Oregon State University

An Update on PEER-Related Next Generation Liquefaction (NGL) Activities

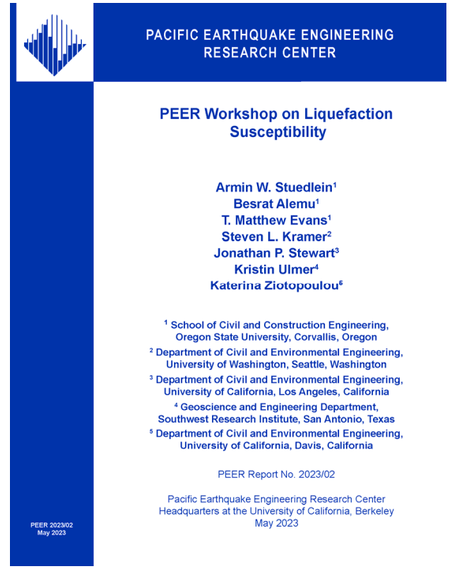
Armin W. Stuedlein

On Behalf of the NGL Project Team Members

COLLEGE OF ENGINEERING

Outline

- NGL Project Overview
- PEER Report 2023/02: Workshop on Liquefaction Susceptibility
- Thrusts of new PEER-NGL Projects
- Envisioned usage of project outcomes
- PEER Report 2023/01: Cyclic Resistance Models for Transitional Silts



PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

PEER Workshop on Liquefaction Susceptibility

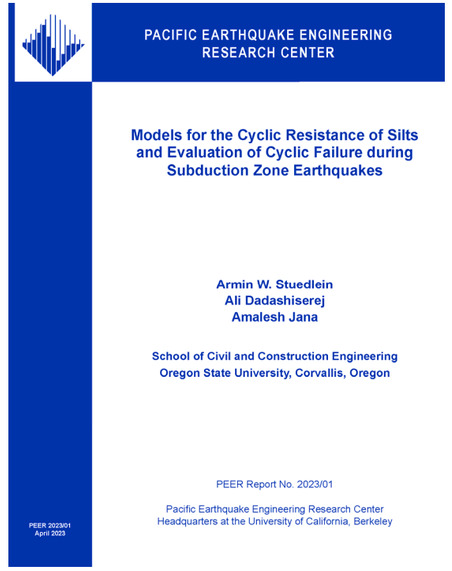
Armin W. Stuedlein[1]
Besrat Alemu[1]
T. Matthew Evans[1]
Steven L. Kramer[2]
Jonathan P. Stewart[3]
Kristin Ulmer[4]
Katerina Ziotopoulou[6]

[1] School of Civil and Construction Engineering, Oregon State University, Corvallis, Oregon
[2] Department of Civil and Environmental Engineering, University of Washington, Seattle, Washington
[3] Department of Civil and Environmental Engineering, University of California, Los Angeles, California
[4] Geoscience and Engineering Department, Southwest Research Institute, San Antonio, Texas
[5] Department of Civil and Environmental Engineering, University of California, Davis, California

PEER Report No. 2023/02

Pacific Earthquake Engineering Research Center
Headquarters at the University of California, Berkeley
May 2023

PEER 2023/02
May 2023



PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

Models for the Cyclic Resistance of Silts and Evaluation of Cyclic Failure during Subduction Zone Earthquakes

Armin W. Stuedlein
Ali Dadashiserej
Amalesh Jana

School of Civil and Construction Engineering
Oregon State University, Corvallis, Oregon

PEER Report No. 2023/01

Pacific Earthquake Engineering Research Center
Headquarters at the University of California, Berkeley

PEER 2023/01
April 2023

MPC MOUNTAIN-PLAINS CONSORTIUM · U.S.NRC · SwRI · PEER · U.S. DEPARTMENT OF THE INTERIOR BUREAU OF RECLAMATION · Caltrans · UDOT Keeping Utah Moving

NGL Project Structure

Joint Management Committee (JMC)
Sponsor Representatives: Caltrans, NRC, USBR

Executive Advisor
I.M. Idriss

Project Management Team (PMT)
Stewart, Kramer, Stamatakos

Advisory Board
Boulanger, Bray, Cubrinovski

Database Development
Brandenberg (Chair), Cetin, Franke, Moss, Zimmaro, Ulmer, Hudson, Stuedlein. (IT support – SwRI)

Focused Studies
Stress effects: Carlton, Ulmer
Susceptibility: Stuedlein, Evans

Model Development
SMT: Kramer (Chair), Zimmaro, Ulmer, Hudson, Brandenberg
VT Team: Green, Mitchell, Rodriguez-Marek, Stafford
TPF Team: Stuedlein, Olson, Lingwall, Rollins, Franke
UW/Tufts Team: Baise, Maurer
UC-Boulder Team: Dashti, Kamai, Liel
Japan Team: Okamura, Kiyota, and PWRI
Turkey-US: Cetin, Moss, Kayen

