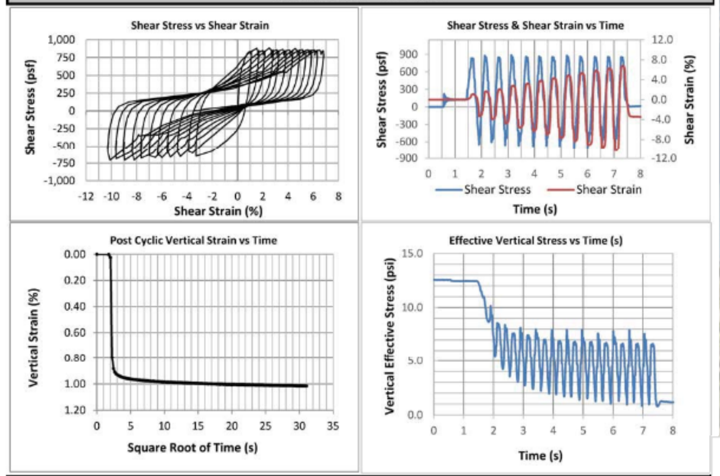




ON-GOING WORK

Cyclic Simple Shear

ASTM D6528 - Modified



Test Conditions		Results		Maximum	Minimum
Confining Condition	Plain Membrane w/Chamber Pressure	Vertical Effective Stress (psf)	Deviatoric	605.3	-224.8
Applied Lateral Effective Stress (psf)	1206.0		Isotropic	1206.0	1206.0
Resulting K_o after applied, σ_{vc}'	0.665	Shear Strain (%)		6.8	-10.3
Applied Loading Frequency (Hz)	0.500	Post Cyclic Vertical Strain (%)		1.02	
Cycle Limit, N	12				
Single Amp. Strain (+/-)	8.6	Cyclic Preshear Specimen Condition			
Applied τ_{cyc} (psf)	887	Preshear Moisture Content (%)		22.61%	
Applied σ_{vc}' (psf)	1813	Preshear Void Ratio		0.6088	
Applied CSR	0.439	Preshear Saturation (%)		99.74%	
		Preshear Dry Density (pcf)		104.12	
				Test Date:	6/27/2019

ASTM D2216	As Received	Final	ASTM D4318 - Wet Method	
Moisture (%):	25.88%	24.31%	Liquid Limit:	
Dry Density (pcf):	102.10	105.39	Plastic Limit:	
Saturation (%):	100.00%	100.00%	ASTM D854 - Measured	
Void Ratio:	0.6288	0.5883	Specific Gravity:	2.686
			Soil Description:	See exploration logs

Project Number:	7091.000.006	Depth:	49.0-49.25 ft.
Sample Number:	TMR17-4 @ 48	Boring #:	TMR17-4
Project Name:	Block C2 Geotechnical Exploration		
Client:	Treasure Island Development Group		
Location:	San Francisco, California		
Tested By:	D. Seibold	Reviewed By:	P. Espinosa

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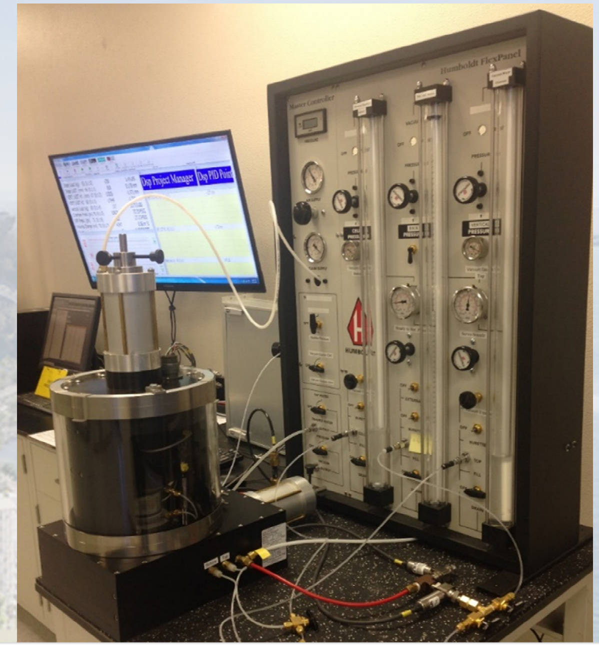

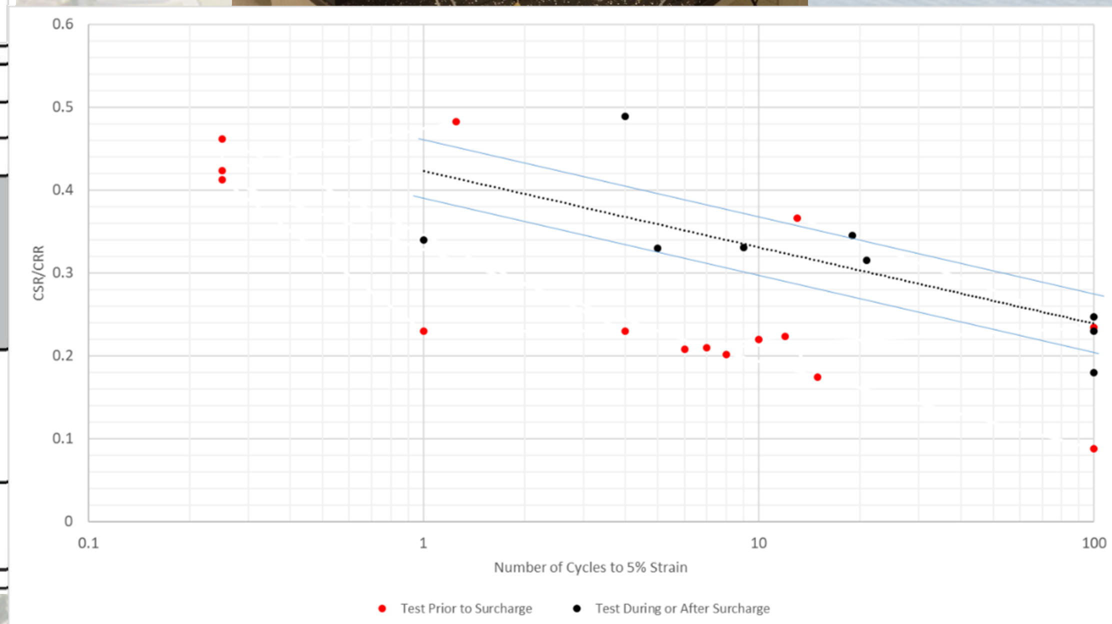

CONCLUSION

- The shoal deposit is very heterogeneous, consisting of sand, non-plastic silt, and high-plasticity fat clay.
- Full-scale DPC test results indicated that no appreciable densification can be obtained within the shoal deposits.
- Rigorous evaluation of the dynamic properties of Shoal with discrete geological logging, cyclic laboratory analysis and index testing
- Using non-linear dynamic analysis the team determined that lateral deformation is insignificant beyond a distance of 250 feet from the shoreline.
- Simplified liquefaction assessments are not able to provide the full picture of dynamic behavior of the native Shoal.

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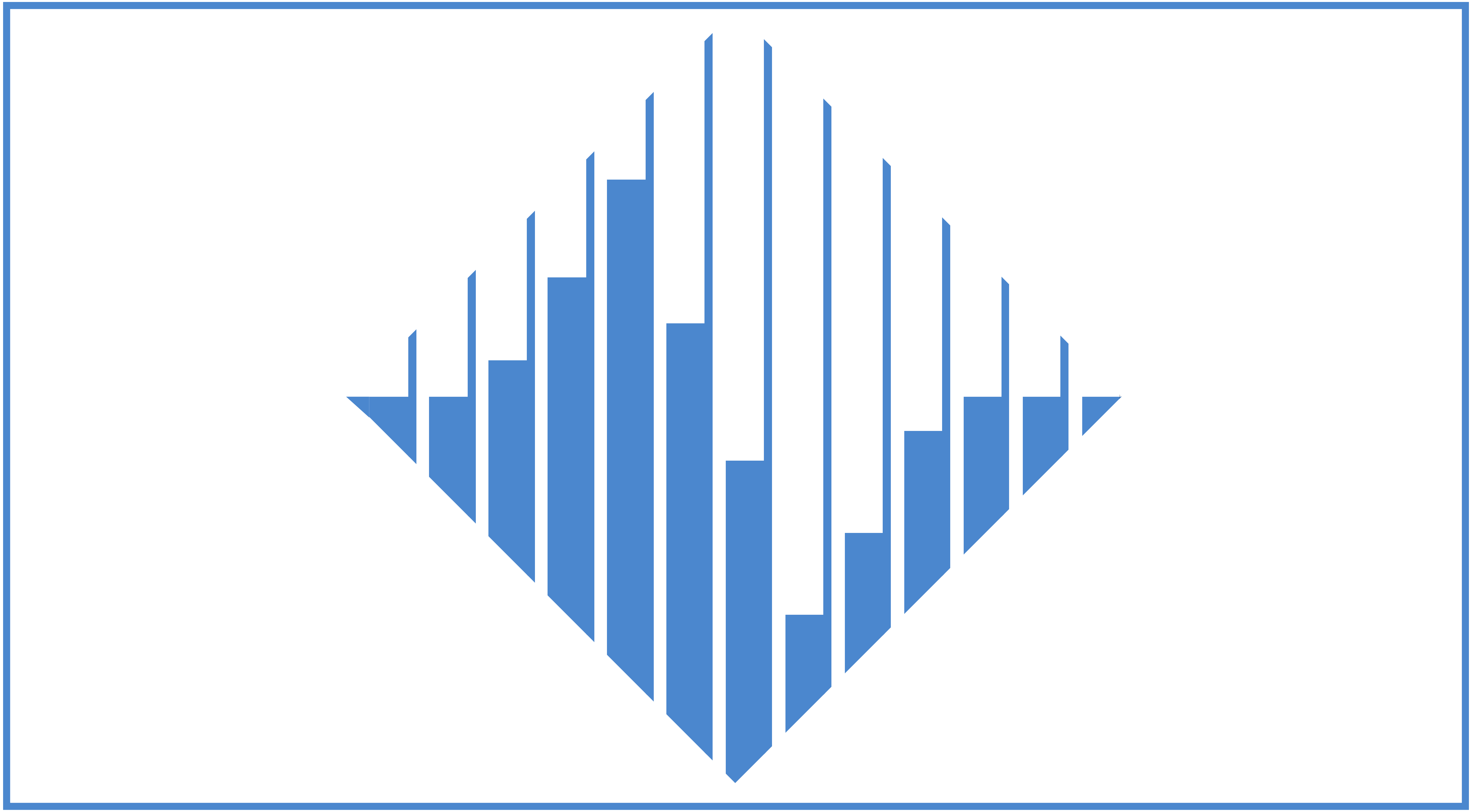
Thank You



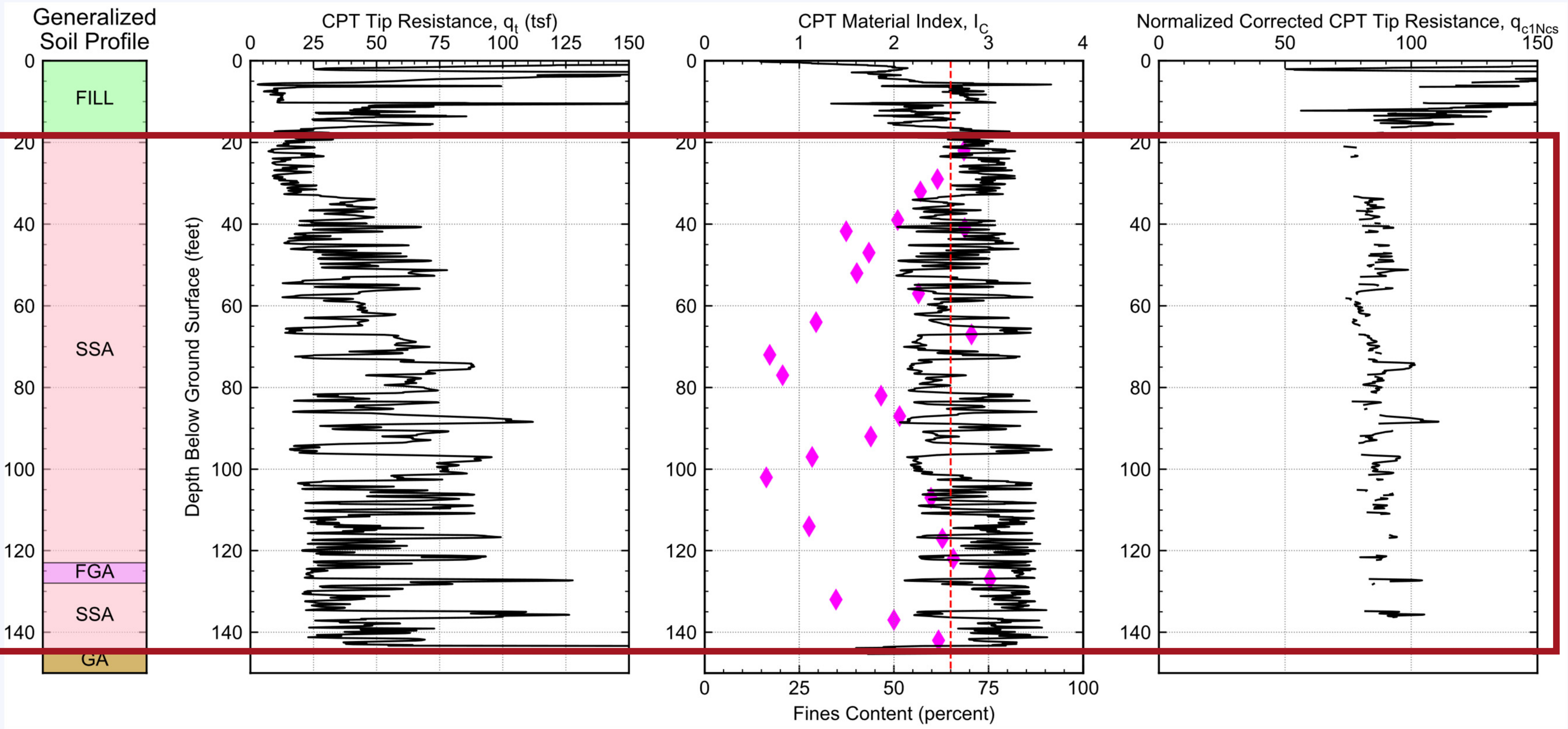
Liquefaction Susceptibility of a Low Plasticity Silty Soil Utilizing Cyclic Direct Simple Shear Testing

Sam Sideras

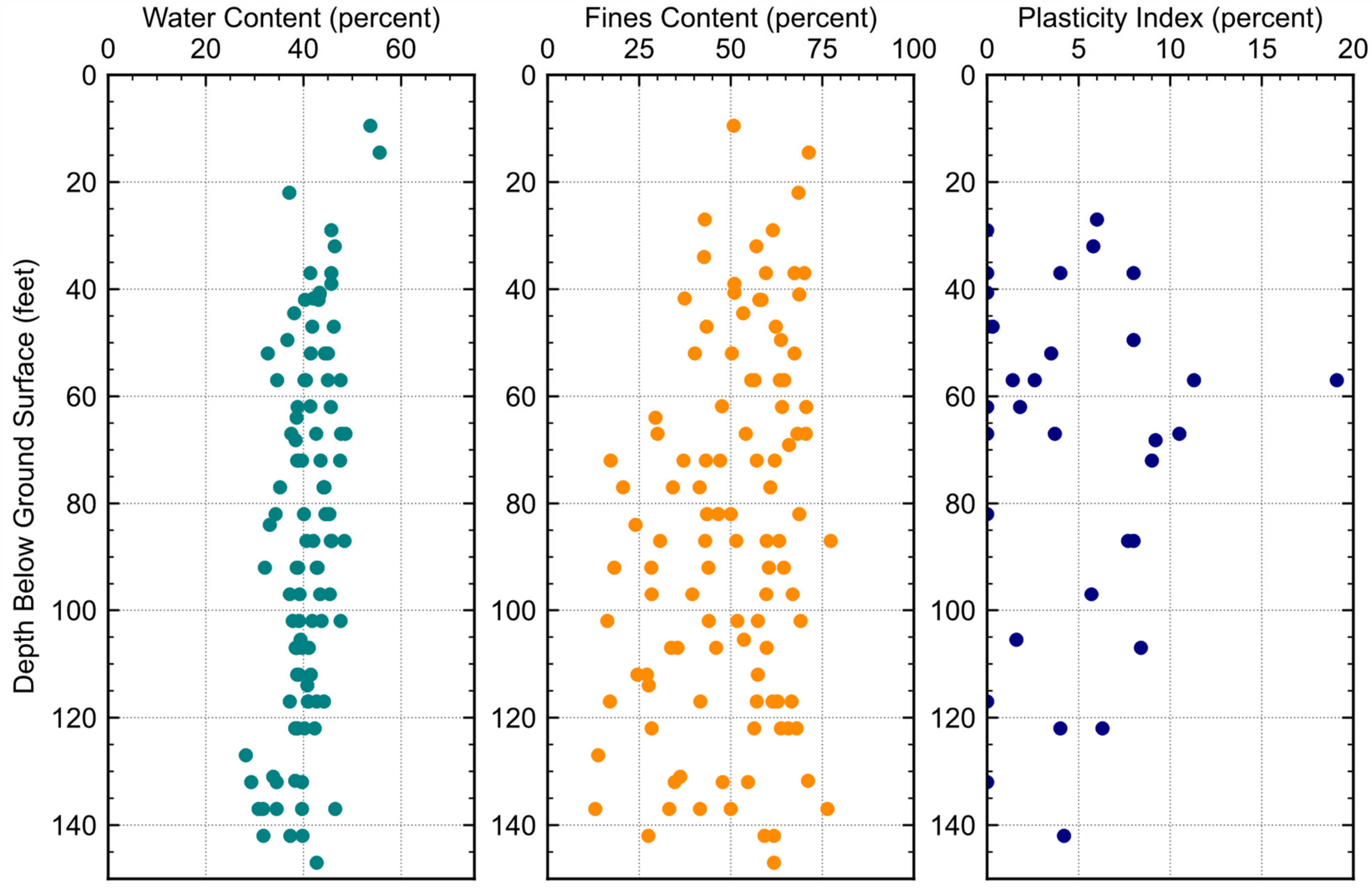
Liquefaction Susceptibility Characterization

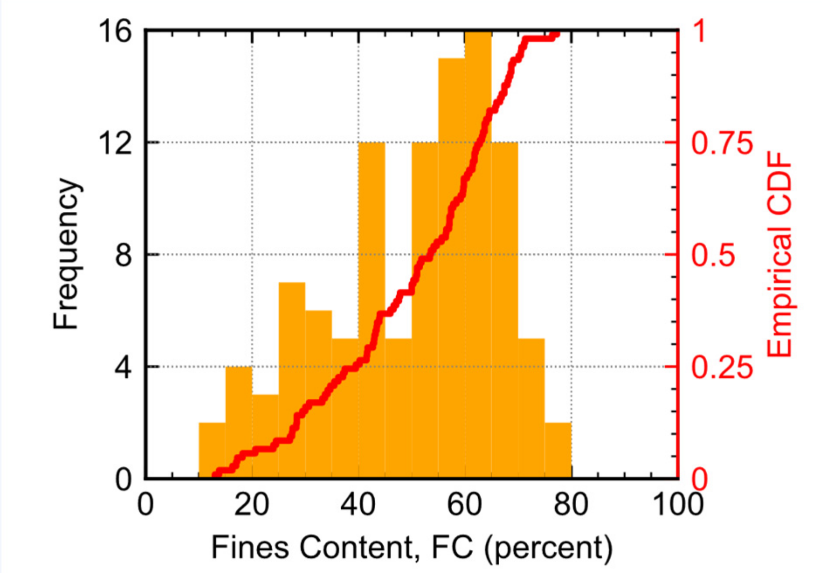
- In-situ and soil index testing summary
- Cyclic and post-cyclic testing summary
- Conclusions

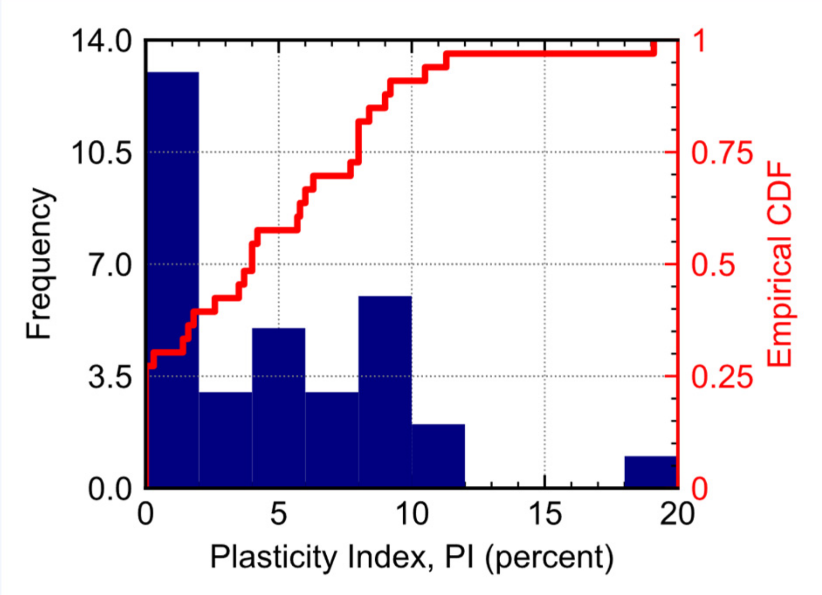
In-situ and soil index tests



In-situ and soil index tests

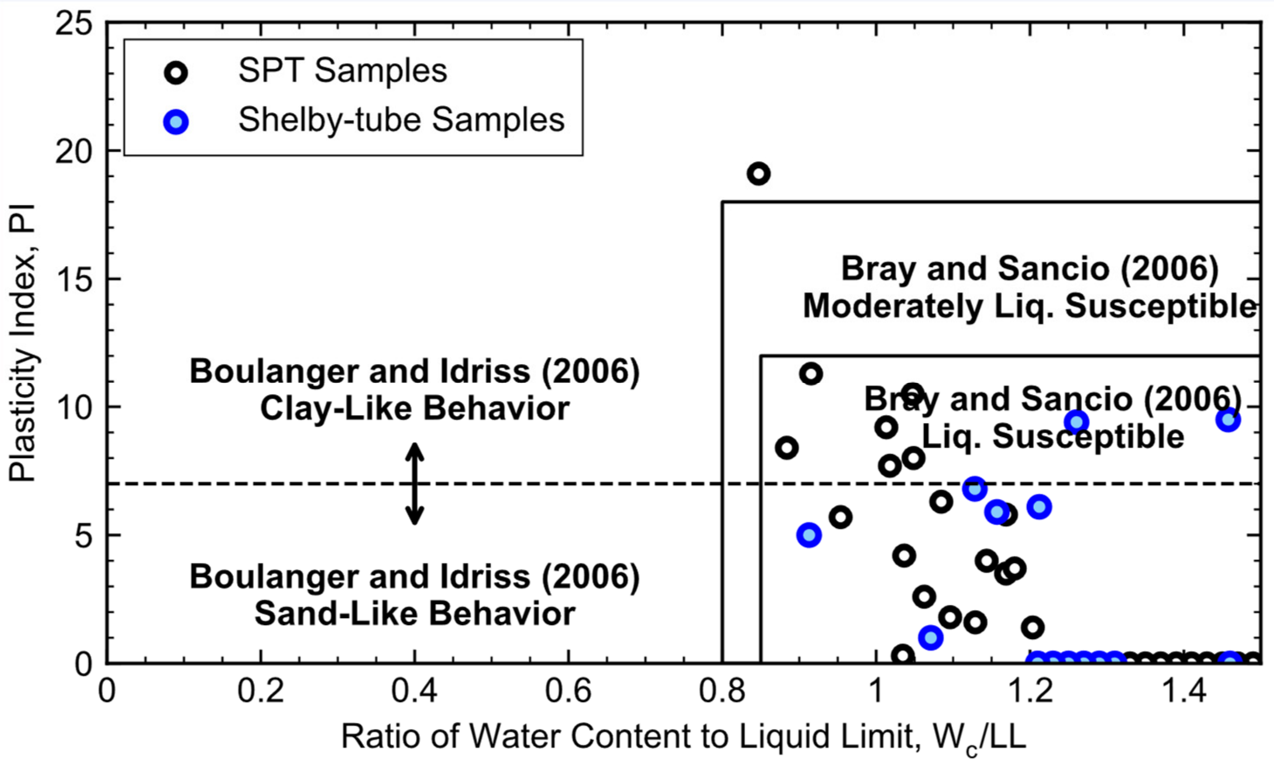






SHANNON & WILSON

In-situ and soil index tests



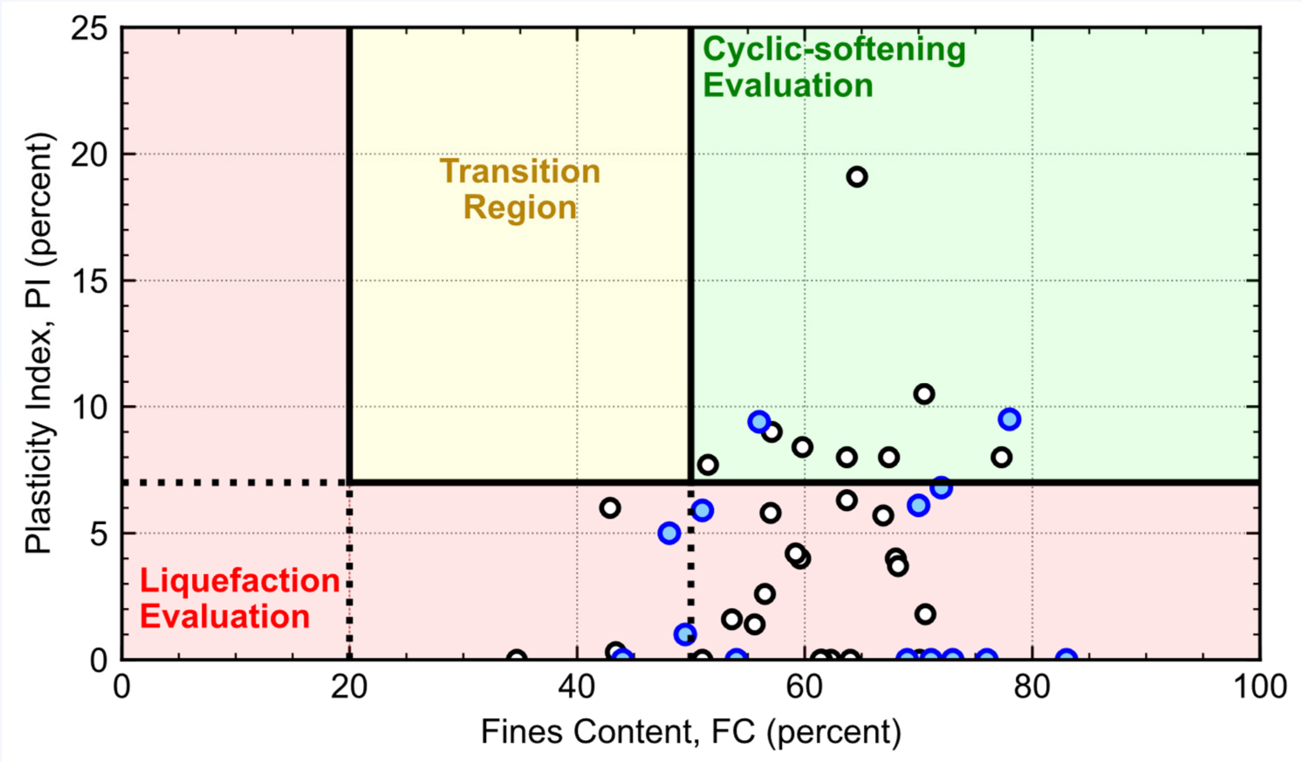
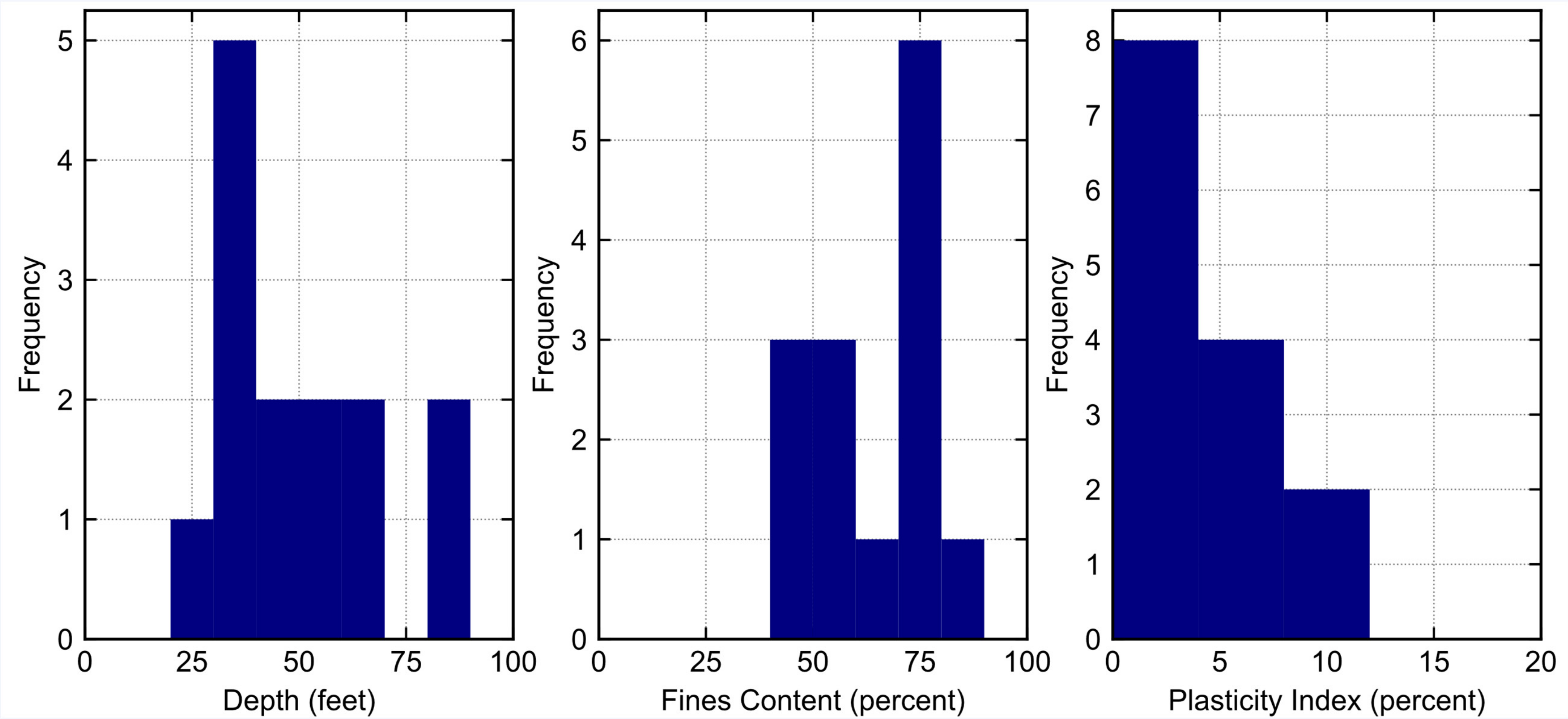


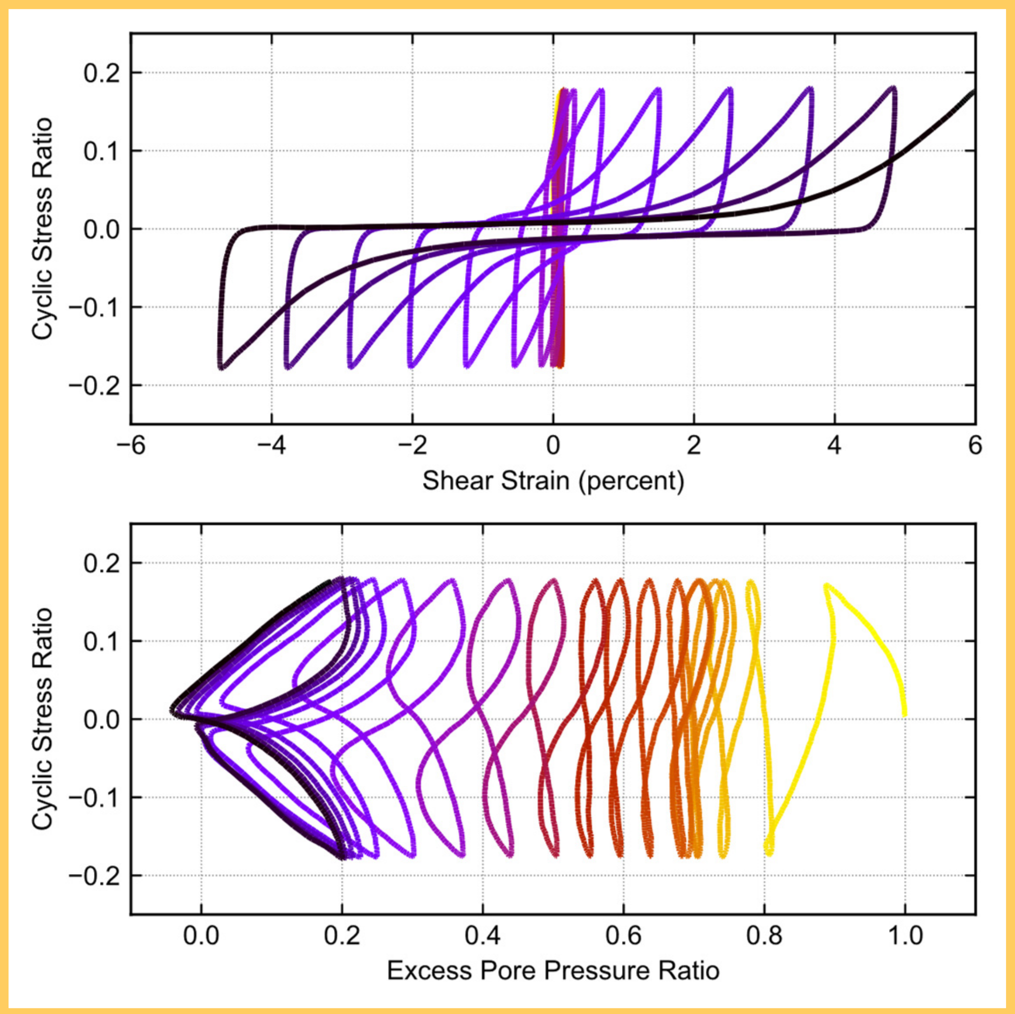
Chart from Armstrong and Malvick (2016)

SHANNON & WILSON

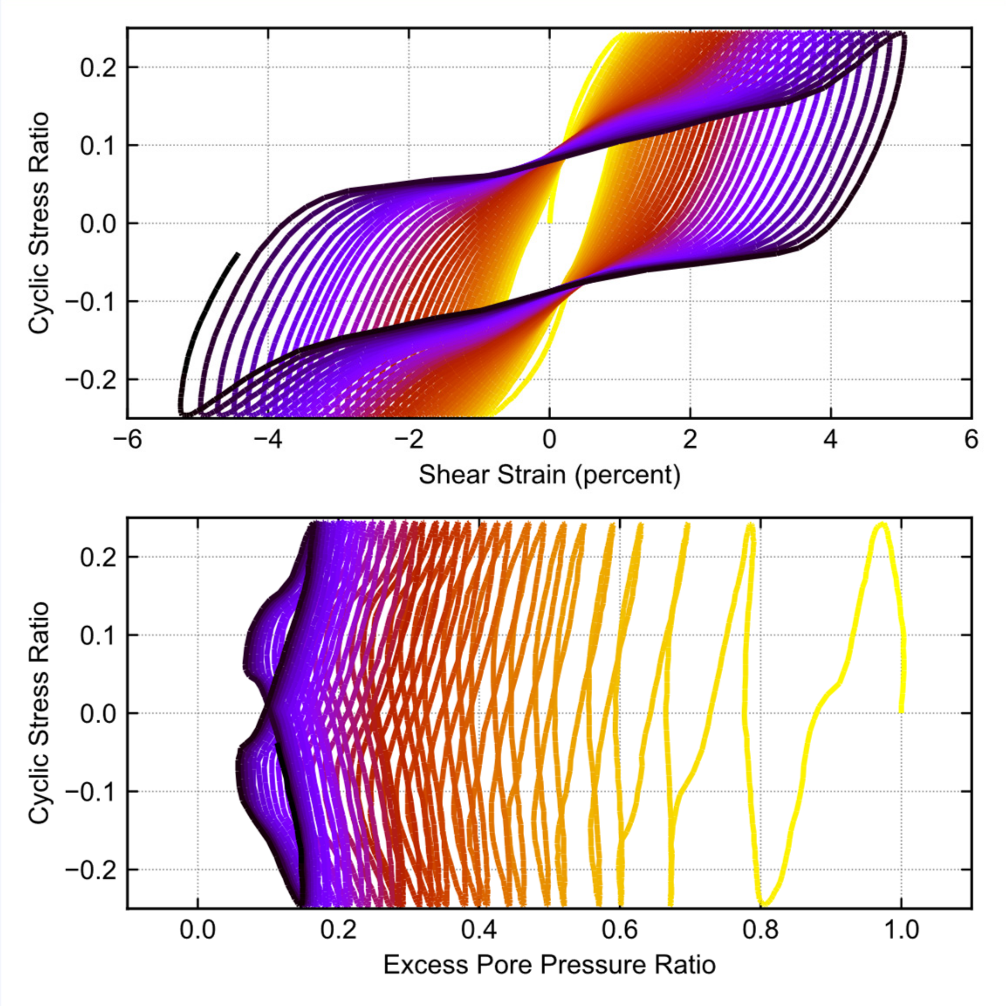
Cyclic and post-cyclic testing: sample summary



Cyclic testing

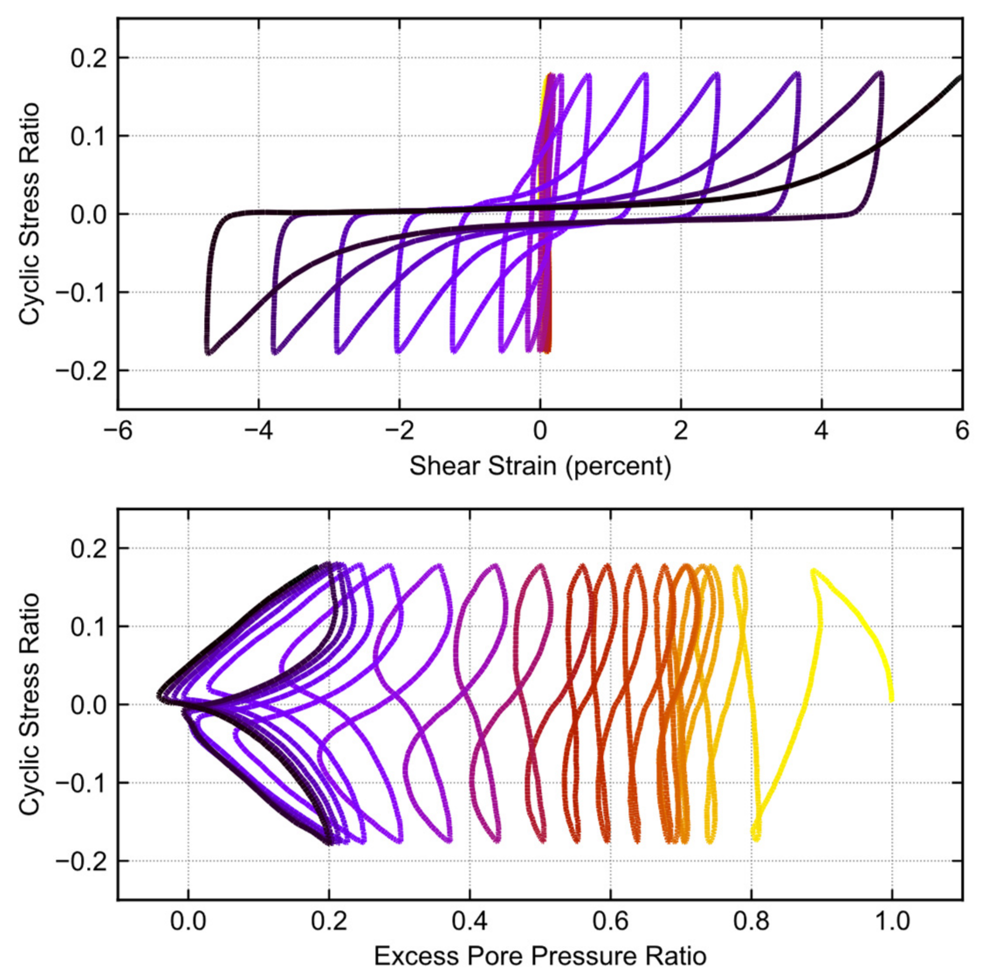


Kwan (2015): Nevada Sand (SP)

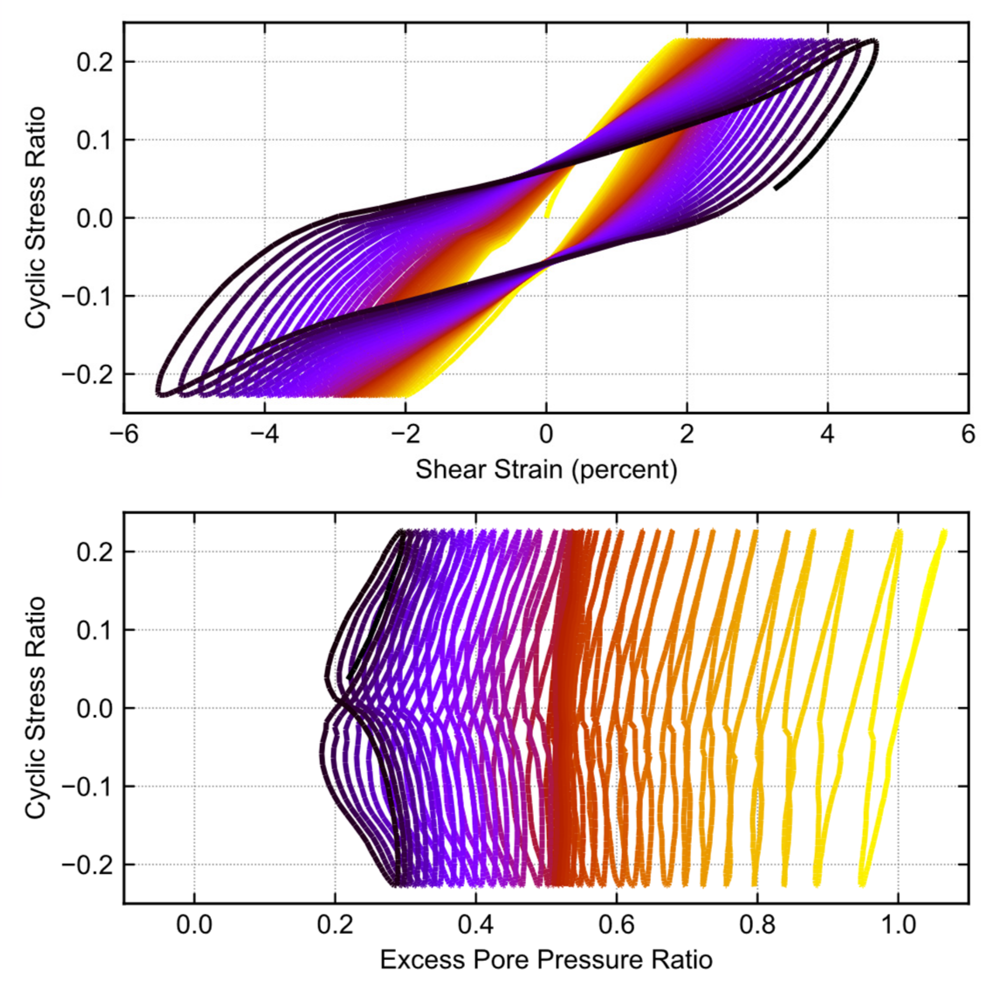


FC = 78%; PI = 9

Cyclic testing

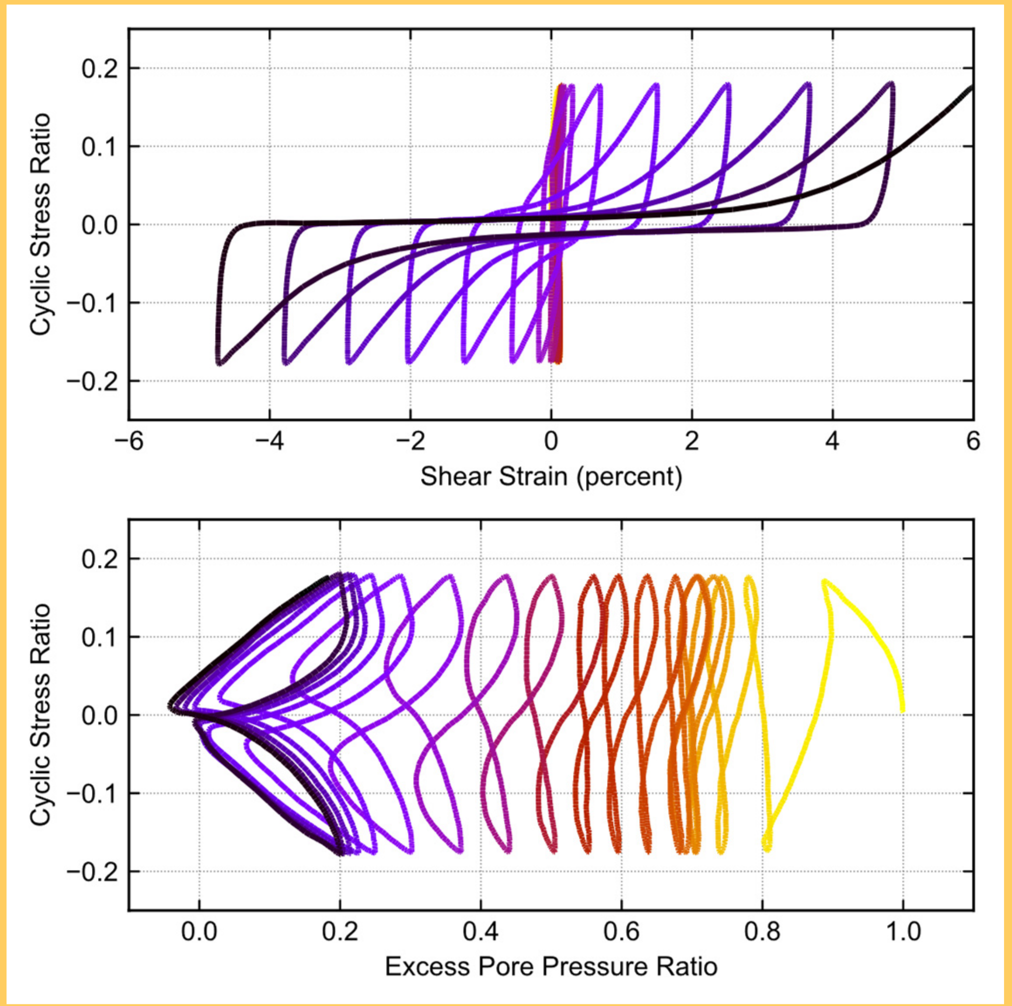


Kwan (2015): Nevada Sand (SP)

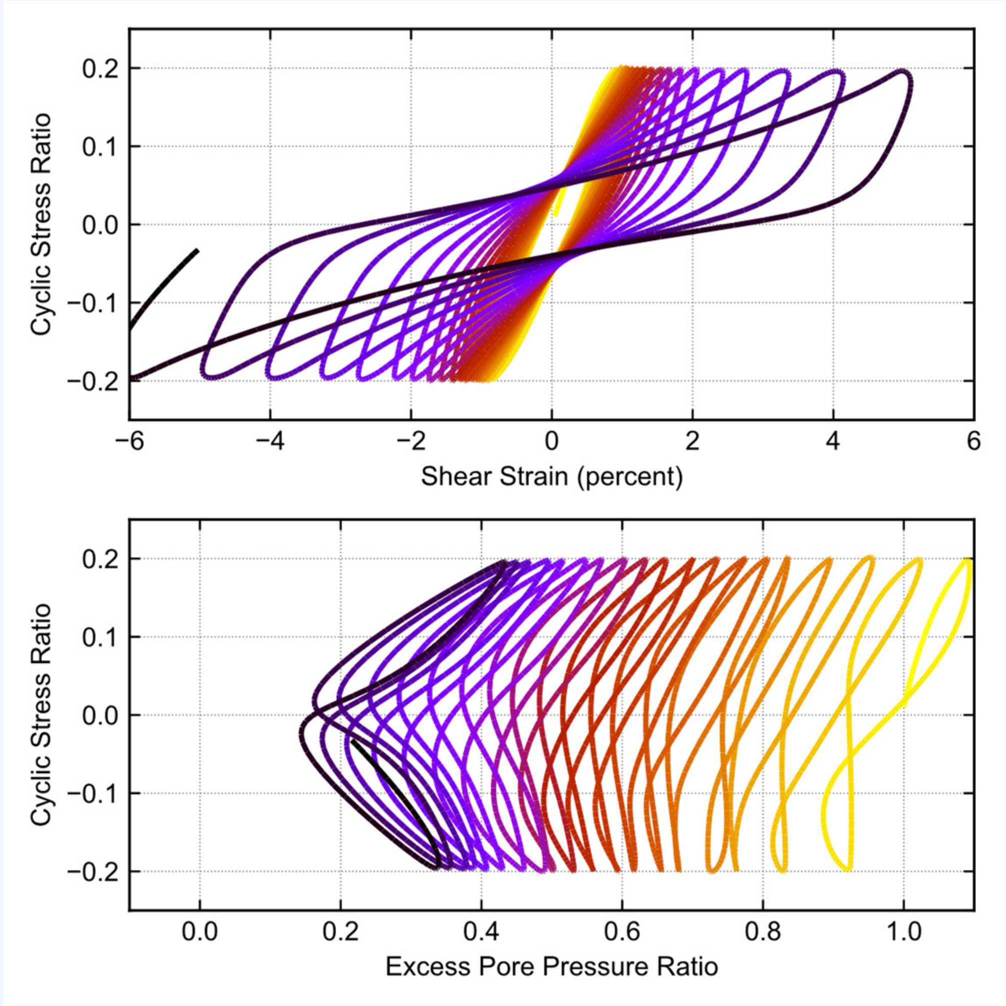


FC = 83%; PI = 0

Cyclic testing



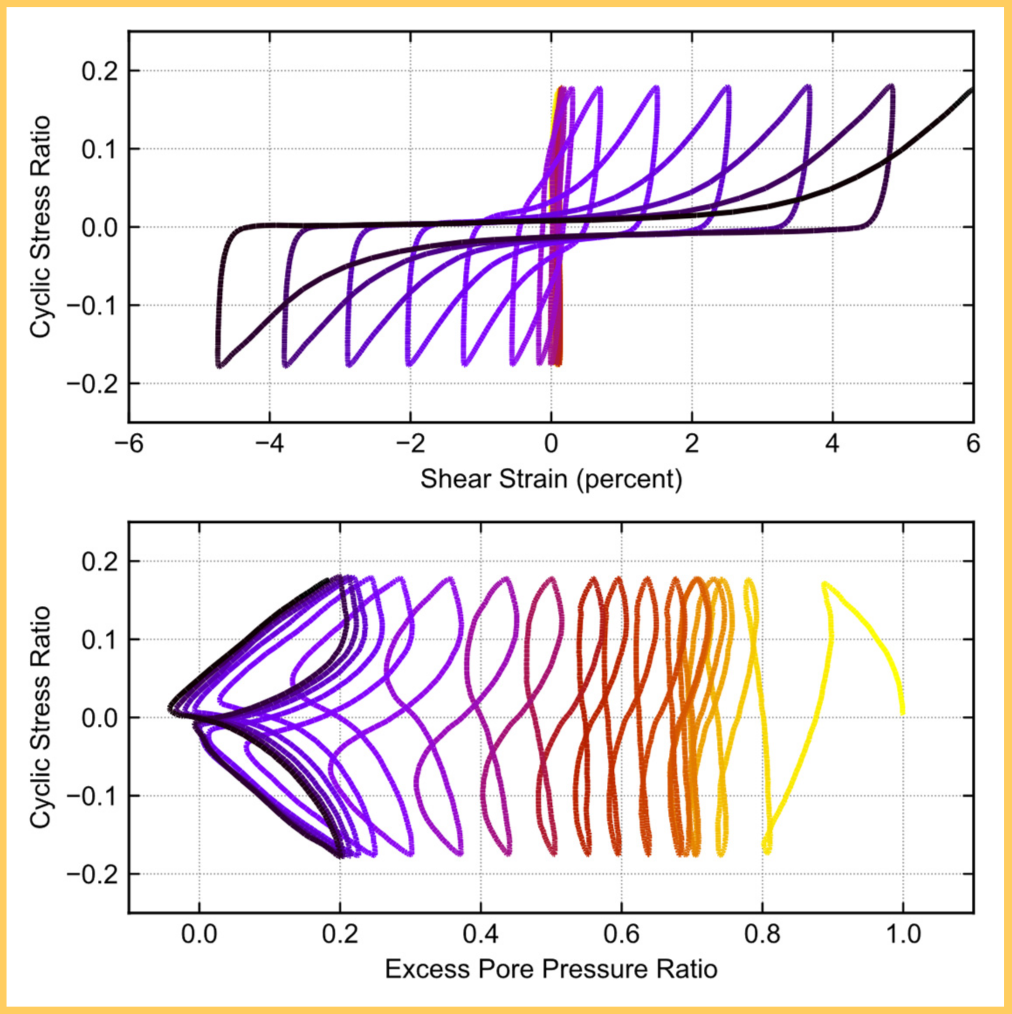
Kwan (2015): Nevada Sand (SP)



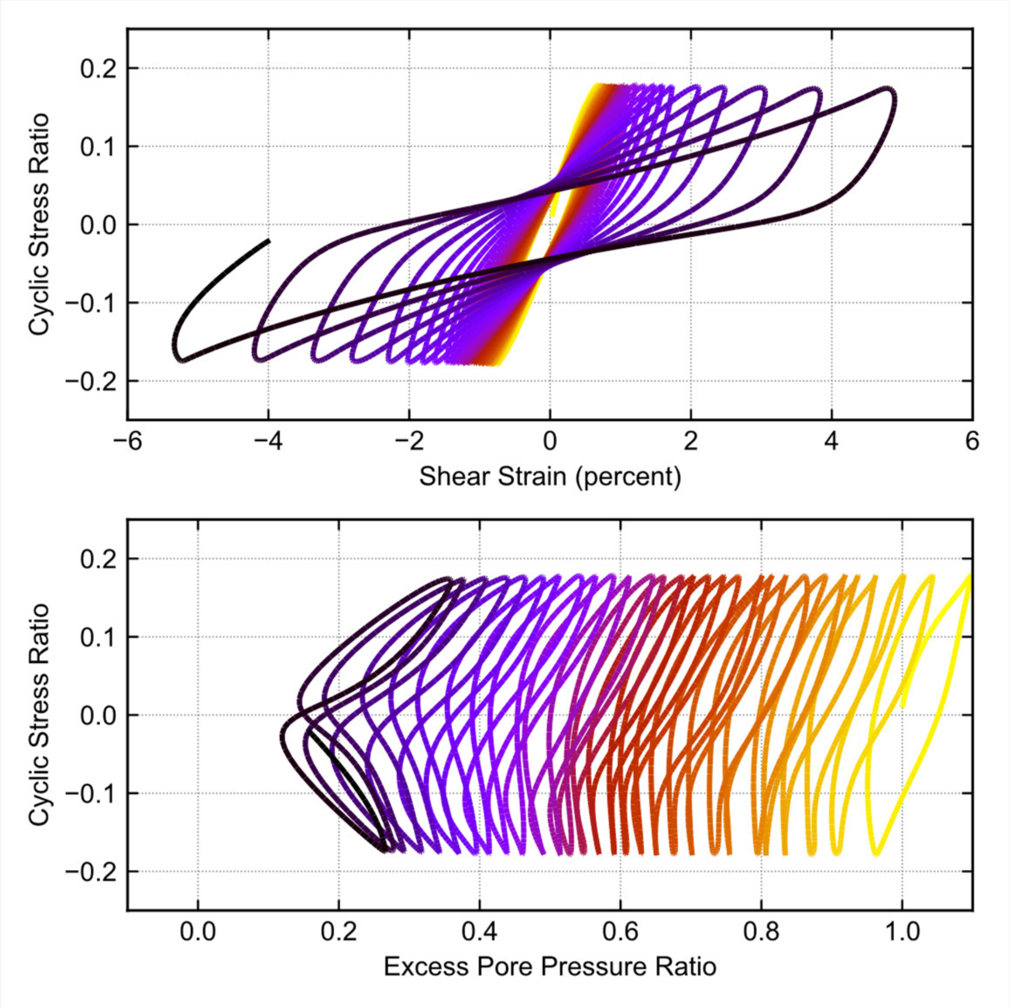
FC = 46%; PI = 5

Shannon & Wilson

Cyclic testing



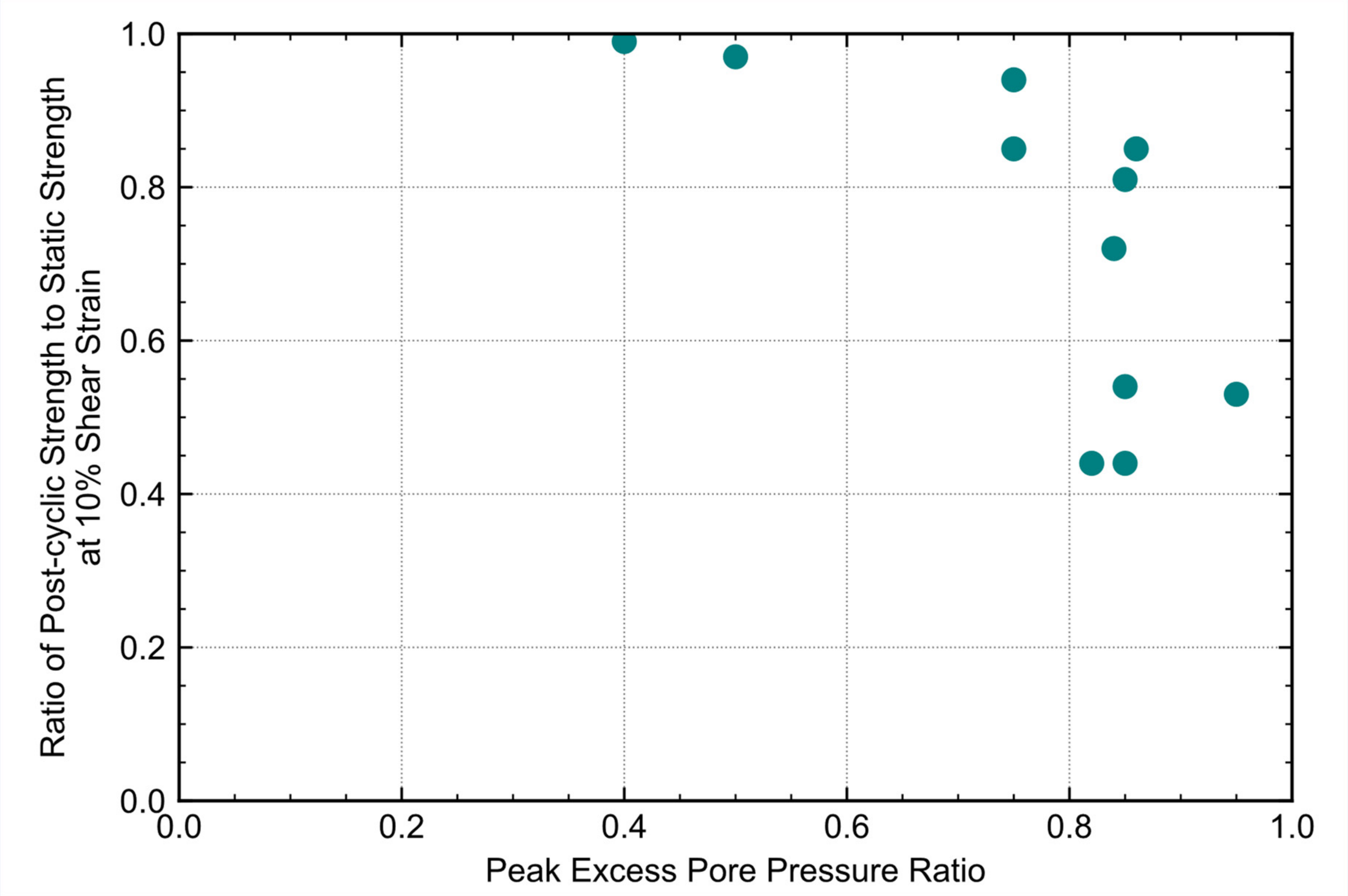
Kwan (2015): Nevada Sand (SP)



FC = 45%; PI = 0

SHANNON & WILSON

Post-cyclic testing



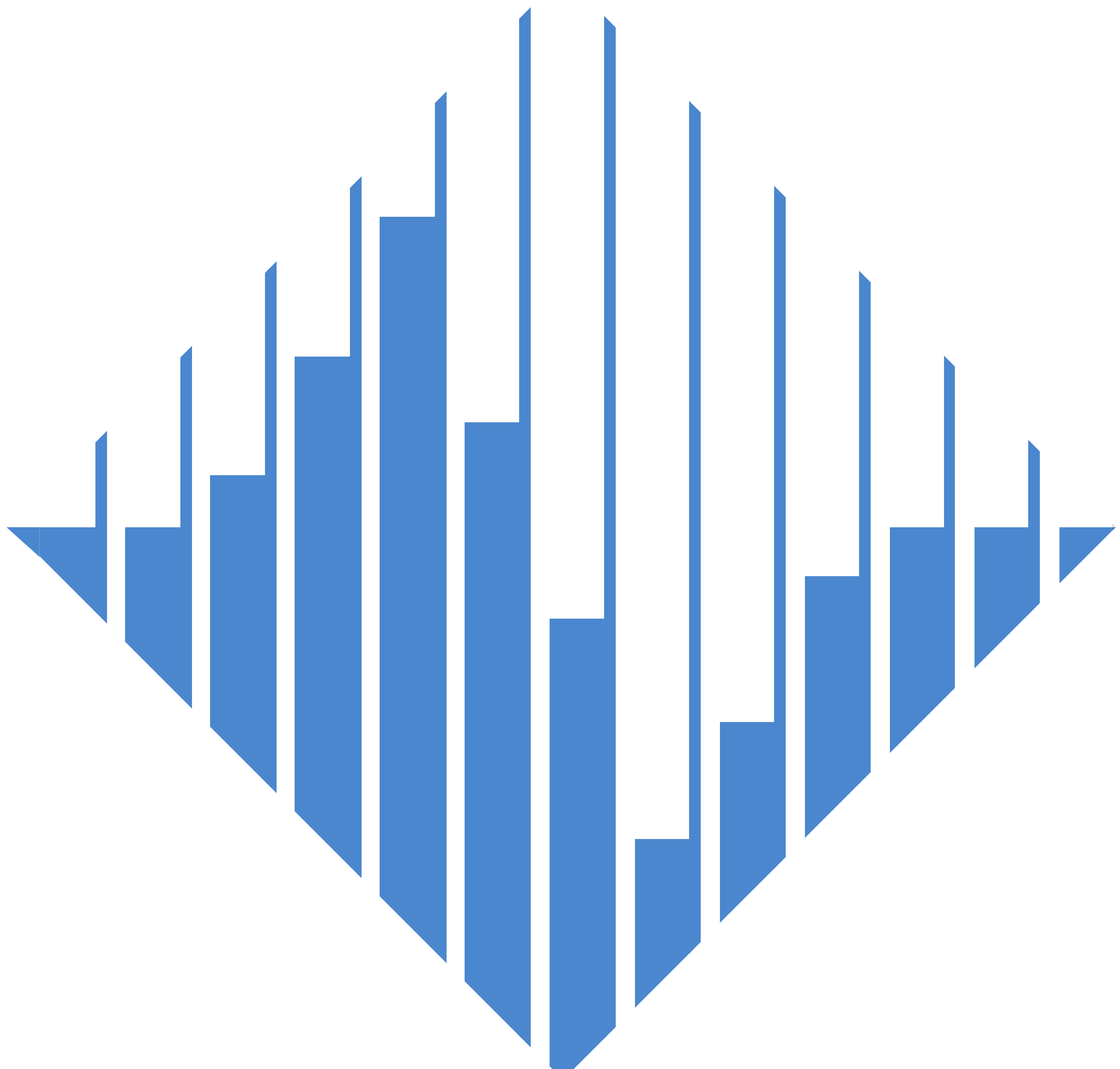
SHANNON & WILSON

Conclusions

- Local fines-content based evaluation of susceptibility
- General criteria of ≈40% fines with consideration for continuity
- Engineering evaluations include sensitivity studies

Thank you

SHANNON & WILSON



Liquefaction Susceptibility of Grays Harbor Silts

Matthew Gibson, PhD, PE
Principal/Owner, Clarity Engineering LLC

September 8, 2022

Clarity Engineering LLC

Acknowledgements

Project Owner: Washington Department of Transportation

Subsurface Explorations:

Landau Associates

Shannon & Wilson, Inc. (S&W)

CDSS Testing: MEG

Original 2010 S&W Evaluation: Matt Gibson, Bob Mitchell

Clarity Engineering LLC

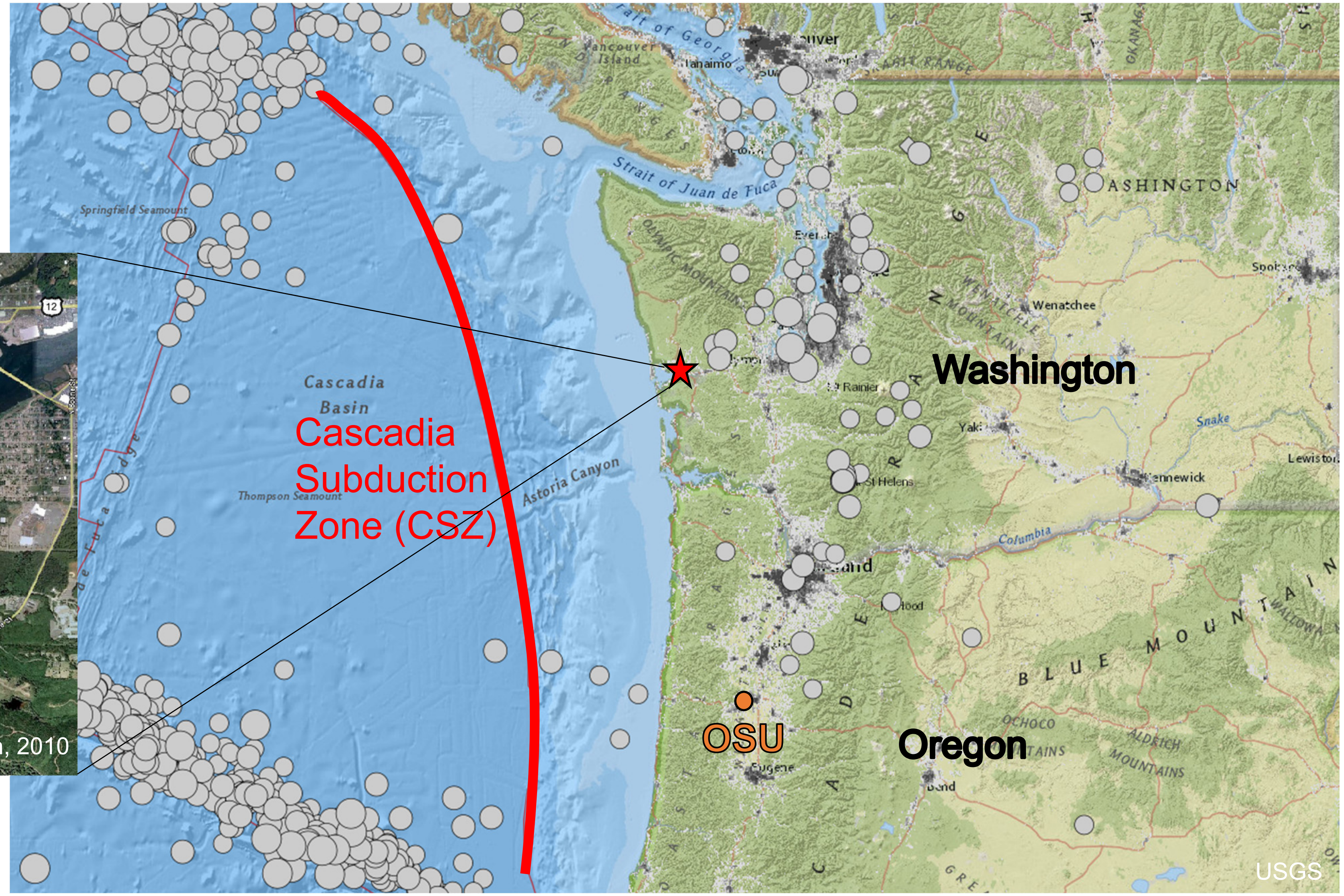
SR 520 Casting Basin: Grays Harbor, WA

Design Year: 2009 - 2010

AASHTO, 975 year return period

M8.3 CSZ

Ground Surface PGA ~ 0.3 g



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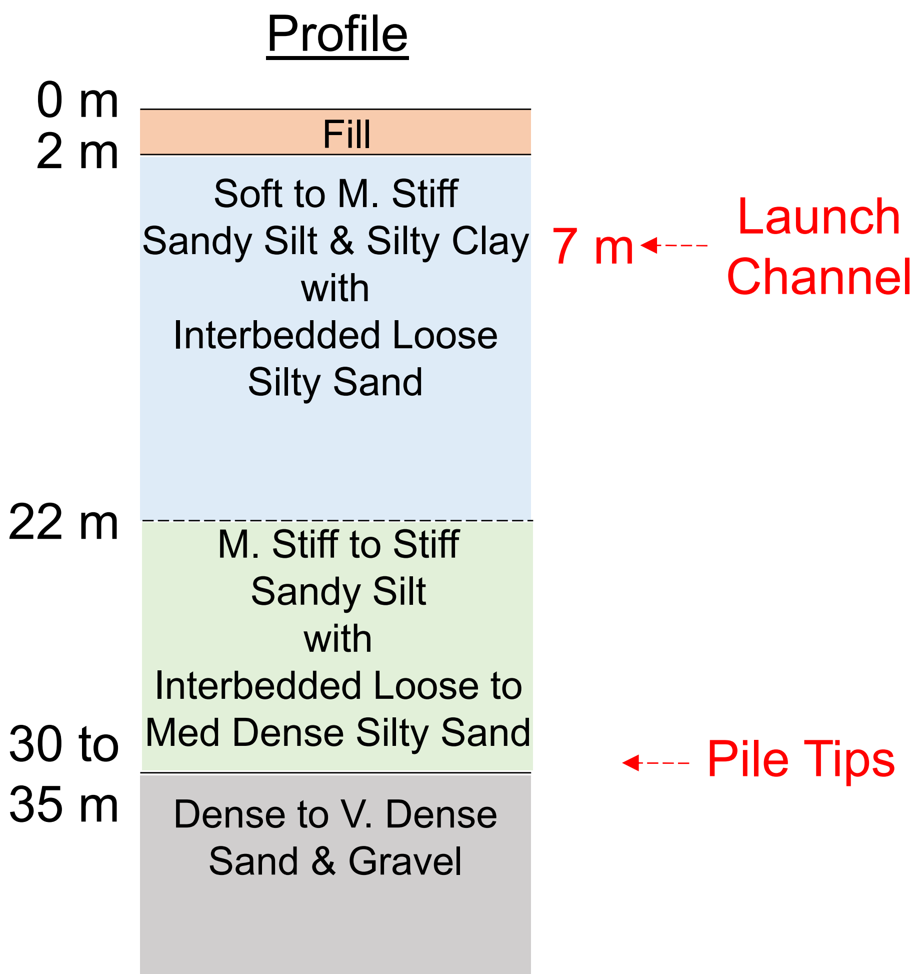
SR 520 Casting Basin Site



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Approach to Silt Liquefaction Susceptibility

- Identify Sand-like vs Clay-like with CPT (SBT)
- Further evaluate silt susceptibility & consequences with physical samples
  - USCS Classification
  - Atterberg Testing
  - CDSS Testing
  - Post-Cyclic Residual Strength
  - Post-Cyclic Consolidation
- Estimate cyclic soil behavior based on CDSS tests

Clarity Engineering LLC

Subsurface Exploration Map

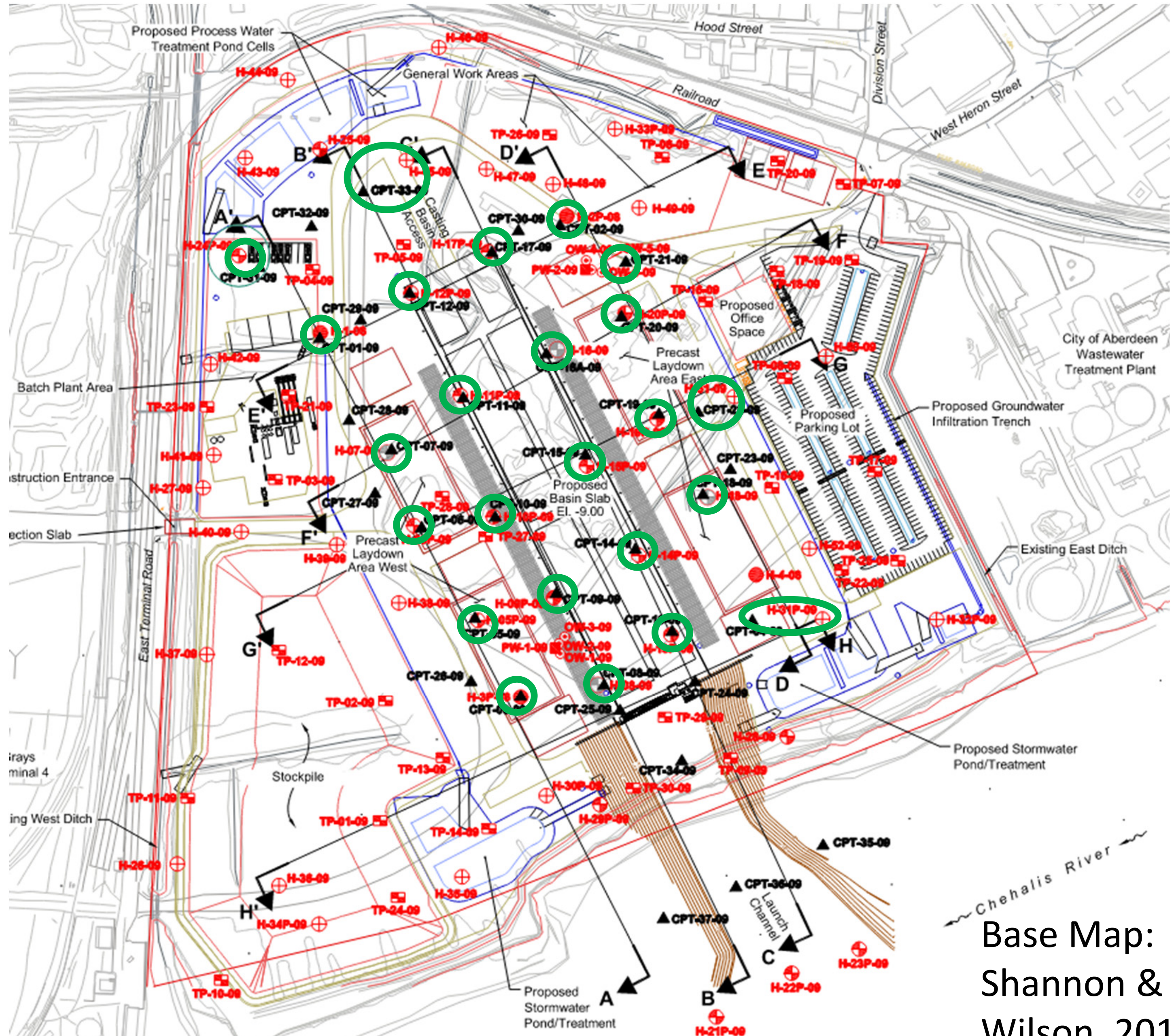
Explorations

- 32 Borings, 26 CPTs
- 27 Pairings
- Vs testing
- Vane Shear
- Pressure Meter

Laboratory

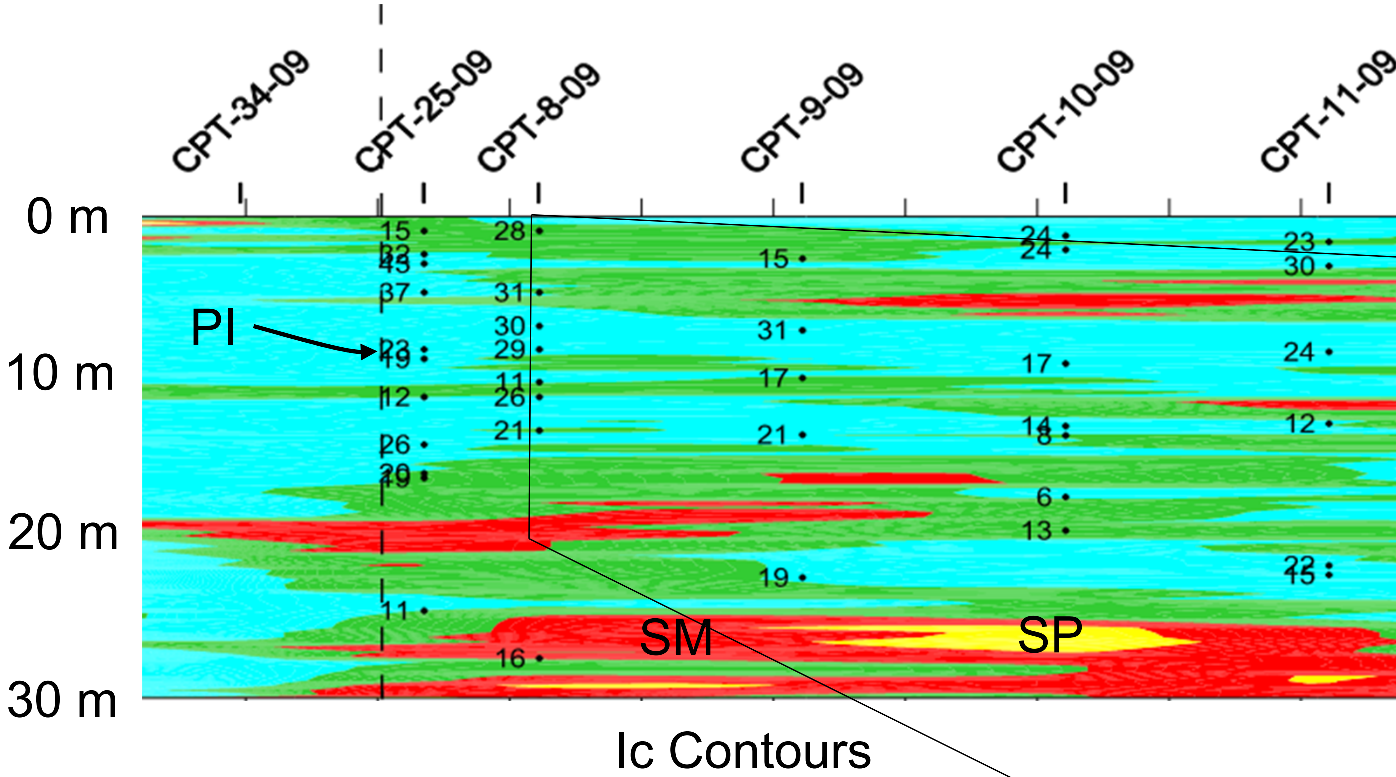
- CDSS
- Atterberg
- Grainsize
- Triaxial Tests
- 1D Consolidation

Clarity Engineering LLC

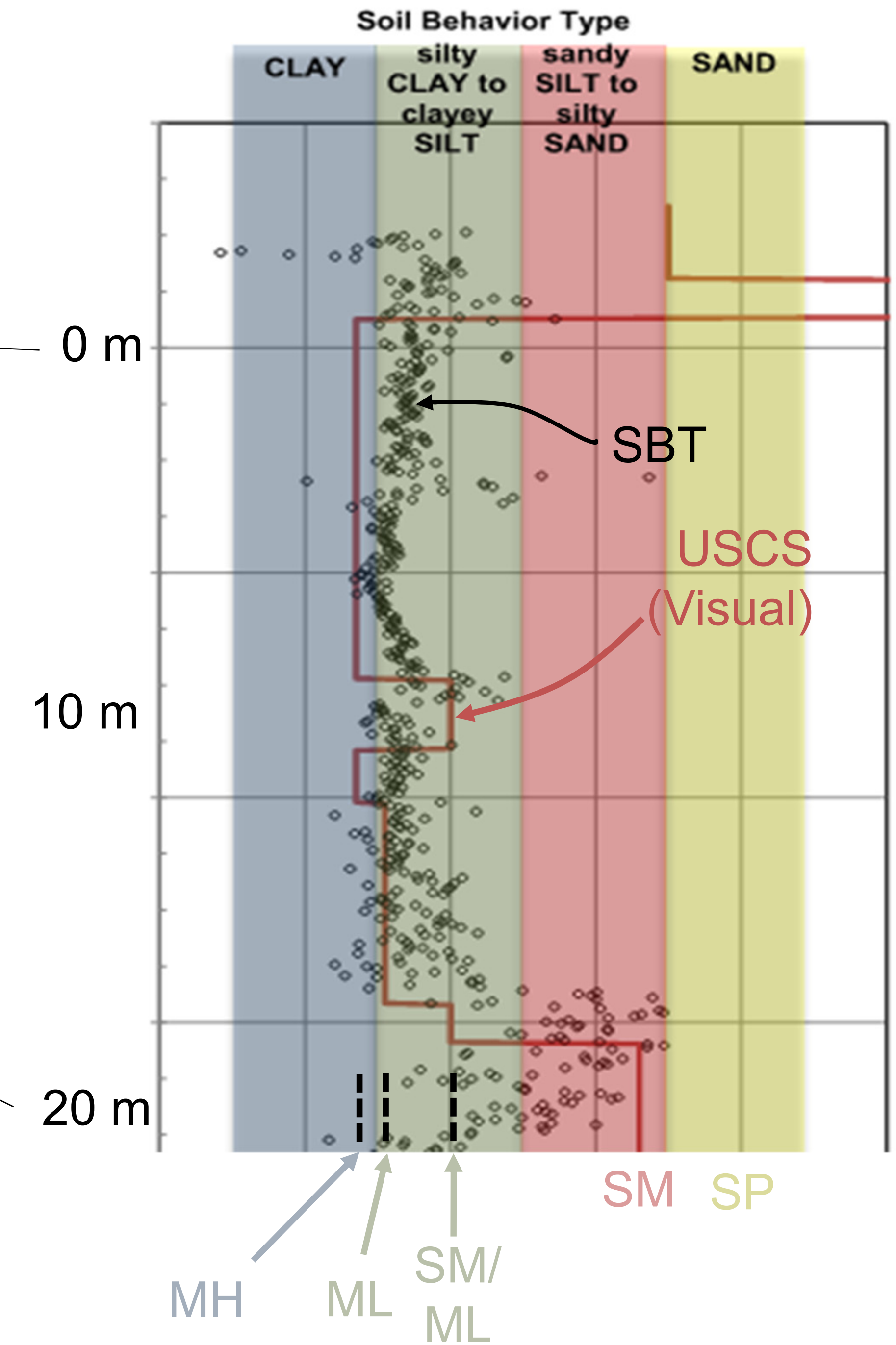


Base Map: Shannon & Wilson, 2010

Subsurface Characterization



CPT vs Boring



Upper Silt (0 to 17m) Properties

- OCR: 1 to 3, median~1.5
- Su: 25 to 50 kPa
- PI: 3 to 50, some values up to 93
- WC/LL ~ 1
- Blowcount = 0 to 5

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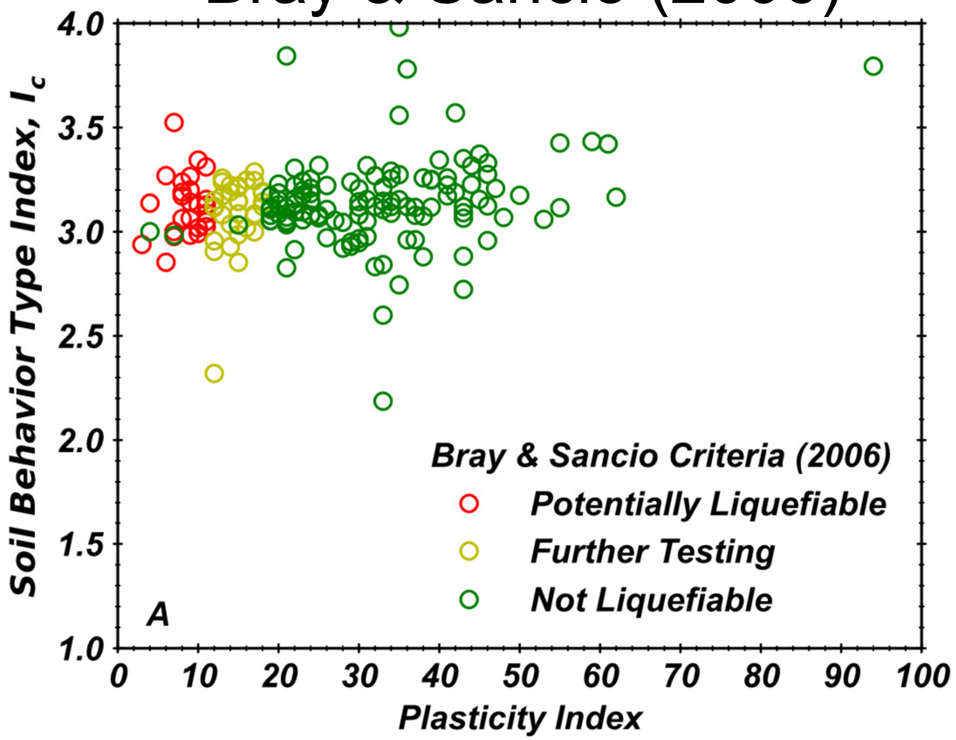
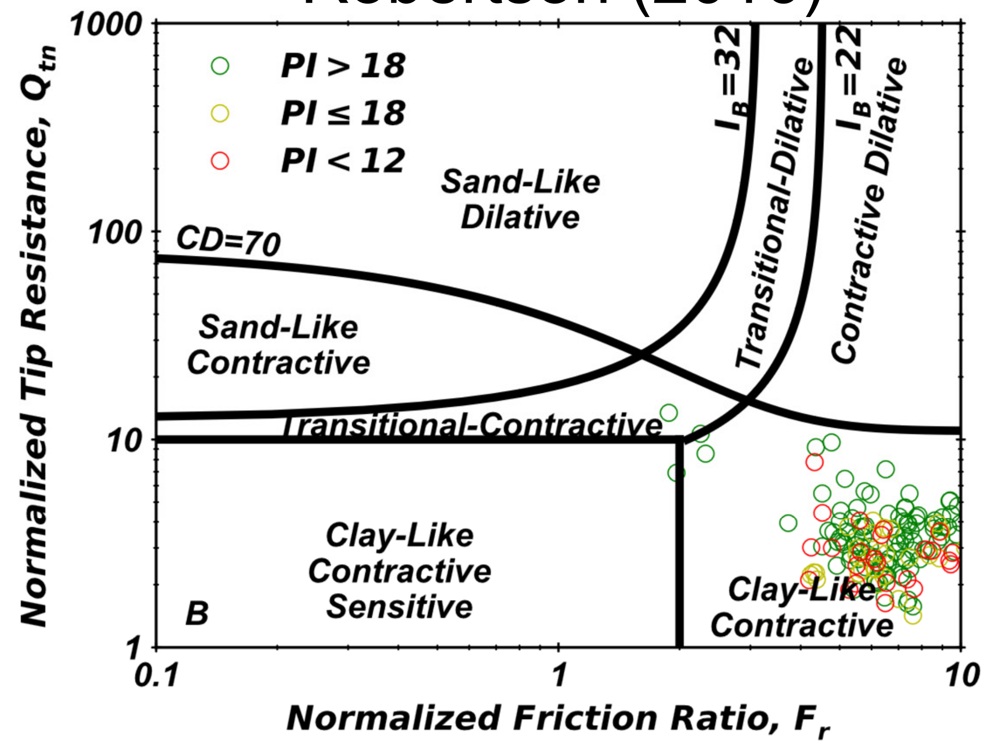
Screening with Susceptibility Criteria

Boulanger & Idriss (2006): Most samples exhibit clay-like behavior

Bray & Sancio (2006)



Robertson (2016)



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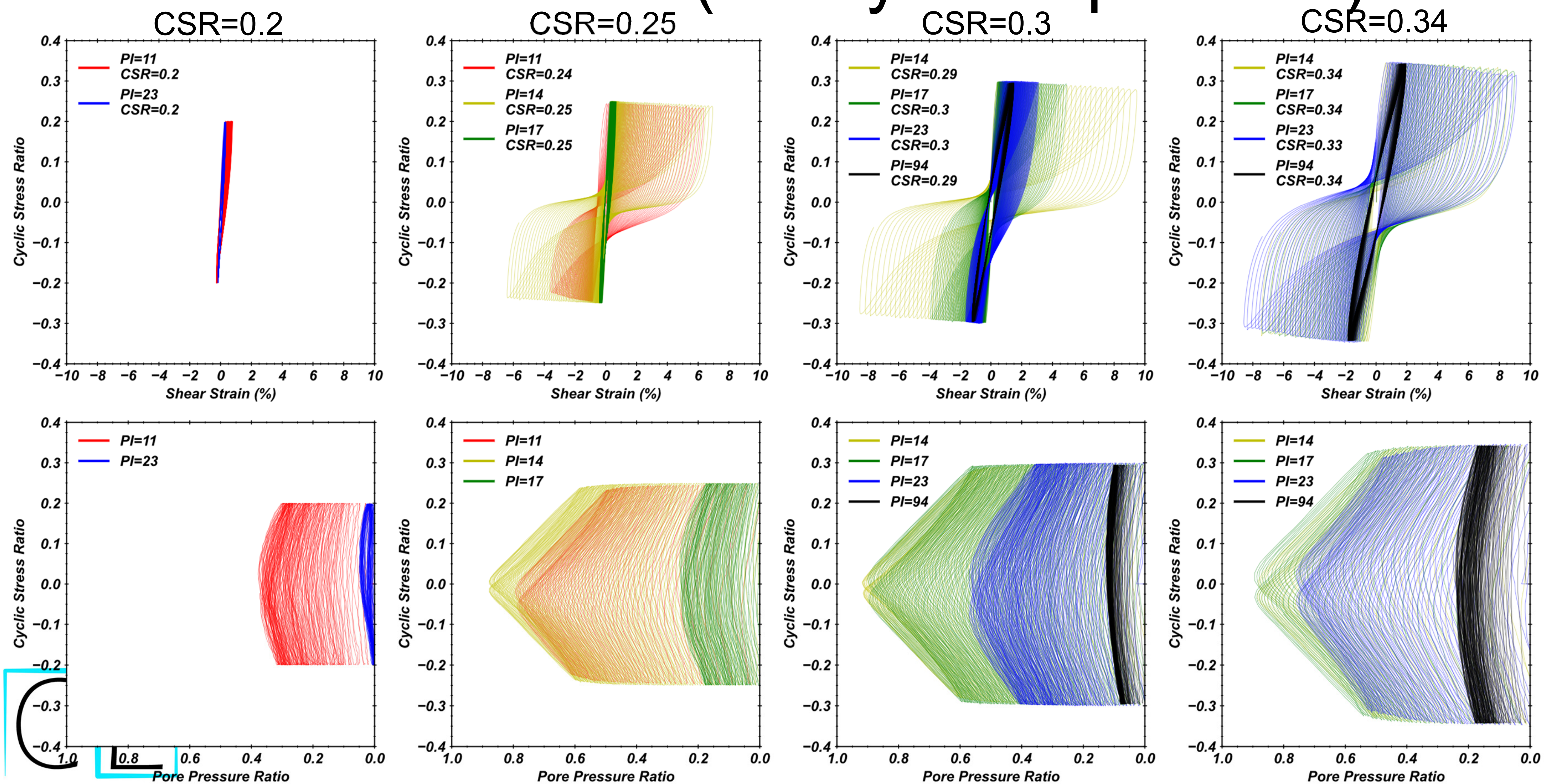
CDSS Test Results (All Cycles up to 100)



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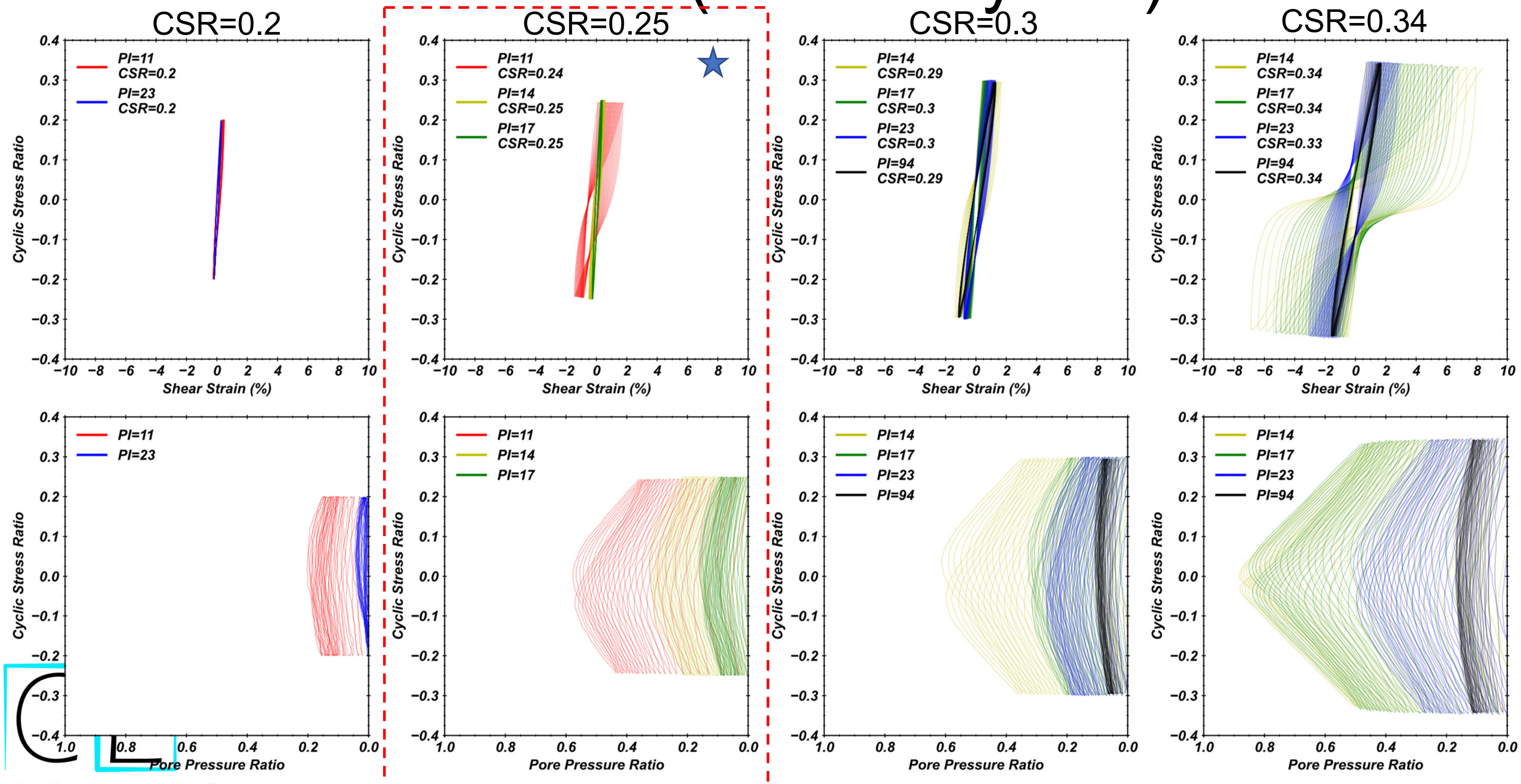
CDSS Test Results (0 to 23 cycles)



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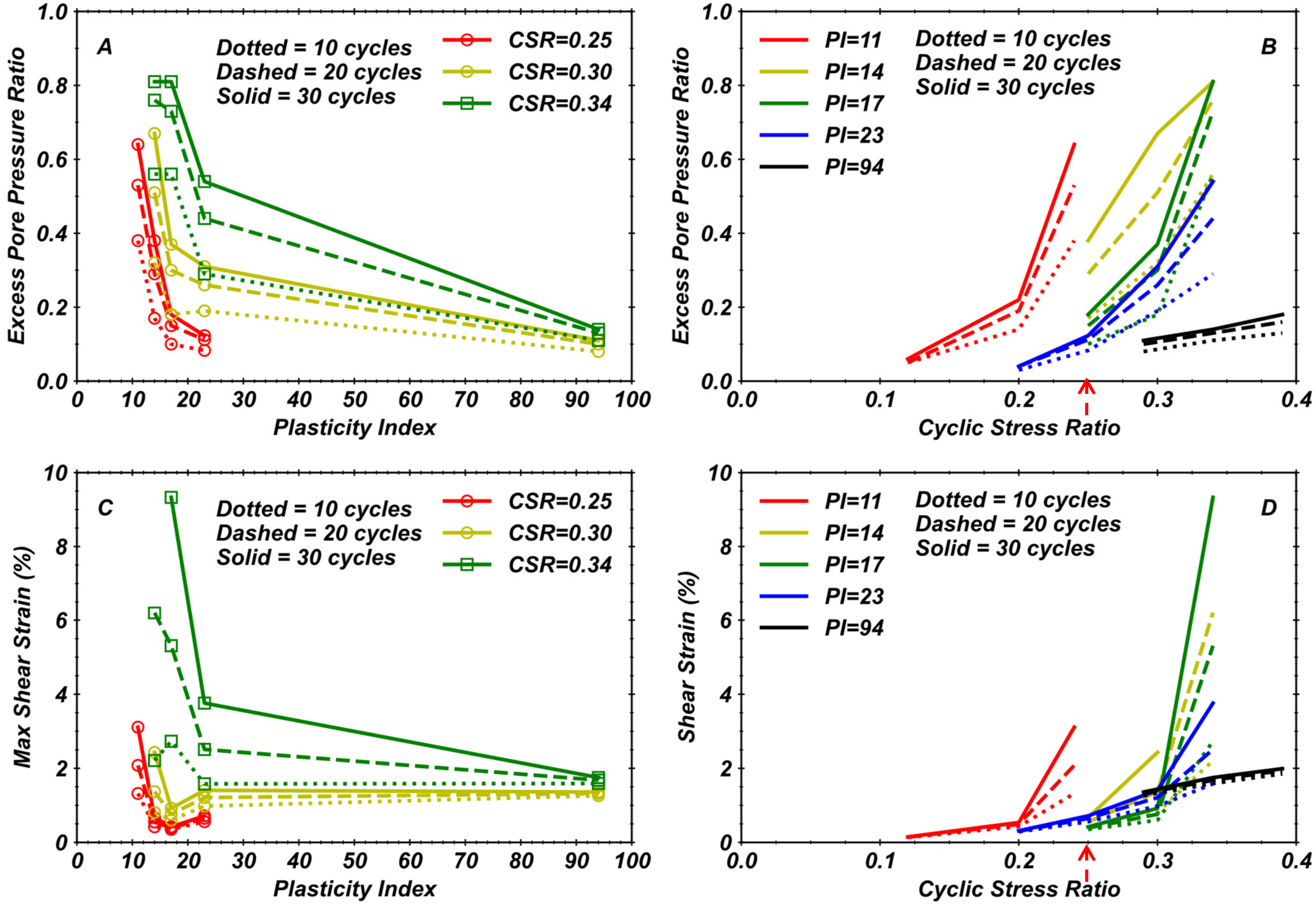
CDSS Test Results



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Conclusions

- CPT (SBT via Ic) did not distinguish well MH, ML or borderline SM/ML.
- Borings and samples were necessary for proper engineering material characterization.
- Combining simplified methods can identify potentially susceptible soils to liquefaction or cyclic mobility.
- A robust cyclic test program showed range of potential soil behavior so performance can be assessed, and analyses set.
- Severity of cyclic silt behavior (strain and pore pressure) is a function of PI, Cycles, and CSR.
- This program was expensive. Small to medium projects generally will not pay for it.

Clarity Engineering LLC

Suggestions to Improve Standard of Practice

- Do not use the term “clay-like” for silts, many think no problems in the context of “liquefaction”.
- Reserve the term liquefaction for sands. For silts, perhaps use “silt-like”.
- Susceptibility for silts must go beyond Yes/No.
- Develop relationships for silts to estimate shear strains and pore pressure given certain EQ loading (Cycles & CSR), PI, etc...
- Amend codes to check for:
    - Sand liquefaction
    - Silt-like behavior
    - Clay-like behavior

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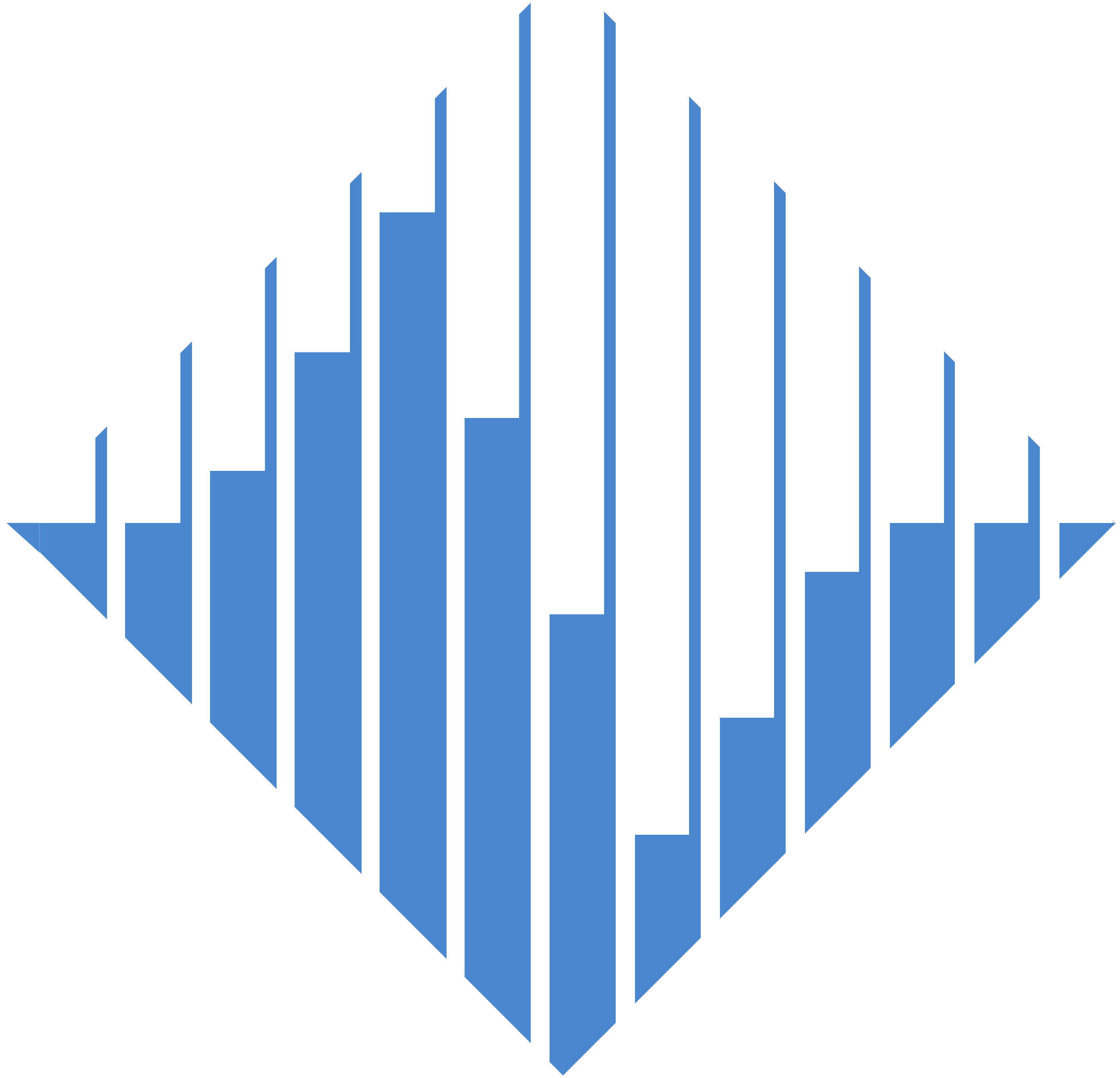


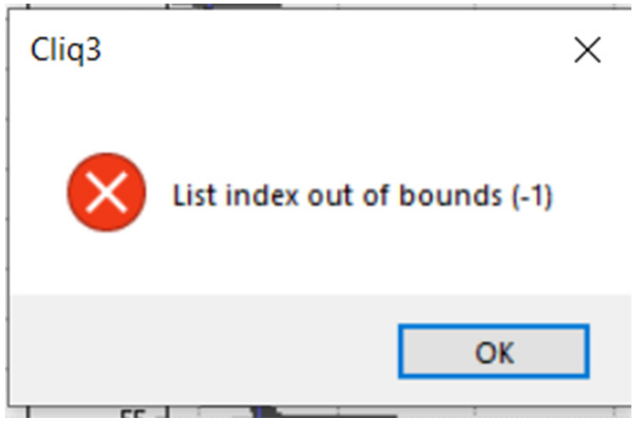
Impacts of Analyzing Deep Sand and Transitional Soil Profiles with State of the Practice Methods

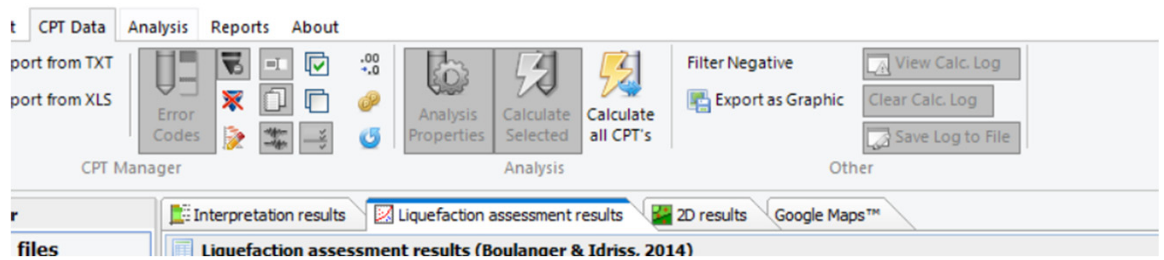
Brice Exley

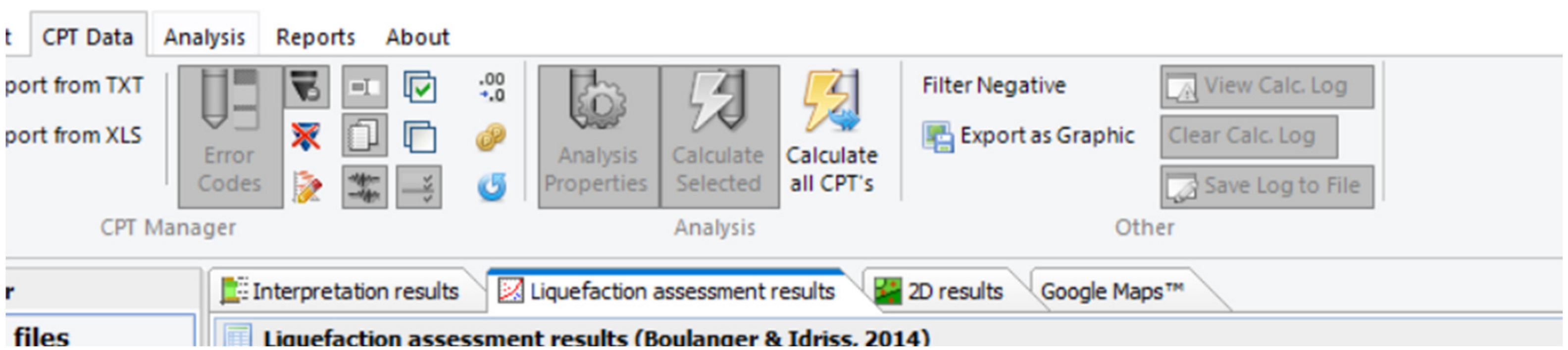
HALEY ALDRICH

Current State-of-Practice Methods

- Not the impacts or limitations I was expecting…



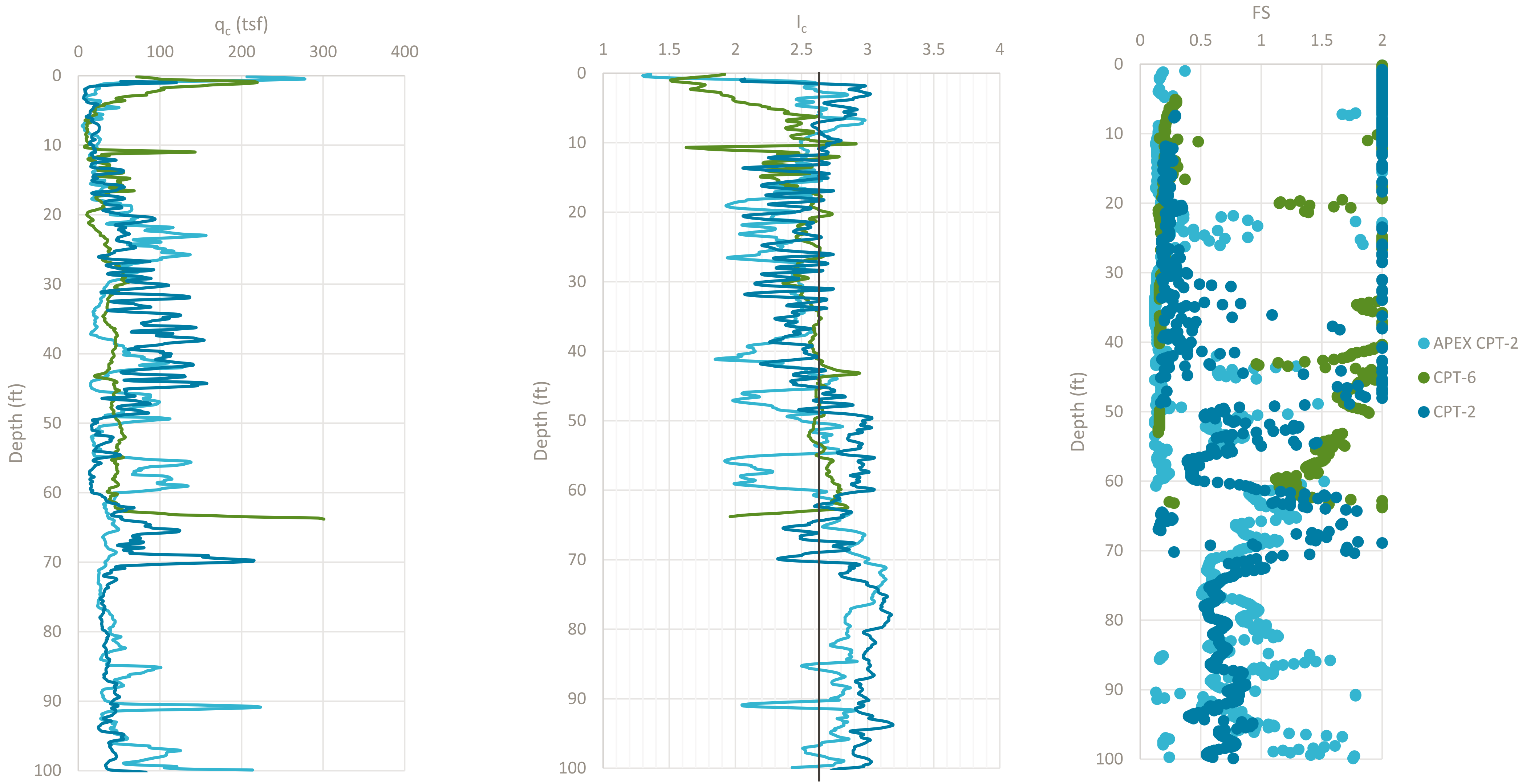




Current State-of-Practice Methods

- Primarily stress based simplified *in situ* methods for sands using SPT and CPT.
  - Select your variation of choice
- Clay like behavior consideration varies widely, but often a combination of Bray and Sancio for screening with Idriss and Boulanger to estimate CRR.
  - Need accurate undrained shear strengths
  - OCR estimates
  - Undrained shear strength ratios
  - What happens when CRR is exceeded?
- Screening by $I_c = 2.6$ for transition between sand-like and clay-like behavior.
- Residual Shear strengths of sands via residual shear strength curve of choice.
- Deterministic CRR curves with associated with approximately 16th percentile combined with 2,475-year event, despite structural design based on 2/3 of 2,475-year event for IBC (layers of factors of safety…)
- Assume water table means fully saturated

Site A: B&I 2014, Clay-Like Behavior Cliq



Site A: B&I 2014, Default Clay Site A: B&I 2014

- 9 of 22 samples from 5 to 55 feet below ground surface susceptible or moderately susceptible to liquefaction using Bray and Sancio (2006).
- Ic typically 2.3 to 2.6
- Residual shear strength ratios of ~0.1 for transitional soils as they're treated as "sand-like" typically applied nearly continuously to depth of approximately 100 feet, resulting in flow failure and lateral spreading indicated
- 5 to 10 inches of free field settlement.
- IBC classifies piles through "fluid soils" as columns. Unbraced for more than 60 feet?

