Oregon State University

# Next Generation Liquefaction Susceptibility Database and Modelling: Part 1

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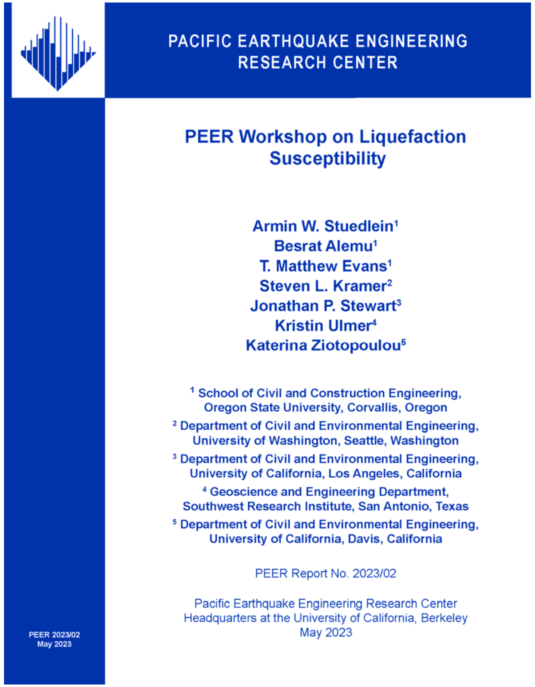
COLLEGE OF ENGINEERING

# Basic Framework for Liquefaction Hazard Assessments

- Liquefaction hazard assessments follow the typical progression:
  - Assessment of liquefaction susceptibility (***could it happen ?***);
  - Determination of liquefaction triggering under given loading (***will it happen ?***);
  - Evaluation of consequences (instabilities, displacements; ***what are the impacts ?***)
- NGL seeks to rationally unpack susceptibility and triggering from manifestation
- PEER- and NRC/USBR-funded NGL activities advance this goal

# PEER Workshop on Liquefaction Susceptibility: Research Needs

- **Vision**: develop Next-Generation Liquefaction susceptibility models which:
  - Predict whether fundamentally-granular behavior will or will not occur
  - Are probabilistic in nature
- **Scope**:
  - (1) Develop a database specifically for the purpose of supporting development of Next-Generation Liquefaction susceptibility models
  - (2) Model development: can identify and treat sources of epistemic uncertainty, incl. regional, interpretations of behavior, and functional form of models



PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

PEER Workshop on Liquefaction Susceptibility

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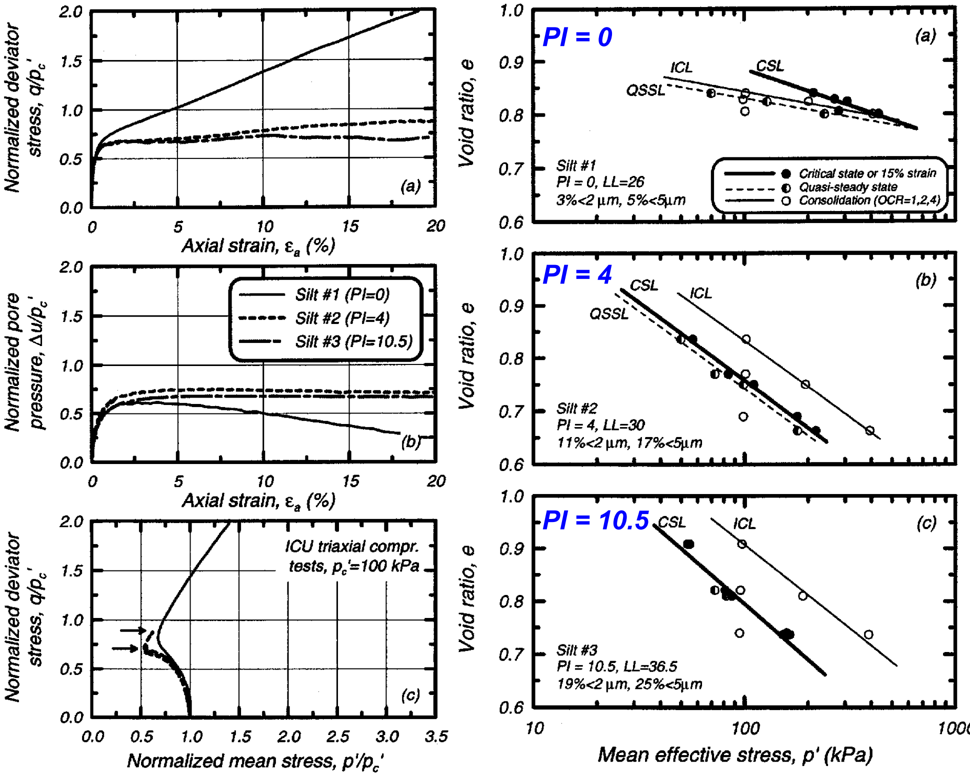
## How to Characterize "Susceptibility" ?