1810.1.3 Deep foundation elements classified as columns.

Deep foundation elements standing unbraced in air, water or fluid soils shall be classified as columns and designed as such in accordance with the provisions of this code from their top down to the point where adequate lateral support is provided in accordance with Section 1810.2.1.

1810.2.1 Lateral support.

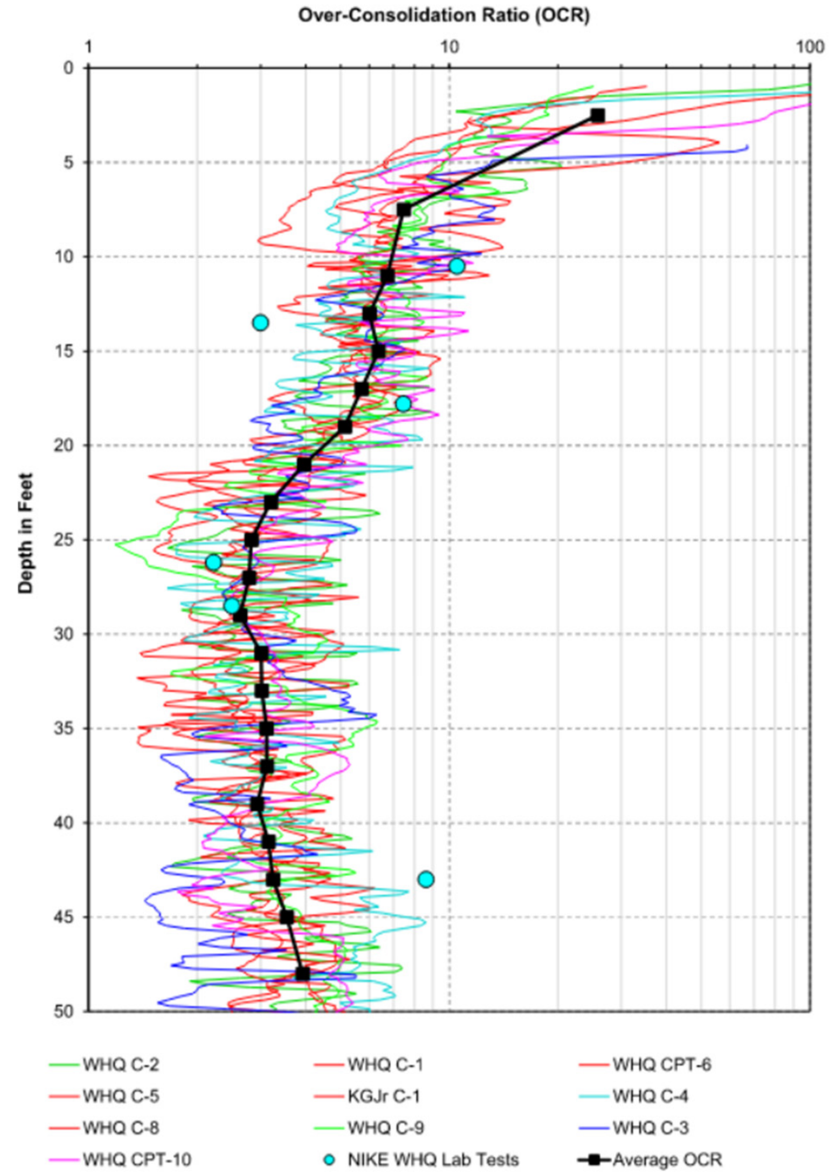
Any soil other than fluid soil shall be deemed to afford sufficient lateral support to prevent buckling of deep foundation elements and to permit the design of the elements in accordance with accepted engineering practice and the applicable provisions of this code.

Where deep foundation elements stand unbraced in air, water or fluid soils, it shall be permitted to consider them laterally supported at a point 5 feet (1524 mm) into stiff soil or 10 feet (3048 mm) into soft soil unless otherwise *approved* by the *building official* on the basis of a geotechnical investigation by a *registered design professional*.

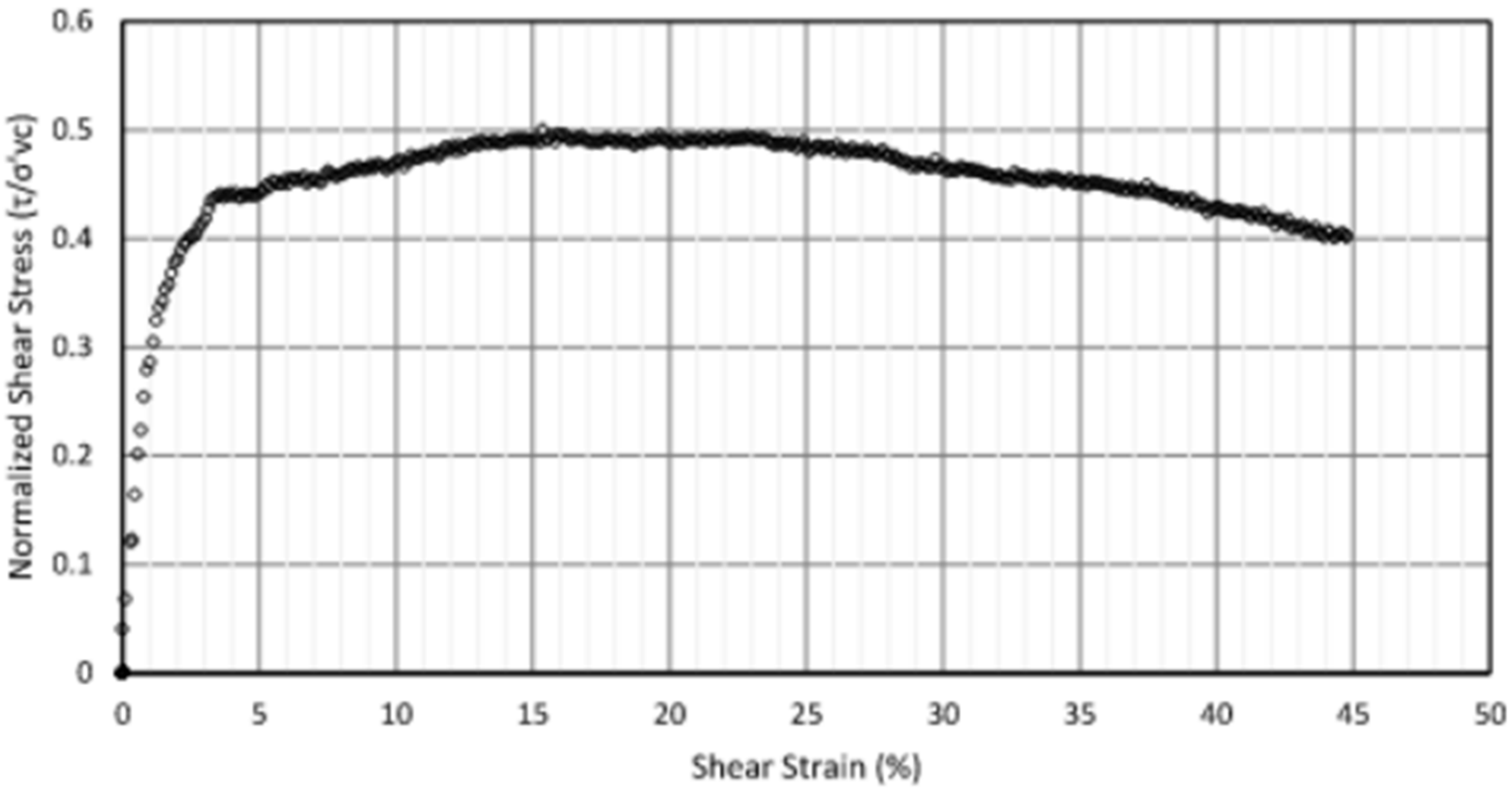
HALEY ALDRICH

Site A: OCR Profiling

- Agaiby & Mayne I_c index dependent m’ performed poorly compared to consolidation tests.

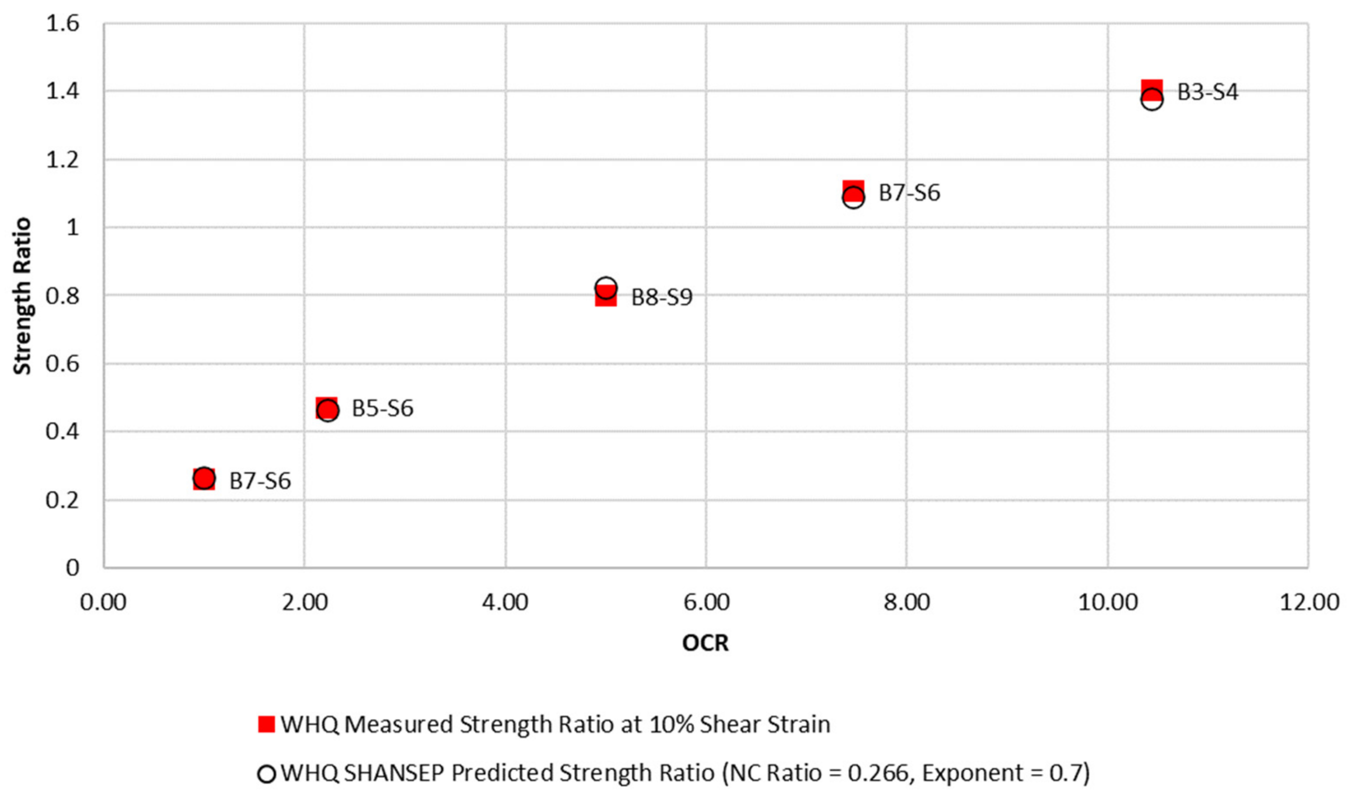


Site A: DSS Testing Sample B5-S6

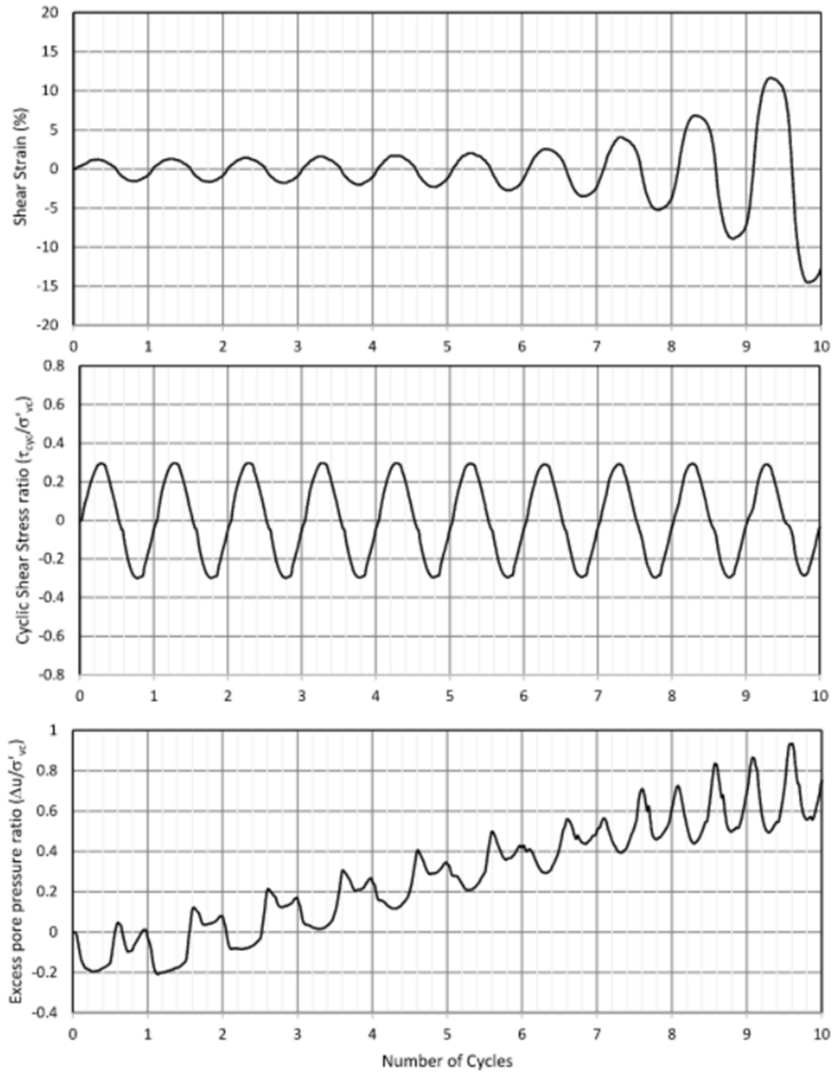


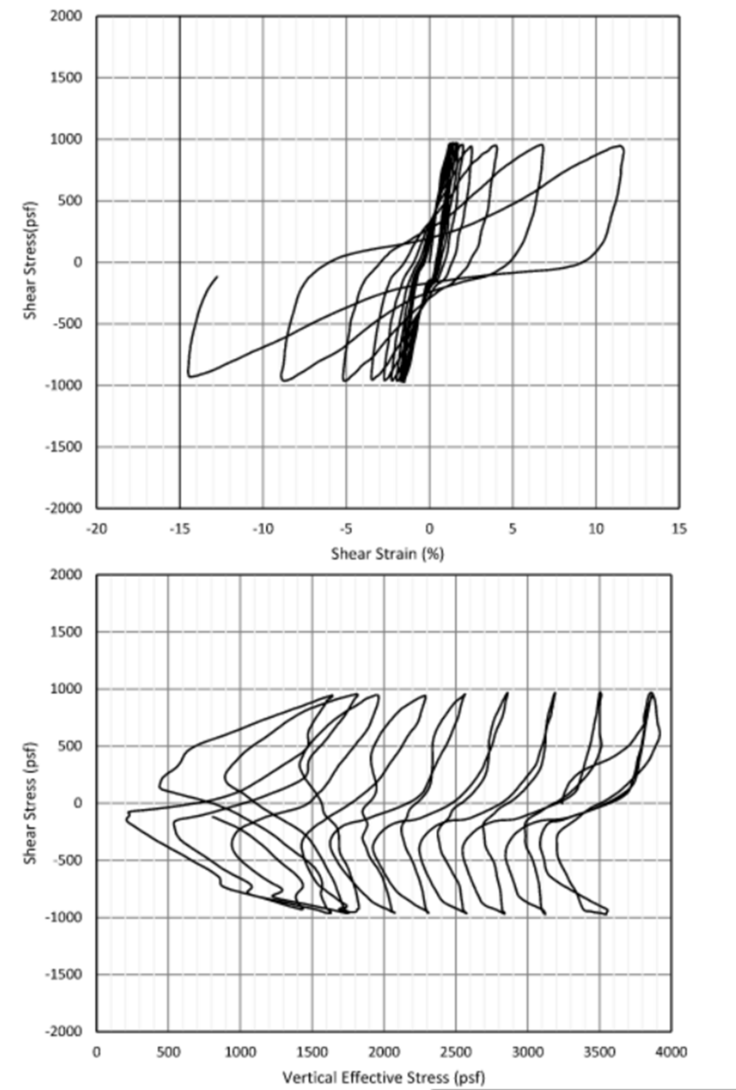
Site A: DSS SHANSEP Based Strength Normalization

- DSS SHANSEP Strength Normalization

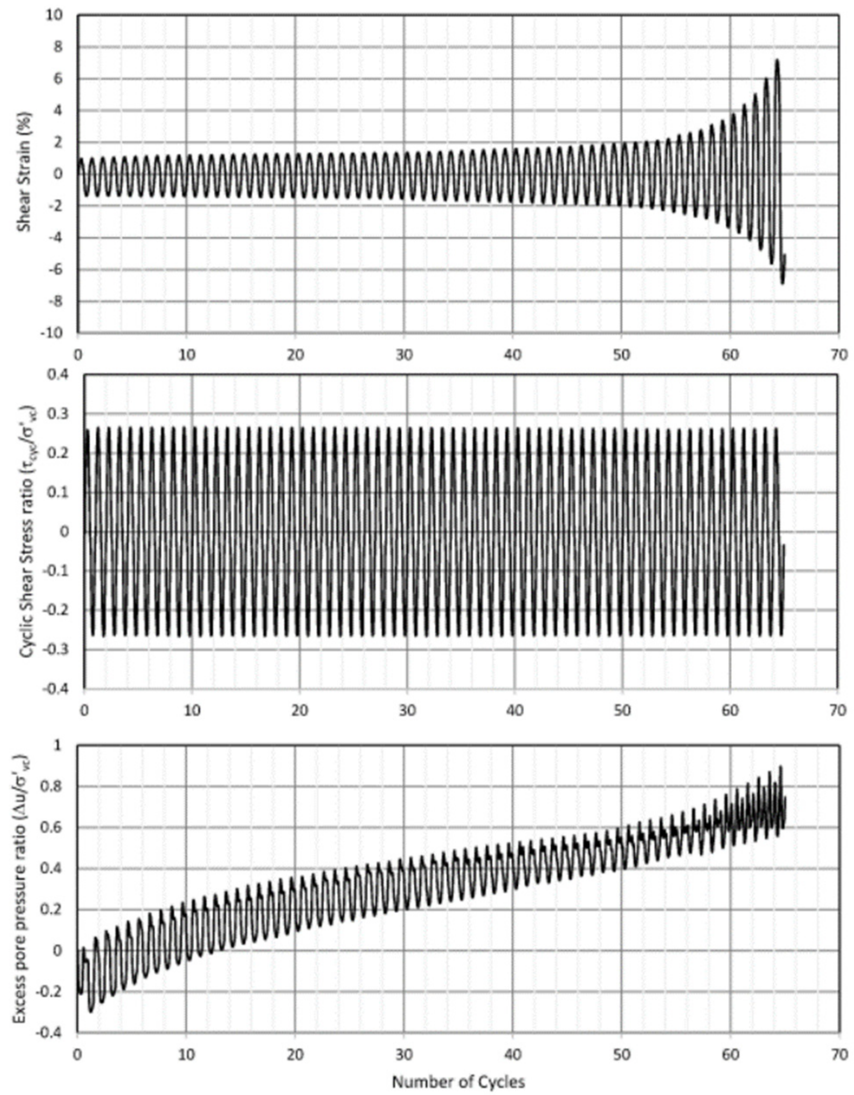


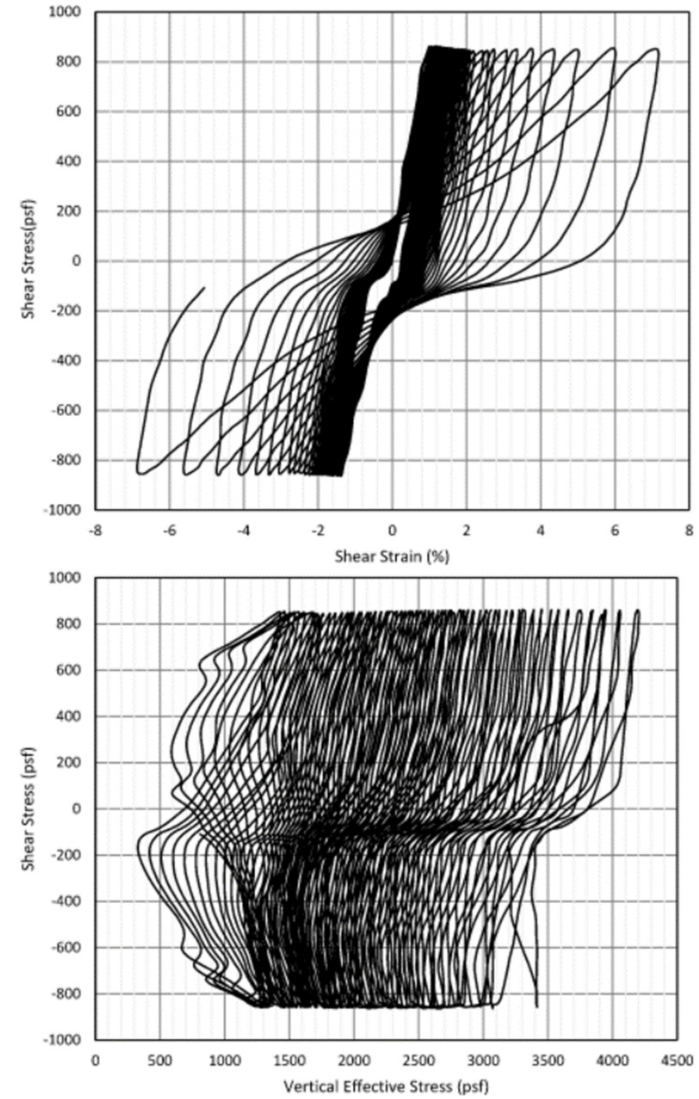
Site A: CDSS Results B5-S6



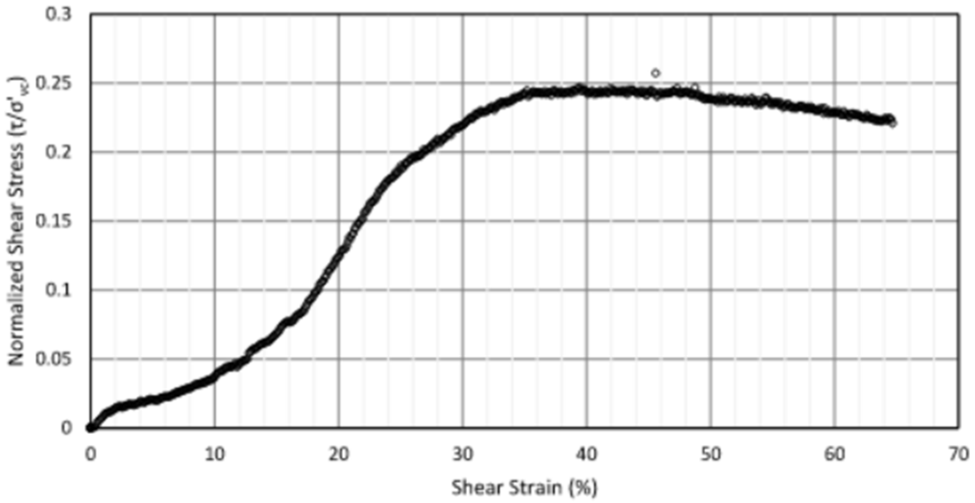


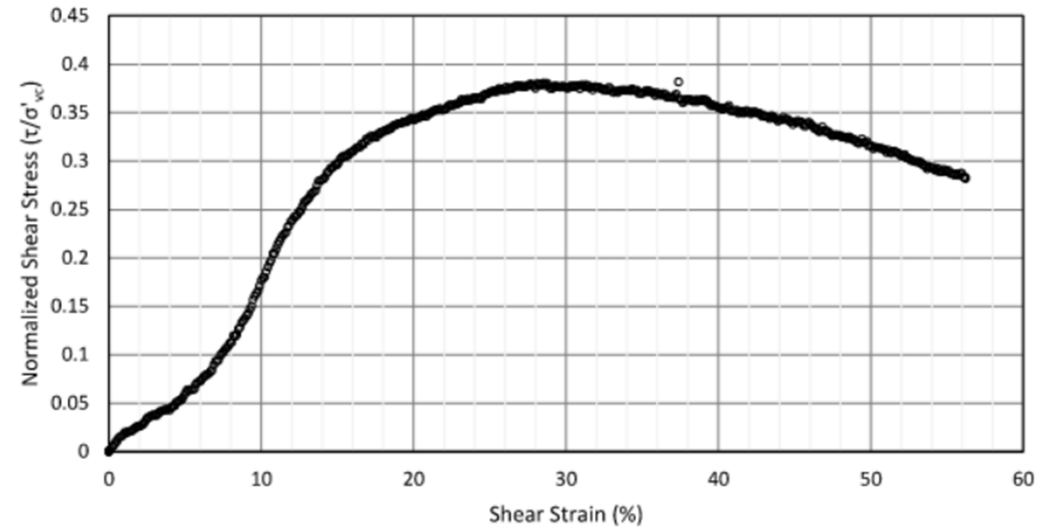
Site A: CDSS Results B5-S6





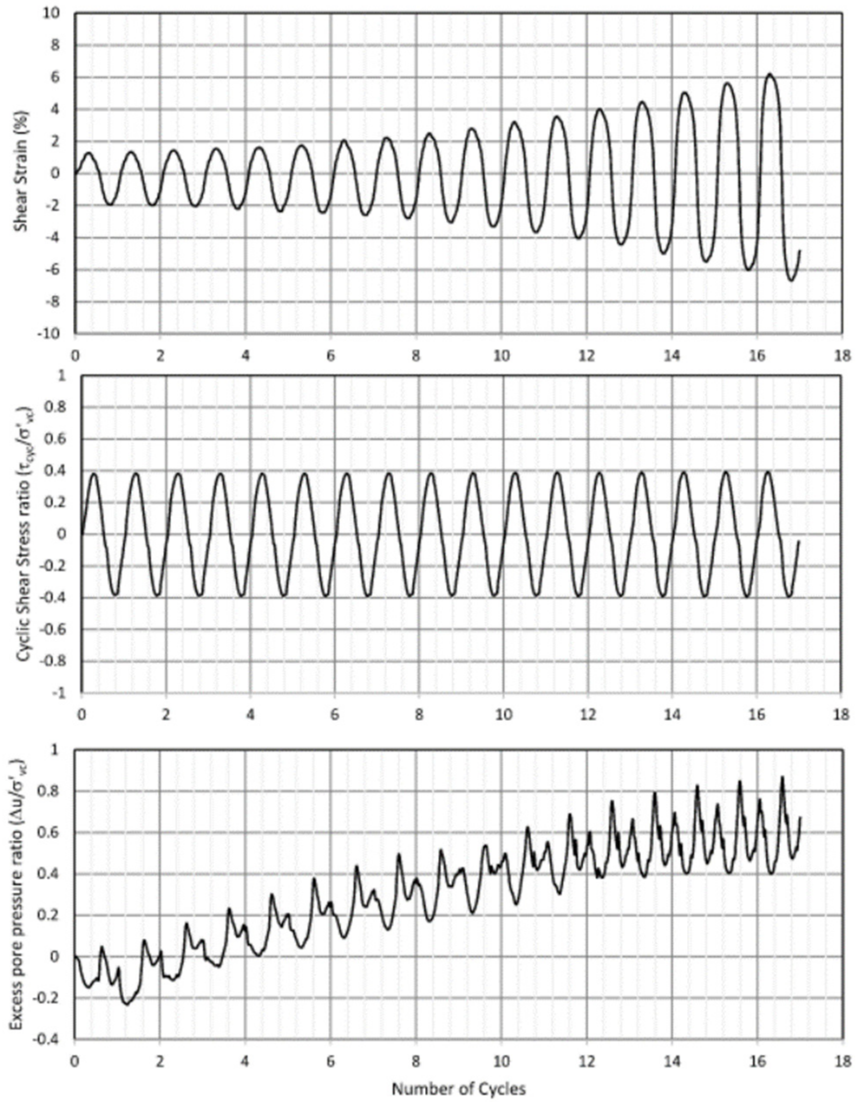
Site A: CDSS Post-Cyclic Shear B5-S6

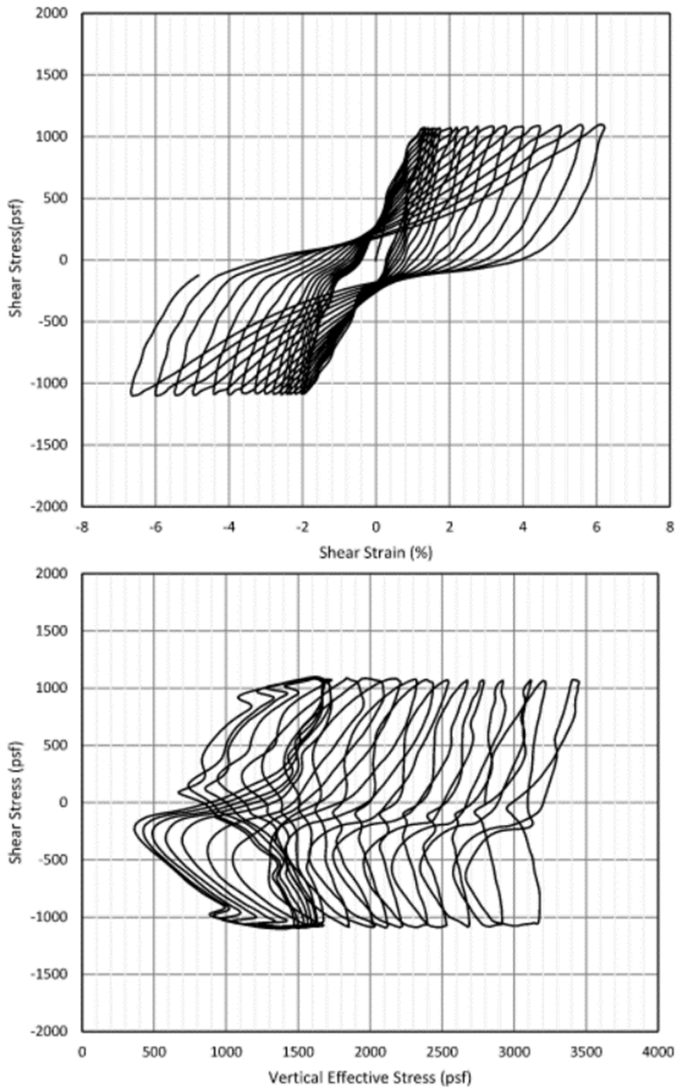




Site A: CDSS Results B8-S9

- Liquefaction?
- Cyclic Softening?

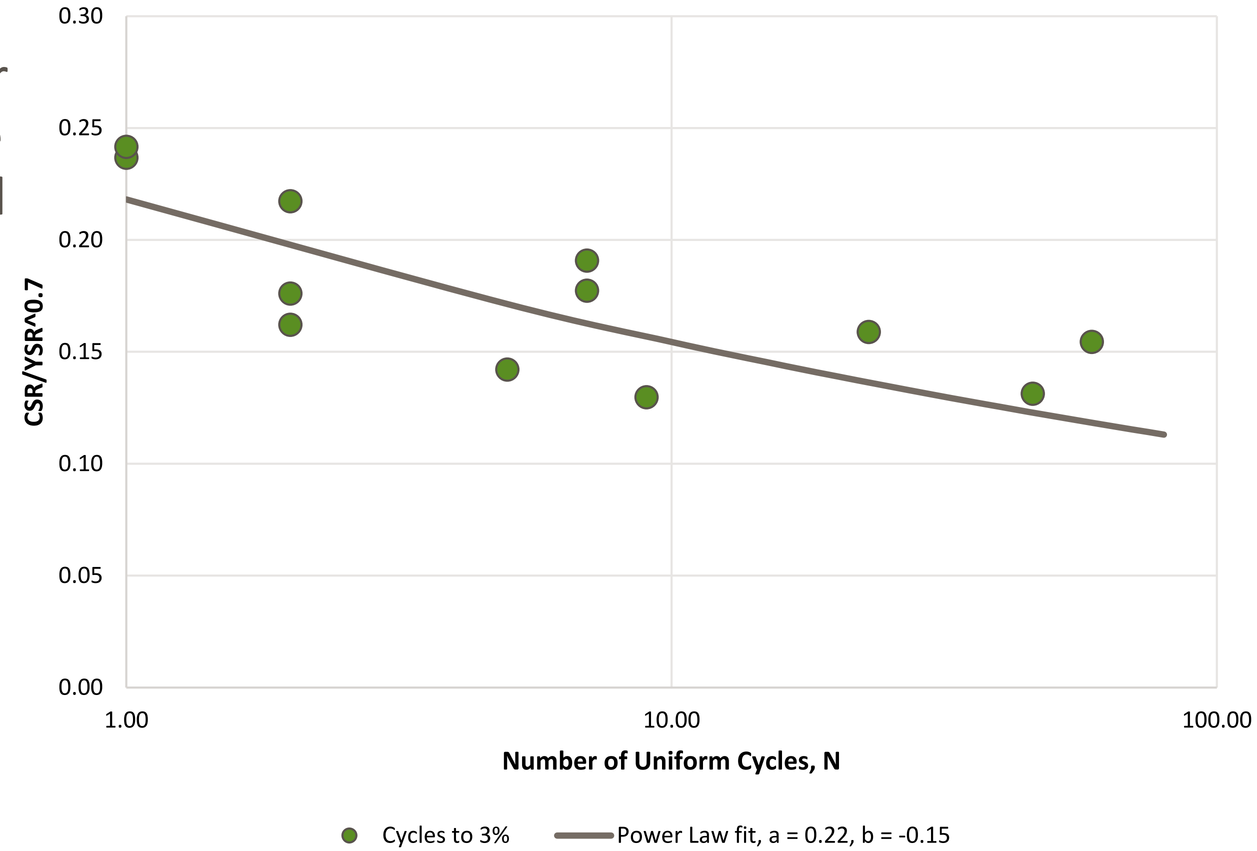




HALEY ALDRICH

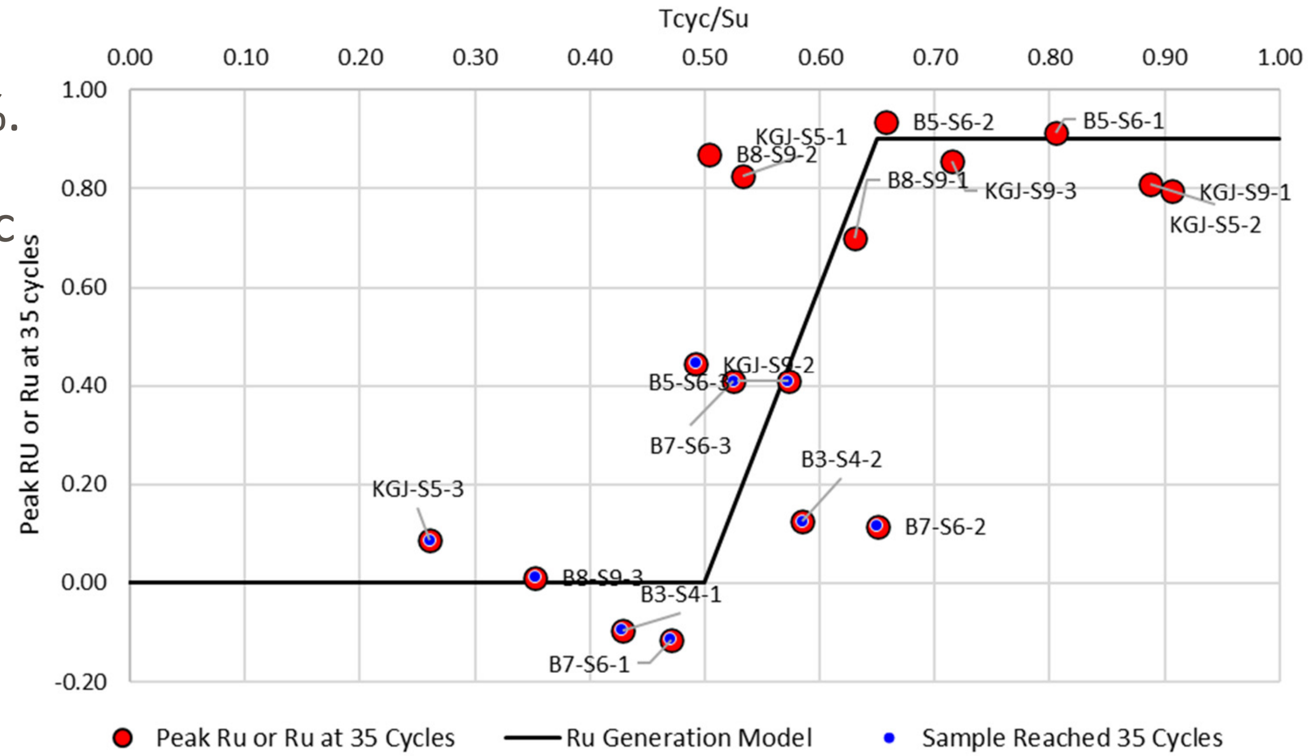
Site A: Cyclic Shear Strength Accumulation

- Stress history normalized power law
- CSR estimate below 80% of undrained shear strength ratio typically assumed for clay-like material at approximately 50% of undrained shear strength ratio.



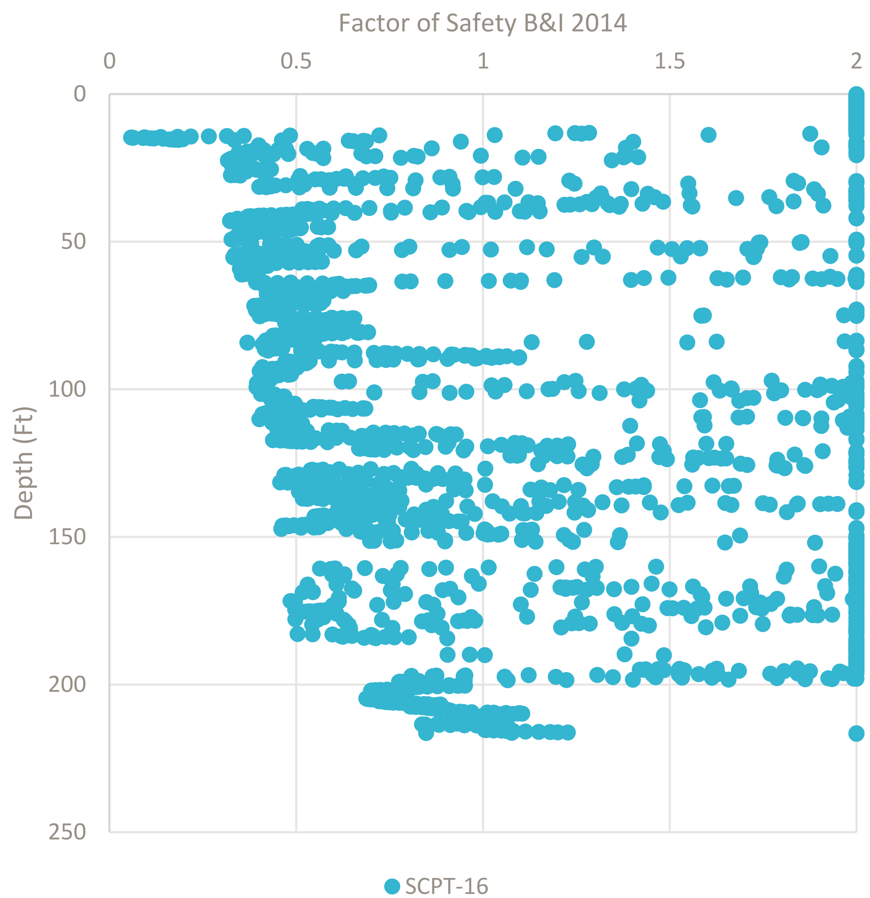
Site A: Post Cyclic Strength and Ru Generation

- When CRR exceeded and Ru was greater than about 0.80, the post cyclic shear strength was reduced by approximately 50%.
- For most OCRs, significantly more post-cyclic strength than predicted using sand curves.



Site B: 250ft+ Sand Profile, simplified methods

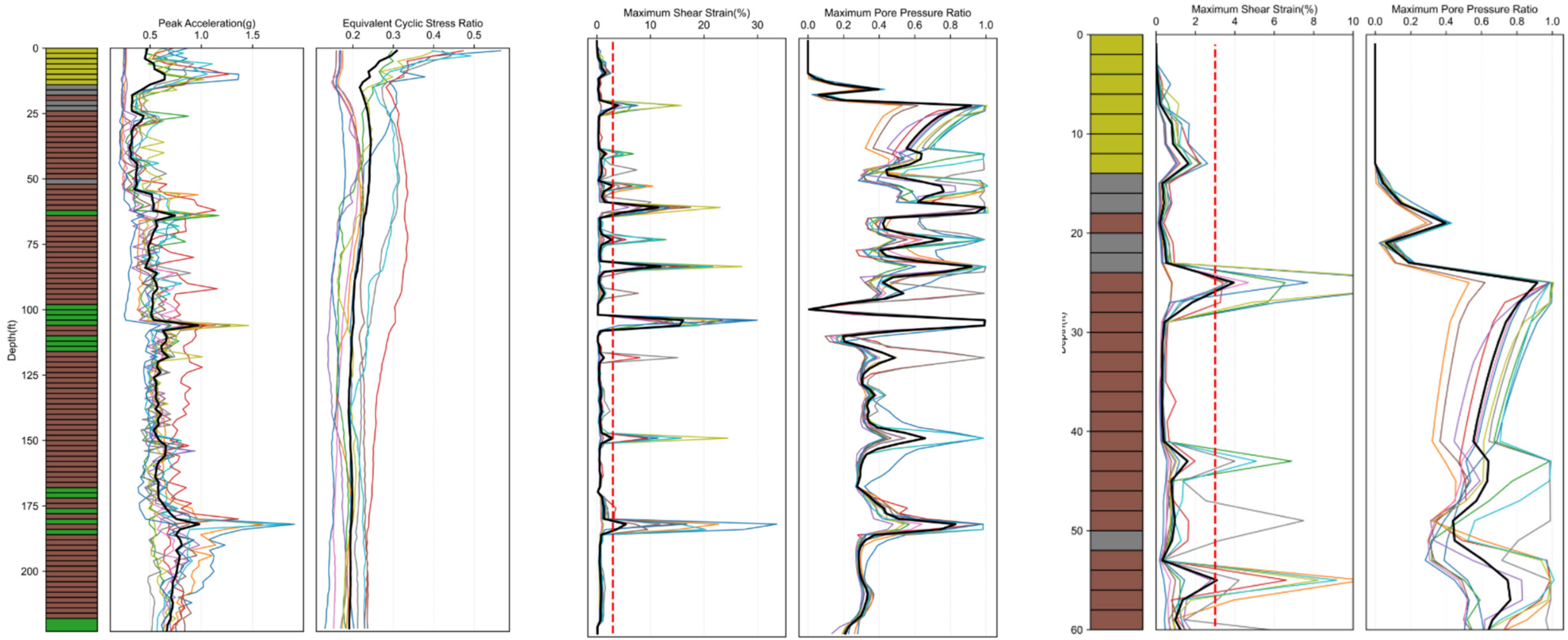
- Simplified methods predict mostly continuous liquefaction to more than 150 feet deep even with site response analysis derived PGA, which is a reduction from code derived PGA.
- Significant impacts on foundation recommendations and project feasibility.



HALEY ALDRICH

Site B: 250ft+ Sand Profile, Advanced SRA

- Intermittent liquefaction with PM4 based site response analysis.



HALEY ALDRICH

Site C: Partial Saturation

- State of practice assumes once a water table is encountered, full saturation occurs.
  - Pore pressure dissipation test derived water table 2 to 3.5 feet deep. Generally consistent with adjacent lake level.
  - Full Saturation more than 25 feet deep based on compression wave velocity tests.
- Presence of reliably crust may significantly impact engineering recommendations

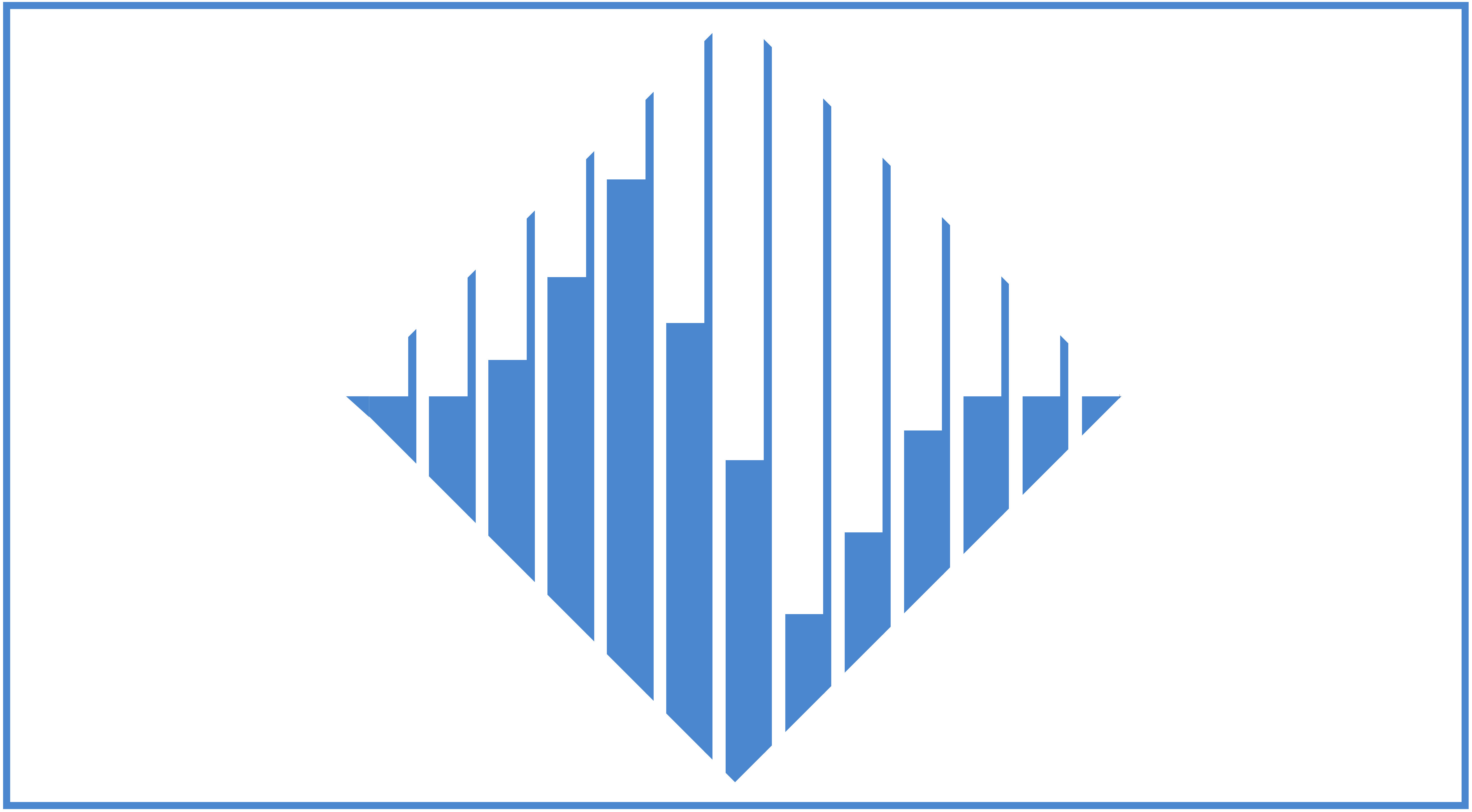
SCPTu COMPRESSION WAVE VELOCITY TEST RESULTS - Vp

Tip Depth (ft)	Geophone Depth (ft)	Ray Path (ft)	Ray Path Difference (ft)	Travel Time Interval (ms)	Interval Velocity (ft/s)
3.61	2.95	6.16			
7.05	6.40	8.38	2.22	3.09	718
10.17	9.51	10.95	2.57	2.98	863
13.45	12.80	13.89	2.95	3.19	925
16.73	16.08	16.96	3.07	3.32	926
20.01	19.36	20.10	3.14	3.42	918
23.36	22.70	23.34	3.24	1.98	1634
26.58	25.92	26.48	3.14	0.94	3328
29.92	29.27	29.76	3.28	0.79	4177
33.20	32.55	32.99	3.23	0.66	4931
36.48	35.83	36.23	3.24	0.64	5057
43.04	42.39	42.73	6.50	1.27	5108
46.33	45.67	45.99	3.26	0.62	5241
49.48	48.82	49.12	3.13	0.58	5390

SCPTu COMPRESSION WAVE VELOCITY TEST RESULTS - Vp

Tip Depth (ft)	Geophone Depth (ft)	Ray Path (ft)	Ray Path Difference (ft)	Travel Time Interval (ms)	Interval Velocity (ft/s)
3.12	2.46	5.80			
6.56	5.91	7.90	2.10	2.31	909
9.84	9.19	10.58	2.68	2.20	1216
13.12	12.47	13.53	2.95	1.21	2431
16.40	15.75	16.60	3.07	1.32	2324
19.69	19.03	19.74	3.14	0.77	4070
22.97	22.31	22.92	3.18	0.77	4122
26.25	25.59	26.12	3.21	0.60	5332
29.53	28.87	29.34	3.22	0.61	5271
32.87	32.22	32.64	3.30	0.62	5308
36.09	35.43	35.82	3.18	0.60	5287
39.30	38.65	39.00	3.18	0.60	5297
42.59	41.93	42.26	3.25	0.56	5797
45.93	45.28	45.58	3.32	0.61	5437
49.15	48.49	48.77	3.19	0.56	5693

HALEY ALDRICH



PEER Workshop *on* Liquefaction Susceptibility

APPENDIX F

Session 2 Presentations

Shideh Dashti: *Incorporating the Spectrum of Soil Behaviors Directly into Systems Level Triggering and Consequence Models*

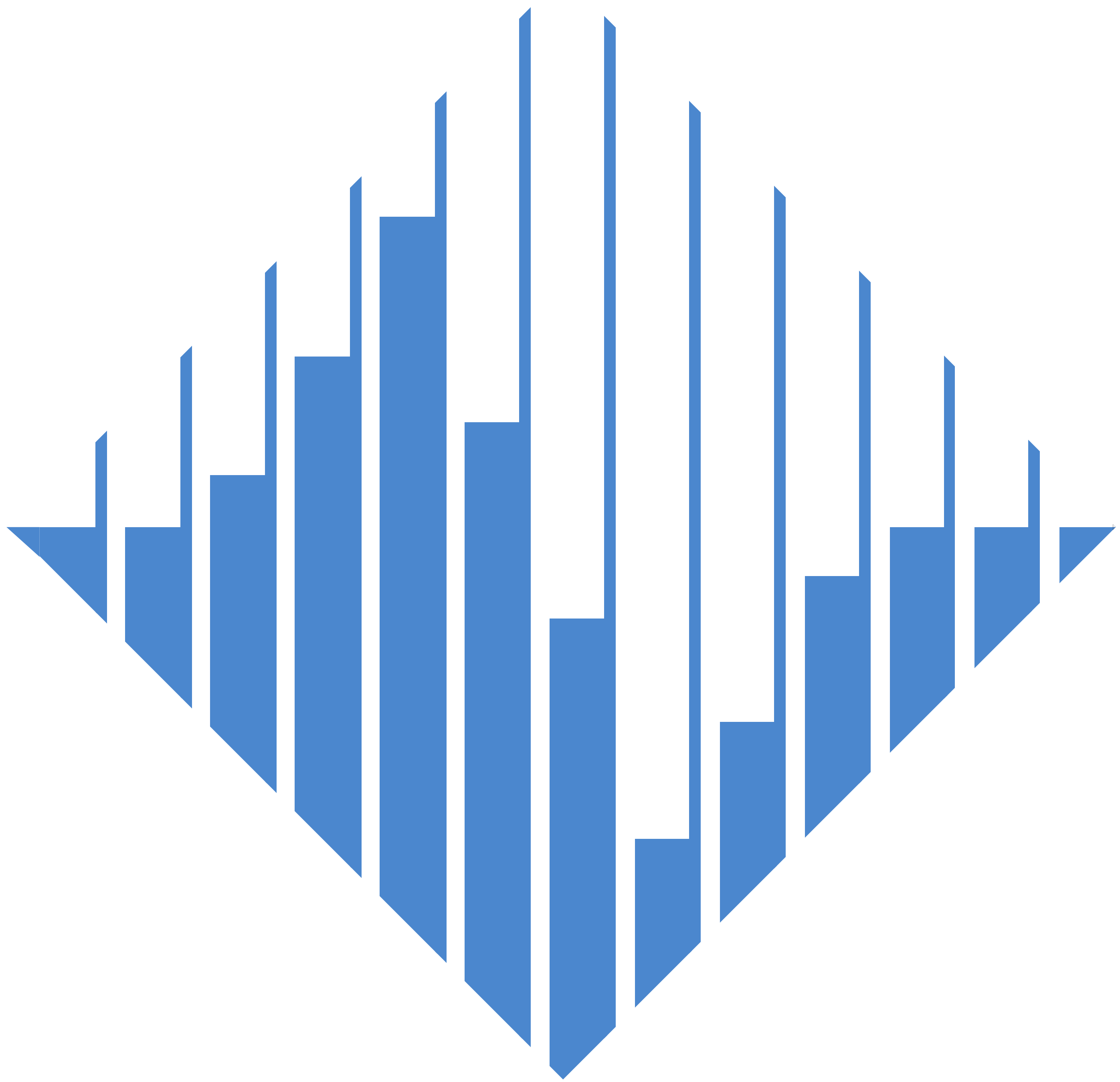
Jonathan Bray: *Liquefaction of Silty Soil*

Dharma Wijewickreme: *Particle Fabric Imaging for Understanding Shear Response of Silts*

Laurie Baise: *Geospatial Models for Liquefaction Susceptibility*

Christine Beyzaei: *Regional Liquefaction Susceptibility Assessments: Data Collection Needs and a Focus on the Central and Eastern U.S.*

Andrew Makdisi: *Incorporating Uncertainty in Susceptibility Criteria into Probabilistic Liquefaction Hazard Analysis*



Incorporating the spectrum of soil behaviors directly into systems level triggering and consequence models

Shideh Dashti & Caroline Bessette

Associate Professor & PhD Student

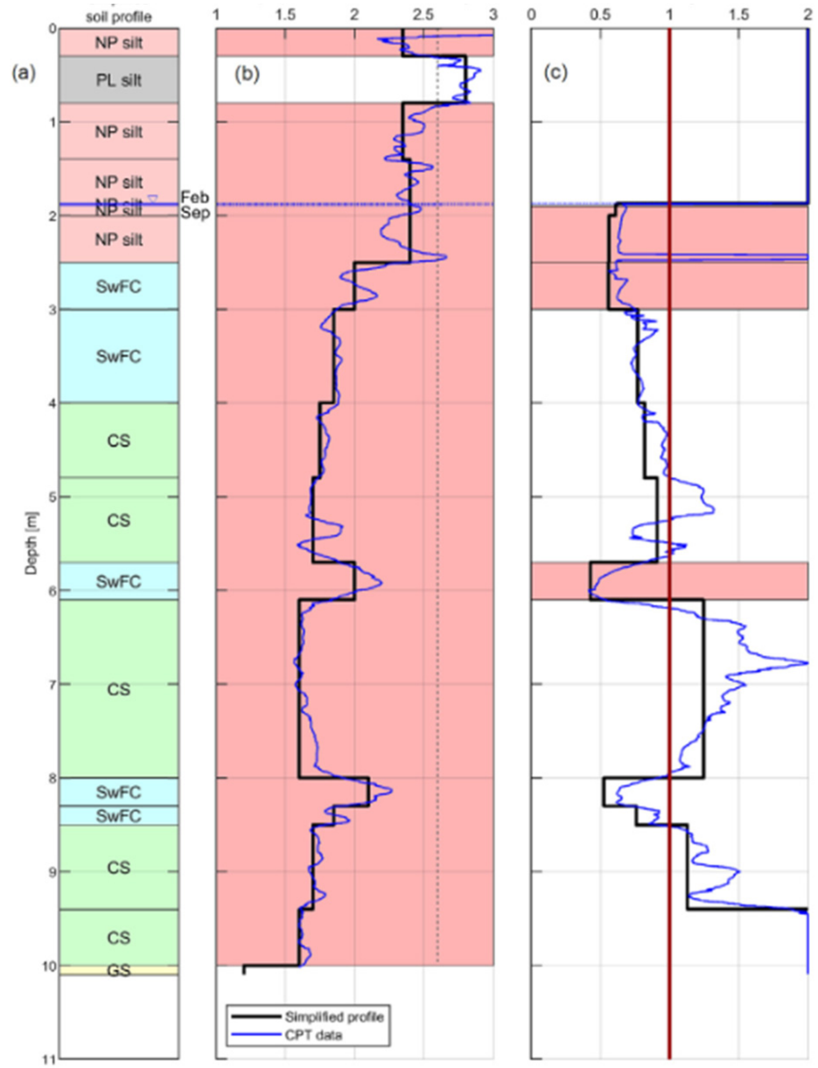
College of Engineering and Applied Sciences

shideh.dashti@colorado.edu & caroline.bessette@colorado.edu

University of Colorado **Boulder**

Current practice in liquefaction assessment relies on a binary "susceptibility" check before evaluating triggering, consequence, and mitigation

Bray et al. (2004)



Cubrinovski et al. (2019)

Liquefaction "susceptibility" check

↓

Liquefaction "triggering" free-field & near-field

↓

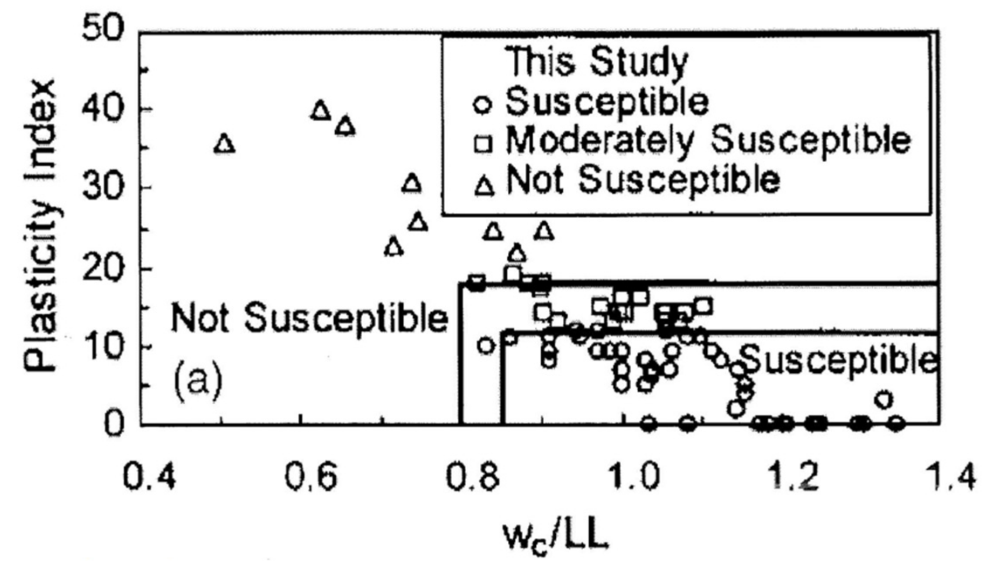
Permanent deformations (vertical and lateral) away from & near structures

↓

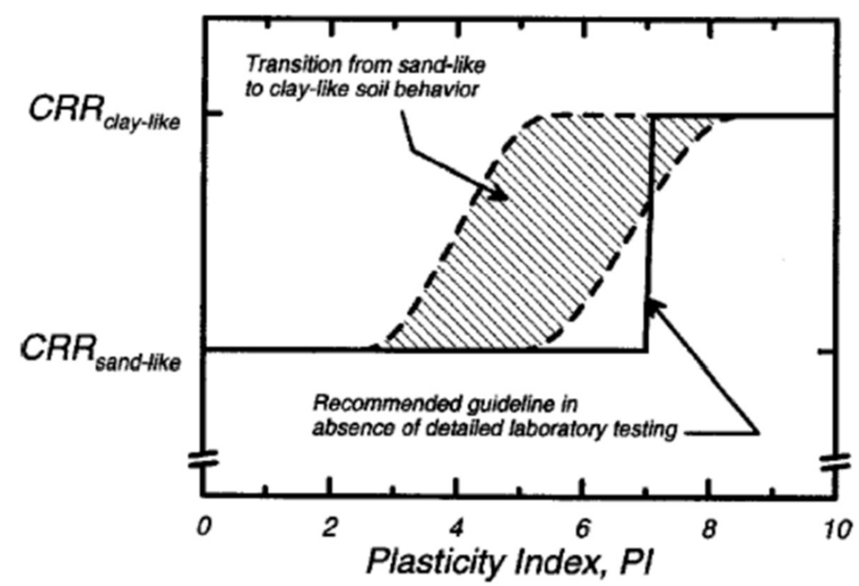
Mitigation to achieve acceptable performance

Current procedures for assessing soil susceptibility distinguish sand-like from clay-like behavior in a binary manner

- Based on plasticity index and water content
- Laboratory tests and observations of surface manifestation (e.g., sand boils or ejecta) from prior case histories
- Current evaluation methods range from in-situ test indices (Ic from CPT) to geotechnical laboratory testing
- Engineering judgment & additional laboratory testing required for intermediate soils near the boundaries



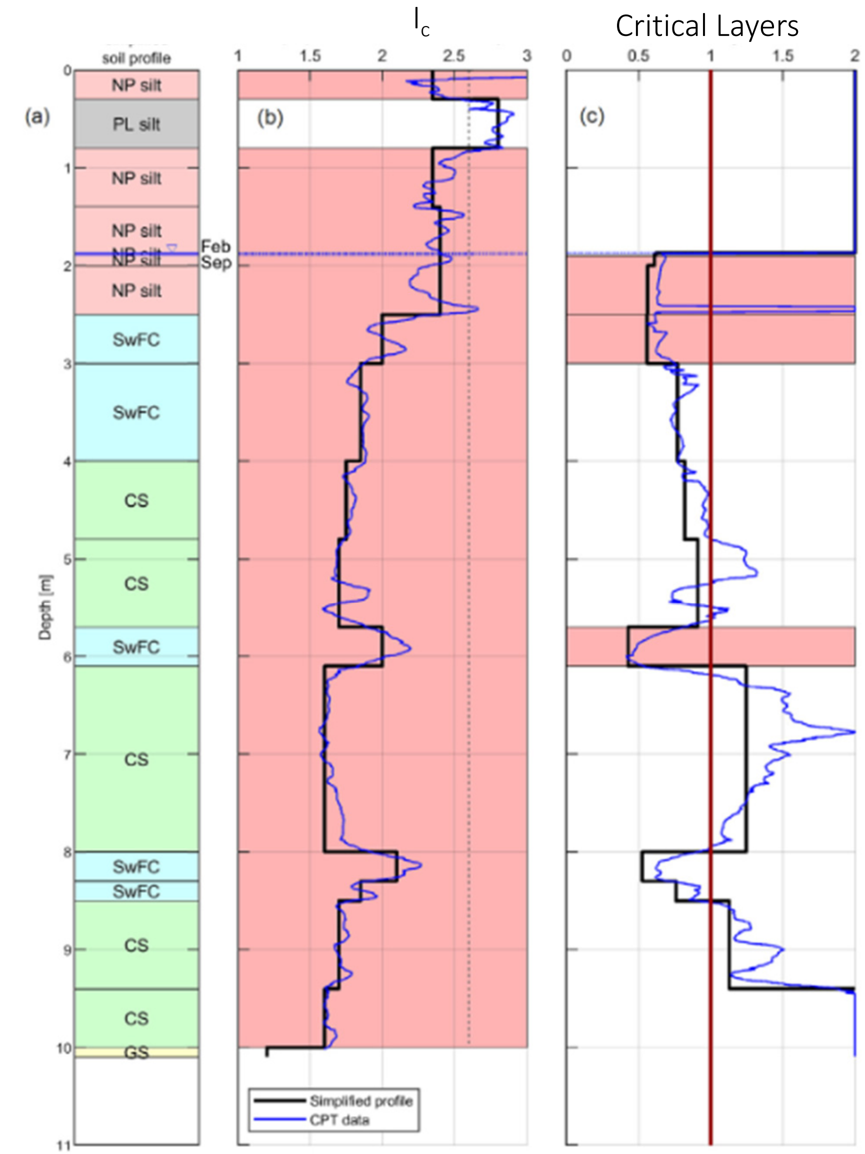
Bray and Sancio (2006)



Boulanger and Idriss (2006)

Triggering and settlement models tend to ignore the presence of "unsusceptible" clay-like soils prone to cyclic softening

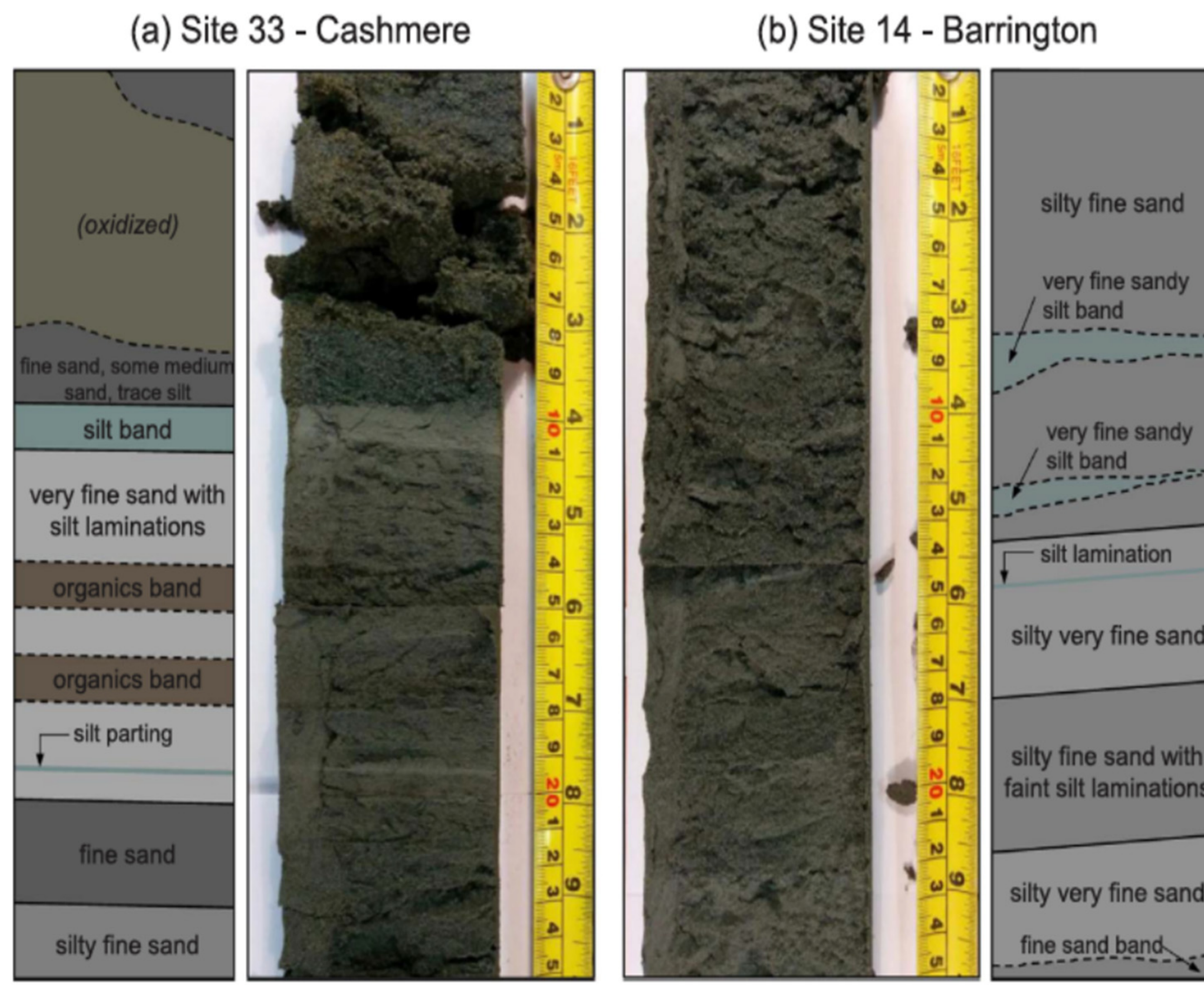
- Triggering & consequence models focus on individual and independent soil layers without cross-layer interactions
- Traditional triggering evaluation relies on selection of critical layers
- Models are conditioned on empirical observations of surface manifestation, hence affected by overall response of a soil deposit
- The distinction among susceptibility, triggering, manifestation, consequence, & damage is blurry



Cubrinovski et al. (2019)

The entire spectrum of soil behaviors contributes to triggering and consequence at a systems level

- Not all sands with fines < 5% act the same (pore pressure or strain)
- Clay-like soils may still experience cyclic softening and excessive deformations (lateral and vertical)
- Low-permeability layers affect EPWP development & redistribution and dynamic response of susceptible layers
- Fines content correction not defined in consequence procedures
- These gaps/shortcomings affect reliability of procedures



Beyzaei et al. (2018)

Effective mitigation requires improved models of susceptibility, triggering and performance, directly accounting for the spectrum of soil behaviors and interlayering

Bray et al. (2004)

Liquefaction "susceptibility" check

↓

Liquefaction "triggering" free-field & near-field

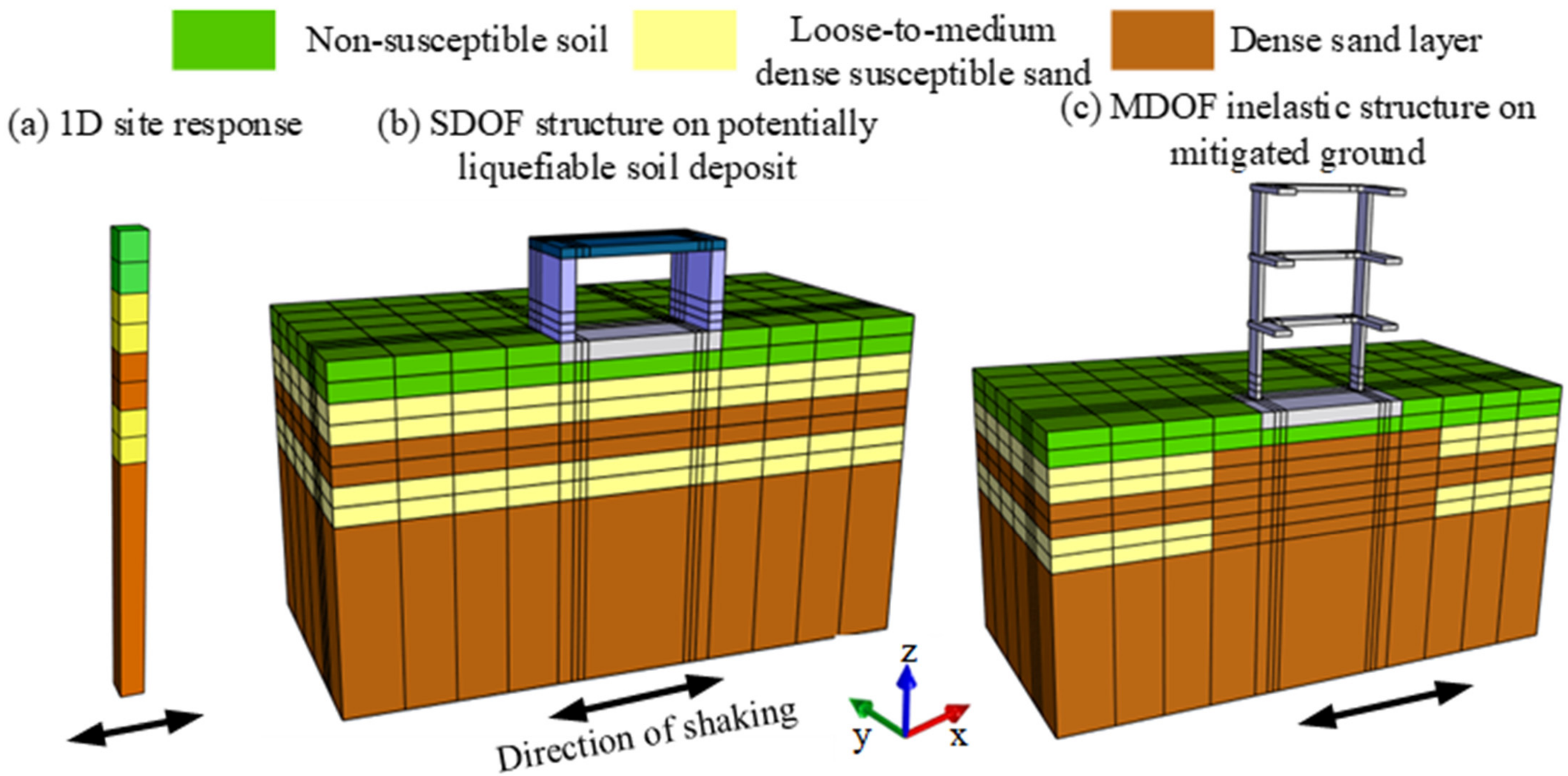
↓

Permanent deformations (vertical and lateral) away from & near structures

↓

Mitigation to achieve acceptable performance

Case history, centrifuge, and numerical database for unified predictive models of triggering, consequence, and mitigation



Simulations: 167,000 1D

Probabilistic models for triggering, validated with manifestation models

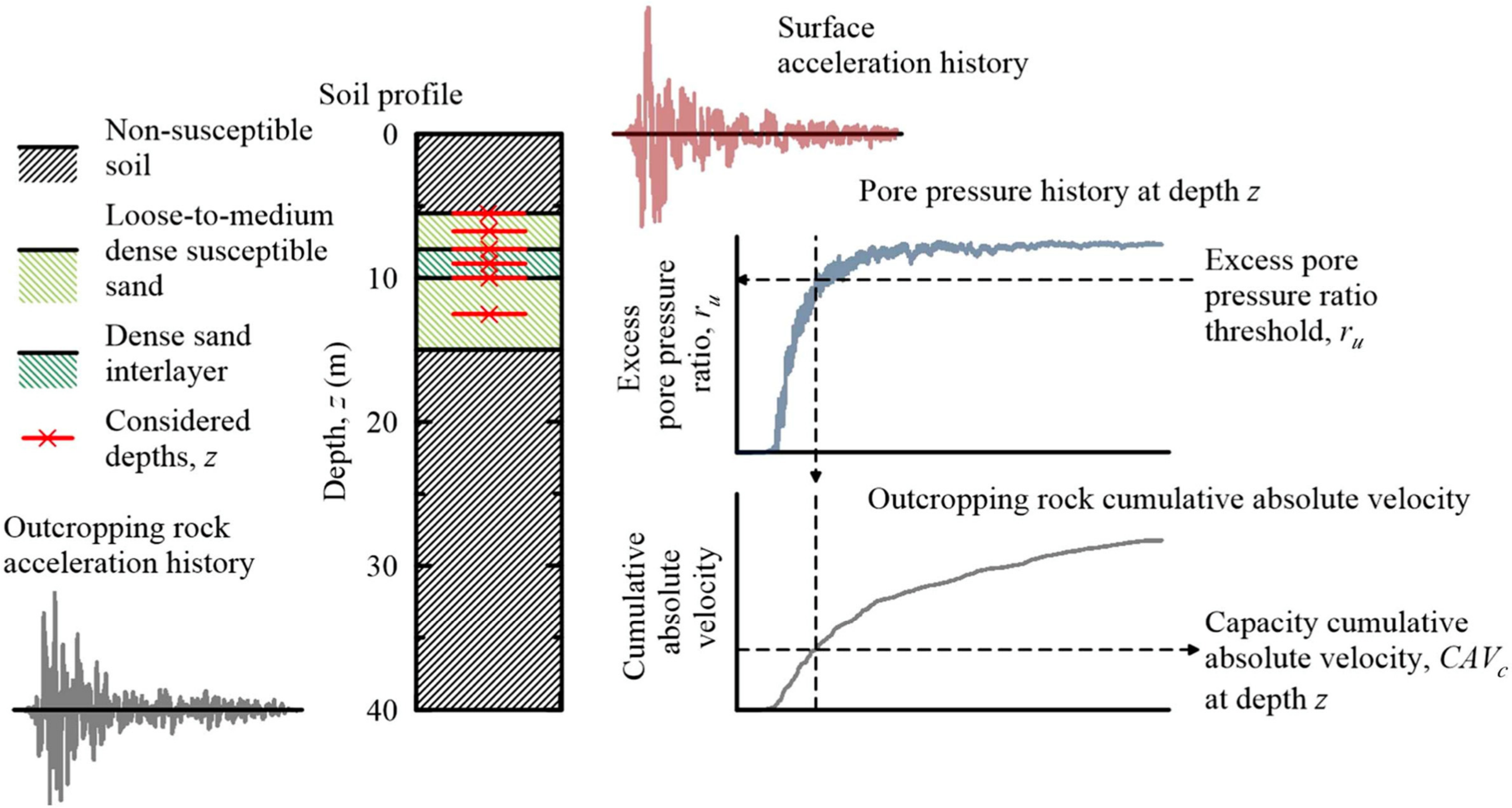
Simulations: 63,000+ 3D

Probabilistic models for building settlement and tilt, validated and adjusted with case histories.

Bullock et al. 2(019a,b, 2021,2022); Hwang & Dashti (2021,2022)

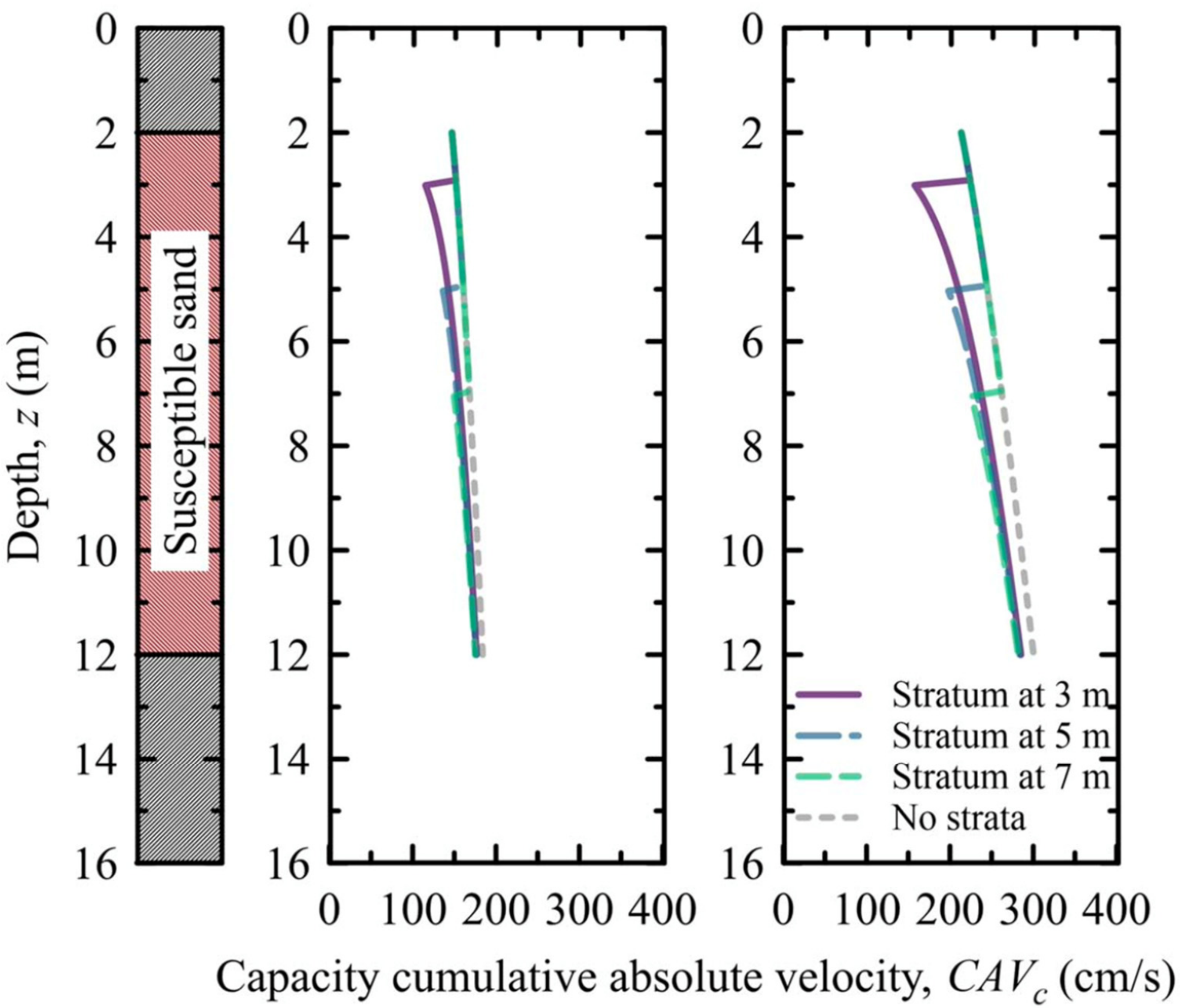
ASCE JGGE & Geotechnique

CAV_C used to define soil resistance to liquefaction triggering at different r_u thresholds and depths



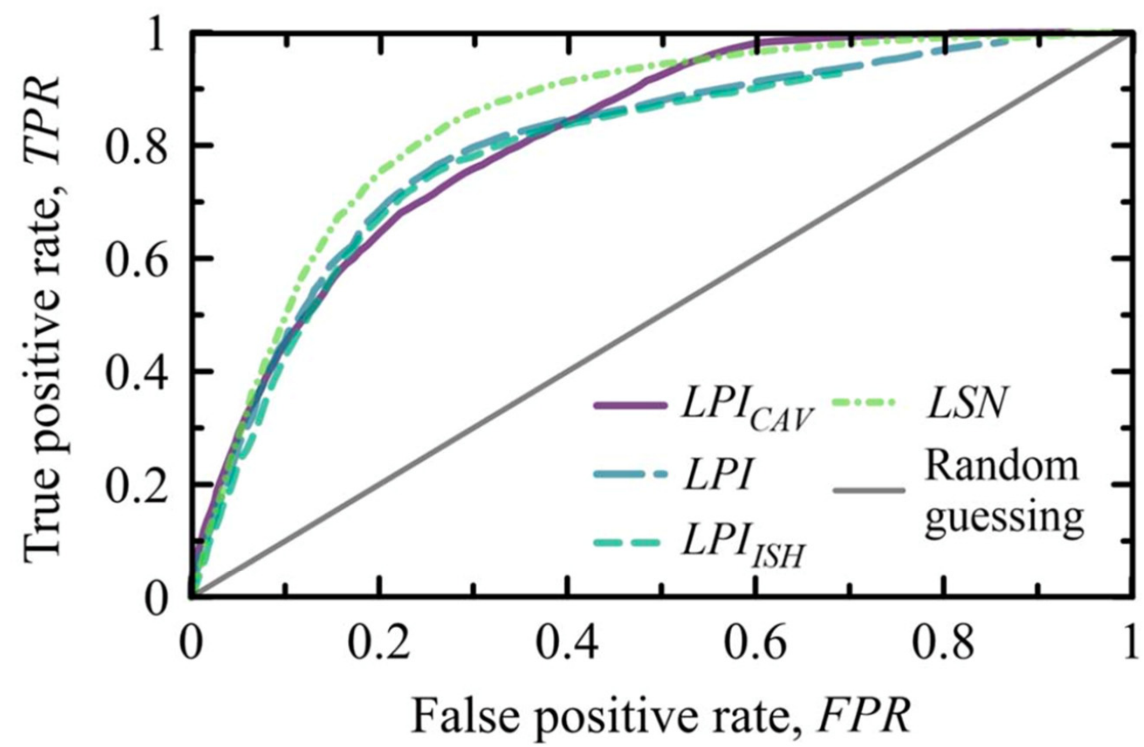
Bullock et al. (2021,2022)
ASCE JGGE & Geotechnique

Our CAV_c model accounts for cross layer interactions but does not consider cyclic softening in clay-like soils or spectrum of soil behavior



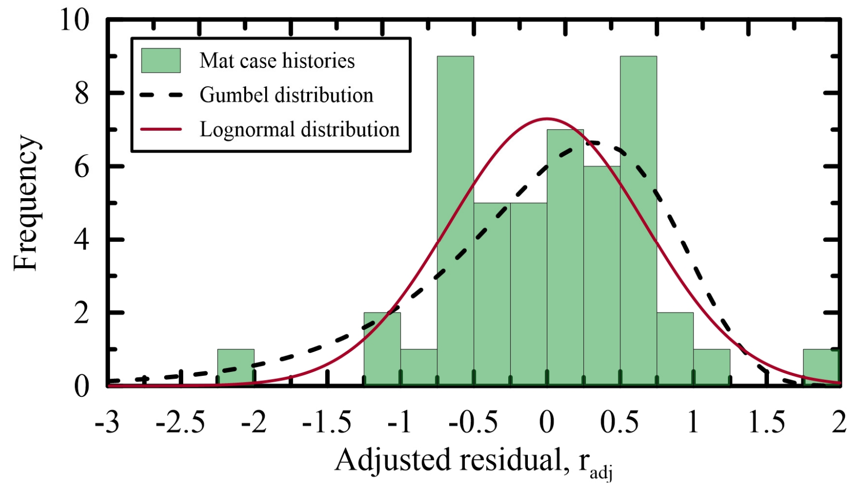
$$FS_{liq} = CAV_c / CAV_D$$

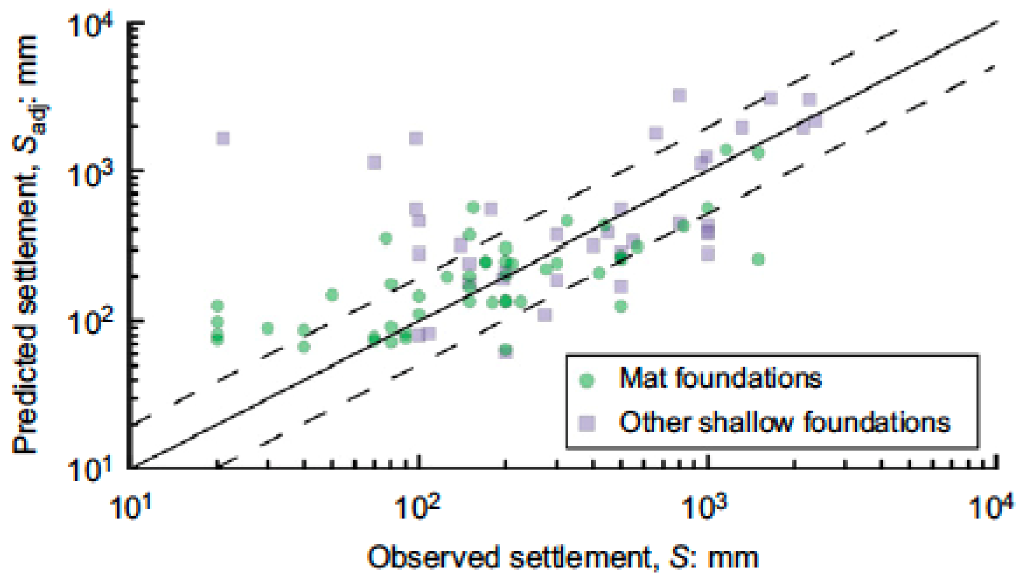
$$\mathrm{LPI_{CAV}} = \int_0^{20m} [\max(0.5 - FS_{liq}, 0)] \times [10 - 0.5z] dz$$

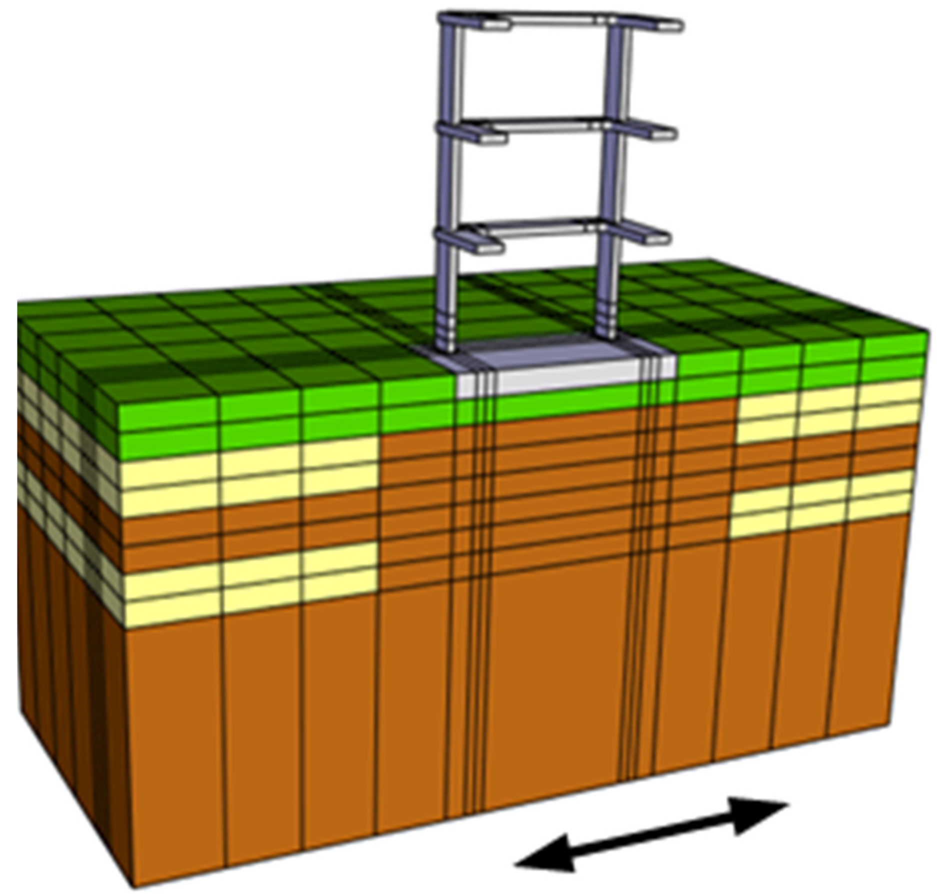


Bullock, Dashti, et al. (2021,2022)

Our probabilistic models for predicting settlement & tilt of shallow founded structures with and without mitigation account for interlayering, but not deformations in clay-like soils



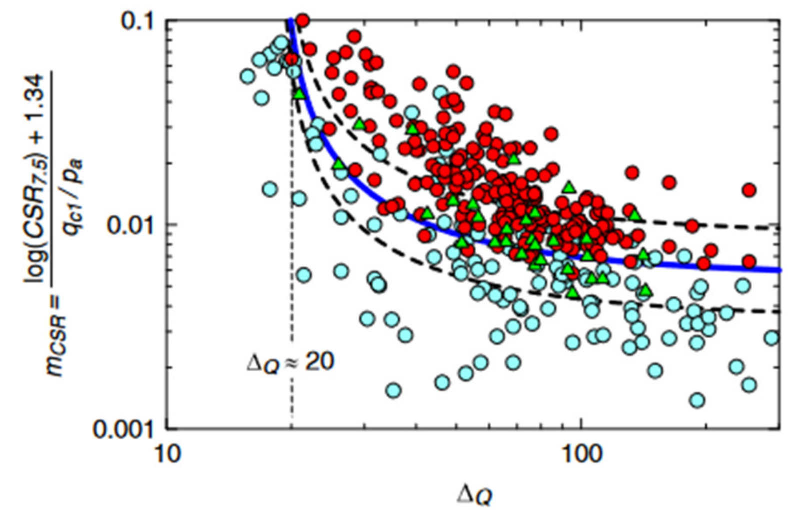




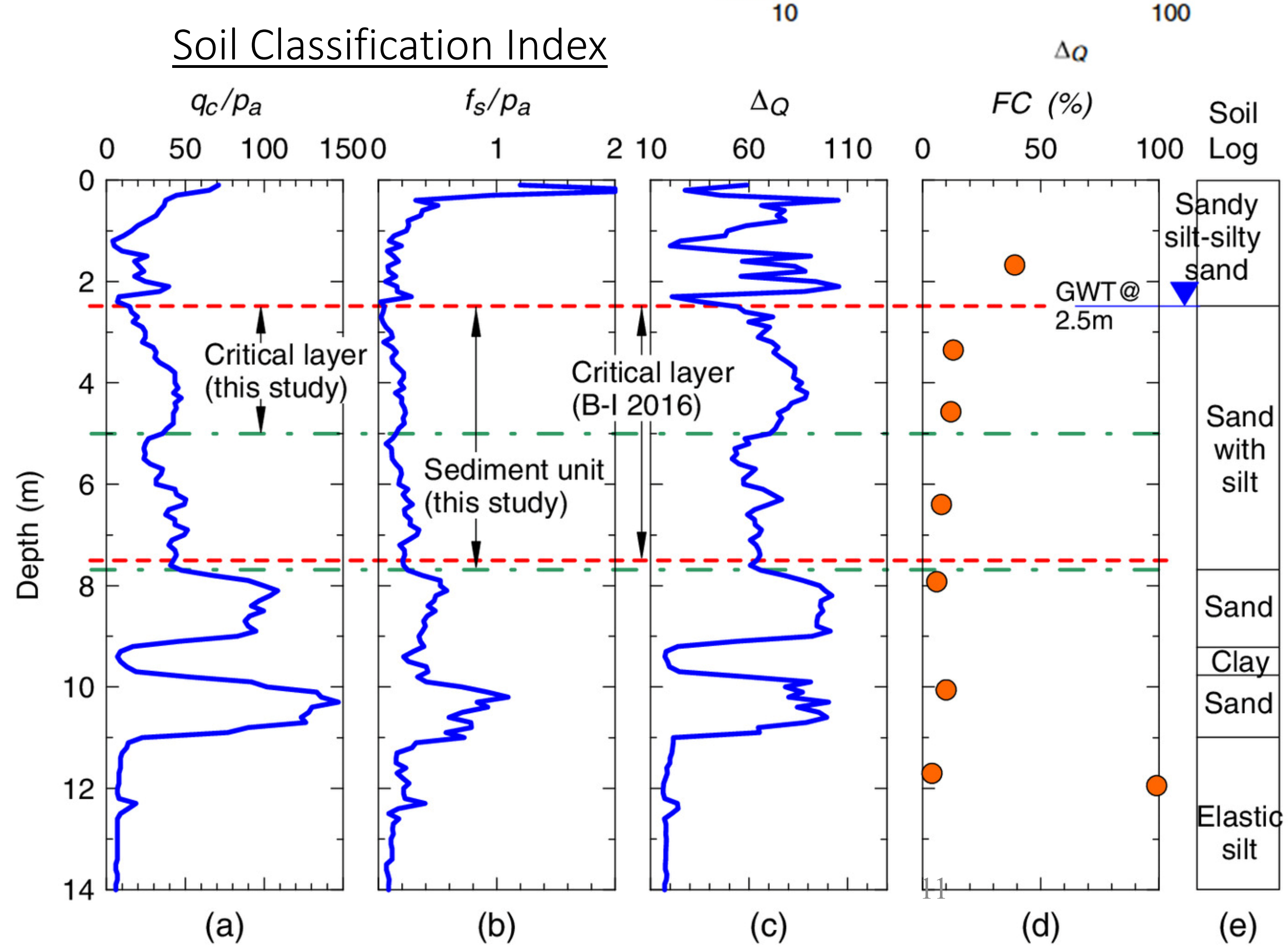
Bullock et al. (2019a,b)

Hwang, Dashti et al .(2022), ASCE JGGE

Common-origin approach to assess level-ground liquefaction susceptibility and triggering in CPT-compatible soils using Δ-Q (Saye et al. 2021)

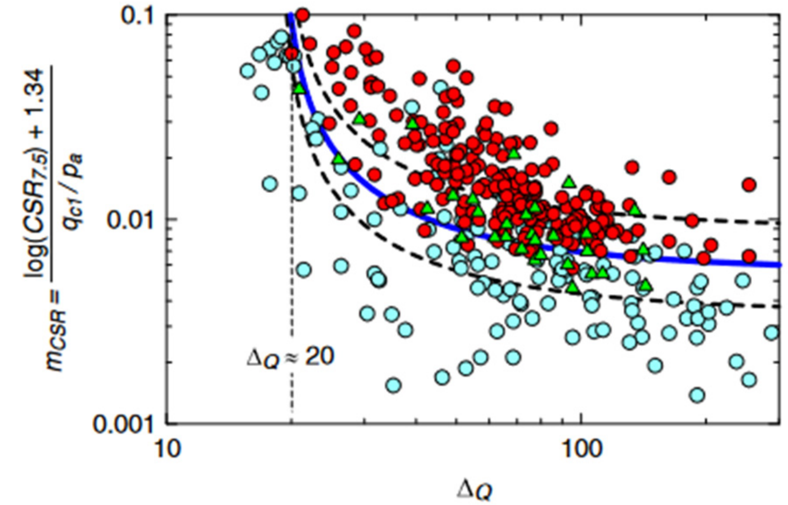


- Δ-Q: a unified method to assess susceptibility & triggering for a spectrum of soil behaviors
- Case histories including low plasticity, fine-grained soils, unifying evaluation of susceptibility & triggering
- No need to estimate equivalent clean sand tip resistance.

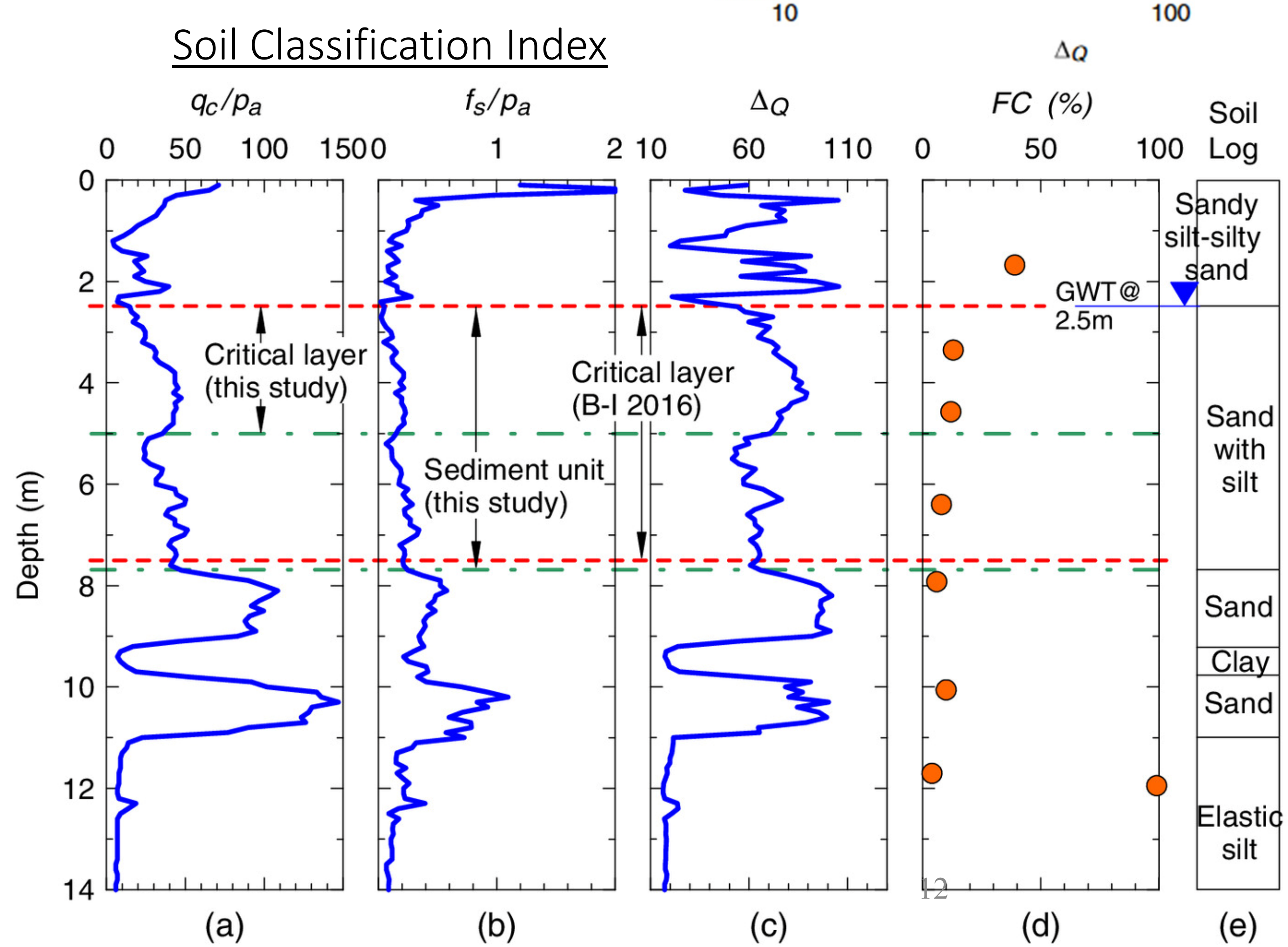


Saye et al. (2021)

Common-origin approach to assess level-ground liquefaction susceptibility and triggering in CPT-compatible soils using Δ-Q (Saye et al. 2021)



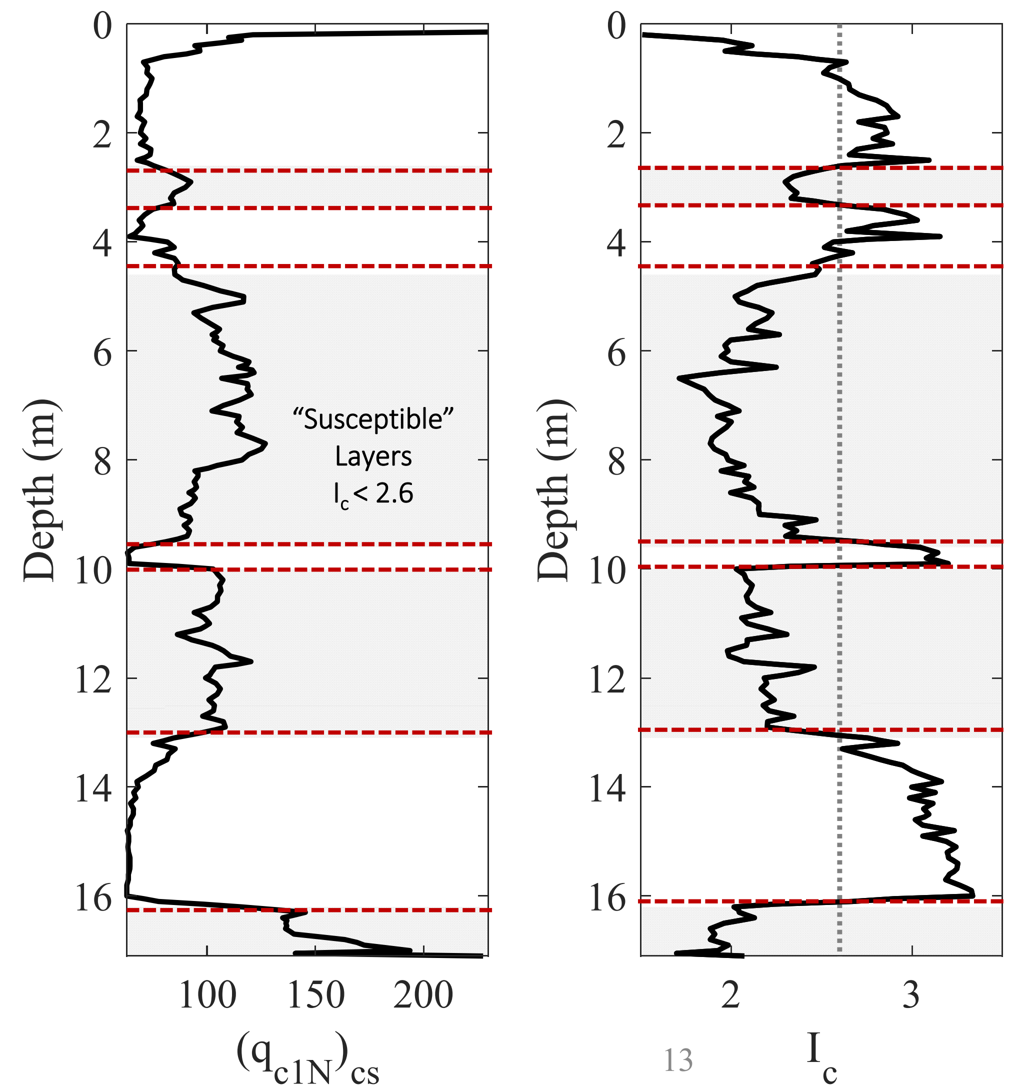
- The procedures rely directly on compressibility, so factors that affect penetration resistance (e.g., mineralogy, grain shape, density, over-consolidation) are incorporated
- Triggering calculation still requires estimation of critical layers & no consideration of interlayering.

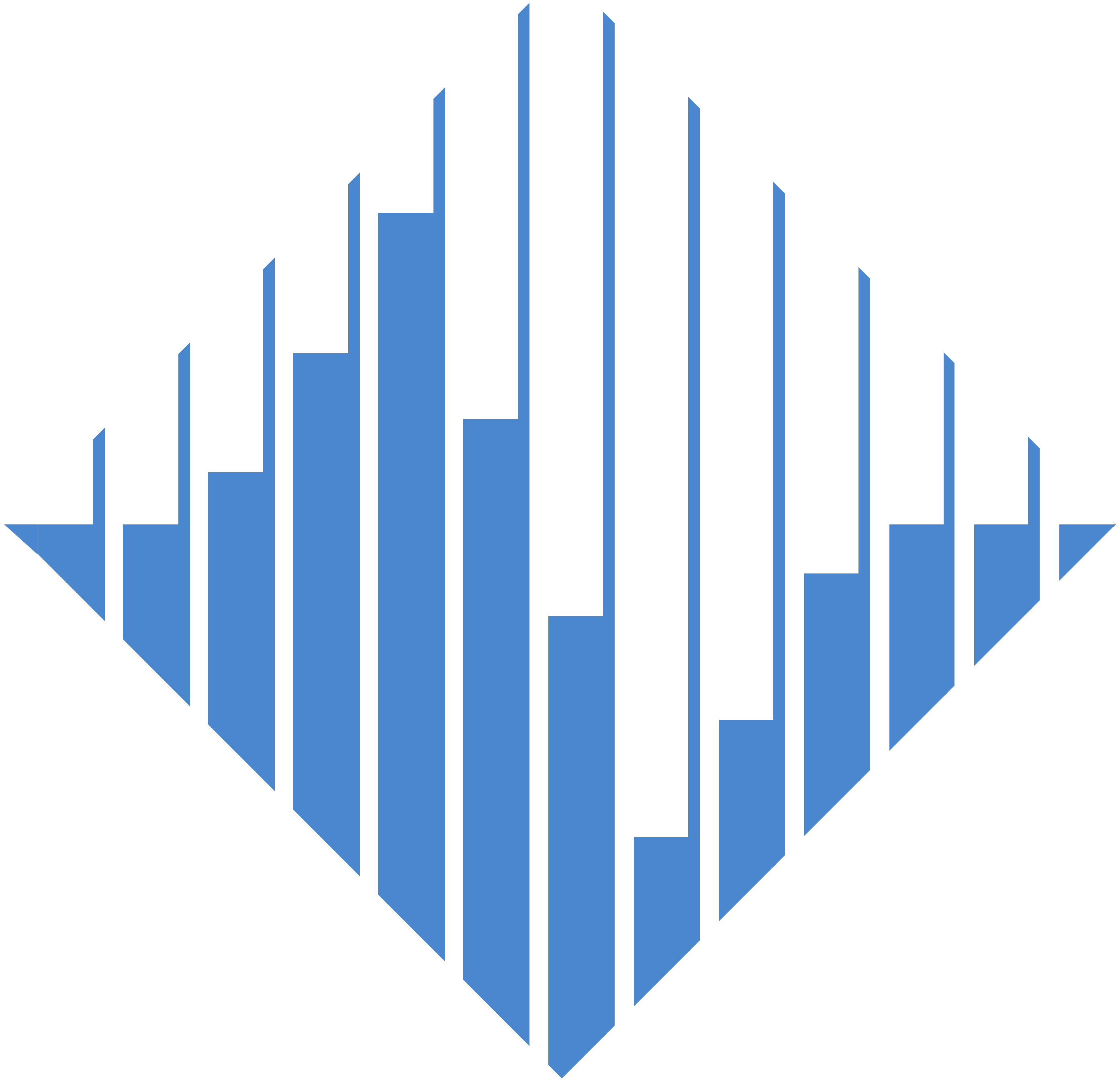


Saye et al. (2021)

How can we move toward a unified method for assessing seismic strength loss, shear, and volumetric strains for the spectrum of CPT-compatible soils (non-sensitive clays → clean sands)?

- Need to separate performance (pore pressures & deformations) within the profile from surface manifestation (ejecta?) in our procedures
- Additional data needed from case histories (with reliable CPT recordings, sampling, lab testing & instrumentation), centrifuge experiments, & numerical simulations
- Coordinated effort among researchers
- Quality-controlled data sharing and curation





2022 PEER WORKSHOP

LIQUEFACTION OF SILTY SOIL

Jonathan Bray, Ph.D., P.E.,NAE
Faculty Chair in Earthquake Engineering Excellence, UC Berkeley

With contributions from: F. Olaya, Z. Mijic, D. Hutabarat, M. Riemer, M. Cubrinovski, C. Beyzaei, C. Markham, R. Sancio, J. Donahue, S. Rees, C. Cappellaro, etc.

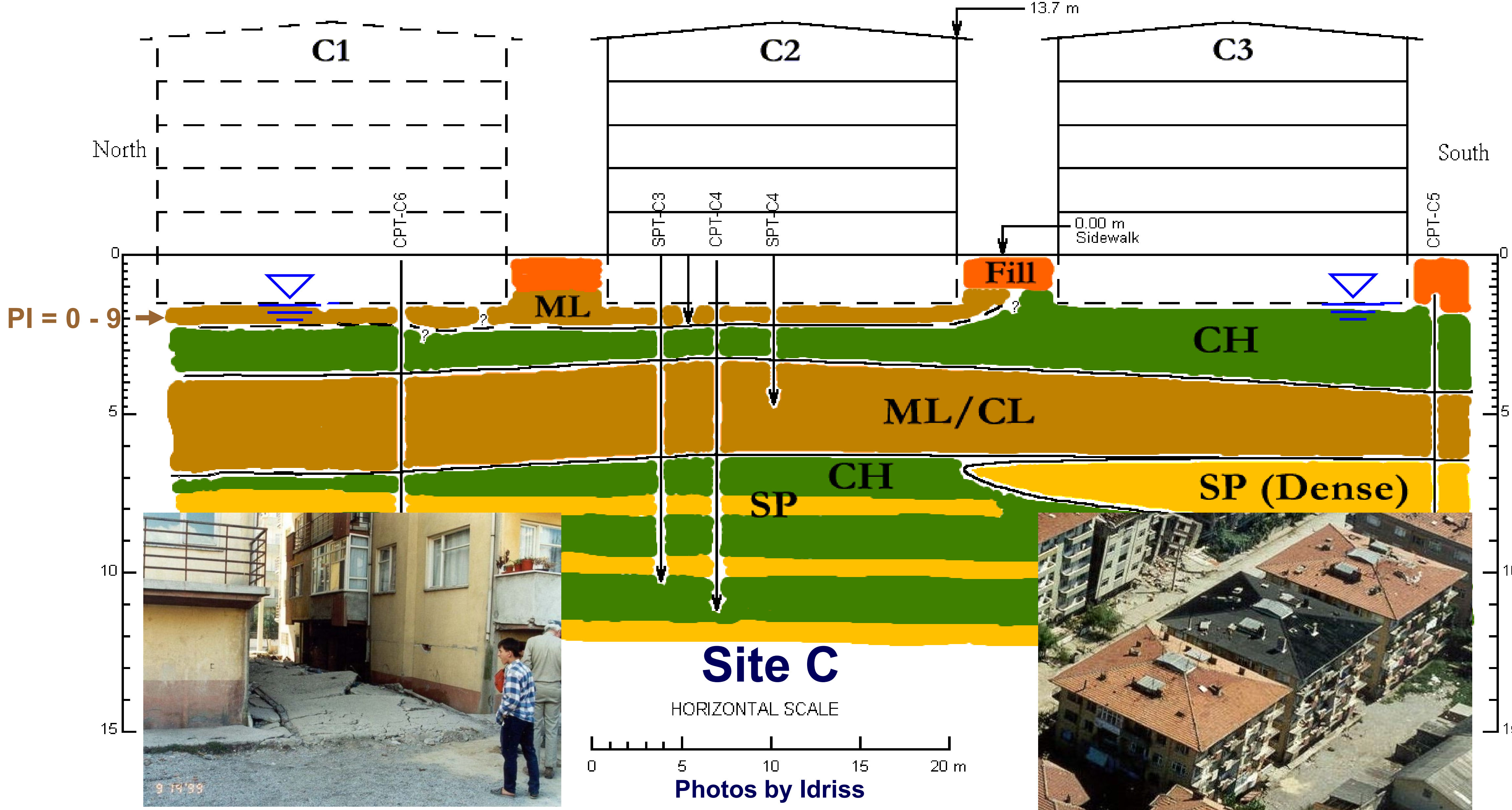
Sponsors: National Science Foundation, Pacific Earthquake Engineering Research Center, Caltrans, Ministry of Business, Innovation & Employment, and Earthquake Commission New Zealand

Effects of Liquefaction-Cyclic Softening in Adapazari, 1999 Kocaeli EQ

NSF GEER

Effects of Liquefaction-Cyclic Softening of Shallow Low Plasticity Silt

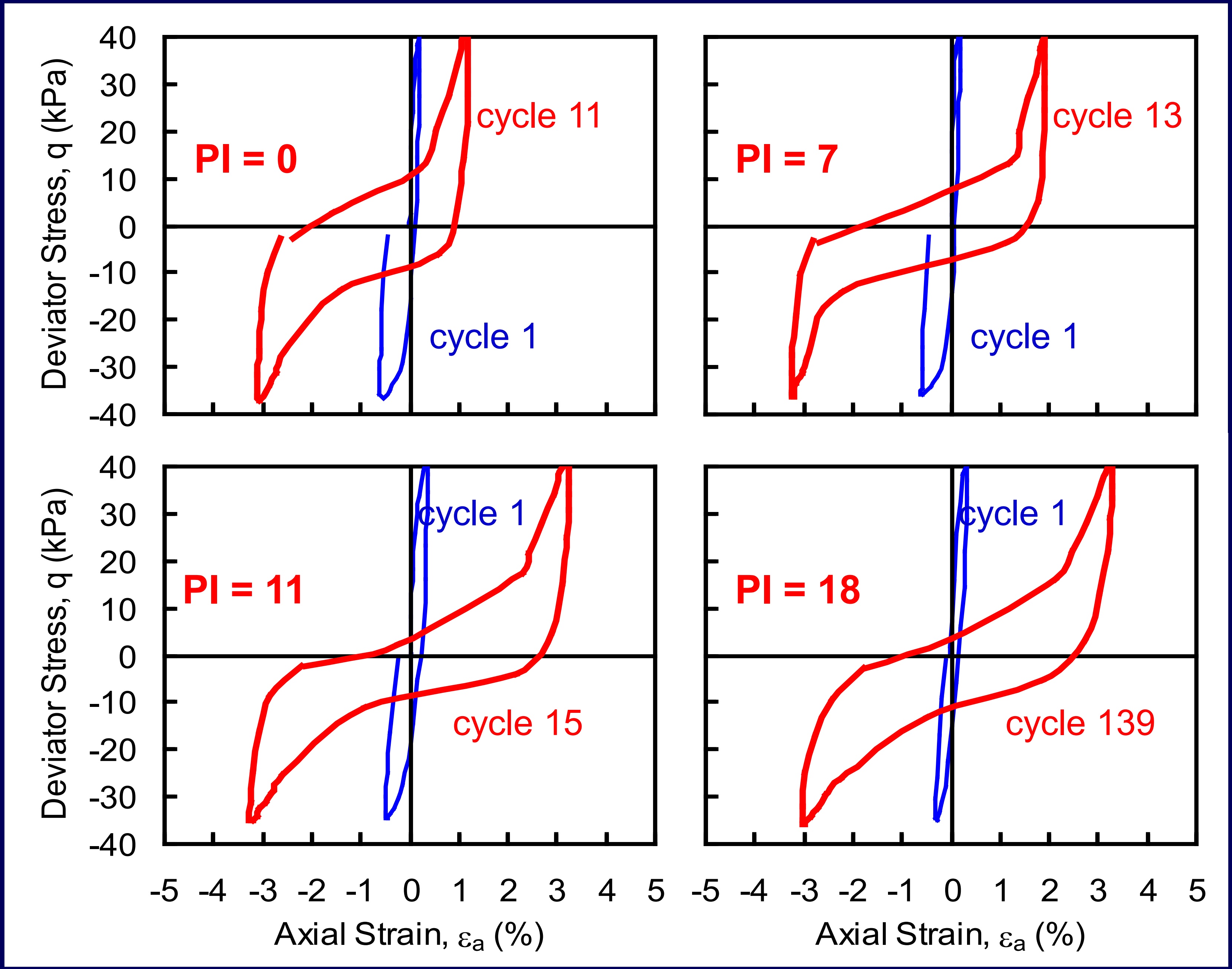
“Ground Failure” “No Ground Failure”



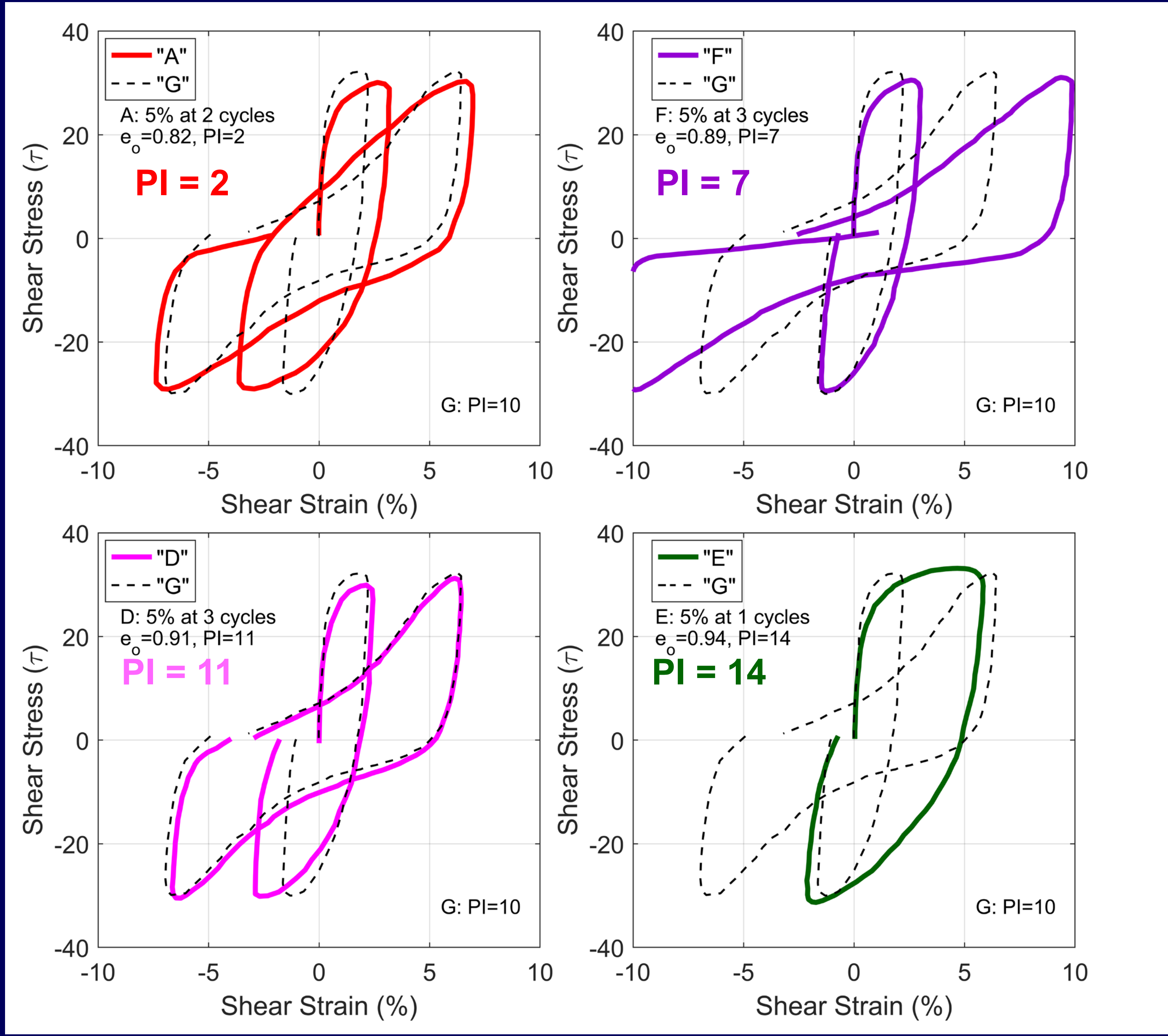
Photos by Idriss

Bray & Sancio 2009

Effect of Soil Plasticity on Liquefaction Susceptibility



Cyclic Response of Low-Plasticity Clayey Silt



Reconstituted Soil Specimens

CSS Testing:

Soil G has PI = 10

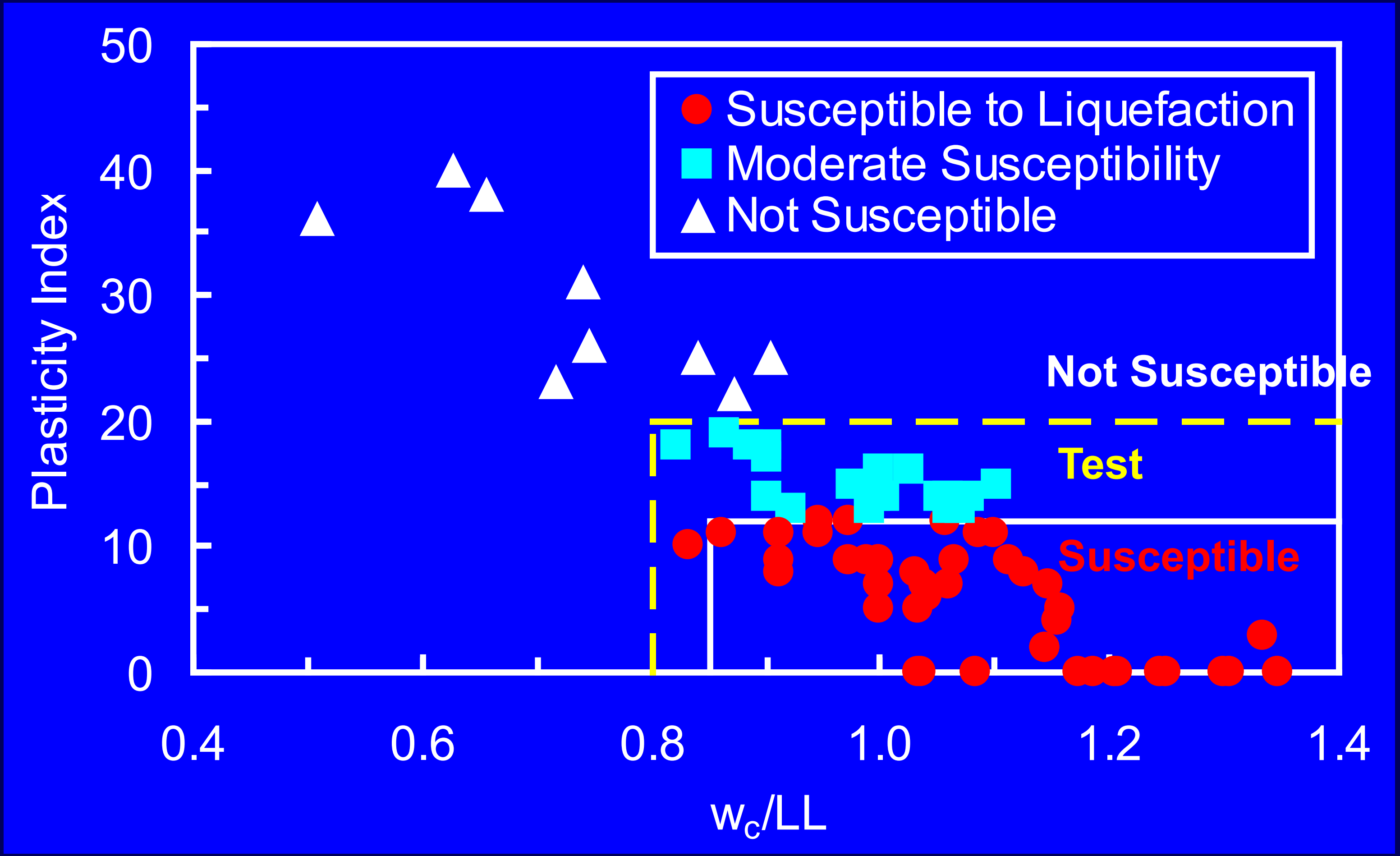
Donahue et al. 2007

Liquefaction Susceptibility Criteria

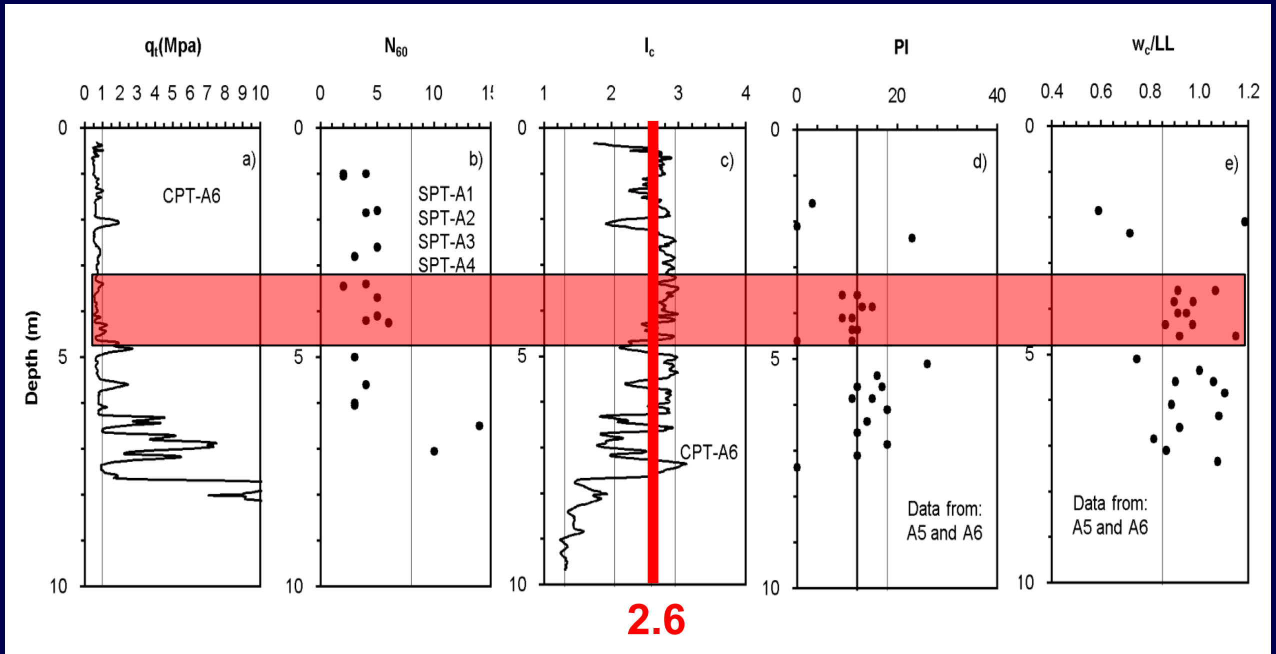
(Bray and Sancio 2006)

Susceptible Soil: PI ≤ 12 & w_c/LL ≥ 0.85

Moderate Susceptibility: w_c/LL ≥ 0.8 & 12 < PI ≤ 20



SILT LIQUEFACTION - 1999 Kocaeli & Chi-Chi EQs



Silt can liquefy (even if I_c > *2.6*)

Perform cyclic testing on high FC soil to assess their seismic response characteristics (they can be sampled effectively)

Bray & Sancio 2006 Sampling & Testing

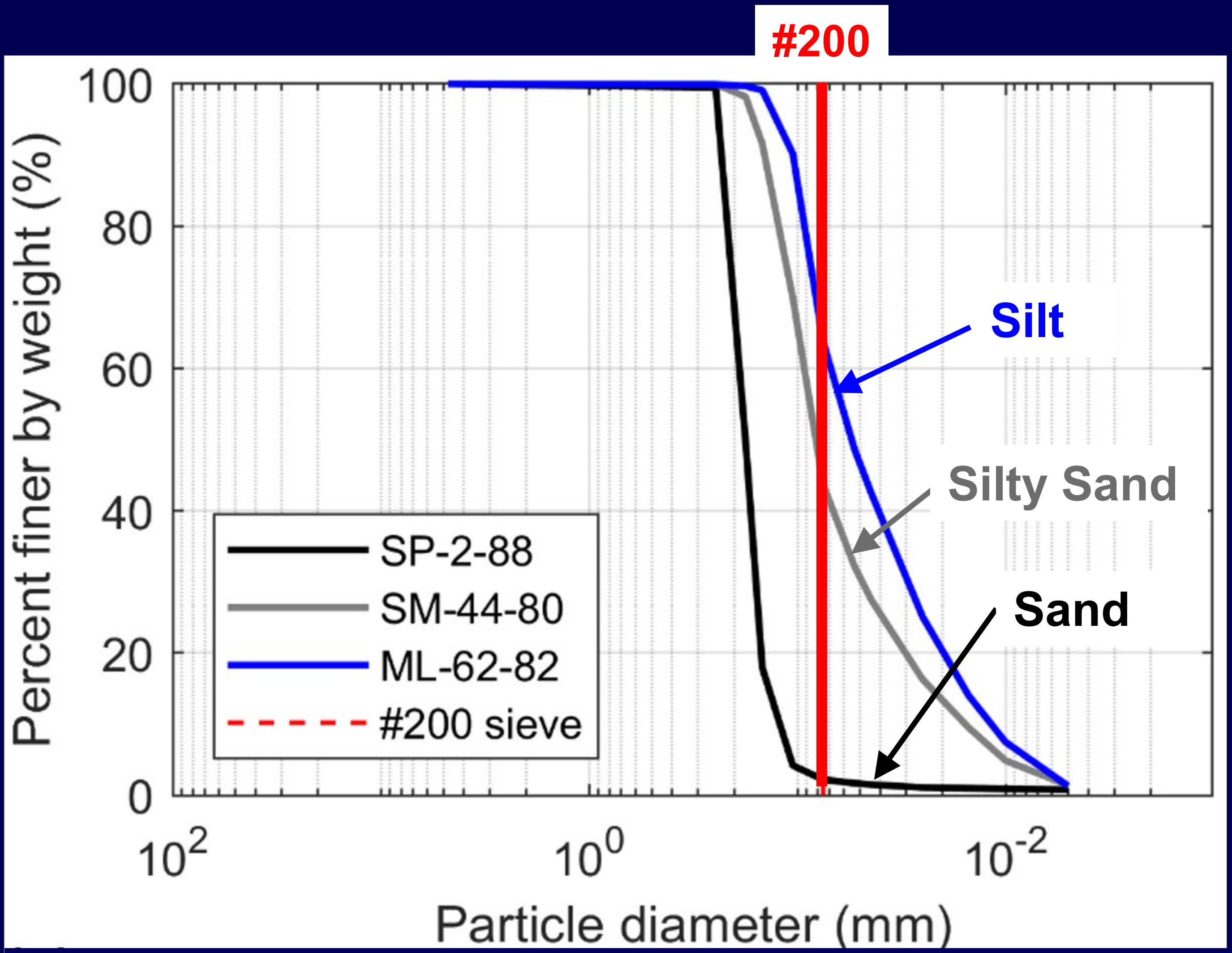
Extreme-to-No Manifestations of Liquefaction - Christchurch, NZ

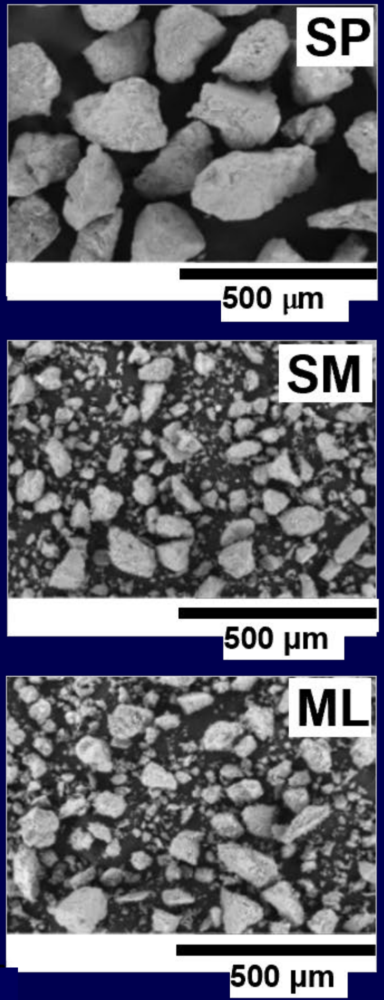
Cubrinovski et al. 2011

Bray et al. 2014

Photograph by R. Wentz

Grain-Size of Christchurch Soil





Does soil '*know*' the #200 sieve exists?

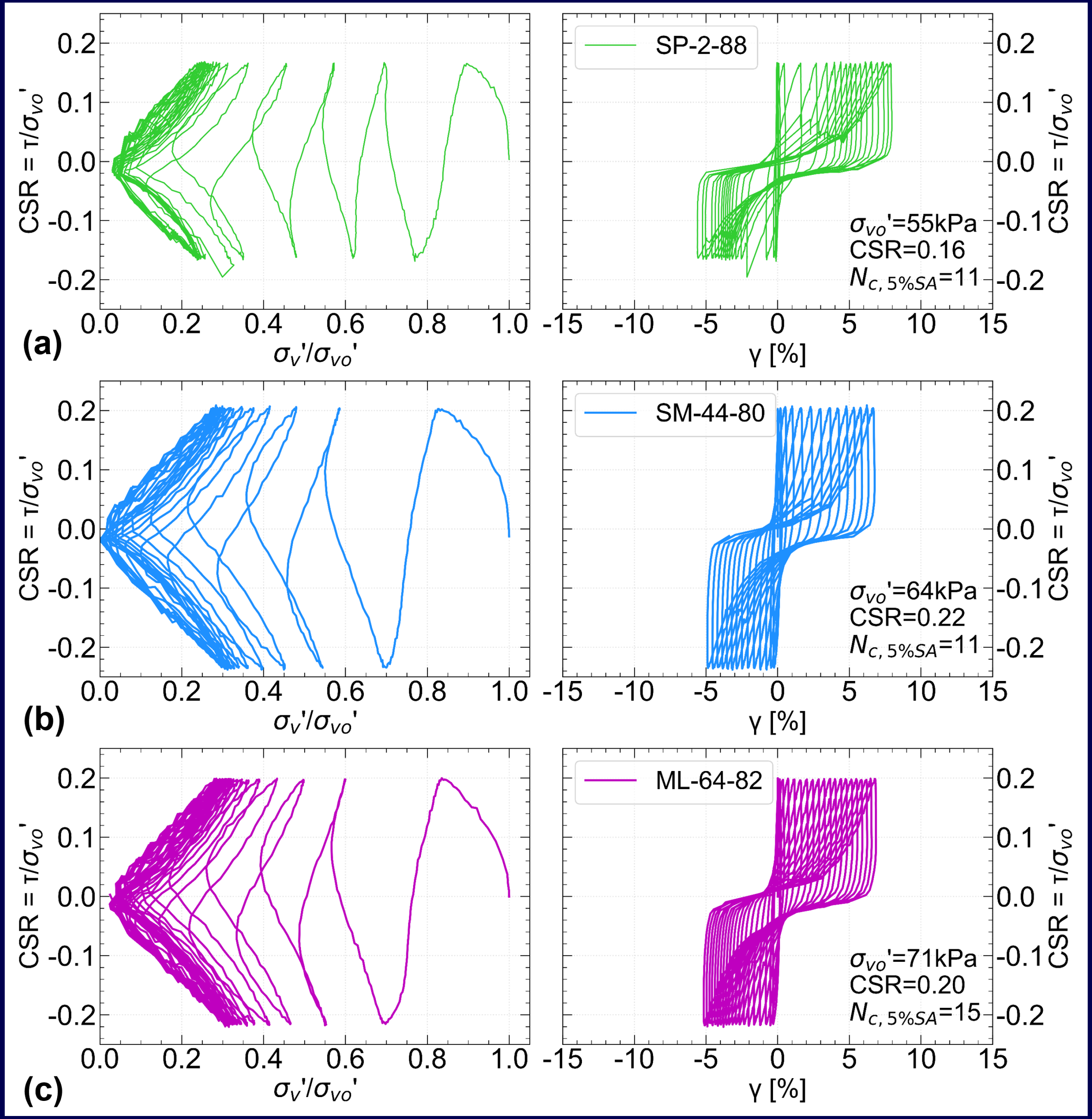
Beyzaei et al. (2018)

Cyclic Simple Shear Tests of “Undisturbed” Nonplastic Christchurch Soil

SP

SM

ML



FC = 2%, D_r = 88%

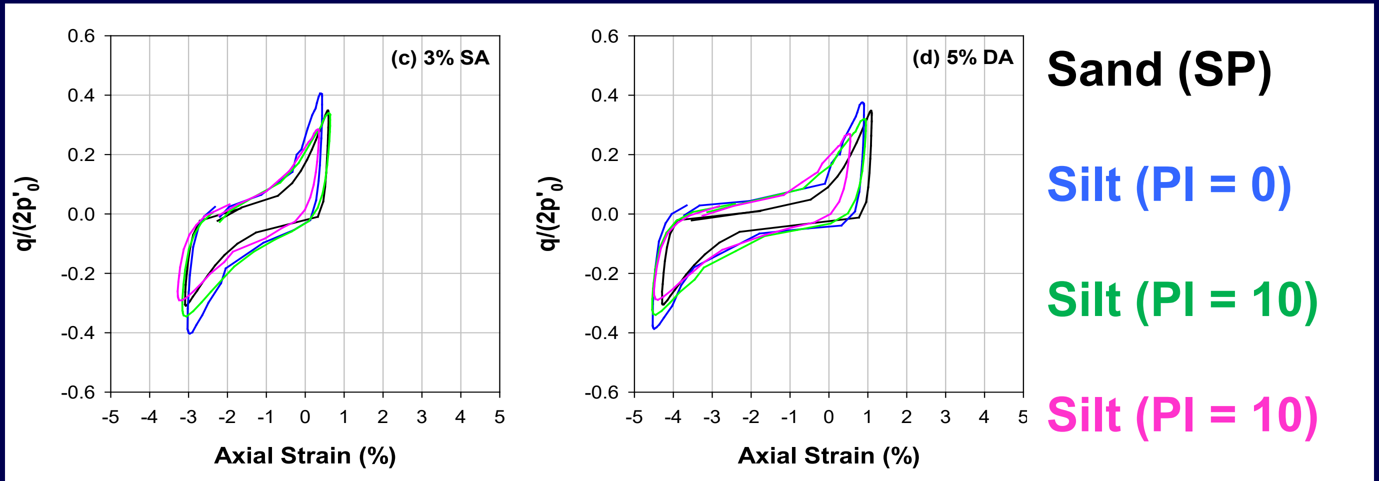
FC = 44%, D_r = 80%

FC = 64%, D_r = 82%

FS_L << 1 CHC EQ

Mijic et al. (2021)

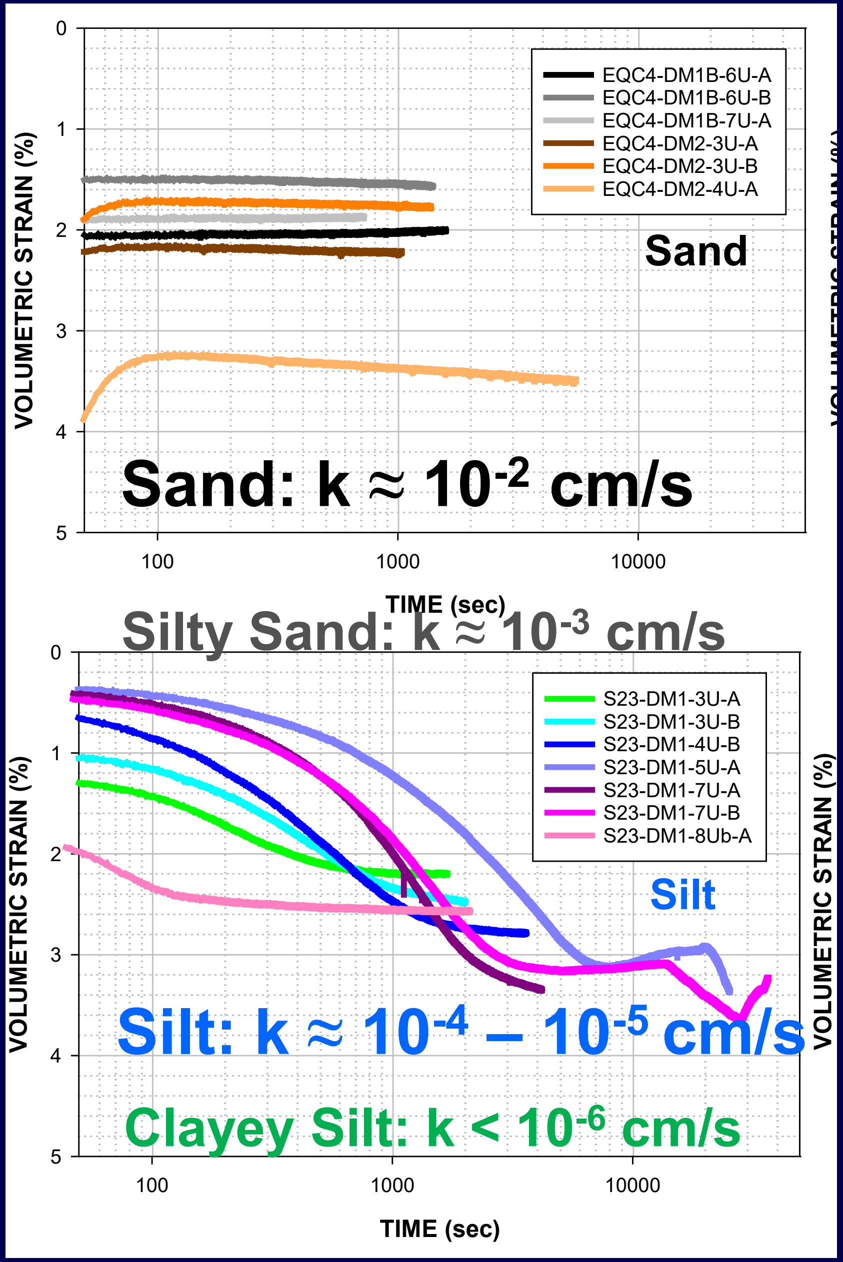
Cyclic Triaxial Tests & Post-Liquefaction Reconsolidation



Clean Sand
(EQC3-DM1-5U-A)

PI = 0 Silt
(S33-DM1-6U-B)

PI = 10 Silt
(S33-DM1-8U-A)



Beyzaei et al. (2018)

Christchurch CPT Profiles

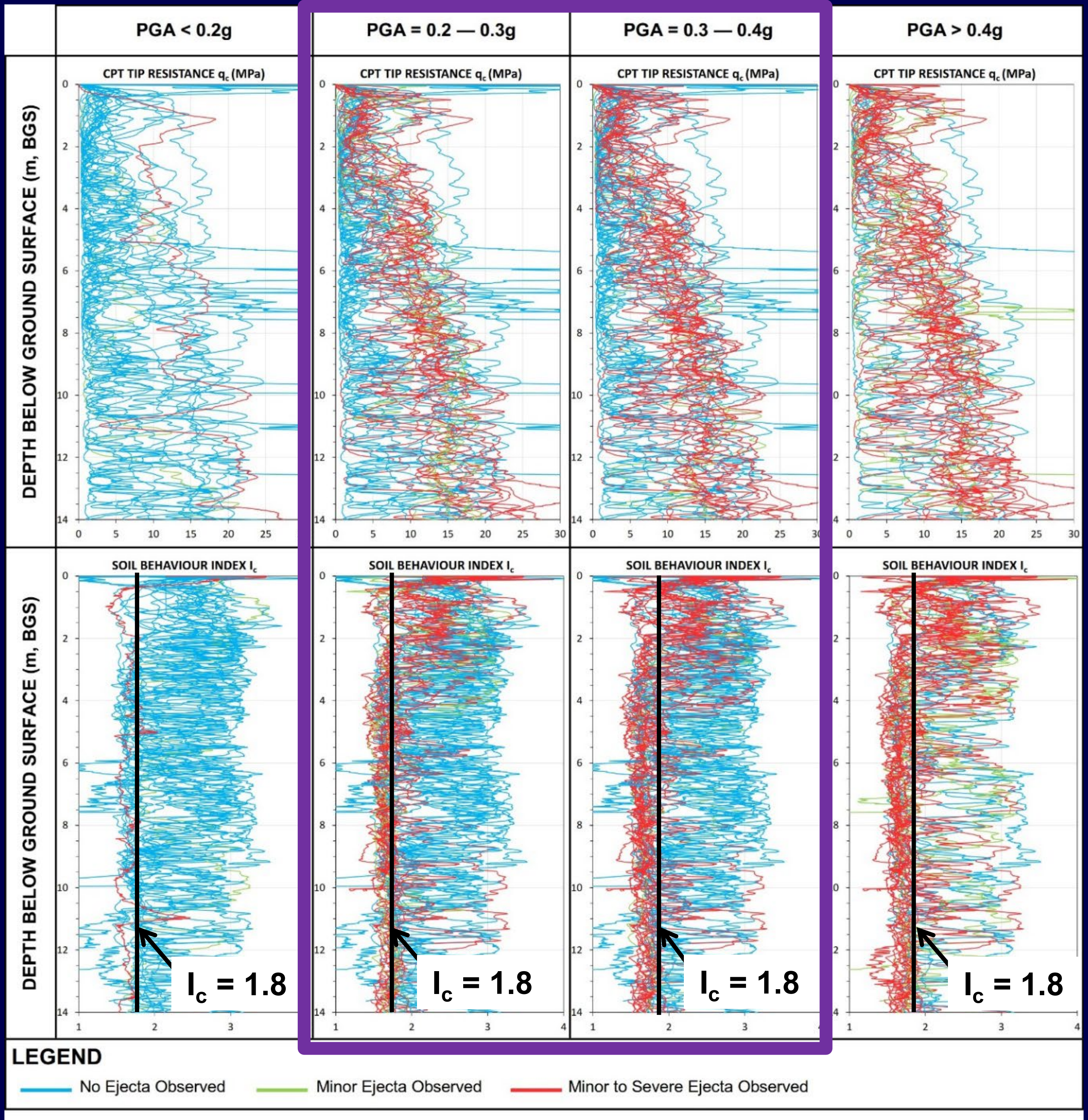
Ejecta

No Ejecta

Increasing PGA

→

Increasing Manifestations



q_c

I_c

Beyzaei et al. 2018

FOCUS ON LIQUEFACTION EFFECTS

1989 Loma Prieta EQ (Bray & Boulanger 1989)

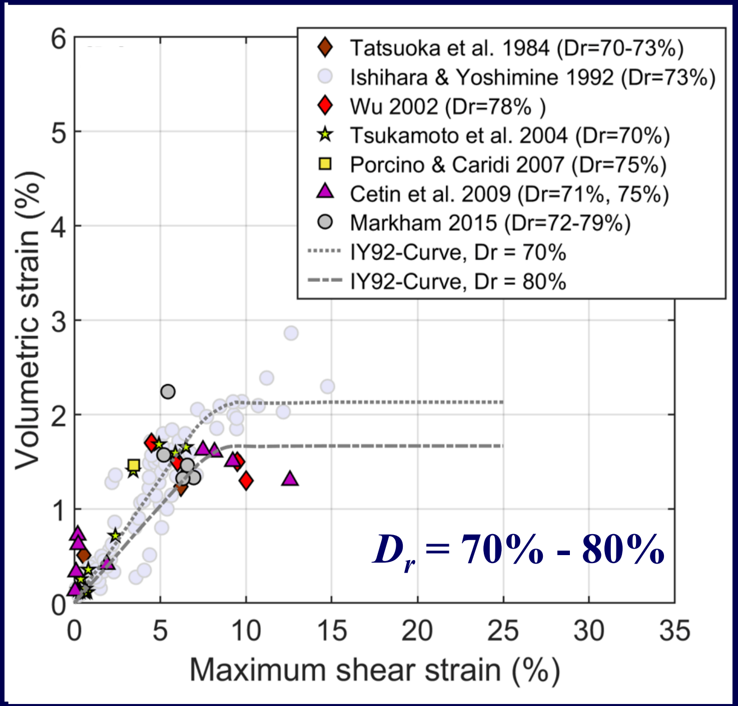
1964 Niigata, Japan EQ (from H.B. Seed)

1964 Niigata, Japan EQ (from H.B. Seed)

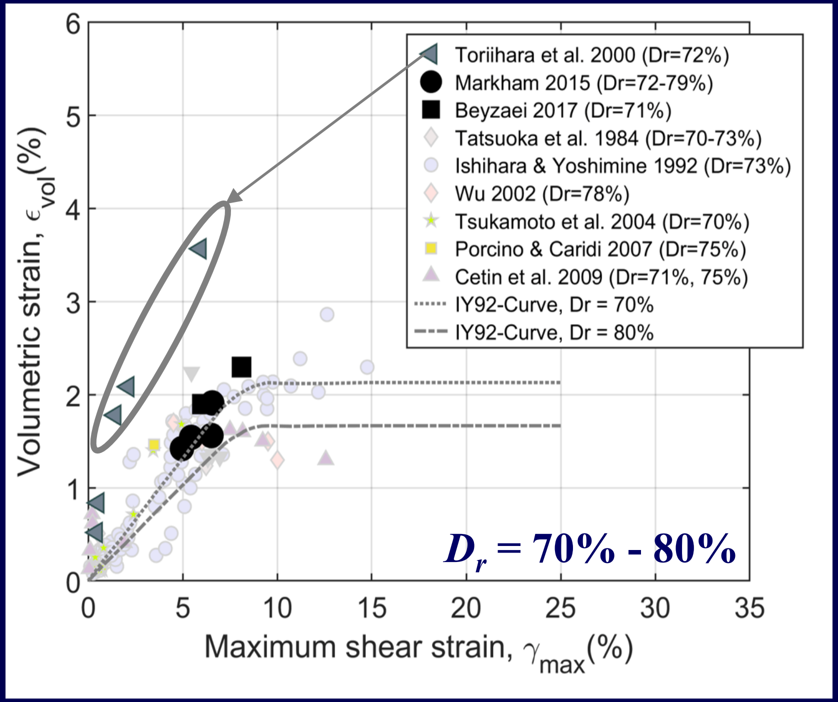
Volumetric Strain (ε_v) Trends Observed in Terms of D_r

- ε_v depends primarily on the induced γ_{max} and not the type of loading or σ'_{vc} = 40 – 400 kPa

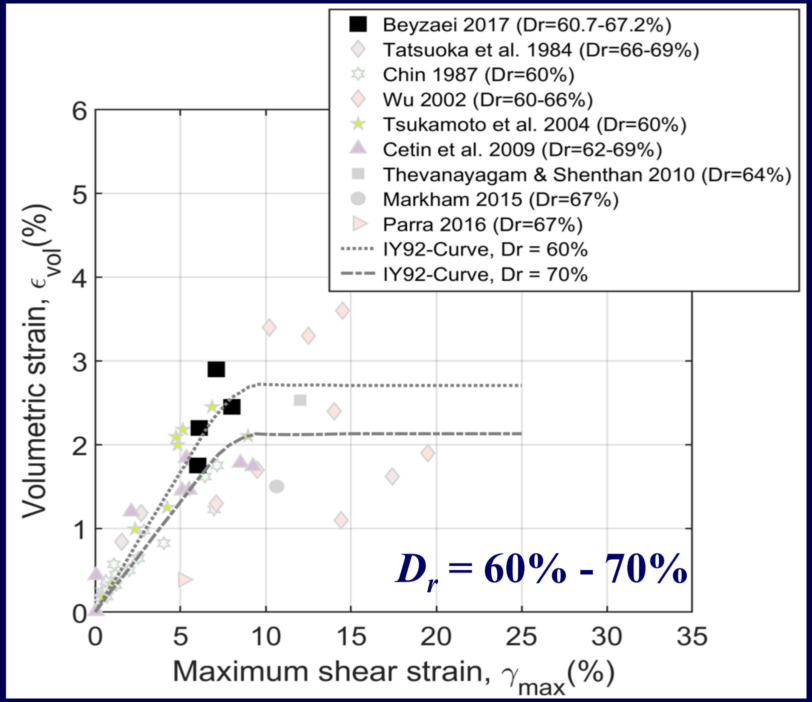
Clean Sand



Nonplastic Silty Sand



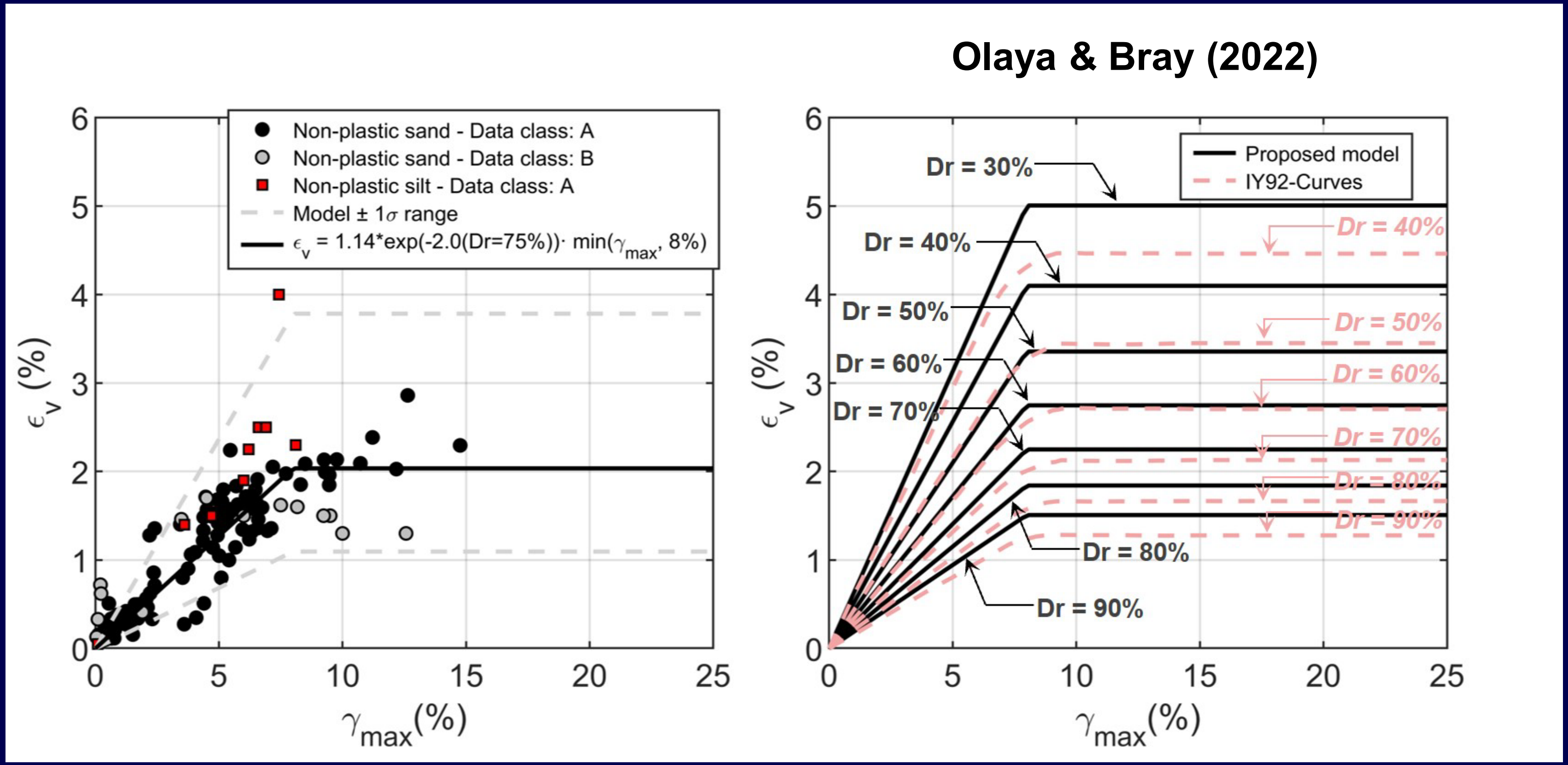
Nonplastic Silts



Soil gradations vary but all are uniform with C_u < 4, except Toriihara et al. 2000 sand, which has C_u = 18 and has compressible / crushable fine soil matrix that governs response

D_r -Based Model for ε_v Potential

Clean Sand & Nonplastic Silty Sand & Nonplastic Silts

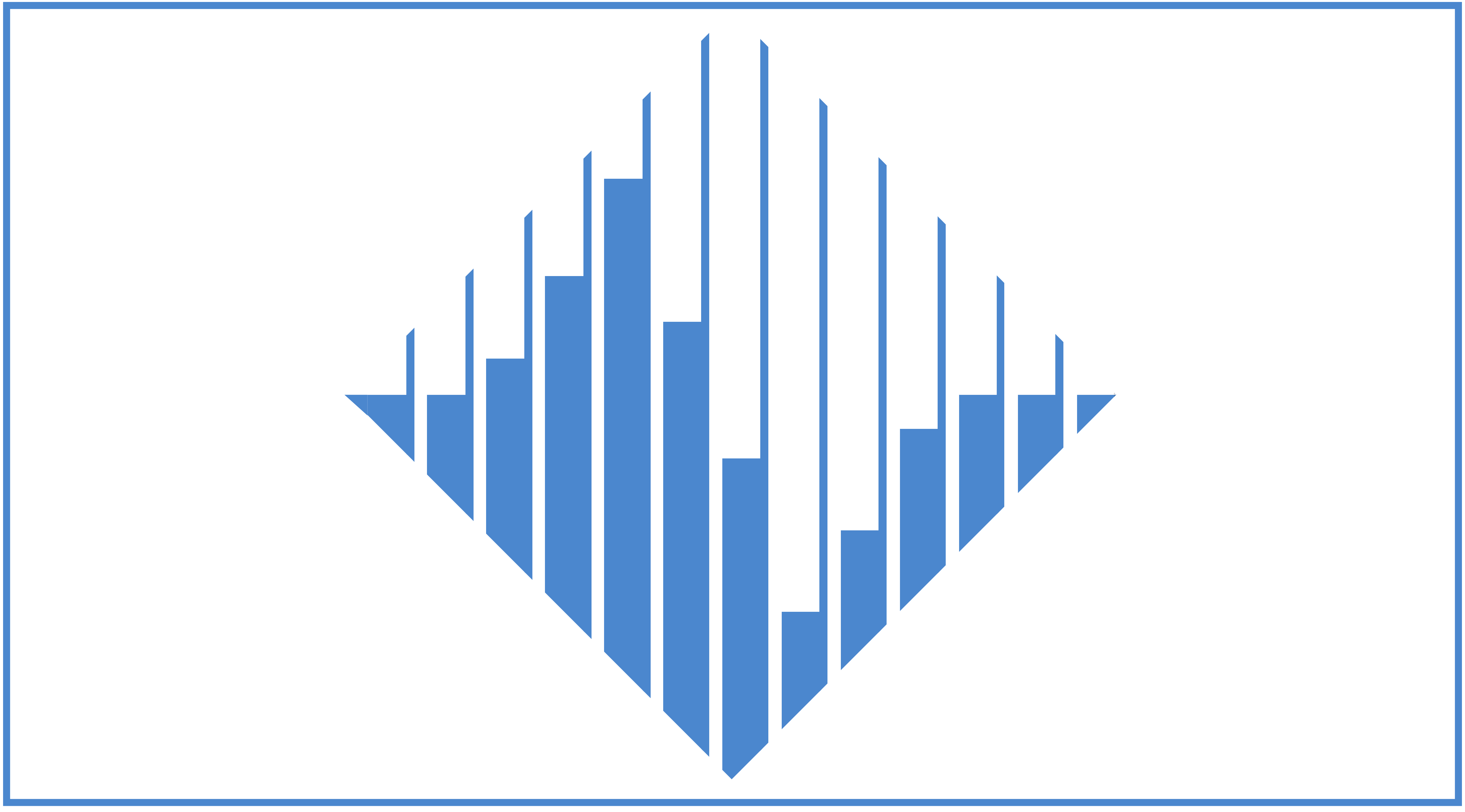


$$\varepsilon_v = 1.14 \exp(-2.0\ D_r) \cdot \min(\gamma_{max}, 8\%) \cdot e^{\varepsilon} \qquad [\sigma = 0.62]$$

- **Scatter in the data due to soil response variability, test variations, and different datasets**

CONCLUSIONS

- Focus on the effects of liquefaction
- Test soil that can be sampled effectively
- Use D_r to examine cyclic response of nonplastic silty soil
- Low-plasticity clayey silty soil responds like nonplastic silty soil
- Consider depositional environment and soil system response



Particle Fabric Imaging for Understanding Shear Response of Silts

PEER Liquefaction Susceptibility Workshop

Oregon State University
Corvallis, Oregon

September 08-09, 2022

Dharma Wijewickreme

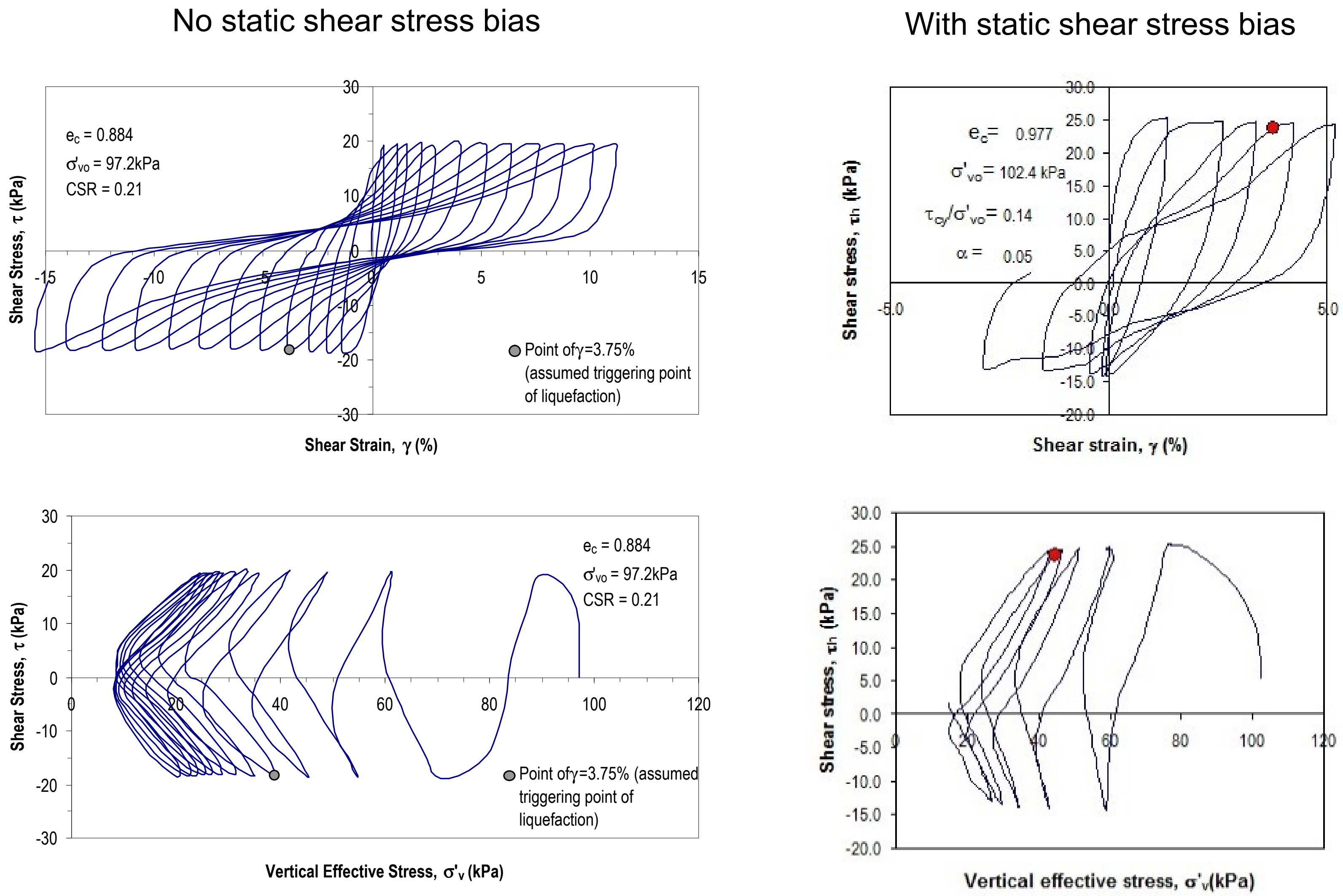
University of British Columbia
Vancouver, BC
Canada

Impetus

- Significant effect of fabric on the soil behaviour that cannot necessarily be expressed based on e - σ' in a continuum framework.
- Further knowledge on the particulate arrangement should support the understanding of silt behaviour.
- Potential of 3D imaging to study fabric – already demonstrated through coarse-grained soils.
- Due to technology advancements in micro-CT imaging, now possible to examine silt fabric.

Typical Cyclic Response of Silt

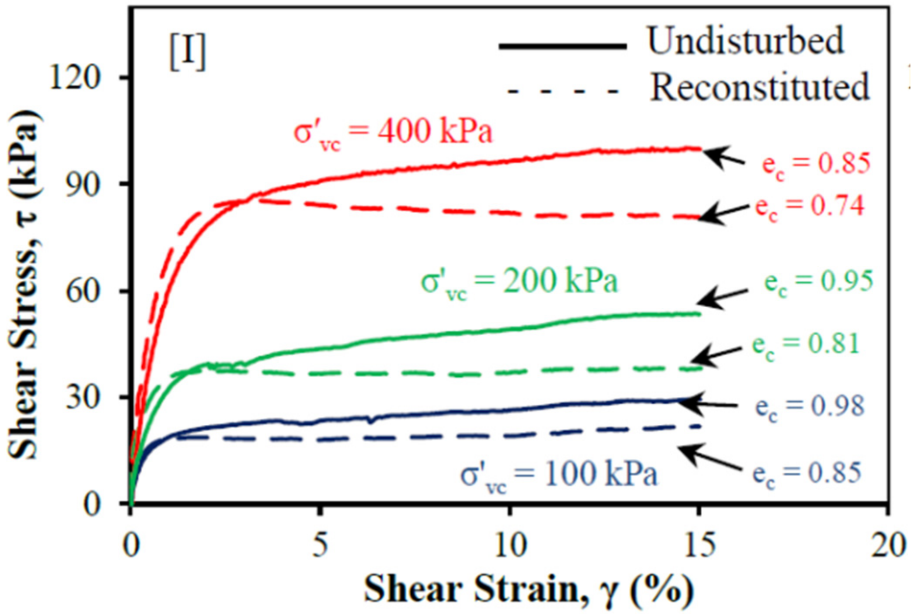
Relatively Undisturbed Natural Fraser River Silt (PI =4)

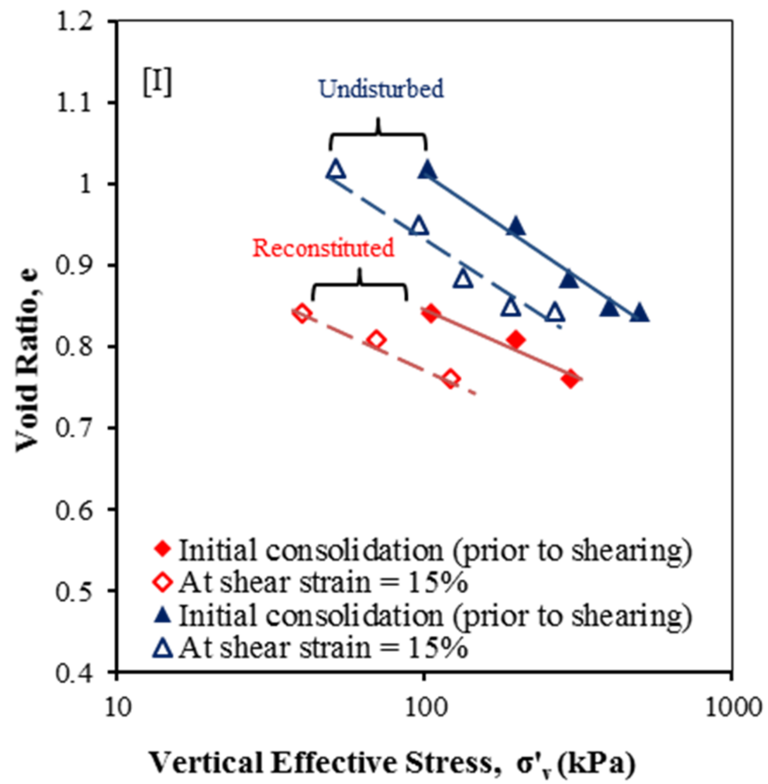


All cyclic mobility– No abrupt degradation of stiffness

Undisturbed vs. Reconstituted

Monotonic Loading – Fraser River Silt - PI = 4%

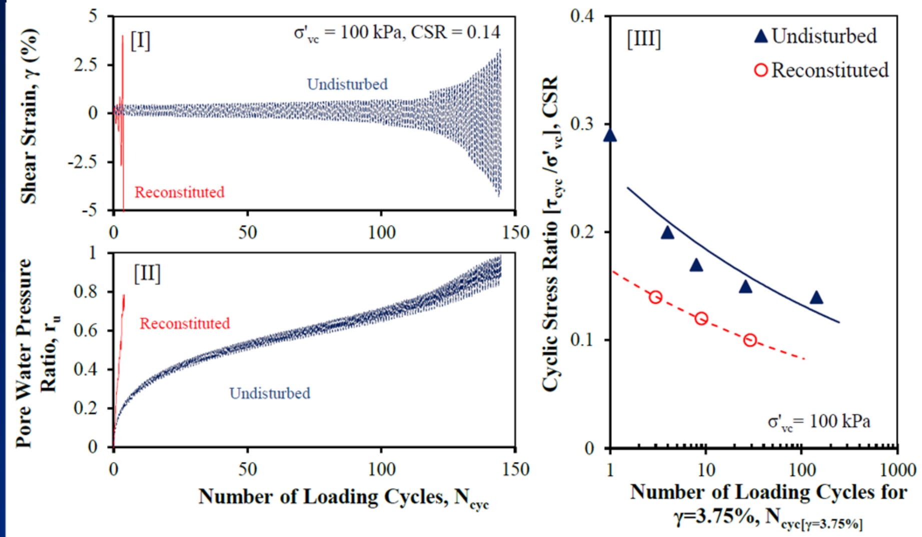




(Wijewickreme & Sanin 2008 and Sanin 2010)

Undisturbed vs. Reconstituted

Cyclic Loading Response

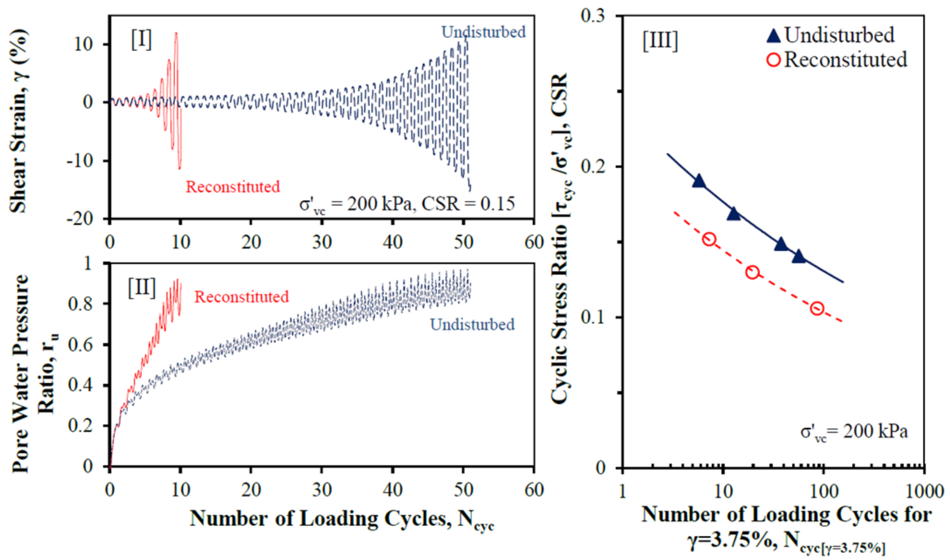


Fraser River Silt : PI = 4%

(Wijewickreme & Sanin 2008 and Sanin 2010)

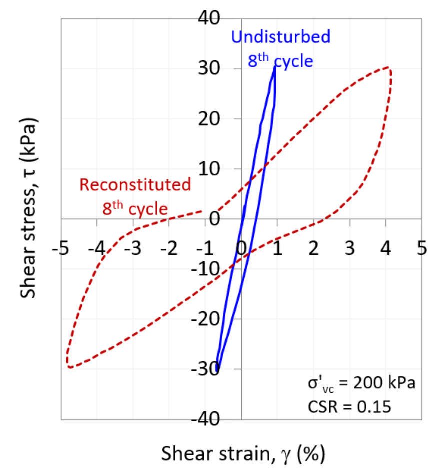
Undisturbed - e_c = 0.98

Reconstituted - e_c = 0.85



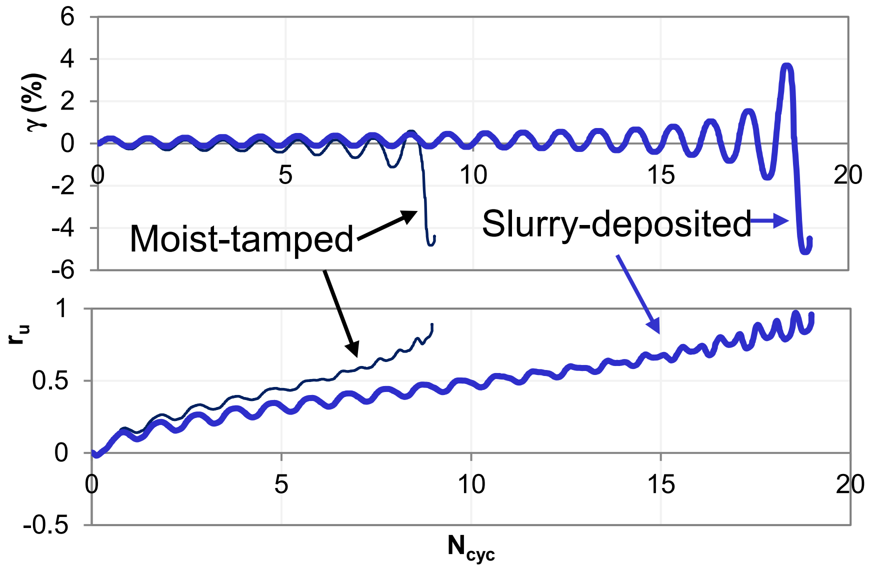
Nicomekl River Silt : PI ~ 7

(Soysa & Wijewickreme 2015)



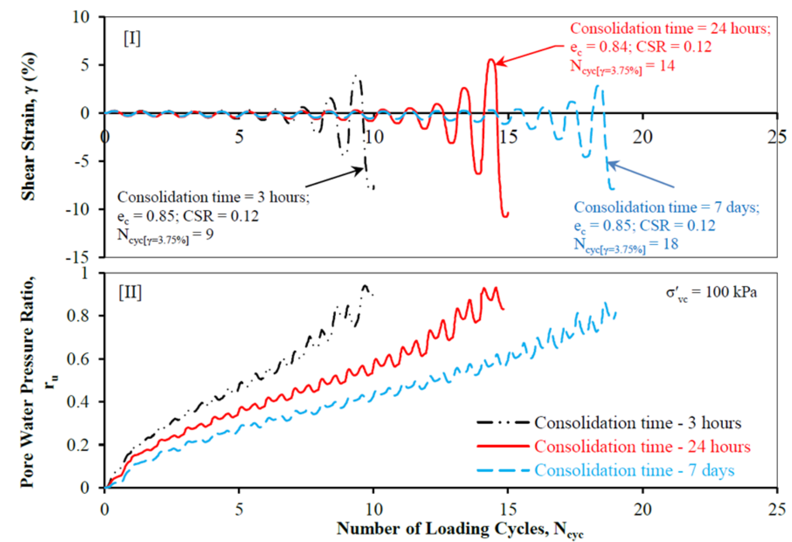
Effect of Specimen Preparation Method

Mine Tailings

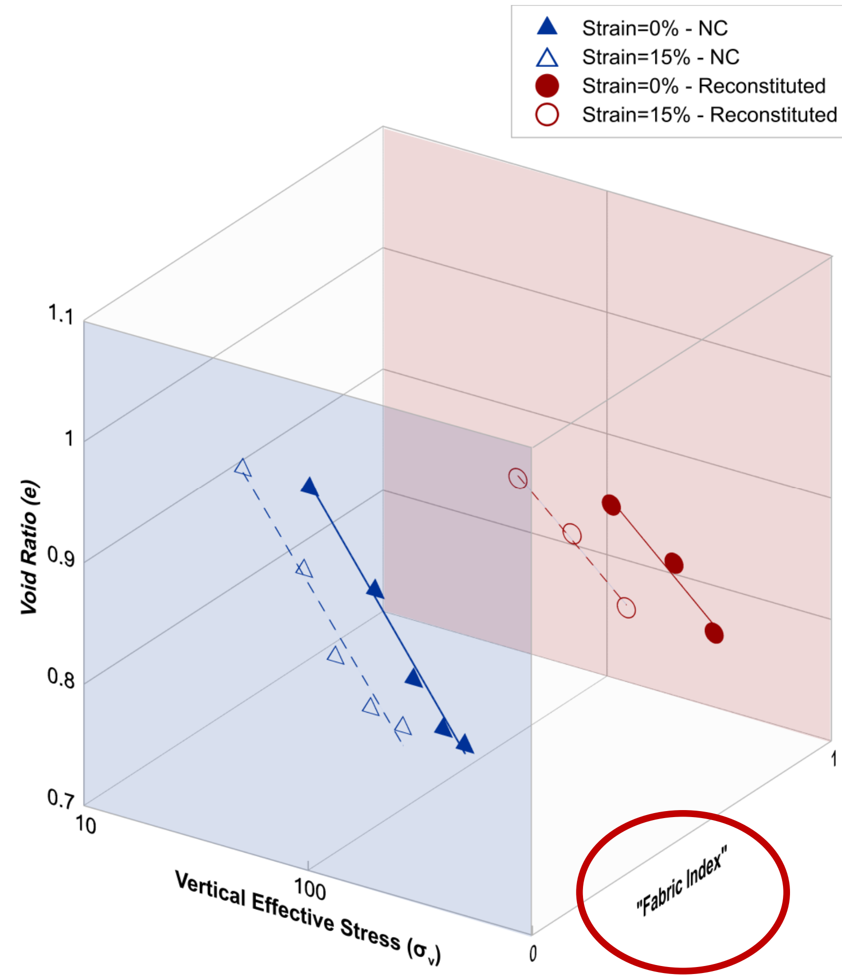


Effect of Ageing

Fraser River Silt
PI = 4%

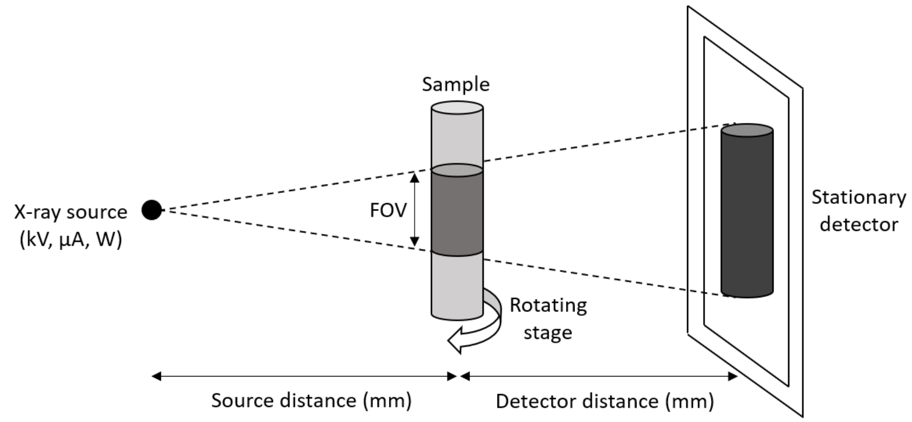


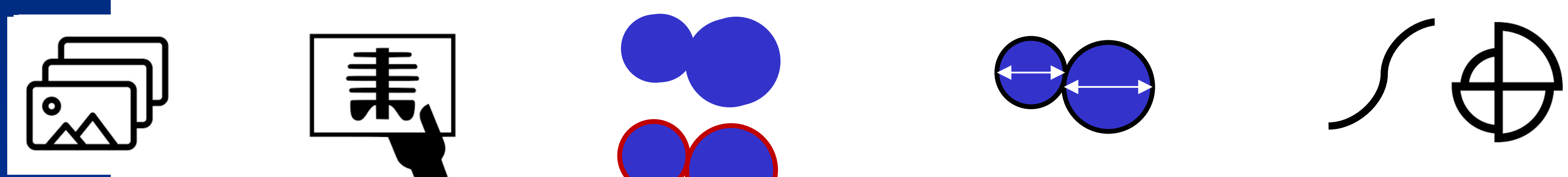
Beyond Element Testing… Need for a quantifying "Fabric Index" ($\mathscr{F}$) …?



X-ray μ-CT Scanning Process

Zeiss (2017)





Obtain Images using X-ray micro-CT technology ➡ Assess Quality ➡ Perform image filtering and particle segmentation ➡ Analysis of digital information on particles

e.g., Avizo software ➡ Possible outcomes:

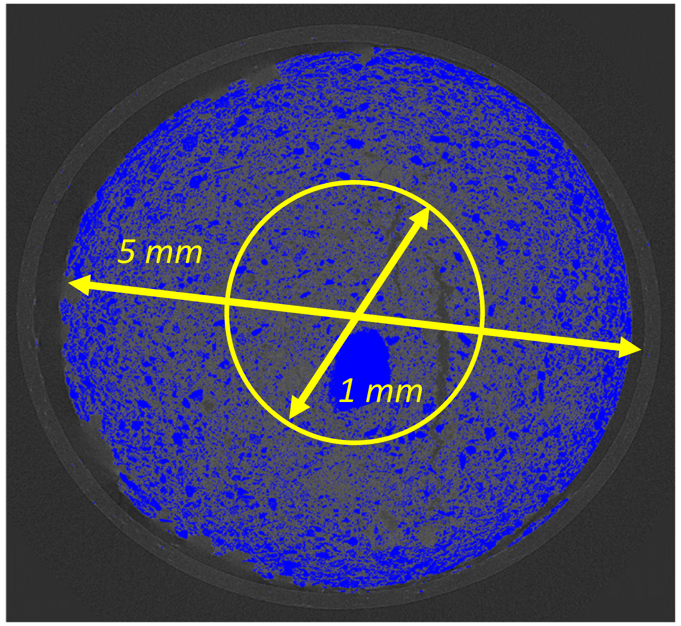
Grain size distribution
Void ratio

Particle contacts and orientations

Preparation of Specimens

- *Sub-samples obtained from usual size (~ 71 mm) tube samples.*
- *Plastic tubes for sub-sampling*
  - *Wall Thickness (t): 0.14 mm*
  - *Tube Diameter (D): 5 mm*
- *D/t: 36 ; D/D_{50} > 65 for silts*

Wall effects



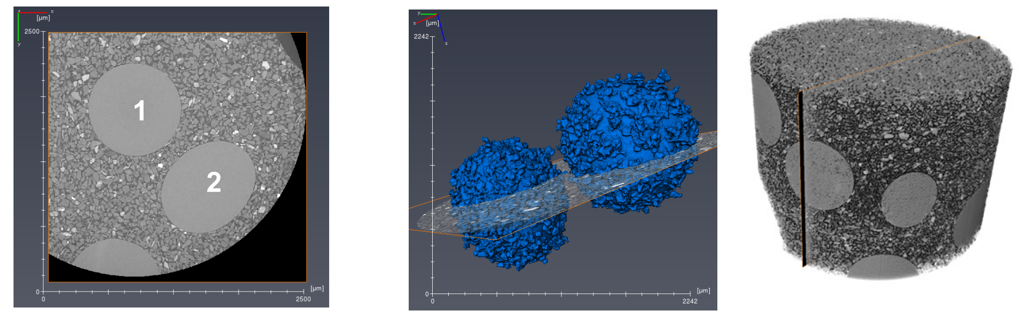
- Soil disturbance ~ 1 mm zone from the wall
- Use of the inner core of 1 mm diameter for imaging considered reasonable

Method Development / Validation Using Standard Particles

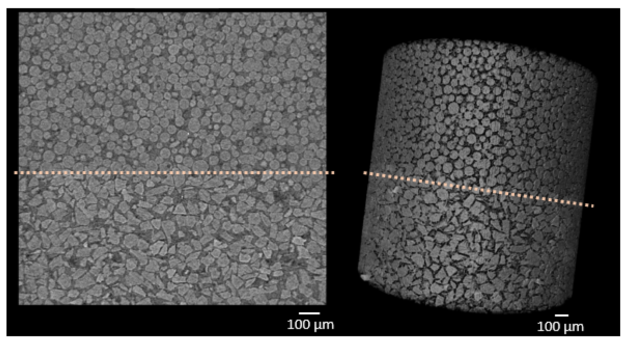
Material

Standard-sized silica particles from SiliCycle, Quebec, Canada. Sizes range in the ranges of: 5 - 20 µm, 20 - 45 µm; and 40 – 63 µm

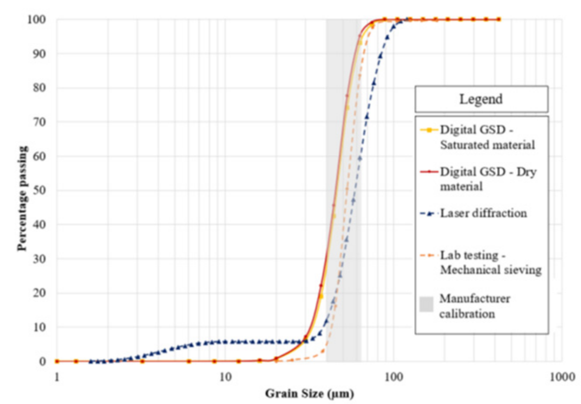
Size Checks



Layering Checks

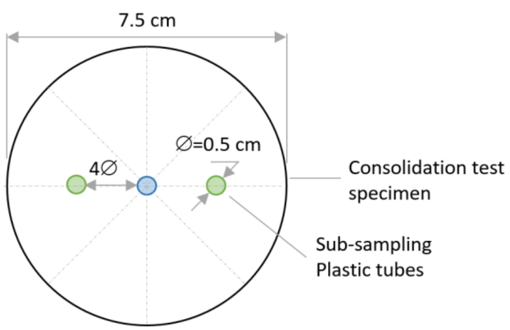


PSD Checks

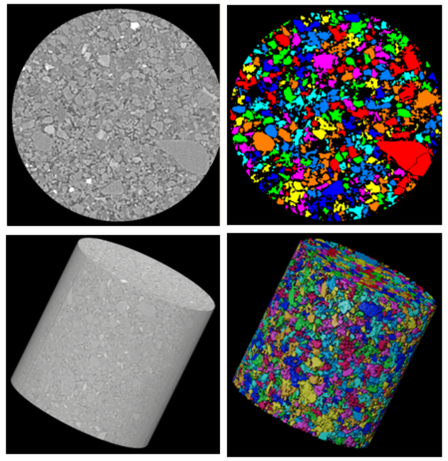


Method successful for images containing particles greater than 20 µm. The methodology was expanded to include natural silty material.

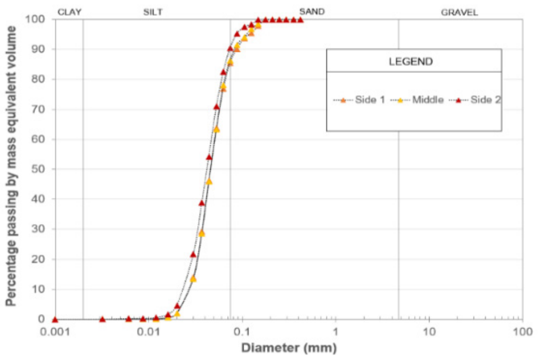
Extension to Imaging of Natural Silts



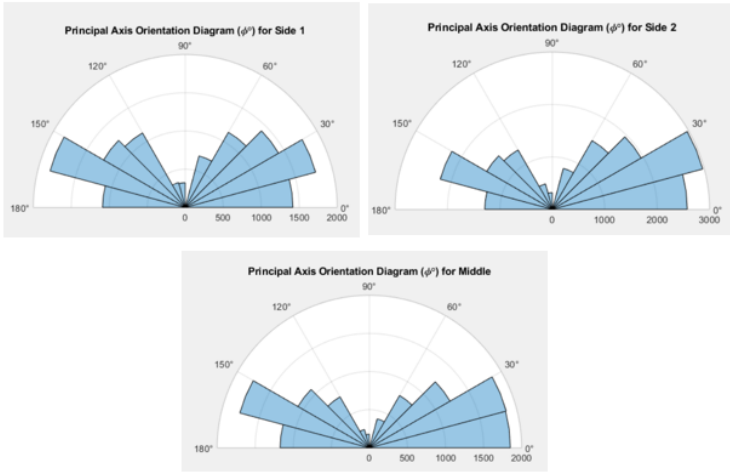
Subsampling of FR silt reconstituted consolidated specimen



Representative raw and processed images for the sub-samples of FR silt.

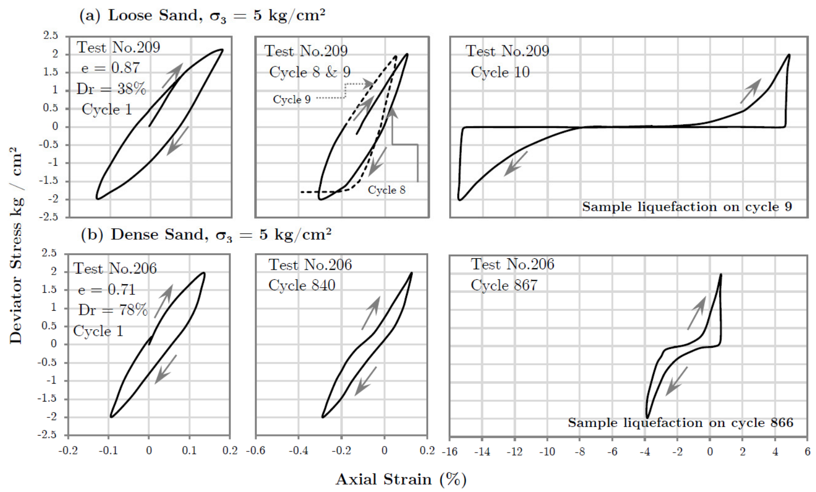


Digital GSD for FR silt

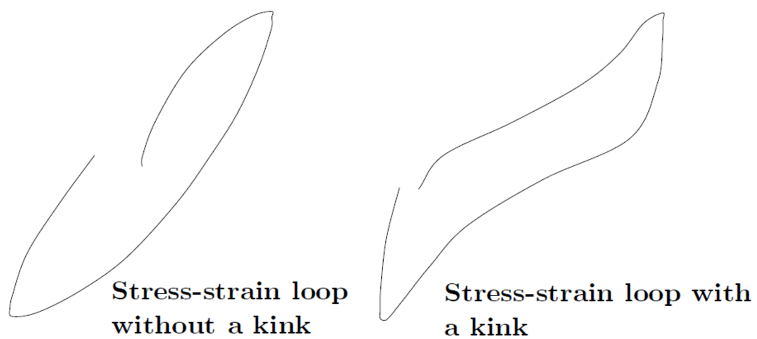


Rose diagrams of particle principal axis orientation for reconstituted specimens.

“Fabric Index” ($\mathscr{F}$) - where we want to be in 5 to 10 years!

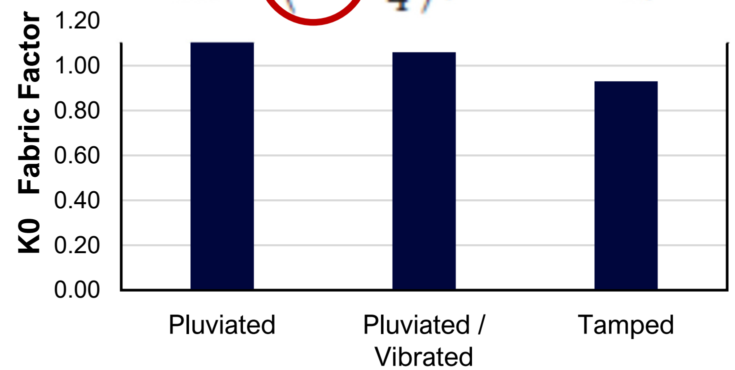


Hysteresis curves (Seed & Lee, 1966)



Stress-strain Loop Patterns
Wijewickreme and Soysa (2016)

$$K_{onc} = \left(F - \frac{D_r^2}{4}\right)(1 - \sin\phi'_{cv})$$



Effect of Fabric on K_o - Northcutt and Wijewickreme (2013)

Drawing from μ-CT images:

- void ratio
- Particle dimensions, shapes, grain orientation
- coordination number, etc.

& correlating those with cyclic loading response features such as:

- Cyclic hysteresis
- pwp generation
- Stiffness degaradation

Great opportunity to establish and quantify a Fabric Index” ($\mathscr{F}$) - Scalar or Tensor!

Summary

- Knowledge on the particulate fabric needed to understand complex silt behaviour. Due to technology advancements in micro-CT imaging, it is now possible to examine silt fabric.

- Excellent capability of X-ray μ-CT to obtain 3D images for silt sizes > 20 μm is demonstrated.

- X-ray μ-CT images would allow obtaining: void ratio, particle dimensions/shapes, grain orientation, coordination number, etc.
- Correlating with the cyclic loading observations such as hysteresis, pwp generation, stiffness degaradation, a great opportunity exists to establish and quantify a Fabric Index" ($\mathscr{F}$) - scalar or tensor

- Future study:
  - Particle arrangement under different shear loading.
  - Effects of density, method of soil specimen reconstitution, etc., on the particle fabric.
  - Develop fabric factor to express macroscopic mechanical behavior of silts.

Acknowledgements

- Natural Sciences and Engineering Research Council of Canada (NSERC)

NSERC CRSNG

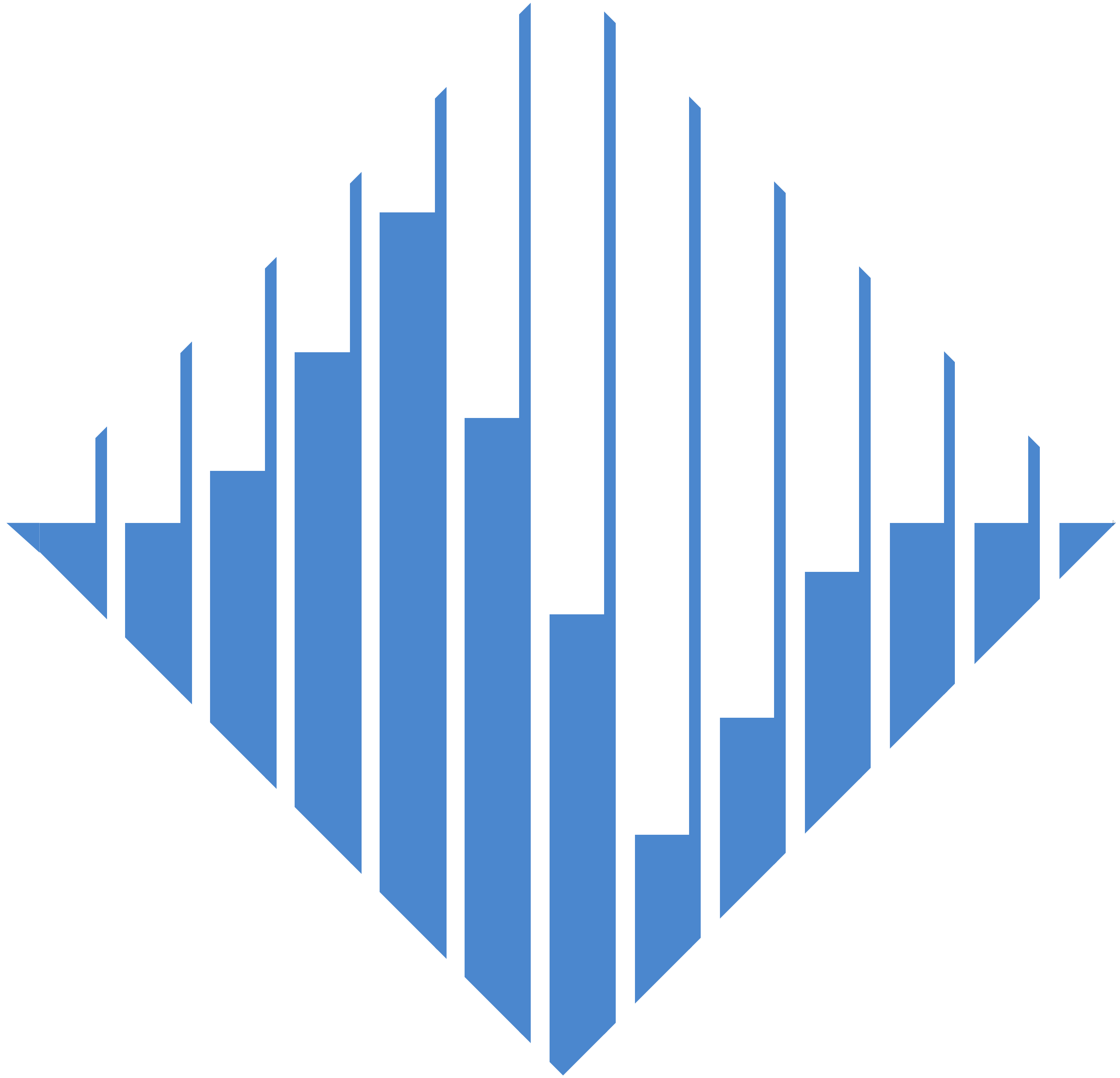
- Dr. Mark Martinez, UBC Pulp and Paper Center and the UBCO Composites Research Network for micro-CT equipment and imaging

- Ana Valverde, PhD Candidate, UBC

- Initial start-up work from previous graduate students

Thank You!

Photo extracted from: https://www.nasa.gov/



PEER Workshop on Liquefaction Susceptibility
Thursday, September 8, 2022

Geospatial Models for Liquefaction Susceptibility

Session 2: Where do we want to be in 5-10 Years?

Laurie Gaskins Baise, Ph.D., Professor and Chair
Department of Civil and Environmental Engineering, Tufts University

Tufts UNIVERSITY

Global Geospatial Liquefaction Models

developed at Tufts and funded by:
NSF Award #1300781 and
USGS NEHRP Award #G16AP00014 and USGS NEHRP Award #G20AP00029 and USGS NEHRP Award #G22AP00048
and support from FM Global

Contributions from:
Tufts: Davene Daley, Jing Zhu, Vahid Rashidian, Michele Meyer, Alex Chansky, Ashkan Akhlaghi, Babak Moaveni, Adel Asadi, Weiwei Zhan
USGS: Keith Knudsen, Eric Thompson, and David Wald

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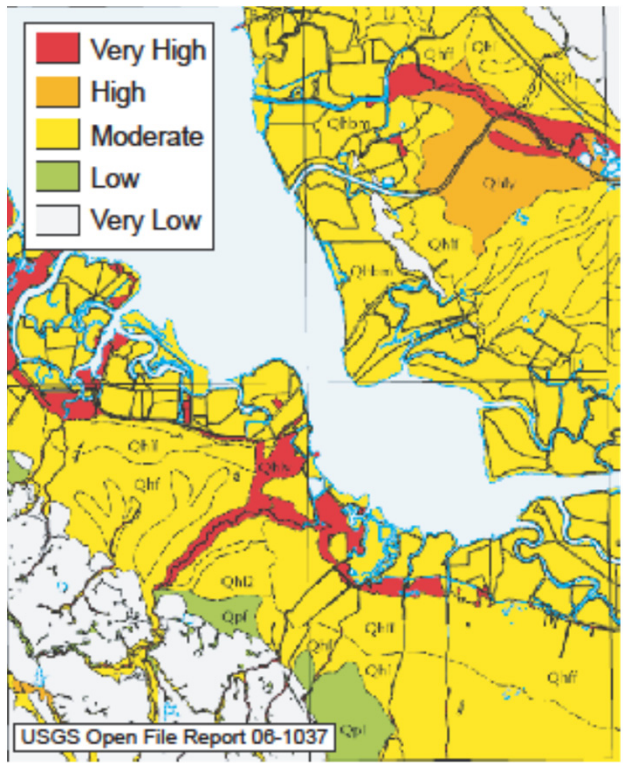
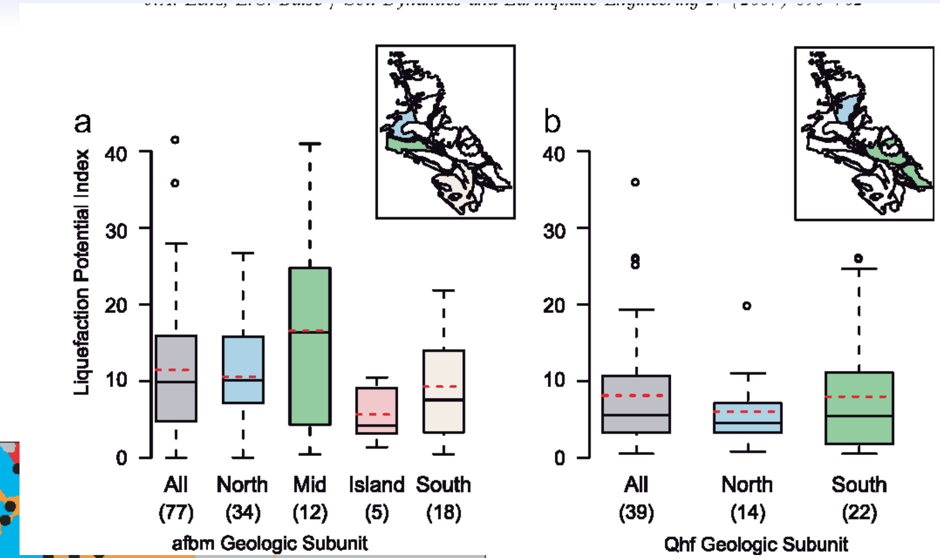
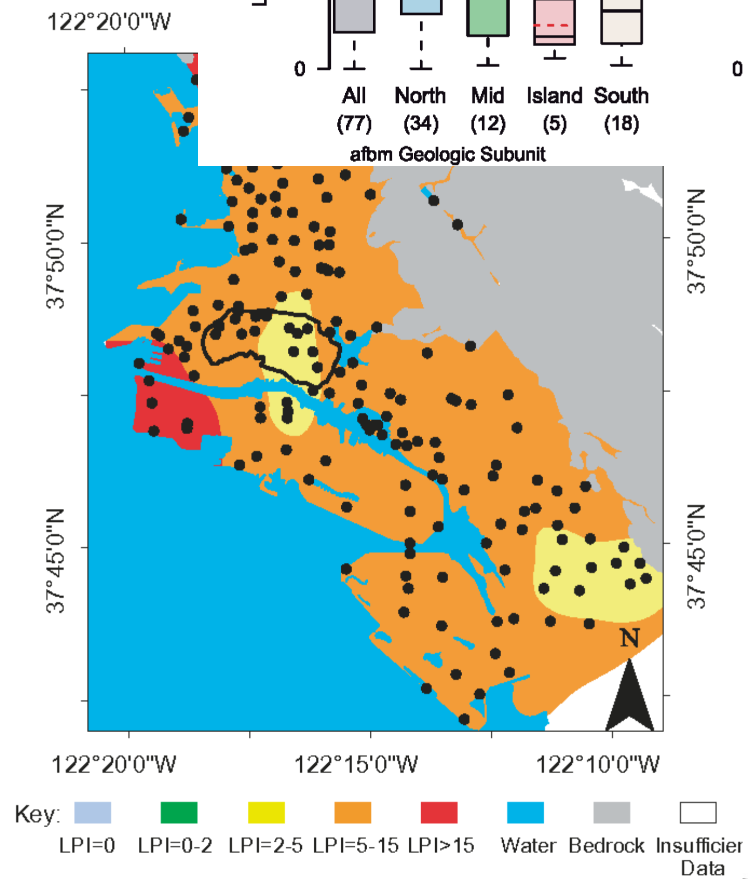
Regional Liquefaction Susceptibility Maps

- Regional Liquefaction Susceptibility Maps
  - Geology
  - Geotechnical





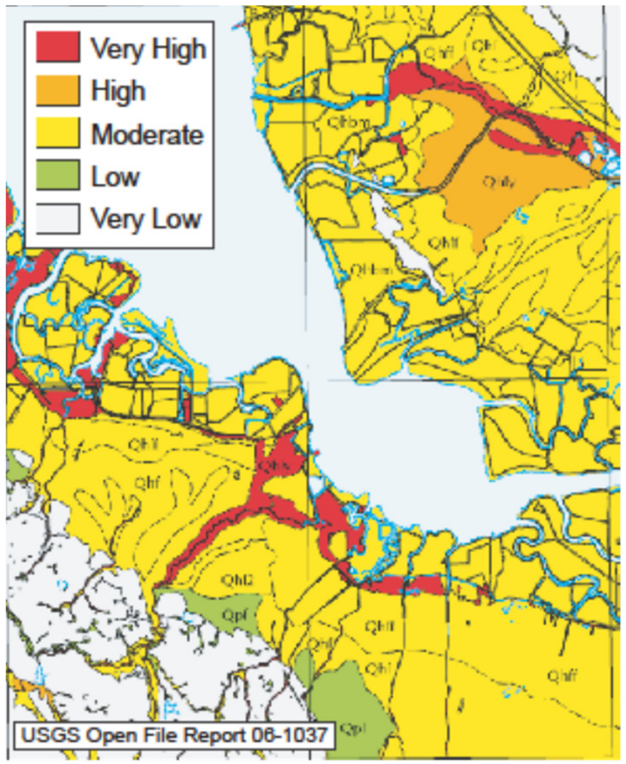


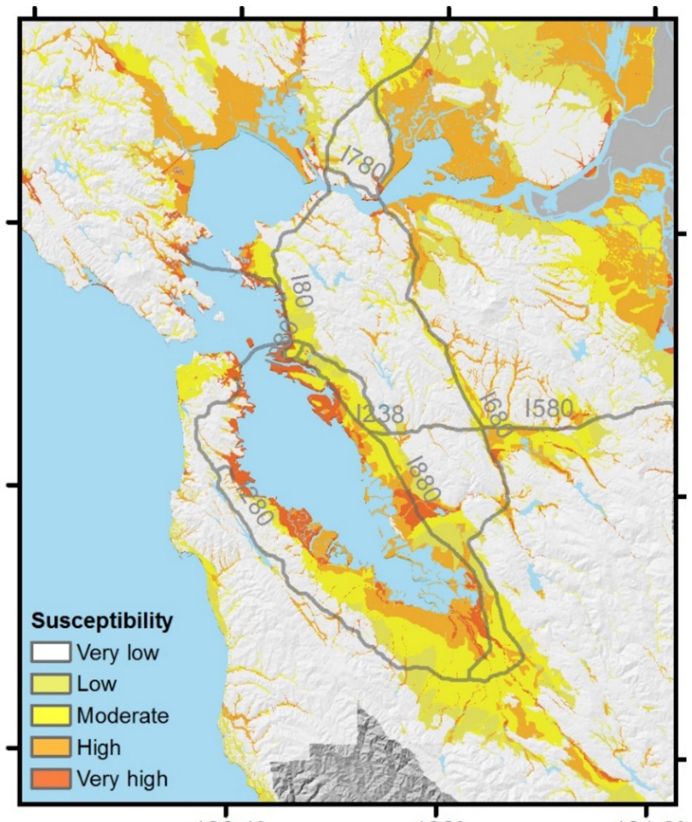
USGS Open File Report 06-1037

Lenz and Baise (2007). Spatial Variability of liquefaction potential in regional mapping using CPT and SPT data. SDEE. 690-702.

Regional Liquefaction Susceptibility Maps

- **Geologic Approach**
  - Rely on detailed Quaternary Surficial Geology Maps
  - Generally Qualitative
  - Susceptibility Map





Youd and Perkins (1978)

Type of deposit (1)	General distribution of cohesionless sediments in deposits (2)	Likelihood that Cohesionless Sediments, When Saturated, Would Be Susceptible to Liquefaction (by Age of Deposit)			
		<500 yr (3)	Holocene (4)	Pleistocene (5)	Pre-pleistocene (6)
(a) Continental Deposits					
River channel	Locally variable	Very high	High	Low	Very low
Flood plain	Locally variable	High	Moderate	Low	Very low
Alluvial fan and plain	Widespread	Moderate	Low	Low	Very low
Marine terraces and plains	Widespread	—	Low	Very low	Very low
Delta and fan-delta	Widespread	High	Moderate	Low	Very low
Lacustrine and playa	Variable	High	Moderate	Low	Very low
Colluvium	Variable	High	Moderate	Low	Very low
Talus	Widespread	Low	Low	Very low	Very low
Dunes	Widespread	High	Moderate	Low	Very low
Loess	Variable	High	High	High	Unknown
Glacial till	Variable	Low	Low	Very low	Very low
Tuff	Rare	Low	Low	Very low	Very low
Tephra	Widespread	High	High	?	?
Residual soils	Rare	Low	Low	Very low	Very low
Sebka	Locally variable	High	Moderate	Low	Very low
(b) Coastal Zone					
Delta	Widespread	Very high	High	Low	Very low
Esturine	Locally variable	High	Moderate	Low	Very low
Beach					
High wave energy	Widespread	Moderate	Low	Very low	Very low
Low wave energy	Widespread	High	Moderate	Low	Very low
Lagoonal	Locally variable	High	Moderate	Low	Very low
Fore shore	Locally variable	High	Moderate	Low	Very low

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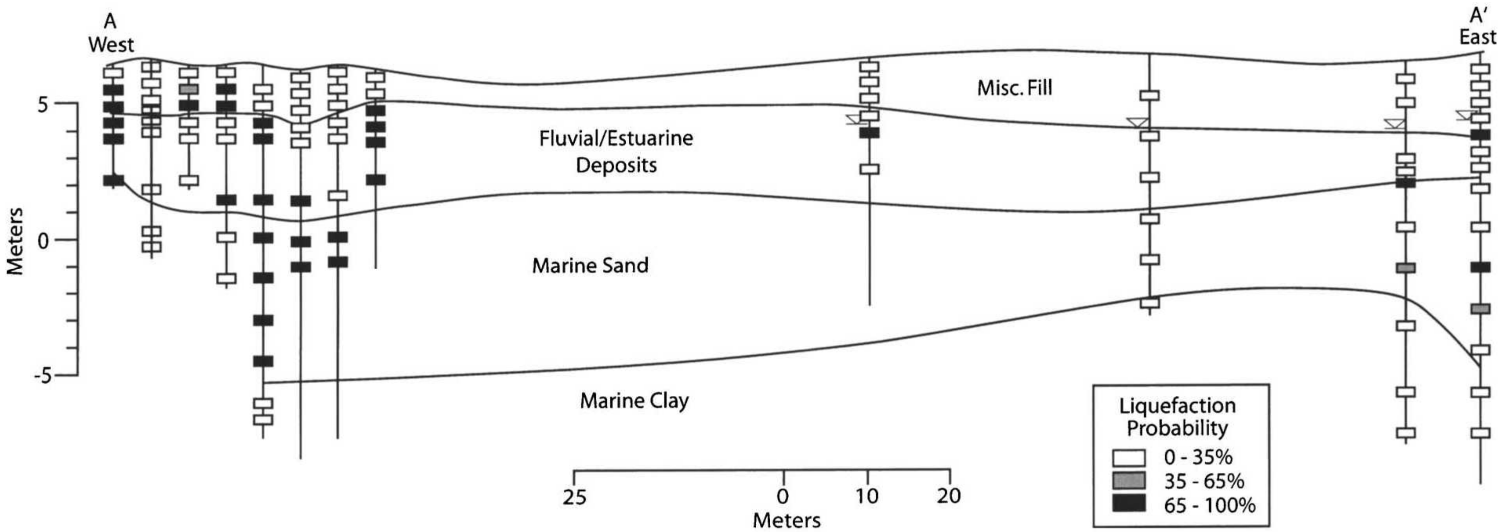
Regional Liquefaction Susceptibility Maps

- **Geotechnical Approach**
  - Rely on geotechnical data-which may be sparse
  - Can be quantitative but are often spatially incomplete
    - Often use Probability or geostatistics to deal with variability
  - Susceptibility map or hazard map



Baise, L.G., Higgins, R.B., and Brankman, C.M. (2006). Liquefaction Hazard Mapping – statistical and spatial characterization of susceptible units, JGGE, 132:6, 705-715.
Brankman, C. M. and Baise, L. G. (2008). Liquefaction Susceptibility Mapping in Boston, Massachusettts, *Engineering and Environmental Geoscience*, **XIV** (1), pp. 1-16.