# How to Characterize “Susceptibility”

- **Material and/or State?**:
  - For example, should material characteristics (mineralogy and thus plasticity) be relied upon solely?
  - Some combination of material and indicator of state (relative to the critical state)?
  - NGL view: material characteristics alone should be used to identify whether soil *is* or *is not* susceptible to liquefaction
  - Practical concern: CPT-based assessments (i.e., stress-dependent $I_c$) will by default consider soil state
- **Monotonic Behavior?**:
  - Can “parallelness” – or lack thereof – between the NCL and CSL be used to judge cyclic behavior?
  - NGL view: *under consideration*
- **Cyclic Behavior?**:
  - NGL view: hysteretic behavior provides the definitive means to assess excess pore pressure generation and loss of stiffness and strength; facilitates linkage to material properties
  - Requires medium to high quality intact samples, appropriate cyclic testing protocols

# Characterization of "Susceptibility": Monotonic Behavior

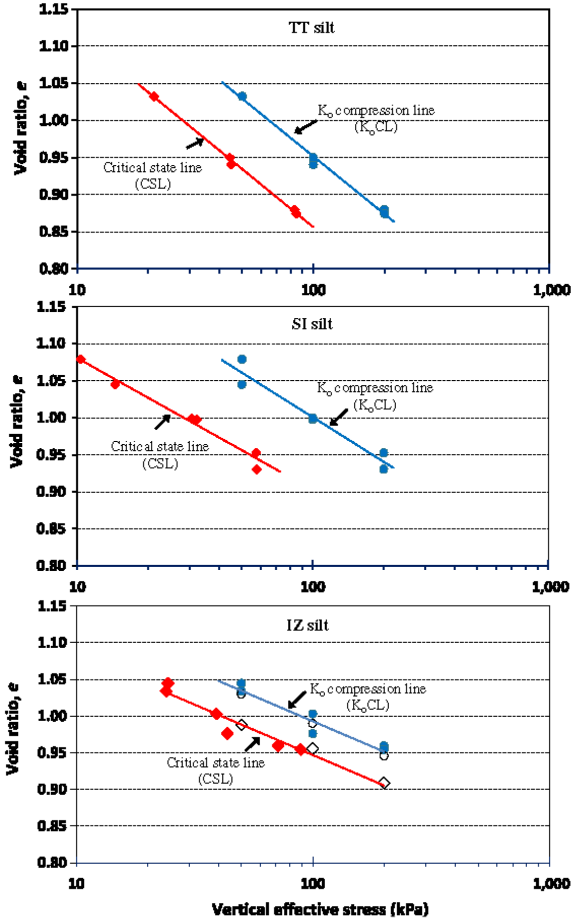
- *Hypothesis*: if the NCL (or ICL) and CSL are parallel, then the material exhibits strength normalizable behavior (~ SHANSEP), a key feature of clay-like behavior
- Here, *PI* = 4 and 10.5 material exhibit parallel or near-parallel ICL and CSLs
- *Question*: what range in stresses should be considered to develop the NCL or ICL?




*Boulanger & Idriss, (2006). "Liquefaction Susceptibility Criteria for Silts and Clays." JGGE, 132(11).*

# Characterization of "Susceptibility": Monotonic Behavior

- Three different **non-plastic silts** tested in DSS apparatus
- IZ silt (bottom right) tested in constant-volume and drained simple shear, identical NCL and CSL slopes
- These materials should not exhibit "parallelness"
- *Is the range in stresses too narrow to establish the NCL?*
- Other pertinent questions:
  - Can damage to fabric in monotonic loading evolve differently than that of cyclic loading?
  - Should normalizability of monotonic strengths be expected to capture cyclic behaviors?




*Monkul et al. (2020). "Undrained shear strength and monotonic behavior of different nonplastic silts: sand-like or clay-like?" GTJ, 43(3)*

# Characterization of "Susceptibility": Monotonic Behavior

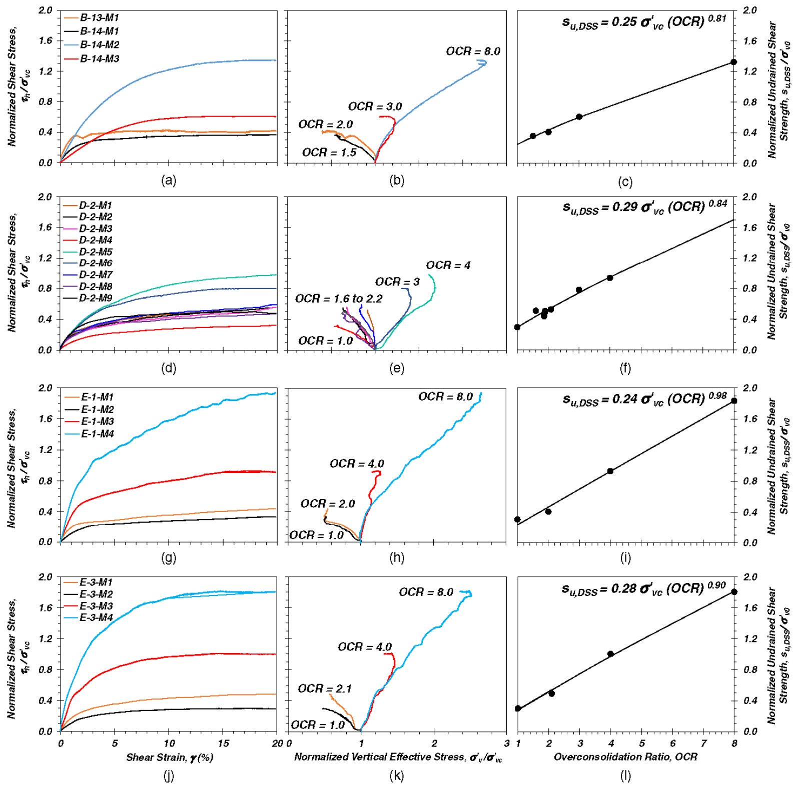
## Monotonic Behavior

- SHANSEP representation of low to medium *PI* silts from Oregon $$\frac{s_{u,DSS}}{\sigma'_{vc}} = S \cdot OCR^m$$
- SHANSEP "*m*" ranges from 0.81 to 0.98
- Cyclic resistance model trained on larger database of silts (Dadashiserej et al. 2024):

$$\frac{\tau_{cyc}}{\sigma'_{vc}} = c_0(PI+1)^{c_1}(OCR)^{c_2}N^{-b}$$

yields exponent $c_2$ of 0.34 to 0.44 (half of *m*), similar to findings by Eslami (2017), Chen & Olsen (2022)