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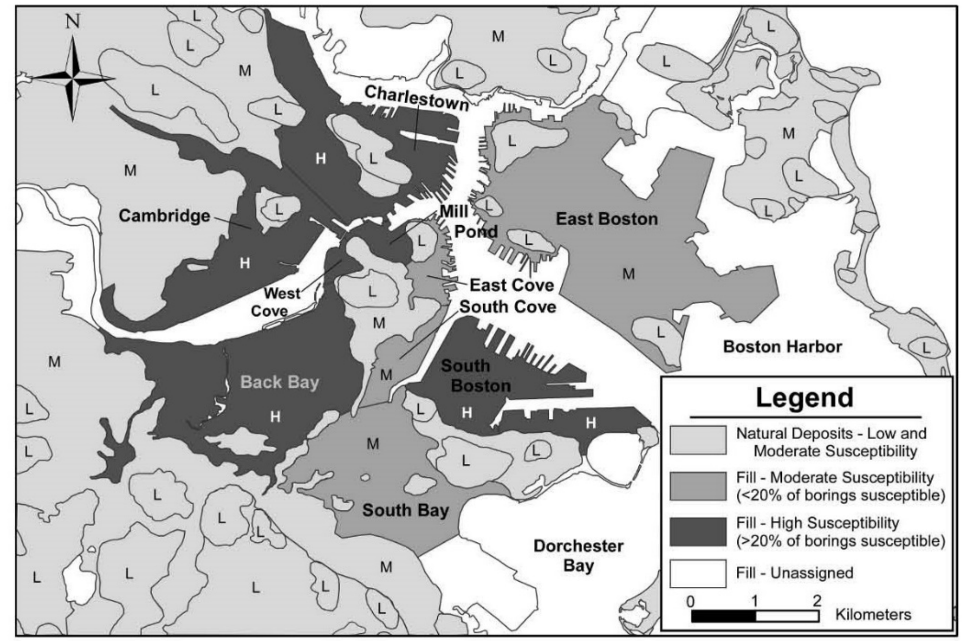
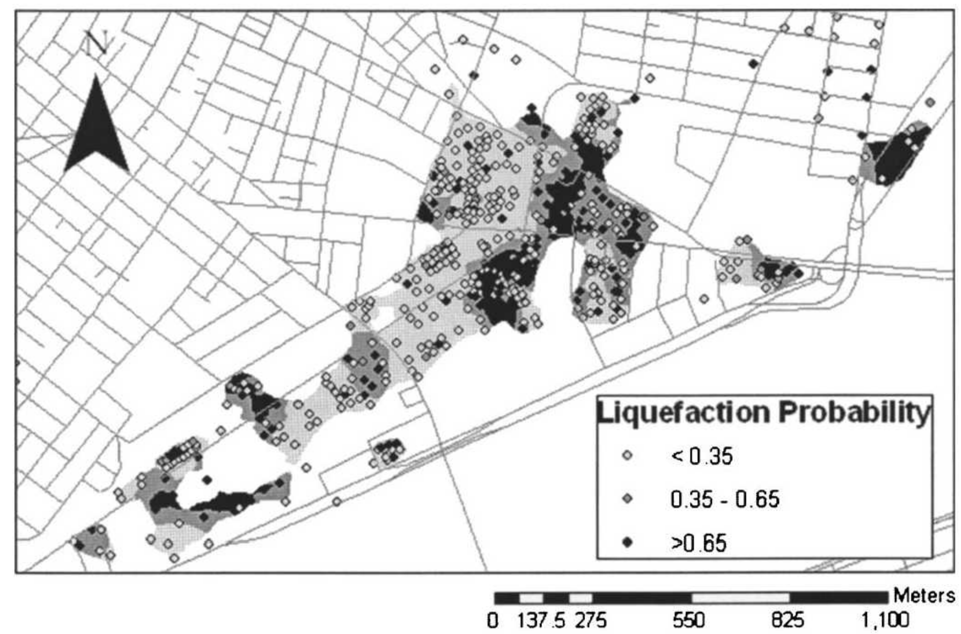
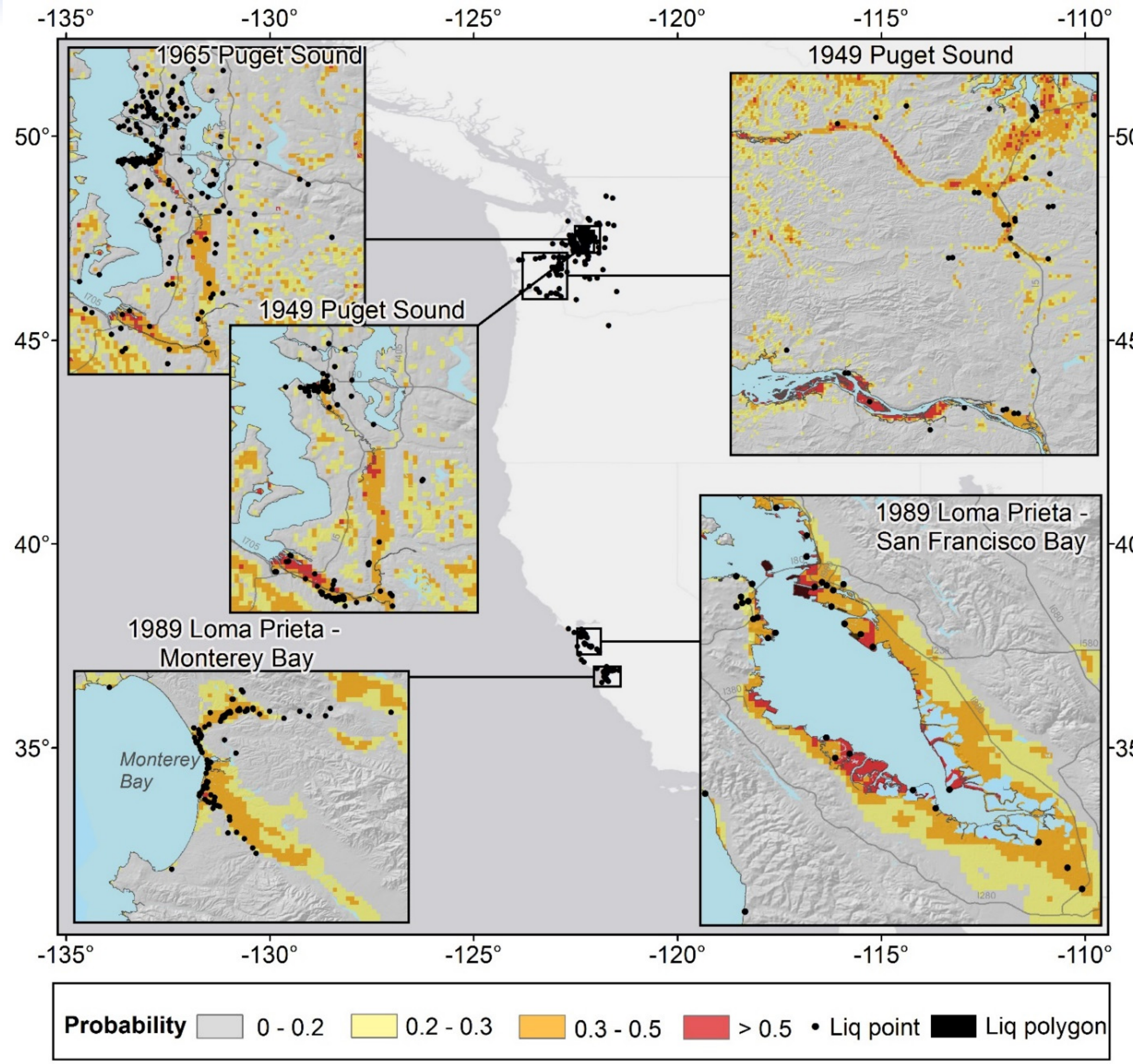


Figure 8. Detail map showing varying liquefaction susceptibility of fill units in downtown Boston.



Geospatial Regional Liquefaction Assessment

- Geospatial Approach
  - Global implementation
  - Widely available geospatial parameters as proxies for important soil properties
    - Slope-derived V_{S30} -> soil density
    - Distance to Water -> soil saturation
  - Include shaking intensity
    - PGA and PGV from ShakeMap for rapid implementation
  - Quantitative Assessment
    - Logistic regression – probability
    - Spatial Extent
    - Can link to loss estimation



Zhu, J., Baise, L.G., and Thompson, E.M. (2017). An Updated Geospatial Liquefaction Model for Global Application, *Bull. Seism. Soc. Am*. 107 (3).

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Geospatial Regional Liquefaction Assessment

- **Why it Works**
  - **Youd and Perkins (1978) and Knudsen and Bott (2011)**
    - **Liquefaction occurs in young sediments, near water bodies, and on low flat ground**
  - Wald and Allen (2007)
    - Topographic slope is related to soil density
  - Topography-based assessment of hydrology (based on DEM)

Type of deposit (1)	General distribution of cohesionless sediments in deposits (2)	Likelihood that Cohesionless Sediments, When Saturated, Would Be Susceptible to Liquefaction (by Age of Deposit): <500 yr (3)	Holocene (4)	Pleistocene (5)	Prepleistocene (6)
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Geospatial Regional Liquefaction Assessment

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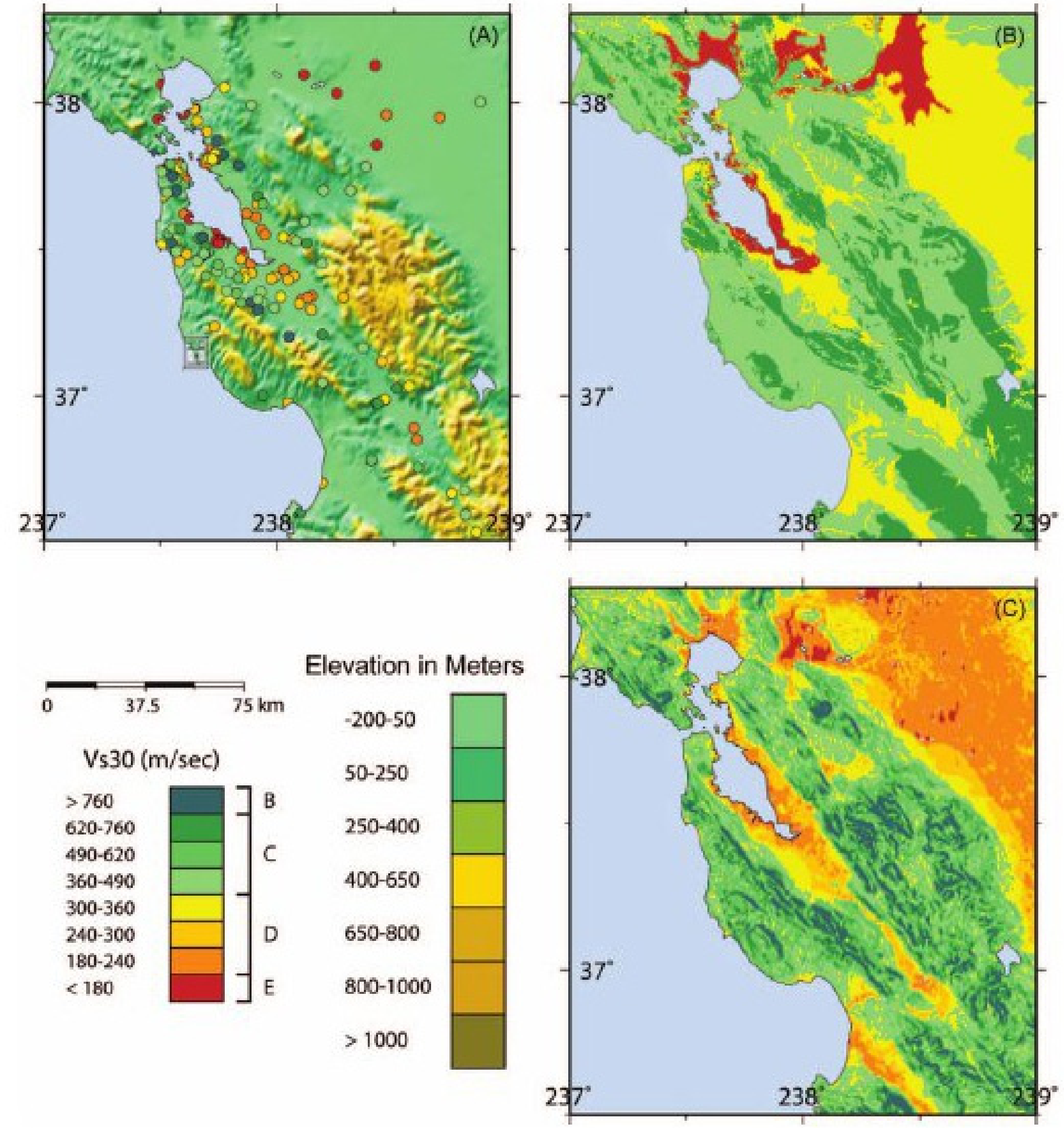
Wald and Allen 2007



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Geospatial Regional Liquefaction Assessment

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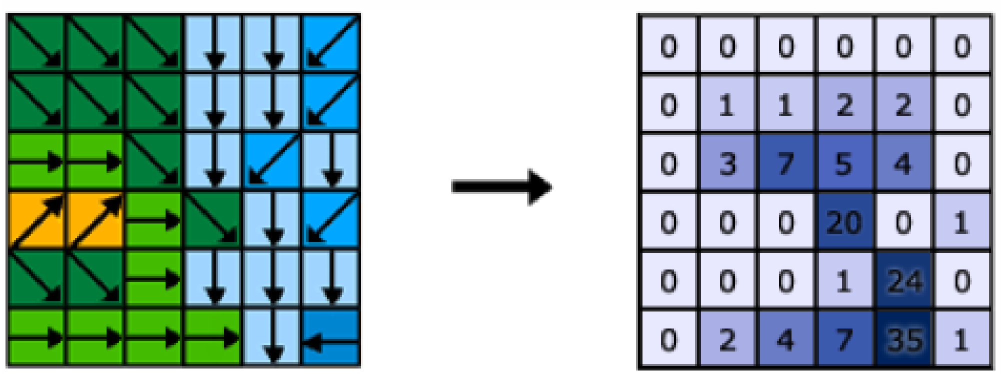
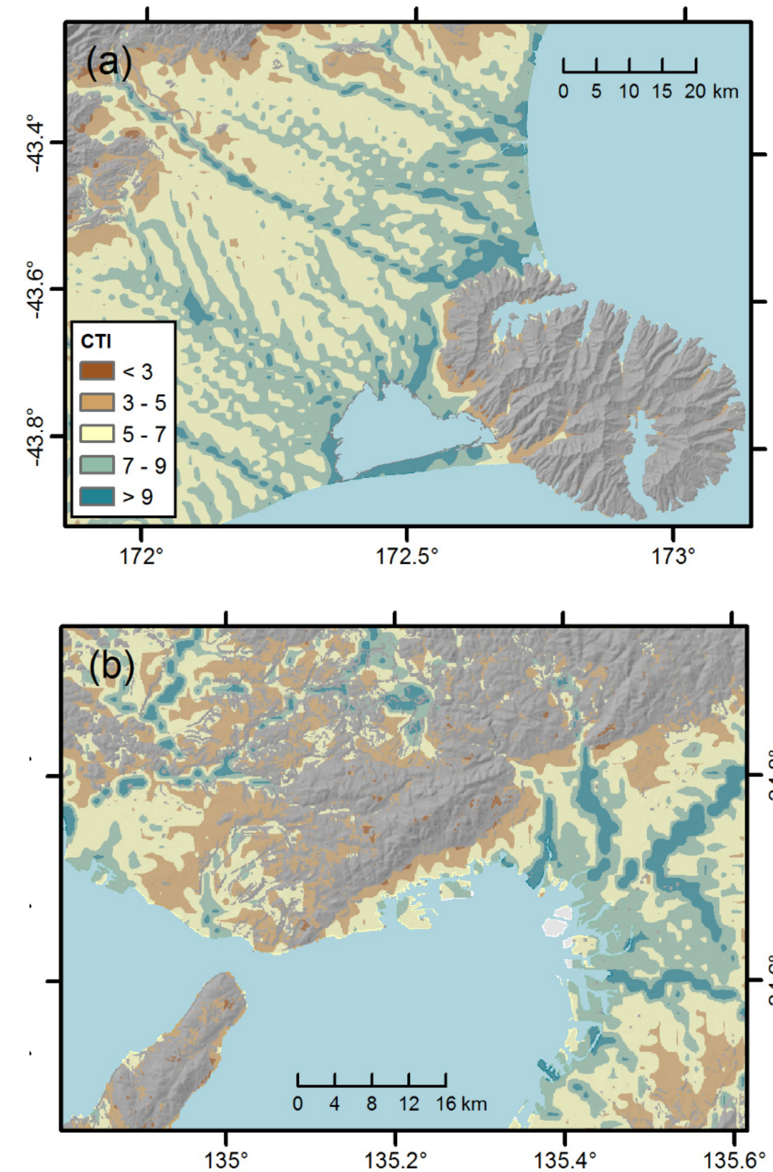
    - Topographic slope is related to soil density
  - **Topography-based assessment of hydrology (based on DEM)**



Flow direction → Flow accumulation

(Esri: Flow accumulation representation)



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GLOBAL/GEOSPATIAL LIQUEFACTION ASSESSMENT

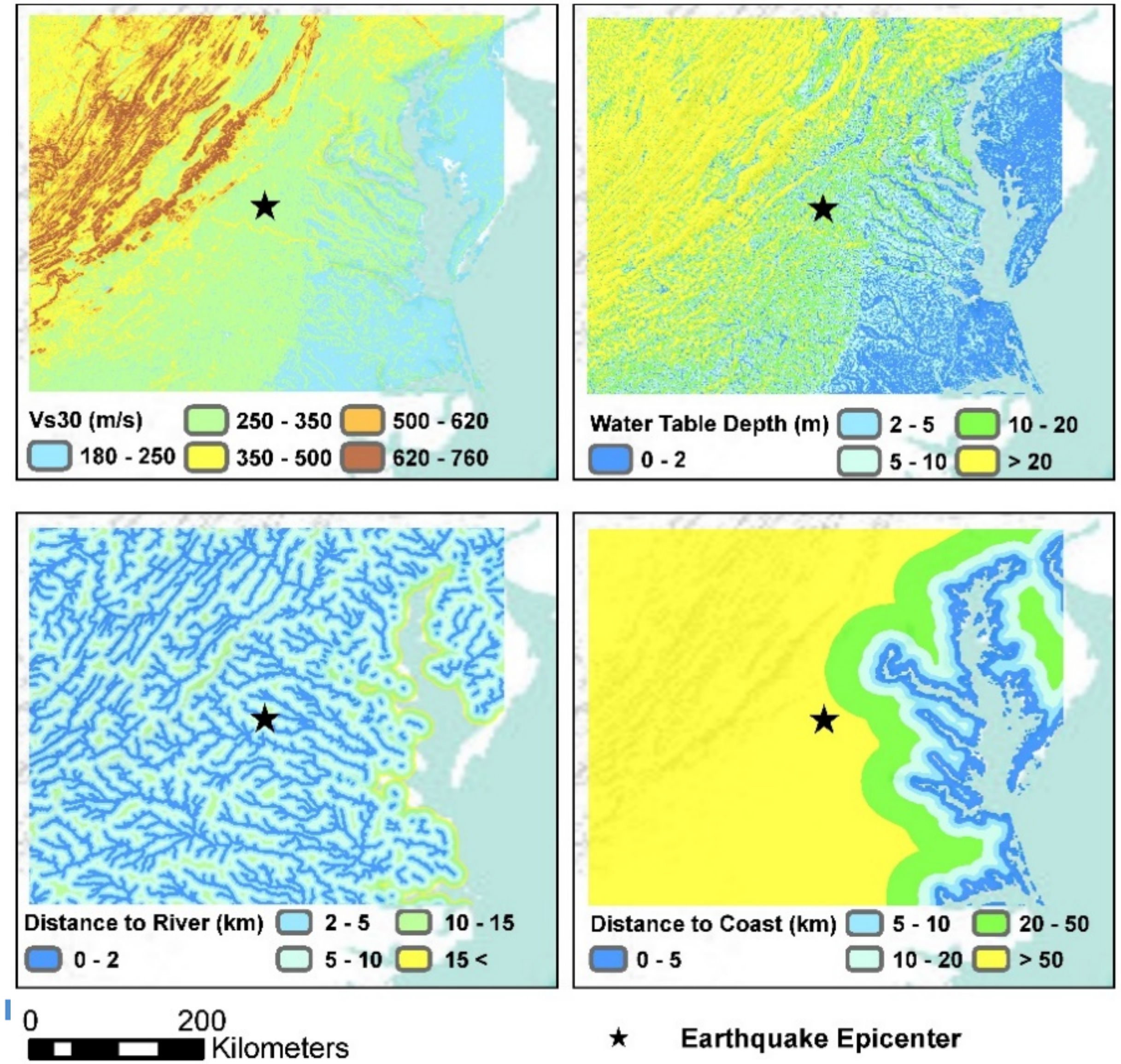
- **METHODOLOGY**

Soil Density

  - GEOSPATIAL PARAMETERS/PROXIES

Variable Name	Variable Description	Density	Saturation	Load
Vs_{30}	Shear-wave velocity over the first 30 m	•		
Elev *(+std)*	Elevation	•		
slope	Topographic slope	•		
soil_thickness	Soil and sedimentary deposit thickness	•		
upland_lowland	Uplands vs. Lowlands	•		
TPI	Topographic Position Index	•		
TRI	Terrain Roughness Index	•		
dc	Distance to the nearest coast	•	•	
dr	Distance to the nearest river		•	
dwb	Distance to the nearest water body		•	
CTI	Compound topographic index		•	
wtd	Global water table depth		•	
zwb	Elevation above the nearest water body		•	
precip	Mean annual precipitation		•	
AI	Aridity index		•	
PGA *(+std)*	Peak ground acceleration			•
PGV *(+std)*	Peak ground velocity			•
Mw	Magnitude			•

2011 Mineral Earthquake



GLOBAL/GEOSPATIAL LIQUEFACTION ASSESSMENT

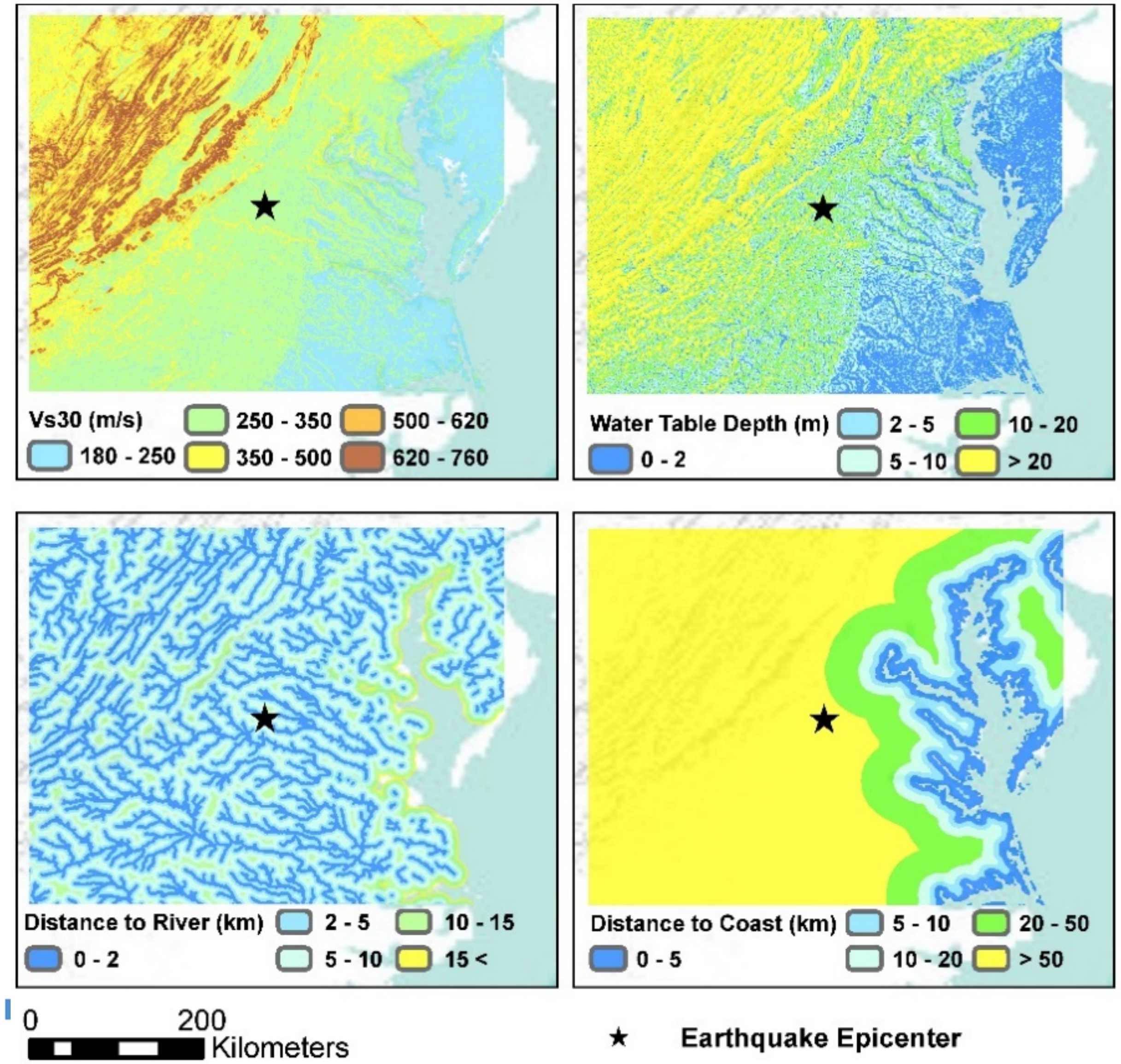
- **METHODOLOGY**

Soil Saturation

  - GEOSPATIAL PARAMETERS/PROXIES

Variable Name	Variable Description	Density	Saturation	Load
Vs_{30}	Shear-wave velocity over the first 30 m	•		
Elev *(+std)*	Elevation	•		
slope	Topographic slope	•		
soil_thickness	Soil and sedimentary deposit thickness	•		
upland_lowland	Uplands vs. Lowlands	•		
TPI	Topographic Position Index	•		
TRI	Terrain Roughness Index	•		
dc	Distance to the nearest coast	•	•	
dr	Distance to the nearest river		•	
dwb	Distance to the nearest water body		•	
CTI	Compound topographic index		•	
wtd	Global water table depth		•	
zwb	Elevation above the nearest water body		•	
precip	Mean annual precipitation		•	
AI	Aridity index		•	
PGA *(+std)*	Peak ground acceleration			•
PGV *(+std)*	Peak ground velocity			•
Mw	Magnitude			•

2011 Mineral Earthquake



Global/Geospatial Liquefaction Assessment

- **Methodology**

Earthquake Loading

- Geospatial parameters/proxies

Variable Name	Variable Description	Density	Saturation	Load
Vs_{30}	Shear-wave velocity over the first 30 m	•		
Elev *(+std)*	Elevation	•		
slope	Topographic slope	•		
soil_thickness	Soil and sedimentary deposit thickness	•		
upland_lowland	Uplands vs. Lowlands	•		
TPI	Topographic Position Index	•		
TRI	Terrain Roughness Index	•		
dc	Distance to the nearest coast	•	•	
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wtd	Global water table depth		•	
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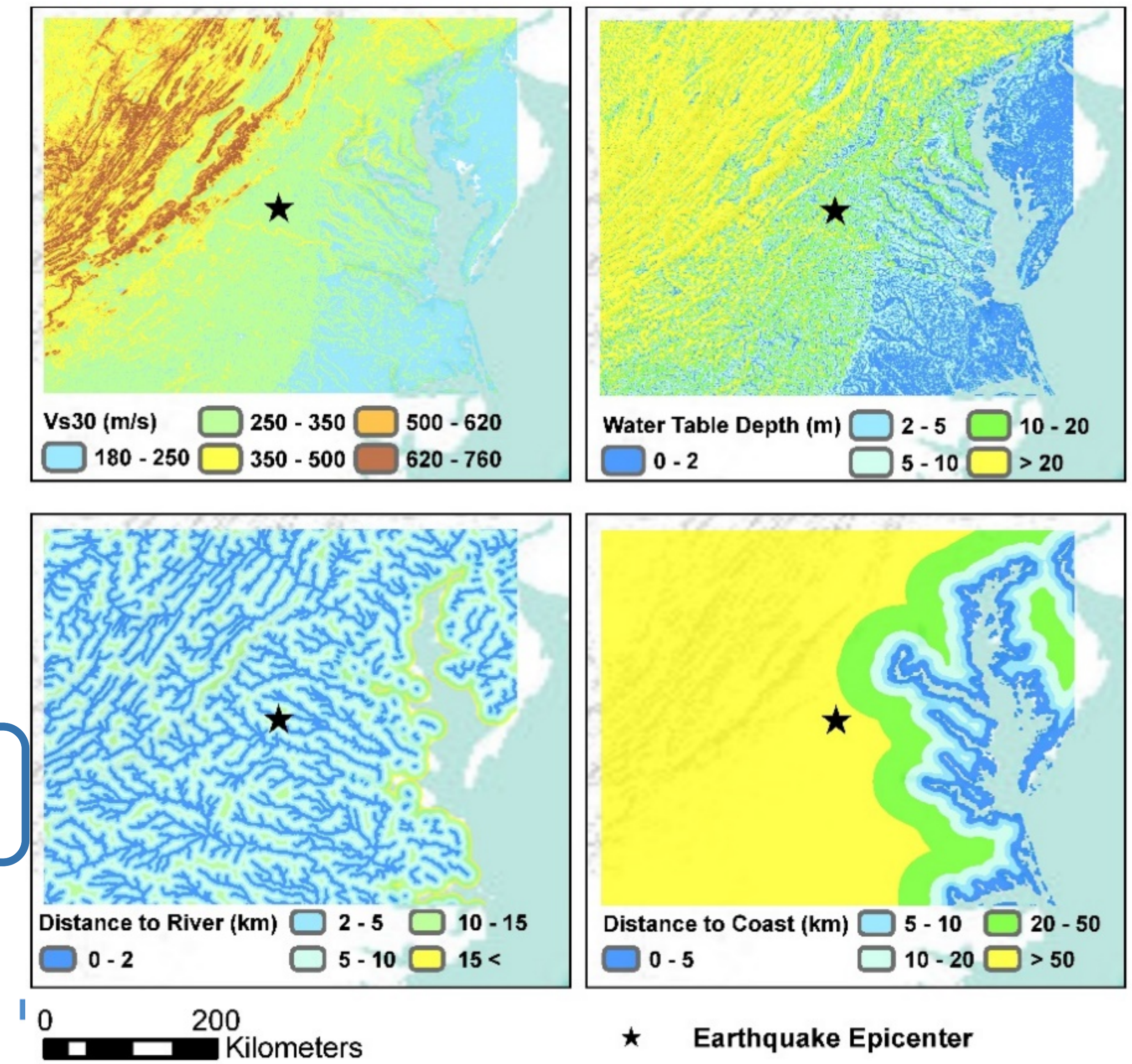
precip	Mean annual precipitation		•	
AI	Aridity index		•	
PGA *(+std)*	Peak ground acceleration			•
PGV *(+std)*	Peak ground velocity			•
Mw	Magnitude			•

2011 Mineral Earthquake



Global Geospatial Liquefaction Assessment

- **Database Development**

  - Build a representative database – Proof of Concept
    - 2 Earthquakes in Christchurch, NZ and 2 Earthquakes in Kobe, Japan (Zhu et al. 2015)

  - Expand Database to include more Regions
    - 27 Earthquakes across 6 countries (Zhu et al. 2017)

  - Continue to update and validate
    - 51Earthquakes (Rashidian and Baise, 2020; Baise and Rashidian, 2020; Baise et al., 2021)

Model Development – Simple Models

- Logistic Regression

$$P(X) = \frac{1}{1 + e^{-X}}$$

- Zhu et al. (2015)
  - Regional model

$$X = \beta_0 + \beta_1 \ln(PGA_M) + \beta_2\, CTI_{30c} + \beta_3\, ND_{3c} + \beta_4 \ln(V_{S30})$$

  - Global model

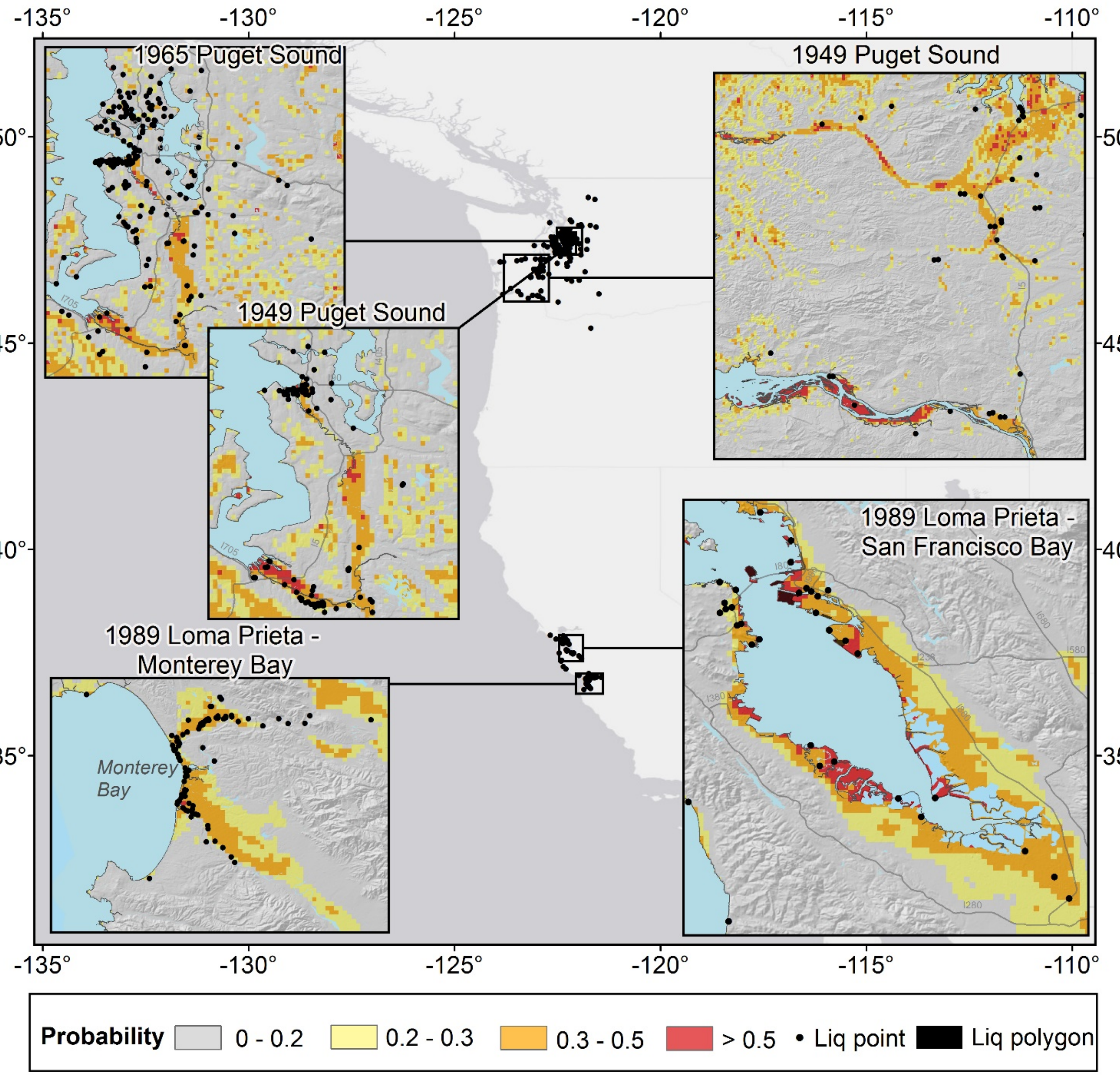
$$X = \beta_0 + \beta_1 \ln(PGA_M) + \beta_2\, CTI_{30c} + \beta_4 \ln(V_{S30})$$

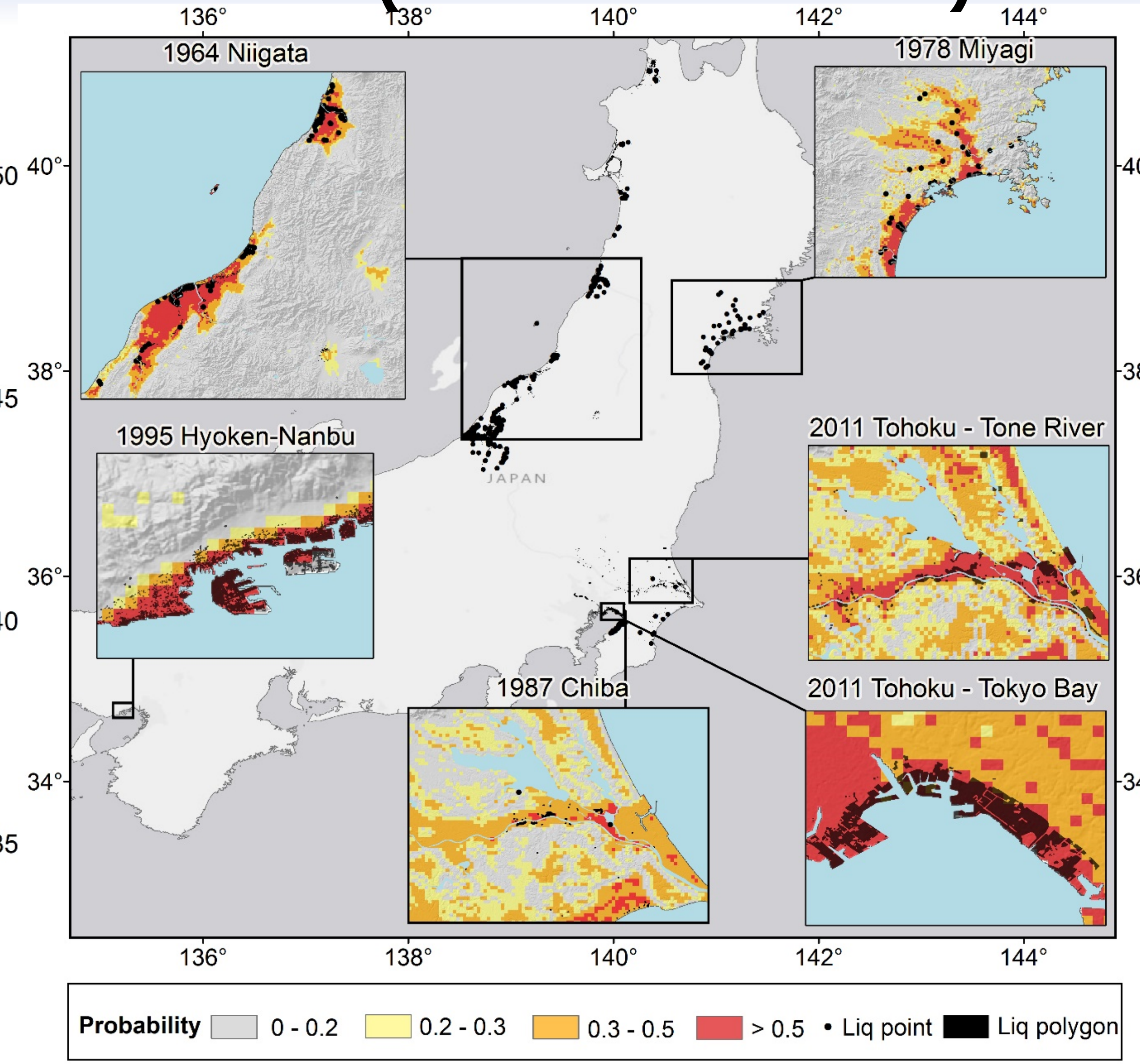
- Zhu et al. (2017) – Global model

$$X = \beta_0 + \beta_1 \ln(PGV) + \beta_2 \ln(V_{s30}) + \beta_3 precip + \beta_4 dw + \beta_5 wtd$$

(Current work expands database and is focused on model development)

PRODUCT – LIQUEFACTION SPATIAL EXTENT MAPS (ZHU ET AL. 2017)





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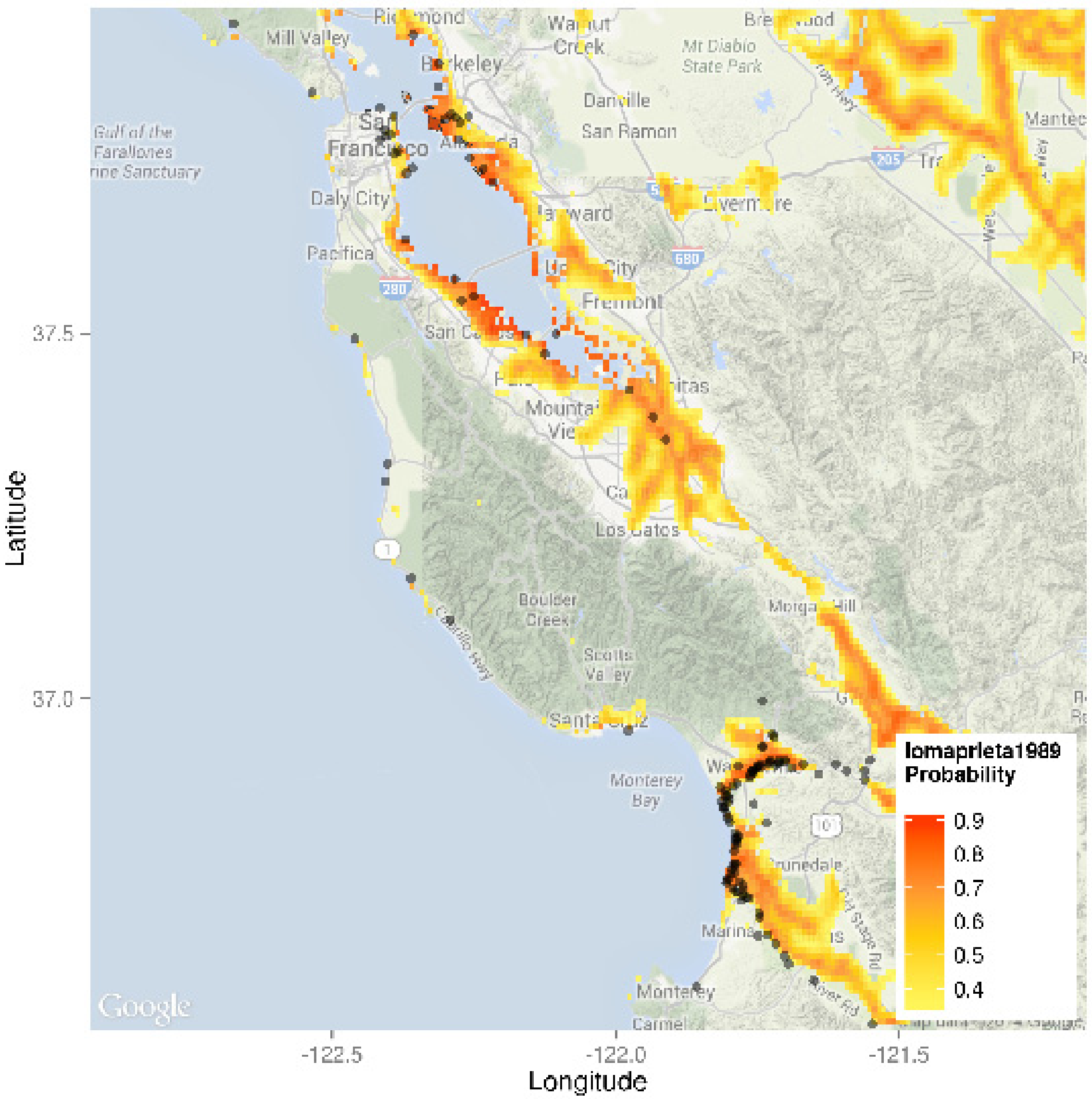
Lessons learned from regional liquefaction mapping

- Geology - derived maps
  – Labor intensive to develop; significant interpretation; Therefore, not available for all locations
  – Geologic units can be highly variable in terms of soil density and water table depth for similar depositional environments
  – Liquefaction occurs in artificial fill and geologically young, saturated and loose sands.
- Geotechnical - derived maps
  – data intensive to develop; therefore, not available for all locations
  – Geotechnical liquefaction potential can have significant variability regionally, limited spatial correlation
- Geospatial – derived maps
  – Simple low-cost maps that capture depositional and saturation trends

1989 Loma Prieta Earthquake - Validation



Comparison - Simplified Method vs. Geospatial Method for the 1989 Loma Prieta Earthquake

CPT
Lenz (2007)

	Obs. Liq.	Obs. NLiq.
Pred. Liq.	71	18
Pred. NLiq.	29	82

76.5%

SPT
Lenz (2007)

	Obs. Liq.	Obs. NLiq.
Pred. Liq.	69	18
Pred. NLiq.	31	82

75.5%

Geospatial
Zhu and Baise (in prep.)

	Obs. Liq.	Obs. NLiq.
Pred. Liq.	77	16
Pred. NLiq.	23	84

80.5%

Liquefaction data from J.C. Tinsley et al. (1998)

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Geyin et al., 2019 show comparable results

Geospatial Liquefaction Susceptibility Maps

$$P(X) = \frac{1}{1+e^{-X}}$$

$$X = \beta_0 + \beta_1 \ln(PGV) + \beta_2 \ln(V_{s30}) + \beta_3 precip + \beta_4 dw + \beta_5 wtd$$

Model 2, Zhu et al., 2017

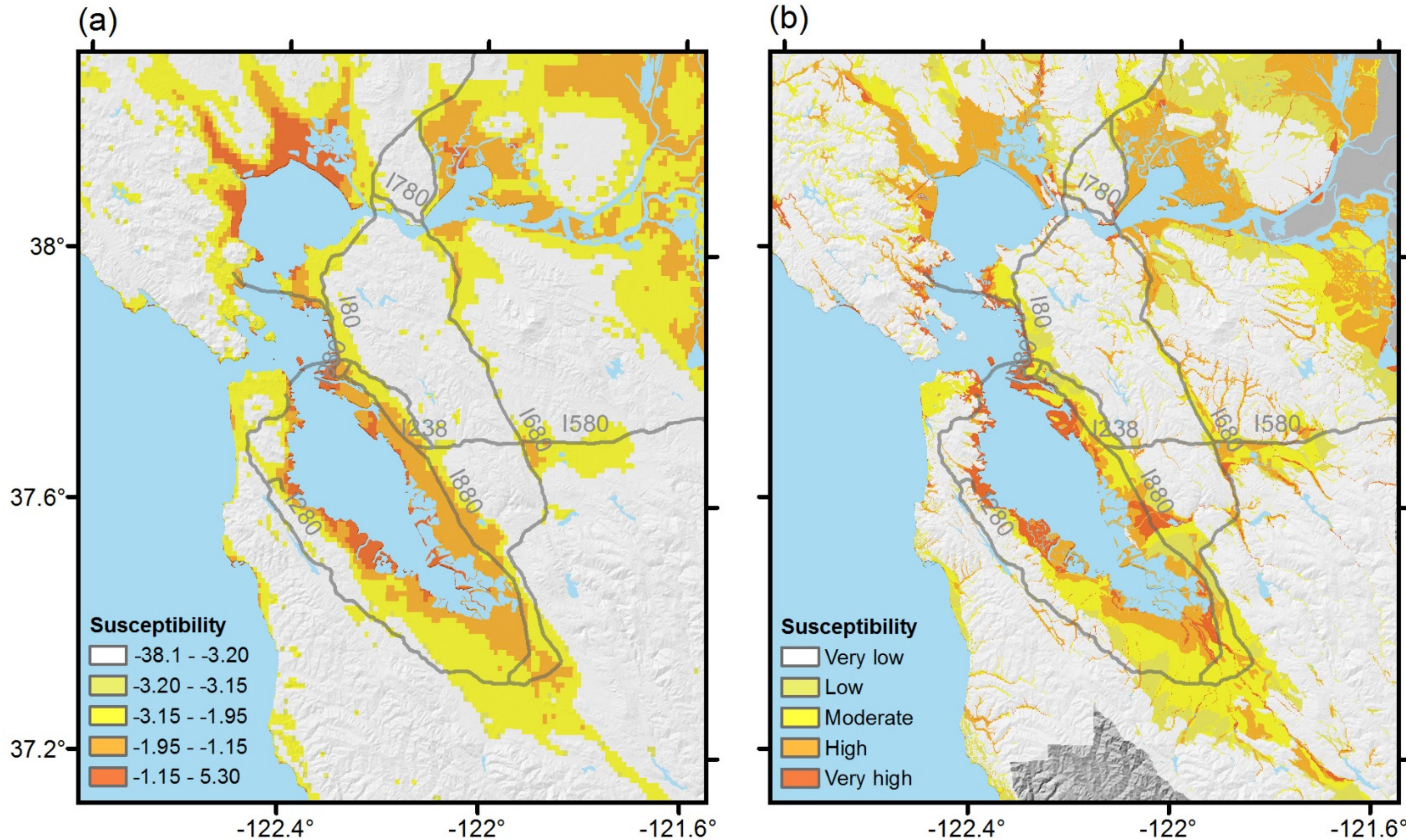
Without the earthquake loading parameters, you have the geospatial equivalent of a liquefaction susceptibility map

LIQUEFACTION SUSCEPTIBILITY MAP FOR GREATER SAN FRANCISCO BAY

Using a geology-based liquefaction map as a guide, we converted the geospatial liquefaction model (Zhu et al. 2017: Model 1) to a liquefaction susceptibility map for the San Francisco Bay area.
Comparison is Witter et al., 2006
(Zhu et al. 2017)

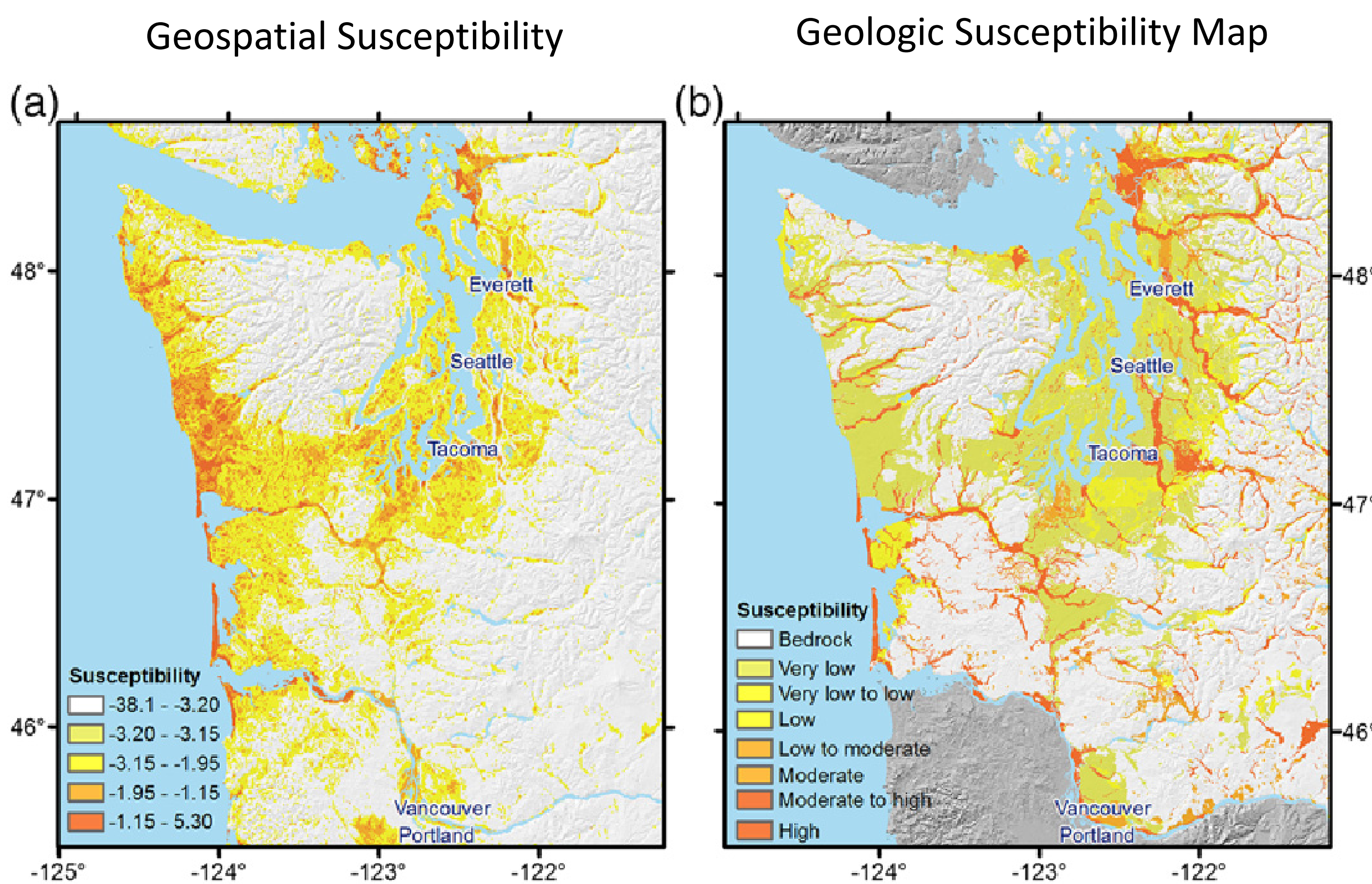
Geospatial Susceptibility

Geologic Susceptibility Map

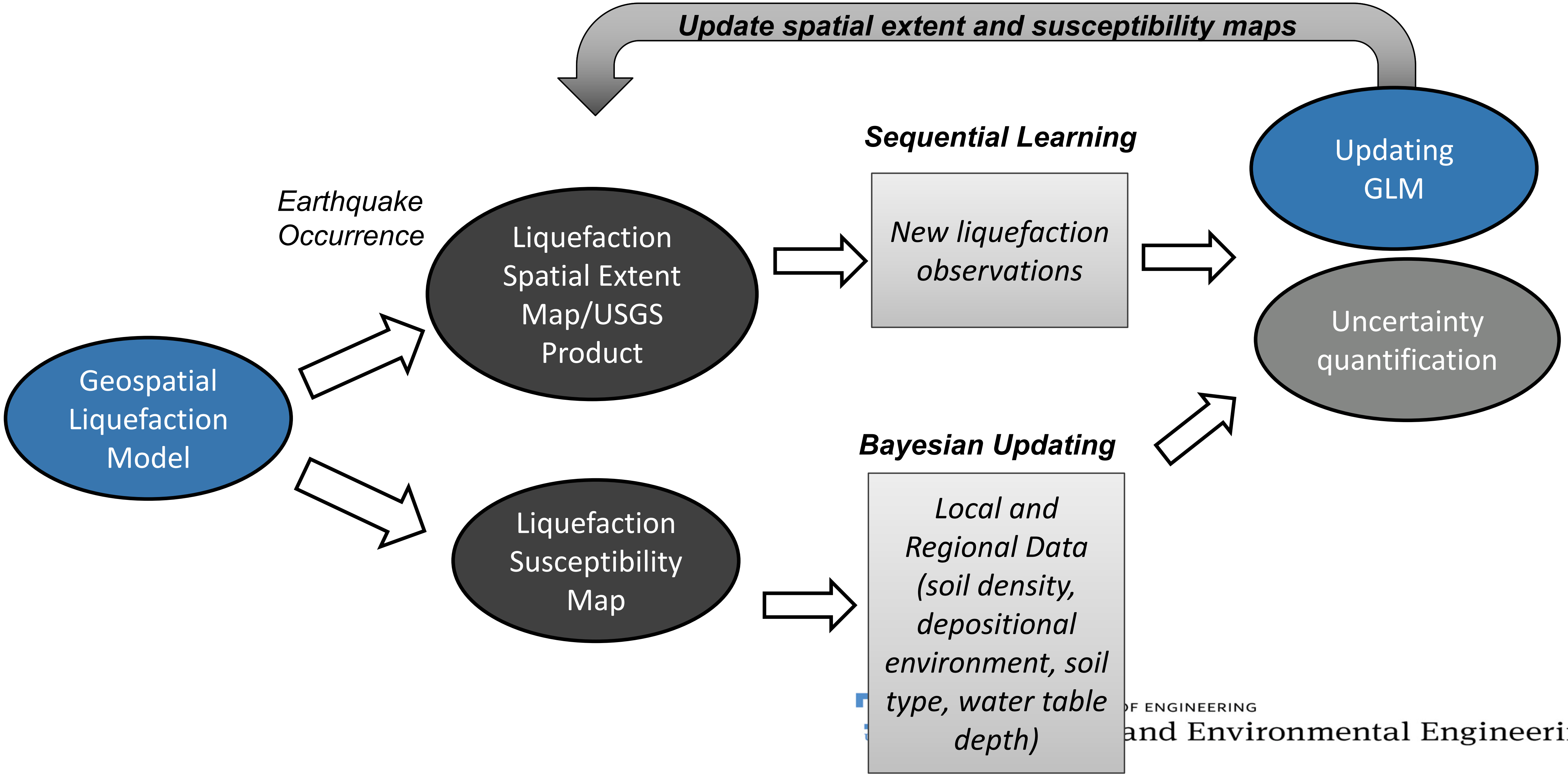


LIQUEFACTION SUSCEPTIBILITY MAP FOR GREATER SEATTLE/TACOMA

Using the same scale for susceptibility as in San Francisco and the geospatial liquefaction model (Zhu et al. 2017: Model 1)
Geospatial liquefaction model
Comparison is Palmer et al., 2004
(Zhu et al. 2017)



ON-GOING WORK: CAN WE COMBINE SIMPLICITY OF GEOSPATIAL METHODS WITH LOCAL GEOLOGIC/GEOTECHNICAL INFORMATION?



NEXT STEPS: HOW DO WE BETTER INCORPORATE REGIONAL SUSCEPTIBILITY INTO LOCAL LIQUEFACTION ASSESSMENT?

Regional Information

Prior

Local Information

Bayesian Updating

Posterior

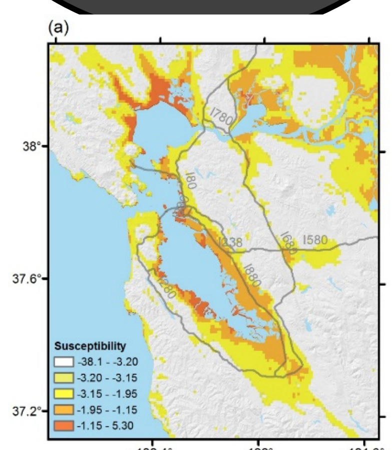
Geology/ Geotechnical Regional Efforts

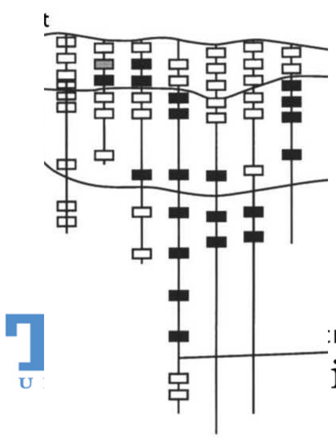
Geospatial Liquefaction Model

Liquefaction Susceptibility Map with uncertainty quantification

Local Data (soil density, soil type, fines, age, water table)

Local Liquefaction Potential





THANK YOU

Publications:

Akhlaghi, Mehdi M., Chansky, A., Baise, L., Moaveni, B., and M. Meyer (2021). An Update to the Global Geospatial Liquefaction Model. 2021 Poster at the SSA Annual Meeting.

Baise, L.G. Akhlaghi, A., Chansky, A., Meyer, M. and Moaveni, B. (2021). Updating the Geospatial Liquefactoin Database and Model. Final Technical Report. USGS Award #G20AP00029.

Baise, L.G., Rashidian, V. (2018). *Validation of a Geospatial Liquefaction Model for Noncoastal Regions Including Nepal.* Final Technical Report to the USGS National Earthquake Hazard Reduction Program Award No. G16AP00014.

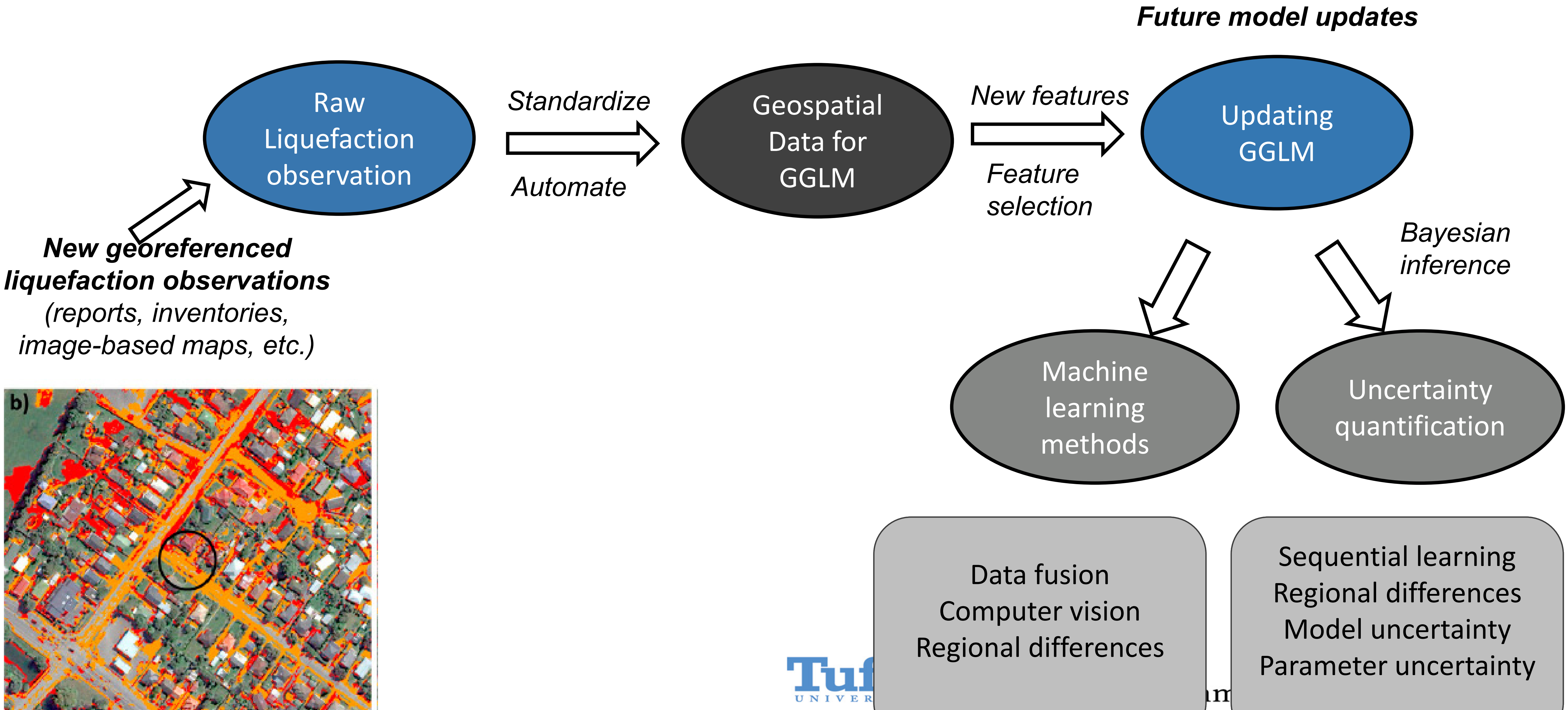
Moss, R.E.S., Baise, L.G., Zhu, J., and Kadkha, D. (2017). Examining the Discrepancy between Forecast and Observed Liquefaction from the 2015 Nepal Earthquakes. Earthquake Spectra. 33 (1). https://doi.org/10.1193/120316eqs220m

Rashidian, V. and Baise, L.G. (2020). Regional efficacy of a global geospatial liquefaction model. *Engineering Geology*. 272, 105644. https://doi.org/10.1016/j.enggeo.2020.105644.

Zhu, J., Baise, L.G., and Thompson, E.M. (2017). An Updated Geospatial Liquefaction Model for Global Application*, Bull. Seism. Soc. Am*. 107 (3).

Zhu, J., Daley, D., Baise, L.G., Thompson, E.M., Wald, D.J., Knudsen, K.L. A (2015). A Geospatial Liquefaction Model for Rapid Response and Loss Estimation. *Earthquake Spectra*, **31** (3), 1813-1837.

Geospatial Liquefaction Model Updates



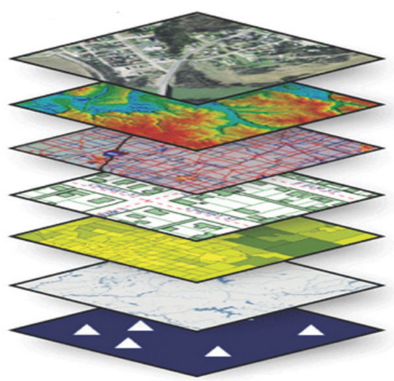
Rashidian et al. (2020)

Sampled Liquefaction Database with Geospatial Parameters

Standardize the data processing and map generation:

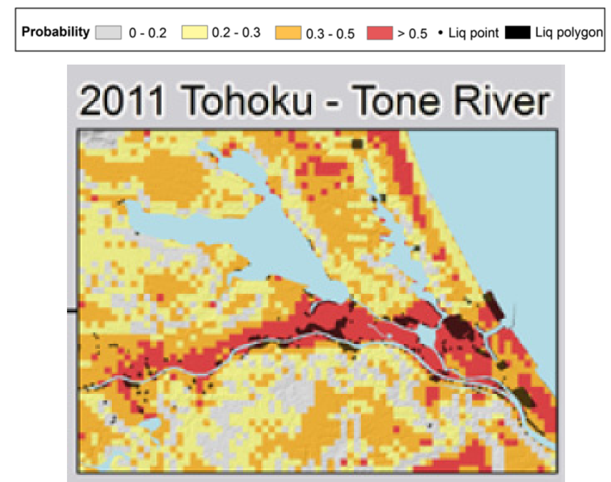
- Use python functions instead of many scripts for different tasks (only requires PGV&PGA downloaded and an event table);
- Fill missing values using geospatially-nearest 3 points.

Raw liquefaction observations



OpenLIQ GIS tool

OpenLIQ database



Real-time geospatial liquefaction hazard assessment

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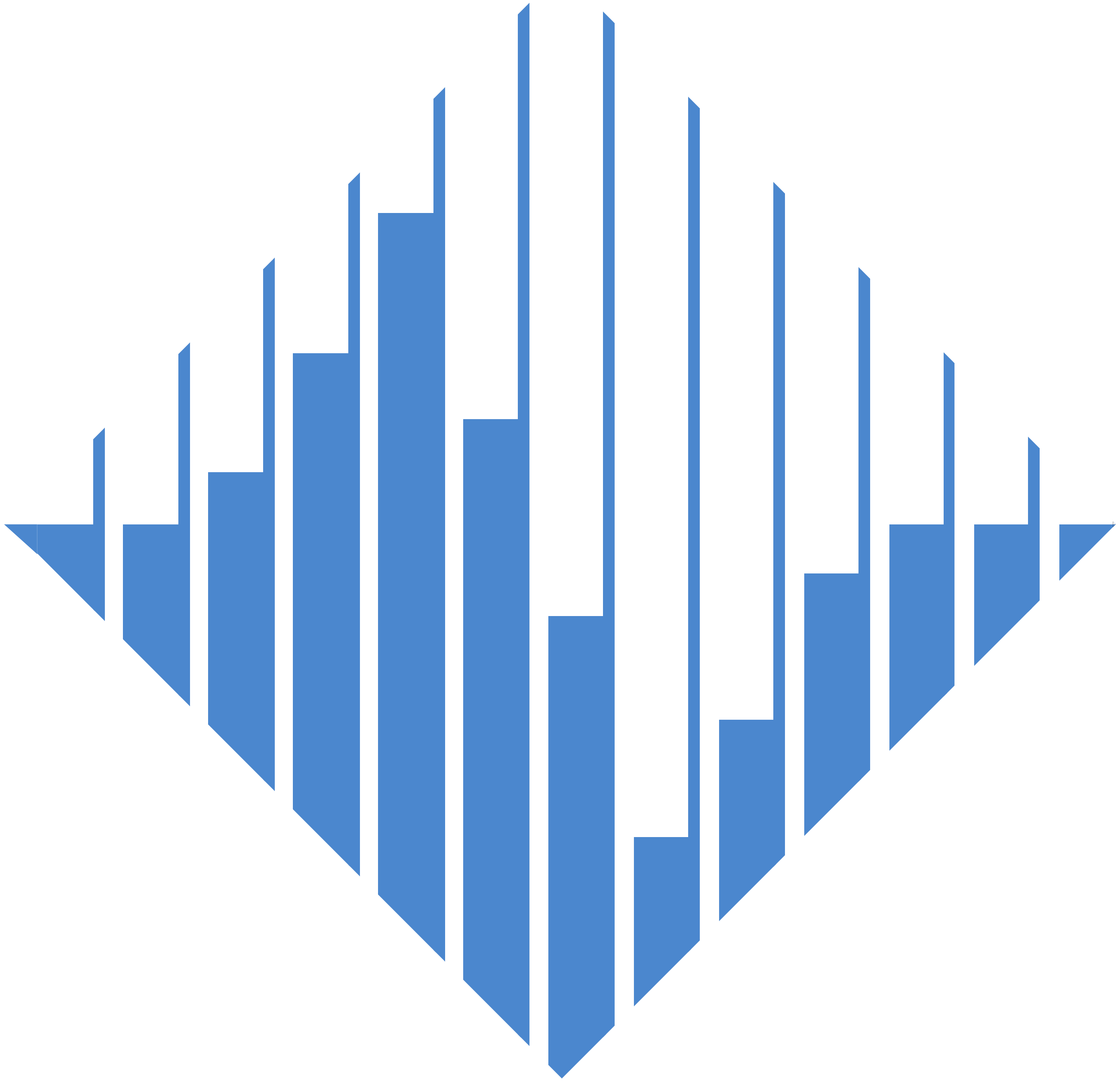

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U.S. DEPARTMENT OF COMMERCE

Regional Liquefaction Susceptibility Assessment: Data Collection Needs and a Focus on the CEUS

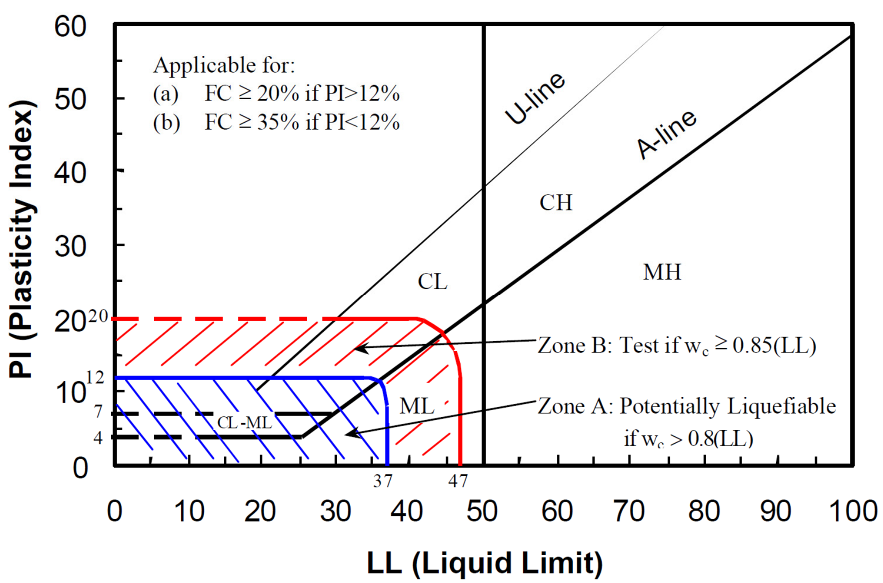
Christine Z. Beyzaei, Ph.D., P.E.
Earthquake Engineering Group
National Institute of Standards and Technology

September 8, 2022

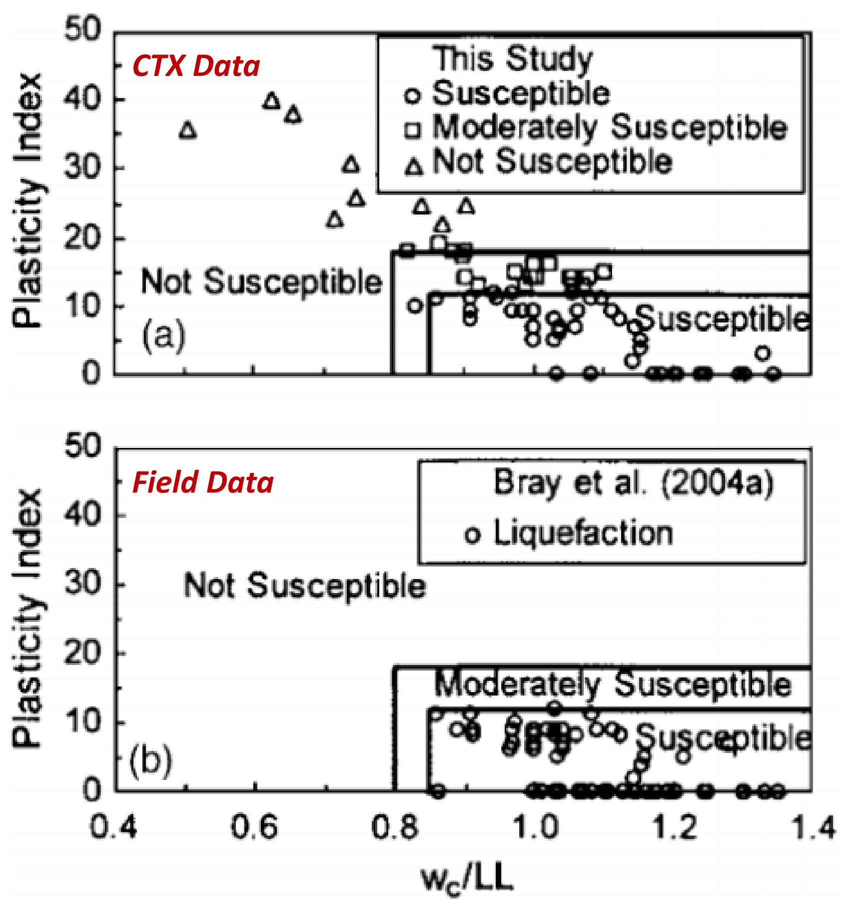
Current State-of-the-Practice and Limitations

NIST

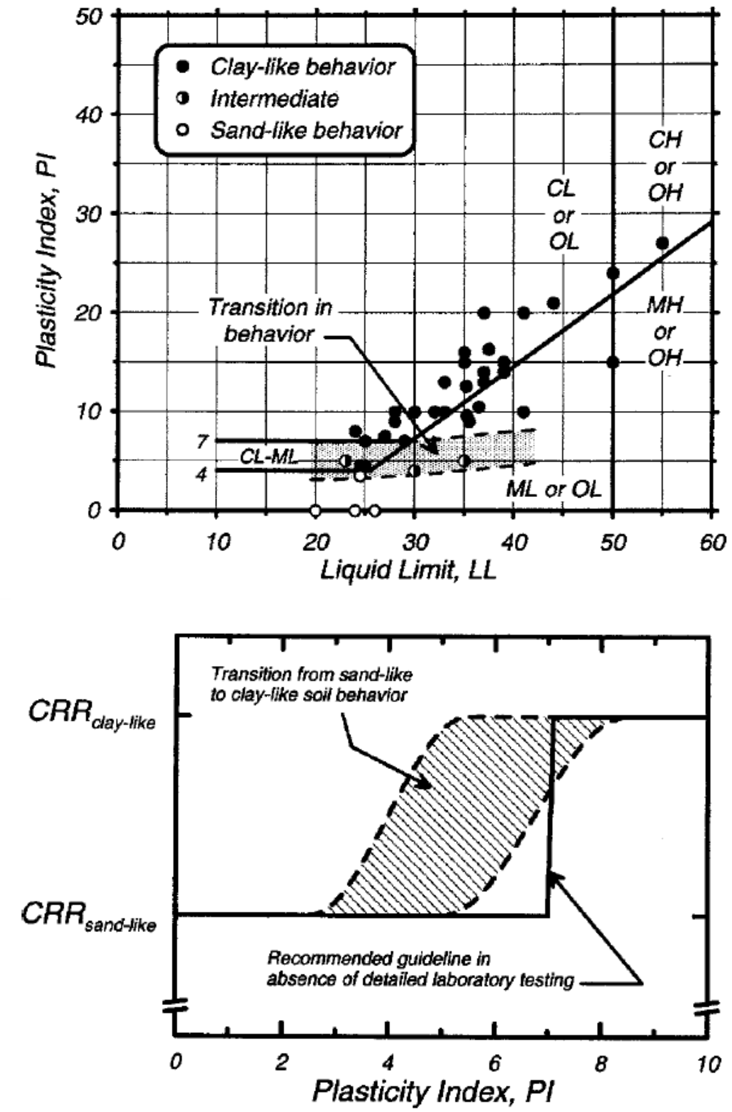
Site-Specific Assessment



Source: Seed et al. (2003)



Source: Bray and Sancio (2006)



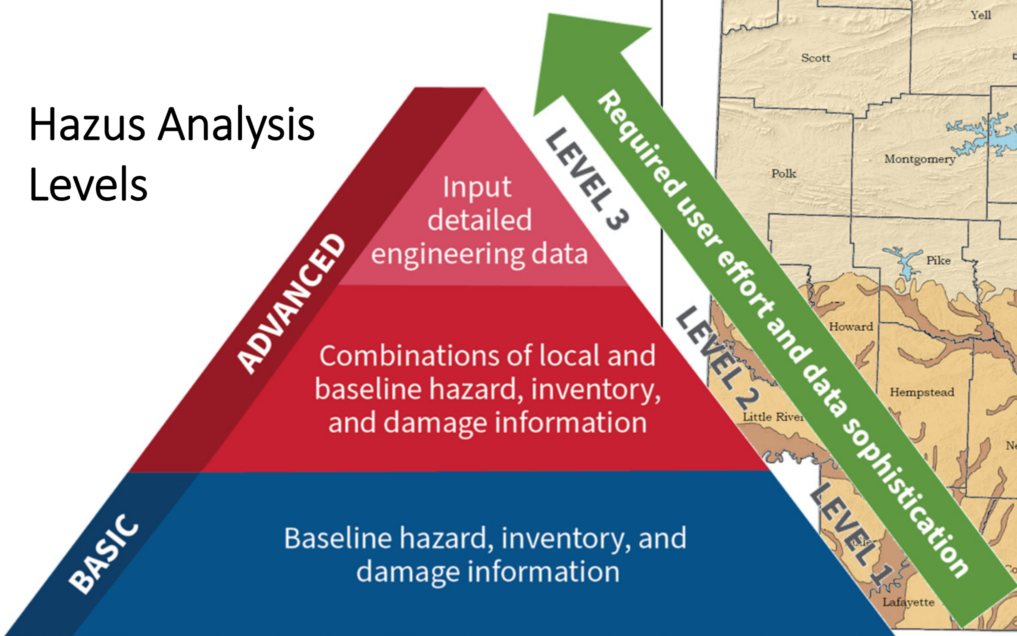
Source: Boulanger and Idriss (2006)

Requires geotechnical data from laboratory testing

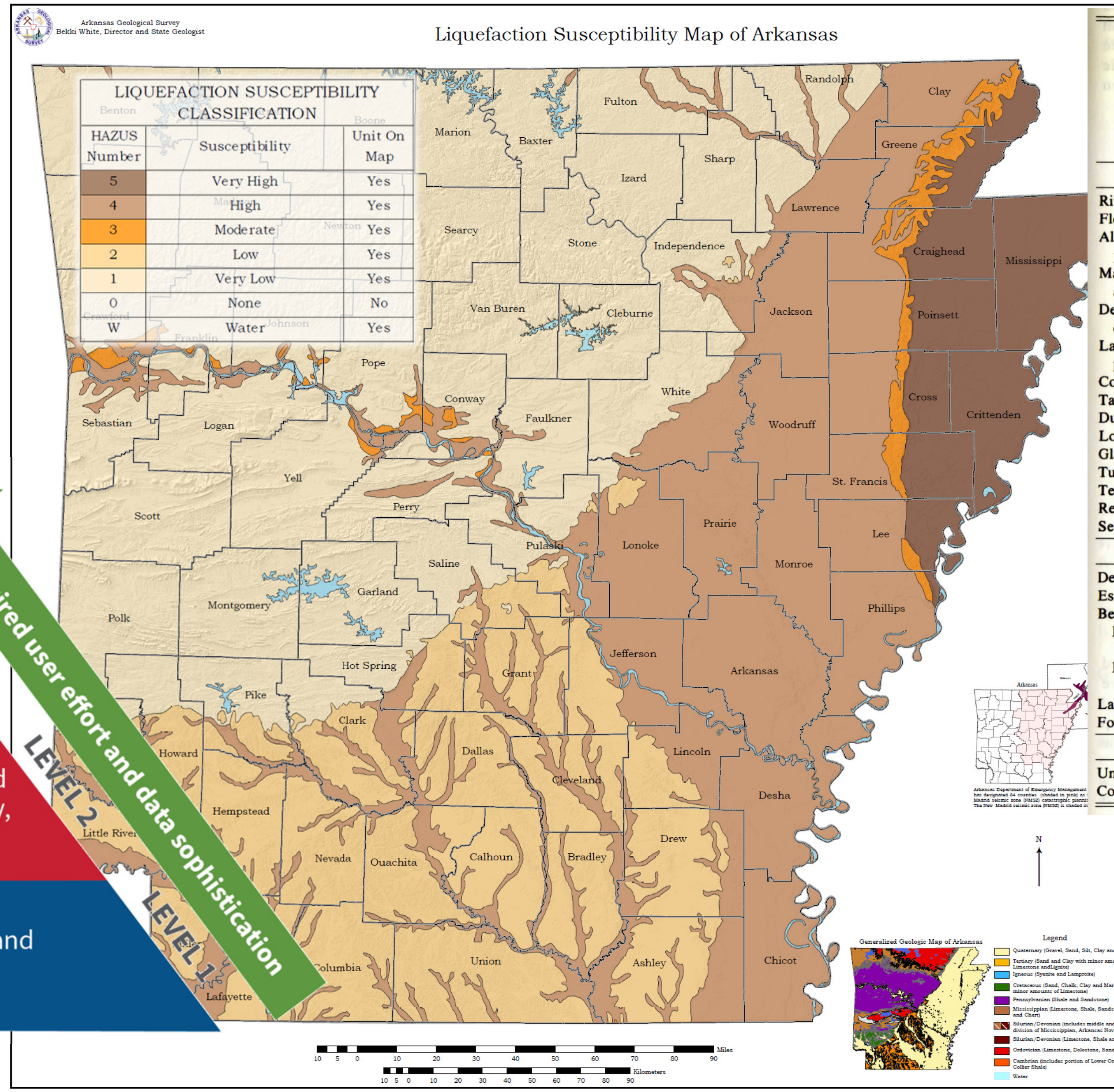
Current State-of-the-Practice and Limitations

Regional Assessment

Hazus Analysis Levels



Source: FEMA – Hazus



Source: Arkansas Geological Survey (2010)

Type of deposit (1)	General distribution of cohesionless sediments in deposits (2)	Likelihood that Cohesionless Sediments, When Saturated, Would Be Susceptible to Liquefaction (by Age of Deposit): <500 yr (3)	Holocene (4)	Pleistocene (5)	Pre-pleistocene (6)
(a) Continental Deposits					
River channel	Locally variable	Very high	High	Low	Very low
Flood plain	Locally variable	High	Moderate	Low	Very low
Alluvial fan and plain	Widespread	Moderate	Low	Low	Very low
Marine terraces and plains	Widespread	—	Low	Very low	Very low
Delta and fan-delta	Widespread	High	Moderate	Low	Very low
Lacustrine and playa	Variable	High	Moderate	Low	Very low
Colluvium	Variable	High	Moderate	Low	Very low
Talus	Widespread	Low	Low	Very low	Very low
Dunes	Widespread	High	Moderate	Low	Very low
Loess	Variable	High	High	High	Unknown
Glacial till	Variable	Low	Low	Very low	Very low
Tuff	Rare	Low	Low	Very low	Very low
Tephra	Widespread	High	High	?	?
Residual soils	Rare	Low	Low	Very low	Very low
Sebka	Locally variable	High	Moderate	Low	Very low
(b) Coastal Zone					
Delta	Widespread	Very high	High	Low	Very low
Esturine	Locally variable	High	Moderate	Low	Very low
Beach					
High wave energy	Widespread	Moderate	Low	Very low	Very low
Low wave energy	Widespread	High	Moderate	Low	Very low
Lagoonal	Locally variable	High	Moderate	Low	Very low
Fore shore	Locally variable	High	Moderate	Low	Very low
(c) Artificial					
Uncompacted fill	Variable	Very high	—	—	—
Compacted fill	Variable	Low	—	—	—

Source: Youd and Perkins (1978)

Data Collection Needs

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Liquefaction susceptibility assessment methods are derived primarily from:

1) Post-earthquake field case histories
2) Laboratory testing

Advancing current methods will require regional data collection and selection of meaningful case history sites for detailed investigations.

Case histories require an observation, ground motion recording or estimate, and geotechnical data.

Immediately after an earthquake it is not feasible to visit and photograph the entire affected area in person, due to time and safety constraints. → **Extensive high-resolution aerial photography**

Aerial Photography: Regional Coverage

2010 – 2011 Canterbury Earthquake Sequence

Source: New Zealand Geotechnical Database (www.nzgd.org.nz)

4 Sept 2010 Darfield Earthquake

22 Feb 2011 Christchurch Earthquake

Aerial Photography:
Data Collection, Dissemination, and Maintenance

2010 – 2011 Canterbury Earthquake Sequence

- Aerial imagery commissioned by the New Zealand Ministry of Civil Defence and Emergency Management
- Data collected within 2 days after major earthquake events
    - 4 Sept 2010 Darfield Earthquake - imagery acquired on 5 Sept 2010
    - 22 Feb 2011 Christchurch Earthquake - imagery acquired on 24 Feb 2011
- Imagery was made publicly available, easily accessible via Google Earth, and has been maintained for over a decade following the events

Source: New Zealand Geotechnical Database (www.nzgd.org.nz)

Extensive regional coverage with high-resolution aerial imagery has enabled research investigations of CES post-earthquake observations to continue to this day.

Selection of Impactful Case History Sites

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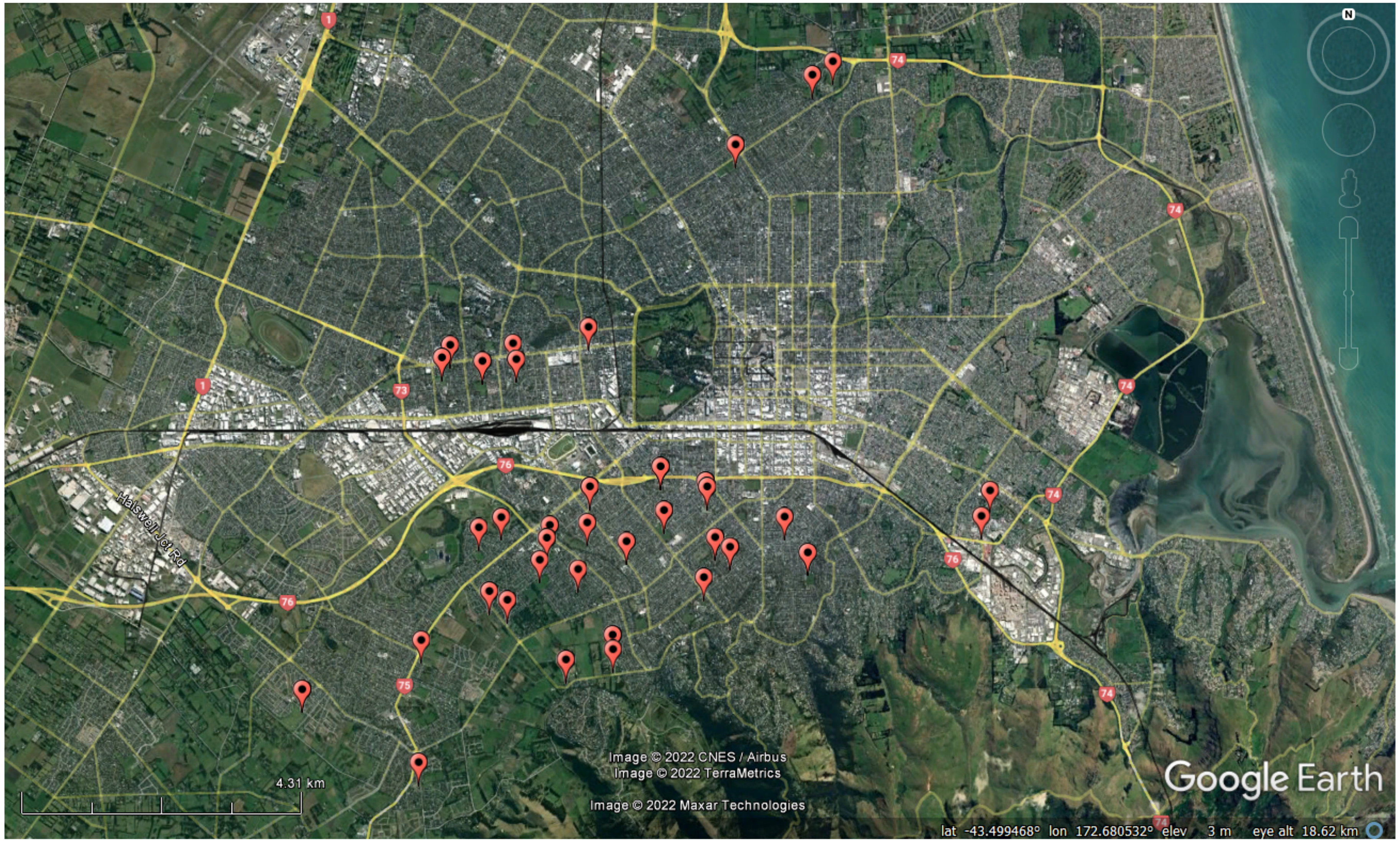
2010 – 2011 Canterbury Earthquake Sequence

Extensive aerial imagery allows researchers to "revisit" sites years later and select critical, impactful case history sites for further investigation and collection of quantitative geotechnical data.

This is especially important for selecting sites that performed well.

For investigating "no liquefaction" sites following the 2010-2011 CES, over 30 candidate sites were narrowed down to 8 sites for detailed investigations.



Challenges with Current Methods

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- Existing methods and proposed frameworks are typically based on examples from the Western U.S. and other areas of high seismic hazard.
- There are several challenges in applying existing assessment methods to the CEUS or other areas of low to moderate seismic hazard:

1) Limited regional data availability (i.e., publicly available subsurface geotechnical and groundwater data)
2) Practitioner and stakeholder liquefaction hazard awareness
3) Fewer earthquake events leading to the perception of liquefaction hazard not being a “local” issue

Challenges with Current Methods

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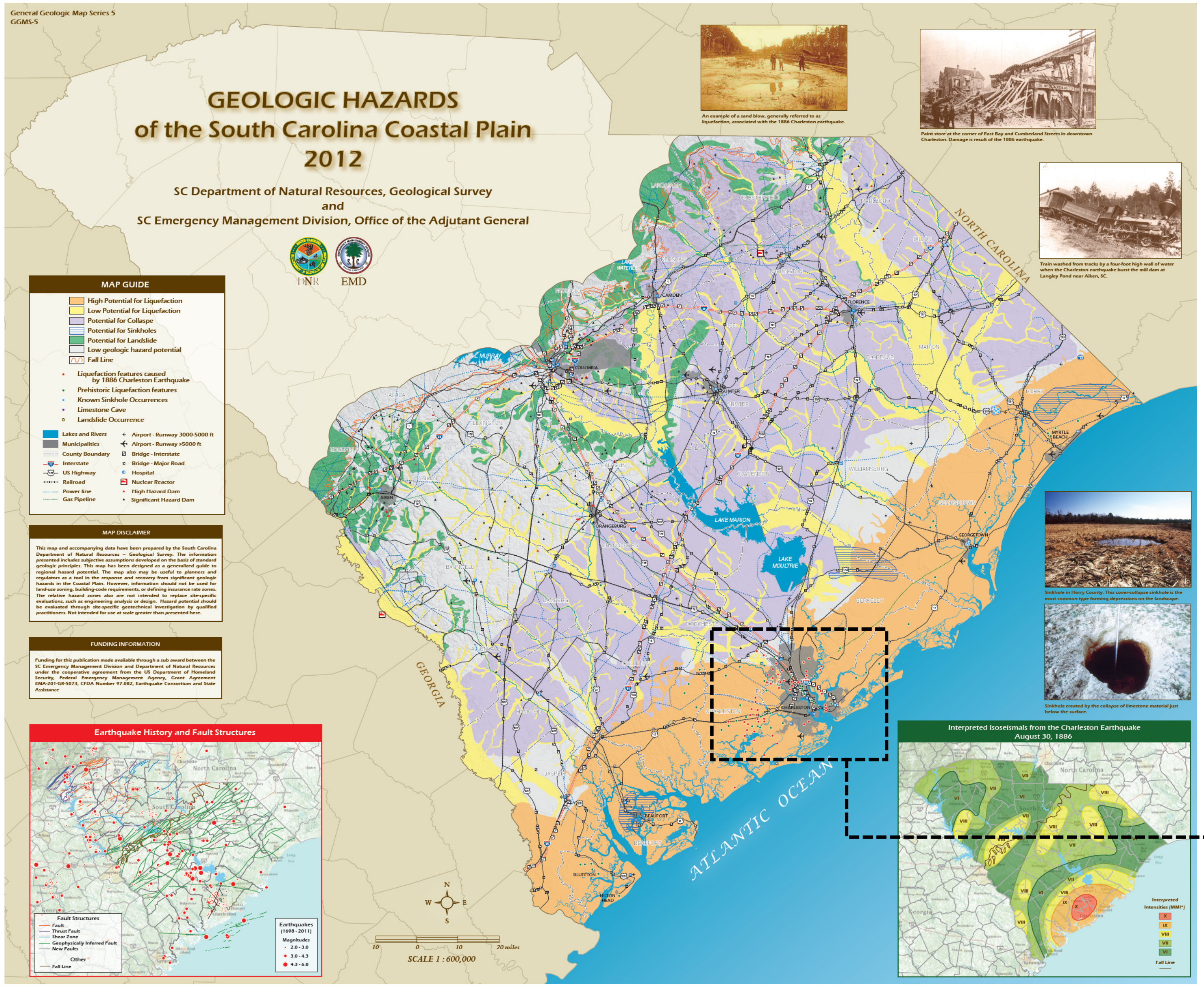
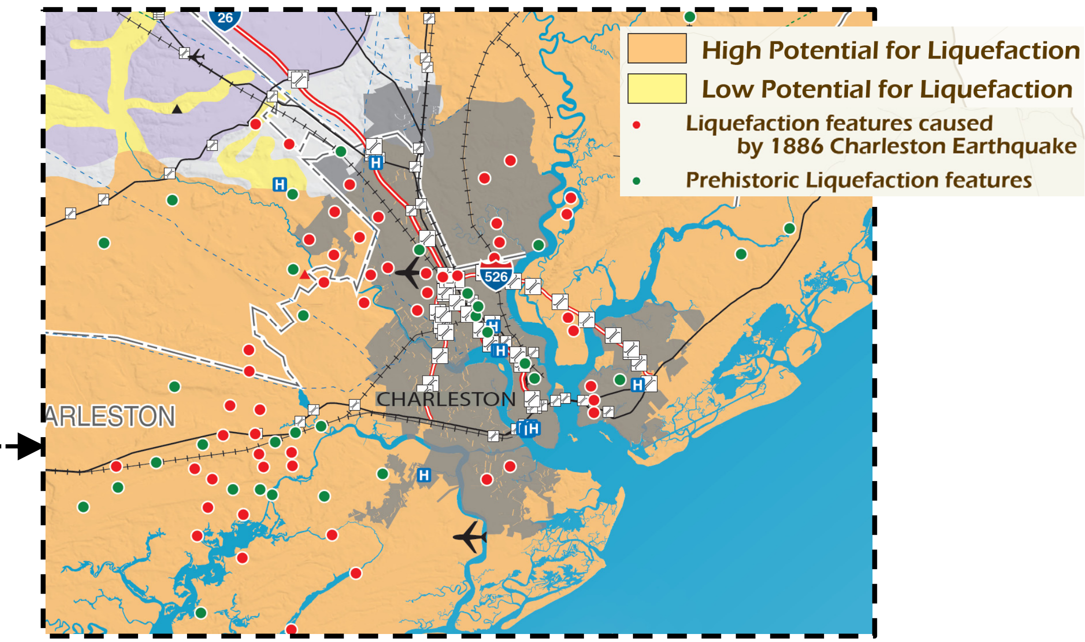


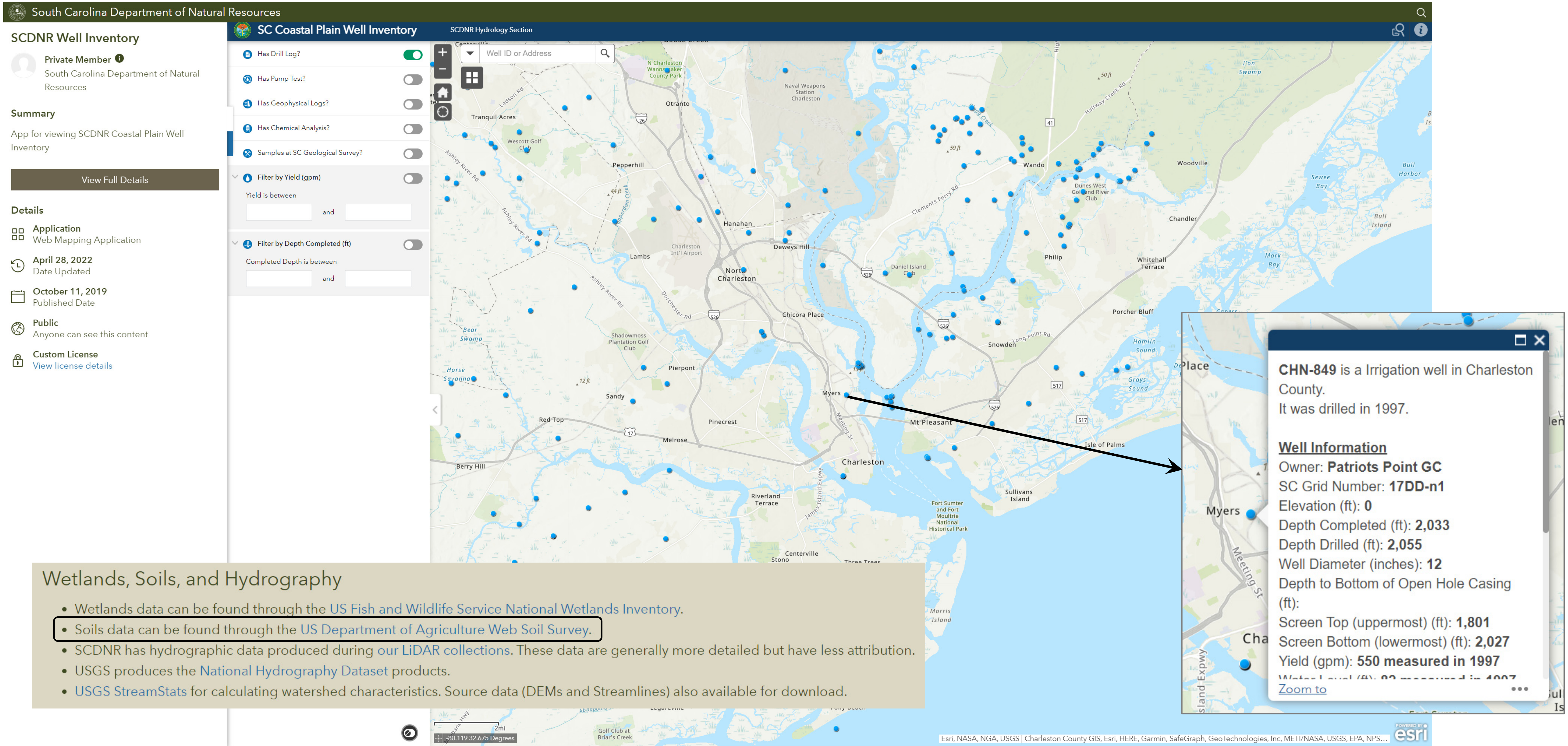
Source: South Carolina DNR, Geological Survey, and Emergency Management Division (2012)

Example: South Carolina

- High Potential for Liquefaction is mapped along the entire coastline, extending approximately 20 miles inland
- Potential for severe ground shaking from Charleston and New Madrid Seismic Zones
- Geotechnical subsurface data is not publicly available, or readily accessible



Geotechnical Data Availability and Accessibility



Wetlands, Soils, and Hydrography

- Wetlands data can be found through the US Fish and Wildlife Service National Wetlands Inventory.
- Soils data can be found through the US Department of Agriculture Web Soil Survey.
- SCDNR has hydrographic data produced during our LiDAR collections. These data are generally more detailed but have less attribution.
- USGS produces the National Hydrography Dataset products.
- USGS StreamStats for calculating watershed characteristics. Source data (DEMs and Streamlines) also available for download.