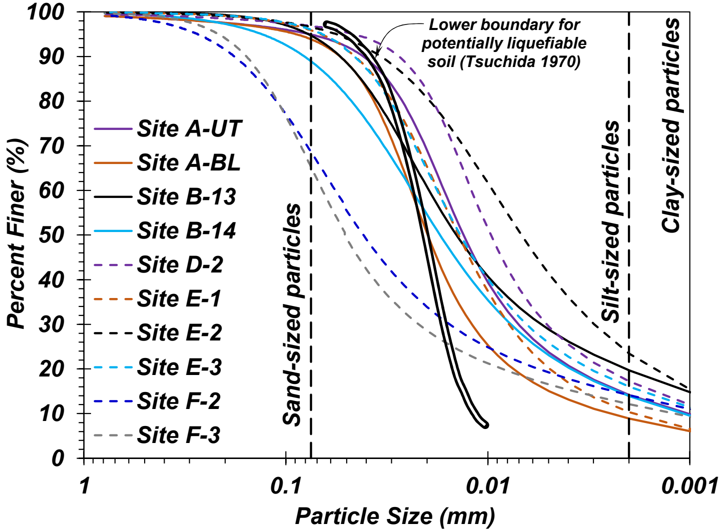
- ***Cyclic loading may damage soil fabric in a sufficiently different manner than monotonic loading***

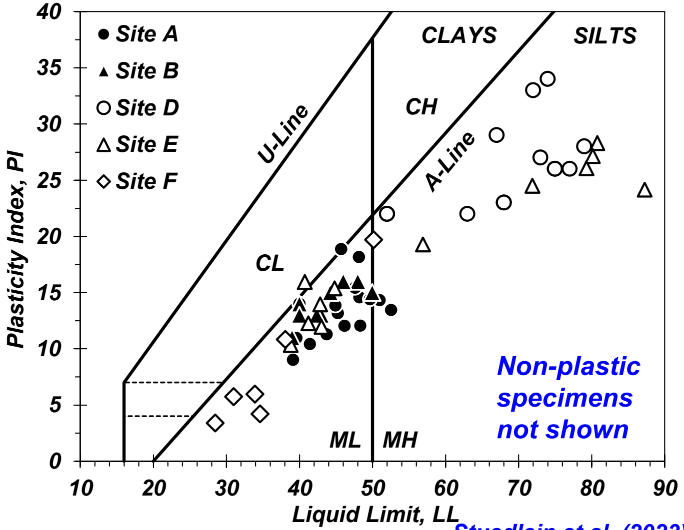



*Stuedlein et al. (2023). "Liquefaction susceptibility and cyclic response of intact nonplastic and plastic silts." JGGE, 149(1)*

# Linking Hysteretic Behavior to Liquefaction Susceptibility

- The laboratory data presented in the following slides consists of natural, ***intact*** specimens consolidated to $\sigma'_{v0}$ 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
- ***All data uploaded to NGL Liquefaction Susceptibility Database and publicly available***



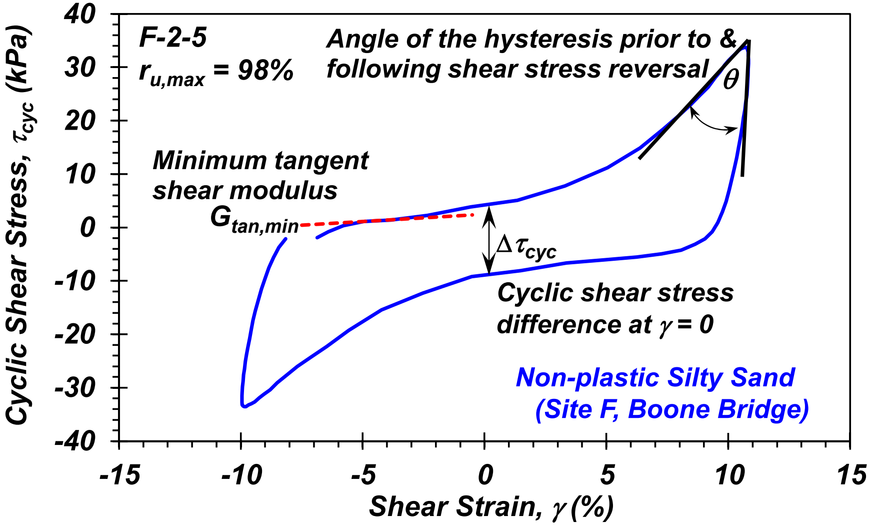




Stuedlein et al. (2023)

# Linking Hysteretic Behavior to Liquefaction Susceptibility

Stuedlein et al. (2023)

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




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

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

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

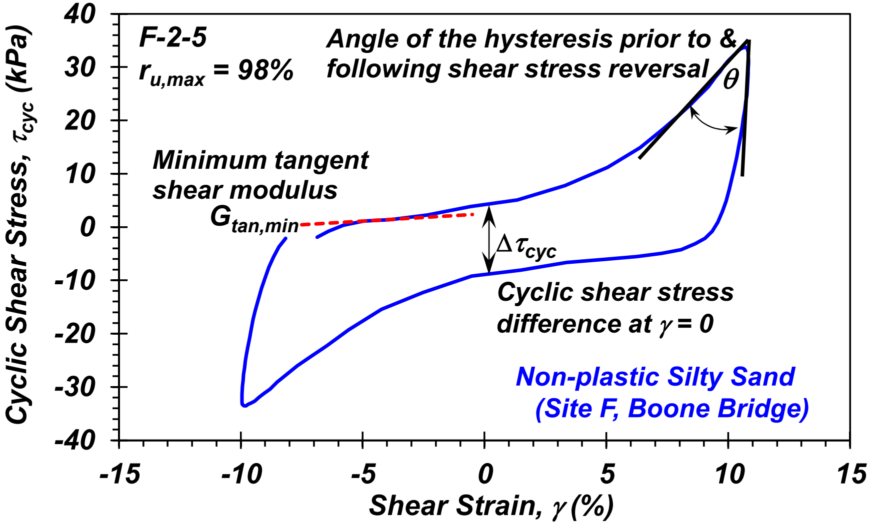
**** Will largely focus on $r_{u,max}$ and $G_{tan,min}/\tau_{cyc}$***

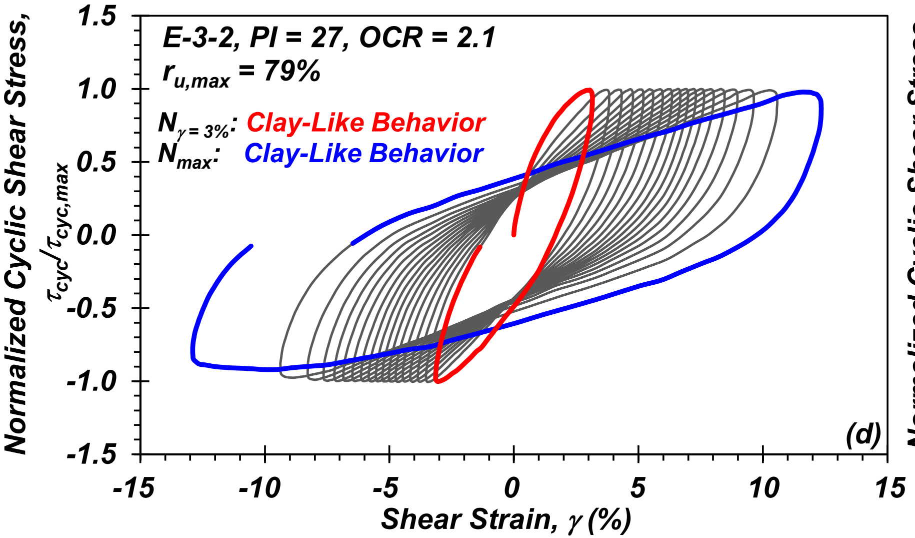
Studlein et al. (2023)

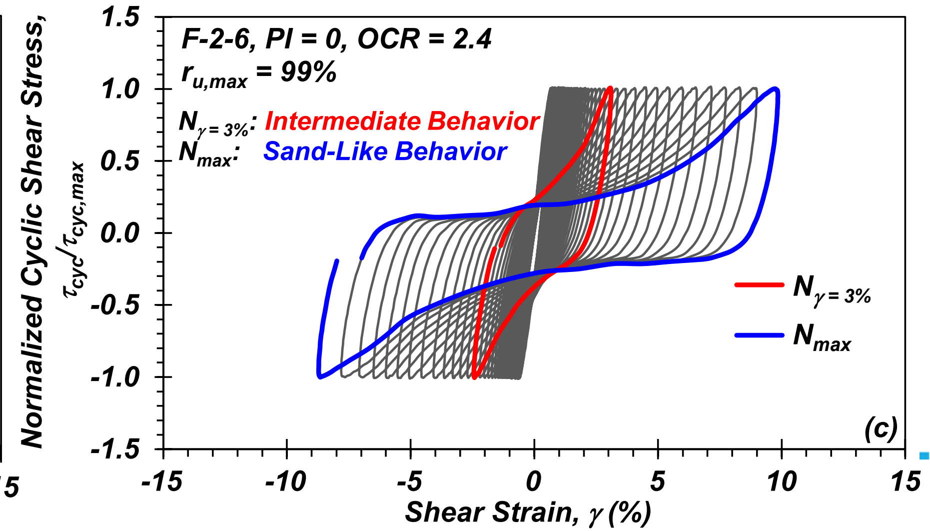
# Linking Hysteretic Behavior to Liquefaction Susceptibility