Potential Consequences from Climate Change

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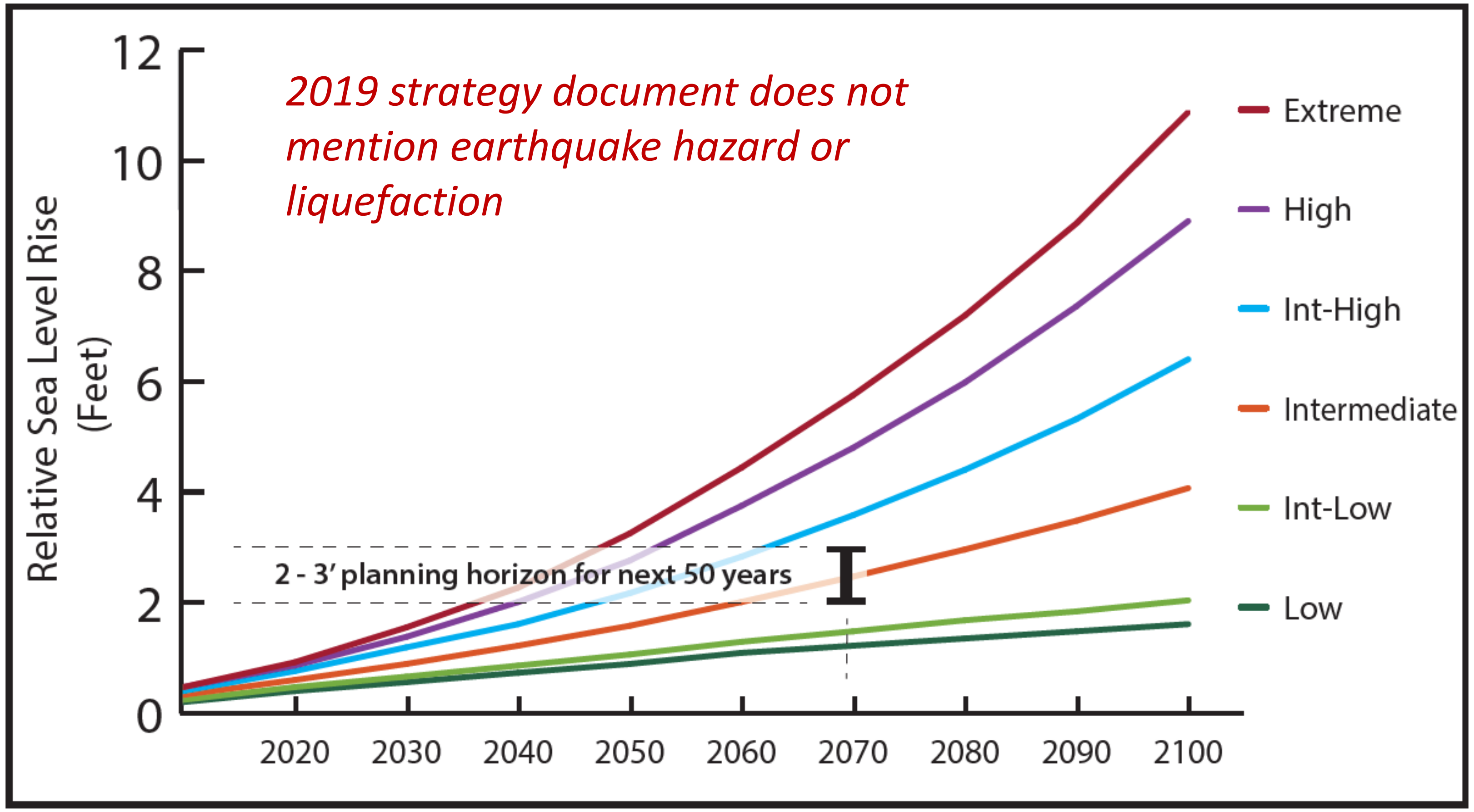
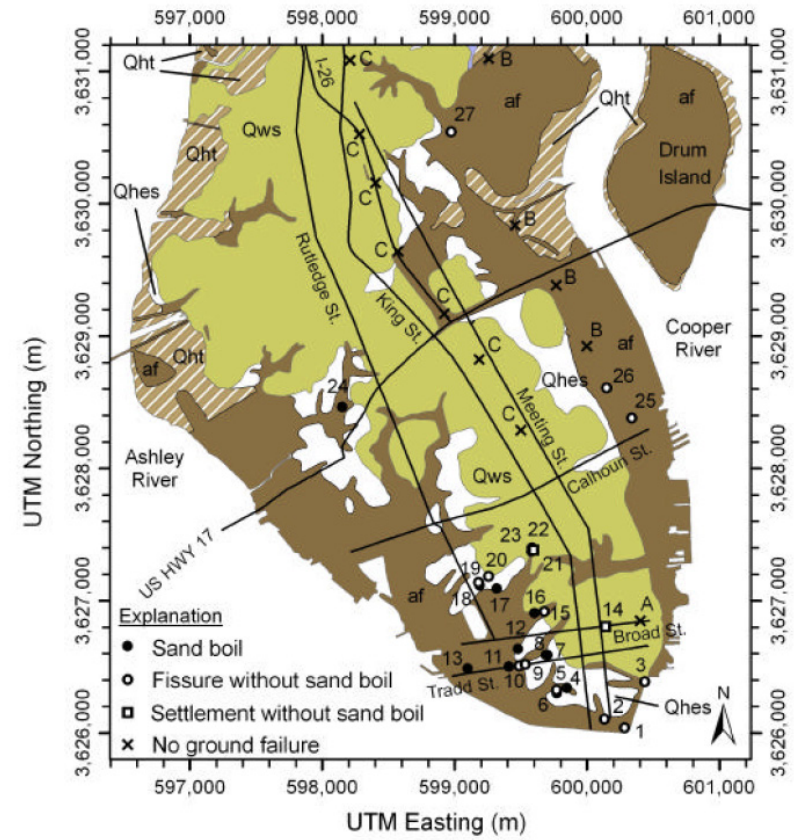
Climate Change Impacts Affecting Liquefaction Susceptibility

Sea Level Rise Projections for Charleston, SC



Source: Charleston, South Carolina Flooding and Sea Level Rise Strategy – 2nd ed. (2019)



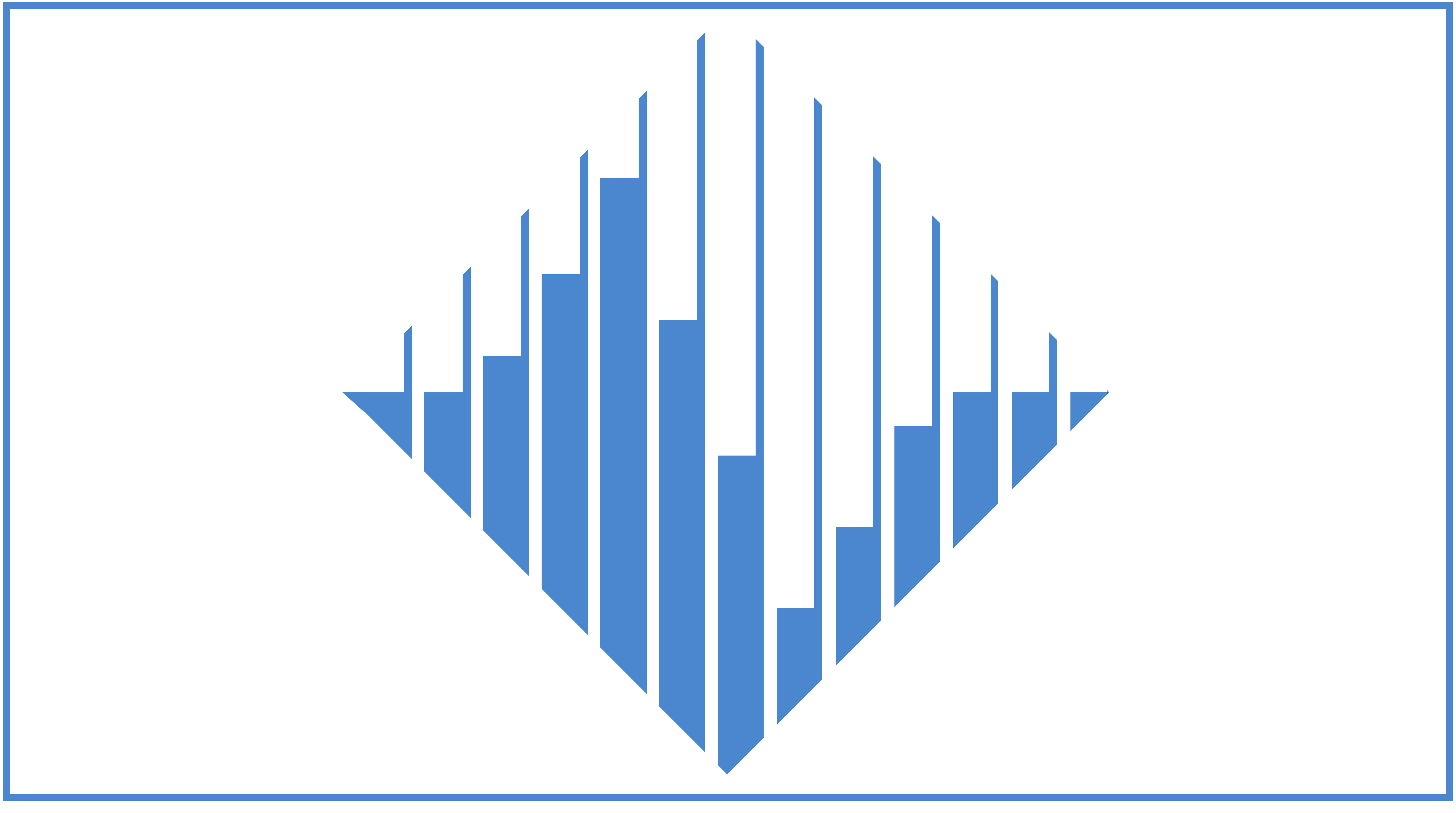
Source: Hayati and Andrus (2007), after Weems et al. (1997)

For projected sea level rise induced liquefaction vulnerability:
"results indicate significant changes in vulnerability to liquefaction by the end of century" (Ghanat 2020)

Conclusion

NIST

- Next generation liquefaction susceptibility models should bridge the gap between current state-of-practice quantitative site-specific methods and qualitative regional methods
- Extensive aerial photography is key during post-earthquake reconnaissance and will allow for selection of impactful case history sites in the years after an event
- Several challenges exist for the use of current methods, particularly in low-to-moderate seismicity areas
  - Limited regional data availability
  - Practitioner and stakeholder awareness
- Improving practitioner and stakeholder awareness of liquefaction hazards and existing liquefaction susceptibility assessment methods should be a primary goal, alongside research, to advance technical knowledge and assessment models.
- **We need to consider the broader spectrum of users for liquefaction susceptibility models and maps**
  - Community resilience modelers and planners, structural engineers, transportation engineers…
- Ideas for paths forward:
  - Community consensus update of Youd & Perkins (1978) with new case histories added
  - Easily accessible state susceptibility maps that align with Hazus categories or alternative methods
  - More widely available interactive state soil boring and CPT maps
  - Outreach in underserved communities



Incorporating Uncertainty in Susceptibility Criteria into Probabilistic Liquefaction Hazard Analysis

Andrew Makdisi, PhD, PE

U.S. Geological Survey

PEER Workshop: Liquefaction Susceptibility Modeling

September 8-9, 2022

OVERVIEW

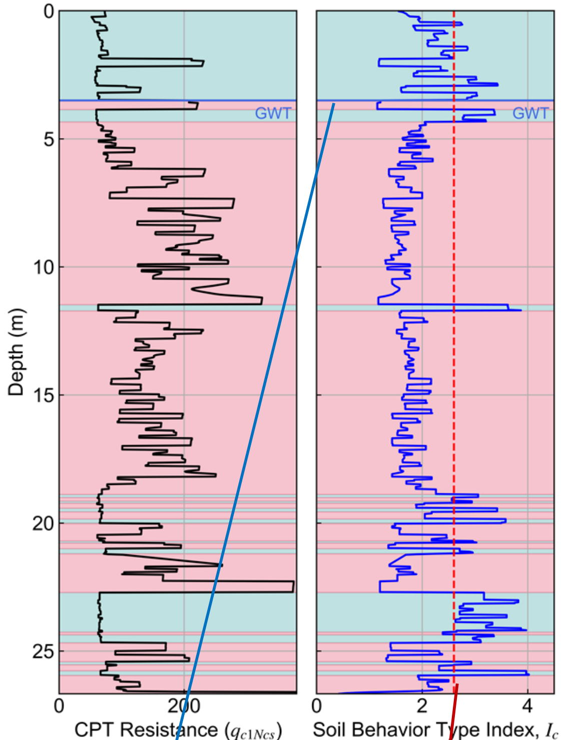
- Susceptibility and liquefaction hazard analysis
  - Current state of practice
  - Current state of the art – probabilistic liquefaction hazard analysis (PLHA)

- USGS Liquefaction Hazard Tool
  - Current capabilities and broader objectives

- Modeling needs and looking ahead (i.e., *"where do we want to be in 5-10 years?"*)
  - *Susceptibility*, ground motion characterization, triggering, vulnerability, consequences
  - Susceptibility characterization and PLHA
    - *Compositional* and *saturation* criteria

Current State of Practice

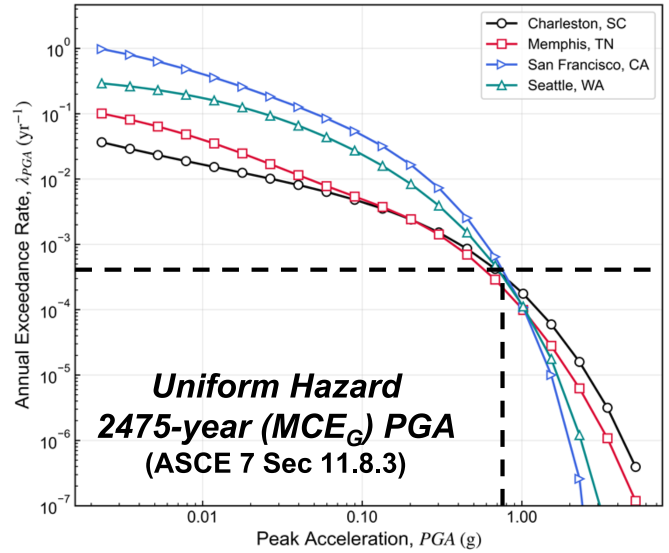
Susceptibility

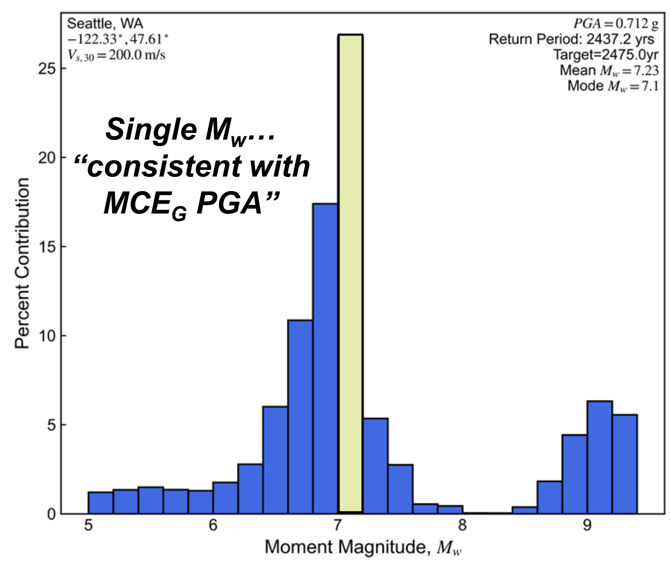


Saturation Criteria
($z > z_{GWT}$)

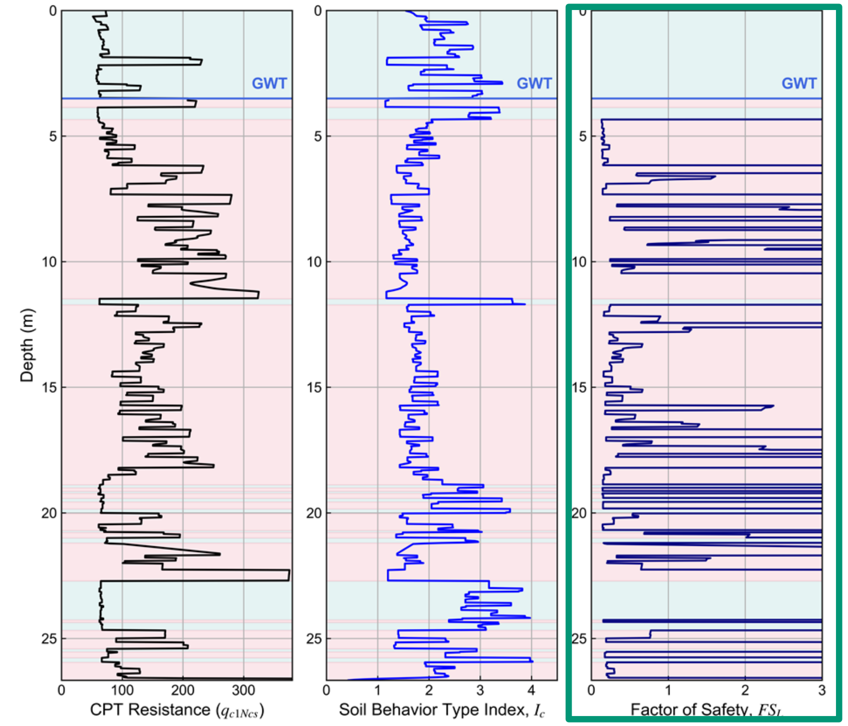
Compositional Criteria (I_c< ~2.6, lab testing)

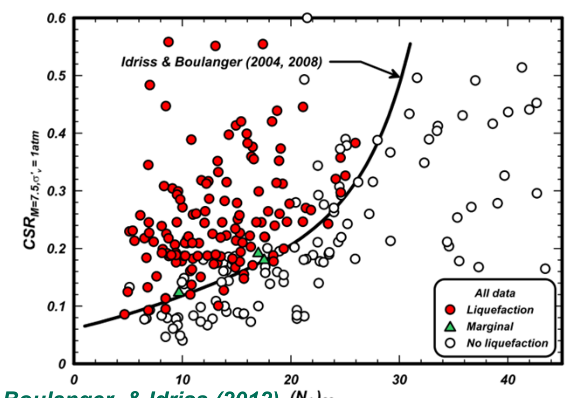
Ground Motions





Triggering

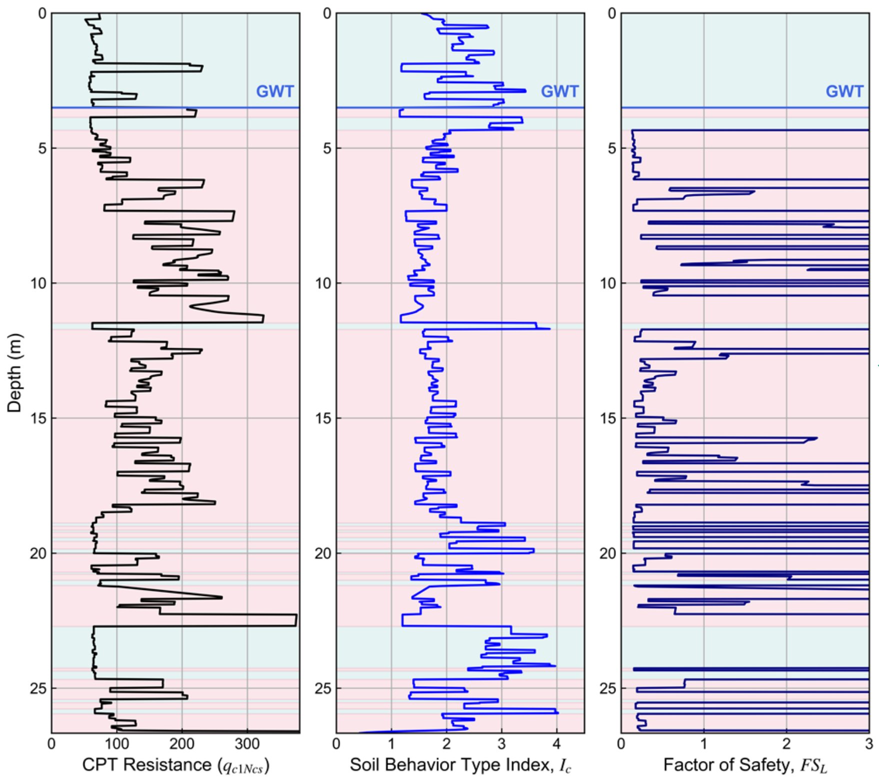




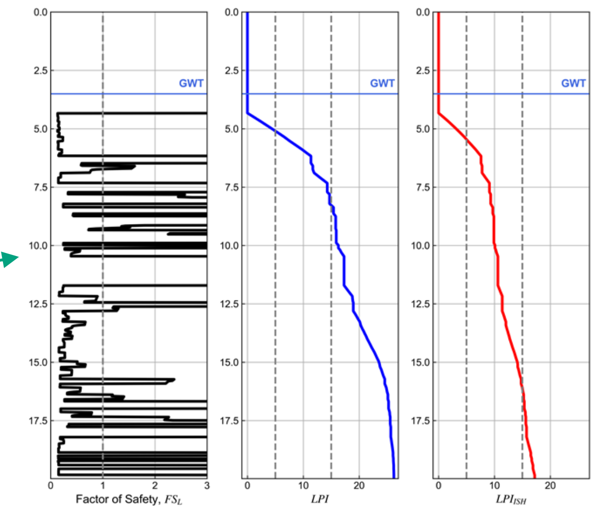
Boulanger & Idriss (2012)

Current State of Practice

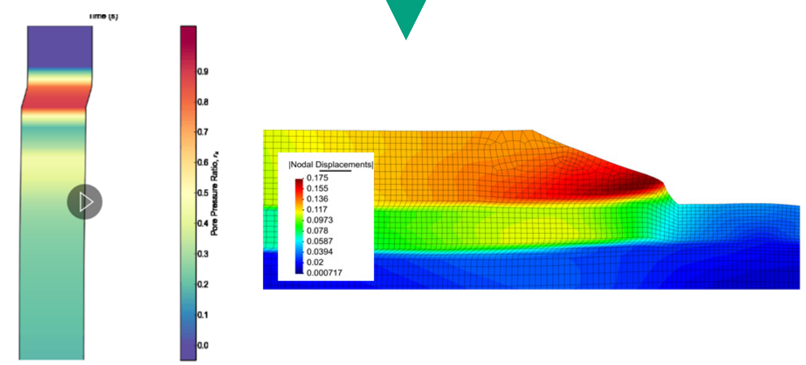
Triggering



Vulnerability and Effects



Liquefaction vulnerability indices or free field displacements



Advanced computational methods

- ***Liquefaction hazard <u>conditional</u> on 2475-year ground motions***
- ***Not the same as 2475-year liquefaction hazard…***

Current State of the Art

Probabilistic Liquefaction Hazard Analysis

- **Considers *all* ground shaking scenarios (i.e. *PGA*-M_w combinations)**
- **Considers uncertainty in estimating liquefaction triggering**
- **Can be further extended to evaluate consequences**

Mean annual rate of non-exceedance of FS^*_L

Likelihood of non-exceedance of FS^*_L given *PGA* and M_w

$$\Lambda_{FS_L}(fs_L) = \sum_{j=1}^{N_m} \sum_{i=1}^{N_{pga}} \mathrm{P}[FS_L < fs_L | susc, PGA_i, M_{w,j}] \cdot \Delta\lambda_{pga_i, m_{w,j}}$$

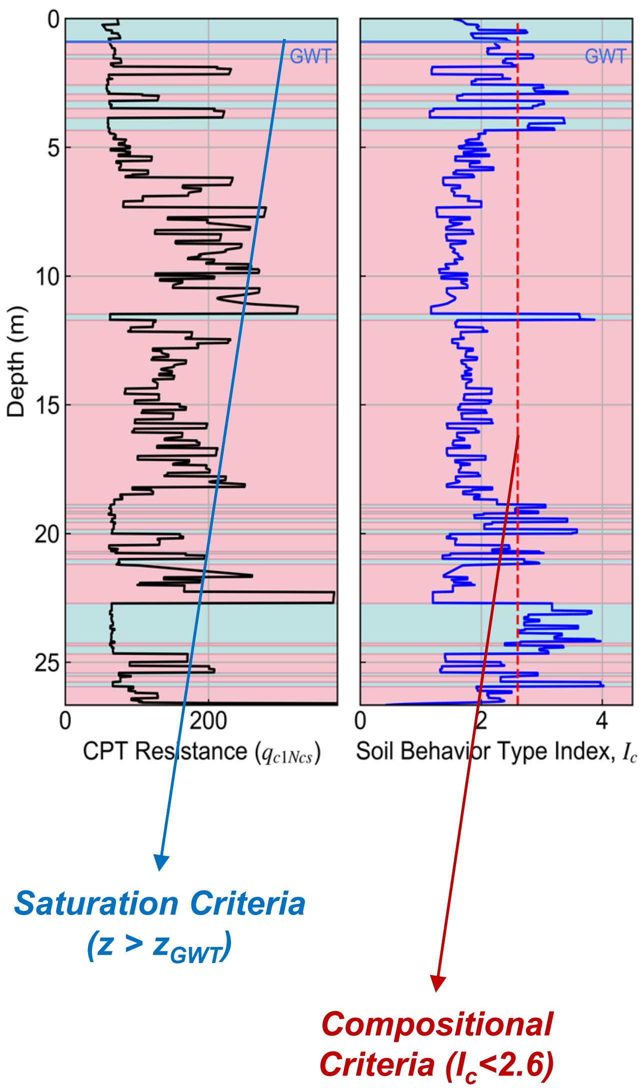
Kramer & Mayfield (2007)

Sum over all combinations of *PGA* and M_w

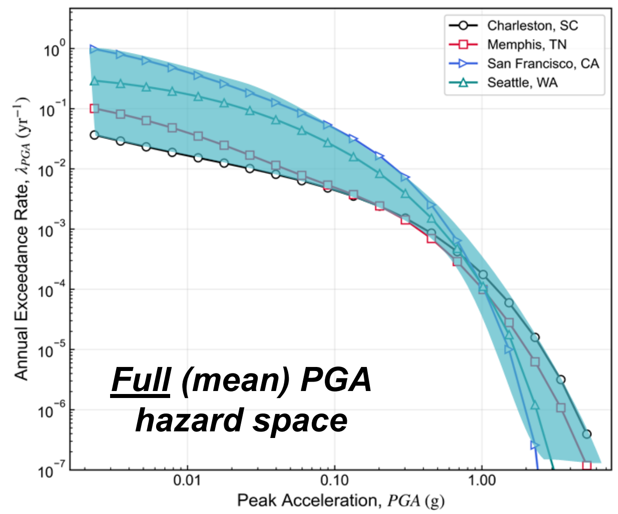
Joint exceedance rate of *PGA* and M_w

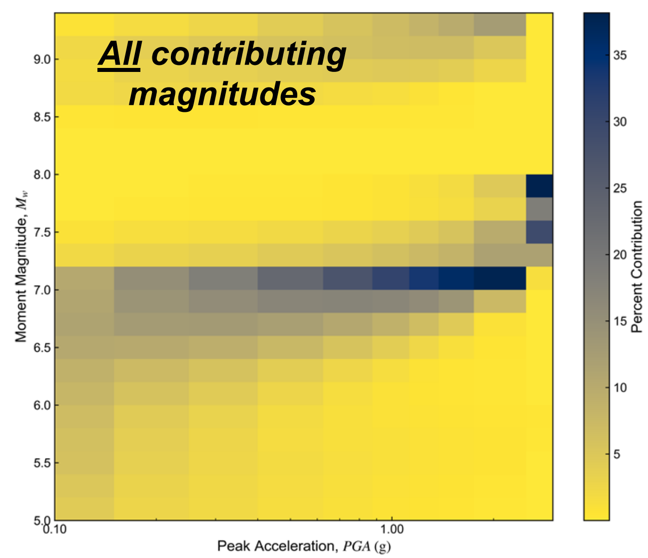
Current State of the Art

Susceptibility

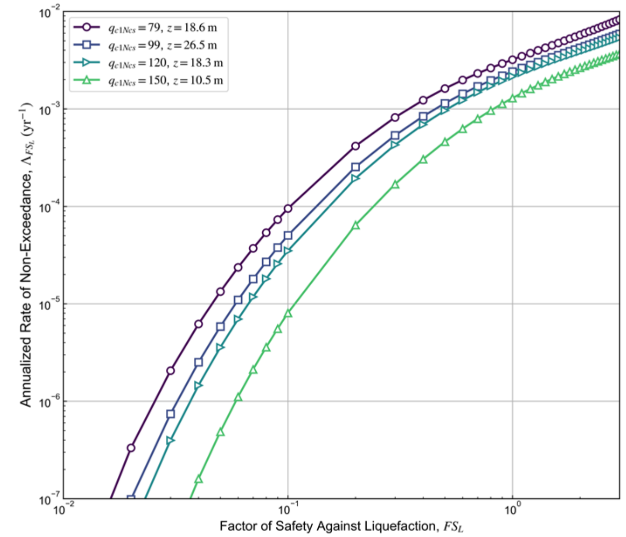


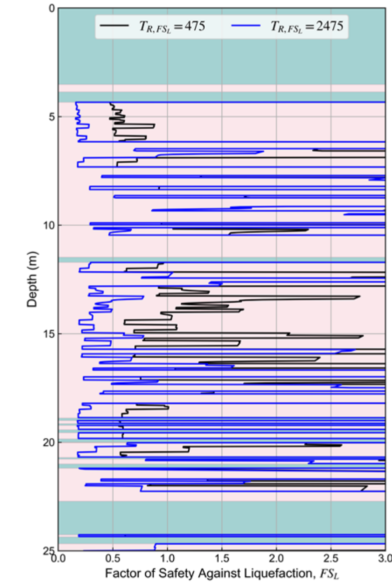
Ground Motions



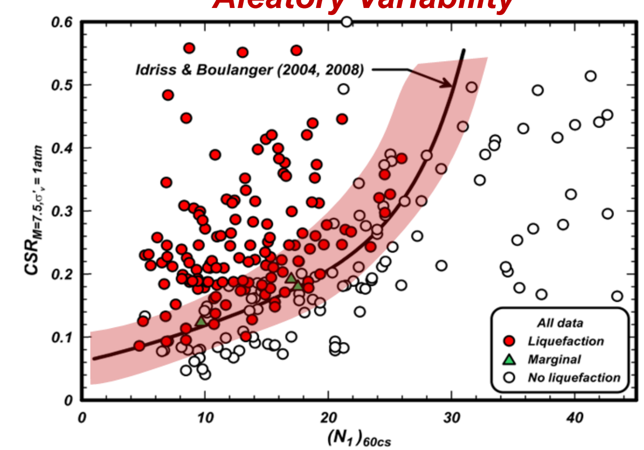


Triggering





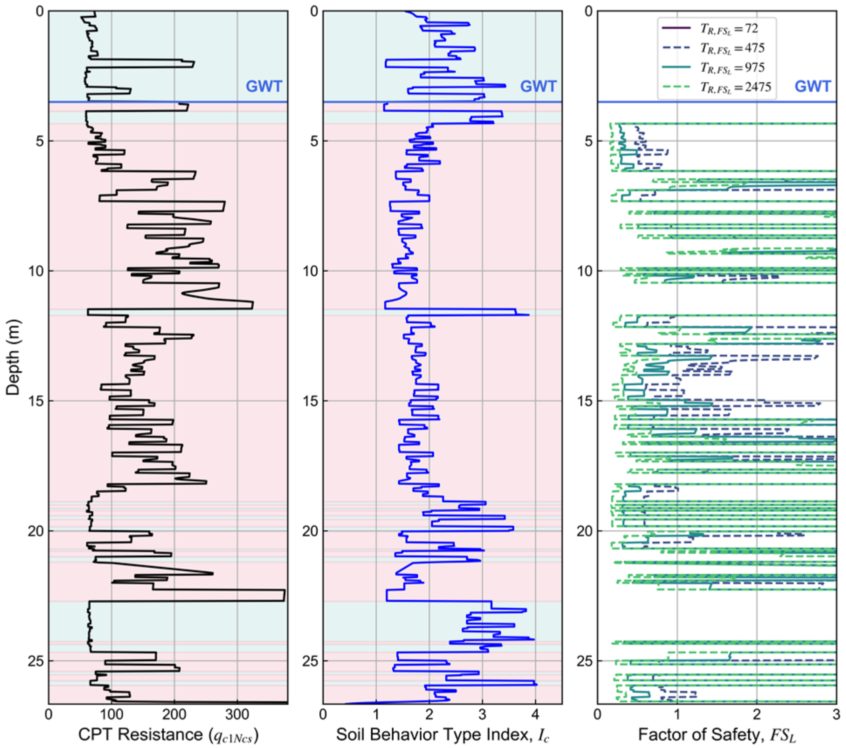
Aleatory Variability



Boulanger & Idriss (2012)

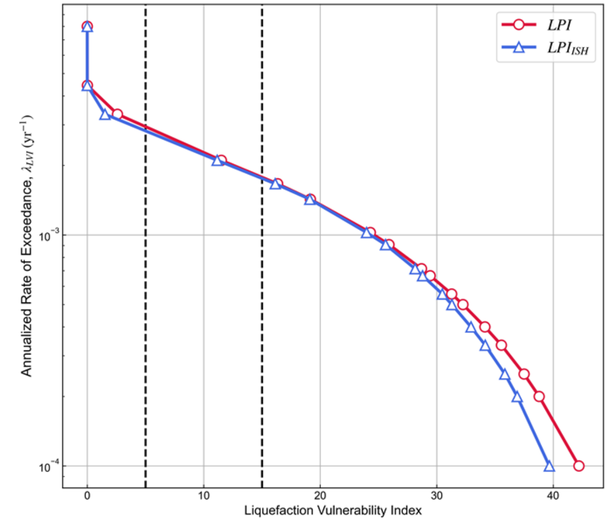
Current State of the Art

Triggering

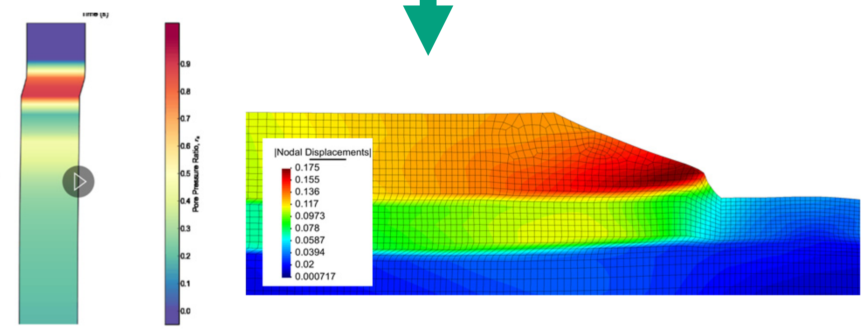


Liquefaction hazard corresponding to a <u>targeted, consistent hazard level of triggering or vulnerability</u>

Vulnerability and Effects



Hazard curves for liquefaction vulnerability or free field displacements



Advanced computational methods

USGS Liquefaction Hazard Tool

- Goal - bring state of art and state of practice closer together
  - Python library in USGS software review

- Current capabilities
  - Hazard curves for triggering, vulnerability index, and surface manifestation hazard curves
  - User can define the models they want or model logic tree+weights

- Looking ahead
  - USGS web tool/web-service
  - Established, consistent set of assumptions, models, weights
  - Consensus-driven approach
    - Working groups, external panel review
    - Researchers, practitioners, public agencies, building code committees
  - Basis for improved liquefaction design guidelines
  - Tool for regional-scale liquefaction hazard/risk assessment

Modeling Needs & Looking Ahead

General Liquefaction Hazard Assessment Needs

Susceptibility

- Improved probabilistic criteria (compositional, saturation)
- *Epistemic uncertainties*

Ground Motions

- *Uncertainties* in hazard curves (i.e., fractiles)
- Hazard characterization for new intensity measures (e.g., *CAV*, I_A)

Triggering

- Expanded suite of triggering models
- *Epistemic uncertainties*

First-Order Consequences

- Hazard curves for vulnerability indices (e.g., *LPI, LSN,* LPI_{ISH})
- Hazard curves for surface manifestation (Geyin & Maurer 2020)

Effects

- Hazard curves for building settlements (e.g. Bullock et al. 2019), lateral spreading, etc.
- Utilizing non-*PGA* IMs
- Not necessarily conditional on FS_L profile(s)
- *Epistemic uncertainties!*

Framework must be applicable and consistent at any site across the U.S.

Modeling Needs & Looking Ahead

Susceptibility-Specific Needs

$$\Lambda_{FS_L}(fs_L) = \sum_{j=1}^{N_m} \sum_{i=1}^{N_{pga}} \mathrm{P}[FS_L < fs_L | susc, PGA_i, M_{w,j}] \cdot \Delta\lambda_{pga_i, m_{w,j}}$$

$$\Lambda_{FS_L}(fs_L) = \sum_{j=1}^{N_m} \sum_{i=1}^{N_{pga}} \mathrm{P}[FS_L < fs_L | susc, PGA_i, M_{w,j}] \cdot \mathrm{P}[susc] \cdot \Delta\lambda_{pga_i, m_{w,j}}$$

State of practice <u>and</u> state of the art

- P[*susc*] = 0 or 1

Joint probability of:

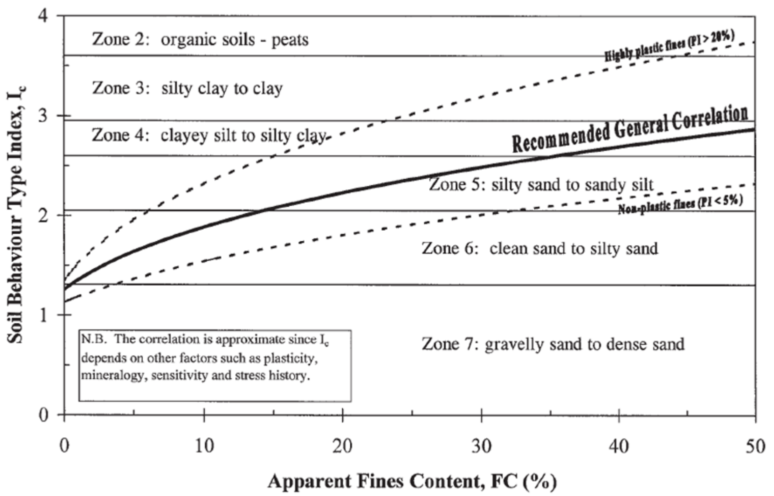
- ***Sand-like behavior (compositional)***
- ***Saturation (groundwater)***

MODELING NEEDS & LOOKING AHEAD

Compositional Susceptibility Criteria

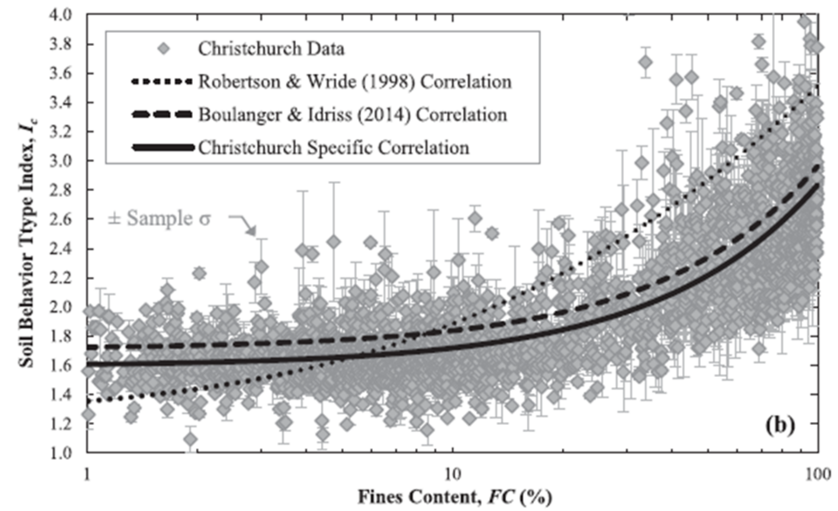
- *I_C*-based Criteria, e.g.

Global Correlations



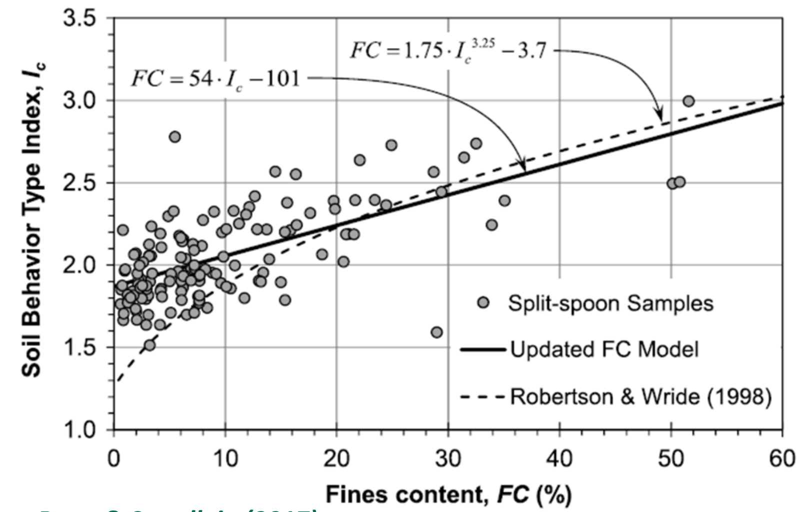
Robertson & Wride (1998)

Regional Correlations (when available)



Maurer et al. (2019)

Site-Specific Correlations (when available)



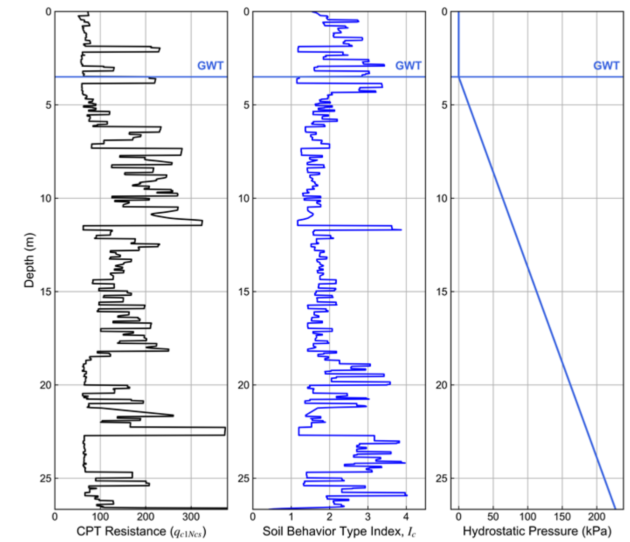
Bong & Stuedlein (2017)

How should we weight correlations at different scales?

Modeling Needs & Looking Ahead

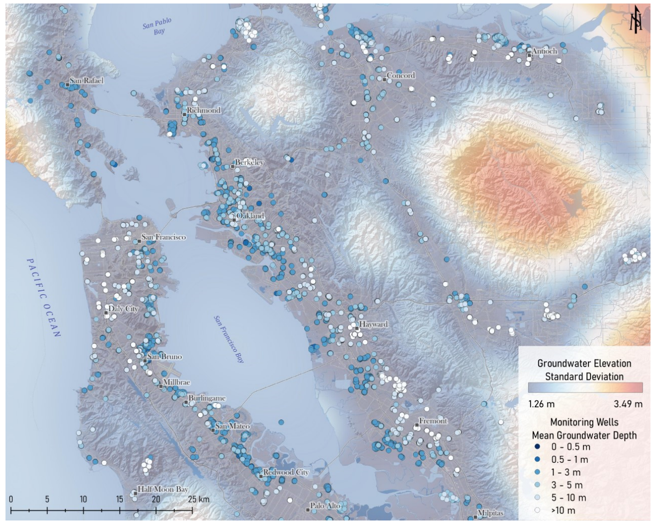
Saturation Susceptibility Criteria

- Liquefaction hazard estimates are *extremely* sensitive to GWT depth
  - e.g., Chung & Rogers (2011), Maurer et al. (2014), Greenfield & Grant (2020)
  - Aim should be for reliable estimates of mean and variation in GWT depth

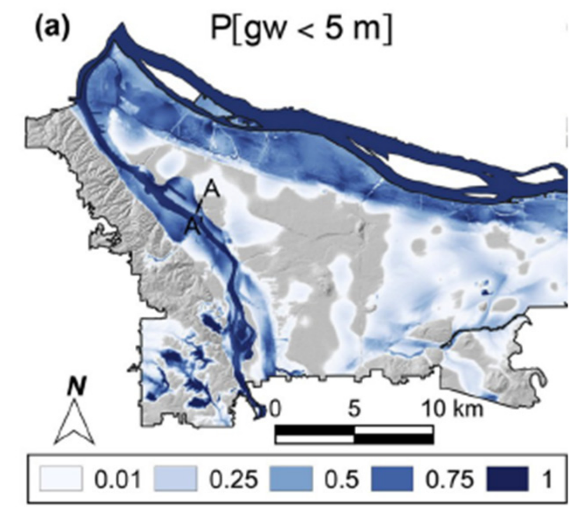


- Site-specific measurements
  - Measurements at time of subsurface investigation
  - *Monitoring data*

- Regional-scale
  - *Mean/standard deviation gwt elevations, based on aggregated monitoring data* (e.g. van Ballegooy et al. 2014, Greenfield & Grant 2020)



Preliminary figure from Tim Estep and Mike Greenfield, not to be used outside of this presentation.



Greenfield & Grant (2020)

Summary & Concluding Remarks

- Current state of practice
  - Liquefaction FS_L, conditional on uniform hazard ground shaking
  - Doesn't meet the goal of uniform performance objectives
- Current state of the art
  - Provides hazard curve estimates of triggering, vulnerability indices, surface manifestation
  - Closer to uniform performance objectives – but it doesn't get us all the way there yet
- Research needs
  - More and improved models of liquefaction consequences
  - Better estimates of *uncertainties* at all stages – susceptibility, triggering, effects
  - Susceptibility-specific
    - Probabilistic characterization of compositional and saturation criteria
    - Consistent framework for blending data and models at different scales
- Reasons for optimism
  - Significant expansion of data and computational tools, ongoing model development
  - Lots of stakeholder involvement, potential for consensus-driven approach

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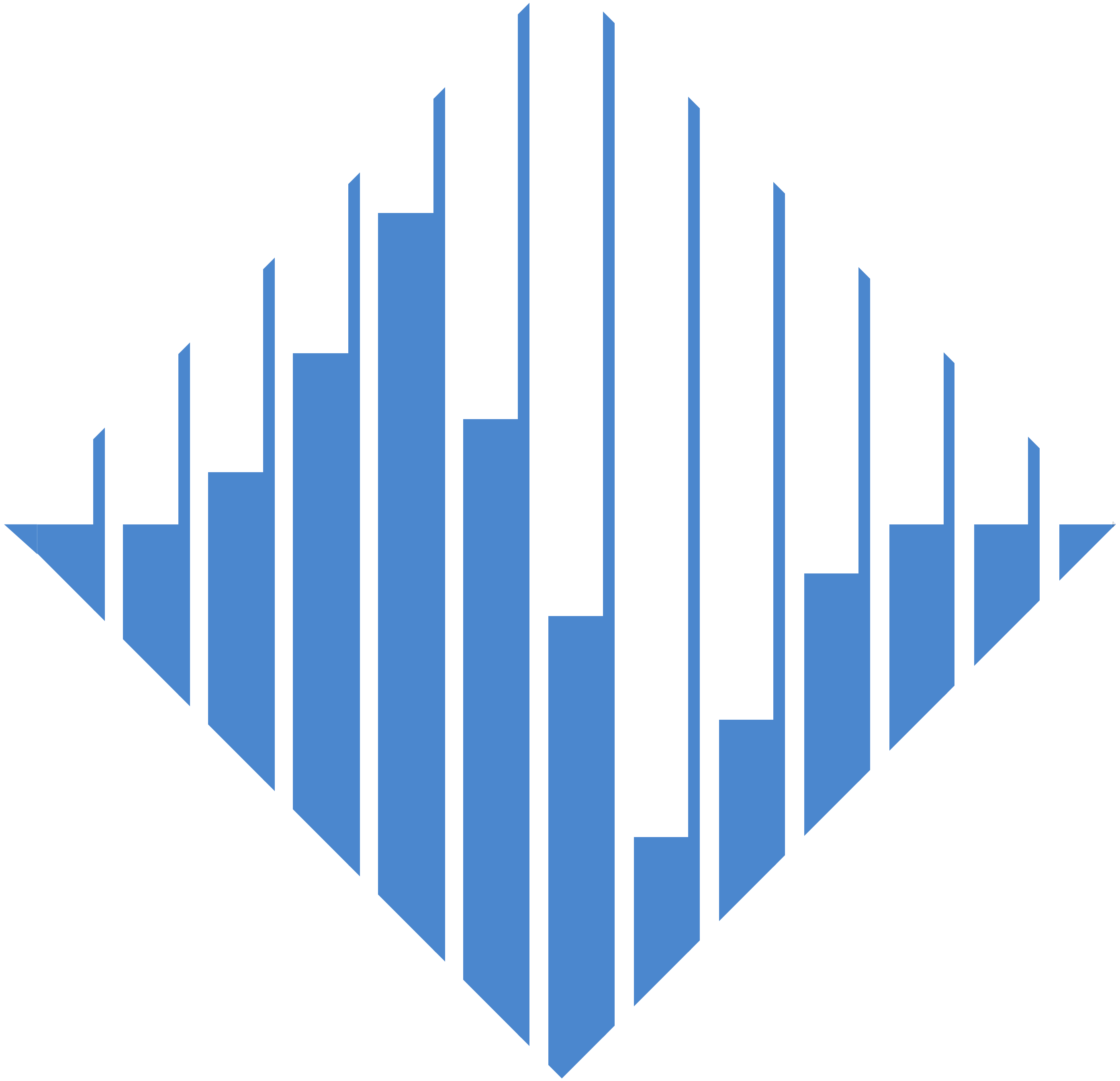


PEER Workshop *on* Liquefaction Susceptibility

APPENDIX G

Session 3 Presentations

Scott Olson: ***Consequence-Based Susceptibility Incorporating Compressibility***

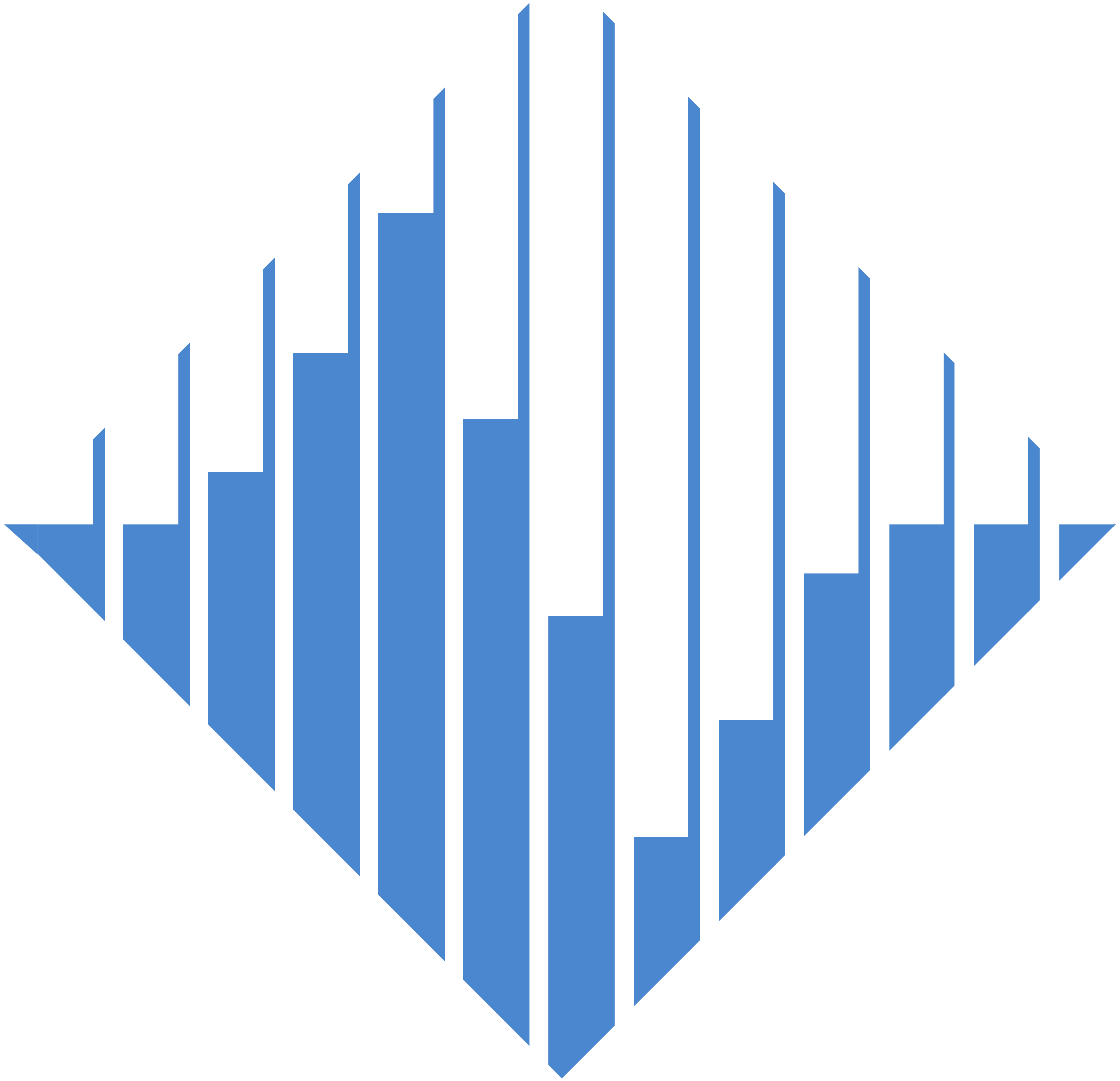
Diane Moug: ***Relating Cyclic Behavior to CPT Data for Intermediate Fine-Grained Soils***

Brett Maurer: ***CPT-Based Probabilistic Prediction of Liquefaction Susceptibility***

Ross Boulanger: ***Susceptibility Criteria for Selecting Engineering Procedures***

Scott Brandenberg: ***Cyclic Behavior of Low Plasticity Fine-Grained Soils of Varying Salinity, and Cyclic Failure due to Dynamic Soil-Structure Interaction***

Armin Stuedlein: ***Linking Hysteretic Behavior to Liquefaction Susceptibility***



Consequence-based susceptibility incorporating compressibility

Scott M. Olson, PhD, PE
Professor, University of Illinois at Urbana-Champaign

Kevin W. Franke, PhD, PE
Associate Professor, Brigham Young University

PEER Workshop on Liquefaction Susceptibility
September 8-9, 2022
Corvallis, Oregon

Acknowledgements

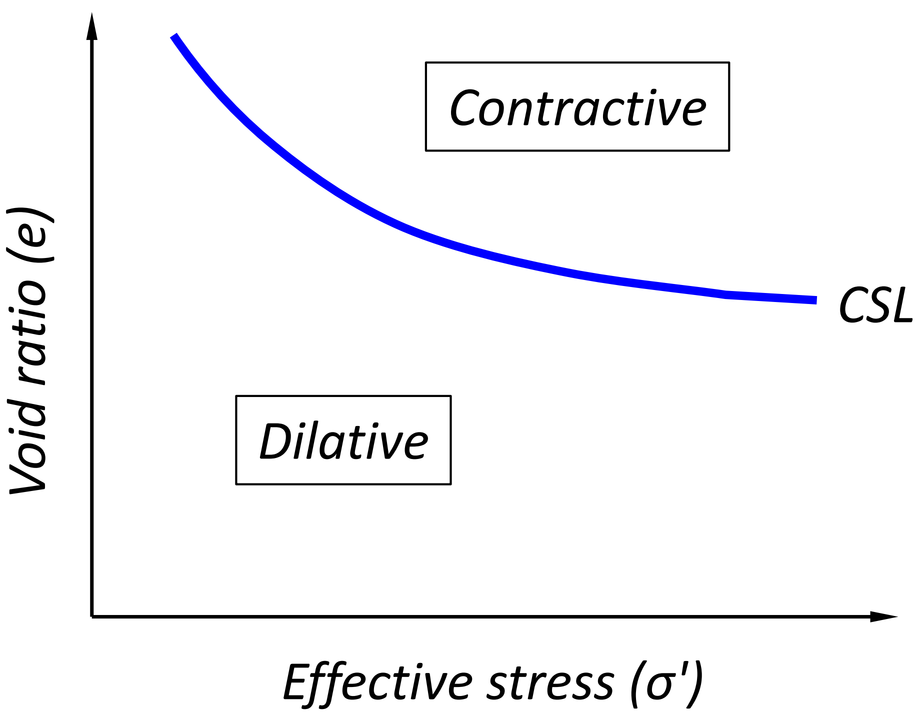
- *Mr. Steven R. Saye, Kiewit Engineering*
- *Prof. Bret Lingwall, South Dakota School of Mines and Technology*
- *Prof. Armin Stuedlein, Oregon State University*

Development of consequence-based susceptibility relations

- *Consequences of liquefaction depend on material behavior (stiffness and strength), which in turn, depend on:*
  - *Material characteristics reflected by* Δ_Q
  - *Soil state reflected by* e *and* σ'_v

Development of consequence-based susceptibility relations

- *Critical state line represents state boundary between contractive soils susceptible to flow liquefaction ("unlimited" deformation) and dilative soils not susceptible to flow liquefaction*



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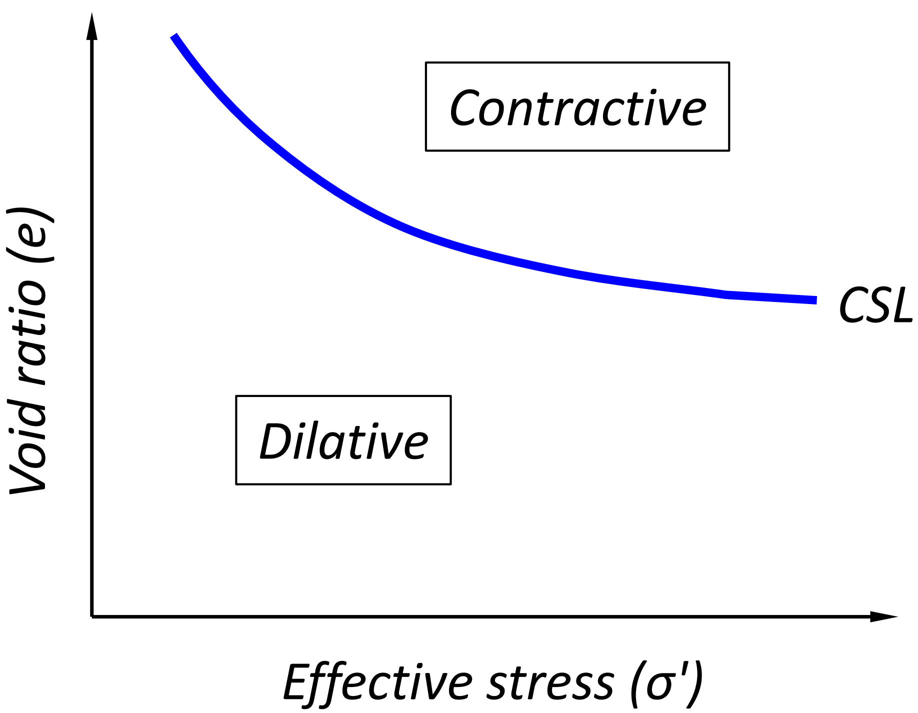
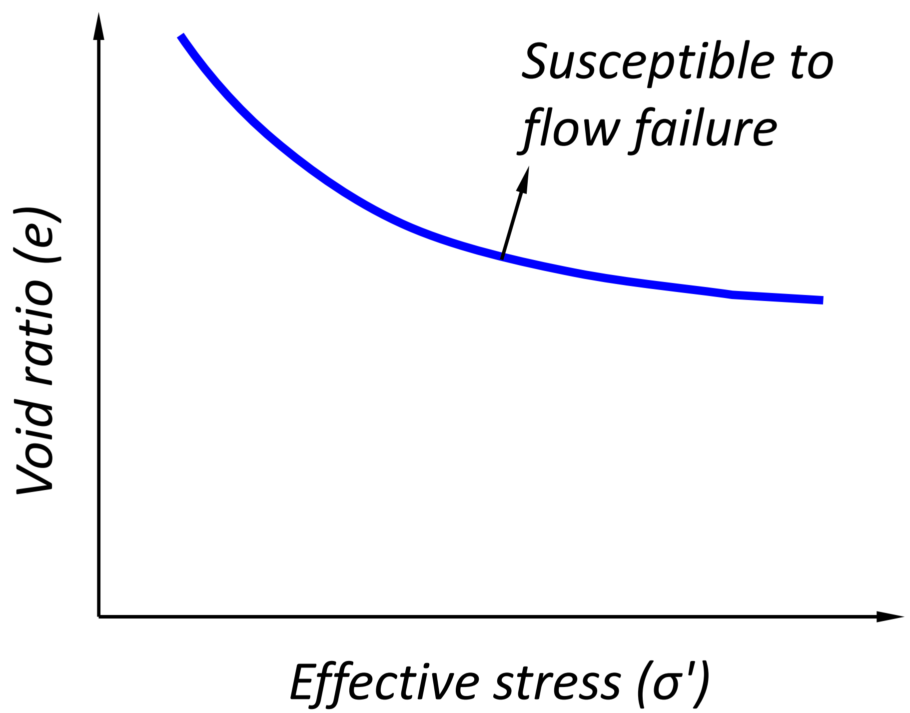
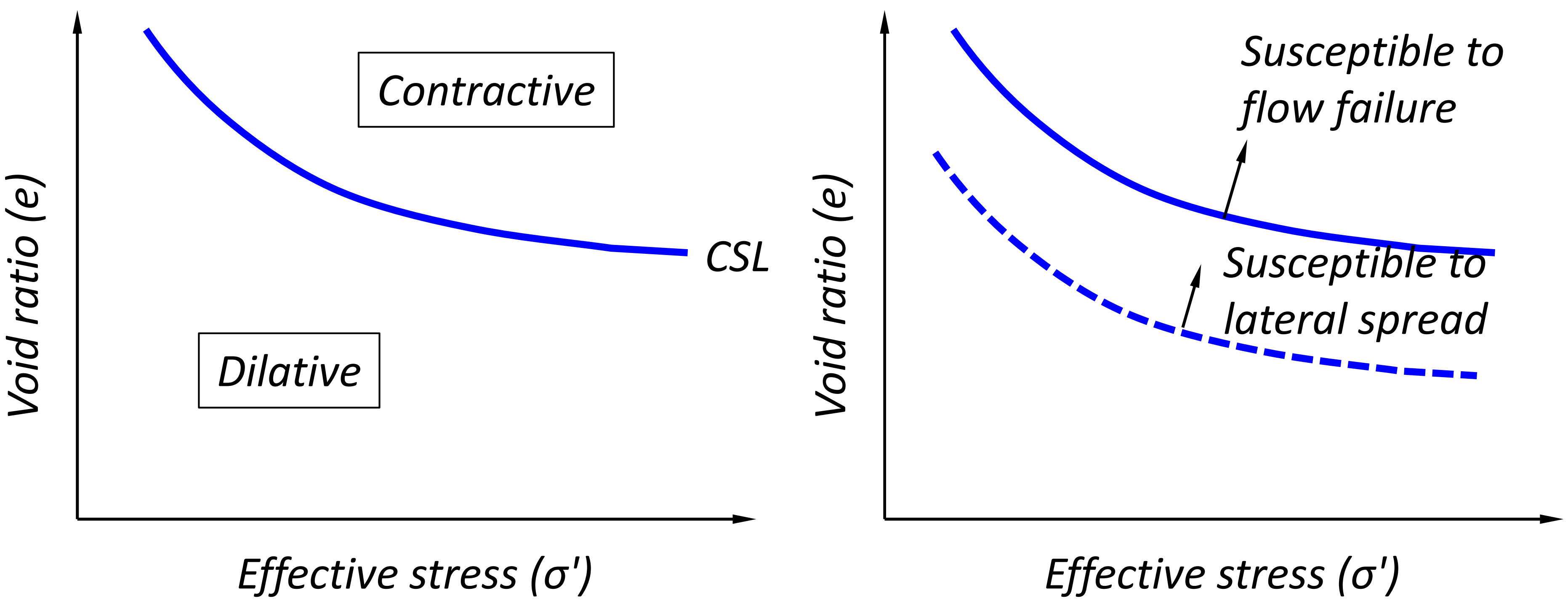




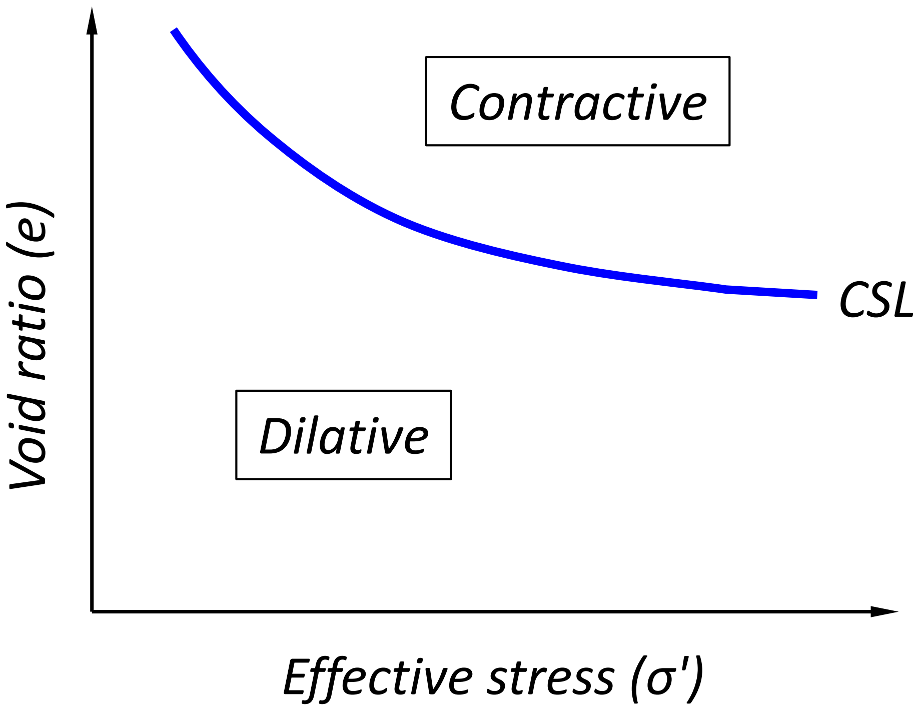
Development of consequence-based susceptibility relations

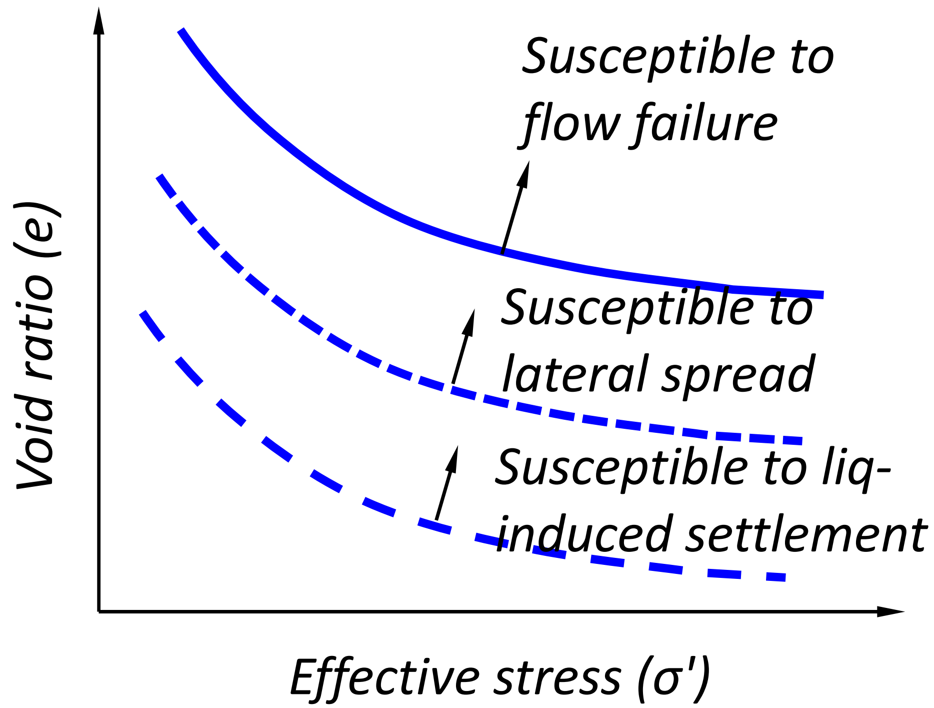
- *Based on field observations and laboratory testing, we know that denser soils can experience lateral spreading (limited deformation)*



Development of consequence-based susceptibility relations

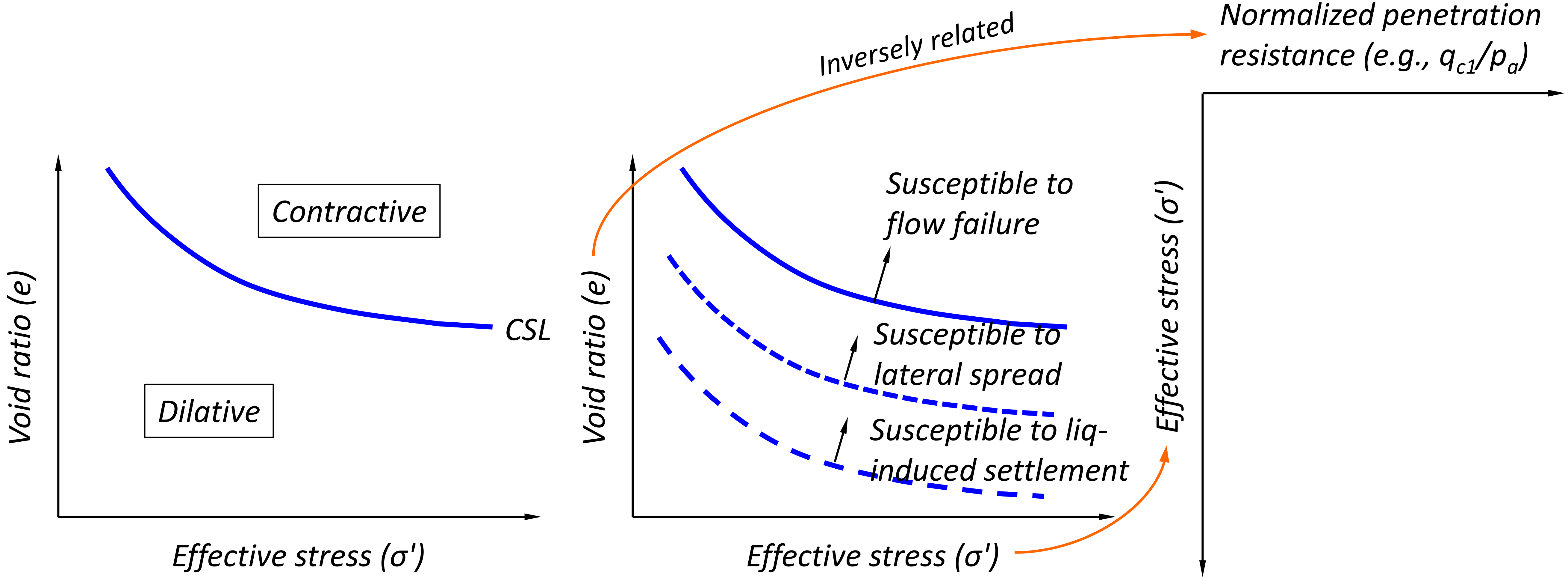
- *Similarly, even denser soils can experience liquefaction-induced settlement (porewater pressure generation and reconsolidation)*





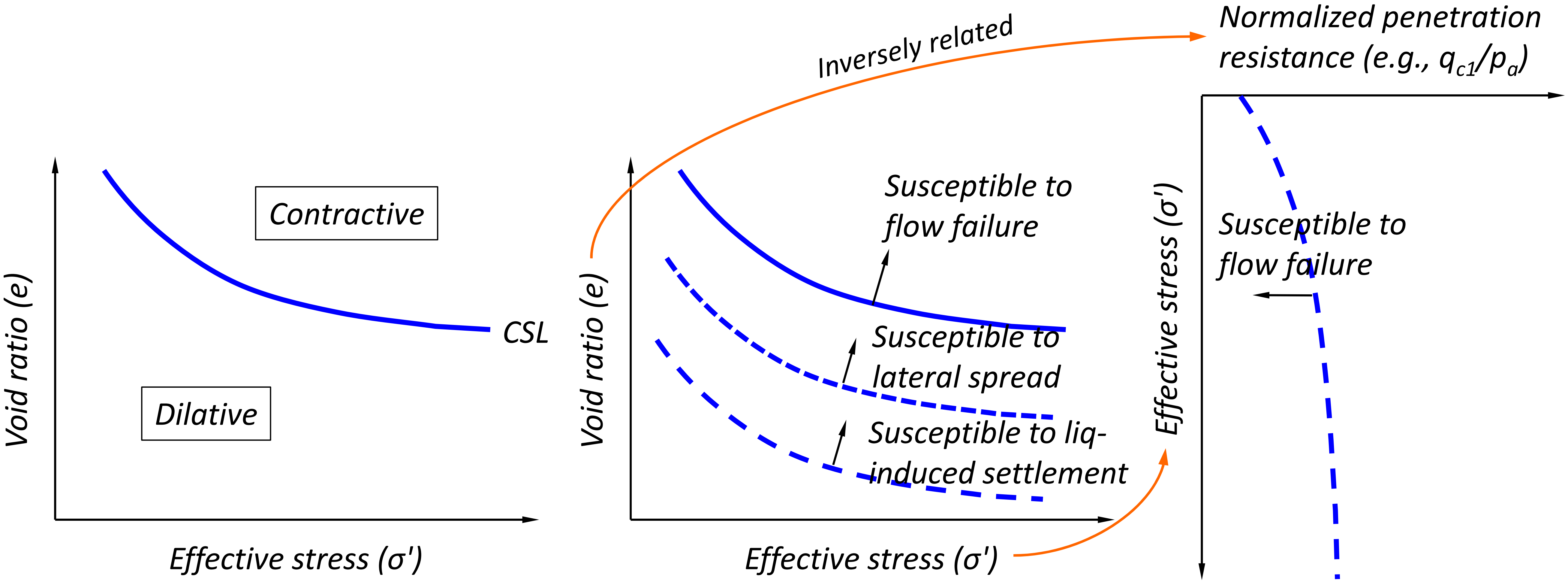
Development of consequence-based susceptibility relations

- *Axes can be inverted to better utilize field case histories*



Development of consequence-based susceptibility relations

- *We then can define conceptual consequence-based susceptibility relations*



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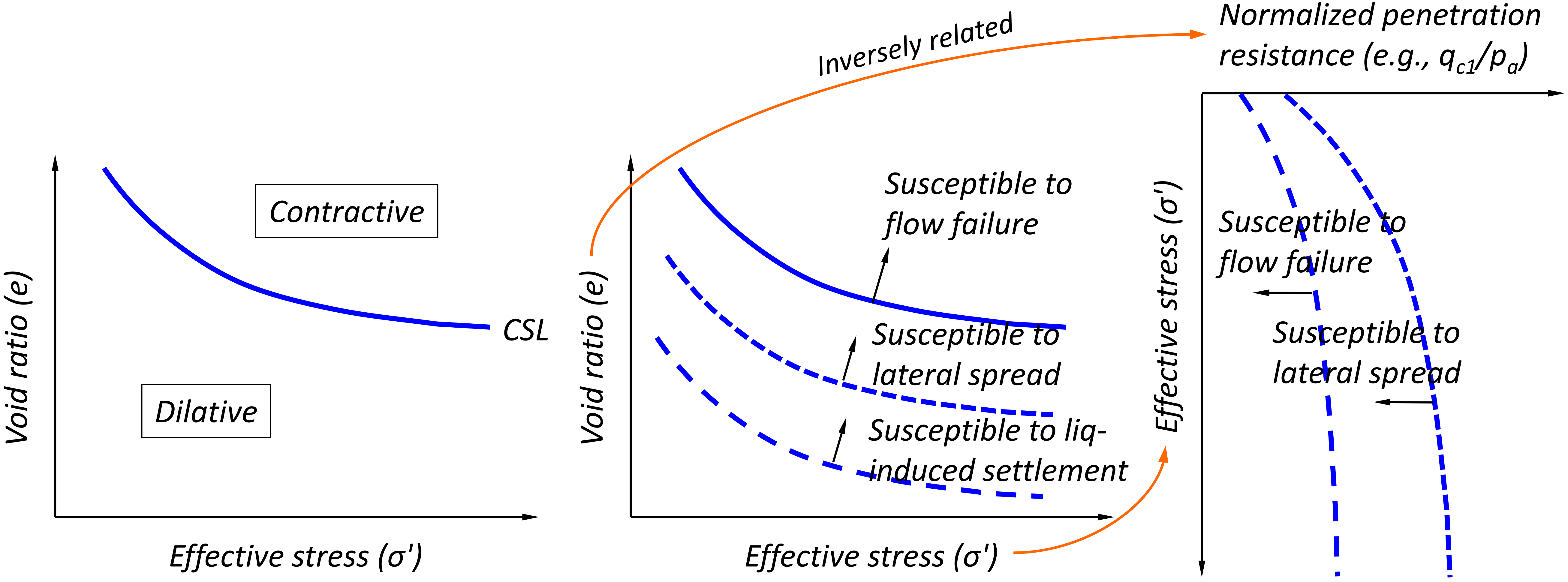

Development of consequence-based susceptibility relations

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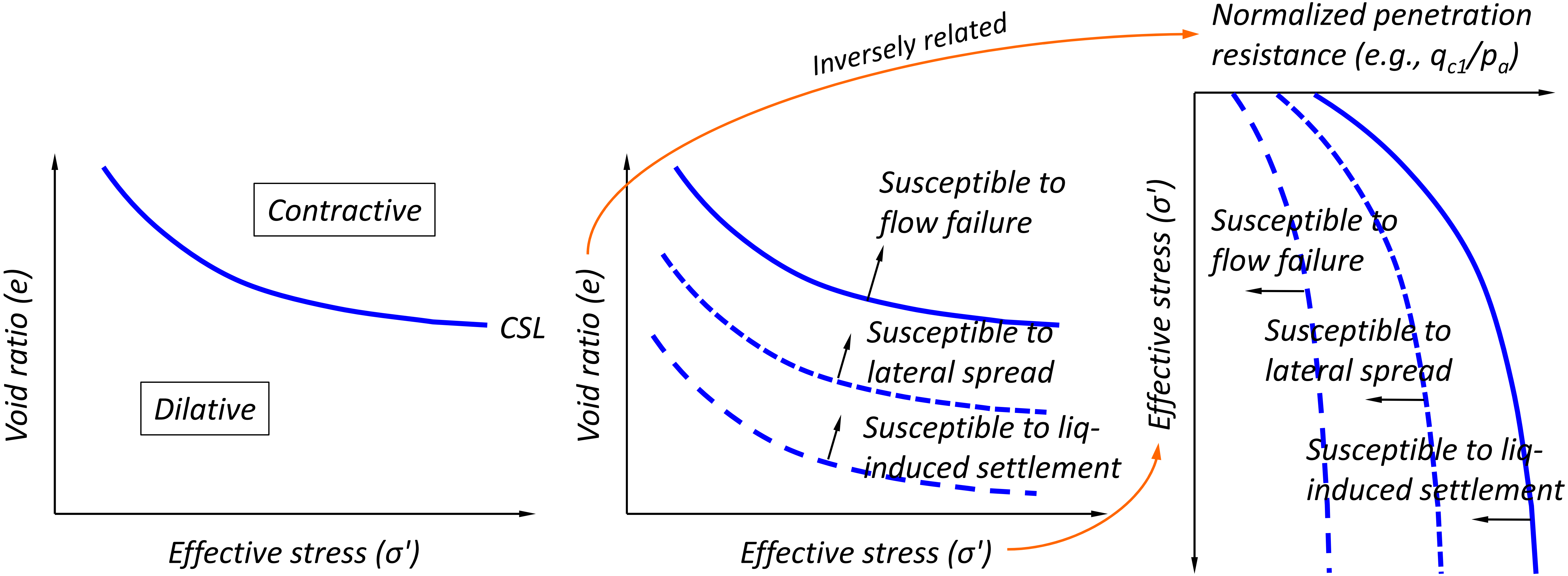
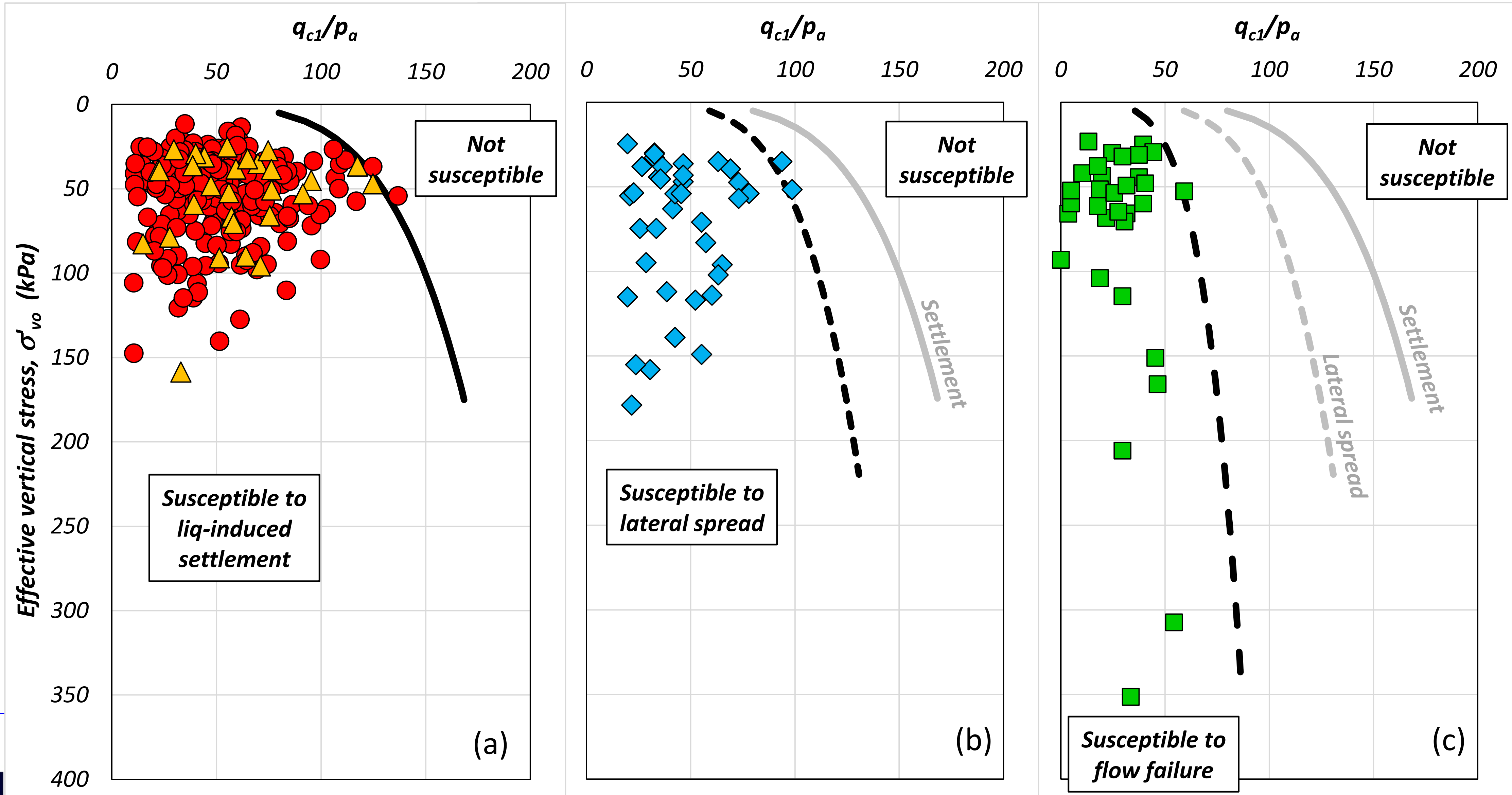


Development of consequence-based susceptibility relations

- *We can go from concept to application using field case histories*



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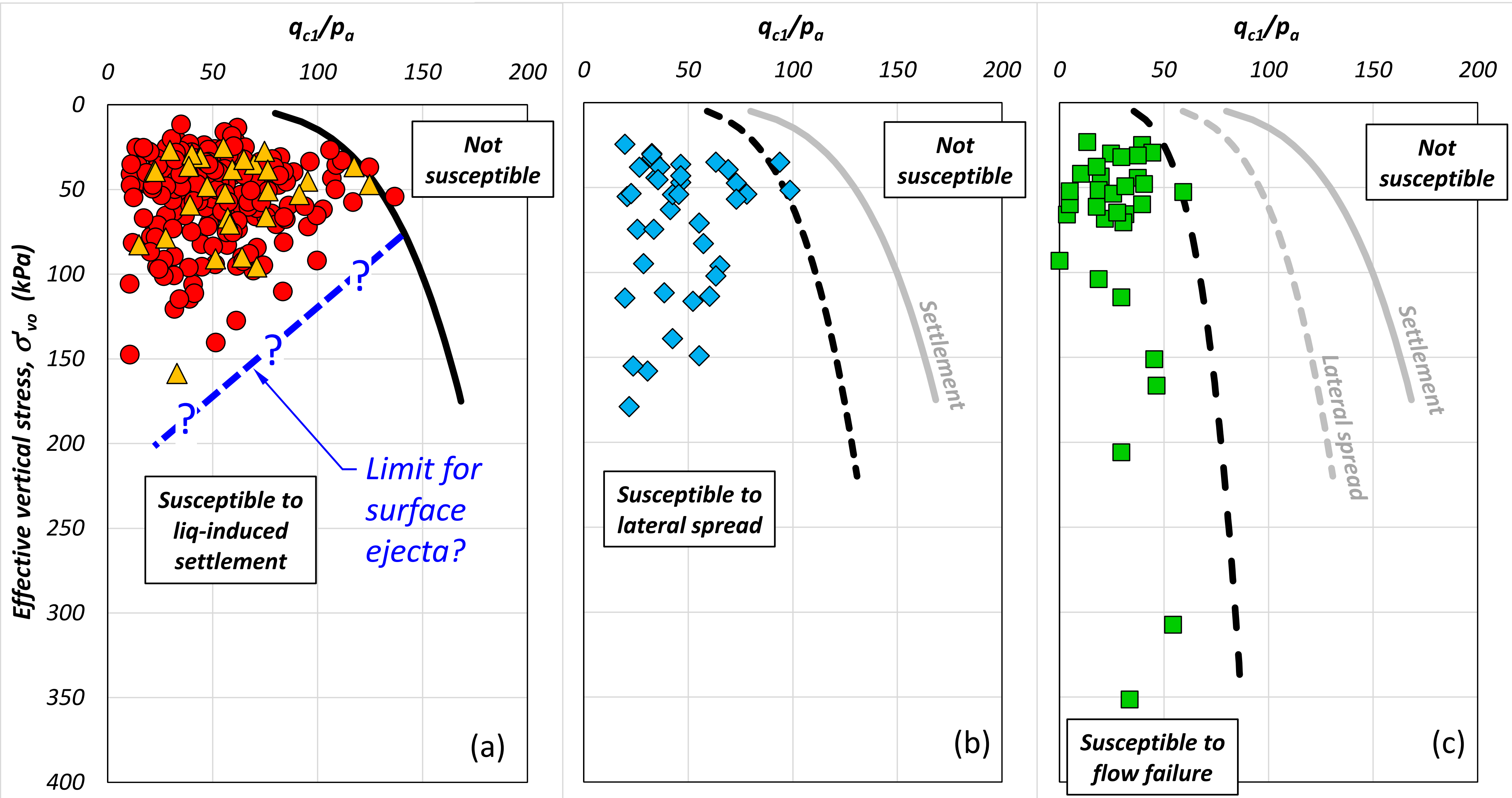
Development of consequence-based susceptibility relations

- *We can go from concept to application using field case histories*



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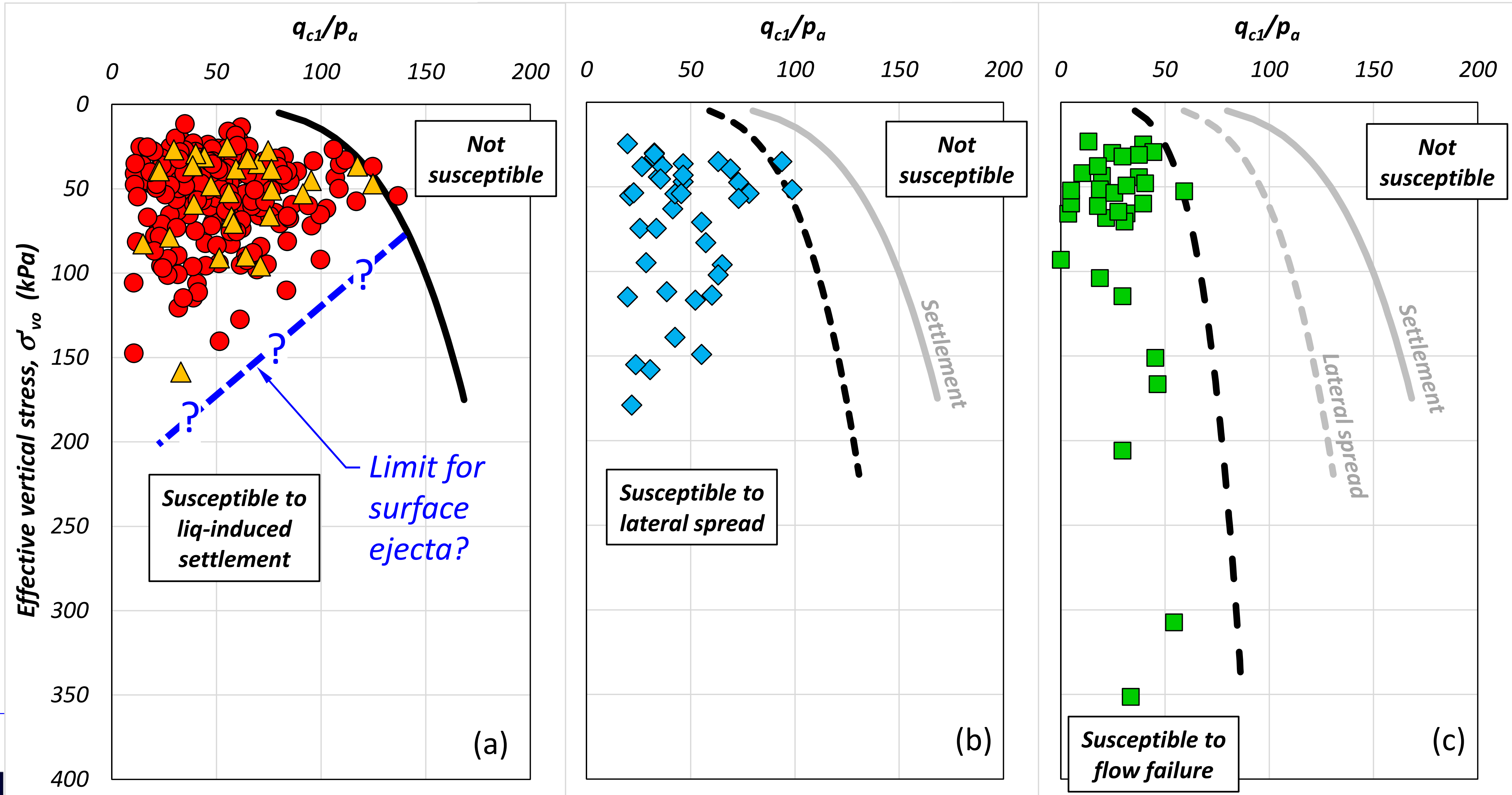
Development of consequence-based susceptibility relations

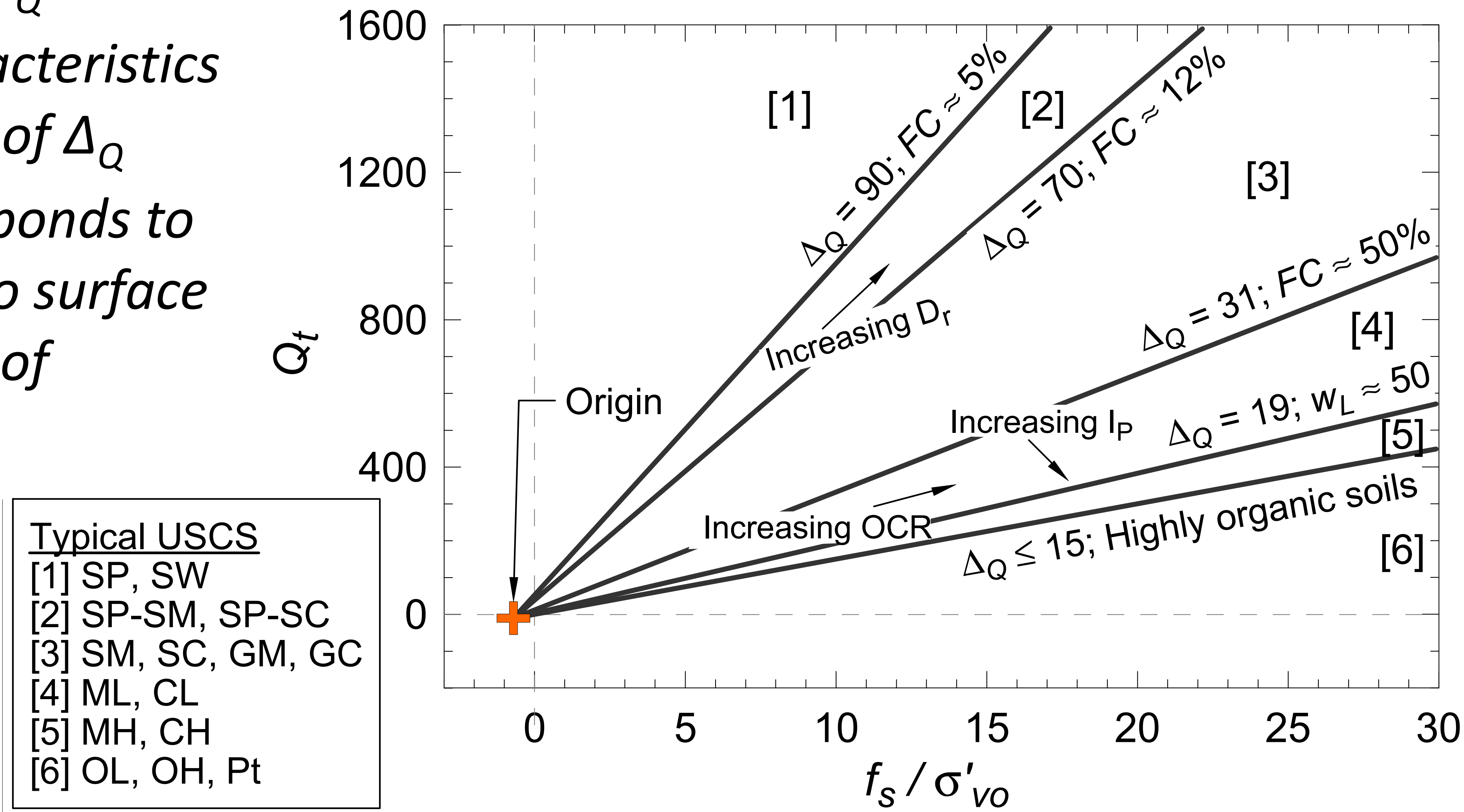
- *These are limiting boundaries; how do we incorporate material characteristics?*



Common origin – Δ_Q method

- *Common origin - Δ_Q method*
  - *Material characteristics are a function of Δ_Q*
  - *$\Delta_Q \approx 20$ corresponds to boundary of no surface manifestation of liquefaction*

Saye et al. (2017)



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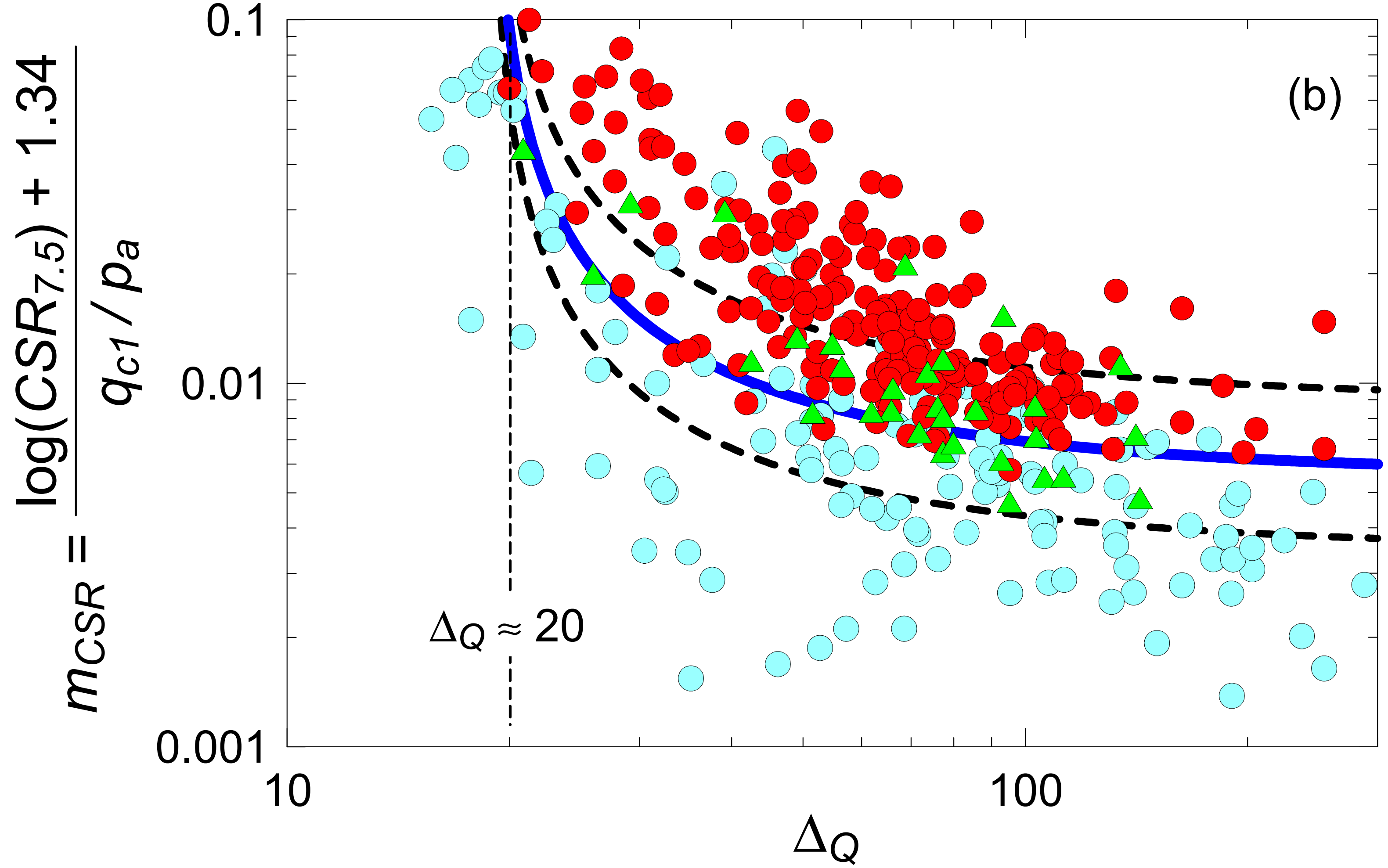
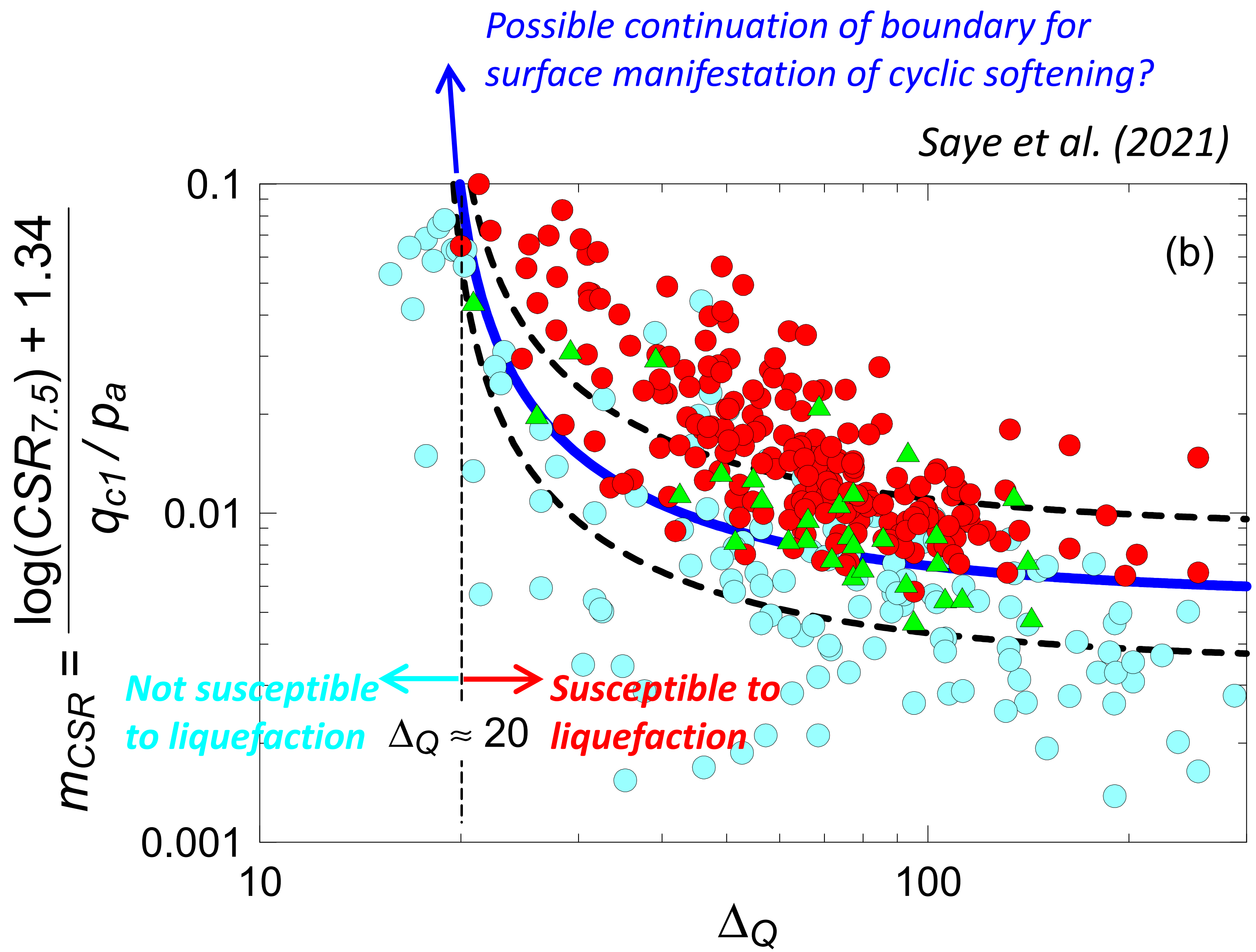


What about cyclic softening?

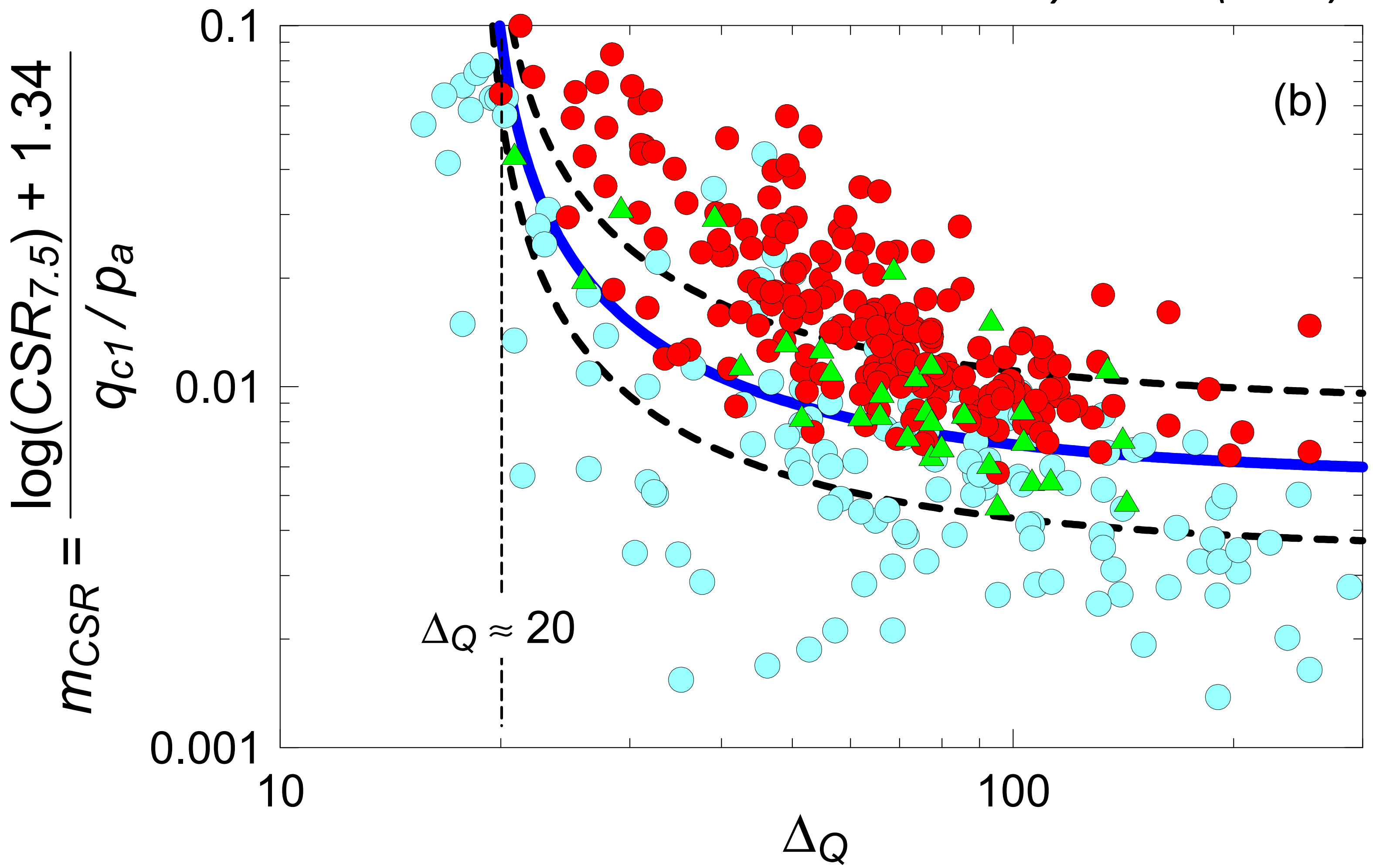
- *Some cases in the Saye et al. (2021) likely are surface manifestations of cyclic softening, not "sand-like" liquefaction*
- *Could we develop a "universal" susceptibility/ triggering model for all CPT-compliant soils if we add more cyclic softening manifestation case histories?*



Incorporating compressibility and susceptibility

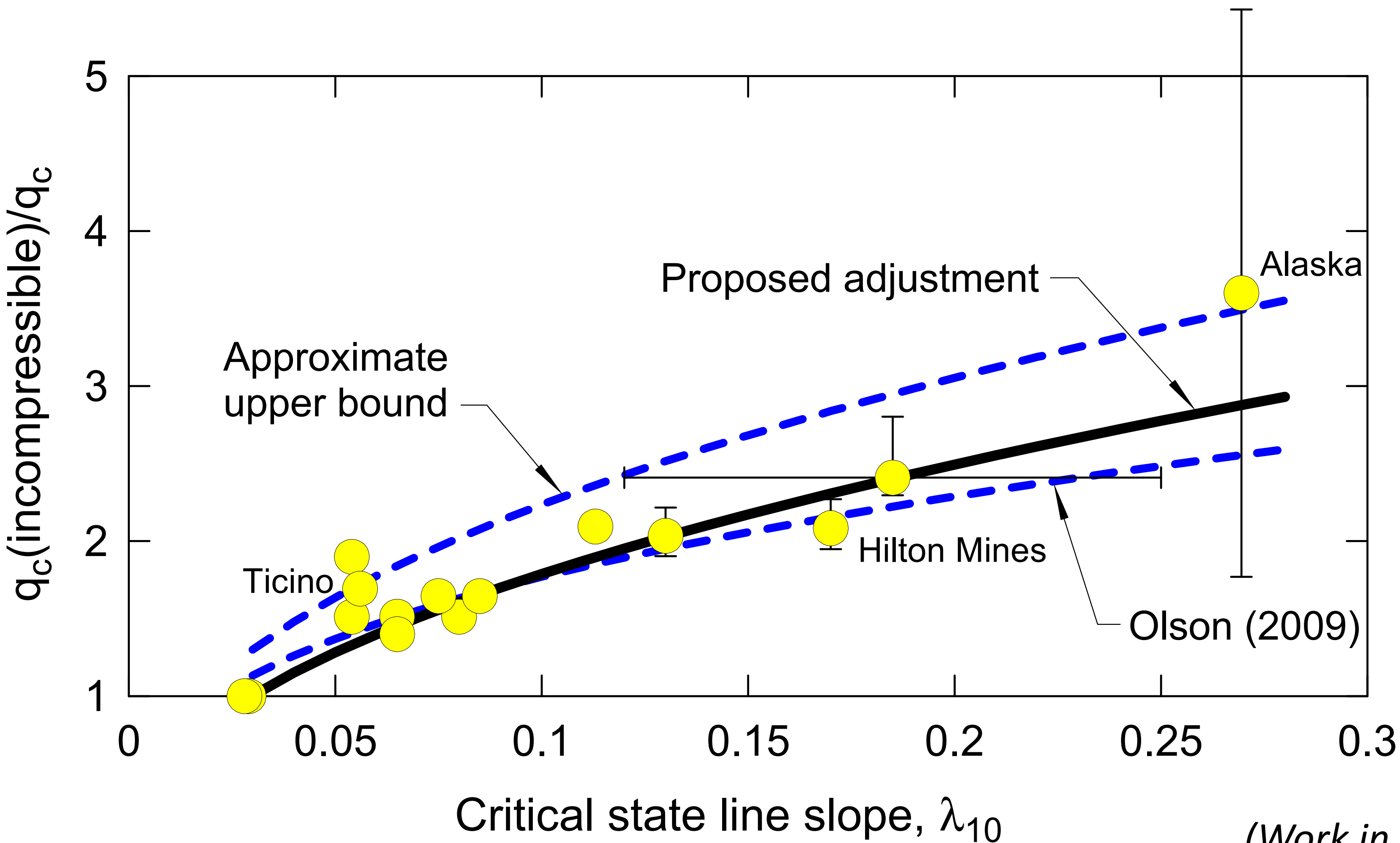
- *We can utilize common origin - Δ_Q liquefaction susceptibility/triggering method to define a "compressibility"(Δ_Q) adjustment for q_{c1}/p_a*

Saye et al. (2021)



Incorporating compressibility and susceptibility

- *CSL slope (λ_{10}) method to define compressibility adjustment*

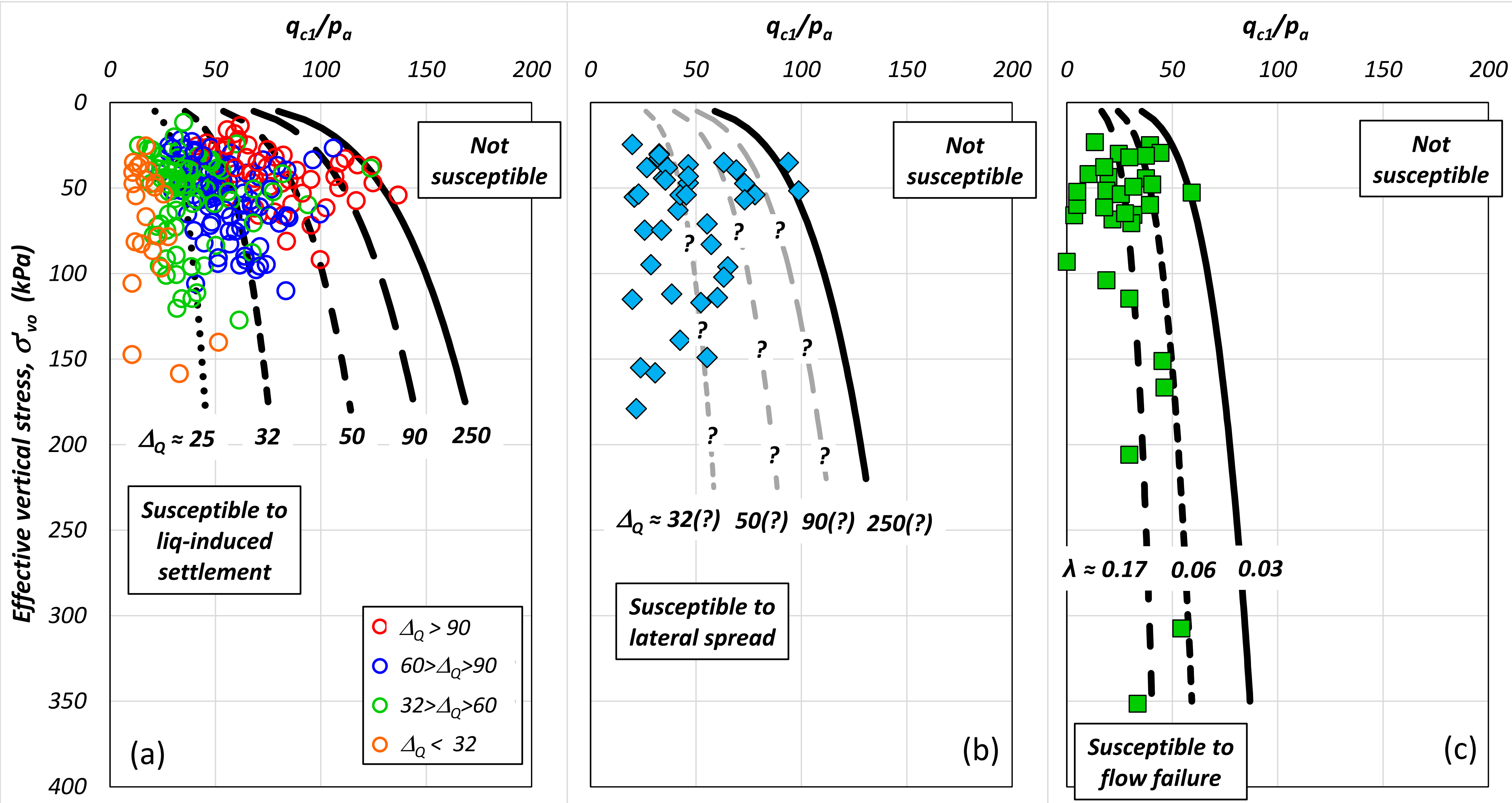


$$C_\lambda = \frac{q_{c,low\ compressibility}}{q_c}$$

(Work in progress)

Incorporating compressibility and susceptibility

- *Adjusting limiting boundary yields compressibility-based boundaries*



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Concluding remarks

- *Susceptibility to consequences of liquefaction (i.e., behaviors related to stiffness and strength) are functions of material characteristics and soil state*
- *Consequence-based susceptibility limiting boundaries for flow liquefaction, lateral spreading, and liquefaction-induced settlement can be defined using case histories*
- *Material characteristics (compressibility) can be incorporated using Δ_Q or λ_{10}*
- *Using compressibility-adjusted q_{c1}/p_a, we can define soil-specific, consequence-based liquefaction susceptibility boundaries*
- *Future work*
  - *With more cyclic softening case history data, possibly could develop a "universal" model for predicting susceptibility/triggering of Liquefaction and Cyclic Softening*
  - *Incorporating probability will allow method to be folded into PBE methods*

Thanks for your attention!