## 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 |



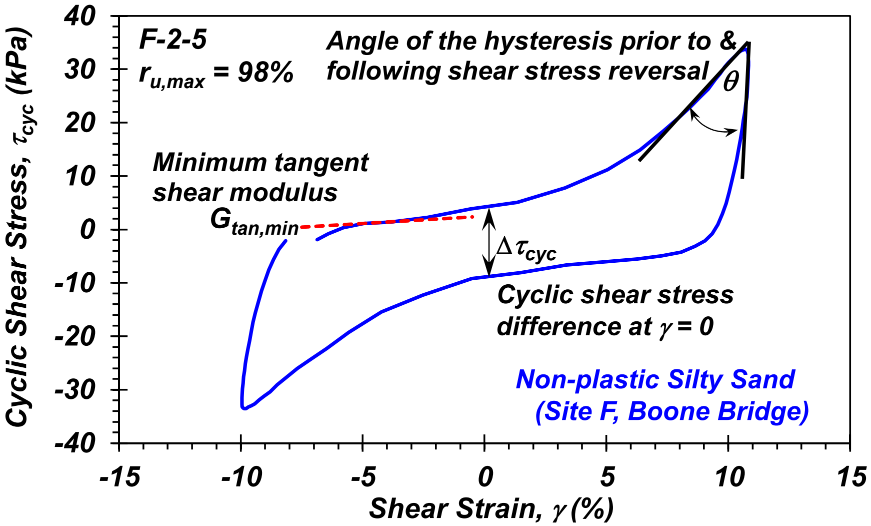



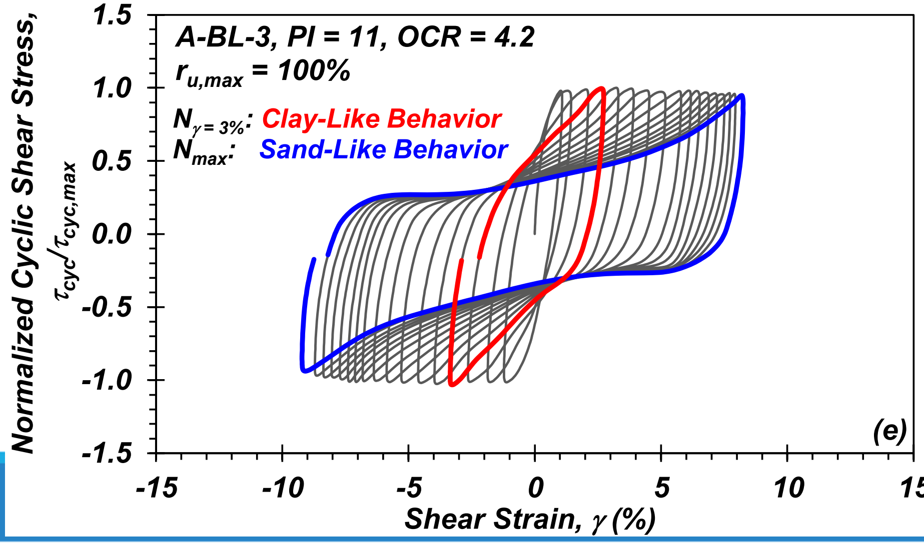
Steudlein et al. (2023)

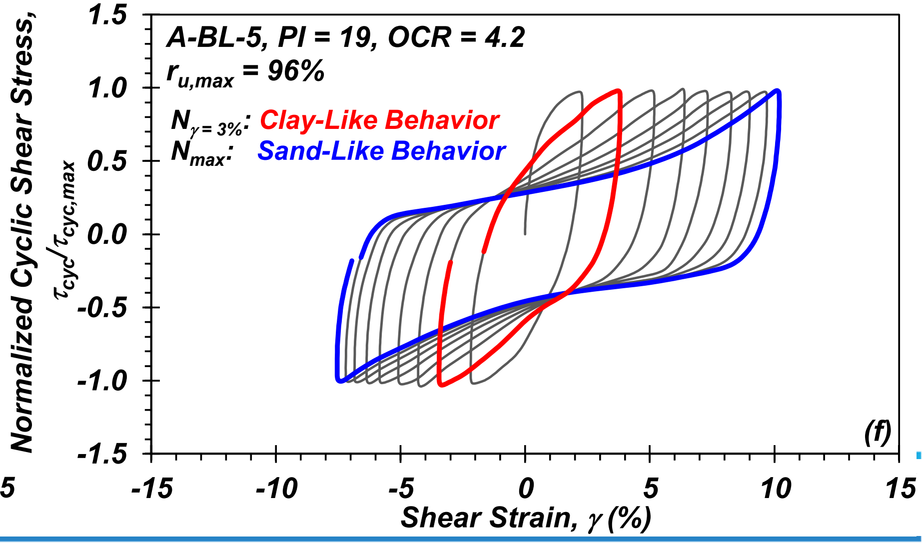
# Linking Hysteretic Behavior to Liquefaction Susceptibility

## 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 |



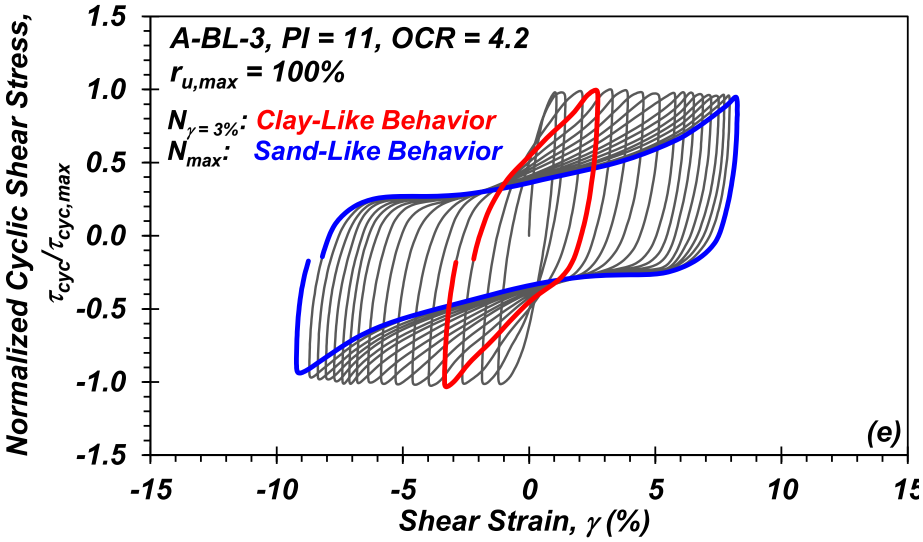

NGL NEXT GENERATION LIQUEFACTION

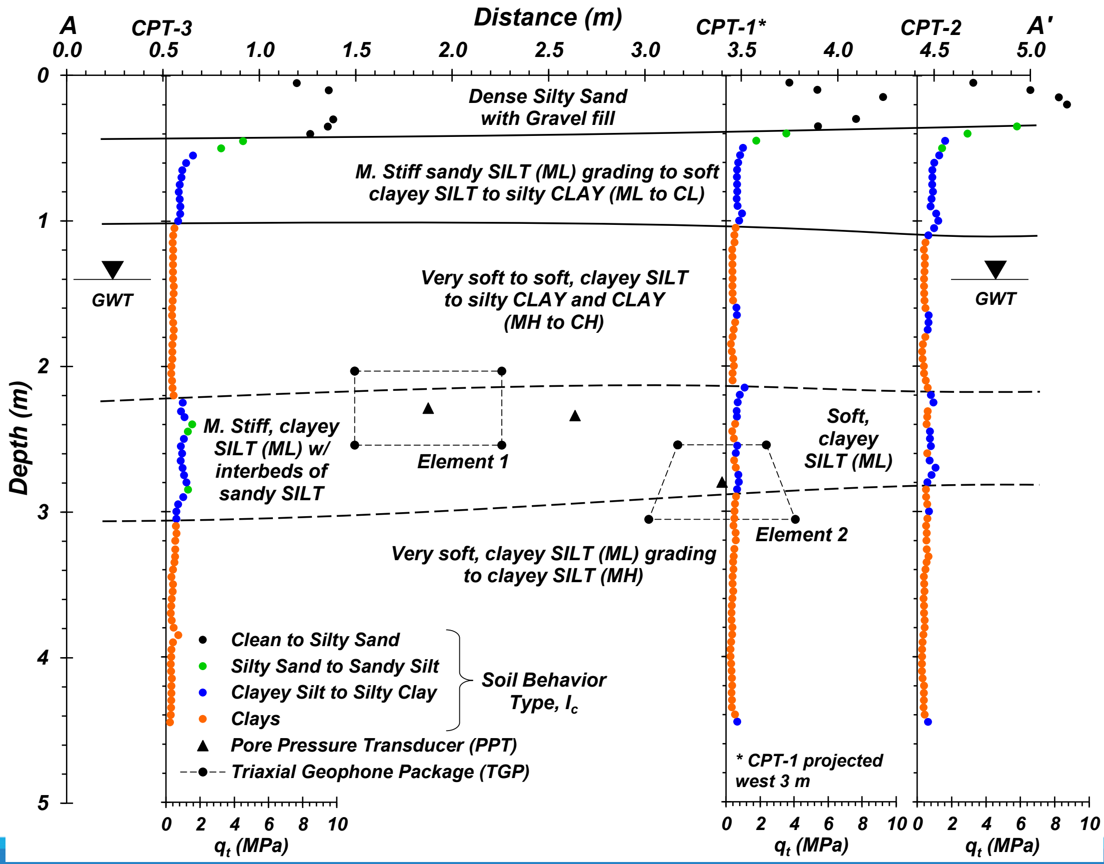
# Observed Field Behavior

*Jana, A. et al. (2023). "Multi-directional Vibroseis Shaking and Controlled Blasting to Determine the Dynamic In-Situ Response of a Low Plasticity Silt Deposit." JGGE, 149 (3).*

## Field Response?

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



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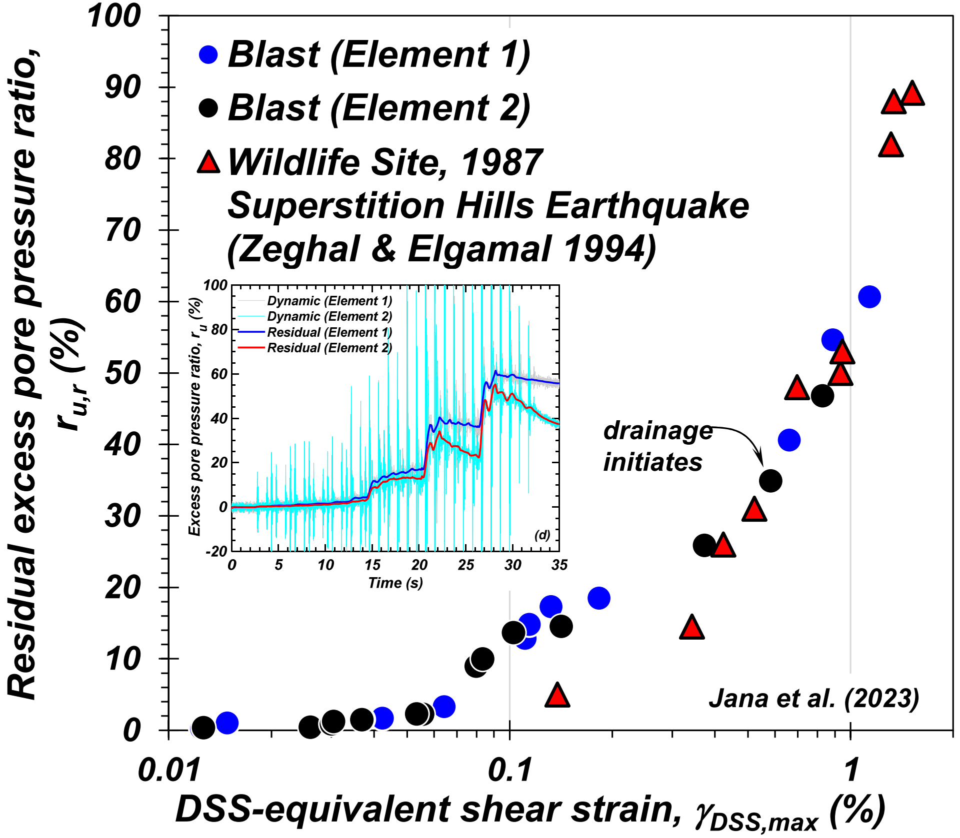
**Field Response?**