Questions?

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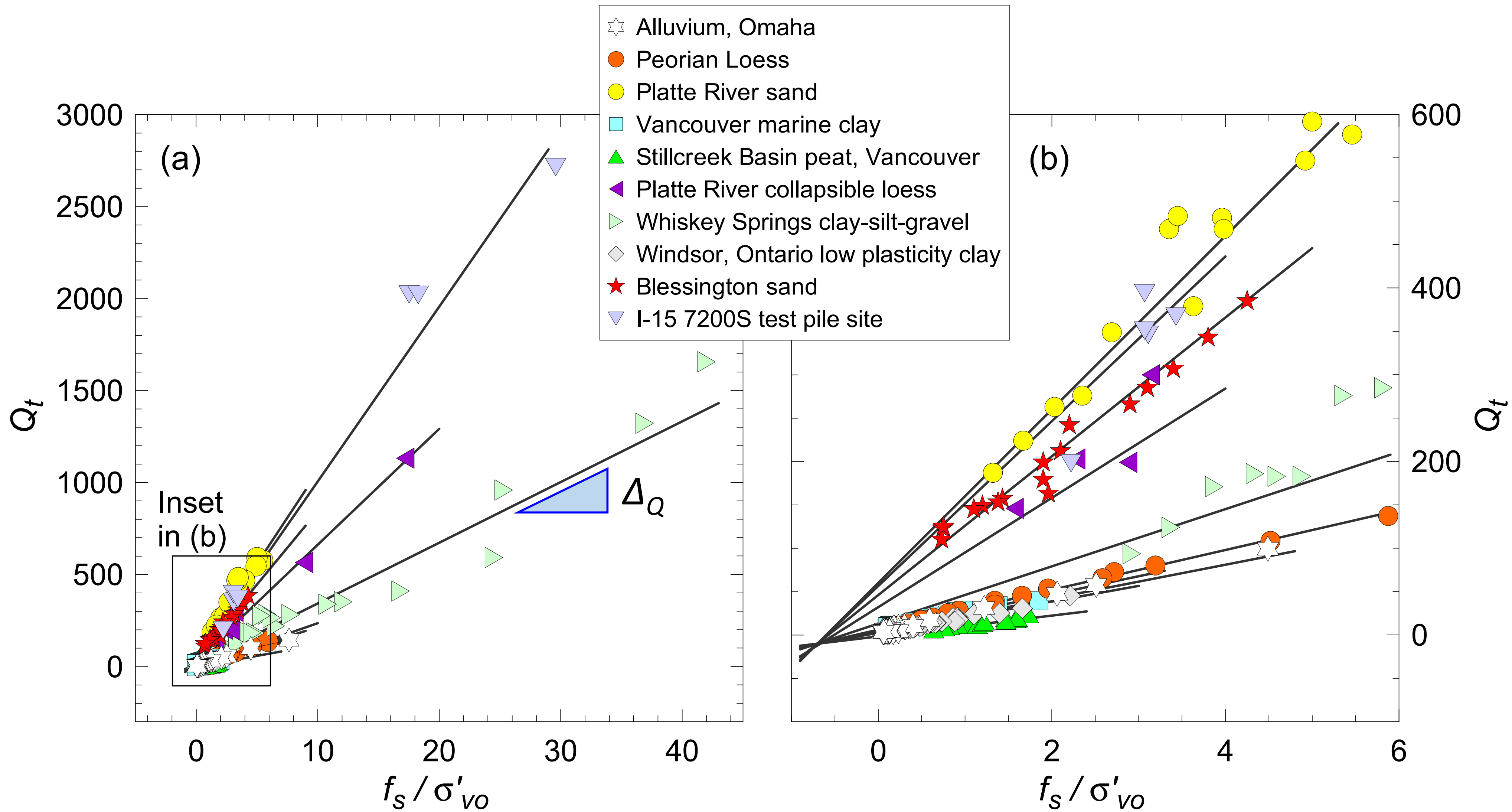
Δ_Q approach for soil identification – site data

- *Δ_Q works for coarse sands through high-plasticity clays and peats*
- *Not affected by OCR*

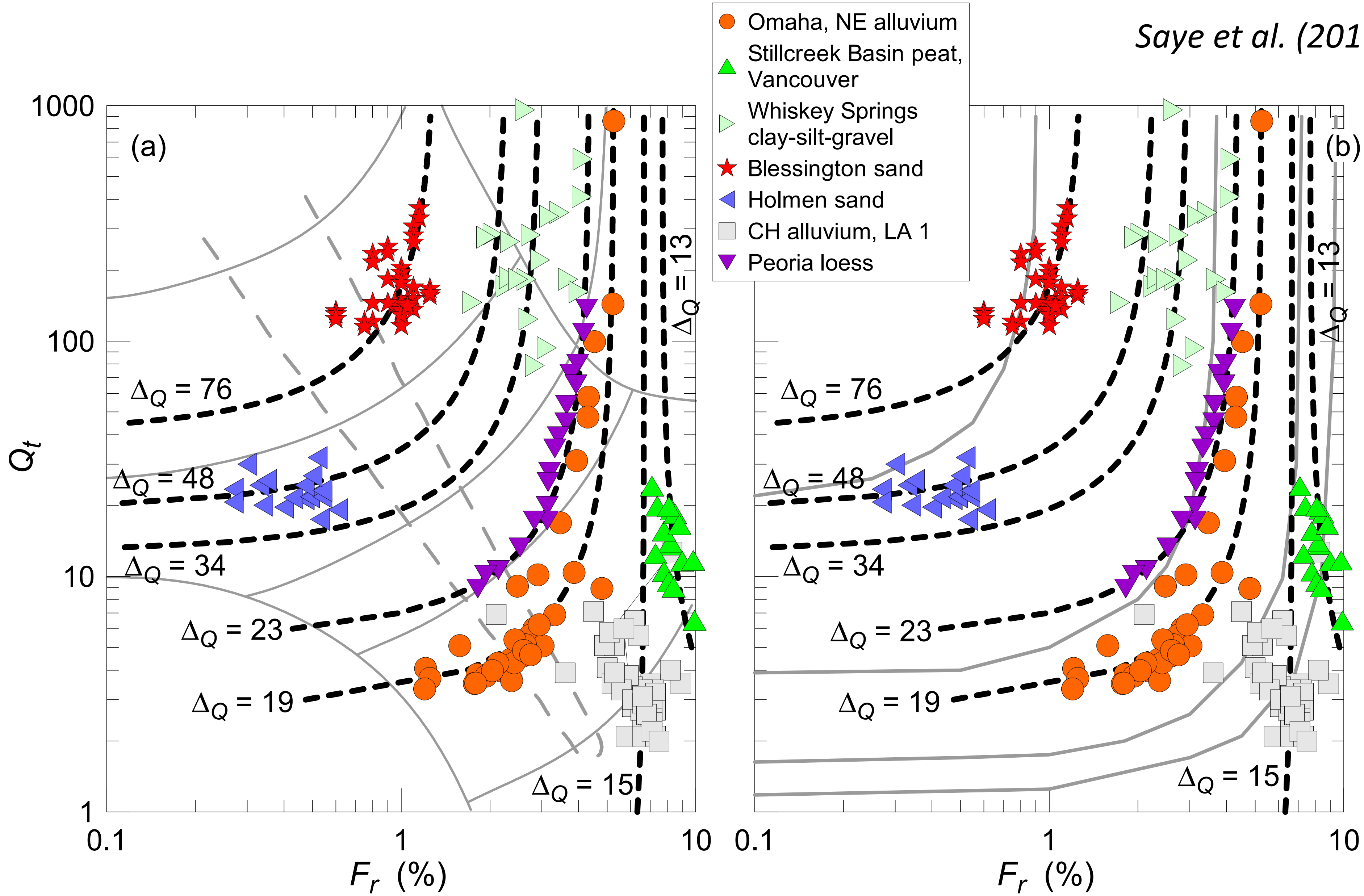


Saye et al. (2017)

Δ_Q approach for soil identification – site data

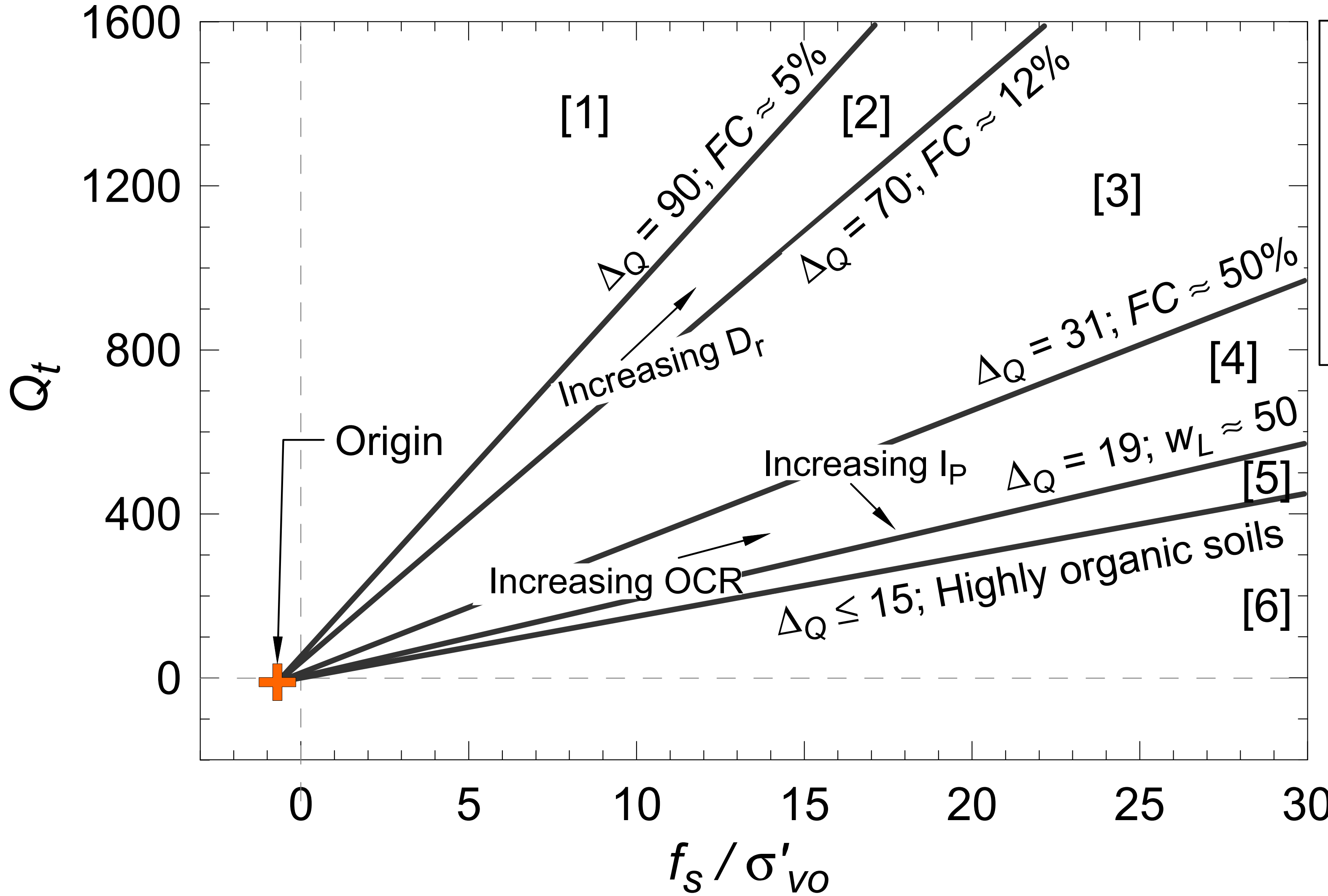
- *Δ_Q works for coarse sands through high-plasticity clays and peats*
- *Not affected by OCR*

Saye et al. (2017)



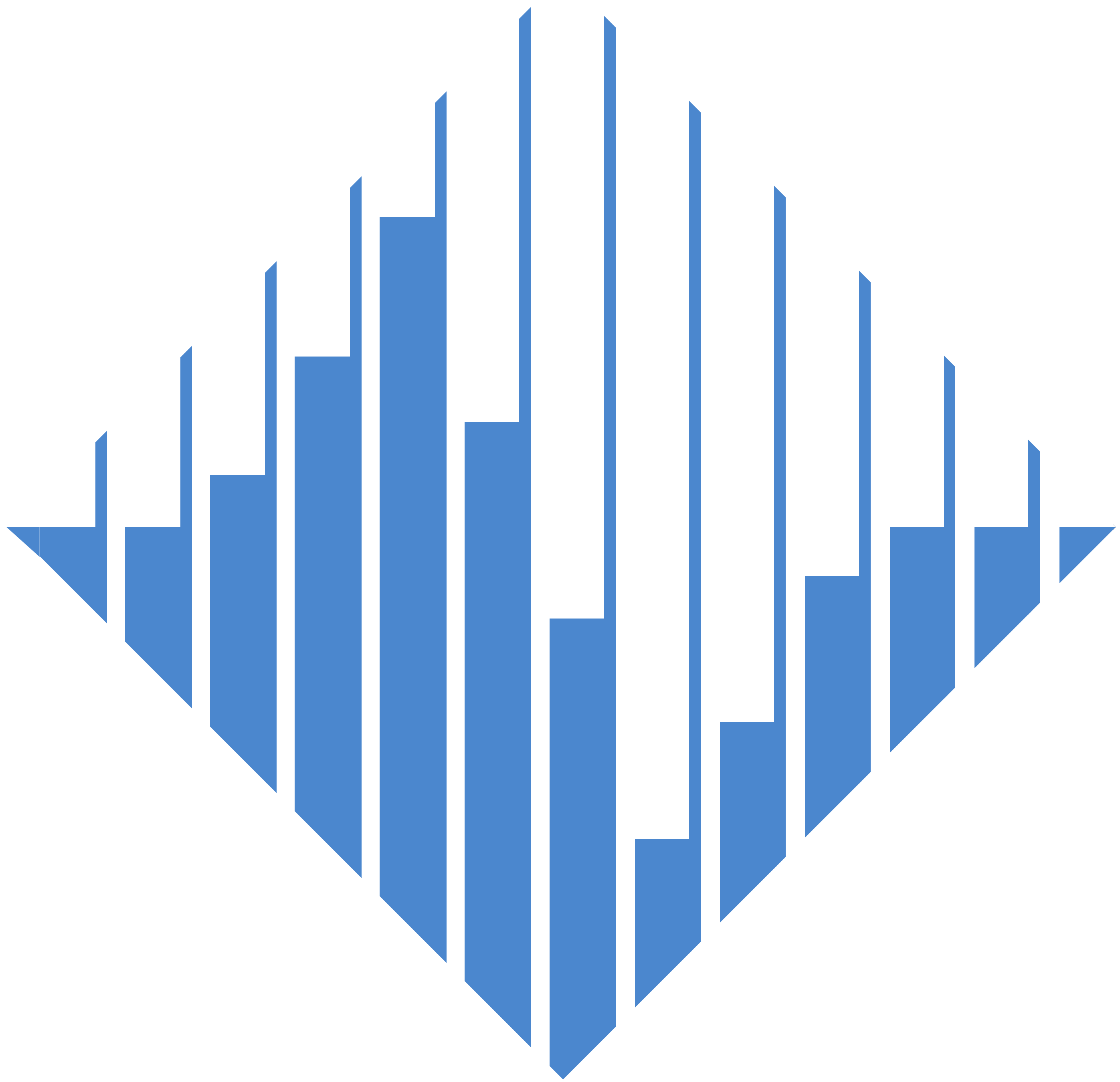
Δ_Q approach for soil identification – summary

- *Δ_Q works for coarse sands through high-plasticity clays and peats*
- *Not affected by OCR*



Typical USCS
[1] SP, SW
[2] SP-SM, SP-SC
[3] SM, SC, GM, GC
[4] ML, CL
[5] MH, CH
[6] OL, OH, Pt

Saye et al. (2017)



Relating Cyclic Behavior to CPT Data for Intermediate Fine-Grained Soils

Diane Moug, Portland State University (dmoug@pdx.edu)
Arash Khosravifar, Portland State University

PEER Workshop on Liquefaction Susceptibility, September 2022

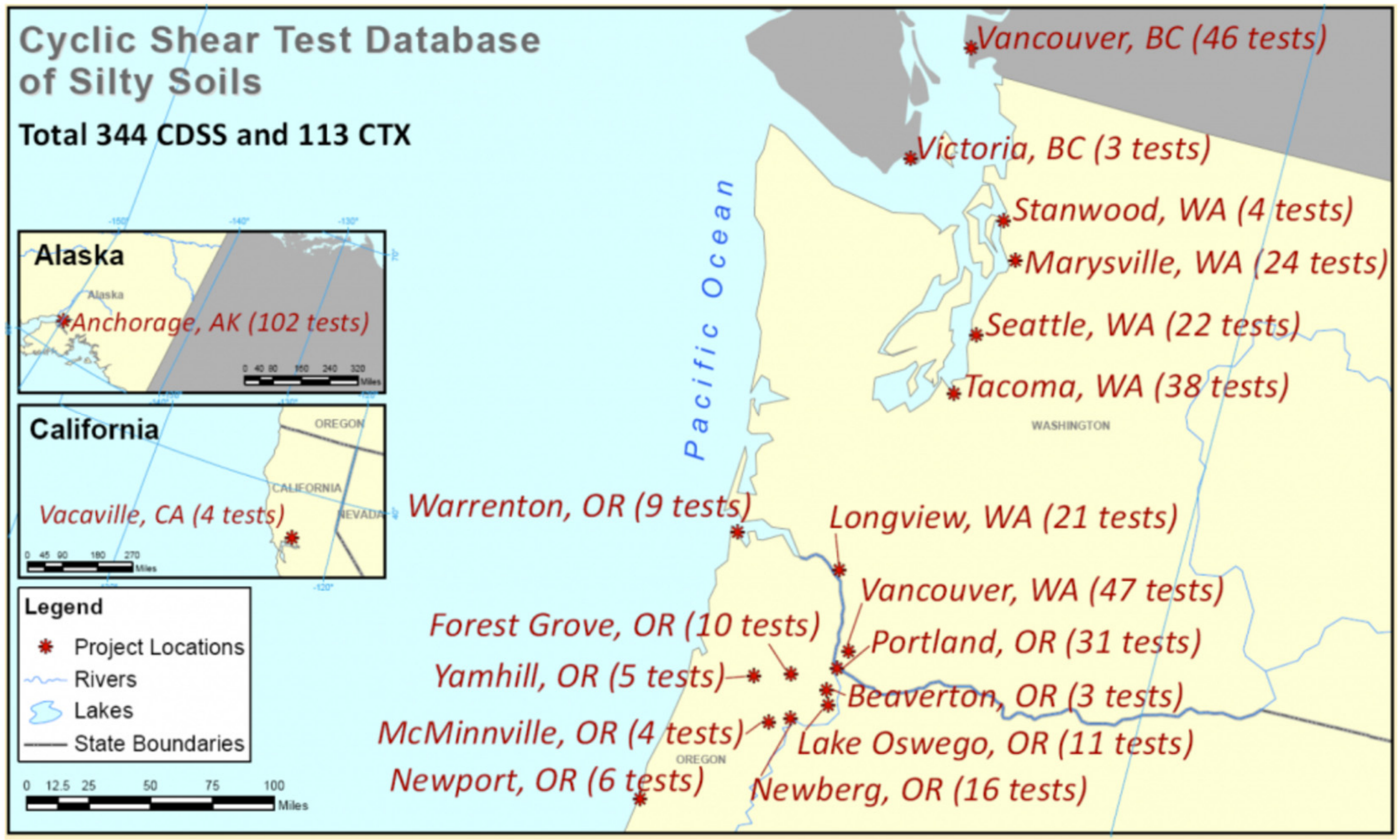
CRR – q_{t1N} Study

1. Pacific Northwest (PNW) database of geotechnical project data from fine-grained soil sites
    - Evaluate CRR – q_{c1N} relationships and CPT-based liquefaction susceptibility criteria from laboratory test and CPT site data

2. Direct axisymmetric cone penetration model with non-plastic and low-plasticity silt
    - Examine how CPT data relate to soil properties, soil state, and drainage conditions

1. Pacific Northwest Silt Database

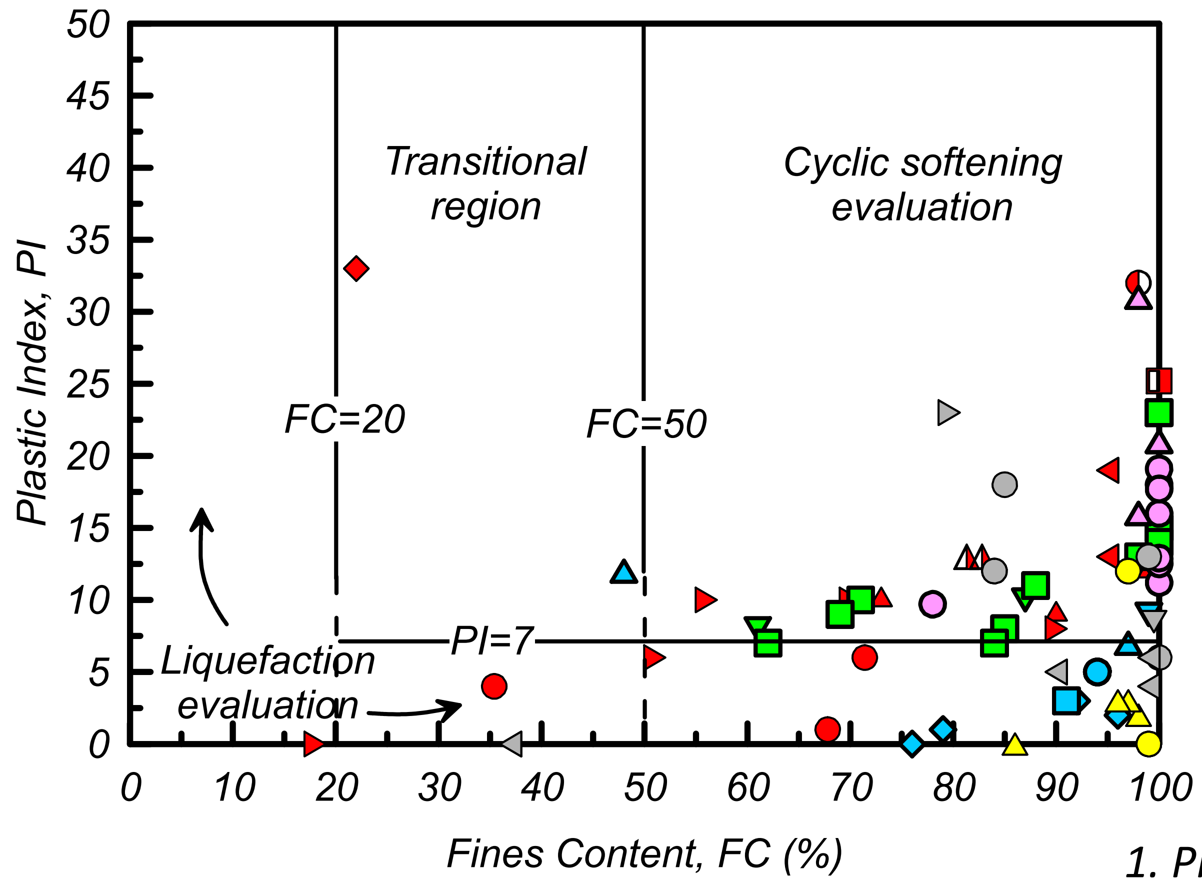
- 37 sites in Oregon, Washington, Alaska and British Columbia
- 200+ cyclic shear tests on intact specimens (DSS and TX)
- Post-cyclic shear and compression testing



https://silt.cee.pdx.edu/

Pacific Northwest Silt Database

- Fines content ranges from 18% to 100%
- PI values range from 0 to 35
- Deposition environments include fluvial, estuarine, coastal near-shore, alluvial, and one gravel processing site



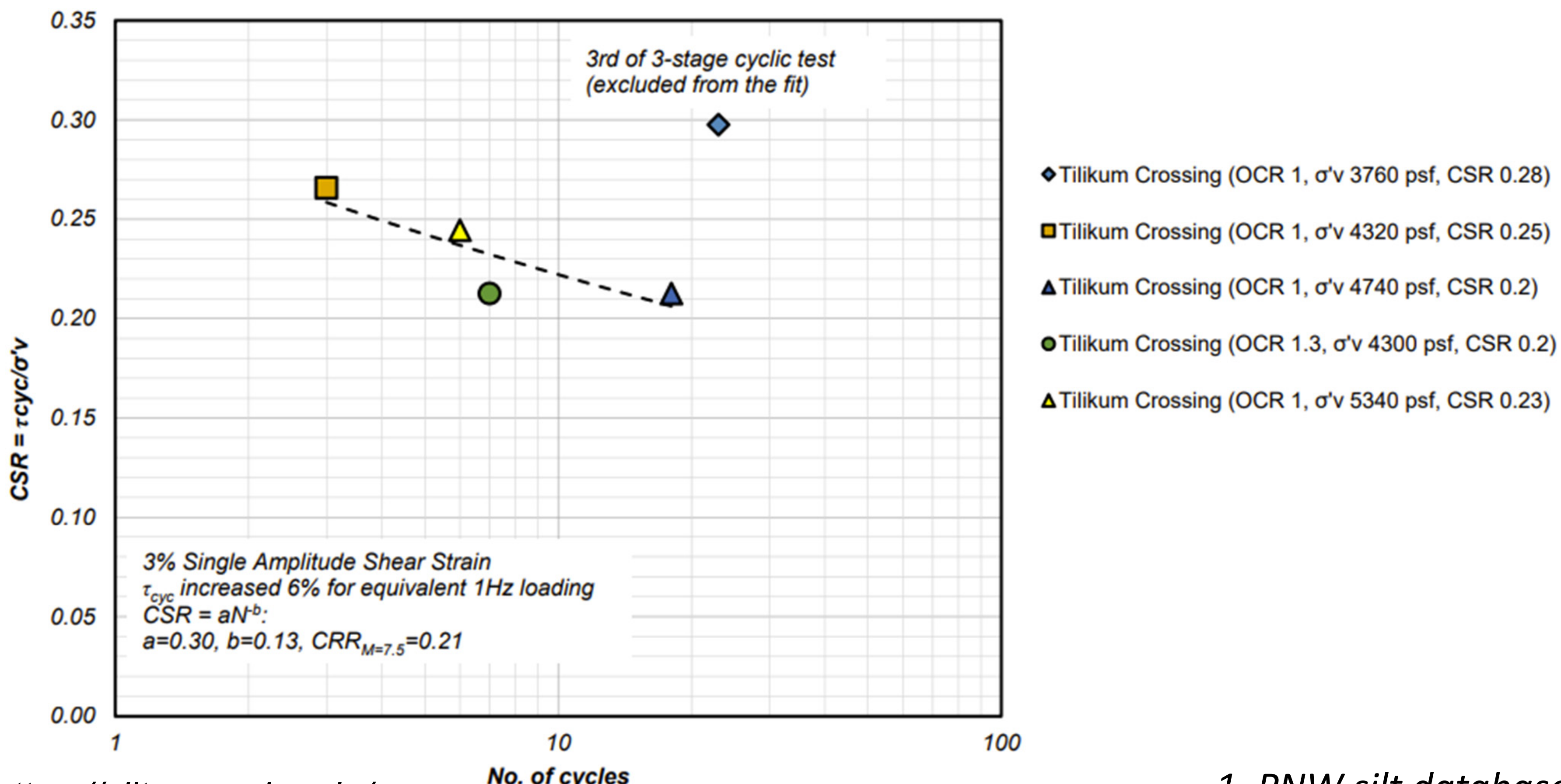
1. PNW silt database

PNW CRR – q_{t1N} Study Data

- 11 sites in western Washington and Oregon with CPT and cyclic test data
  - Fluvial-deposited soils
  - OCR values between 1 and 3; 70% had OCR = 1 to 1.5
  - Pleistocene to Holocene-aged
  - Fines content and plasticity index were measured on lab-tested specimens
  - Evaluate sand-like, transitional, or clay-like behavior qualitatively based on cyclic testing

CRR Values

- Obtained from stress-controlled cyclic DSS and TX tests on intact Shelby-tube sampled specimens

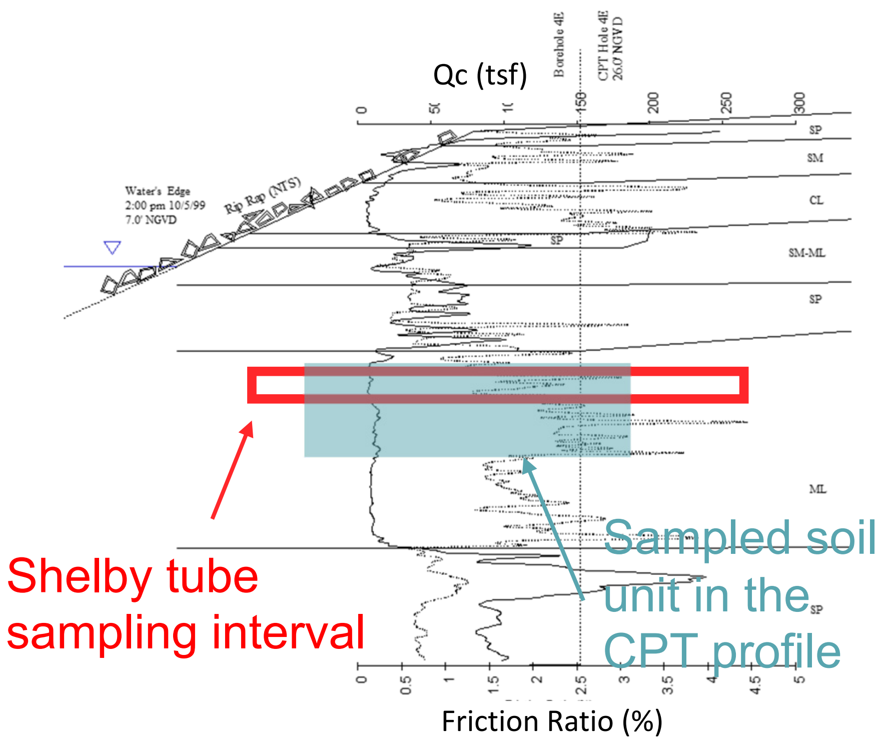


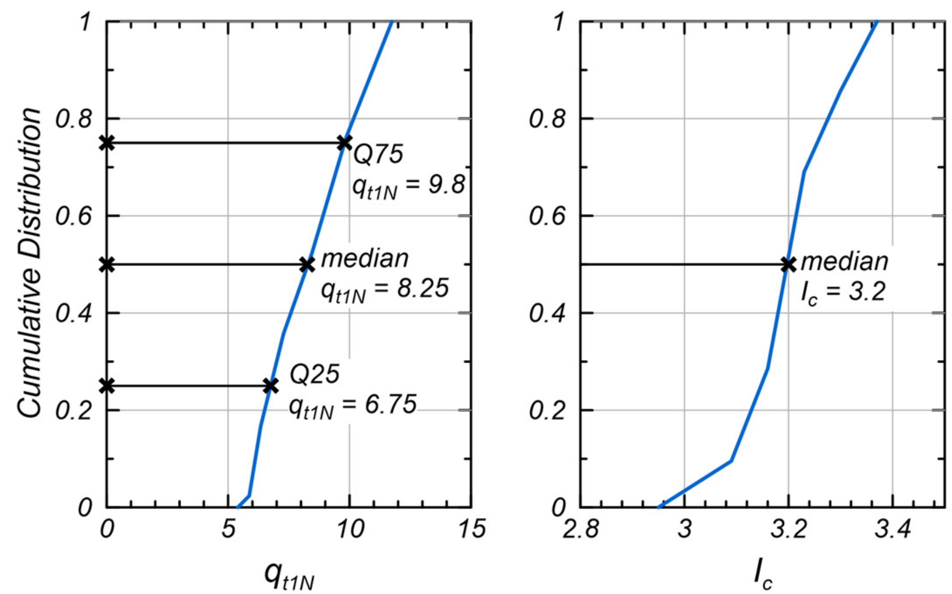
https://silt.cee.pdx.edu/

1. PNW silt database

Representative CPT data

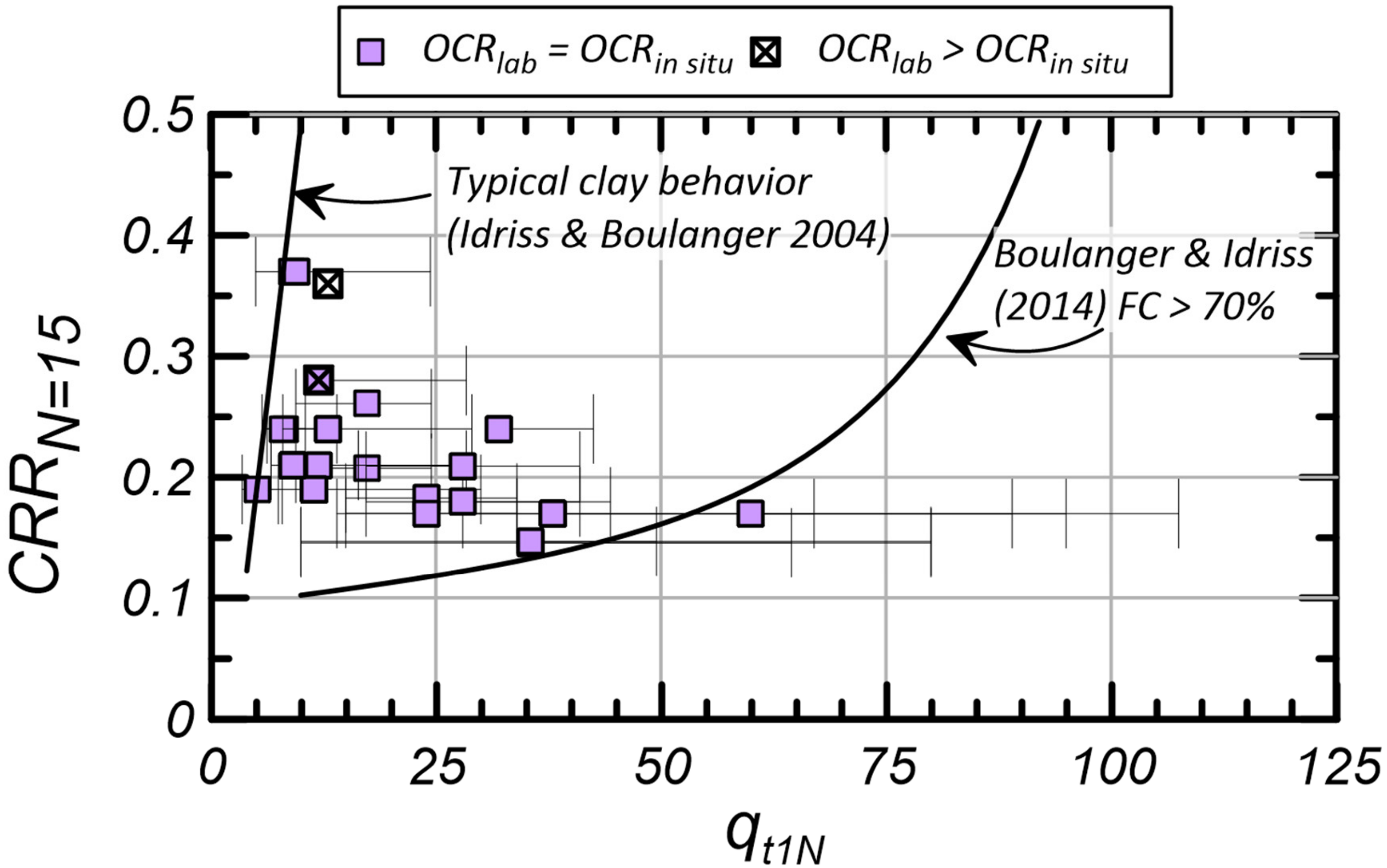
- Identify the sampled soil unit in at least one CPT profile near the sampling borehole
- Select a range of q_{c1N} and I_c values from frequency distributions of data within the sampled soil unit.





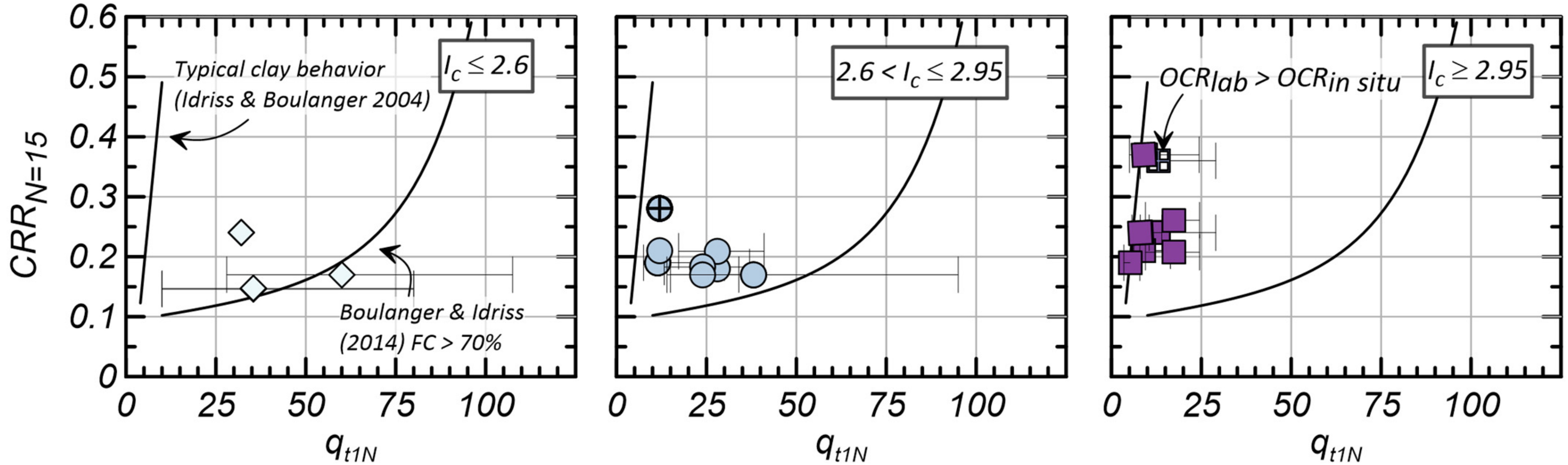
1. PNW silt database

CRR – q_{t1N} data



1. PNW silt database

I_c and CRR – q_{t1N}

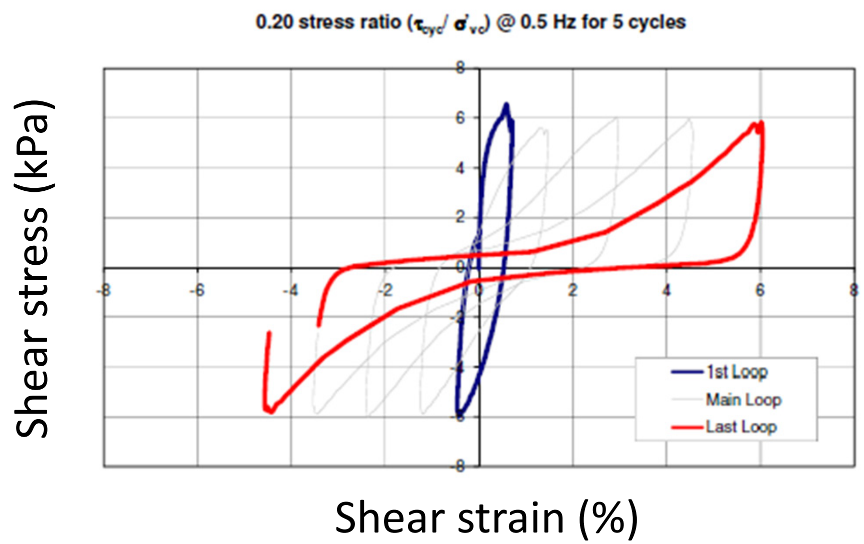


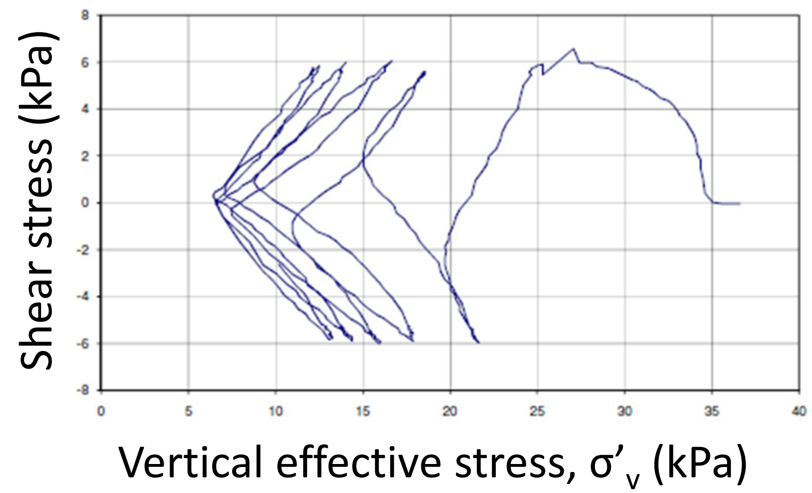
- I_c < 2.6 may indicate a CRR-q_{t1N} relationship consistent with sands
- I_c > 2.95 may indicate a CRR-q_{t1N} consistent with clays
- I_c between 2.6 and 2.95 may represent transitional CRR-q_{t1N} relationships

1. PNW silt database

Sand-like

Project ID: W_09: Vancouver, NE 134 Street, Salmon Creek Interchange
I_c approximated as 2.48



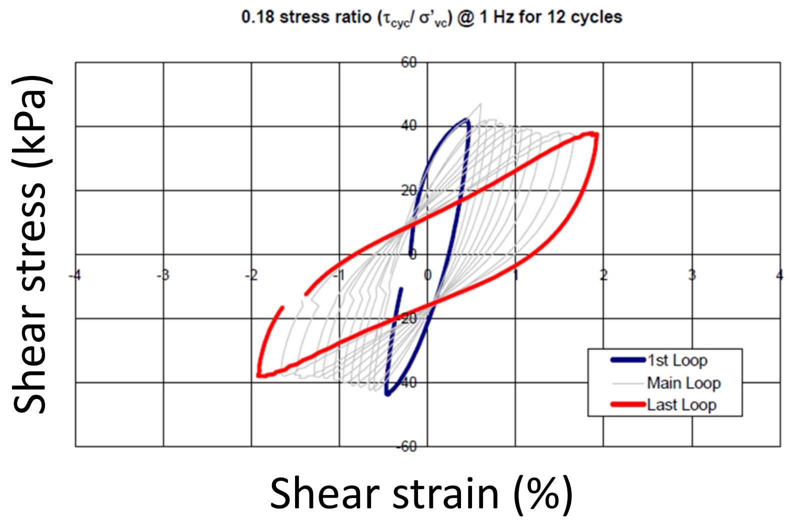


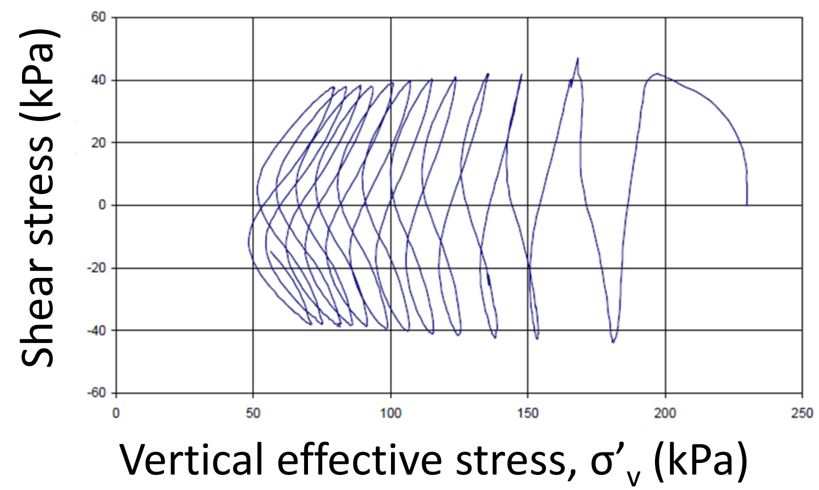
- Sand-like:
  - Intervals of zero stiffness during cyclic loops
  - Generate excess porewater pressures

1. PNW silt database

Clay-like

Project ID: W_02: Marysville, WR-529, Ebey Slough
I_c approximated as 2.93



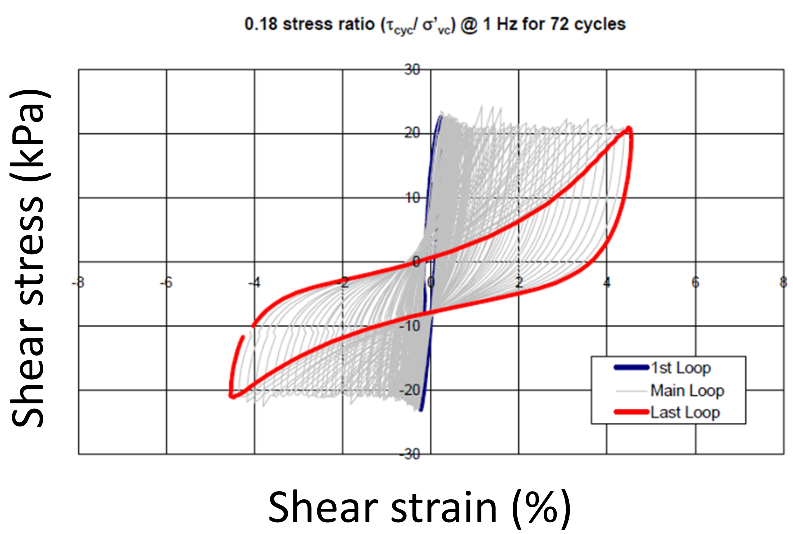


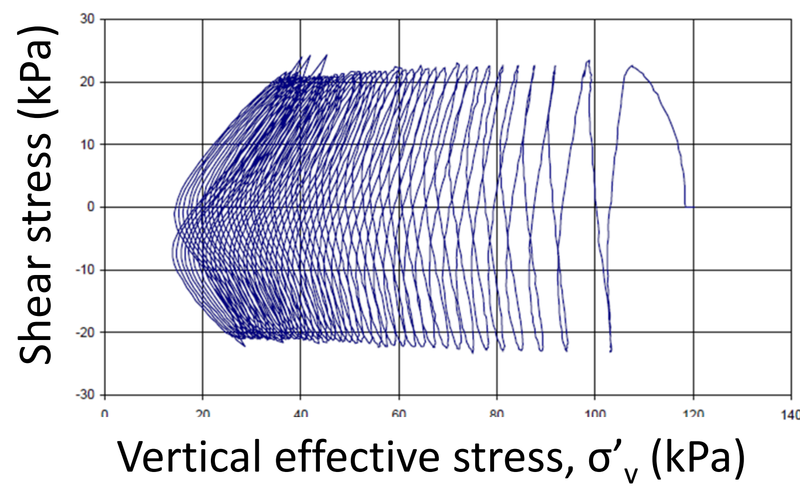
- Clay-like:
  - Strain-softening stress strain cyclic loops

1. PNW silt database

Transitional

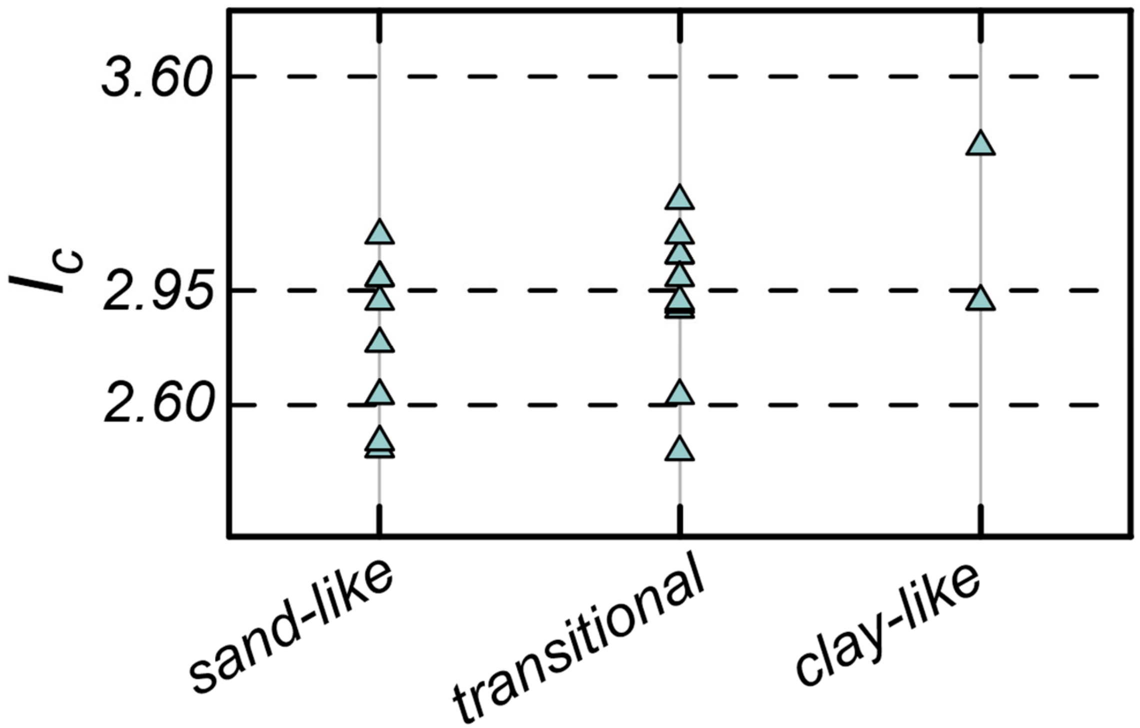
Project ID: W_02: Marysville, WR-529, Ebey Slough
I_c approximated as 2.93





1. PNW silt database

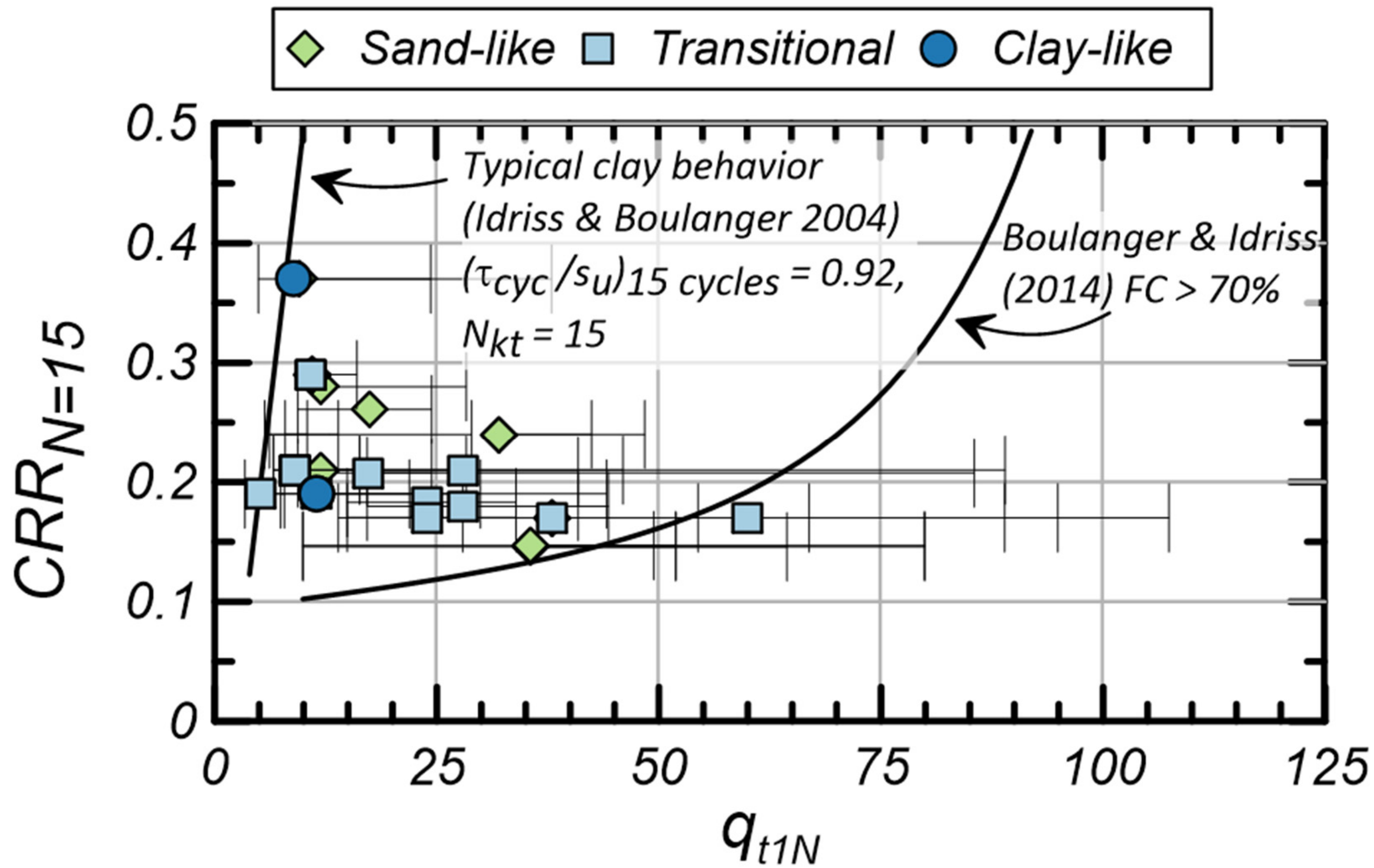
I_c and cyclic behavior



- Evaluated the laboratory test data as either "sand-like", "transitional" or "clay-like"

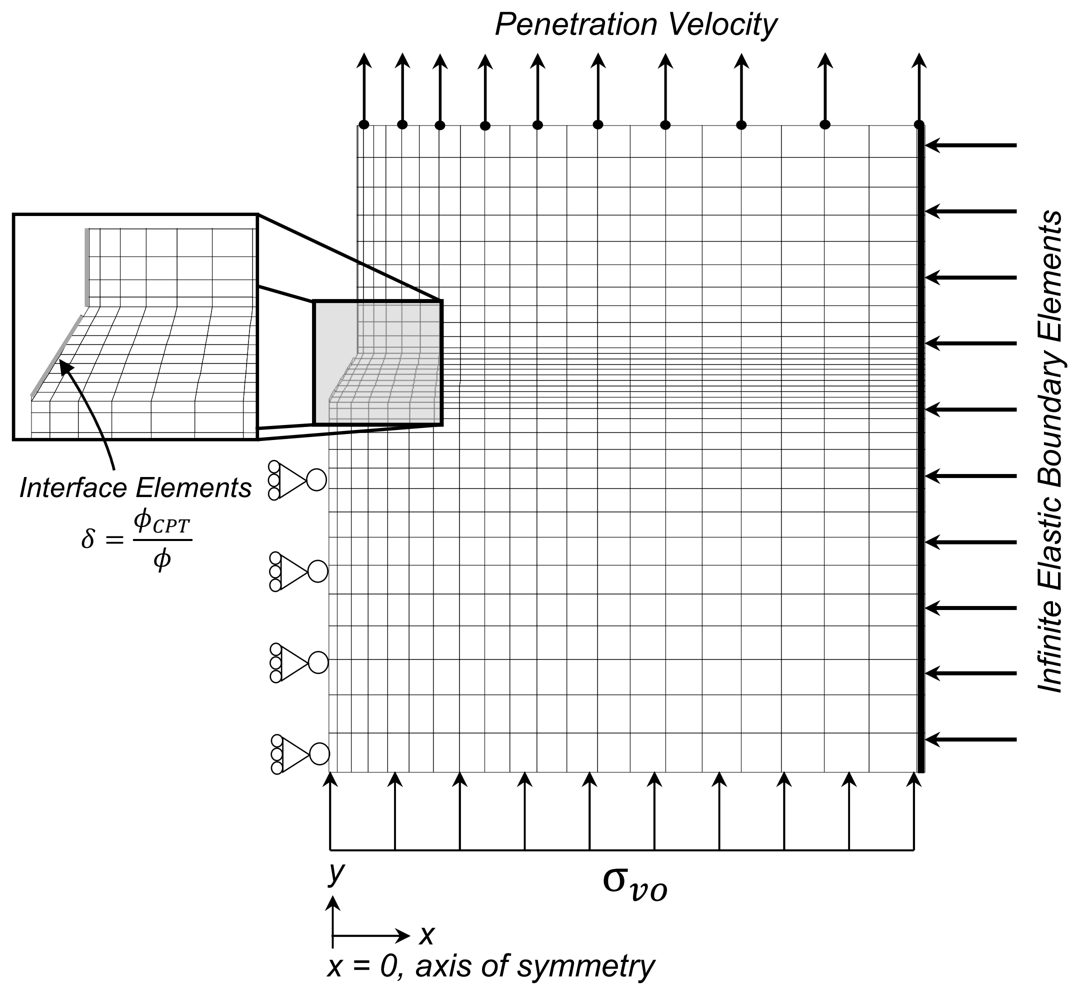
1. PNW silt database

CRR – q_{t1N} data



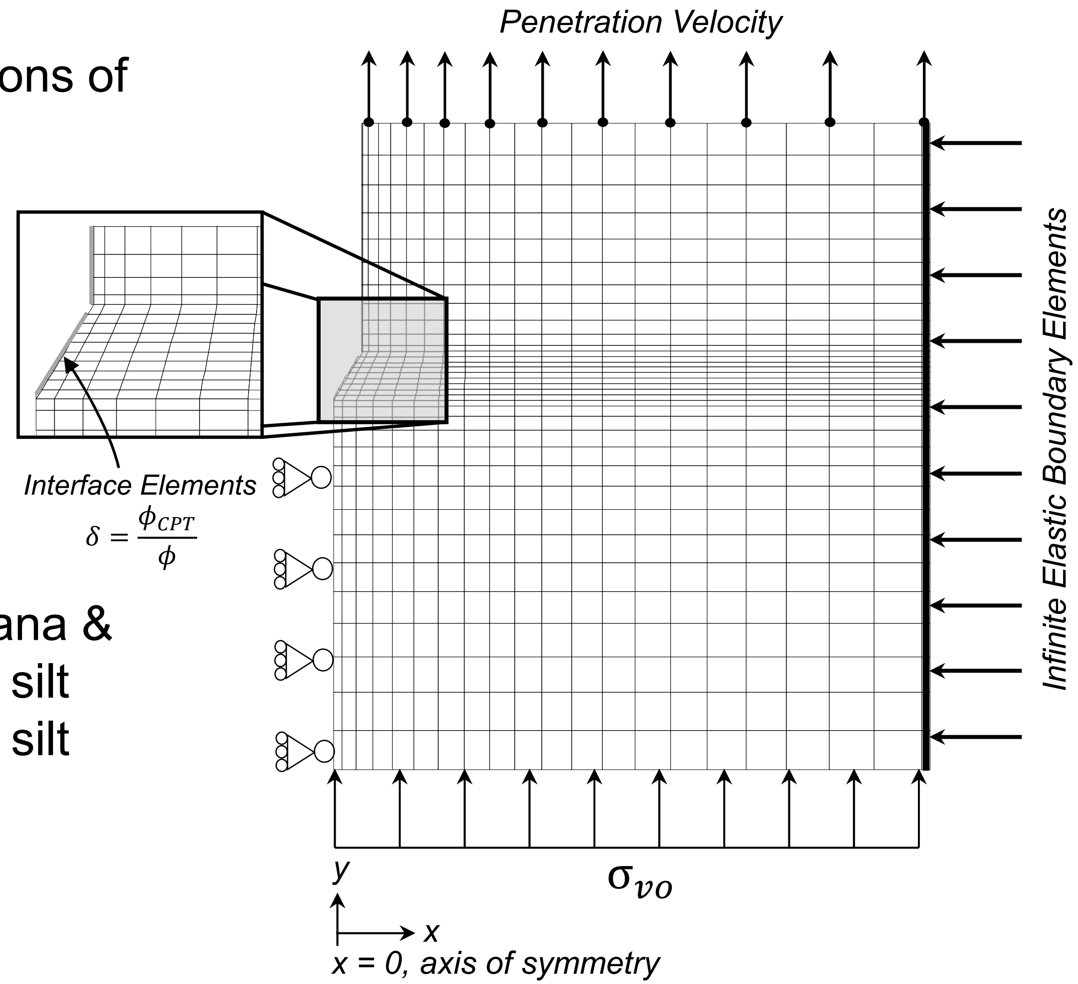
1. PNW silt database

2. q_t in low-plasticity silt



q_t in low-plasticity silt

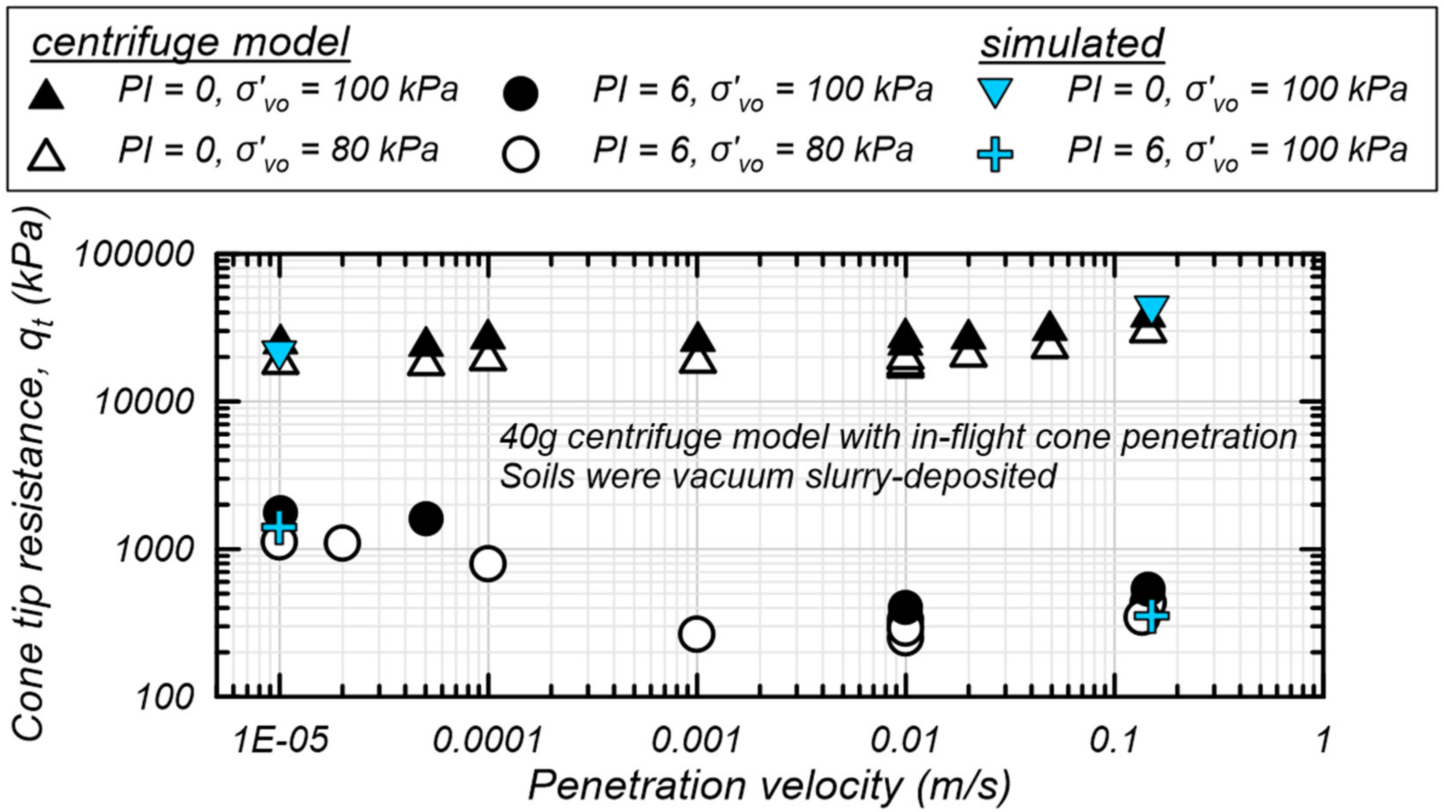
- Numerical axisymmetric simulations of direct cone penetration
- User-defined arbitrary Lagrangian Eulerian rezoning and remapping algorithm implemented in FLAC 8.0 (Moug et al. 2019)
- MIT-S1 constitutive model (Pestana & Whittle 1999) calibrated for PI=0 silt (Moug & Price 2023), and PI = 6 silt (Price 2018)



q_t, soil type, and drainage

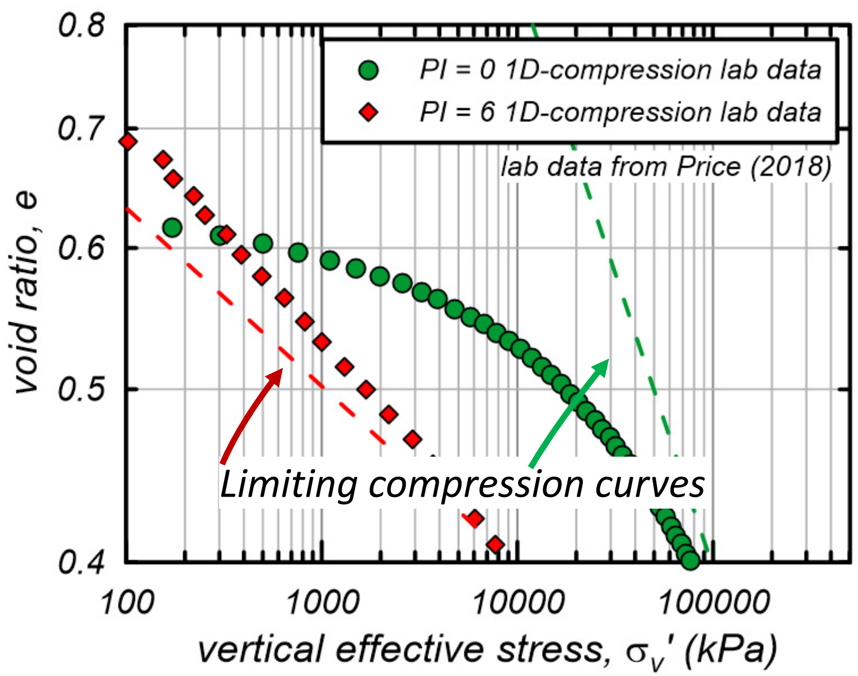
- Significant decrease in q_t across drainage conditions from PI = 0 to PI = 6

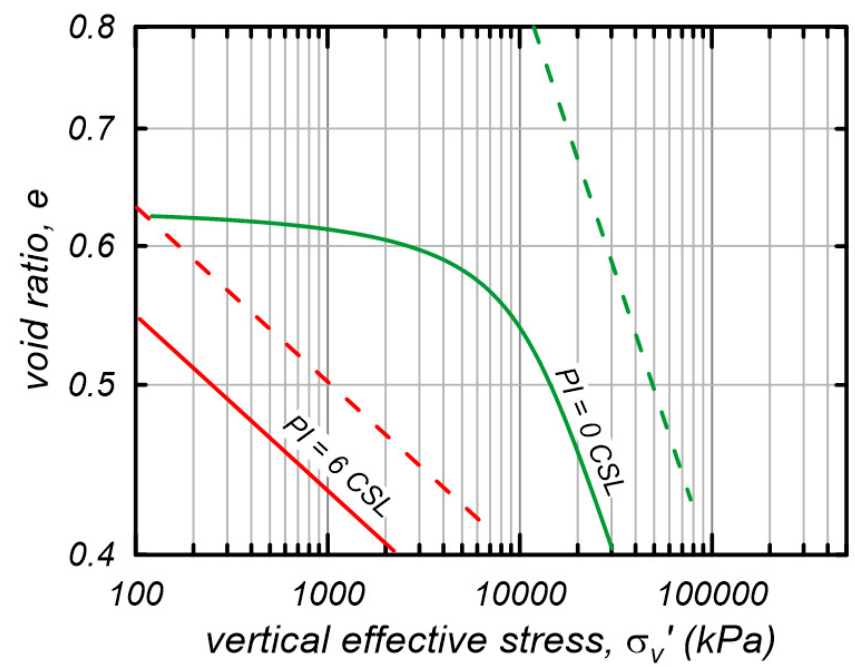
Centrifuge data from Price (2018) with simulated q_t



q_t, compressibility, and CSL

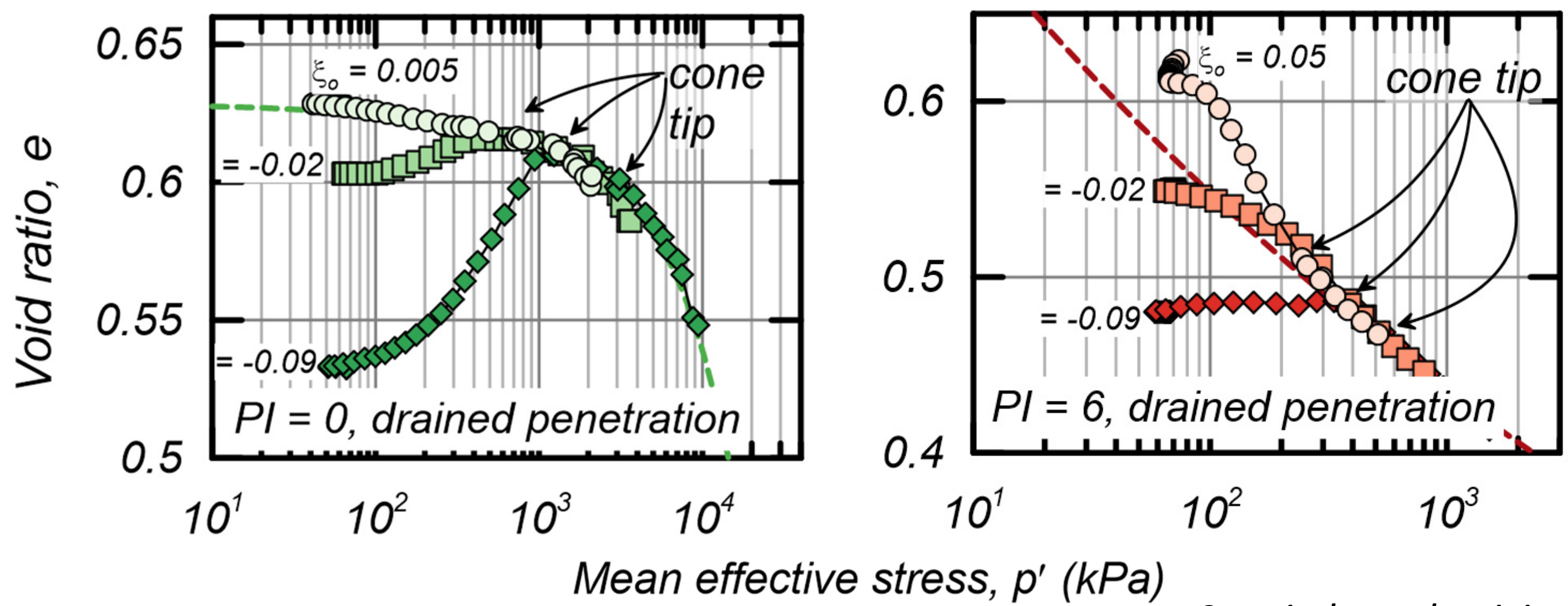
- Decrease in q_t related to soil compressibility and critical state line position





Simulated q_t, CSL, and initial state (ξ_o)

- During cone penetration loading, soil near the cone is loaded to the CSL
- CPT data will relate to CSL position, ξ_o, drainage conditions, etc.
- Potential CSL basis for studying CPT - ξ_o relationships across fine-grained soils



2. q_t in low-plasticity silt

Conclusions & Ongoing work

- Analysis of cyclic laboratory and CPT data for 11 PNW fine-grained soil project sites
  - I_c values may indicate consistency with clay, sand or transitional CRR – q_{t1N} relationships
  - Further investigation into laboratory response of clay-like, sand-like or transitional behaviors

- Ongoing evaluation of the database with additional projects and analysis

- Cone penetration model allows investigation into relationships between CPT data, CRR, liquefaction susceptibility, ξ_o

Acknowledgements

The database includes generous contributions from:.

- *Steve Dickenson, New Albion Geotechnical Inc.*
- *Adam Price, Fugro*
- *Jan Six, ODOT (retired), Shannon & Wilson Inc. (currently)*
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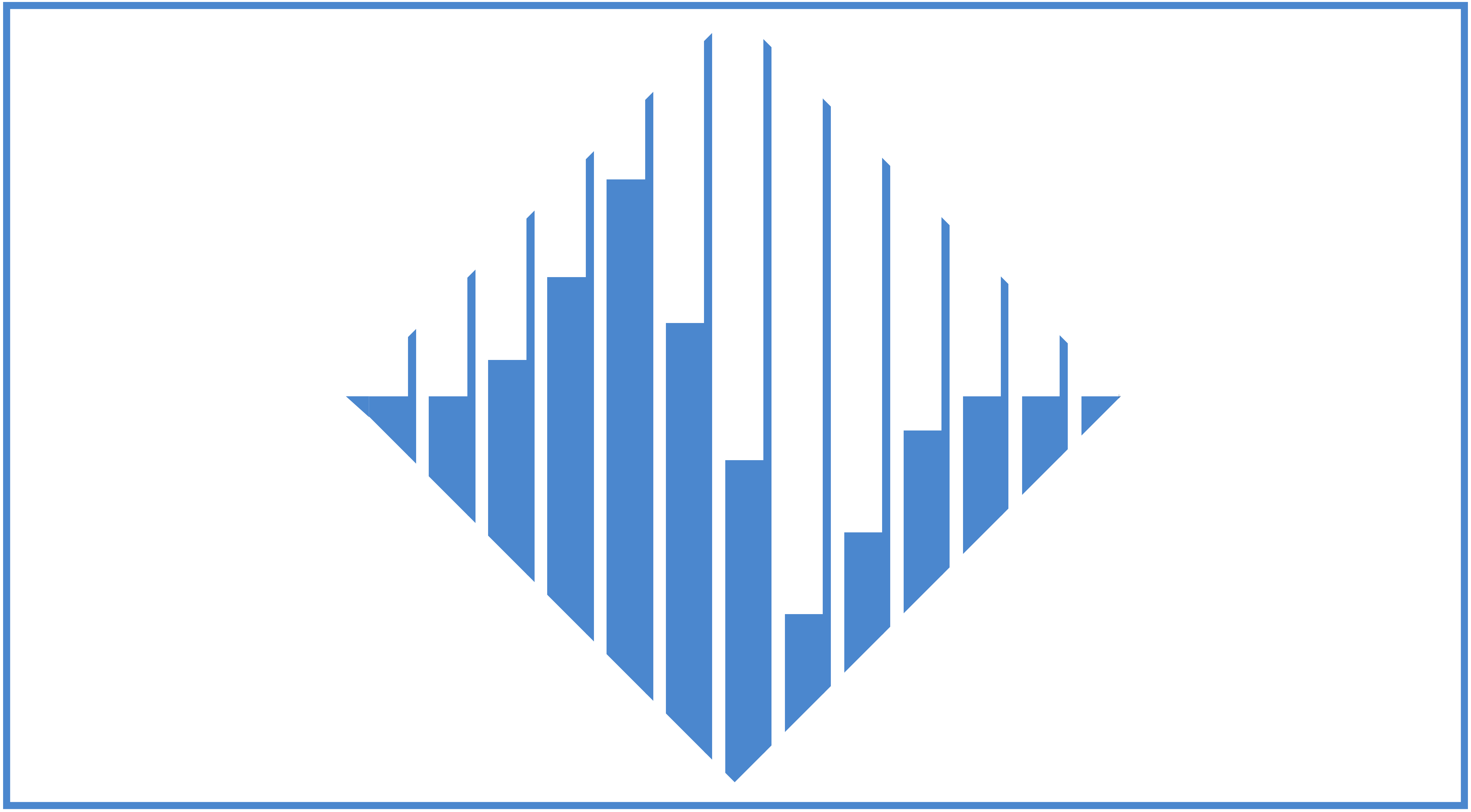
- *Tony Allen, WSDOT*
- *Donald Anderson, Jacobs*
- *Monique Anderson, Shannon & Wilson, Inc.*
- *Alan Bean, Northwest Geotech, Inc.*
- *King Chin, GeoEngineers, Inc.*
- *Sam Christie, Kleinfelder, Inc.*
- *Karen Dawson, Jacobs*
- *Michael Eller, Jacobs*
- *Jack Gordon, GRI, Inc.*
- *Mike Greenfield, Greenfield Geotechnical*
- *Ben Haines, ODOT*
- *Nason McCullough, Jacobs*
- *Reda Mikhail, Golder*
- *Scott Mills, NV5 (GeoDesign, Inc.)*
- *Robert Mitchell, Shannon & Wilson, Inc.*
- *Todd Mooney, WSDOT*
- *Travis Munson, Jacobs*
- *Ender Parra, MEG Consulting (Tertra Tech)*
- *Nick Paveglio, NV5 (GeoDesign, Inc.)*
- *Bill Perkins, Shannon & Wilson, Inc.*
- *Park Piao, Shannon & Wilson, Inc.*
- *Seungcheol Shin, Jacobs*
- *Brett Shipton, NV5 (GeoDesign, Inc.)*
- *Sam Sideras, Shannon & Wilson, Inc.*
- *Wes Spang, GRI, Inc.*
- *James Struthers, WSDOT*
- *John Sully, MEG Consulting (Tetra Tech)*
- *Paul Sully, MEG Consulting (Tetra Tech)*
- *Deanne Takasumi, Jacobs,*
- *Andy Vessely, Cornforth Consultants, Inc. (retired)*
- *Rick Wentz, Wentz Pacific, Ltd.*

Thank You and Questions



PROBABILISTIC PREDICTION OF LIQUEFACTION SUSCEPTIBILITY VIA CPT DATA: A LOCAL STUDY WITH BROADER IMPORT

Brett Maurer | University of Washington

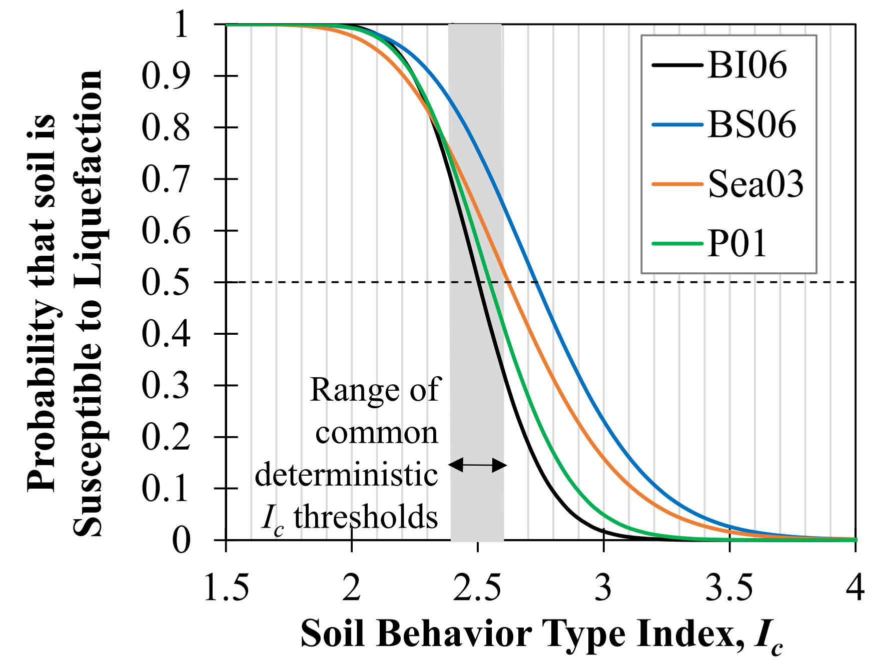
PEER

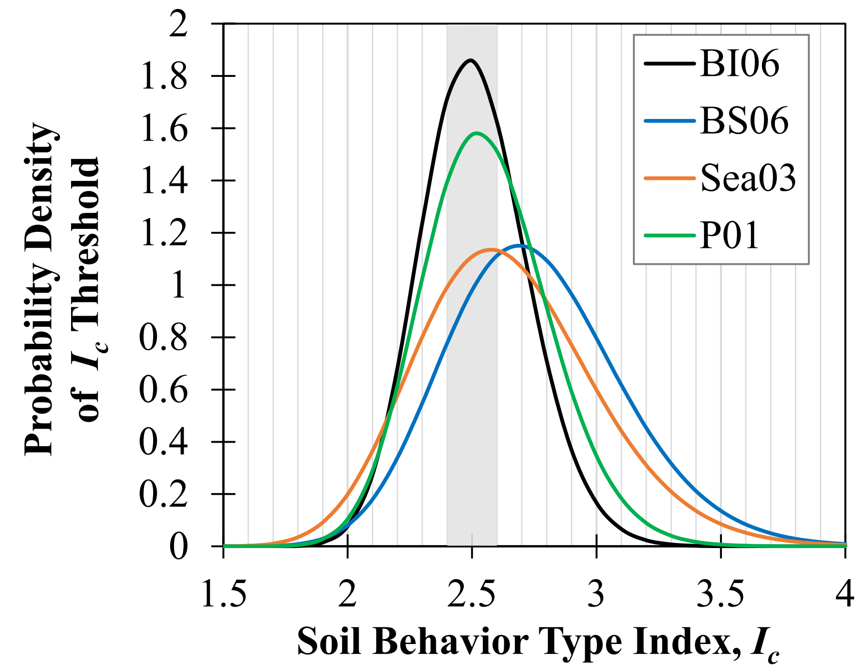
Workshop on Liquefaction Susceptibility

Session 3: Opportunities for Synthesizing Laboratory and Field-based Observations

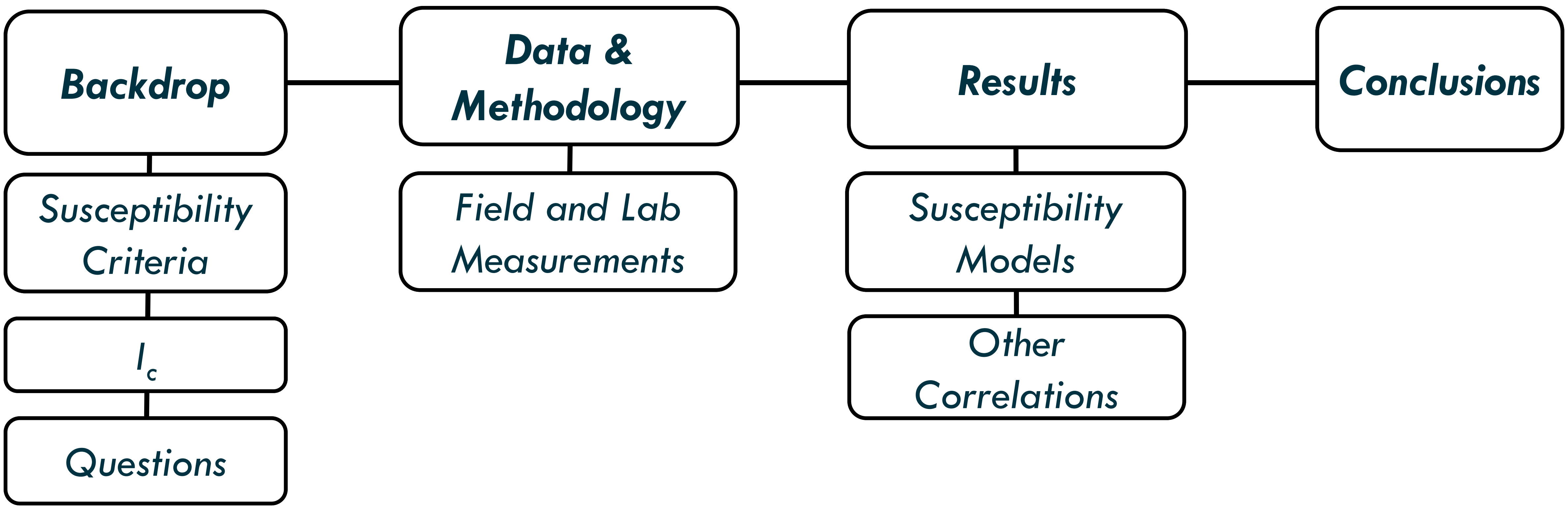
Synopsis

- *Using data from the NZ Geotechnical Database, Maurer et al. (2019) studied 2,620 split-spoon samples from 825 SPTs driven parallel to CPTs.*
- *All samples had FC and w_n measurements; 574 had LL and PI measurements.*
- ***Q1:** What is the relationship between CPT soil behavior type index (I_c) and liquefaction susceptibility?*
- ***Q2:** Can susceptibility be better predicted by different/additional CPT measurements?*





Outline

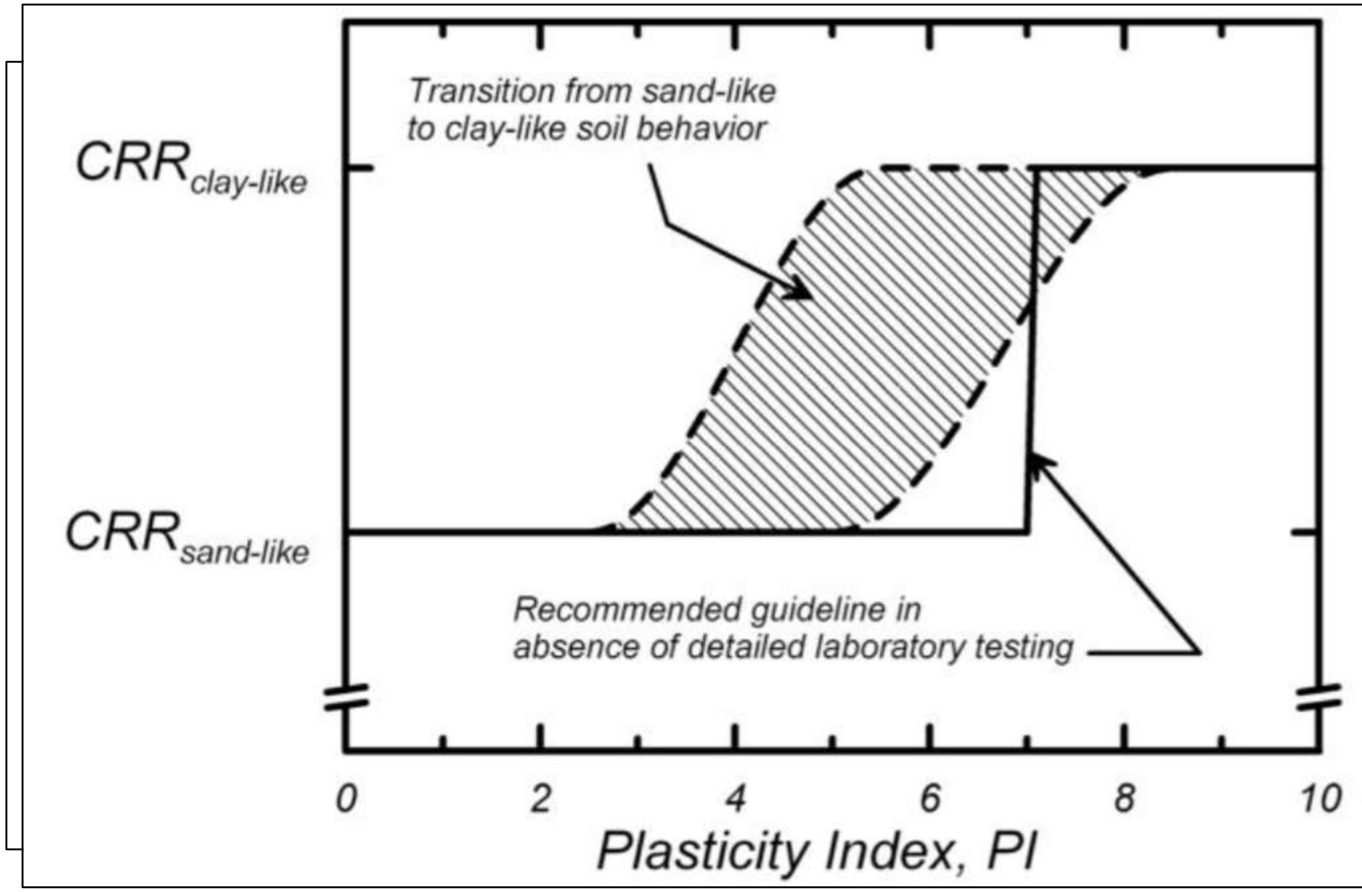


Backdrop
Data & Methodology
Results
Conclusions
Susceptibility Criteria
I_c
Questions
Field and Lab Measurements
Susceptibility Models
Other Correlations

Susceptibility Criteria

➢ ***Four susceptibility criteria based on Atterberg limit data will be used:***

- *Polito (2001) [P01]*
- *Seed et al. (2003) [Sea03]*
- *Bray & Sancio (2006) [BS06]*
- *Boulanger & Idriss (2006) [BI06]*

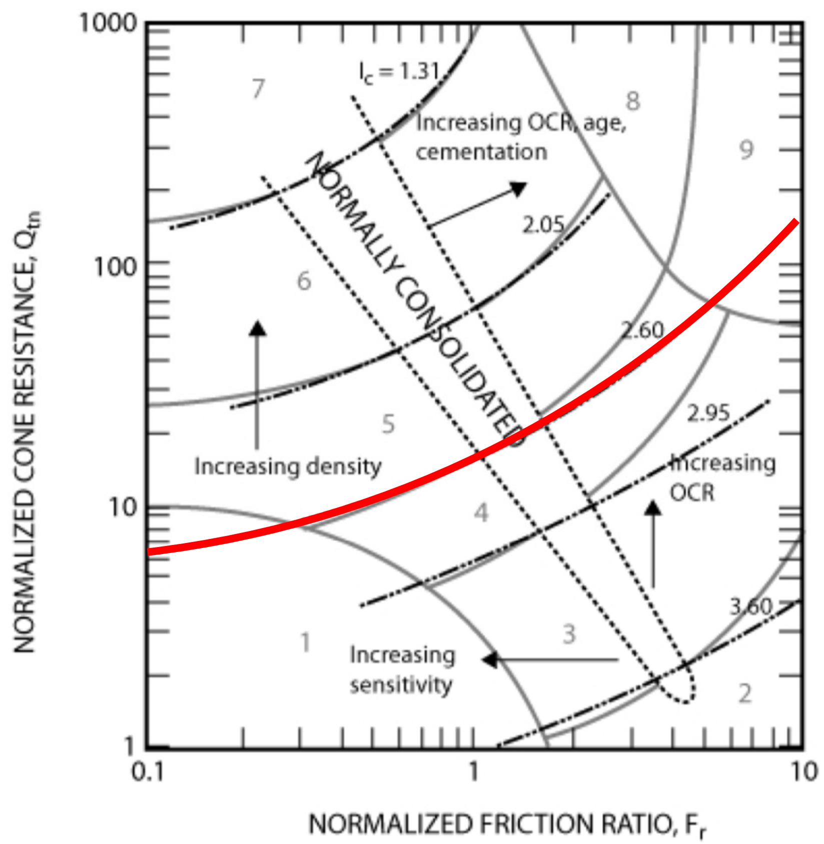


- *BI06 is sometimes favored as it was explicitly developed to choose the most appropriate model for predicting cyclic behavior (i.e., "sand-like" vs "clay-like" response).*

I_c and other CPT indices

- ***In the absence of cyclic or lab index tests, susceptibility is most often inferred via I_c:***

Figure 22 Normalized CPT Soil Behavior Type (SBT_n) chart, Q_t - F (Robertson, 1990, updated by Robertson, 2010).



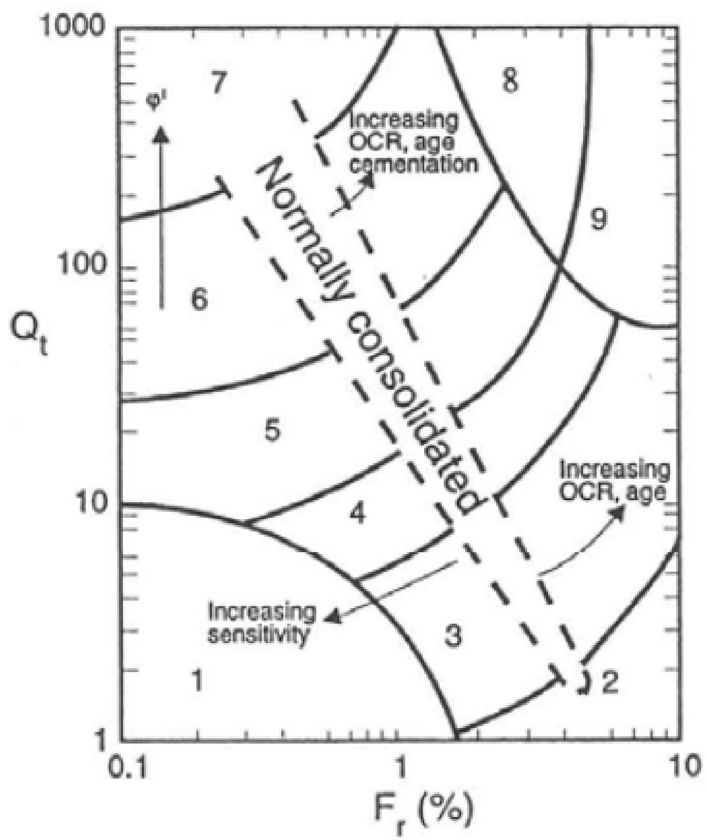
Zone	Soil Behavior Type	I_c
1	*Sensitive, fine grained*	N/A
2	*Organic soils – clay*	> 3.6
3	*Clays – silty clay to clay*	2.95 – 3.6
4	*Silt mixtures – clayey silt to silty clay*	2.60 – 2.95
5	*Sand mixtures – silty sand to sandy silt*	2.05 – 2.6
6	*Sands – clean sand to silty sand*	1.31 – 2.05
7	*Gravelly sand to dense sand*	< 1.31
8	*Very stiff sand to clayey sand**	N/A
9	*Very stiff, fine grained**	N/A

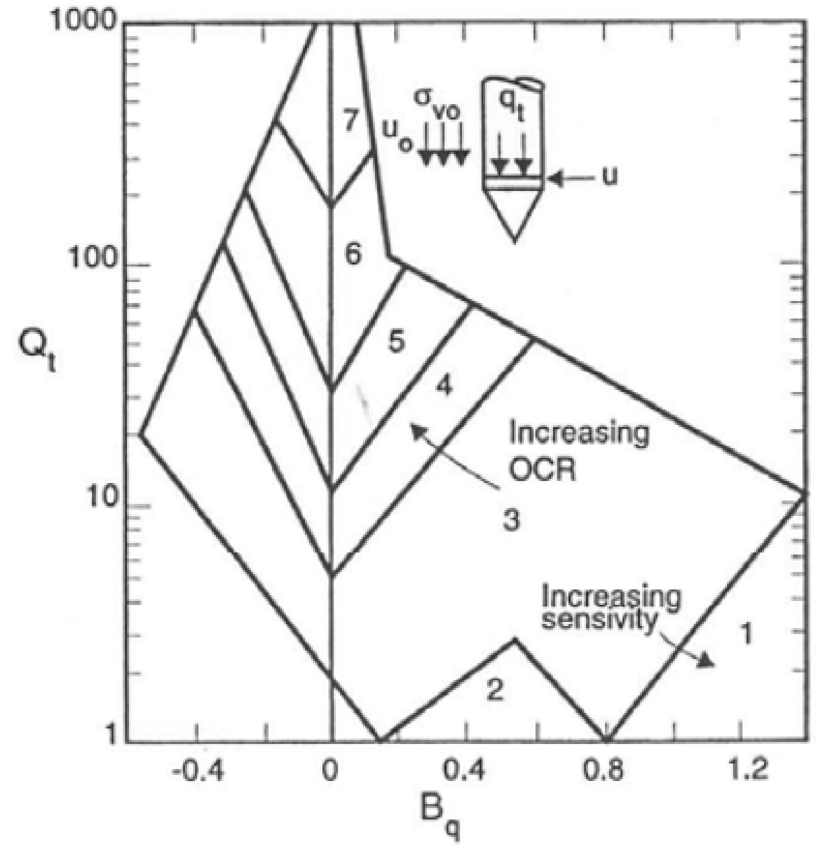
I_c = 2.6 is the most common default threshold for deterministically inferring "susceptible" and "non-susceptible" soils.