- Specimen from the OSU Blast Array, Port of Longview, WA
- Consider the *in-situ* performance of this material (controlled blasting; Jana et al. 2023)
- Excess pore pressures rise sharply with shear strain until drainage initiates; and,
- Appears to track the response of the Wildlife Array (▲, silty sand)
- Takeaway: large strain cyclic behavior points to smaller strain dynamic responses



Studedlein et al. (2023)

# Proposed Hysteretic Metrics for Liquefaction Susceptibility

- 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:

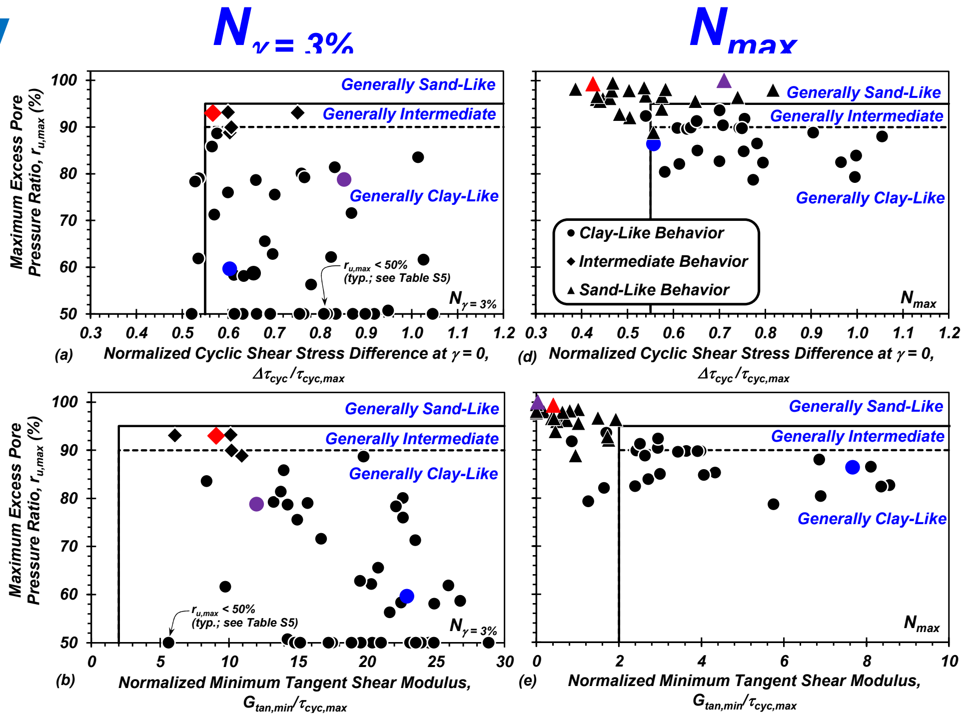
$r_{u,max} < 90\%$, $G_{tan,min} / \tau_{cyc,max} \gtrapprox 2$, $\Delta\tau_{cyc}/\tau_{cyc,max} \gtrapprox 0.55$

**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:

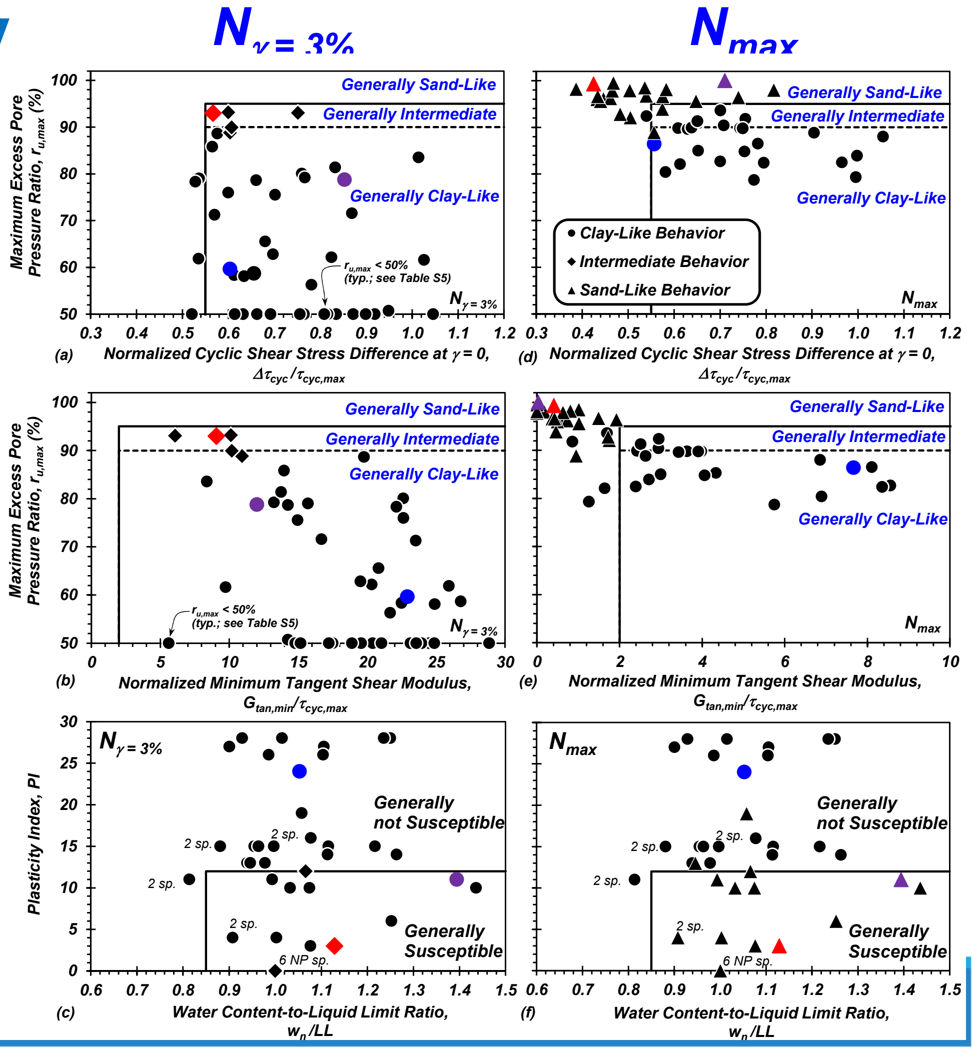
$r_{u,max} > 95\%$ and $G_{tan,min}/\tau_{cyc,max} \lessapprox 2$, $\Delta\tau_{cyc}/\tau_{cyc,max} < 0.55$