- *Of course, it's well known that the I_c = 2.6 threshold is uncertain…*
- ***Q1: What is the relationship between I_c and lab-based susceptibility criteria?***

I_c and other CPT indices

- *Other (or additional) CPT measurements have shown promise for classifying susceptibility where I_c fails. For example, the pore pressure ratio, B_q:*





$$\boldsymbol{B_q = \frac{u_2 - u_o}{q_t - \sigma_{vo}}}$$

$$Q_t = \frac{q_t - \sigma_{vo}}{\sigma'_{vo}}$$

$$F_r = \frac{f_s}{q_t - \sigma_{vo}} * 100\%$$

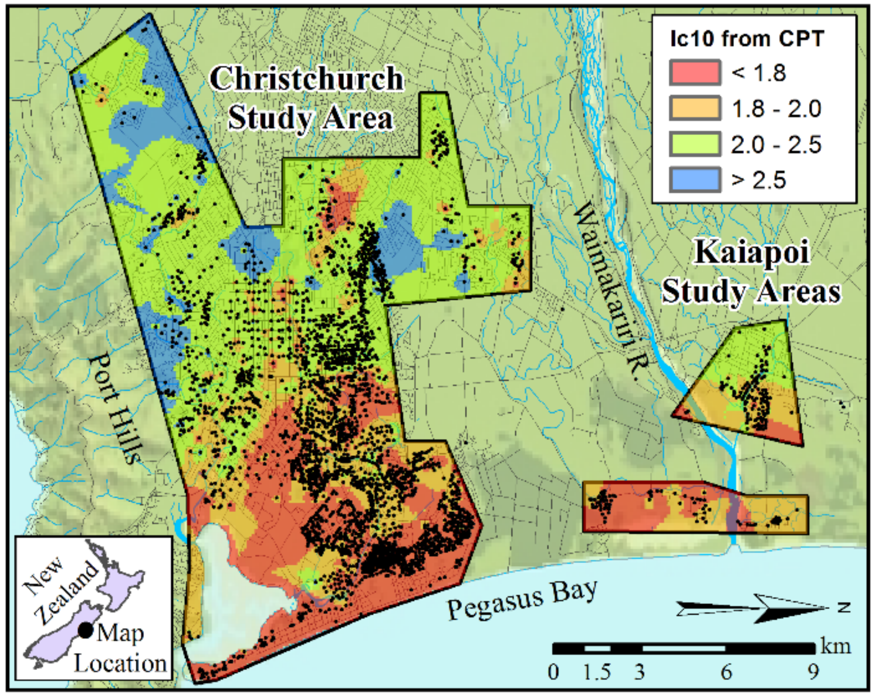
- ***Q2:** How do CPT metrics (I_c, R_f, B_q) correlate to metrics of susceptibility (FC, PI, LL)? **Can CPT-based predictions of lab-derived susceptibility be improved?***

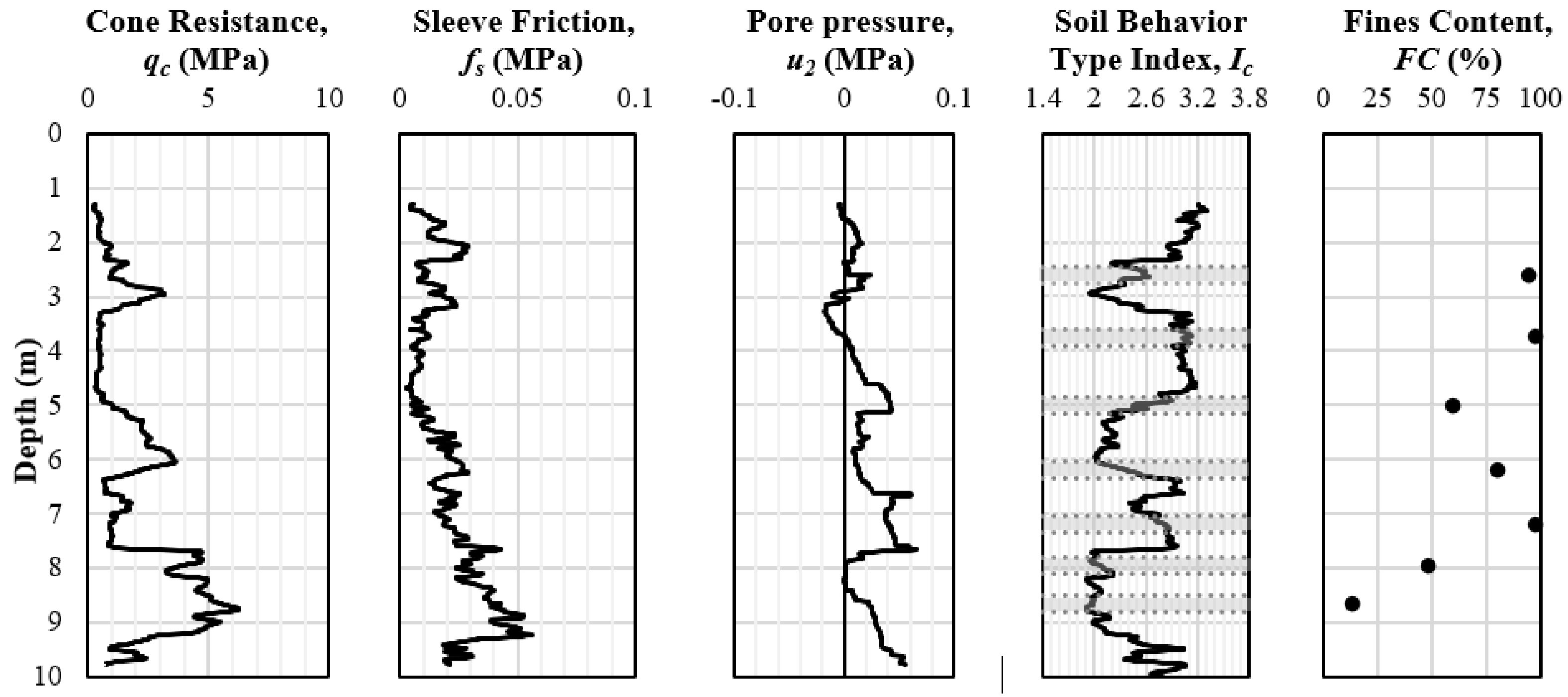
Outline

- **Backdrop**
  - *Susceptibility Criteria*
  - *I_c*
  - *Questions*
- **Data & Methodology**
  - *Field and Lab Measurements*
- **Results**
  - *Susceptibility Models*
  - *Other Correlations*
- **Conclusions**

Data and Methodology

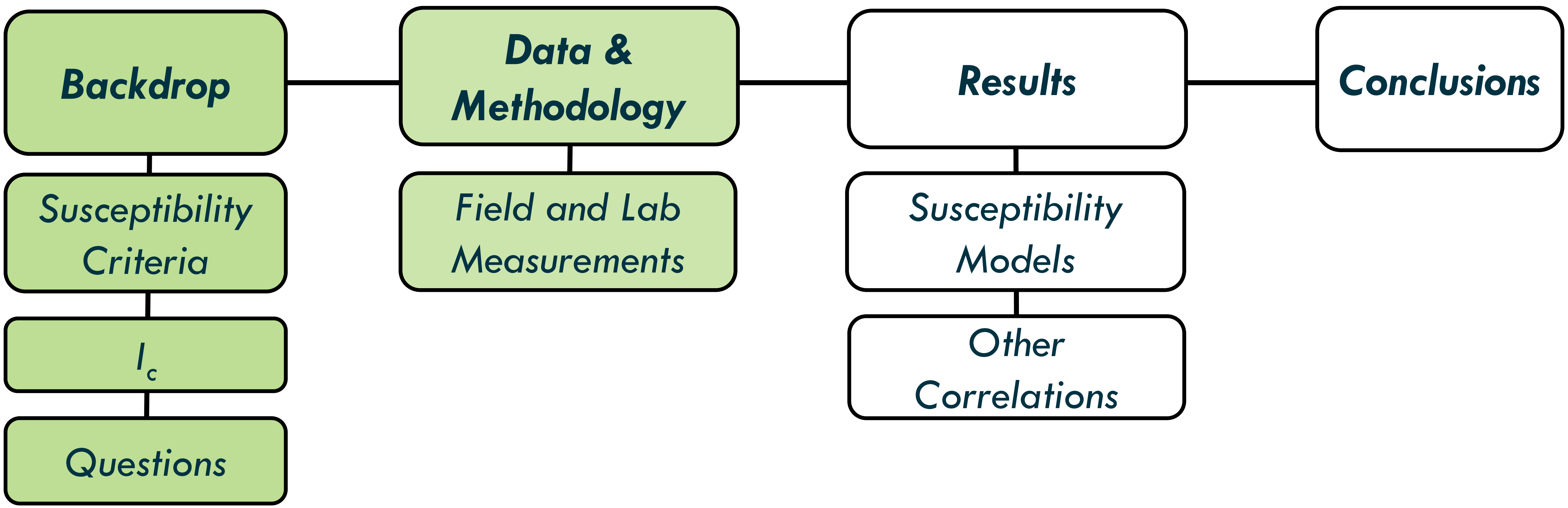
➢ *Data from Christchurch and Kaiapoi, New Zealand (NZ Geotechnical Database)*





- *2,620 split-spoon samples with FC and w_n measurements; 574 with LL and PI.*
- *Susceptibility classified using each of the four lab-based criteria.*
- *SPT and CPT pairs typ. 1-2 m apart.*
- *CPT statistics (I_c, R_f, B_q) sampled over the 300 mm depth interval of the physical sample.*

Outline


Backdrop
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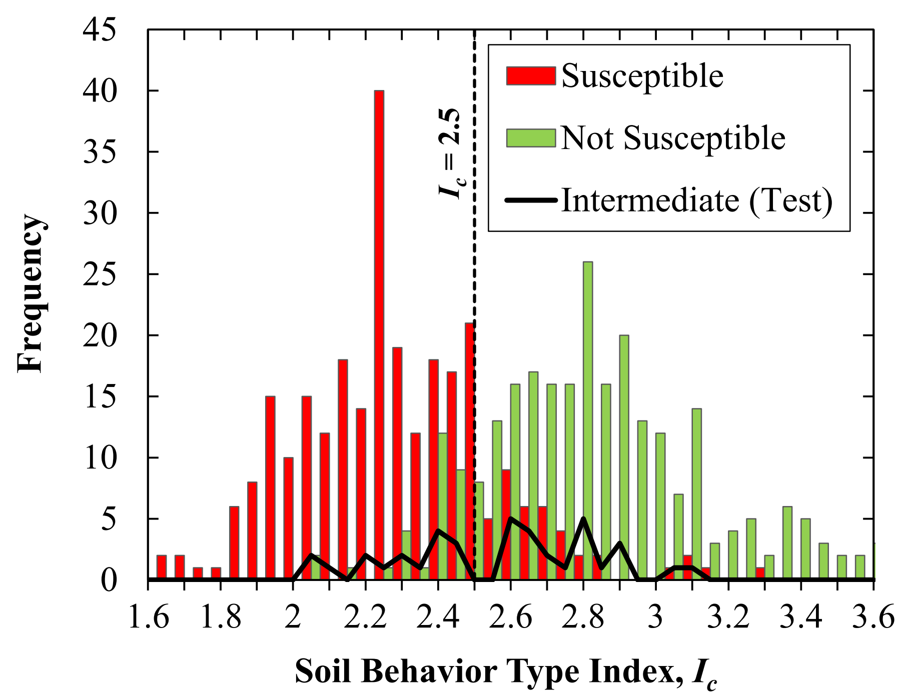
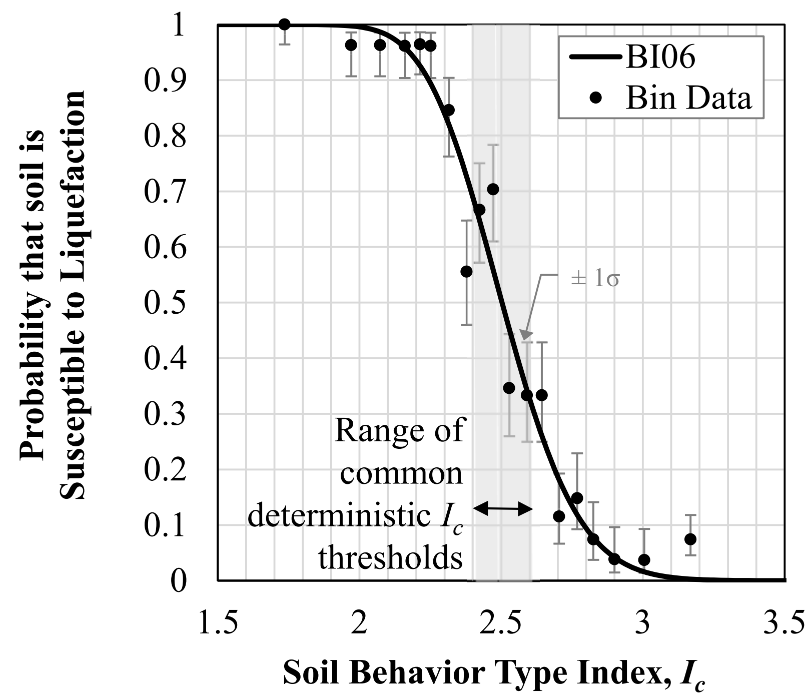
Other Correlations
Questions

Results: Susceptibility Models

- *Probability of susceptibility models were developed using a log-normal cumulative distribution, as fit to the data classified by each of the lab criteria. In this context, "susceptibility" is whatever definition the developers of the respective criteria used.*
- *For example, **using the BI06 criterion**:*

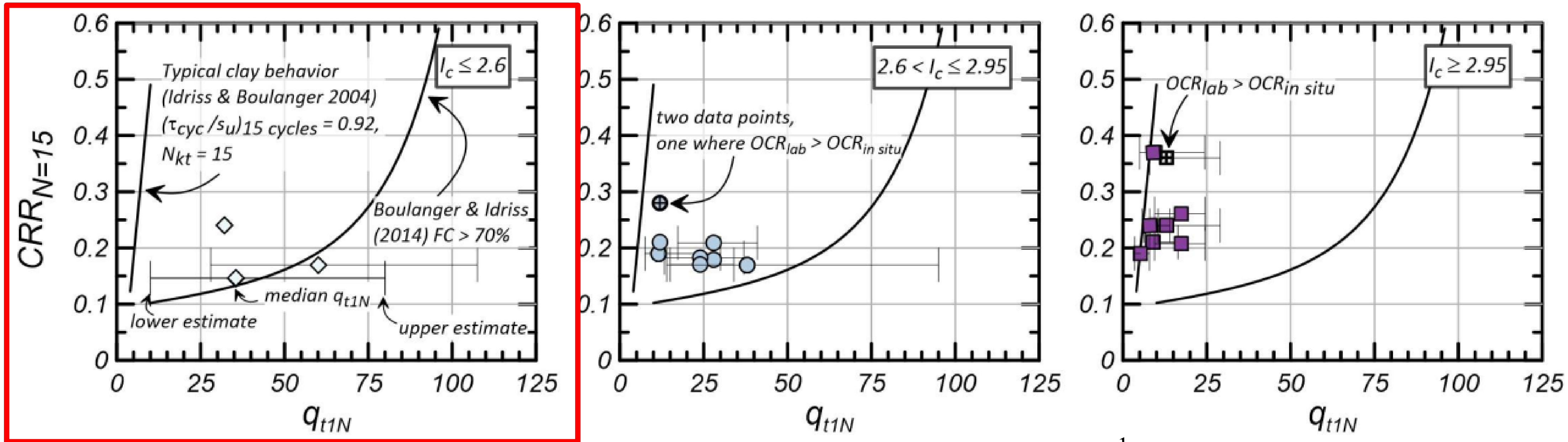




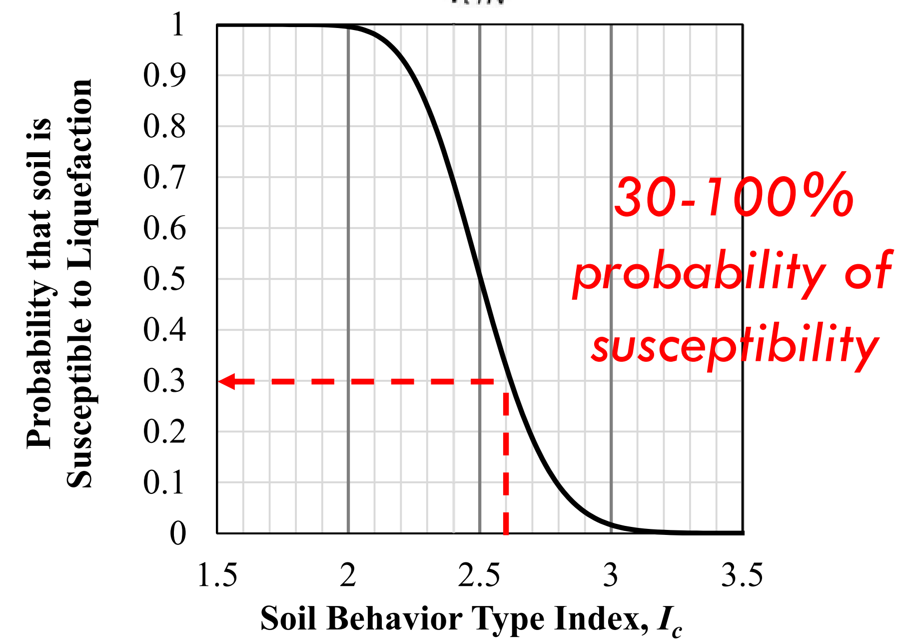
- ***For BI06, the probability of susceptibility is 50% at I_c = 2.5.***

Results: Susceptibility Models

- *Comparing these results to Moug et al. (2022) in Oregon/Washington:*

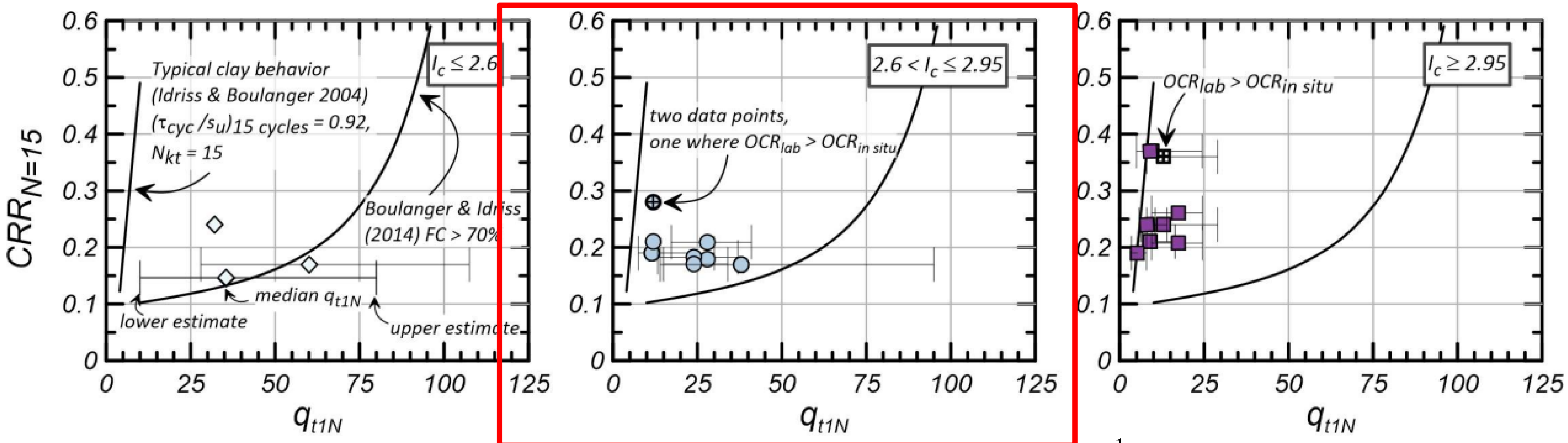


"Soils with I_c < 2.6 may be reasonably characterized with CRR-q_{t1N} relationships for sand-like soils with high FC"

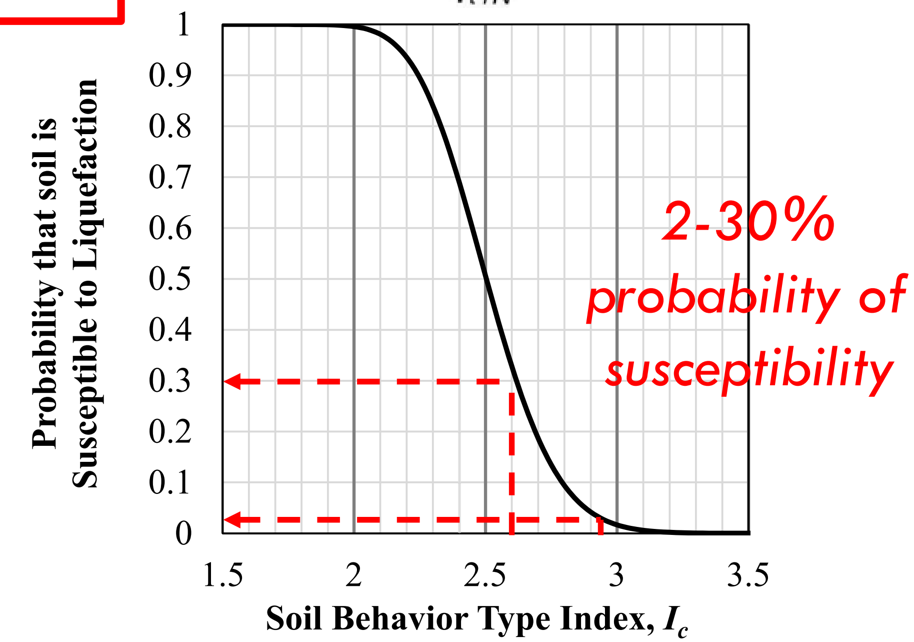


Results: Susceptibility Models

- *Comparing these results to findings from Moug et al. (2022) in Oregon/Washington:*

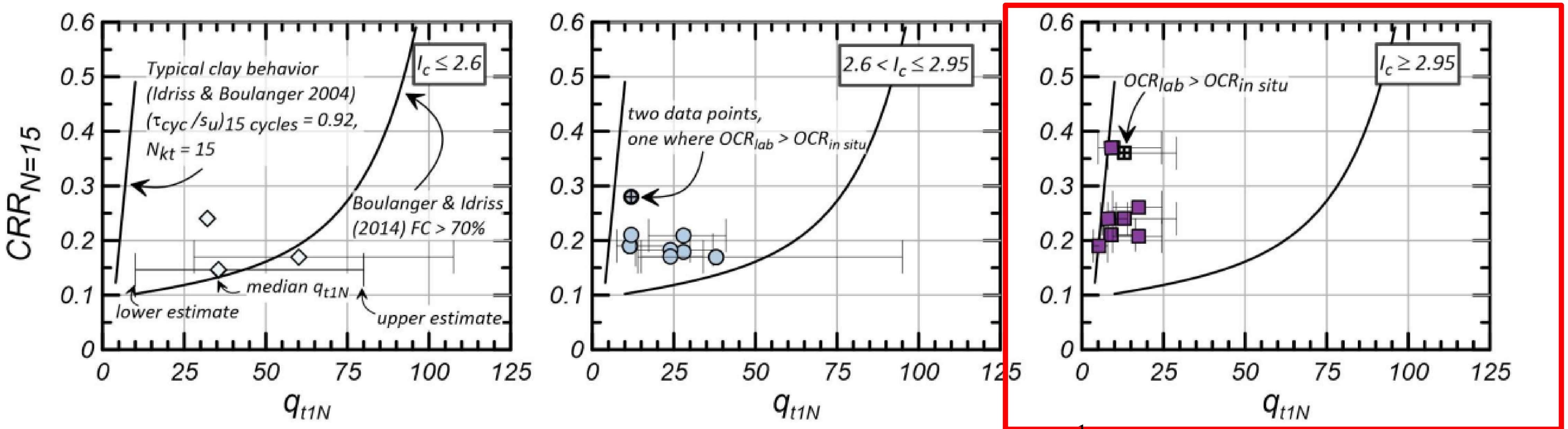


"Soils with 2.6 < I_c < 2.95 appear to transition between sand-like and clay-like CRR-q_{t1N} relationships"

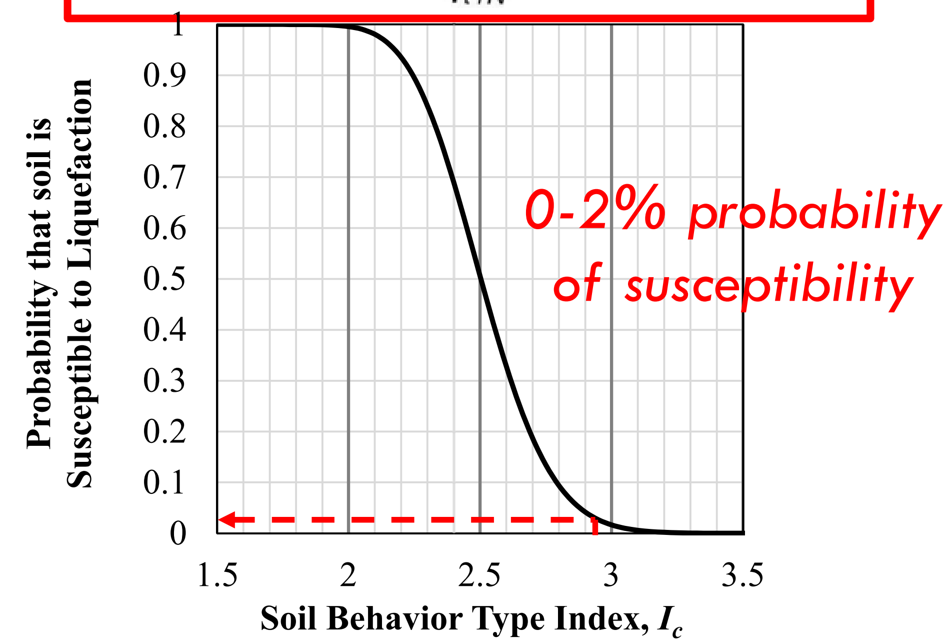


Results: Susceptibility Models

- *Comparing these results to findings from Moug et al. (2022) in Oregon/Washington:*

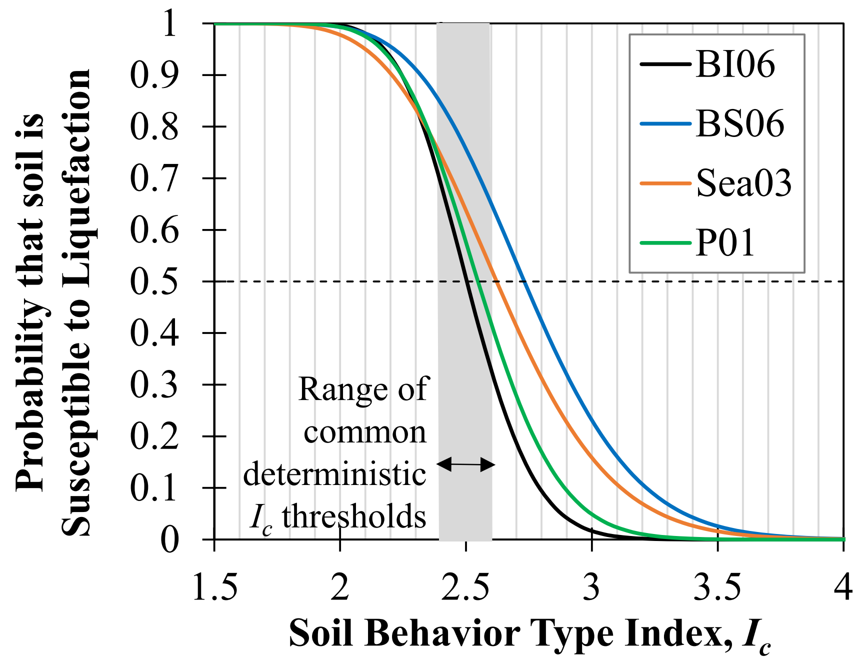


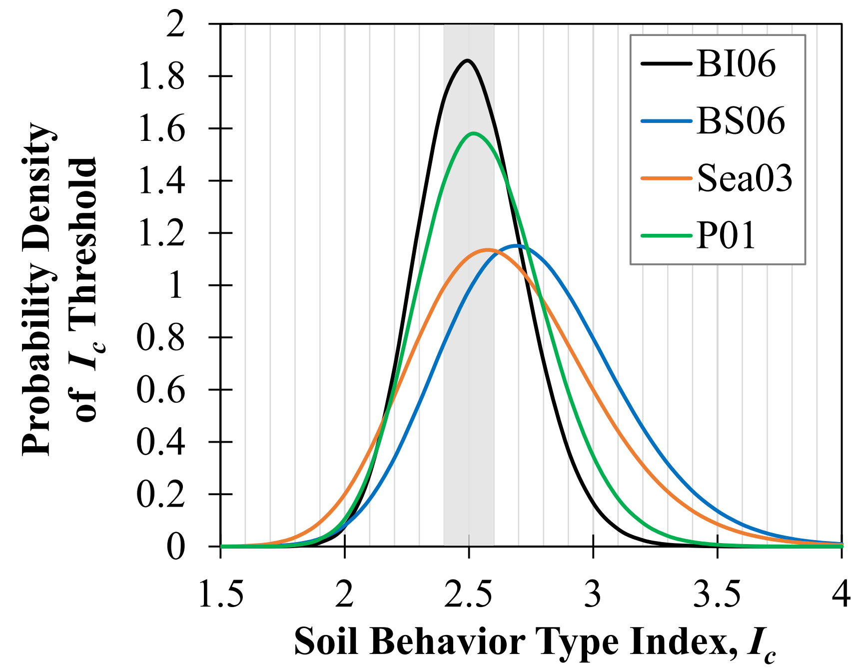
"Soils with I_c > 2.95 plot near and to the right of the CRR-q_{t1N} relationship for clay-like soil."



Results: Susceptibility Models

- *Repeating for all criteria:*



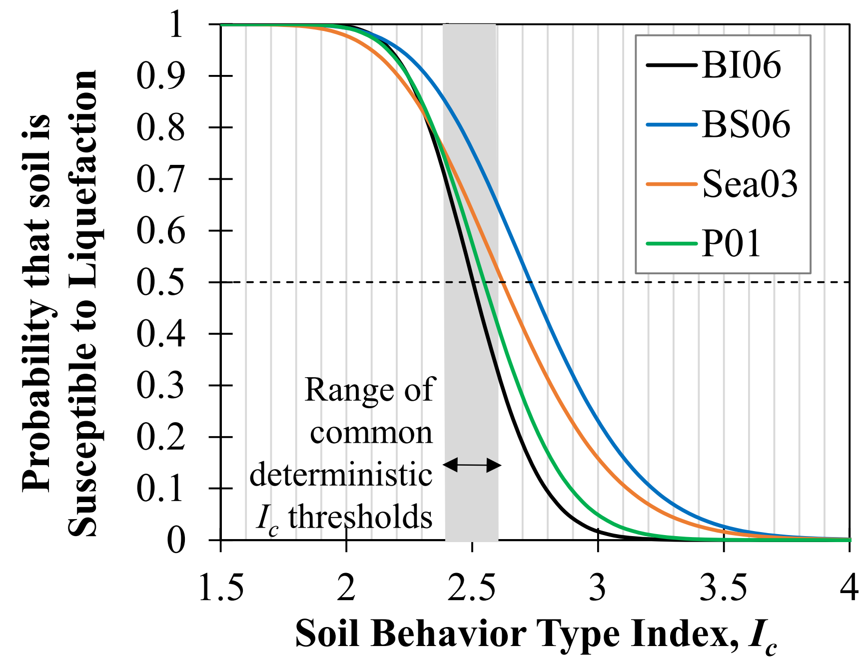


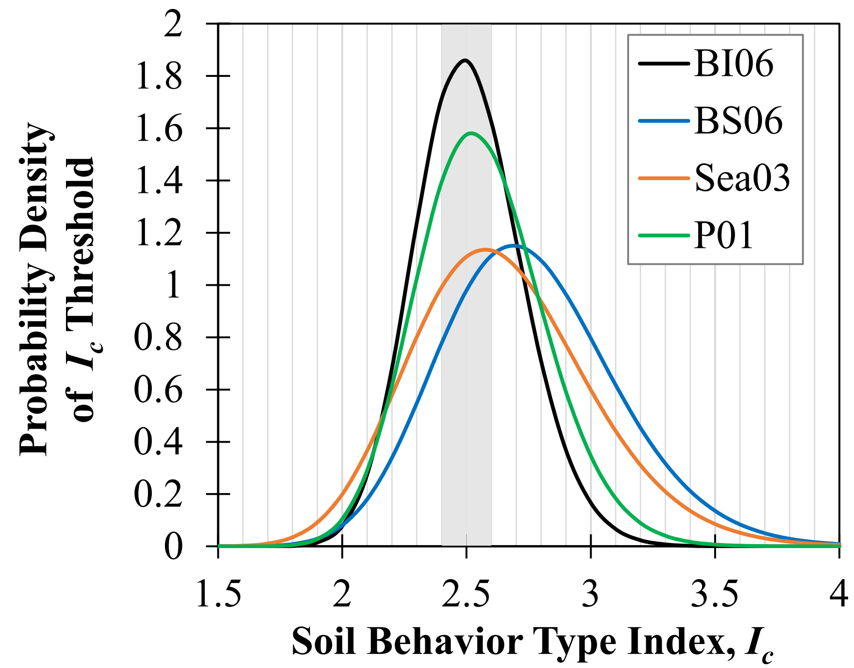
- ***Model medians (I_c at 50% probability): 2.5 [BI06], 2.55 [P01], 2.6 [Sea03], 2.75 [BS06]***
- *Models may be reconceptualized as the probability density of the I_c threshold.*
- *Common I_c thresholds (e.g., 2.6) are reasonable medians, but what about uncertainty? Using BI06, there is a 15% probability that soil with $I_c \approx 2.3$ is **not** susceptible, and similarly, a 15% probability that soil with $I_c \approx 2.75$ **is** susceptible.*

Results: Susceptibility Models

➢ ***It's important to note that these models do not explicitly quantify/consider:***

- *Measurement uncertainty (in I_c, PI, LL, w_n)*
- *Spatial variability between SPT and CPT site (typically 1-2 m apart)*
- *Finite-sample uncertainty*
- *The uncertainty of which functional form is used for the I_c-susceptibility relationship*
- *Uncertainty in the lab-based susceptibility criteria themselves (none are probabilistic)*

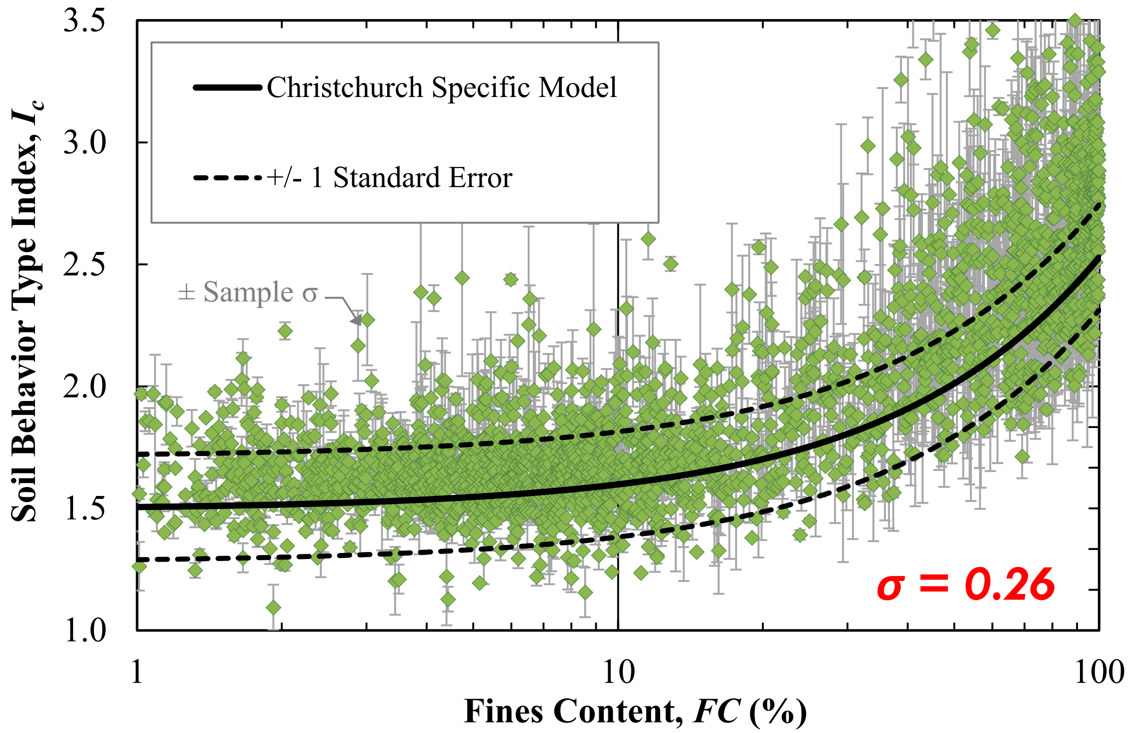




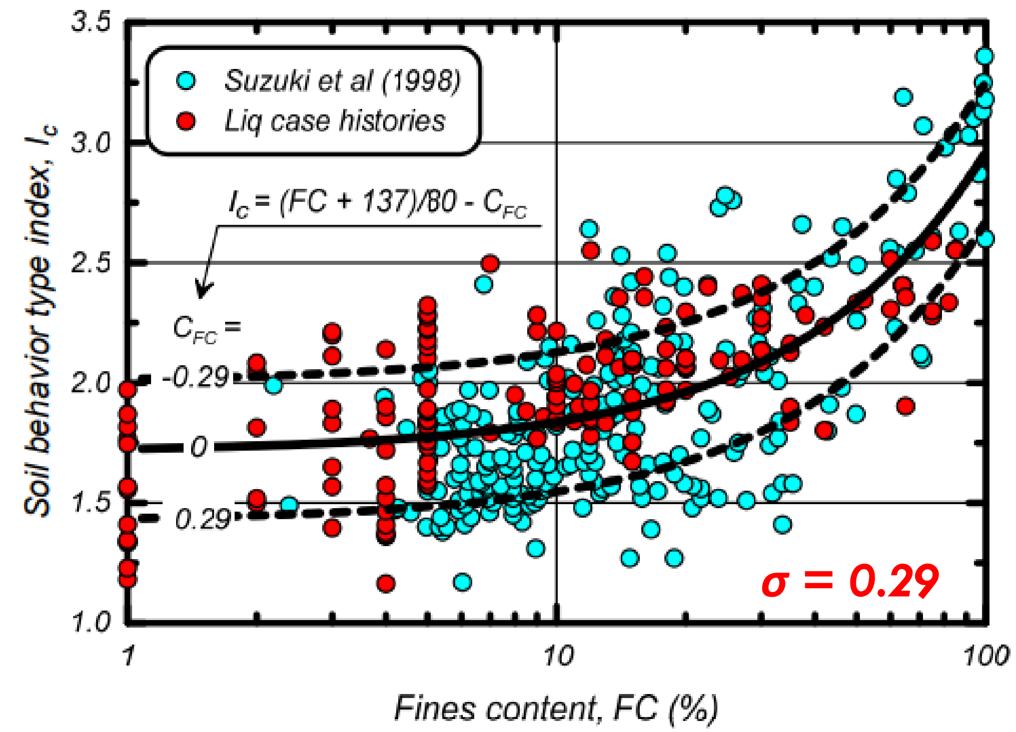
Results: Other Correlations and Improving CPT Predictions of Susceptibility

- I_c-FC correlations:

Christchurch Correlation



Global Correlation (Boulanger and Idriss 2014)

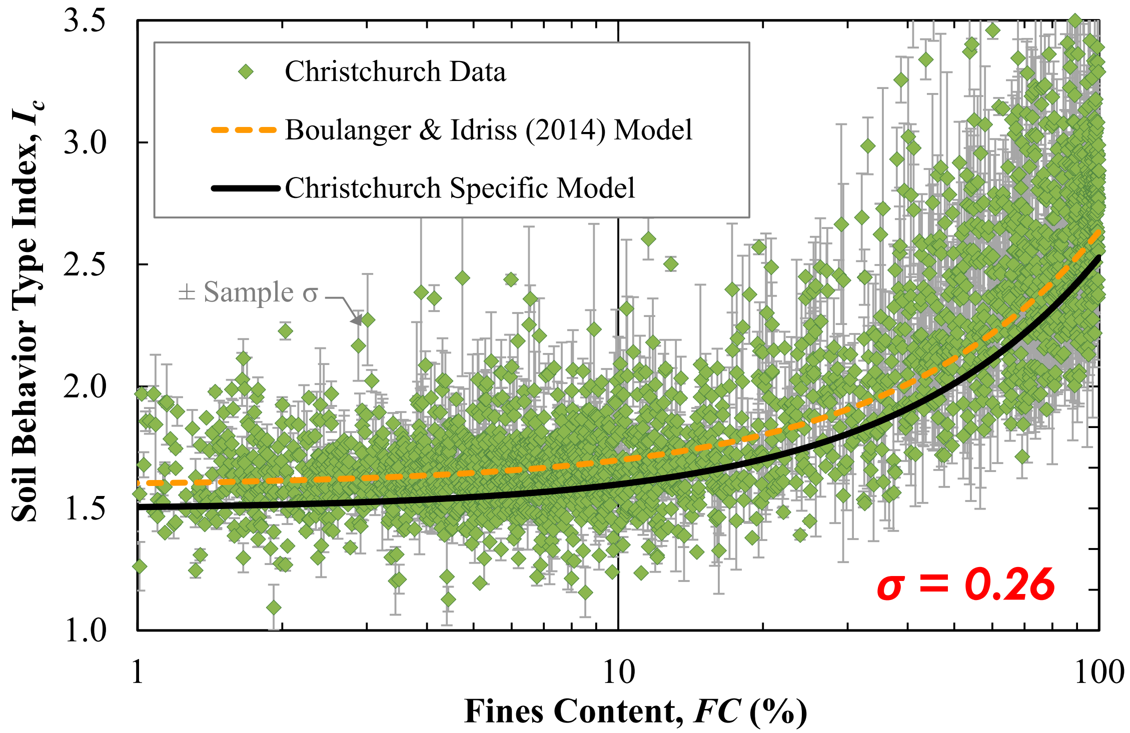


- Boulanger and Idriss (2014) form fits Christchurch data well; uncertainty is appropriate.

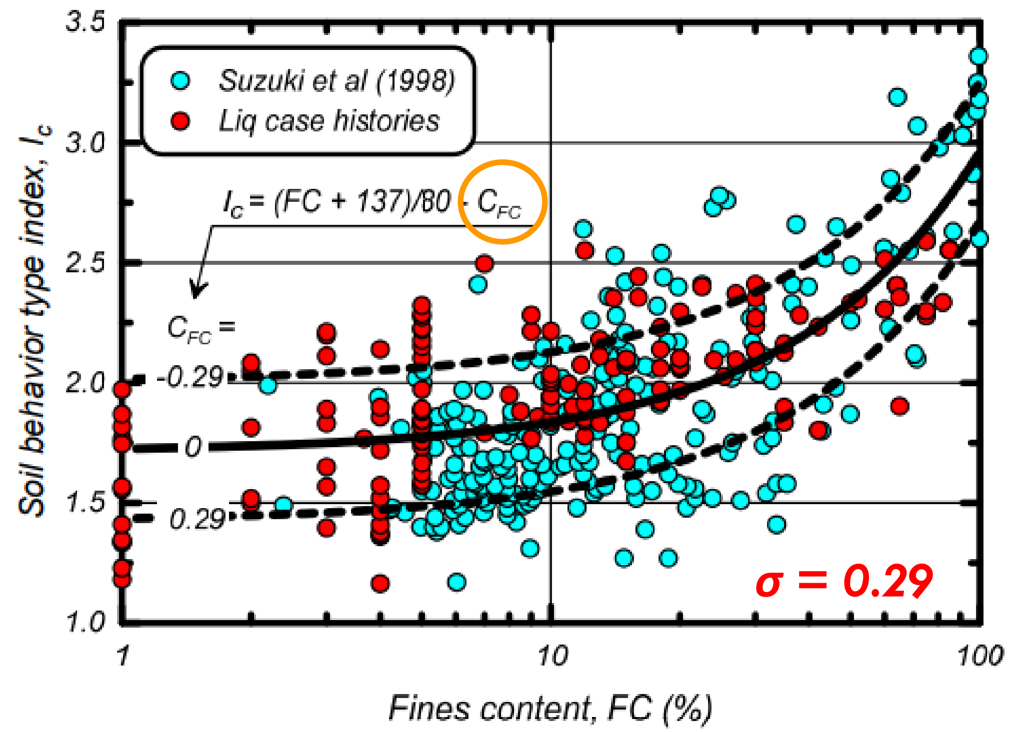
Results: Other Correlations and Improving CPT Predictions of Susceptibility

- *I_c-FC correlations:*

Christchurch Correlation



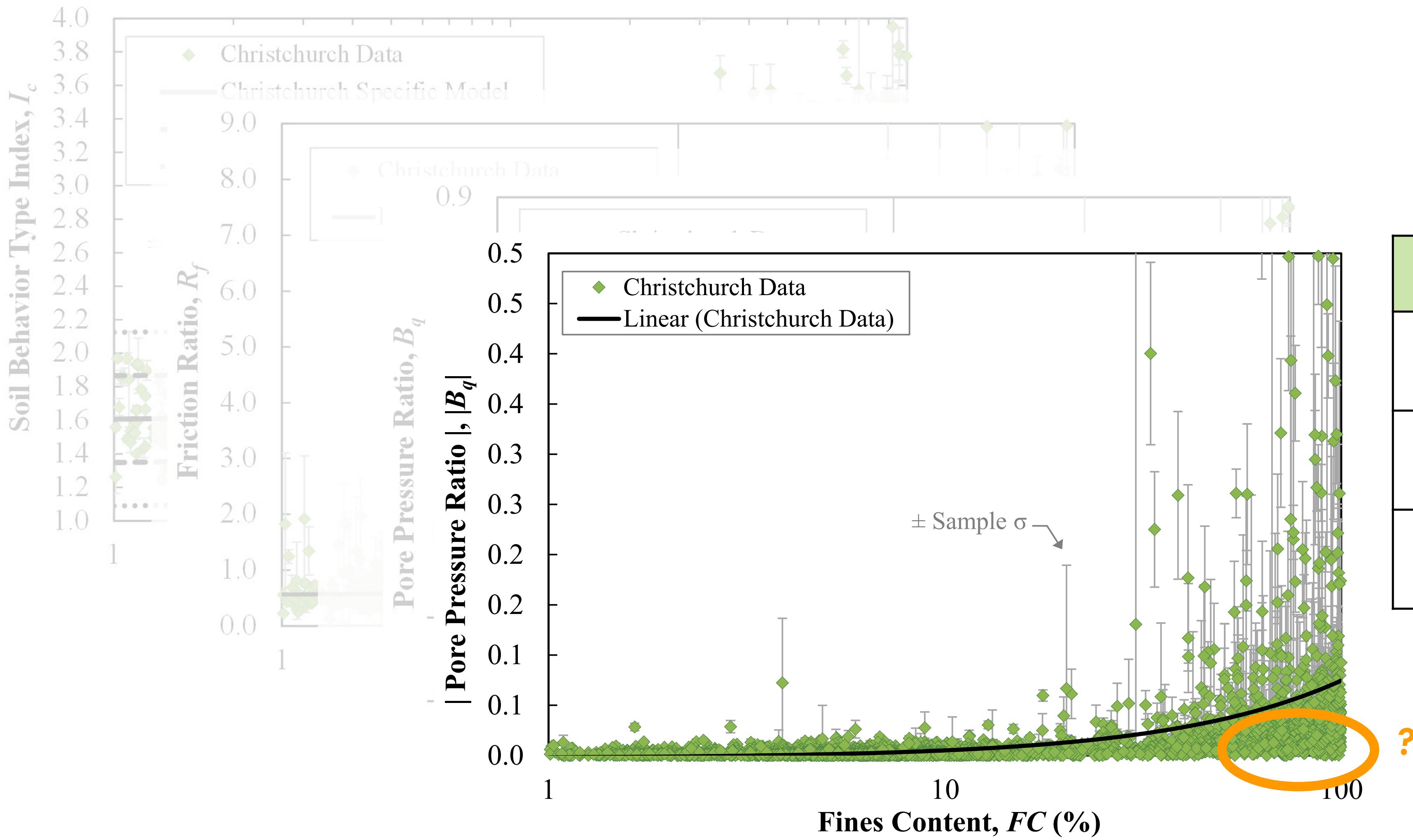
Global Correlation (Boulanger and Idriss 2014)



- *Boulanger and Idriss (2014) form fits Christchurch data well; uncertainty is appropriate.*

Results: Other Correlations and Improving CPT Predictions of Susceptibility

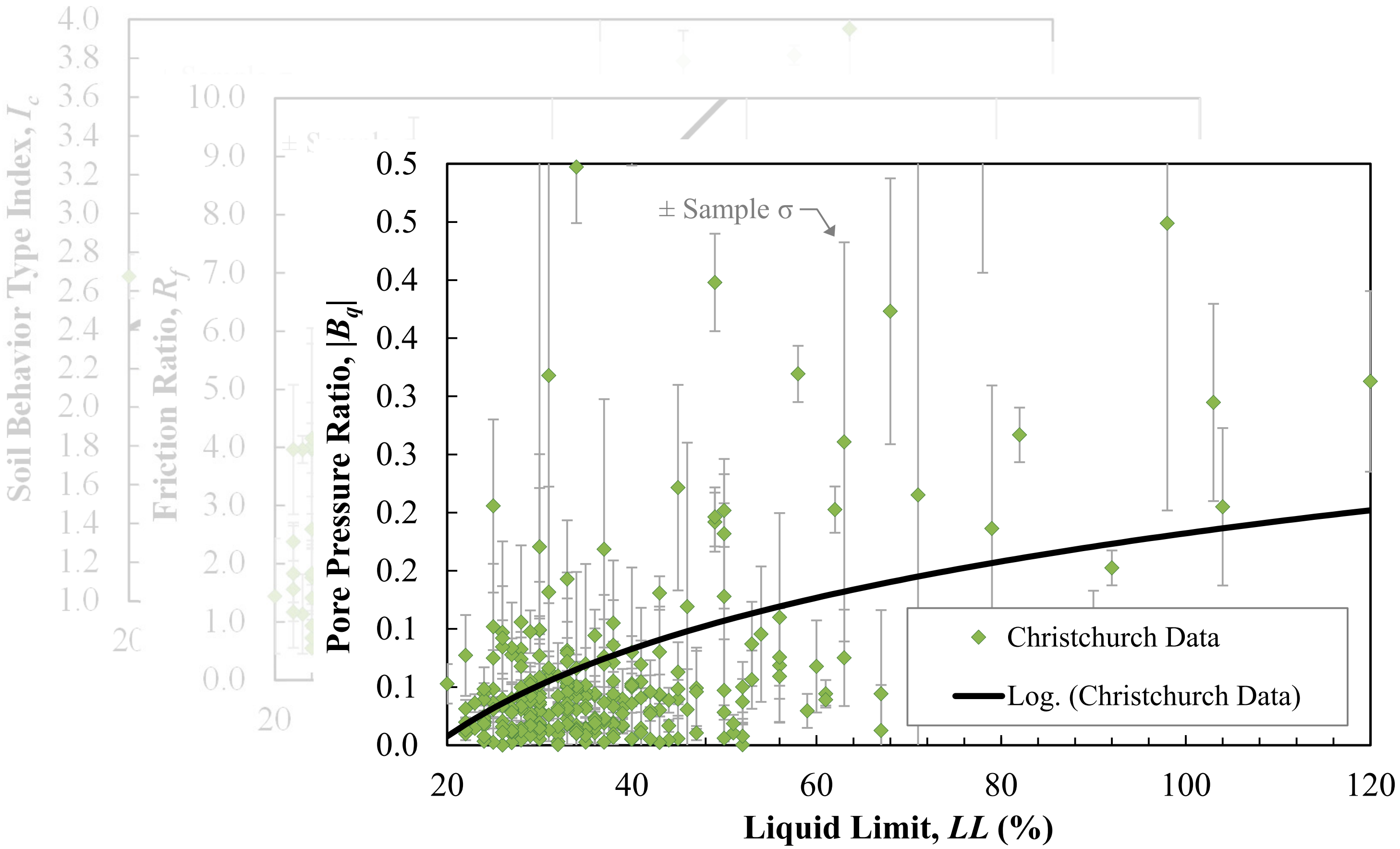
- *FC correlations:*



Spearman ρ	
I_c - FC	0.749
R_f - FC	0.561
$\|B_q\|$ - FC	0.675

Results: Other Correlations and Improving CPT Predictions of Susceptibility

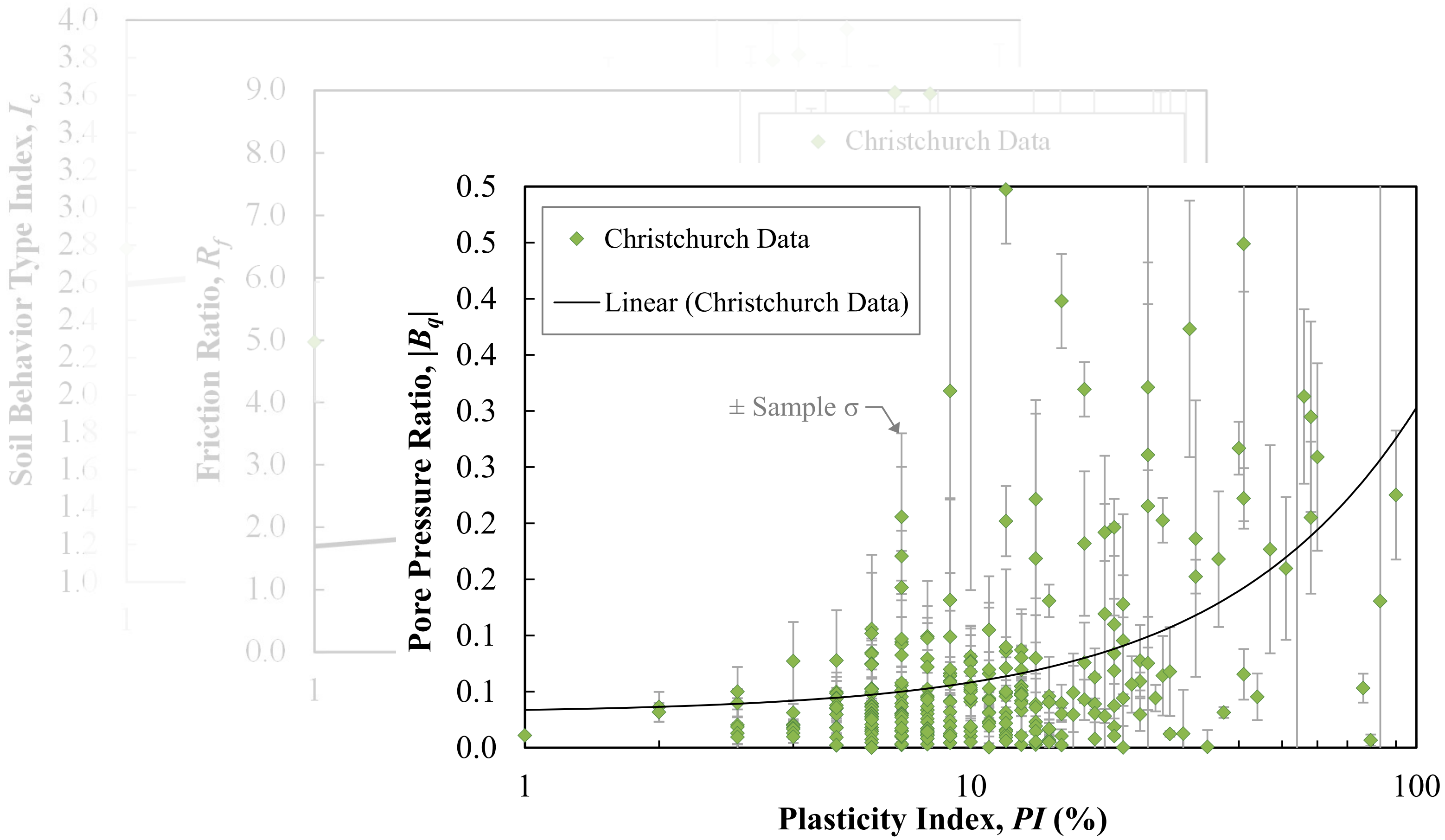
- *LL correlations:*



Spearman ρ	
I_c - LL	0.655
R_f - LL	0.297
$\|B_q\|$ - LL	0.318

Results: Other Correlations and Improving CPT Predictions of Susceptibility

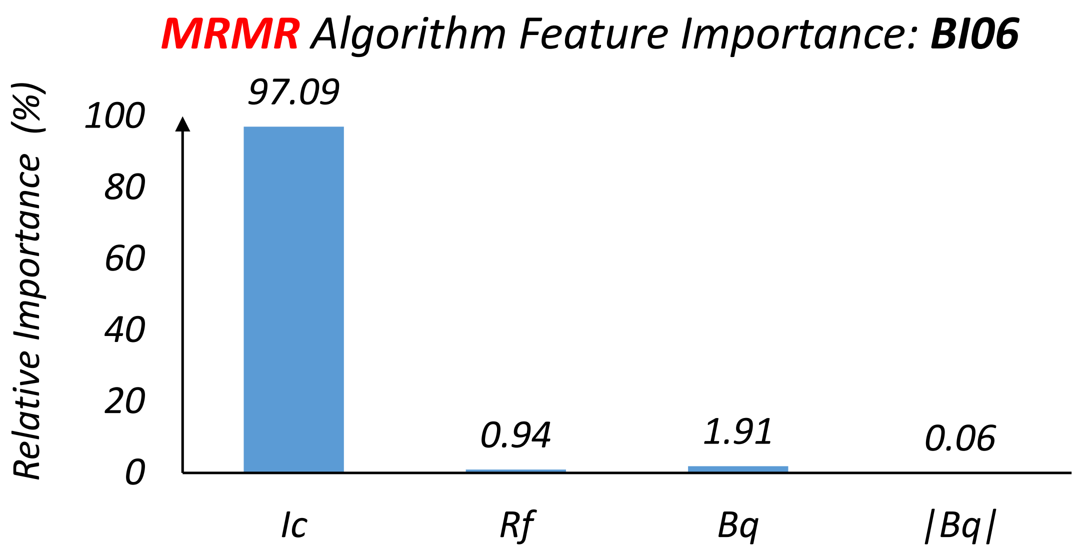
➢ *PI correlations:*

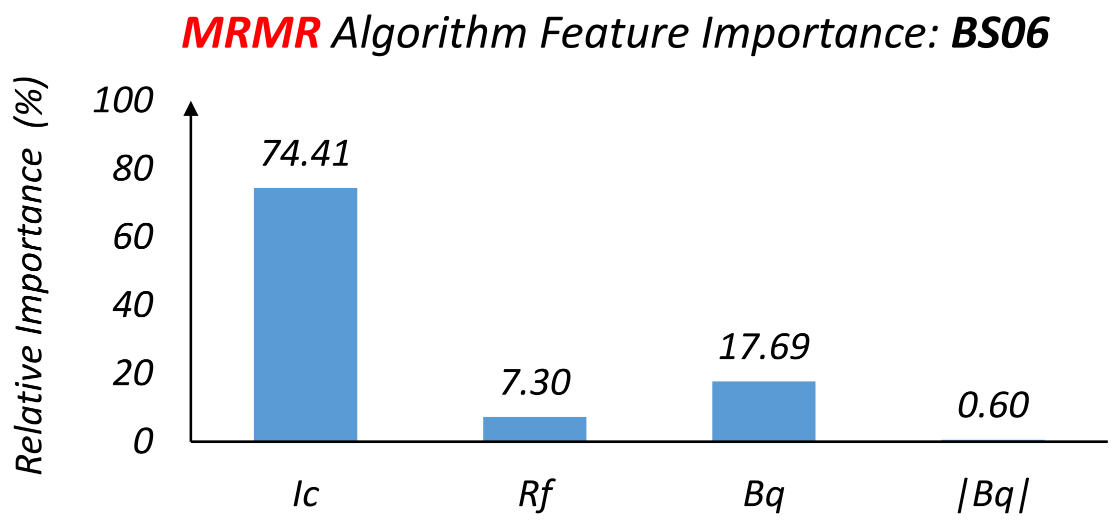


Spearman ρ	
I_c - PI	0.772
R_f - PI	0.654
$\|B_q\|$ - PI	0.438
I_c - $\|B_q\|$	0.702
I_c - R_f	0.715

Results: Other Correlations and Improving CPT Predictions of Susceptibility

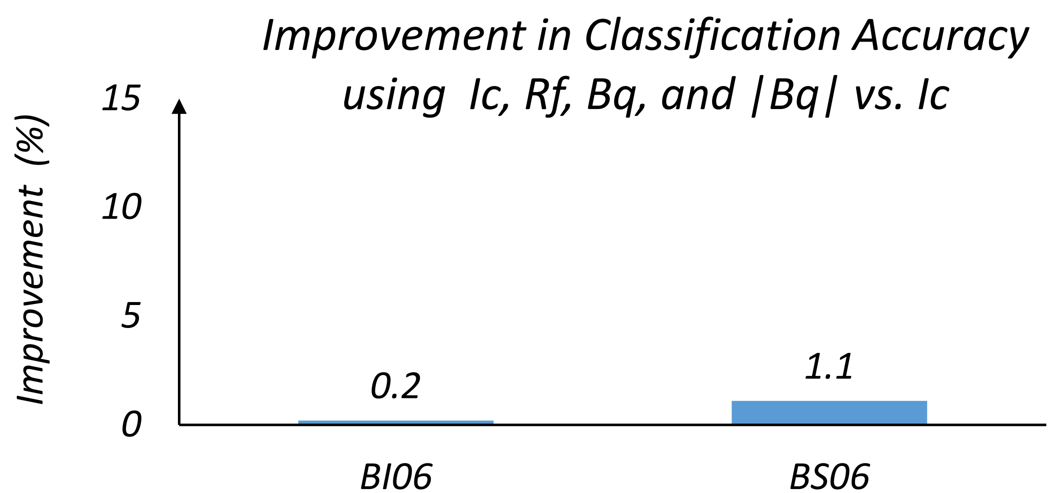
- *Algorithmic Learning to predict BS06 and BI06 susceptibility classifications:*
- ***Can combinations of I_c, R_f, B_q, and | B_q | predict susceptibility better than I_c alone?***
- *Feature importance averaged across five popular feature selection algorithms (MRMR, Chi2, ReliefF, ANOVA, Kruskal Wallis):*





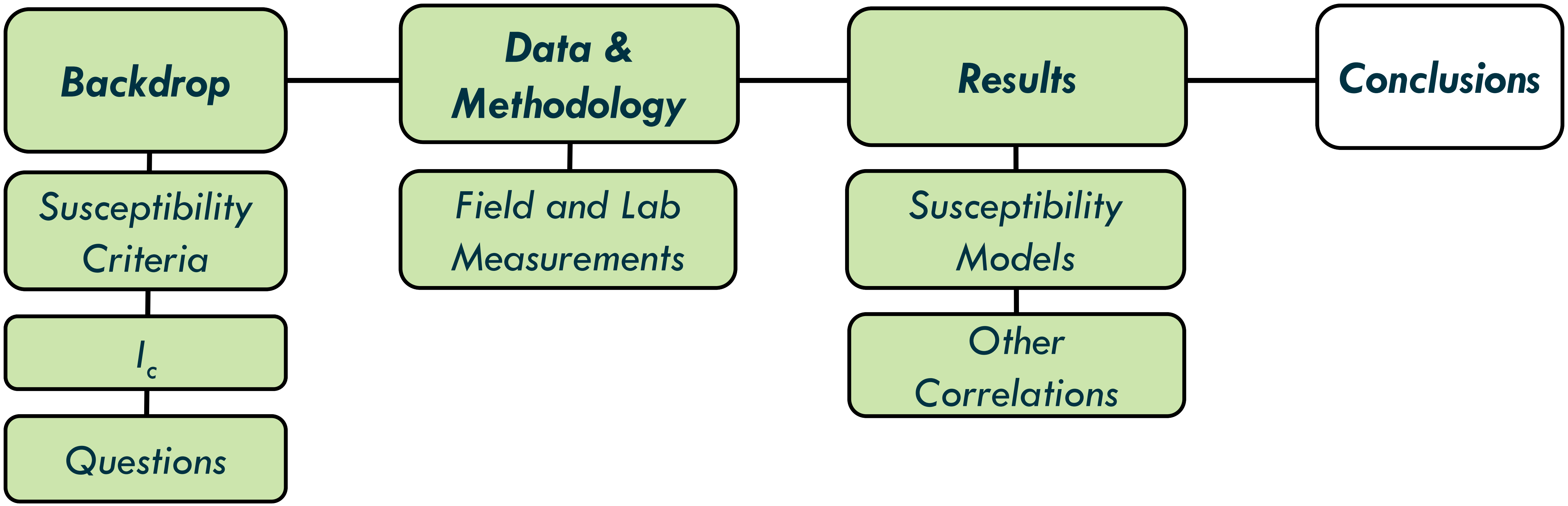
Results: Other Correlations and Improving CPT Predictions of Susceptibility

- *Data randomly split into 85% training, 15% test*
- *Various ML algorithms trained: decision trees and tree ensembles (i.e., bagging, boosting), SV machines, KNN classifiers, GP models, stacked models…*
- *Improvements on **test set** using **best respective models**:*



➢ ***I_c predictions of susceptibility cannot be readily improved with these added variables.***

Outline


Backdrop
Data & Methodology
Results
Conclusions
Susceptibility Criteria
I_c
Questions
Field and Lab Measurements
Susceptibility Models
Other Correlations

Concluding Remarks

- *The global applicability of the Canterbury susceptibility models cannot be known, and thus, recommendations for or against the use of these models elsewhere* ***cannot be made.***

  Nonetheless, several broader conclusions can be derived:

1) *Criteria based on Atterberg limits may provide very different predictions of susceptibility.*
   - ***Should the definition of "susceptibility" be the same (e.g., can't ensemble models)?***

2) *The most common I_c threshold of susceptibility (i.e., $I_c = 2.6$) is a reasonable median, but the relationship between I_c and susceptibility is uncertain (more than appreciated?).*
   - ***Should this be considered/accounted for? And, because lab-based susceptibility criteria are not probabilistic, the actual uncertainty between susceptibility and I_c is unclear.***

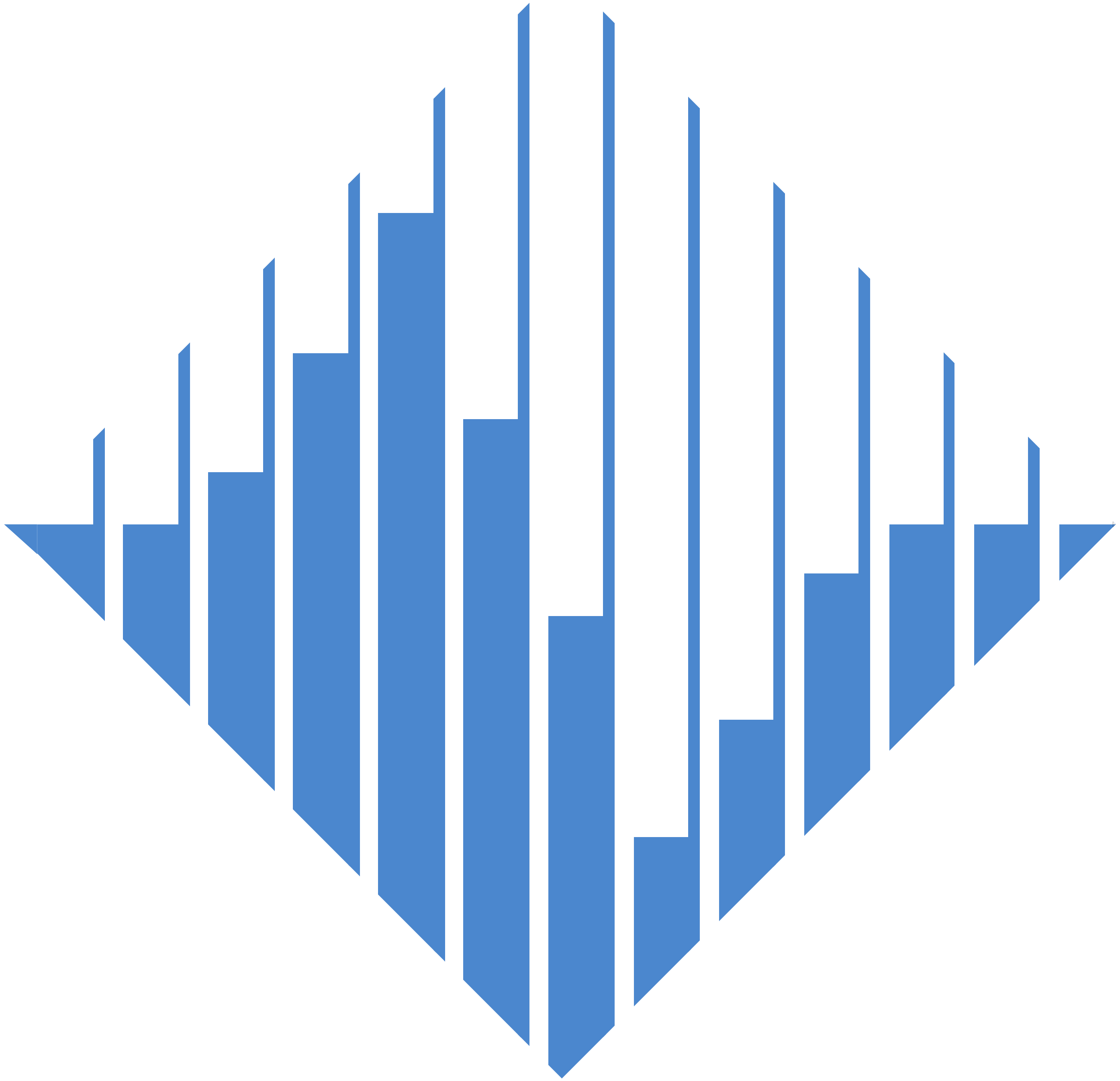
Concluding Remarks and Recommendations

- ***Nonetheless, several broader conclusions can be derived:***

3) *The models developed in Canterbury provide a methodology that can be repeated at site, regional, or global scale.*

4) *The uncertainty between I_c and Atterberg limit-based susceptibility suggests that other/additional variables could provide more efficient and/or sufficient predictions.*
   - ***Yet, given the data and CPT predictors readily available, improvements do not appear trivial. This could be different in other soils, with other u_2 data, and/or with other predictors.***

Questions?



PEER Workshop on Liquefaction Susceptibility
Corvallis, Oregon – September 8 & 9, 2022

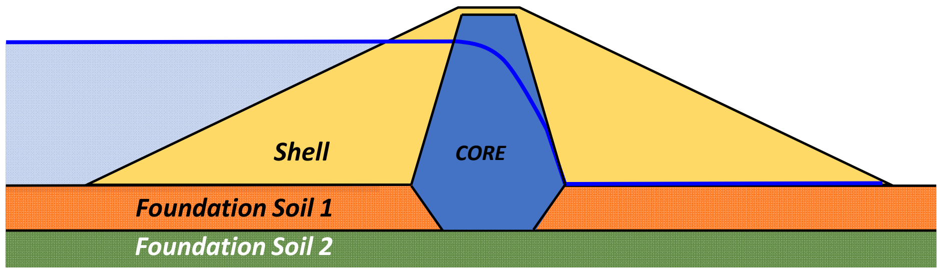
Susceptibility criteria for selecting engineering procedures

UCDAVIS
UNIVERSITY OF CALIFORNIA

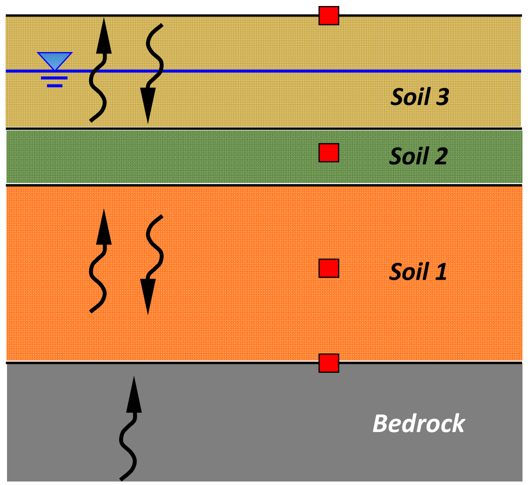
Ross W. Boulanger, PhD, PE, NAE
Distinguished Professor, Director of CGM

General objective: Estimating deformations

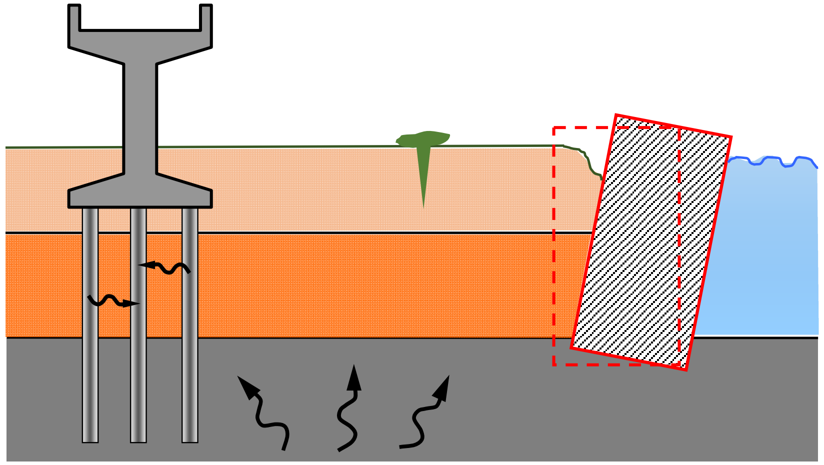
- Estimating deformations requires estimating strains (small to large) in a wide range of soils across a range of states and loading intensities using a hierarchy of analysis procedures



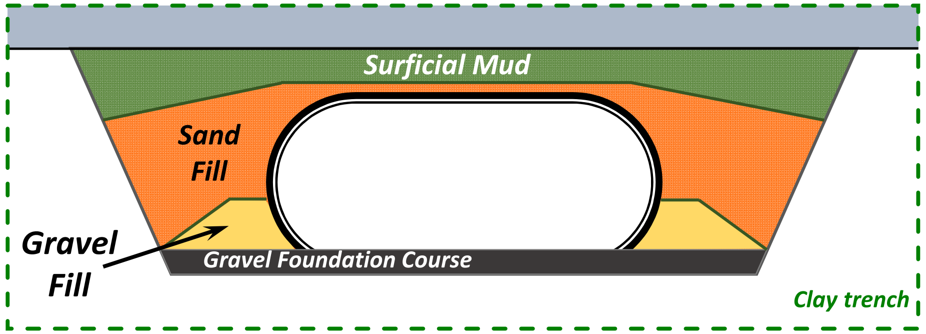
Embankment Dam



1D Site Response Analysis



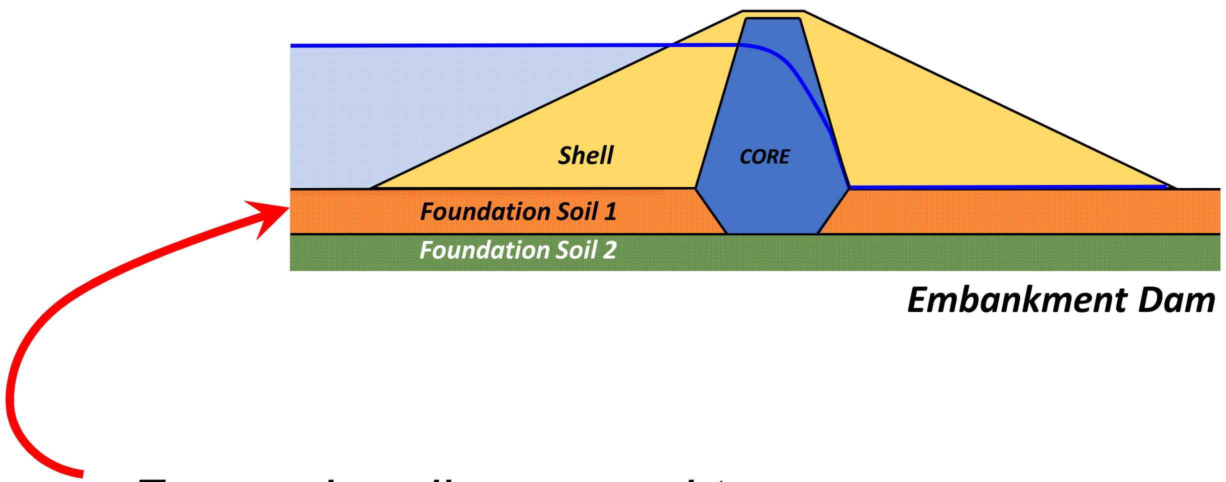
Soil-Pile-Quay Wall Interaction



Tunneling – Soil-Structure Interaction

General objective: Estimating deformations

- *Estimating deformations requires estimating strains (small to large) in a wide range of soils across a range of states and loading intensities using a hierarchy of analysis procedures*

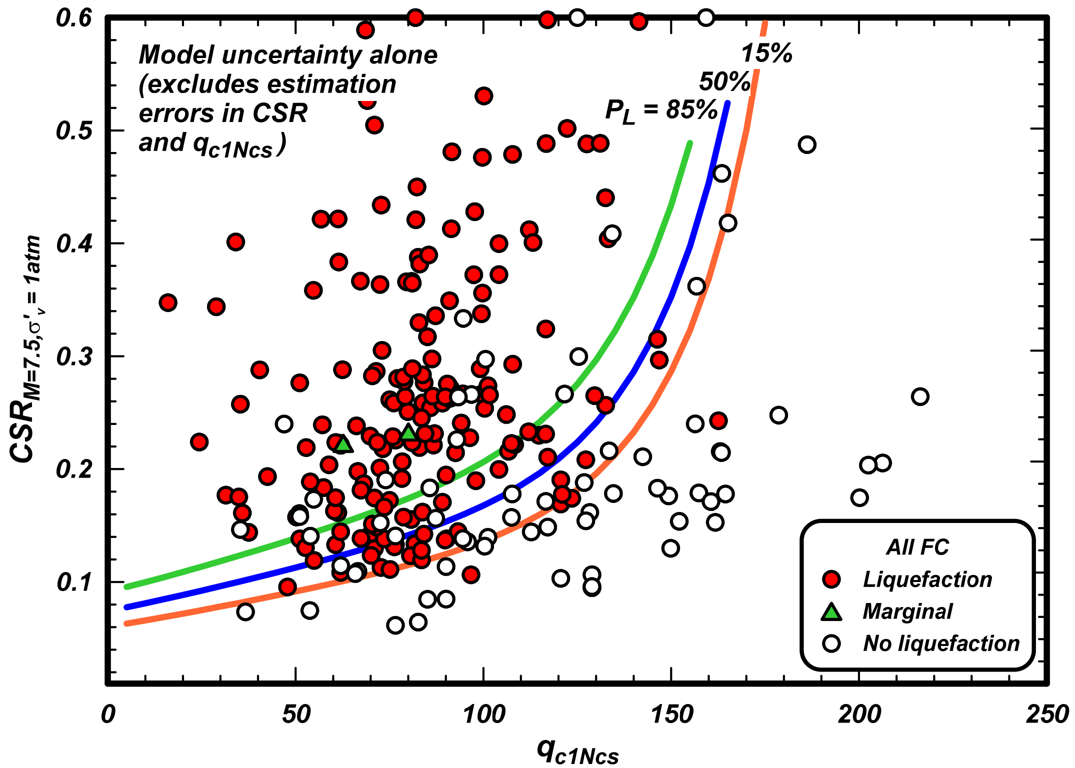


For each soil, we need to:

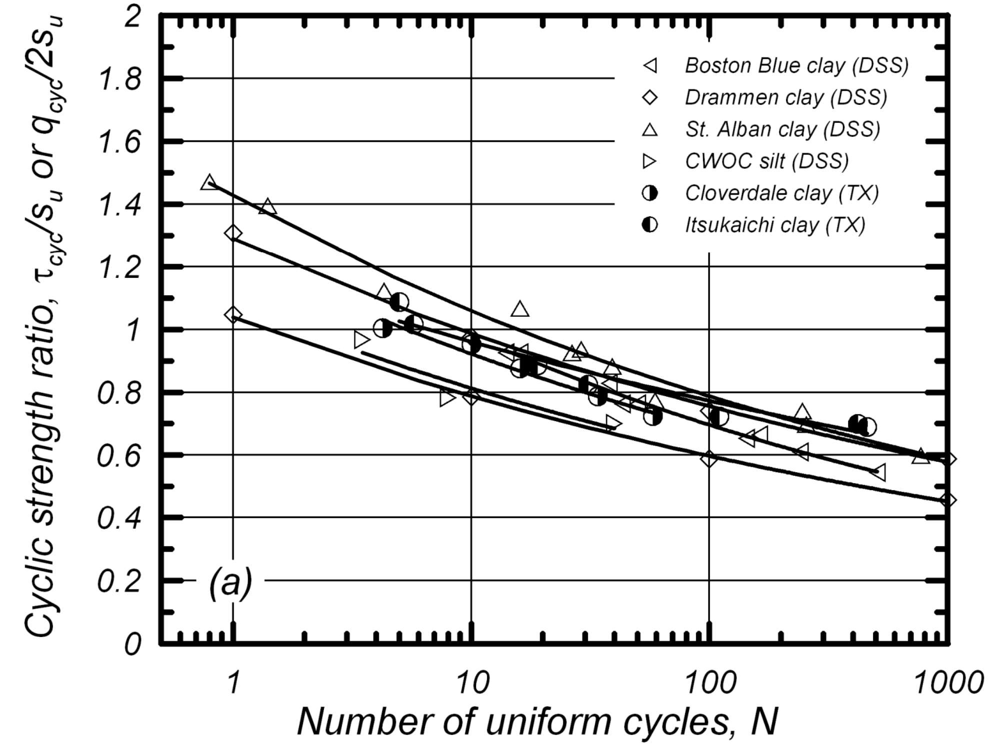
- *Estimate values for the static strength, cyclic strength, post-earthquake strength, moduli/damping, … or more generally its stress-strain response characteristics*
- *Decide on the appropriate in-situ tests, laboratory tests, and/or engineering correlations/relationships to use for estimating those properties*

Estimating cyclic strengths

➢ *Tool boxes are different for sand-like and clay-like soils*



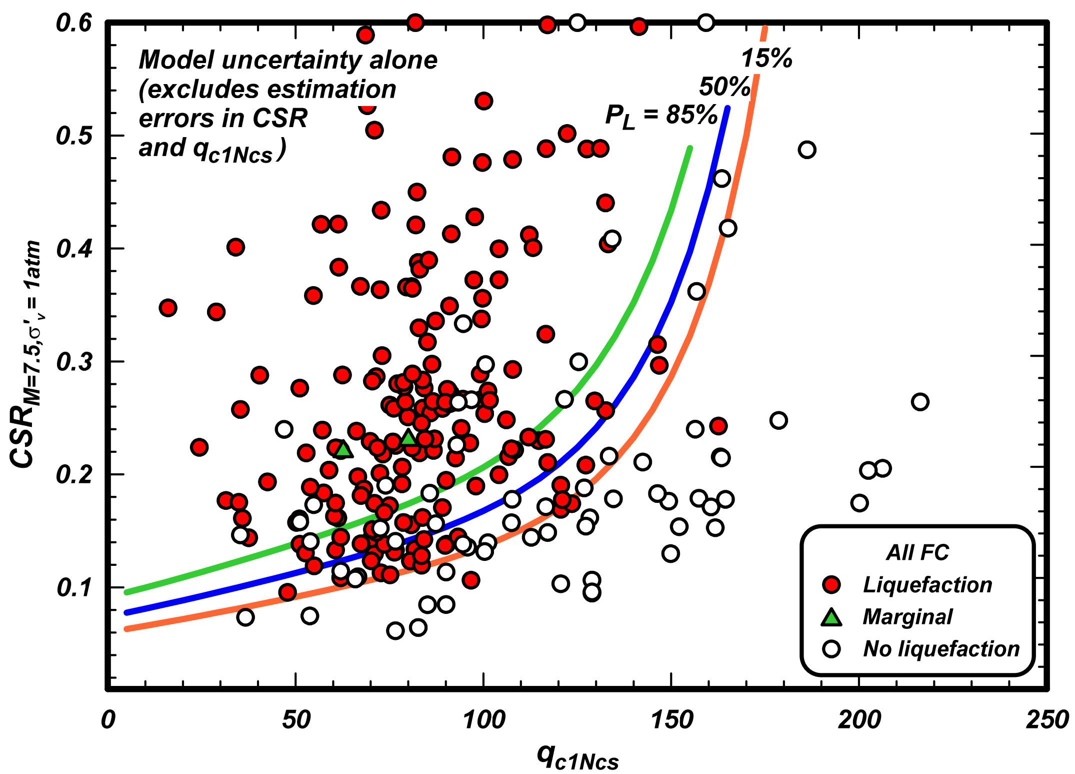
Sand-like soils



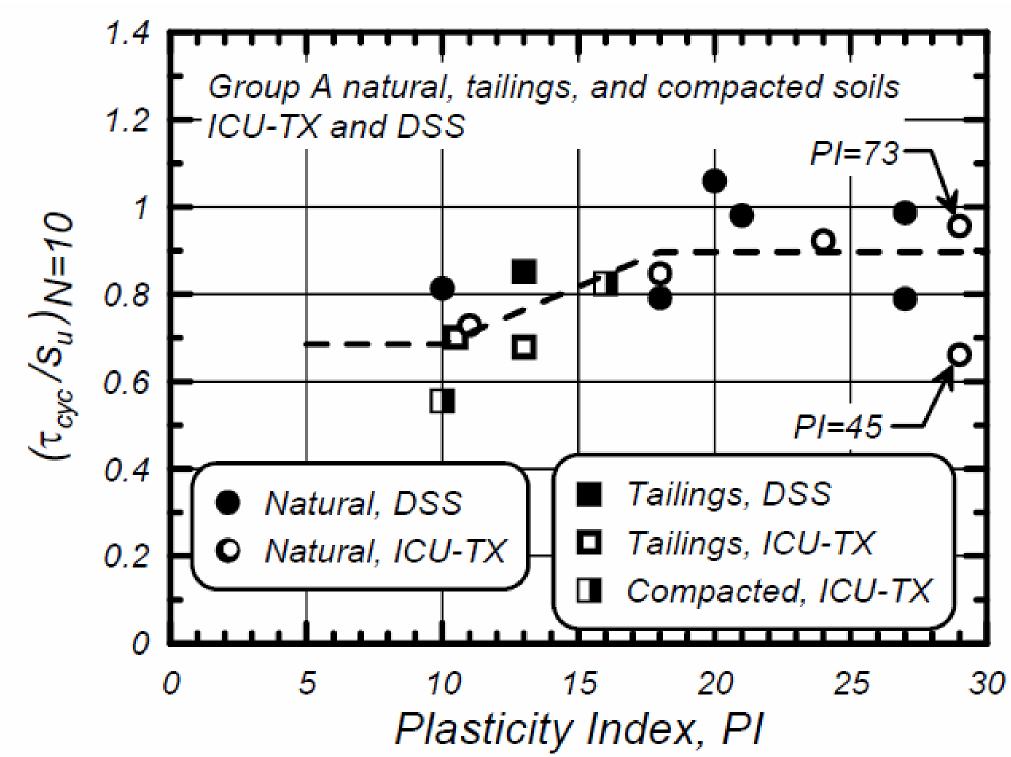
Clay-like soils

Estimating cyclic strengths

➢ *Tool boxes are different for sand-like and clay-like soils*



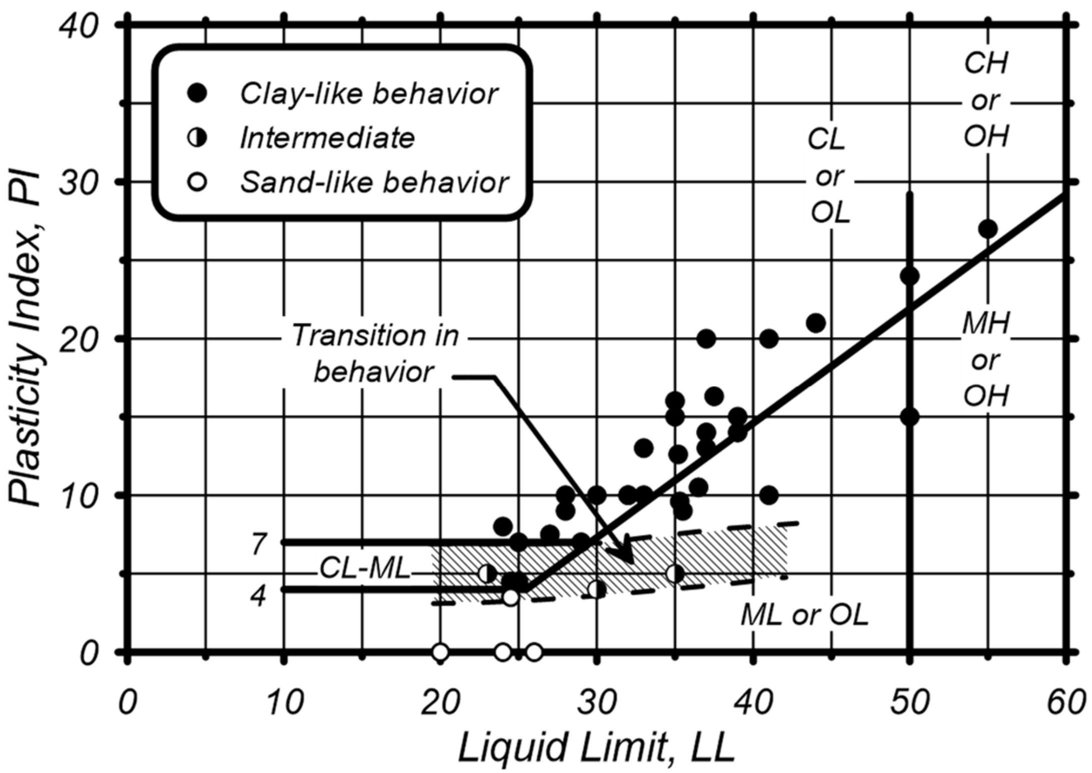
Sand-like soils



Clay-like soils

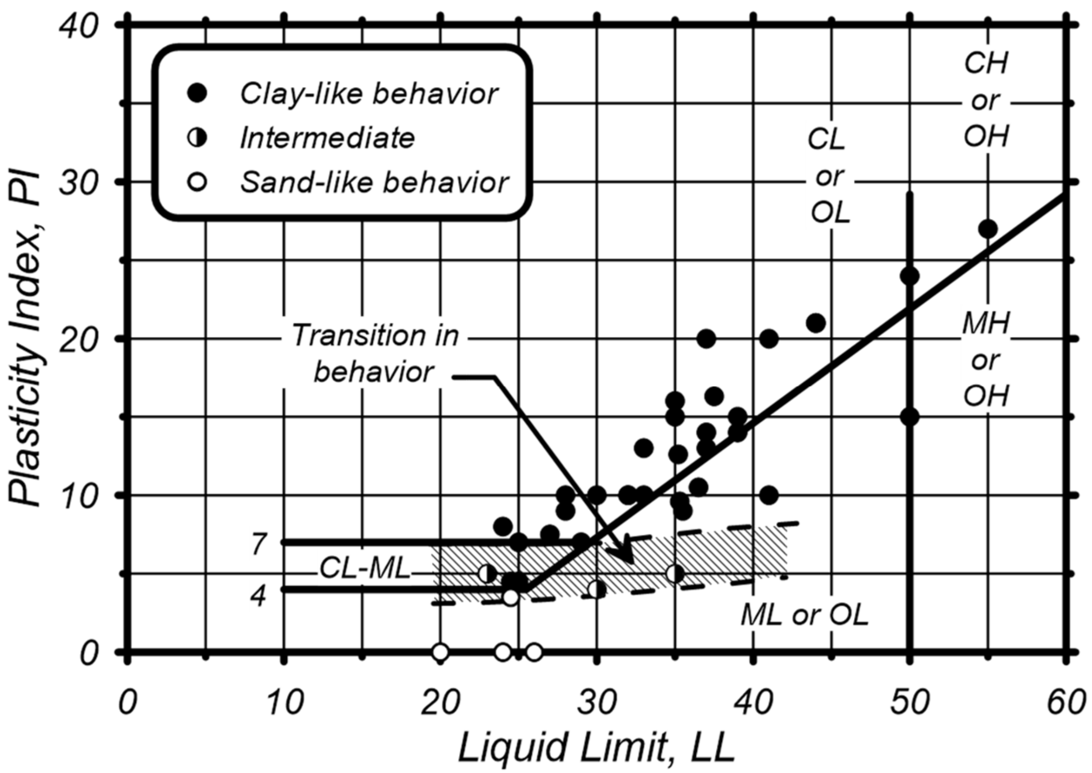
Cyclic strength evaluation criteria

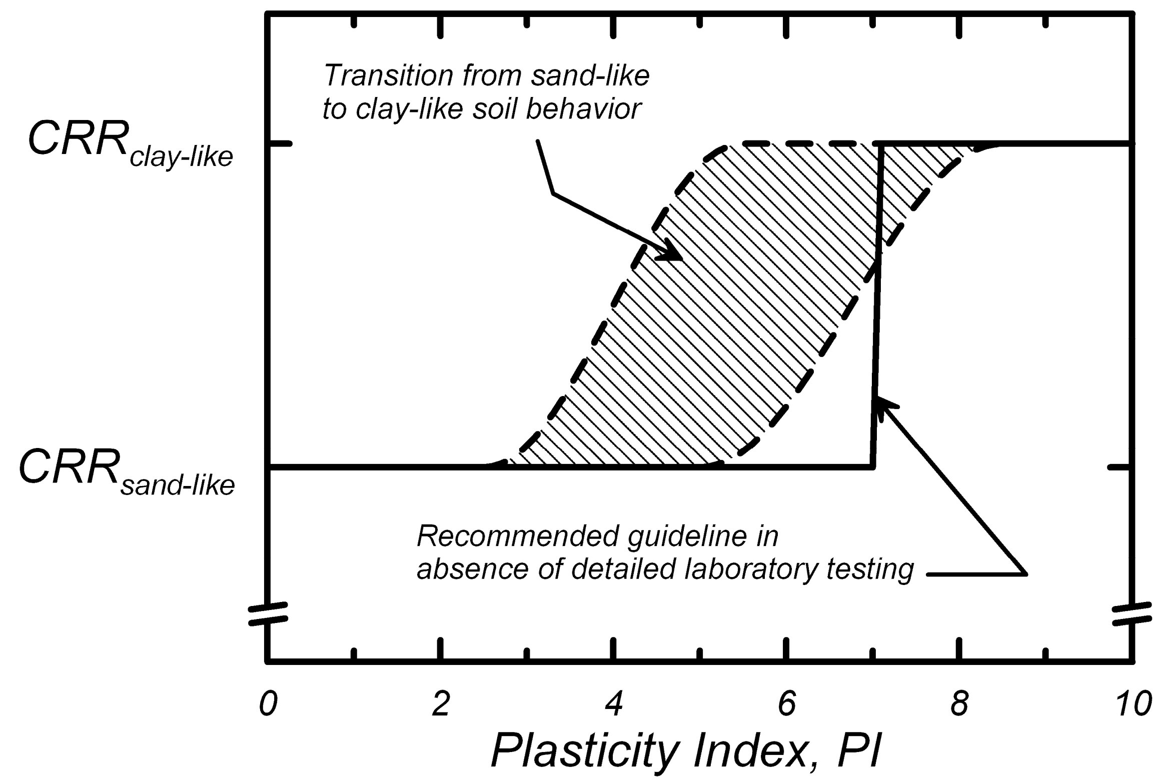
- *The Boulanger & Idriss (2006) ~~liquefaction susceptibility~~ cyclic strength evaluation criteria are mapped to the recommended engineering procedures for estimating cyclic strengths*



Cyclic strength evaluation criteria

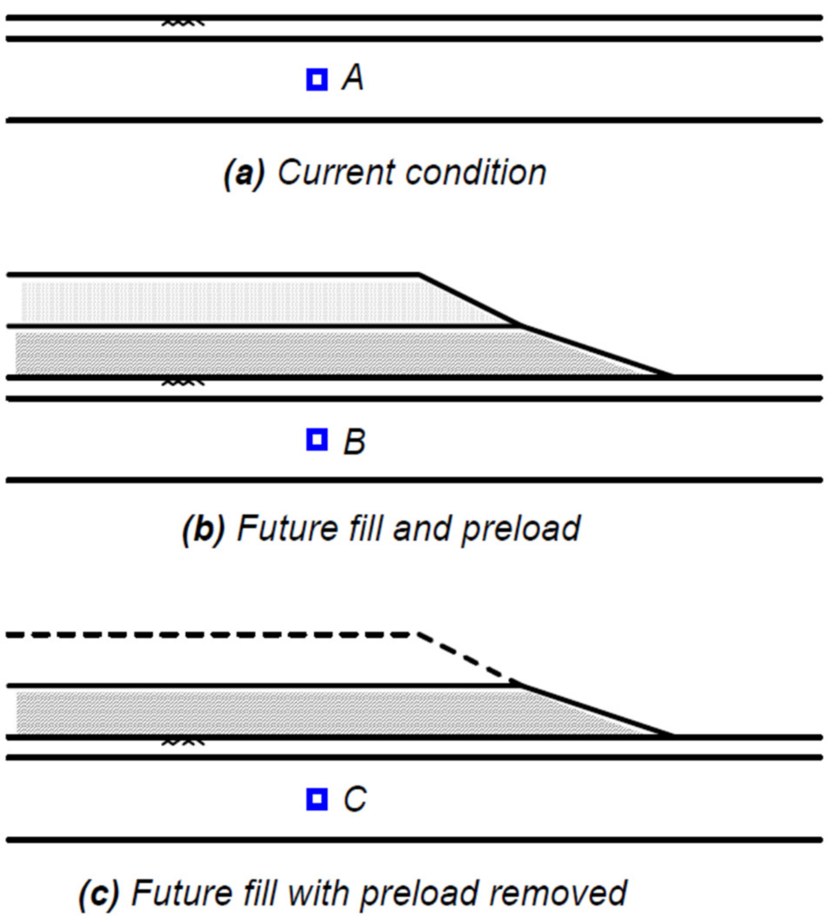
- The "transition" zone represents uncertainties in both the properties and the ability to manage sample disturbance effects. The ability to manage disturbance effects depends on more than just index properties and requires engineering effort to evaluate.

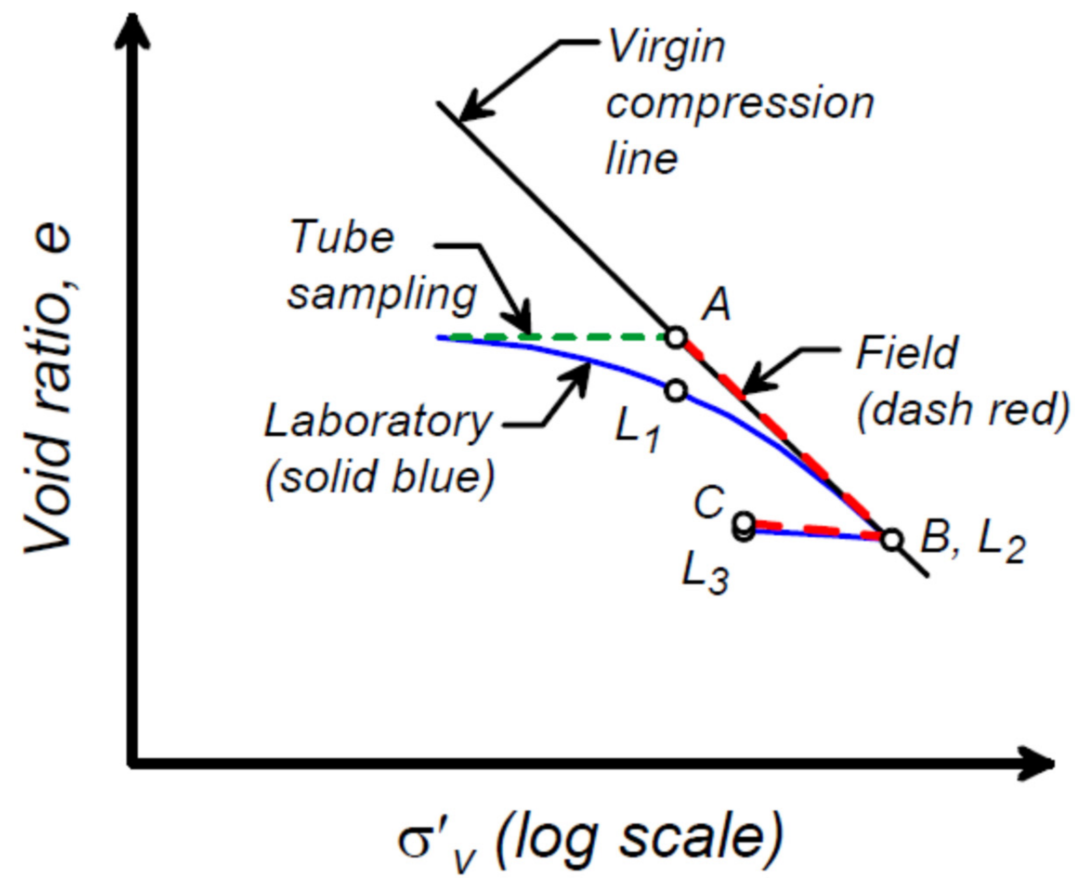




Managing sample disturbance effects

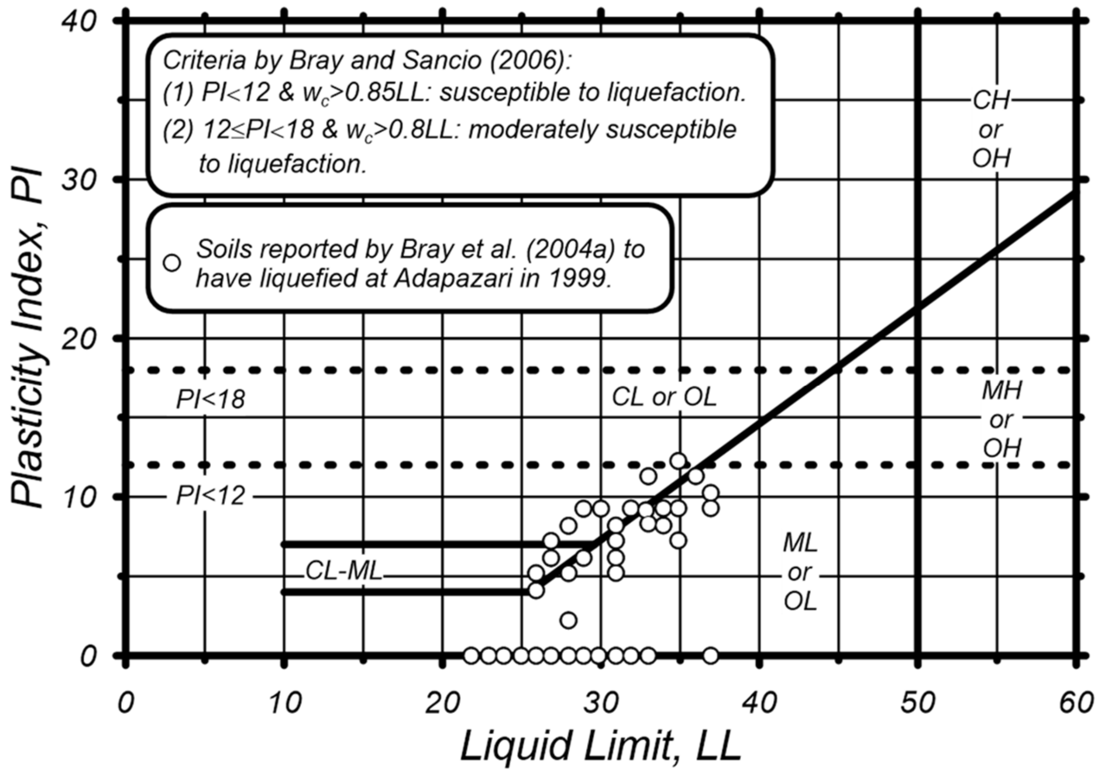
- *Ability to minimize/manage sample disturbance effects depends on the anticipated static and seismic loading conditions*



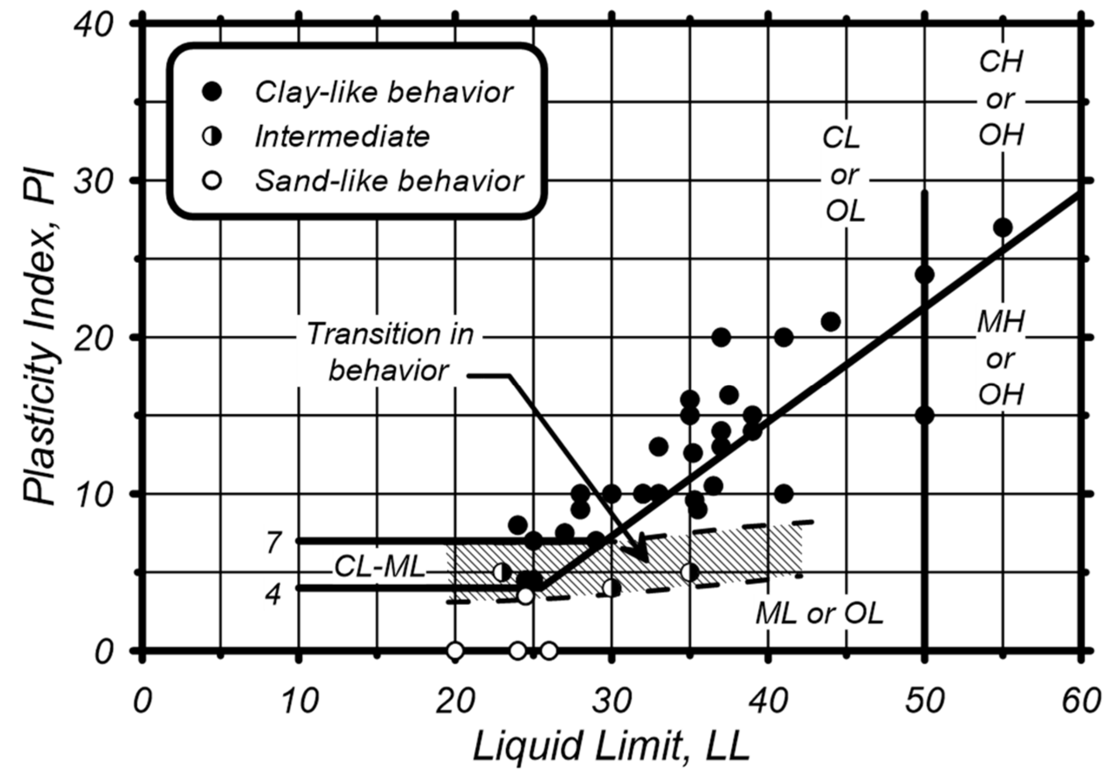


Improved terminology would improve communication

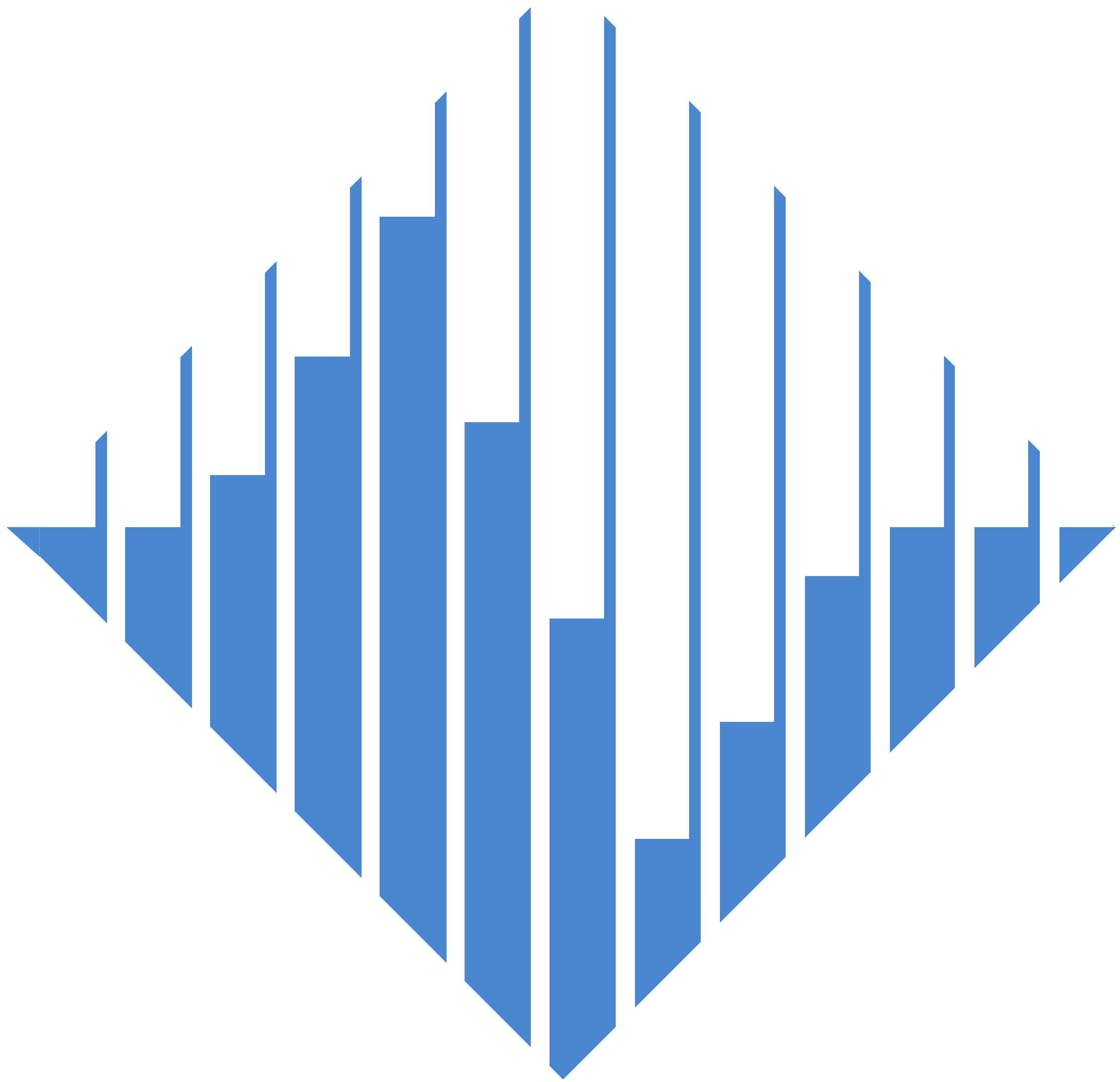
- Using the same name for criteria with different purposes has caused confusion



"Cyclic deformation susceptibility criteria"



"Cyclic strength evaluation criteria"



Cyclic Behavior of Low Plasticity Fine-Grained Soils of Varying Salinity

SEPTEMBER 8, 2022

SCOTT J. BRANDENBERG AND JONATHAN P. STEWART

NGL
NEXT GENERATION LIQUEFACTION

Motivation

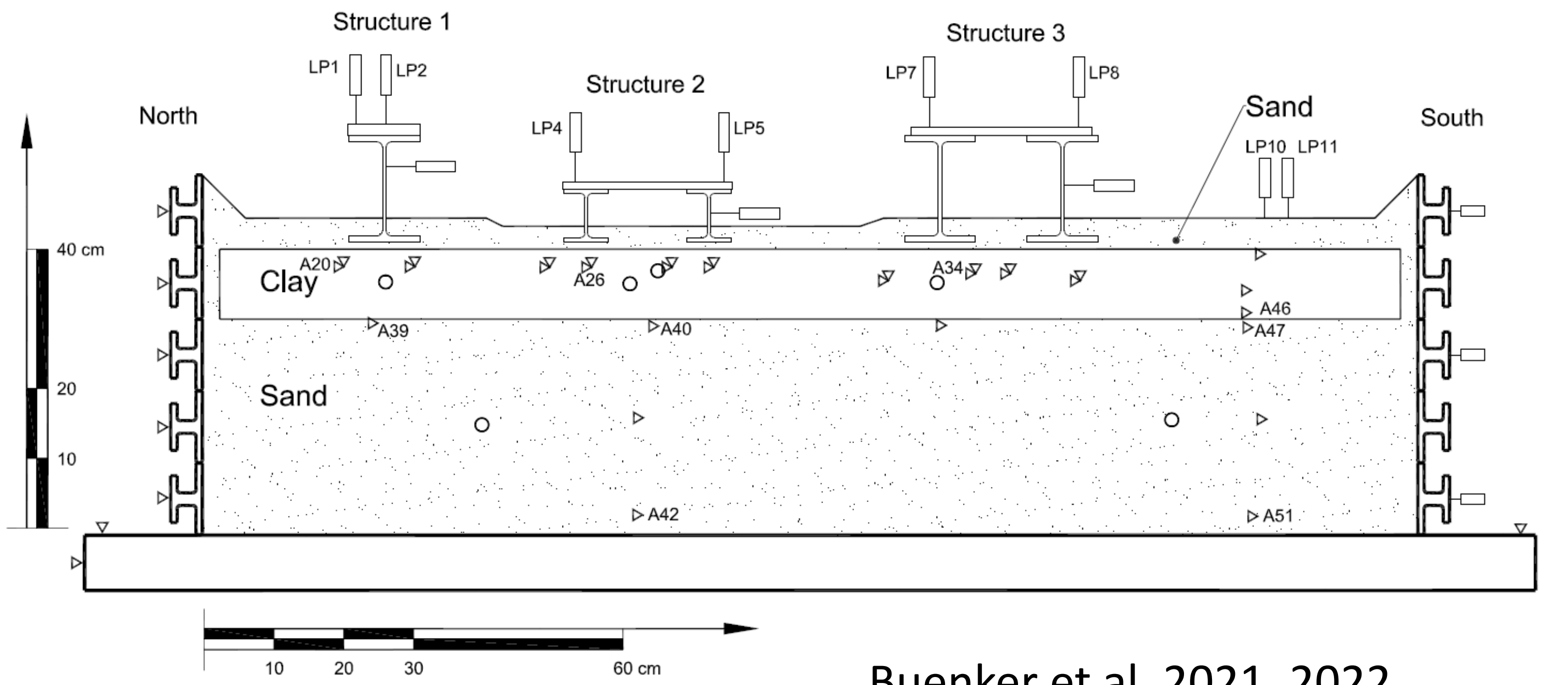
- Cyclic failure of fine-grained soils often manifests in zones of high static shear stress (e.g., beneath structures), but not in the free field.

https://apps.peer.berkeley.edu/publications/turkey/adapazari/phase1/site_b/index.html

Chu, D.B., Stewart, J.P., Lee, S., Tsai, J.S., Lin, P.S., Chu, B.L., Seed, R.B., Hsu, S.C., Yu, M.S., and Wang, M.C.H. (2004). “Documentation of soil conditions at liquefaction and non-liquefaction sites from 1999 Chi-Chi (Taiwan) earthquake.” (2004). *Soil Dyn. Eq. Eng.* 24, 647-657

Motivation

- Cyclic failure of fine-grained soils often manifests in zones of high static shear stress (e.g., beneath structures), but not in the free field.
- We performed a set of centrifuge model tests at UC Davis to study this problem.



Buenker et al. 2021, 2022

Motivation

- Cyclic failure of fine-grained soils often manifests in zones of high static shear stress (e.g., beneath structures), but not in the free field.
- We performed a set of centrifuge model tests at UC Davis to study this problem.
- As part of the centrifuge test program, we performed cyclic direct simple shear tests on low-plasticity fine-grained soils to evaluate their strength loss potential.

Table 1. Properties of mixtures used in experimental program

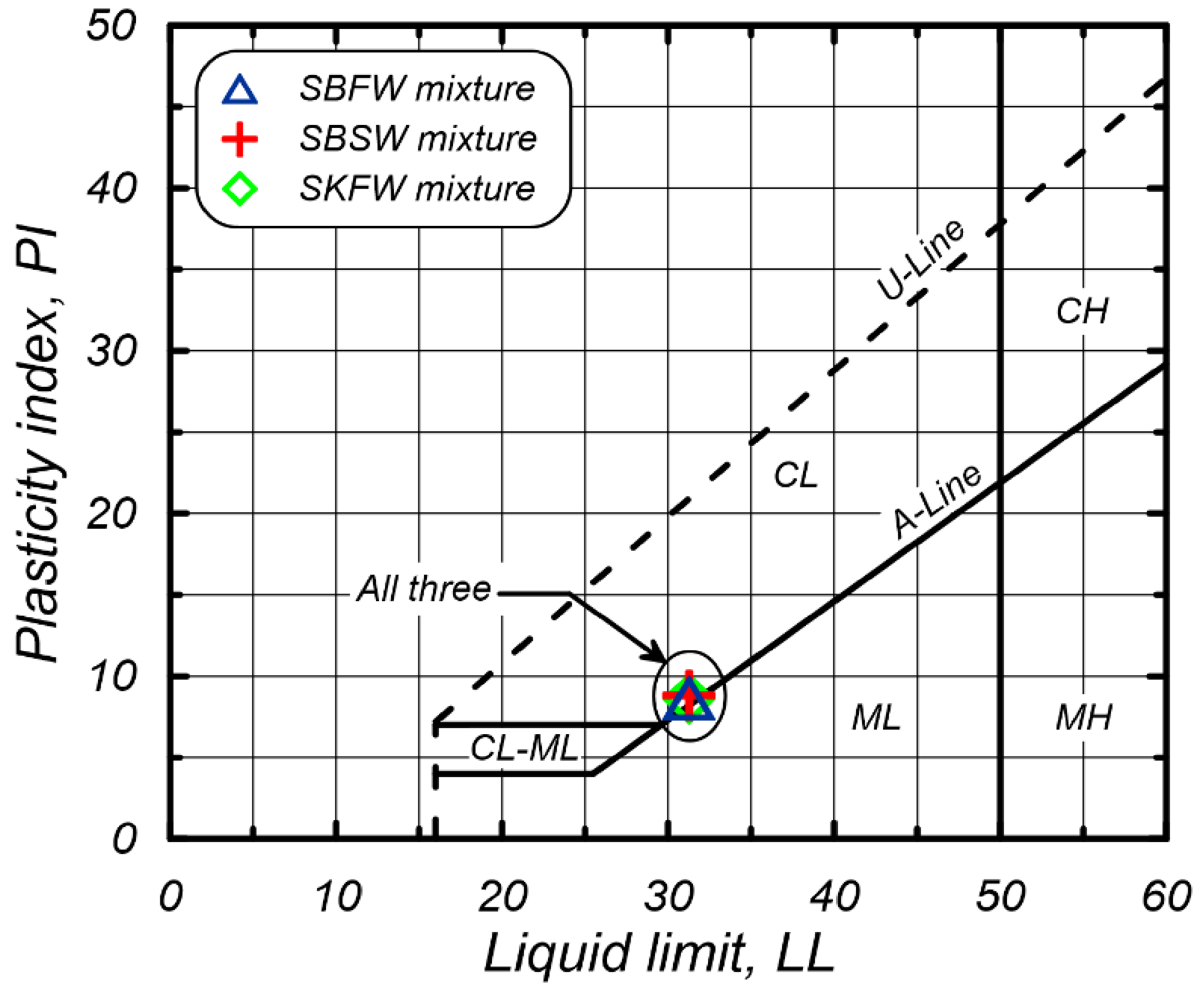
ID	% silt[a]	% Bentonite[b]	% Kaolinite[c]	Pore-fluid	G_s	LL	PL	PI
SBFW	95	5	0	Fresh water	2.64	31.2	22.6	8.6
SBSW	90	10	0	Saline water	2.67	31.9	23.1	8.8
SKFW	78	0	22	Fresh water	2.63	30	21.4	8.6
SKSW	78	0	22	Saline Water	2.63	29.4	20.8	8.6

[a] Sil-co-sil #45 ground silica, Non-plastic

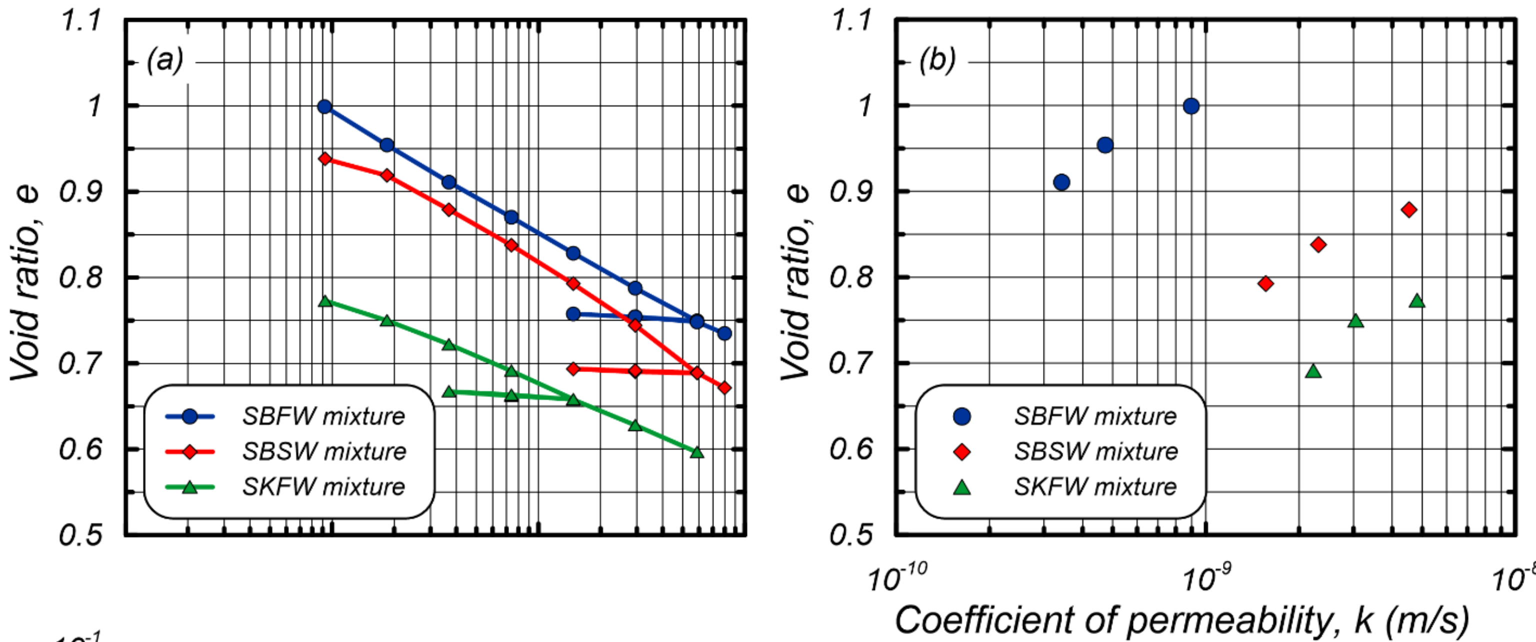
[b] LL = 455.3, PL = 39.6, PI = 415.7

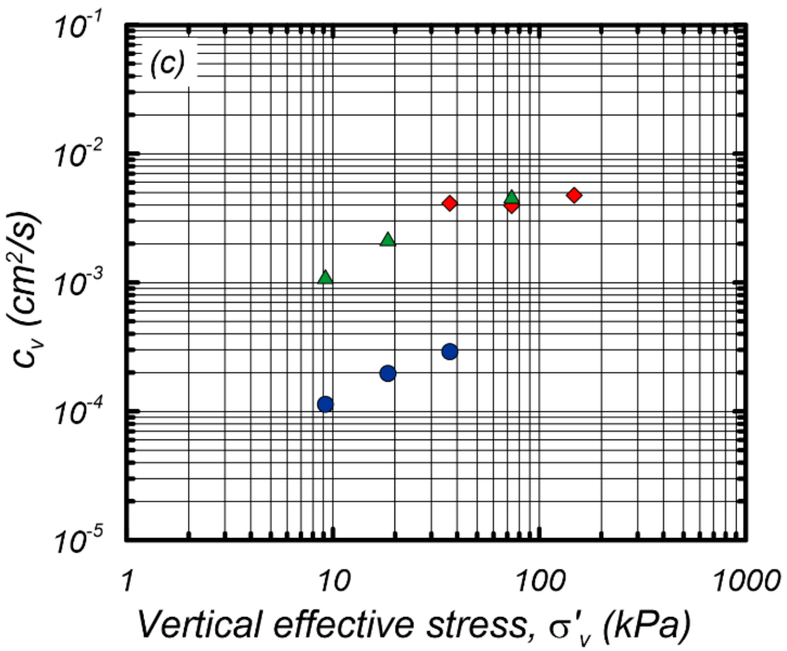
[c] LL = 66.1, PL = 35.8, PI = 30.3

NGL NEXT GENERATION LIQUEFACTION

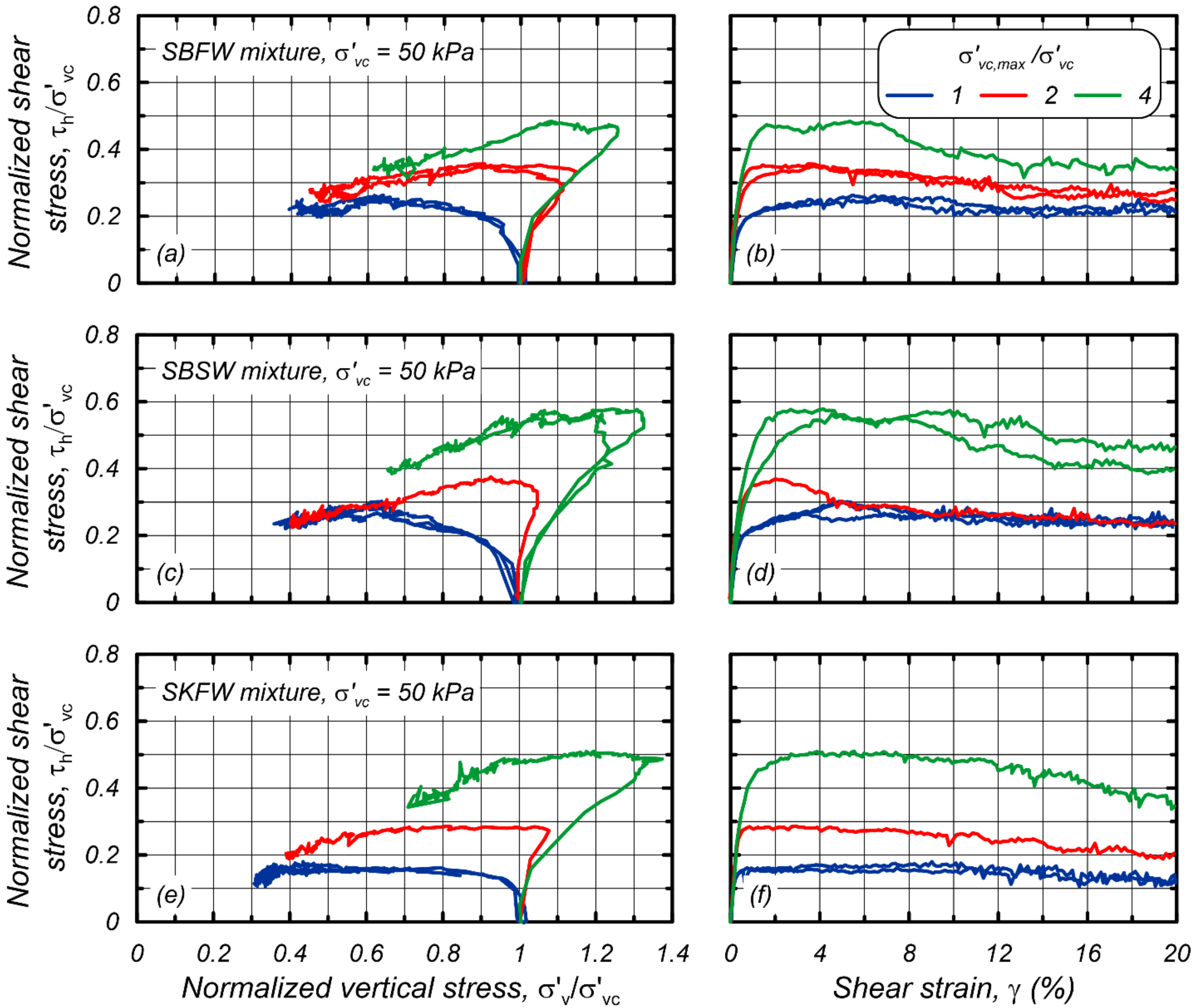


Plasticity index, PI
Liquid limit, LL
0
10
20
30
40
50
60
SBFW mixture
SBSW mixture
SKFW mixture
U-Line
A-Line
CH
CL
ML
MH
CL-ML
All three



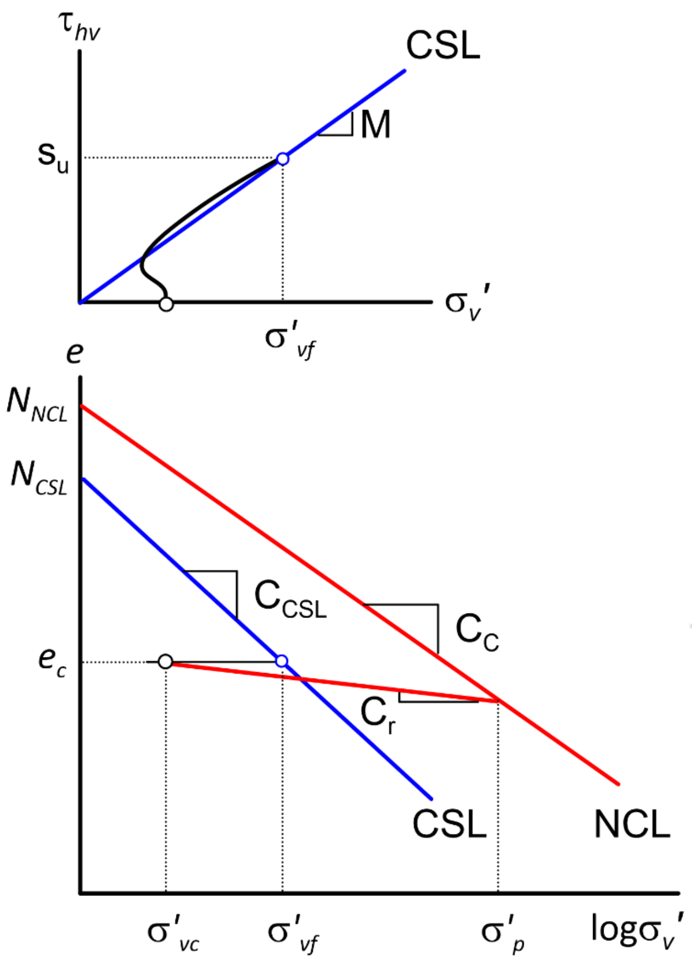


Mixture	C_c	C_r	C_k	C_α	e_{ref}	$\sigma'_{v,ref}$
SBFW	0.138	0.014	0.089	0.011	0.95	18.42
SBSW	0.145	0.008	0.079	0.008	0.88	36.9
SKFW	0.097	0.022	0.091	0.014	0.75	18.42



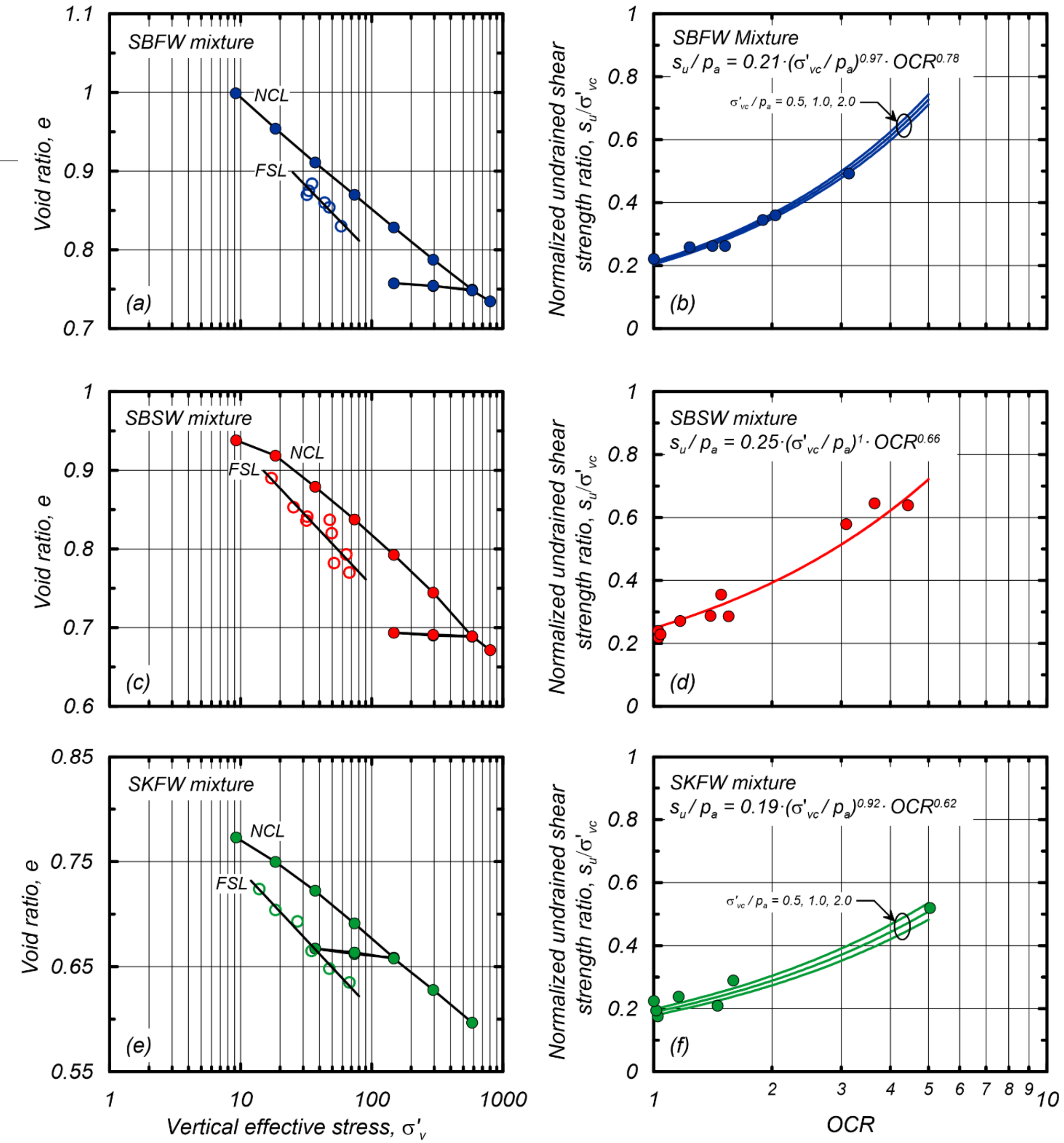
NGL NEXT GENERATION LIQUEFACTION

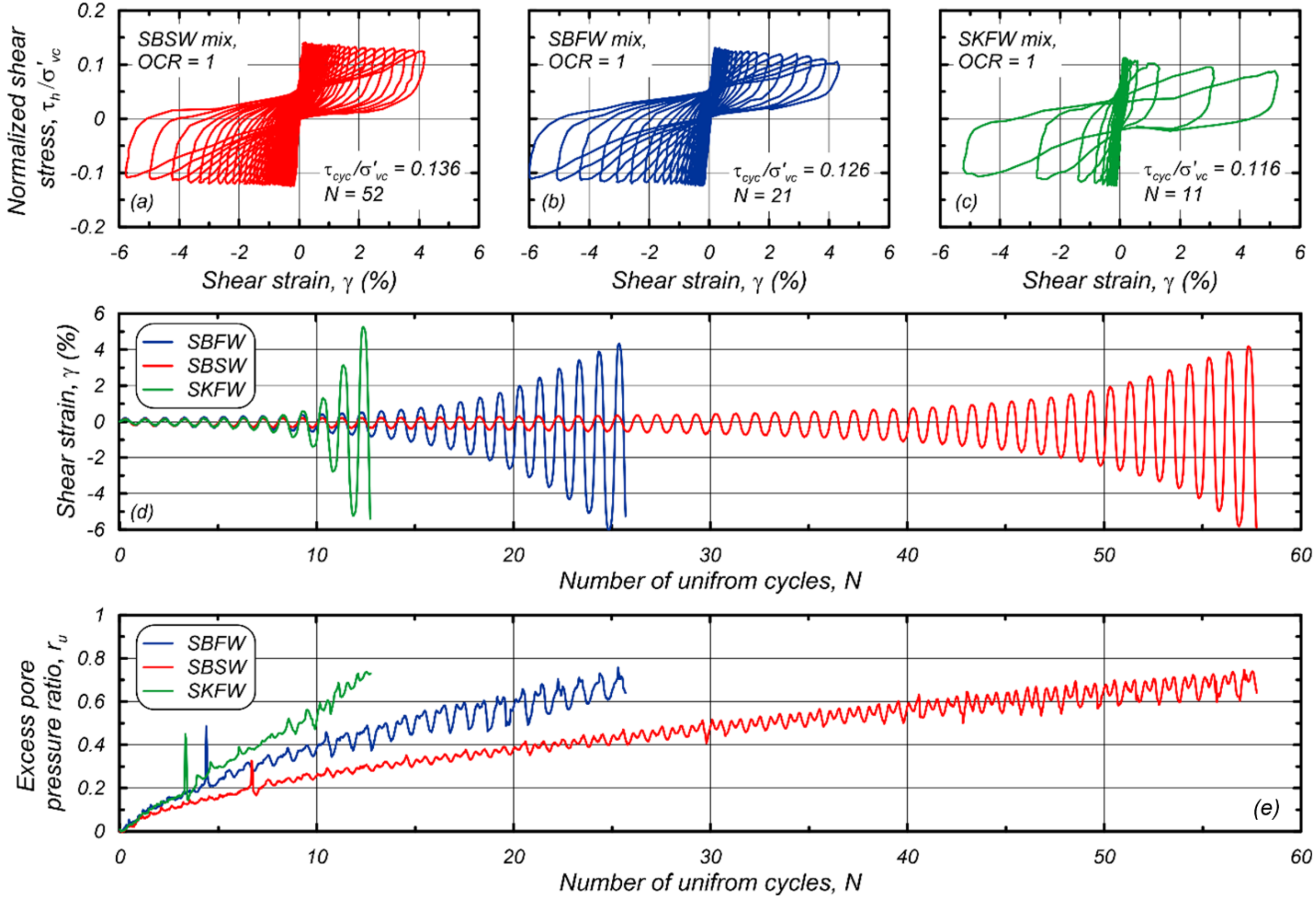
Strength Normalization



$$\frac{s_u}{p_a} = S \cdot \left(\frac{\sigma'_{vc}}{p_a}\right)^n \cdot OCR^m$$

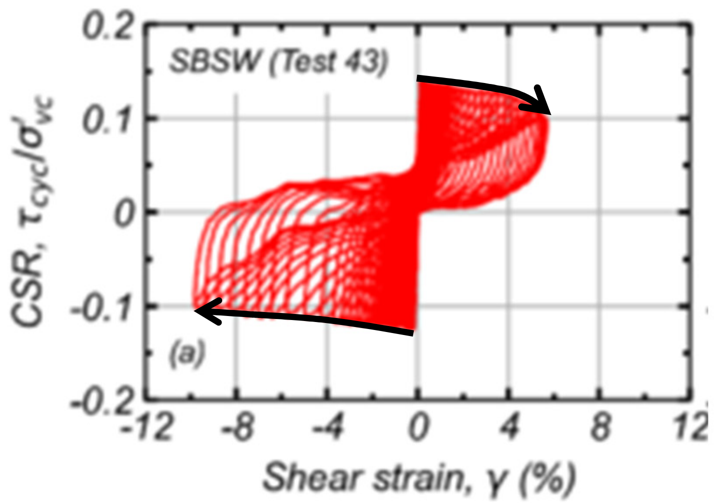
Mixture	S	n	m
SBFW	0.21	0.97	0.78
SBSW	0.25	1.00	0.66
SKFW	0.19	0.92	0.62





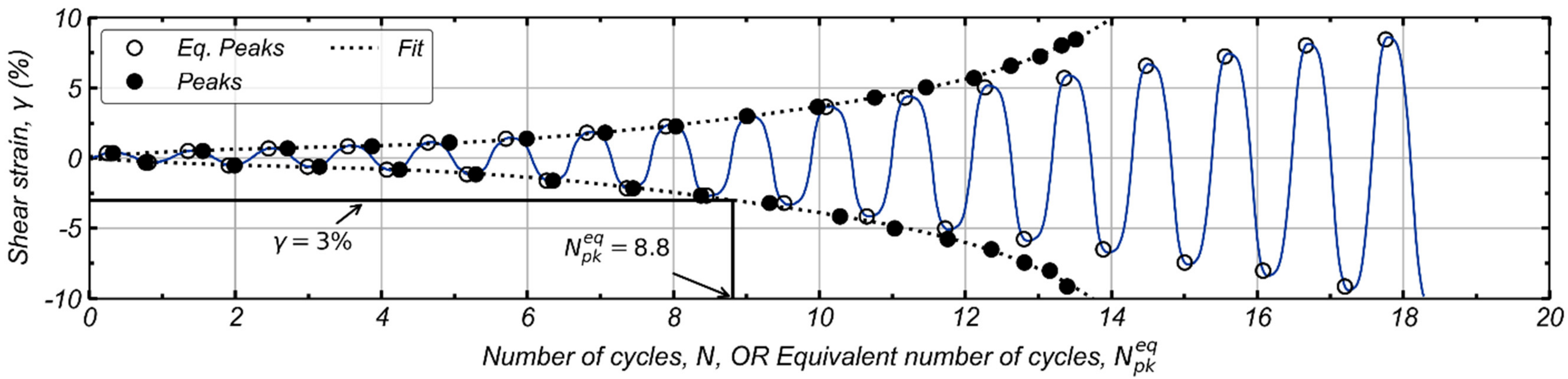
NGL NEXT GENERATION LIQUEFACTION

Cycle Counting



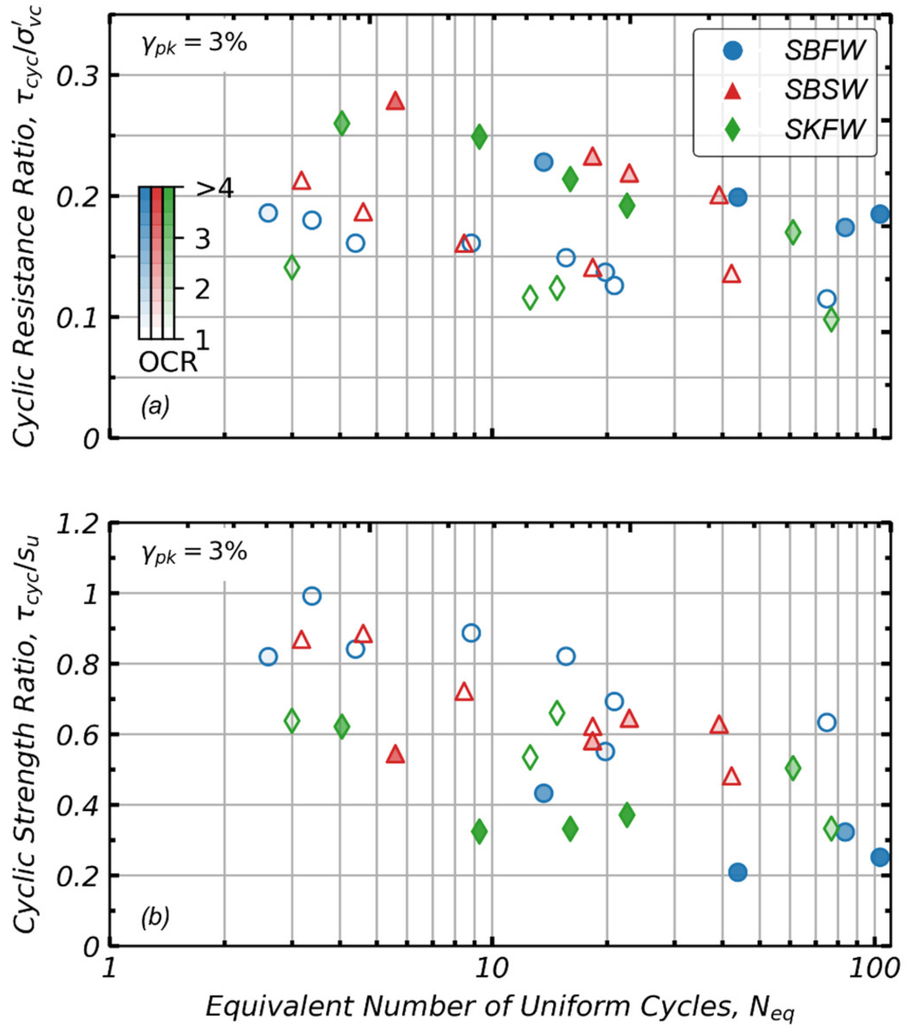
Stress amplitude often decreases as strain increases due to control system errors. CSR time series is therefore not harmonic.

$$N_{pk,i}^{eq} = \sum_{j=0}^{i} 0.5 \left(\frac{|CSR_{pk,j}|}{CRR} \right)^{1/b}$$



NGL
NEXT GENERATION LIQUEFACTION

Cyclic Strengths



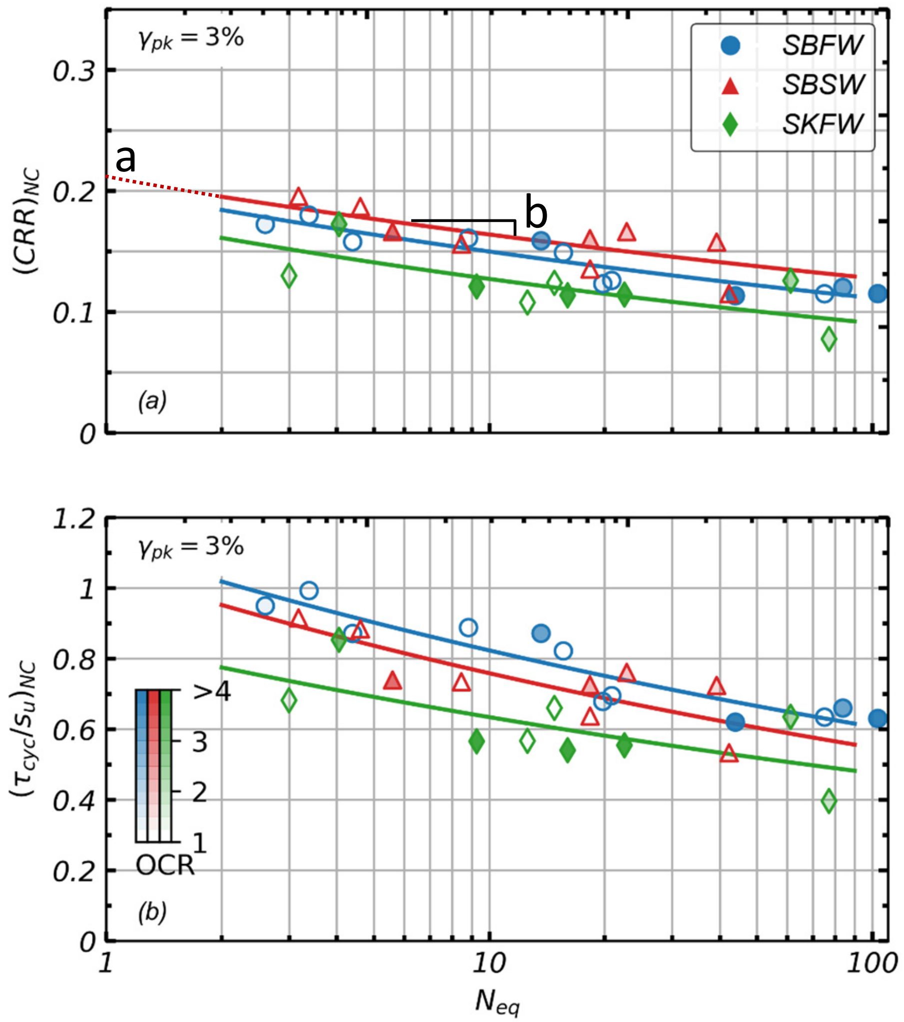
NGL
NEXT GENERATION LIQUEFACTION

Cyclic Strengths

$$(CRR)_{NC} = \frac{CRR}{OCR^c}$$

$$(\tau_{cyc}/s_u)_{NC} = \frac{\tau_{cyc}/s_u}{OCR^{c'}}$$

Mixture	a	a'	b	c	c'
SBFW	0.20	1.12	0.130	0.33	-0.64
SBSW	0.21	1.05	0.125	0.47	-0.28
SKFW	0.18	0.85	0.136	0.35	-0.27



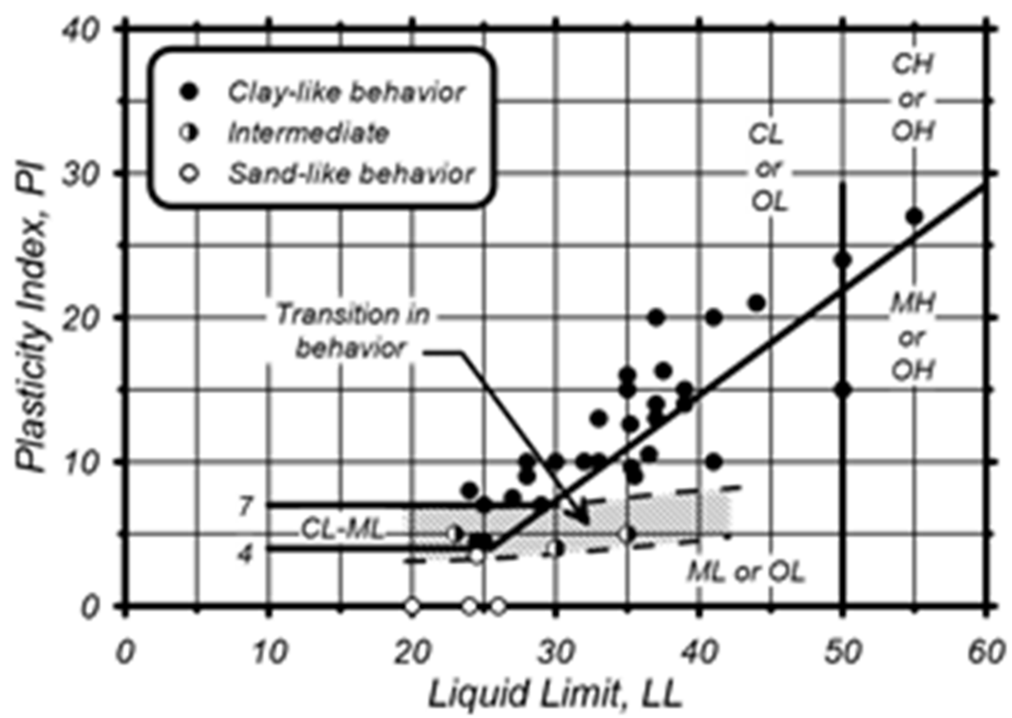
Conclusions

- Three fine-grained soils with PI between 8 and 9 different responses
- The bentonite/silt blends were more clay-like while the kaolinite blend was more sand-like
- Observing the hysteretic behavior of the soil and buildup of strain with number of cycles is the best method of ascertaining sand-like from clay-like behavior
- Evaluating whether NCL and CSL are straight and parallel provides another indicator of clay-like vs. sand-like behavior

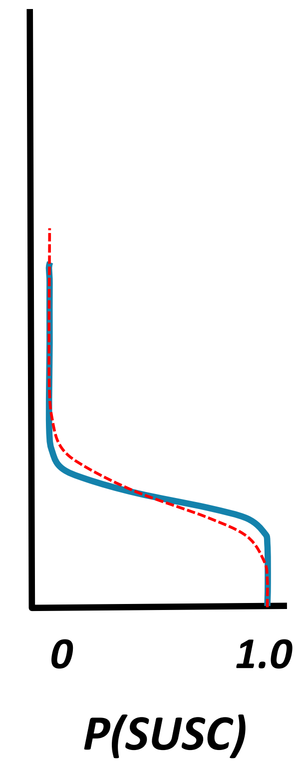
SMT Approach for Susceptibility Modelling

Probabilistic form of current, PI-based models

- Expressed as a CDF with mean & σ
- σ increased to reflect measurement variability (Phoon & Kulhawy '99)



Boulanger and Idriss, 2006



Huang, 2008

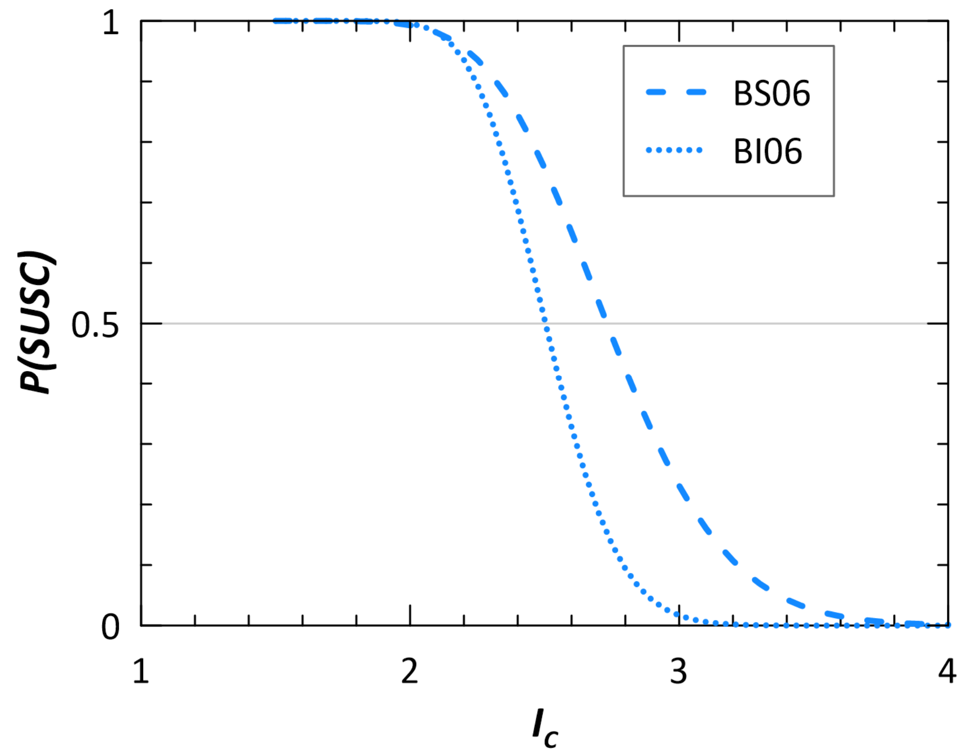
NGL NEXT GENERATION LIQUEFACTION

SMT Approach for Susceptibility Modelling

Probabilistic form of current, PI-based models

I_c-based versions of current susceptibility models

- Maurer et al. 2017
- Database of CPT data & co-located samples with index test data
- Range reflects aleatory variability from respective datasets



Adapted from Maurer et al. 2017

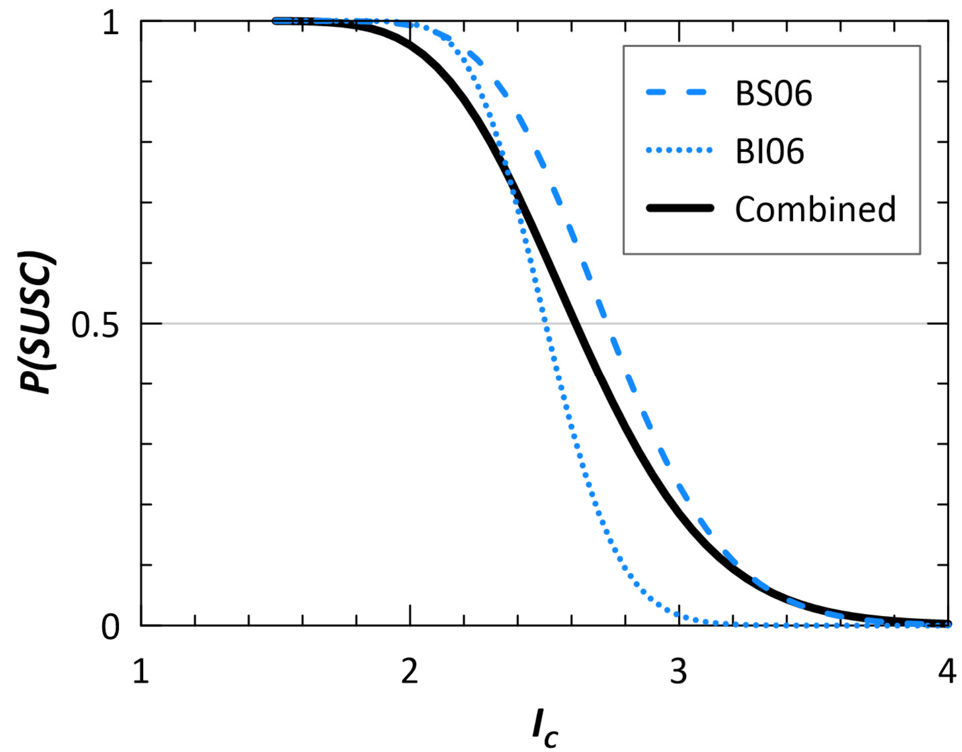
NGL NEXT GENERATION LIQUEFACTION

SMT Approach for Susceptibility Modelling

Probabilistic form of current, PI-based models

I_c-based versions of current susceptibility models

Combined model includes between-model uncertainty



NGL
NEXT GENERATION LIQUEFACTION

SMT Approach for Susceptibility Modelling

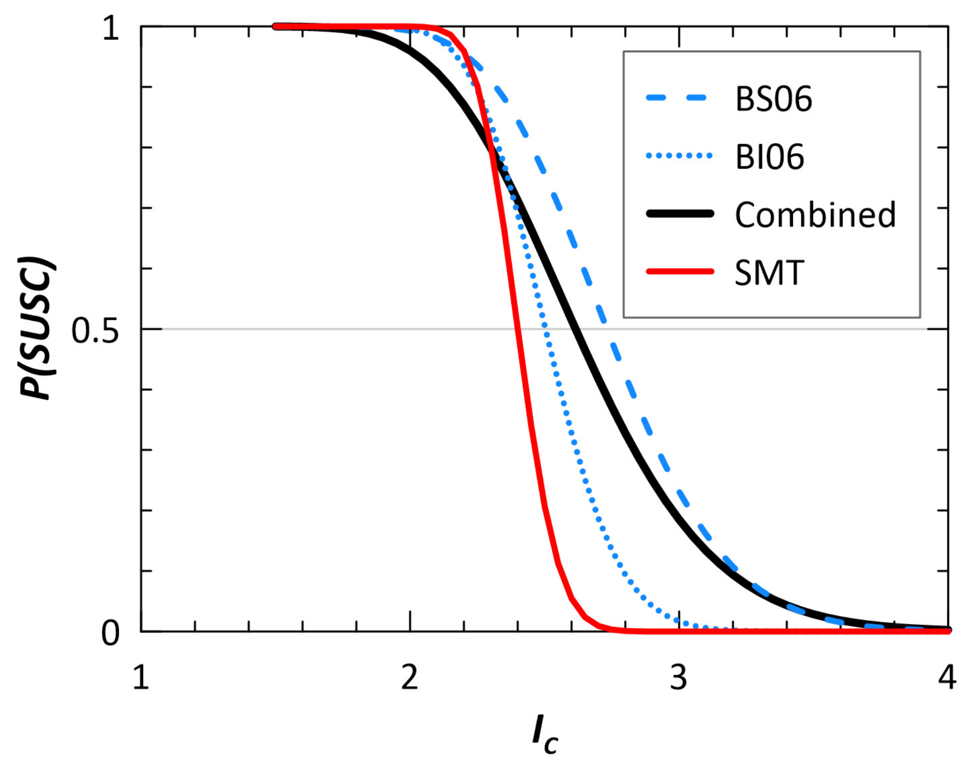
Probabilistic form of current, PI-based models

I_c-based versions of current susceptibility models

Combined model includes between-model uncertainty

SMT case history interpretation favored low-I_C critical layers

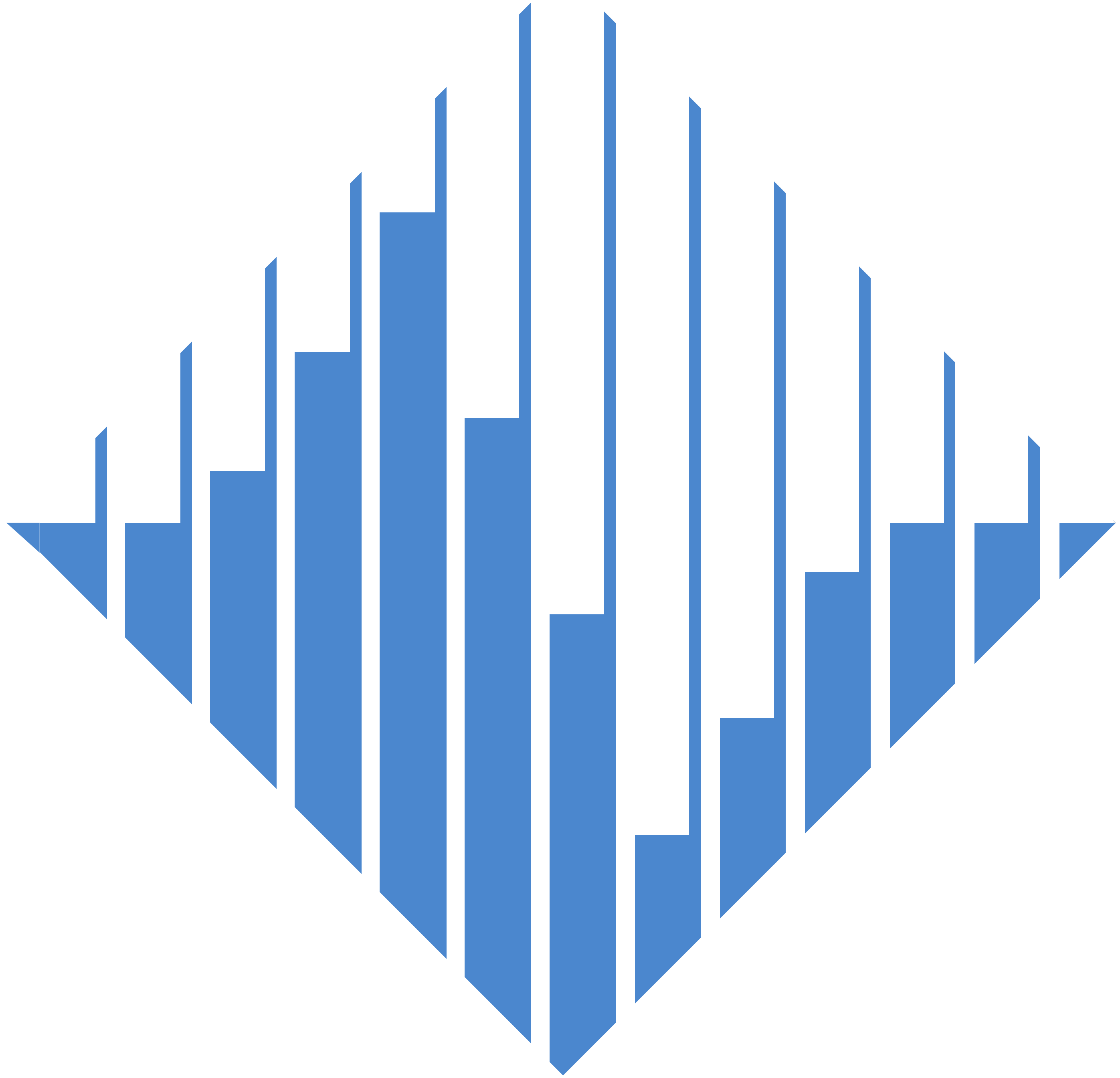
- Preliminary, for CL selection only



∴ two working SMT P(SUSC) models

NGL NEXT GENERATION LIQUEFACTION

Thank You!



Linking Hysteretic Behavior to Liquefaction Susceptibility

Armin W. Stuedlein and T. Matthew Evans

with Ali Dadashiserej, Amalesh Jana, and Susan Ortiz

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Acknowledgements

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  - National Science Foundation
  - Port of Portland
  - Cascadia Lifelines Program
  - Oregon DOT
  - Pacific Earthquake Engineering Research Center
- **Students contributing to this talk:**
  - Dr. Ali Dadashi
  - Dr. Amalesh Jana
  - Mrs. Susan Ortiz, MS

Study Sites

Largely Focused on Silts (~2016)

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Research Approach:

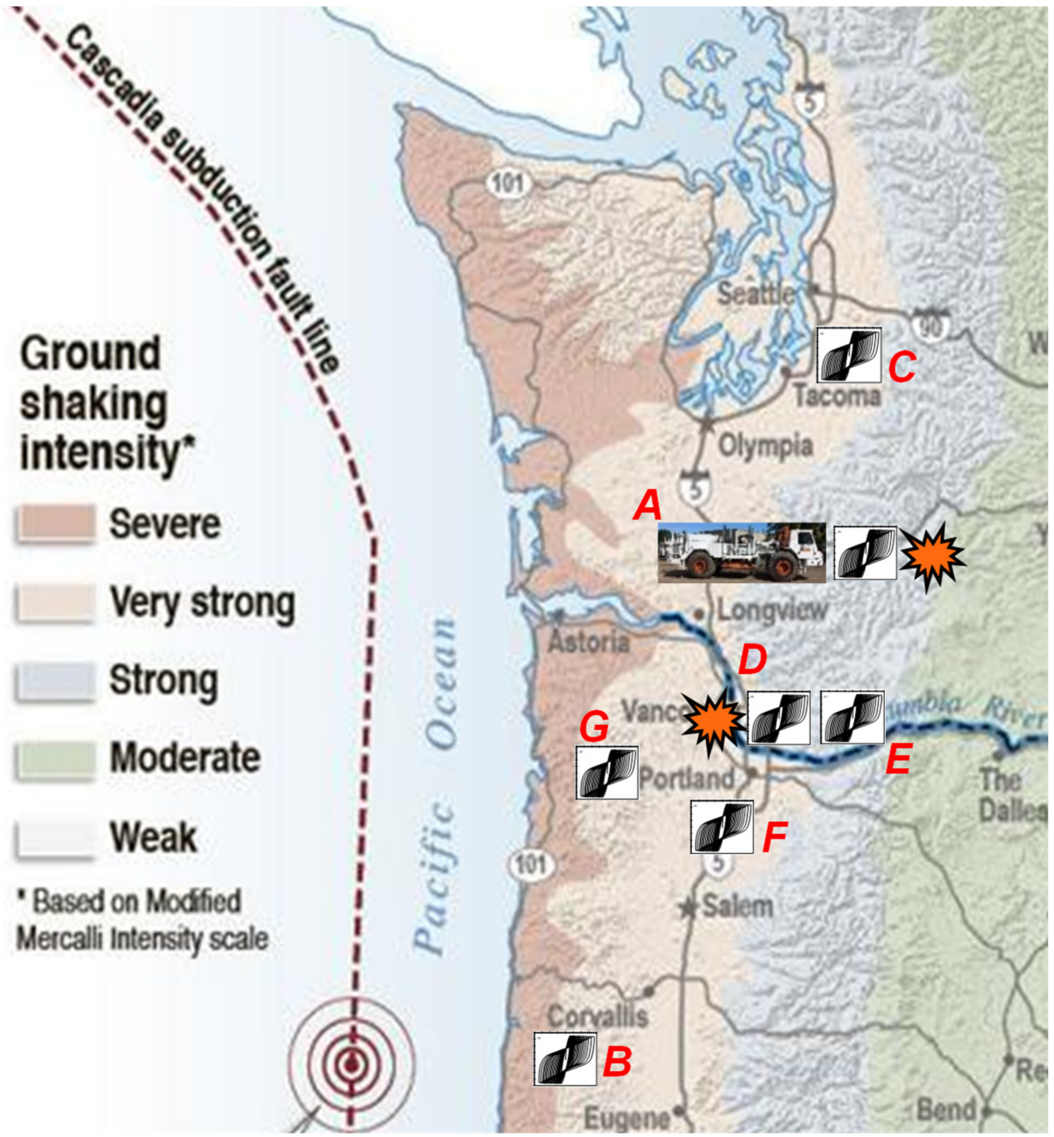
- Cyclic Direct Simple Shear Tests
- Controlled Blasting
- Vibroseis Truck, T-Rex 

Each site includes: Sampling + testing, CPT, V_s

Test Sites:

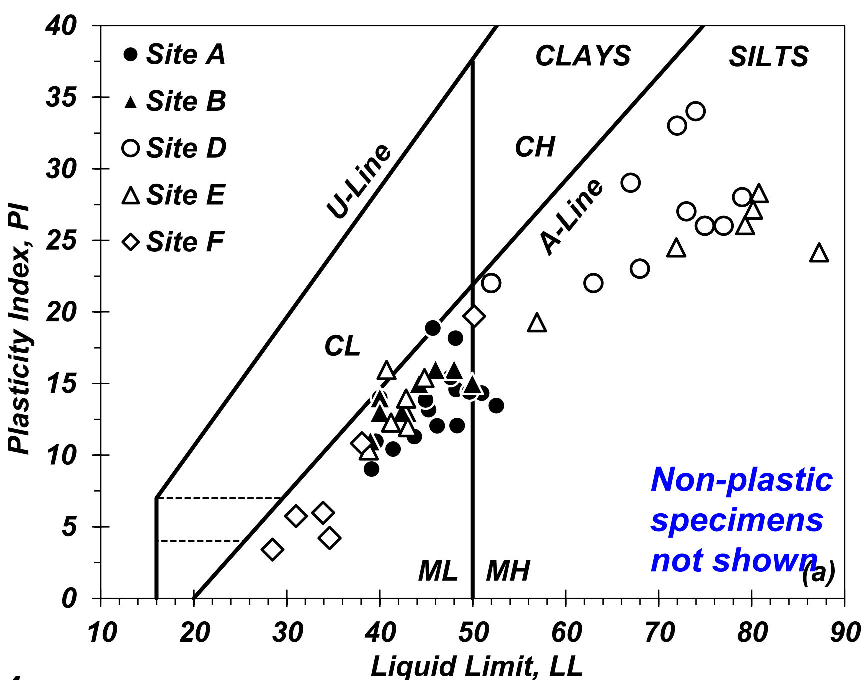
- Site A: Barlow Point, Longview, WA 
- Site B: Van Buren Bridge, Corvallis, OR
- Site D: Port of Portland, PDX, Portland, OR
- Site E: Port of Portland, PDX-TS4, Portland, OR
- Site F: Boone Bridge, Wilsonville, OR

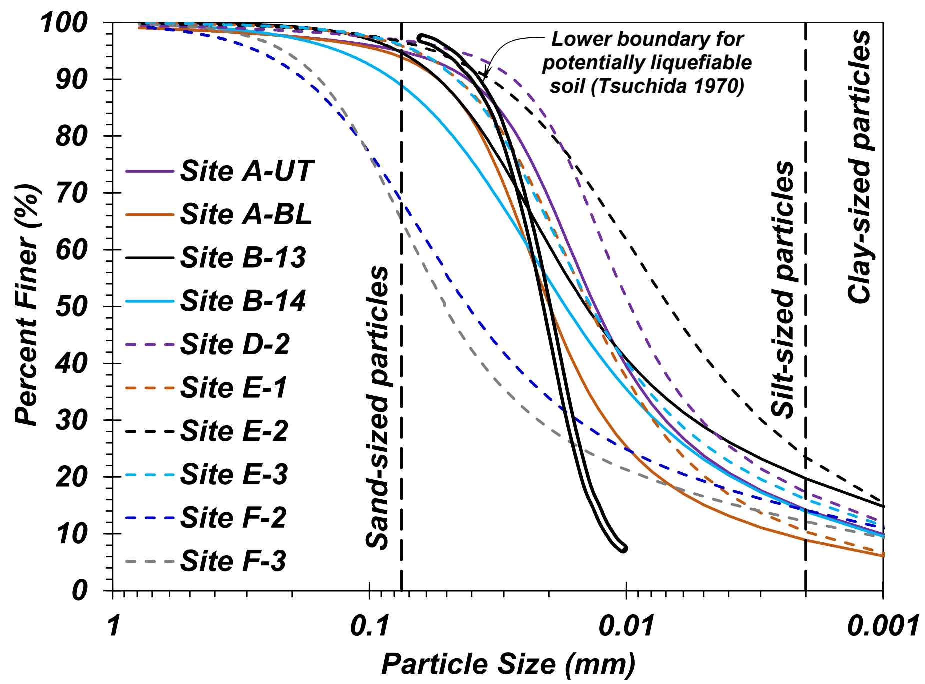
Sites C and G not included in the dataset discussed today



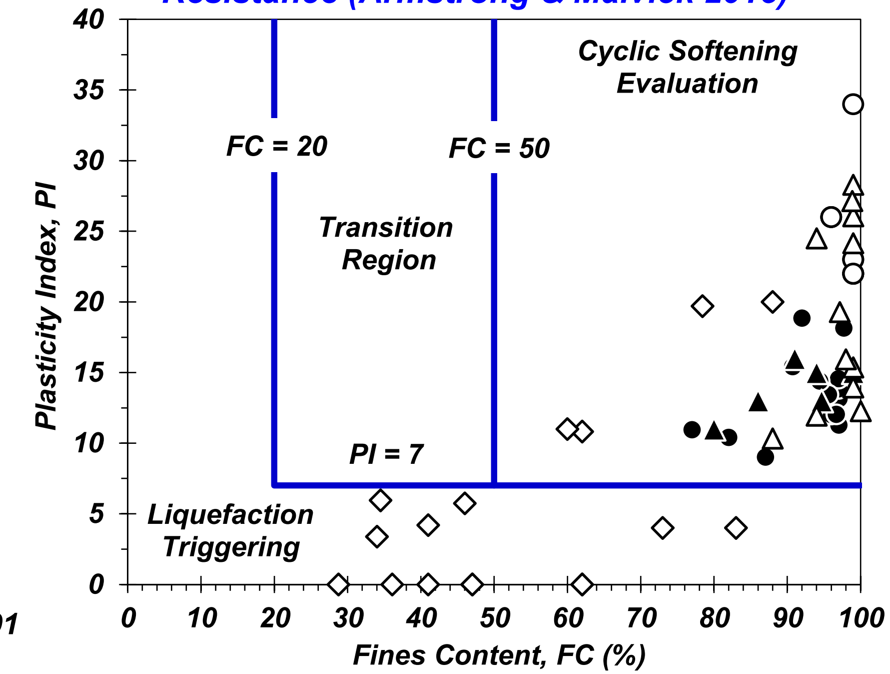
Materials Investigated

- The data presented today consists of natural, intact specimens consolidated to σ'_{v0} with some artificially NC specimens, only
- Well-graded silty sands to sandy silts and clayey silts
- ***PI***s range from 0 to 39, ***LL***s from 28 to 70
- ***OCR***s range from 1 to 4.2



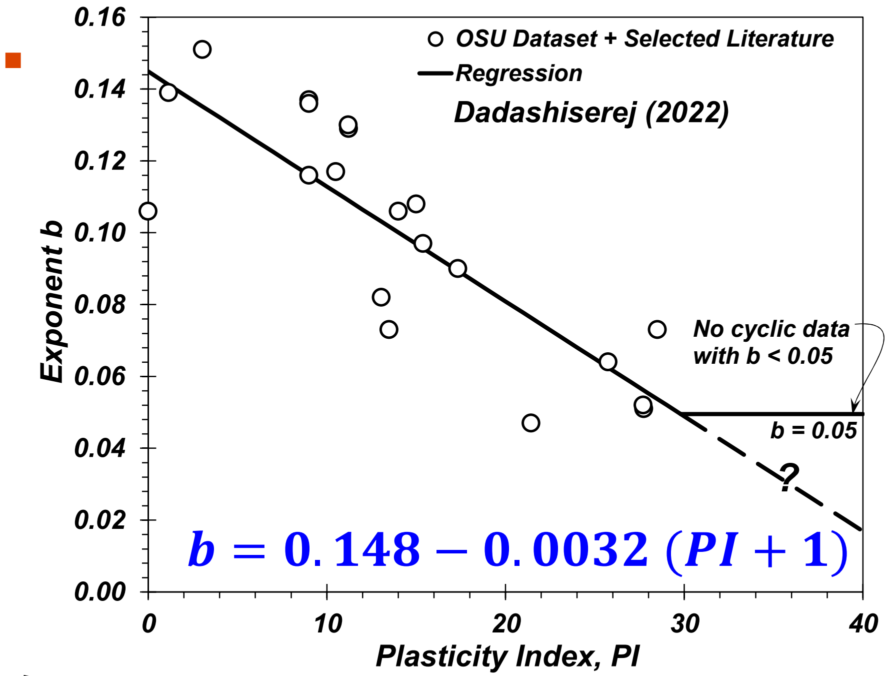


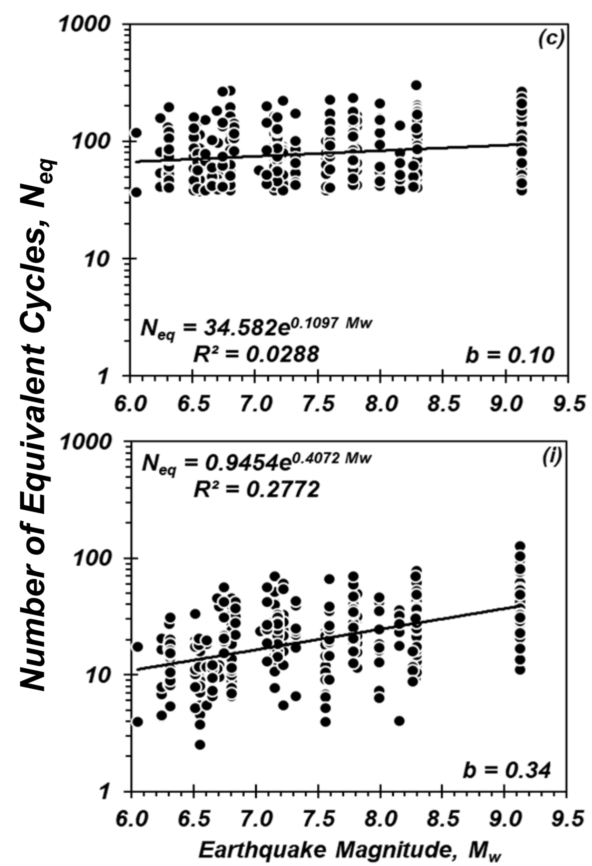
Suggested Regions for Evaluation of Cyclic Resistance (Armstrong & Malvick 2015)

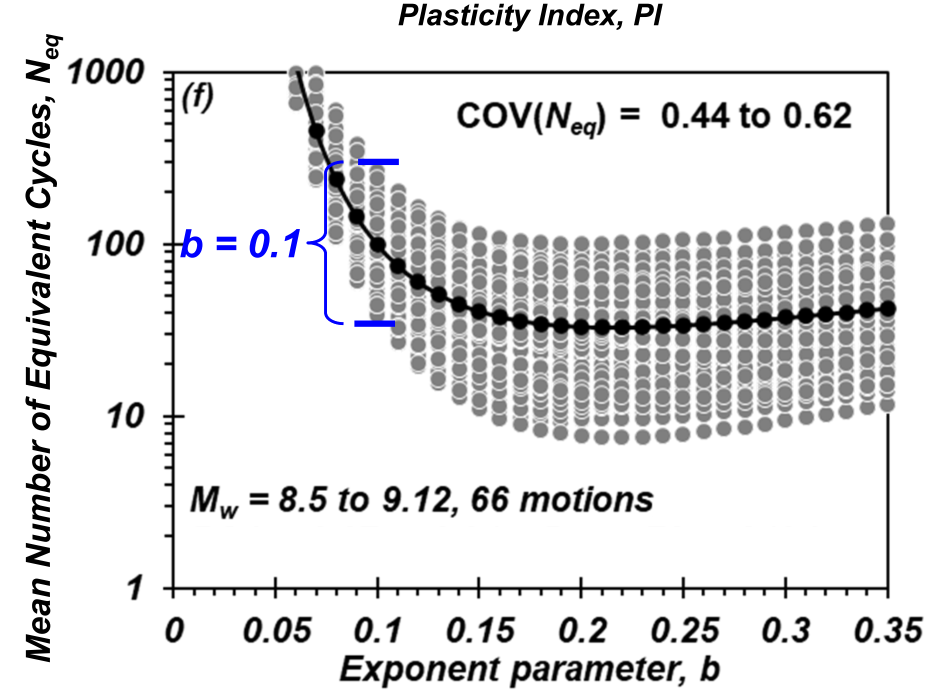


Subduction Zone Earthquakes… = Large N_{eq}

- Resistance: $CRR(N_{\gamma=3\%}) = \frac{\tau_{cyc}}{\sigma'_{v0}} = a \cdot N^{-b}$
- Curvature of the power law driven by ***PI*** → number of loading cycles driven by ***PI***
- Effect of ***b*** on N_{eq} assessed using motions screened from *NGASub* database
- For typical ***b*** = 0.1 (low ***PI*** silts), M_w = 9.0, N_{eq} ranges from *40* to *300*, w/ means of:
  - $M_w = 9.0$: $N_{eq} \approx 93$
  - $M_w = 7.5$: $N_{eq} \approx 75$

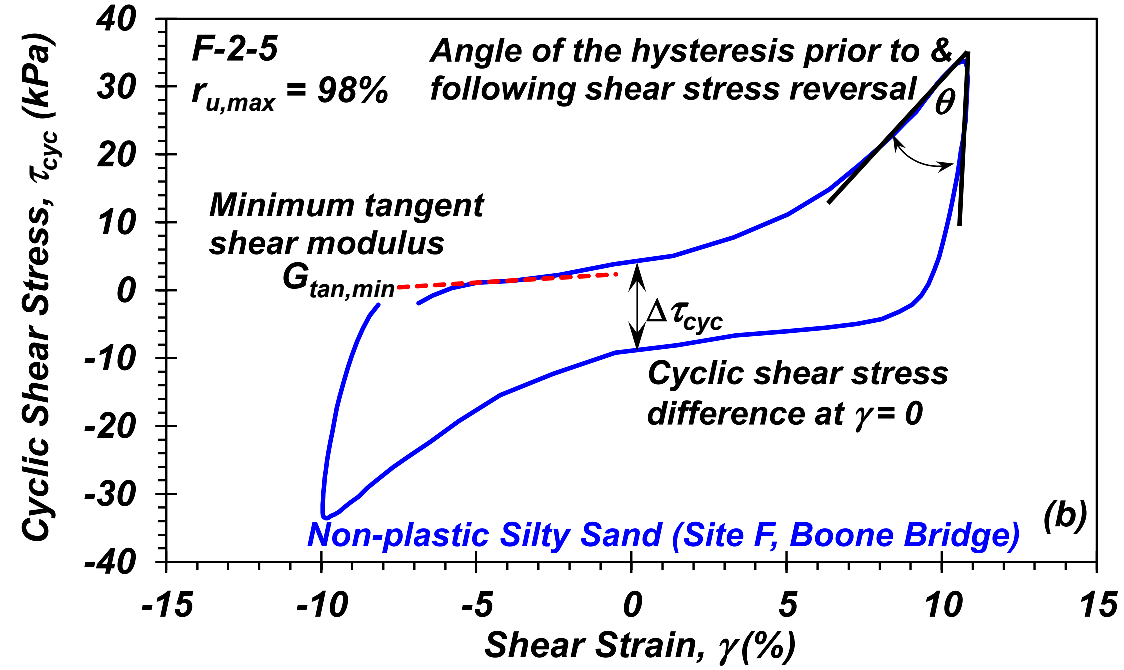






Stuedlein et al. (2021)

Linking Hysteretic Behavior Liquefaction Susceptibility



- We can quantify certain hysteretic metrics for an objective assessment of behavior:
  - Angle of γ-τ_{cyc} hysteresis prior to & following unloading
  - Cyclic shear stress difference at γ= 0, $\Delta\tau_{cyc}$
  - Minimum tangent shear modulus, $G_{tan,min}$
  - Maximum excess pore pressure generated, $r_{u,max}$
- Can assess differences between $N_{\gamma=3\%}$ and N_{max} (γ_{max} > 5%)

Potential bias through CSR; hence Normalize by $\tau_{cyc,max}$:

- $\Delta\tau_{cyc}/\tau_{cyc,max}$

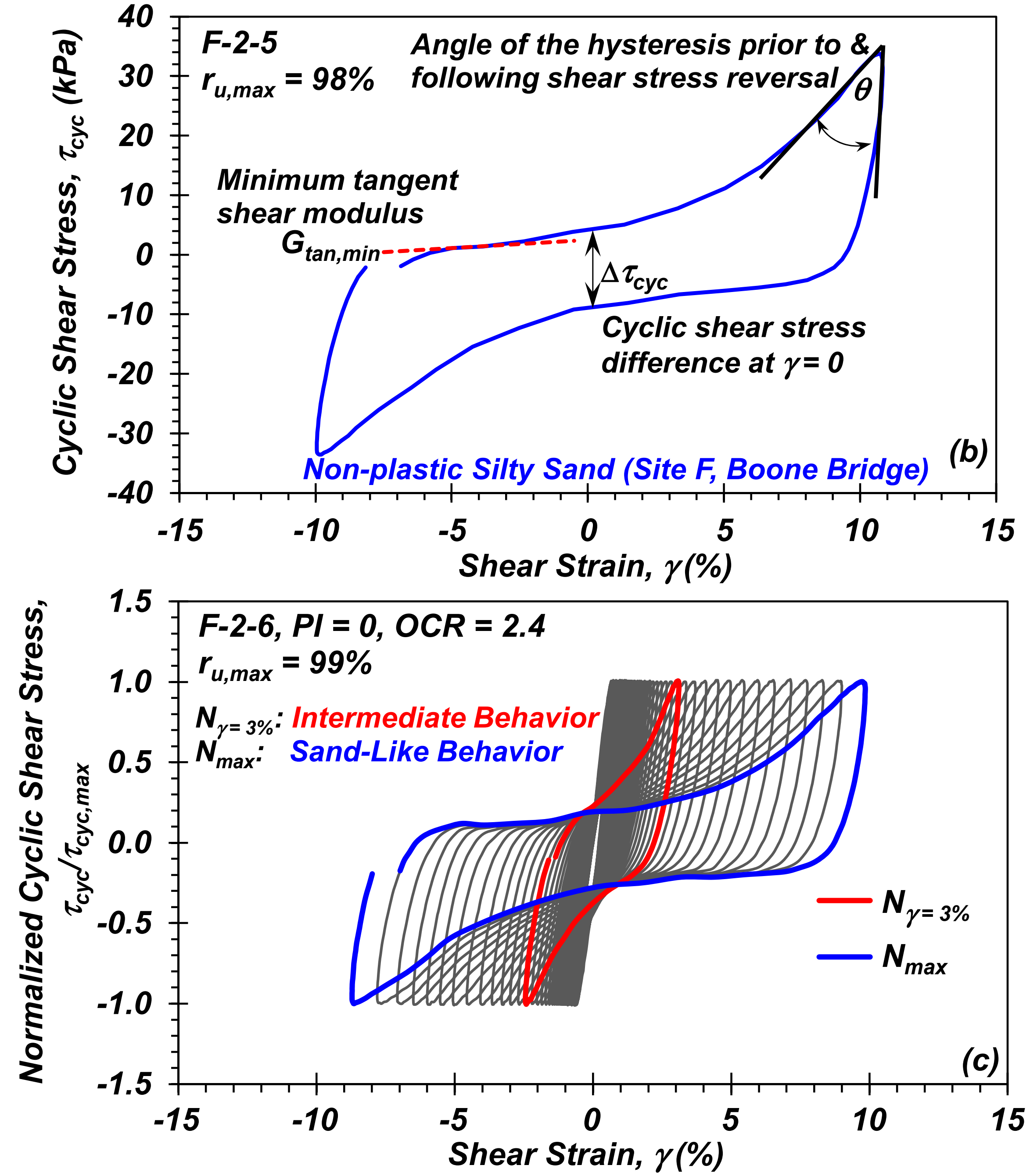
- $G_{tan,min}/\tau_{cyc,max}$

**** Will largely focus on $r_{u,max}$ and $G_{tan,min}/\tau_{cyc}$***

Linking Hysteretic Behavior Liquefaction Susceptibility

Example behaviors @ $N_{\gamma=3\%}$ and N_{max}

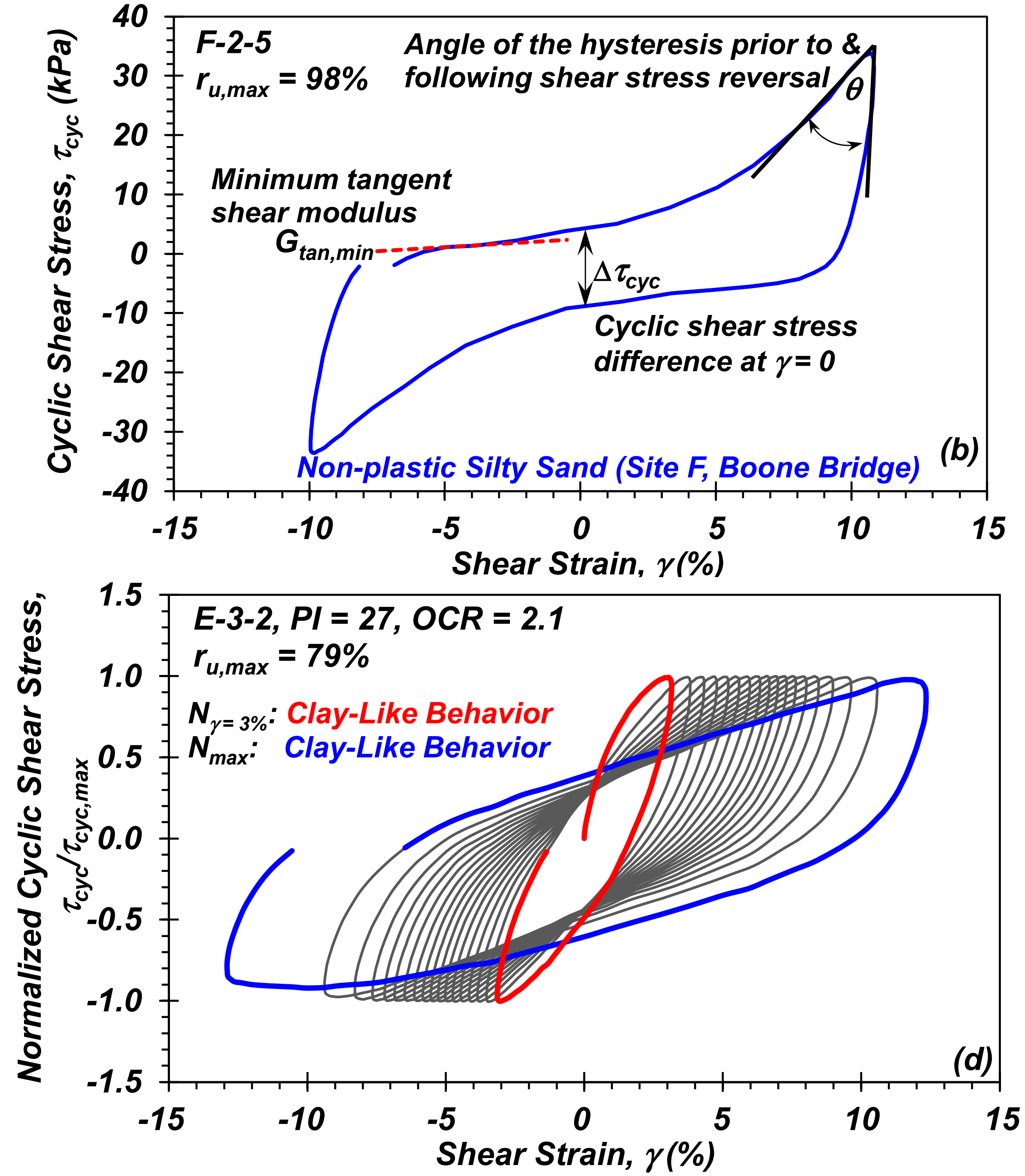
Specimen	Behavior		$r_{u,max}$ (%)		$G_{tan,min}/\tau_{cyc,max}$		$\Delta\tau_{cyc}/\tau_{cyc,max}$	
	$N_{\gamma=3\%}$	N_{max}	$N_{\gamma=3\%}$	N_{max}	$N_{\gamma=3\%}$	N_{max}	$N_{\gamma=3\%}$	N_{max}
F-2-6	Interm.	Sand	93	99	10.12	0.00	0.60	0.47



Linking Hysteretic Behavior Liquefaction Susceptibility

Example behaviors @ $N_{\gamma=3\%}$ and N_{max}

Specimen	Behavior		$r_{u,max}$ (%)		$G_{tan,min}/\tau_{cyc,max}$		$\Delta\tau_{cyc}/\tau_{cyc,max}$	
	$N_{\gamma=3\%}$	N_{max}	$N_{\gamma=3\%}$	N_{max}	$N_{\gamma=3\%}$	N_{max}	$N_{\gamma=3\%}$	N_{max}
F-2-6	Interm.	Sand	93	99	10.12	0.00	0.60	0.47
E-3-2	Clay	Clay	8	79	20.41	1.26	0.76	1.00

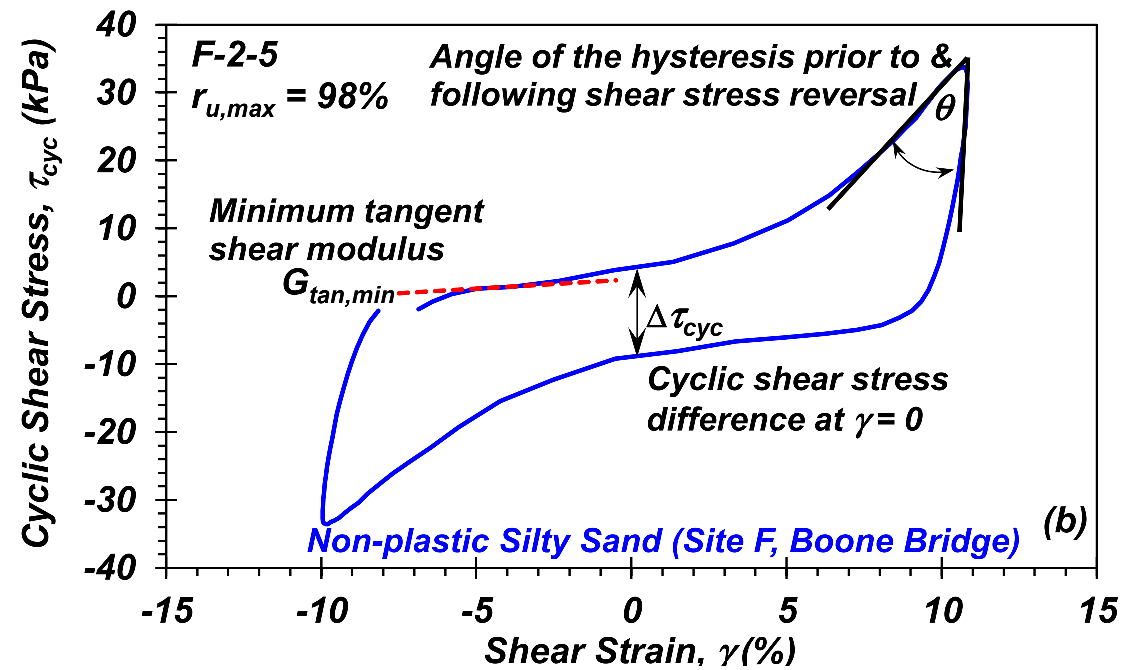


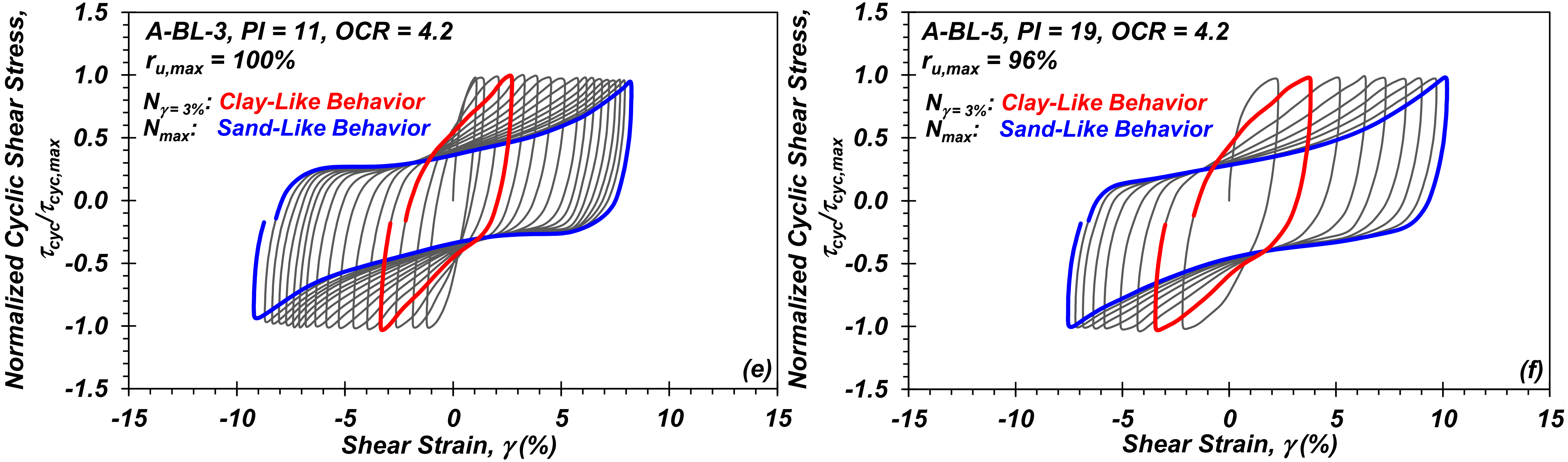
Stuedlein et al. (2023), Dadashiserej (2022)

Linking Hysteretic Behavior Liquefaction Susceptibility

Example behaviors @ $N_{\gamma=3\%}$ and N_{max}

Specimen	Behavior		$r_{u,max}$ (%)		$G_{tan,min}/\tau_{cyc,max}$		$\Delta\tau_{cyc}/\tau_{cyc,max}$	
	$N_{\gamma=3\%}$	N_{max}	$N_{\gamma=3\%}$	N_{max}	$N_{\gamma=3\%}$	N_{max}	$N_{\gamma=3\%}$	N_{max}
F-2-6	Interm.	Sand	93	99	10.12	0.00	0.60	0.47
E-3-2	Clay	Clay	8	79	20.41	1.26	0.76	1.00
A-BL-3	Clay	Sand	79	100	12.01	0.04	0.85	0.71
A-BL-5	Clay	Sand	62	96	9.74	1.93	1.03	0.74





Observed Field Behavior

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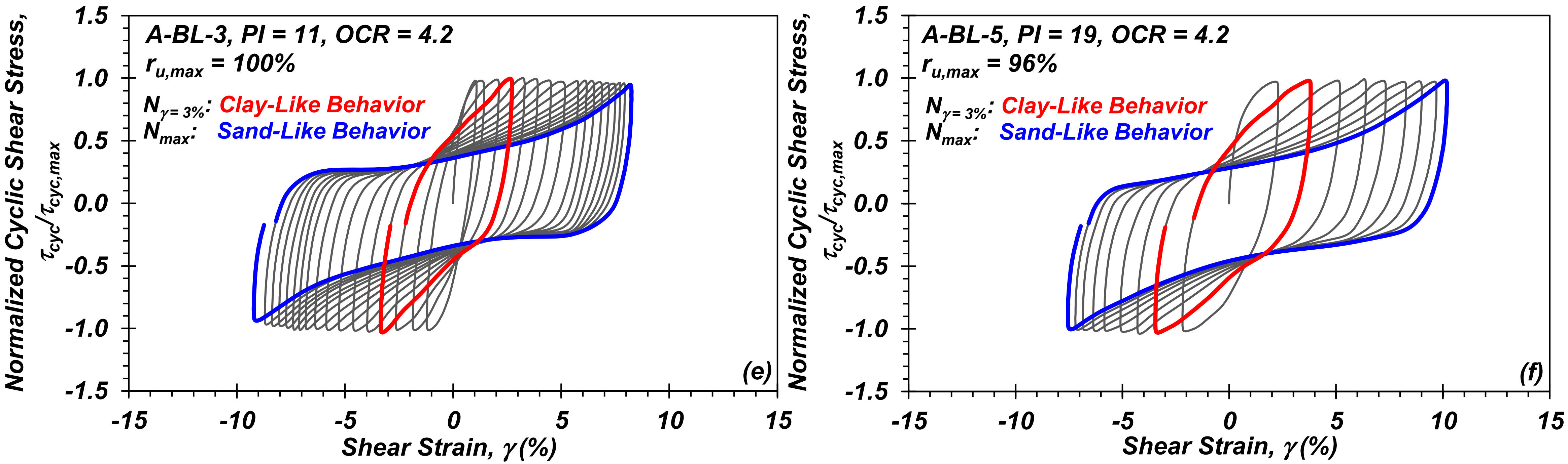
Field Response?



Observed Field Behavior

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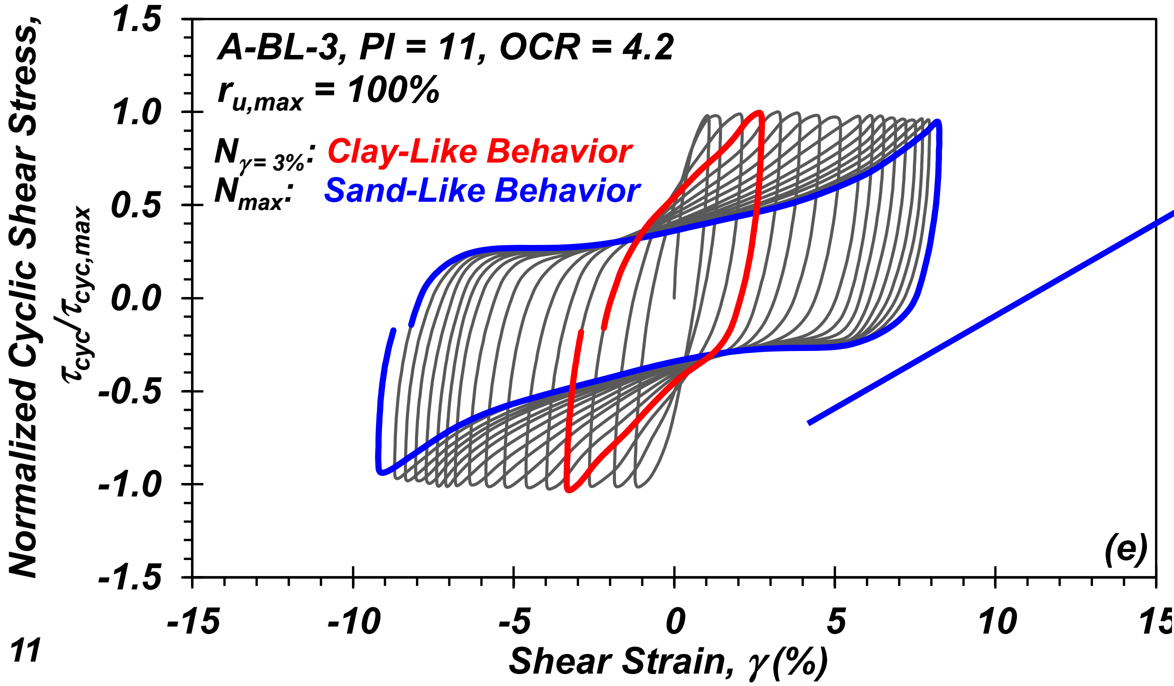
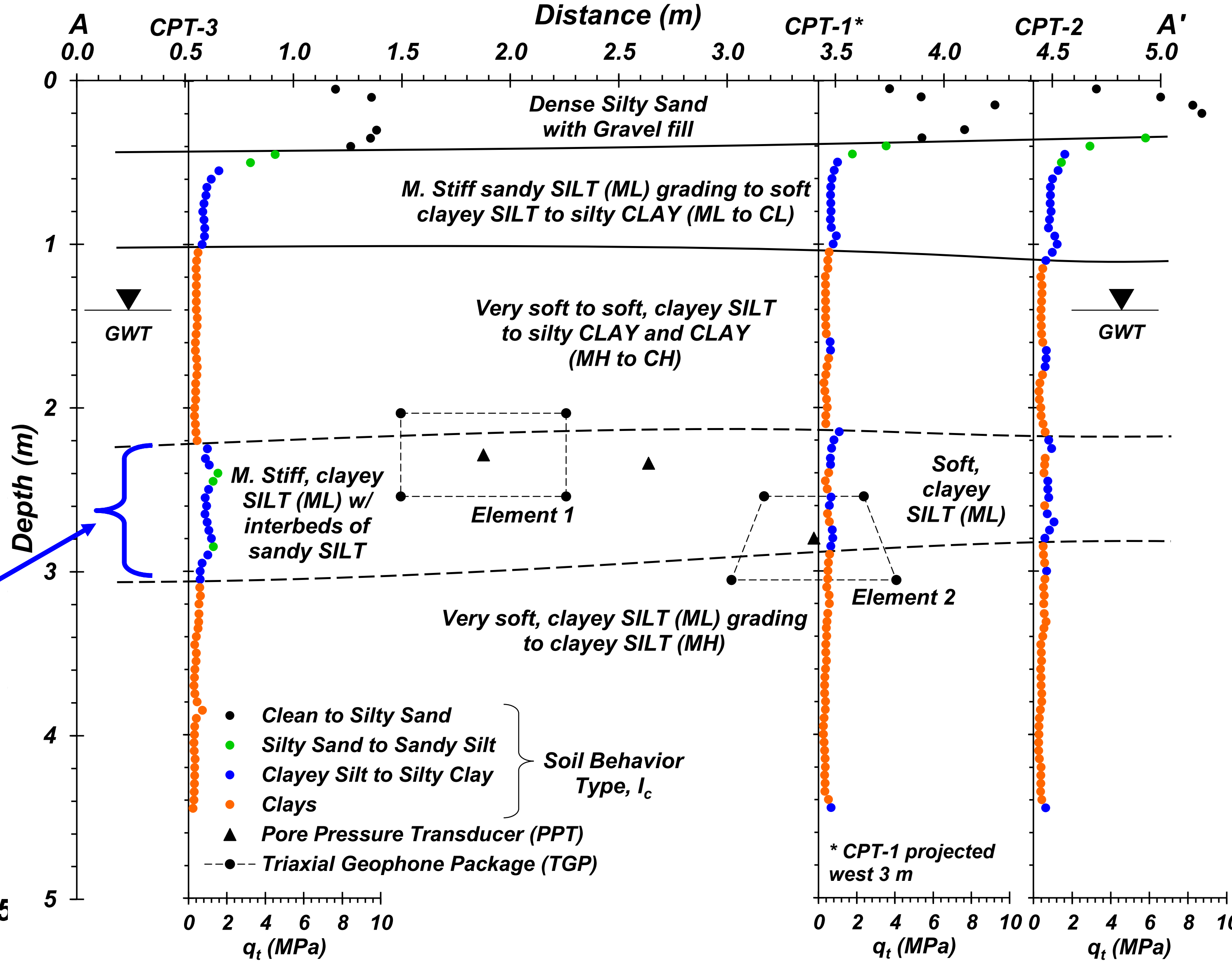
Field Response?

- Specimen from the OSU Blast Array, Port of Longview, WA

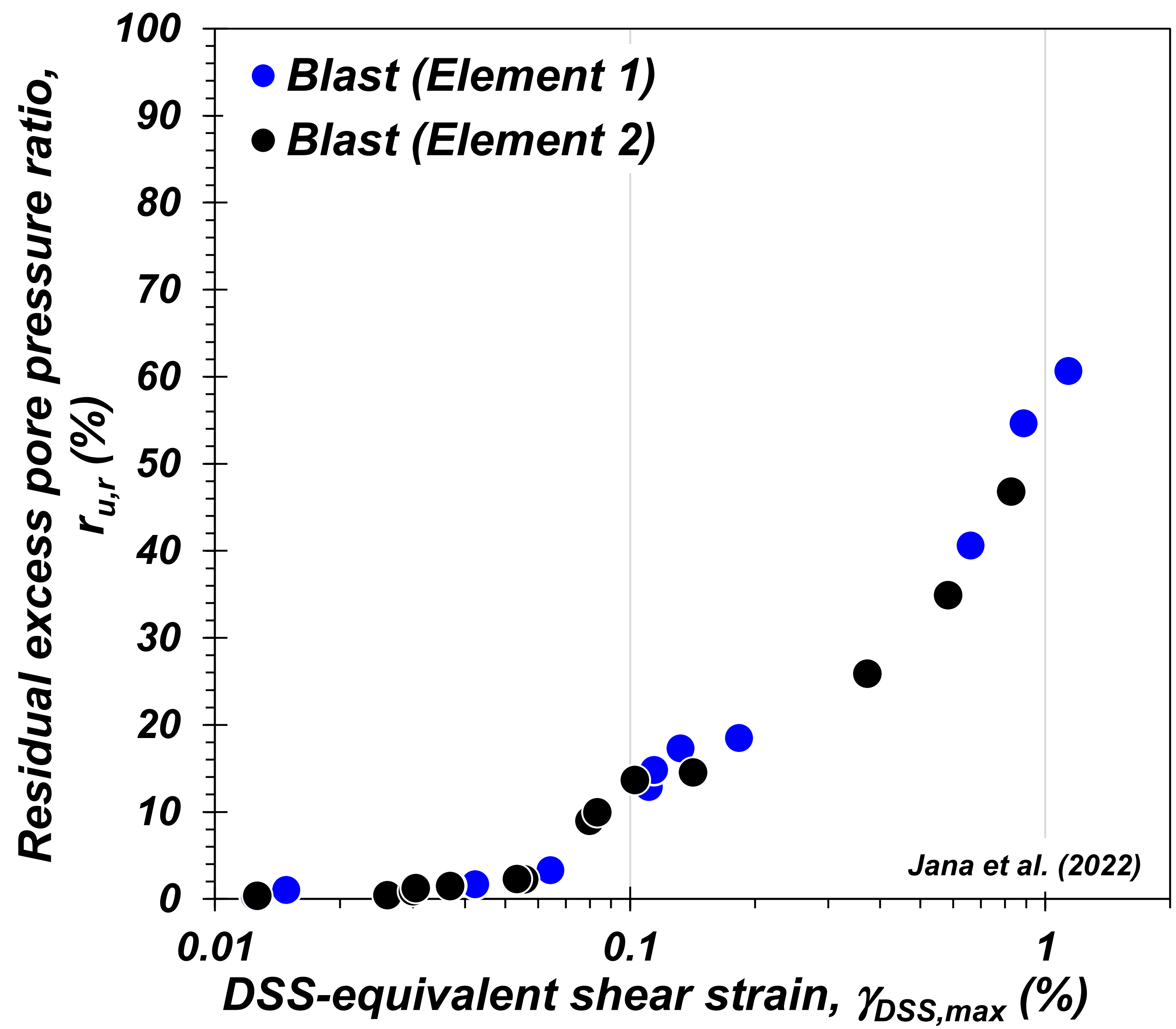




Observed Field Behavior

Field Response?

- Specimen from the OSU Blast Array, Port of Longview, WA
- Consider the *in-situ* performance of this material (controlled blasting; Jana et al. 2022)
- Excess pore pressures rise sharply with shear strain until drainage initiates; and,



Observed Field Behavior

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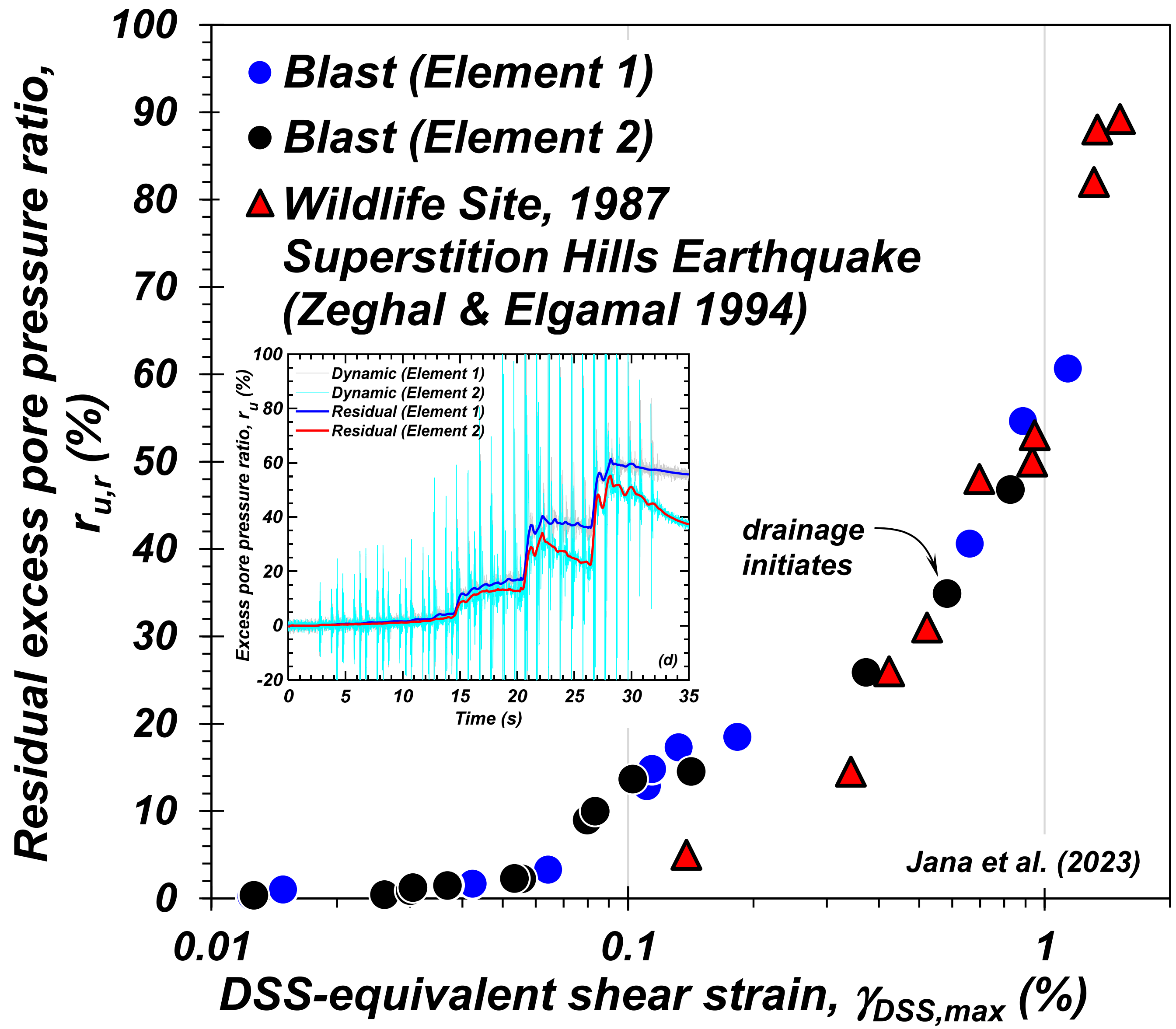
Field Response?

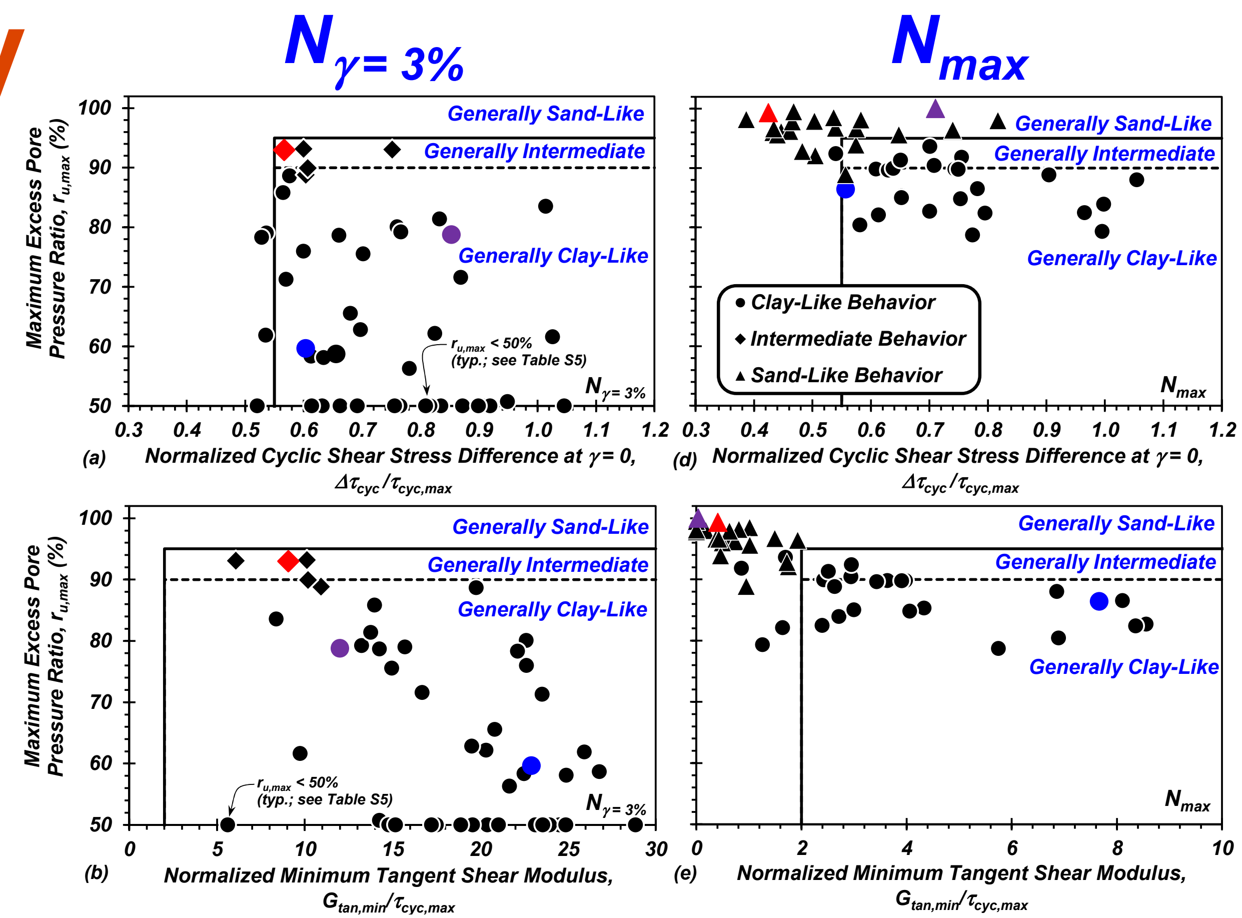
- Specimen from the OSU Blast Array, Port of Longview, WA
- Consider the *in-situ* performance of this material (controlled blasting; Jana et al. 2022)
- Excess pore pressures rise sharply with shear strain until drainage initiates; and,
- Appears to track the response of the Wildlife Array (silty sand)



Proposed Hysteretic Metrics for Liquefaction Susceptibility

Stuedlein et al. (2023), Dadashiserej (2022)

- No specimens exhibited Sand-Like behavior at $N_{\gamma=3\%}$
- Hysteretic behavior evolves following exceedance of $\gamma = 3\%$ for many specimens: *clay-like and intermediate* → **sand-like**



Clay-Like behavior suggested for:

$r_{u,max} < 90\%$, $G_{tan,min}/\tau_{cyc,max} \gtrapprox 2$, $\Delta\tau_{cyc}/\tau_{cyc,max} \gtrapprox 0.55$

Intermediate behavior suggested for:

$90 \lessapprox r_{u,max} < 95\%$, $G_{tan,min}/\tau_{cyc,max} \gtrapprox 2$, $\Delta\tau_{cyc}/\tau_{cyc,max} \gtrapprox 0.55$

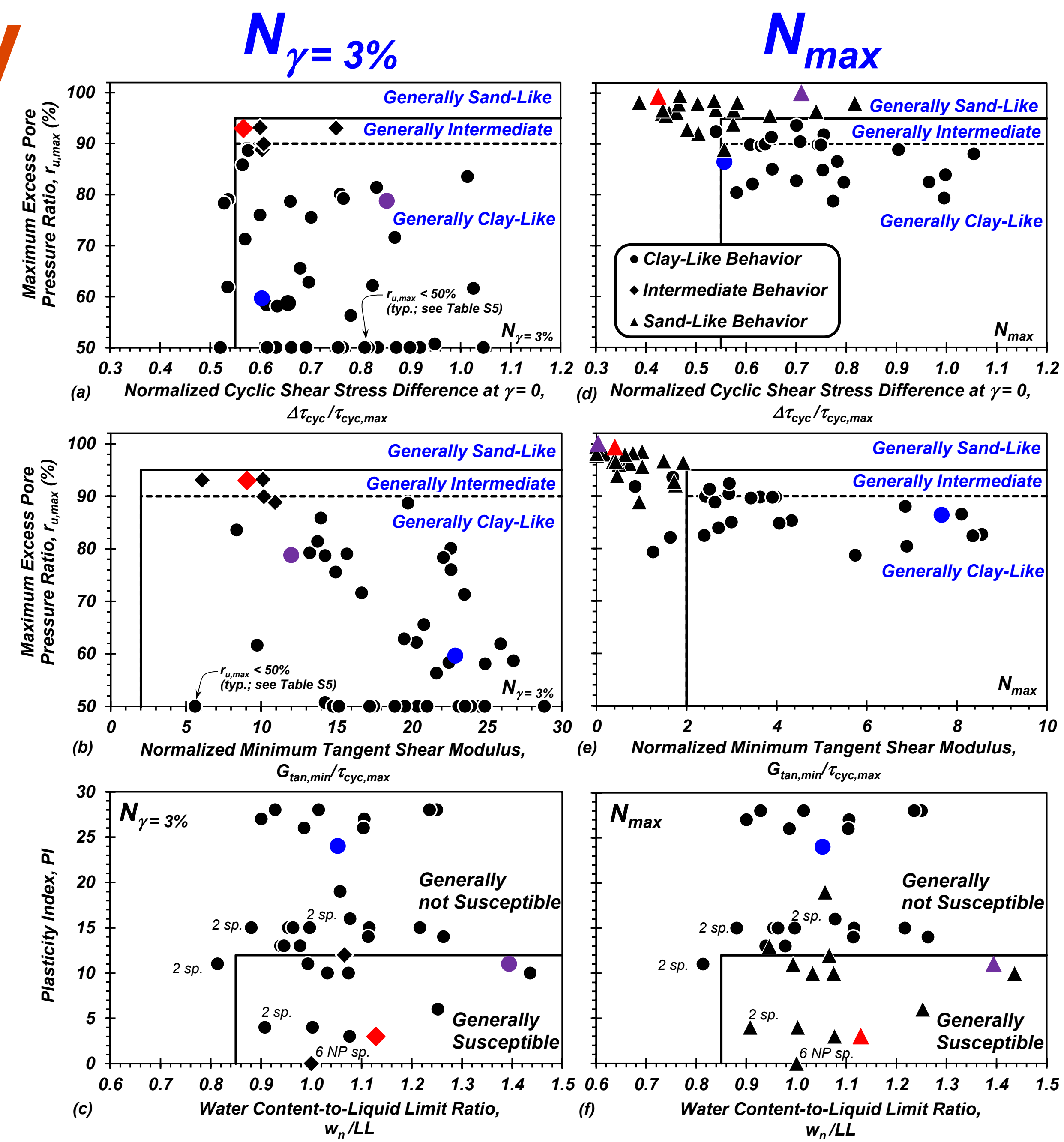
Sand-Like behavior suggested for:

$r_{u,max} > 95\%$ and $G_{tan,min}/\tau_{cyc,max} \lessapprox 2$, $\Delta\tau_{cyc}/\tau_{cyc,max} < 0.55$

Proposed Hysteretic Metrics for Liquefaction Susceptibility

Stuedlein et al. (2023), Dadashiserej (2022)

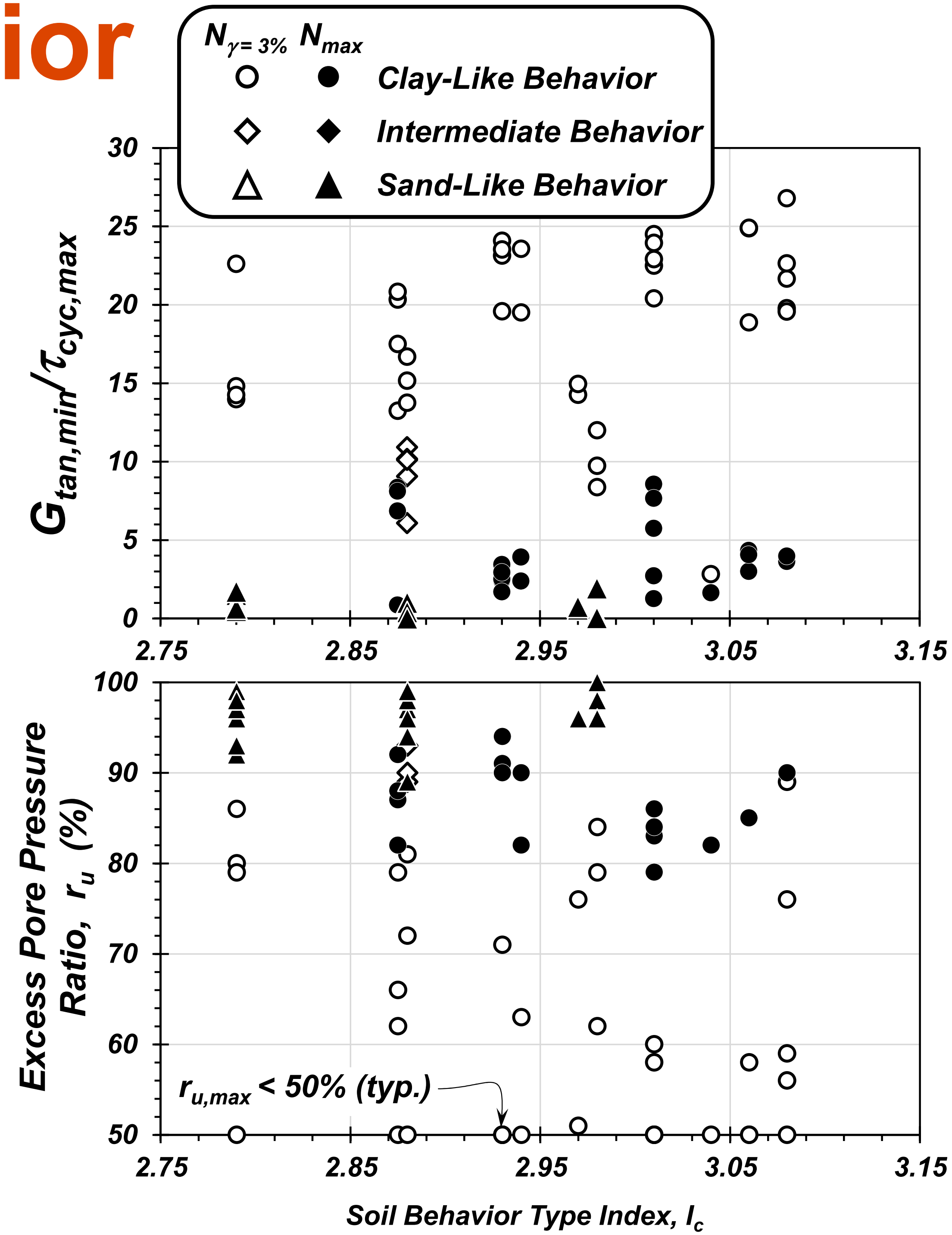
- What if you don't have cyclic test data?
- Modified Bray and Sancio (2006) seemed to *generally* capture large-strain cyclic behavior
- PI ≲ 12, w_c/LL ≳ 0.85: generally exhibits ultimate sand-like behavior
- What about CPT-based indications?



Comparison to Soil Behavior Type Index

- CPTs generally located within 2 to 3 m of borehole
- Geometric average of I_c over sample interval from which specimen derived
- For the soils in our database, I_c does not correlate to ultimate hysteretic behavior at large strain (γ > 5%)
- Transient liquefaction observed for as large as $I_c \approx 2.95$

CPT-Assessments from Ortiz (2022)



Concluding Remarks

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- Ultimate hysteretic behavior may not be apparent for typical cyclic shear strain failure criteria
- Particular concerning for silt deposits in the PacNW: mean and maximum N_{eq} can be very large
- Objective hysteretic metrics can shed light on ultimate behavior → leads to reliable susceptibility assessments
- Suggest parallel cyclic test programs:
  - Design *CSRs* to large shear strain → identify susceptibility using hysteretic metrics
  - Design *CSRs* and N_{eq} (crustal, subduction zone, etc.) → post-cyclic test program
- CPT-based Soil Behavior Type Index, I_c
  - Does not appear to correlate to ultimate hysteretic behavior (*for the soils evaluated in this study*)
  - Impact of partial drainage on q_t, f_s ?