Stuedlein et al. (2023)

# Proposed Hysteretic Metrics for Liquefaction Susceptibility

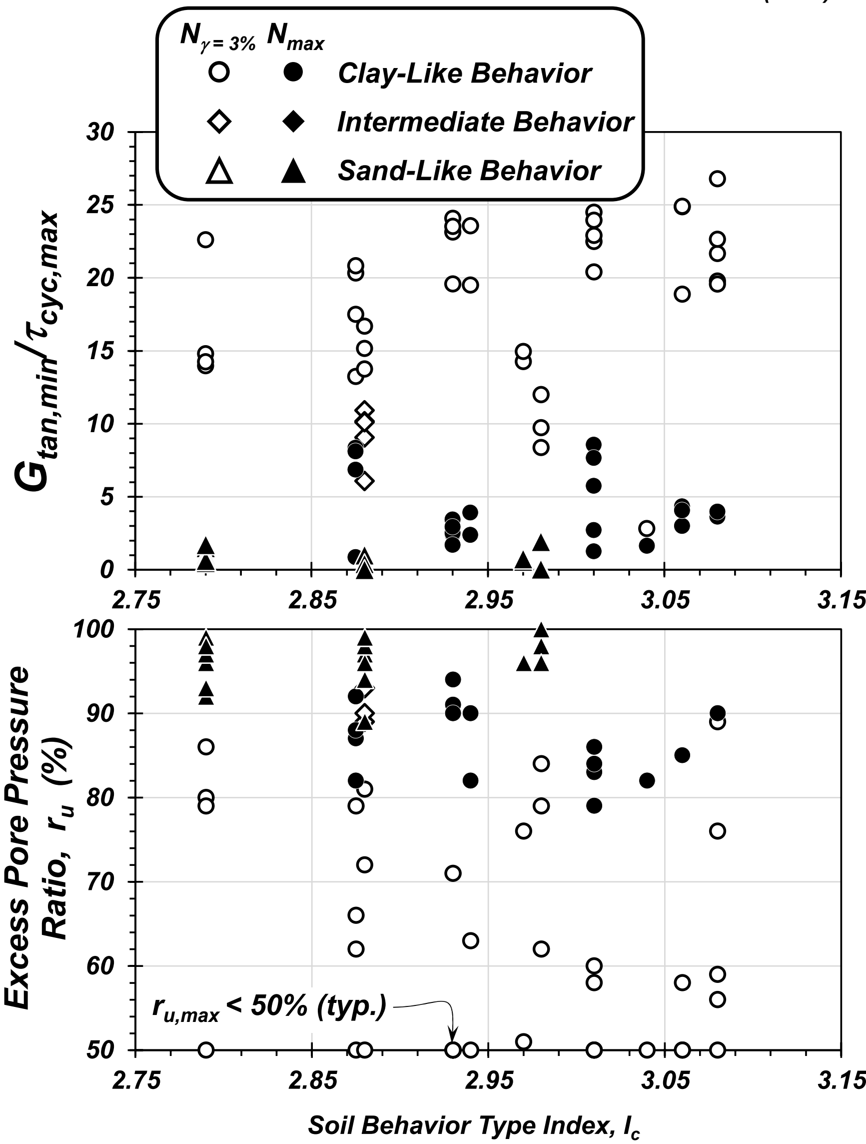
- What if you don't have cyclic test data?
- Modified Bray and Sancio (2006) seemed to *generally* capture large-strain cyclic behavior
- PI ≲ 12, $w_c/LL$ ≳ 0.85: generally exhibits ultimate sand-like behavior
- Workshop organizers suggest dropping $w_c/LL$ to remove influence of "state"



# Comparison to Soil Behavior Type Index

- CPTs 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 ($\gamma > 5\%$)
- Transient liquefaction observed in specimens with $I_c \approx 2.95$
- Findings align with Maurer et al. (2019), *SDEE*, 117

CPT-Assessments from Ortiz (2022)



# Scope of PEER-funded Effort

- **Database development:** specifically for the purpose of supporting development of NGL susceptibility models:
  - Database entry should be associated with geographic coordinates; include paired CPT, borehole, and laboratory test data
  - Cyclic test data, and ideally monotonic data, must be available; testing should be performed to sufficiently large strain to identify ultimate hysteretic behavior
  - Metadata must be available (e.g., index test data)

*Workshop report identified numerous sources of such data;*

*Jon's talk will discuss database development efforts and interpretations*

- **Model development:** can identify and treat sources of epistemic uncertainty:
  - Regional
  - Interpretations of behavior
  - Functional form of models

# [ Thank You ]