Tools & Resources for Interacting w/Data

- Graphical User Interface (GUI) https://nextgenerationliquefaction.org/
- Connect to the NGL database through Jupyter Notebooks on DesignSafe https://www.designsafe-ci.org/
- Schema website https://nextgenerationliquefaction.org/schema/index.html
- NGL Tools and Documentation
  - CPT Layer Detection Algorithm; Hudson et al. 2023 (https://onlinelibrary.wiley.com/share/author/H3PXJ3WU8MEVNAMSDNUT?target=10.1002/eqe.3961)
  - Use case documentation on DesignSafe (https://www.designsafe-ci.org/rw/use-cases/)
  - https://ngl-tools.readthedocs.io/en/latest/
  - CPT-based FC correlations for liquefaction case history sites forthcoming
- NGL YouTube Channel
  - Webinars on case histories and related topics
  - October DesignSafe Workshop: creating Jupyter Notebooks
  - https://www.youtube.com/channel/UCtcbOIVb3soaJ5X60vdgKkw

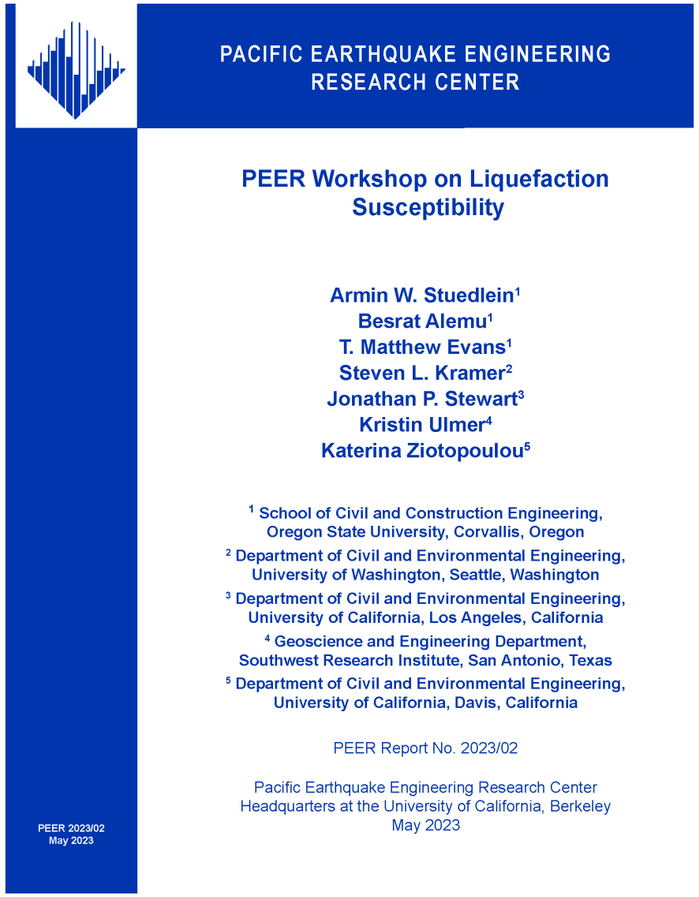
Basic Framework for Liquefaction Hazard Assessments

- 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-funded NGL activities advance this goal

[NGL-PEER Activities]

2023/02: PEER Workshop on Liquefaction Susceptibility

- Held 8 - 9 September 2022 in Corvallis, OR
- 50 participants from six countries, including academics, practitioners, and government employees
- **Key Item #1**: Should liquefaction susceptibility consider:
  - Material (inherent) characteristics alone (e.g., plasticity)
  - Material and state (e.g., D_r *or* e) characteristics
- **Key Item #2**: Terminology & usage of current criteria:
  - "liquefaction susceptibility," focus on *behavior*
  - "cyclic strength evaluation criteria," focus on *engineering procedures*
- **Key Item #3**: Research needs



Key Item #2: Liquefaction Susceptibility

Ground failure in silt, Adapazari 1999

- Two widely-available criteria are available
- Bray & Sancio (2006, 2008*): criteria developed based on silty soils which exhibited cyclic mobility type behaviors (lab specimens) and ground failure during 1999 Kocaeli EQ
- Boulanger & Idriss (2006, 2008*): "liquefaction" associated with those soils for which penetration resistance-based liquefaction triggering models may be used to quantify cyclic strength (hence "cyclic strength evaluation criteria")
- The Workshop Report and extended abstracts discuss similarities and differences between the criteria, serving to clarify their use

MPC U.S.NRC SwRI PEER U.S. Department of the Interior Bureau of Reclamation Caltrans UDOT Keeping Utah Moving

* Closures to 2006 papers in ASCE JGGE

Key Item #3: Research Needs

- **Vision**: develop Next-Generation Liquefaction susceptibility models which:
  - Predict whether fundamentally-granular behavior will or will not occur: “material susceptibility”
  - Are probabilistic in nature (broad, though not unanimous, agreement among participants)
- **Scope**: (1) Develop a database specifically for the purpose of supporting development of the Next-Generation Liquefaction susceptibility model:
  - 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 strength normalization and ultimate hysteretic behavior
  - Metadata related to tests performed, index test data, etc., must be available

  Workshop report identified numerous sources of such data
- (2) Model development: can identify and treat sources of epistemic uncertainty, incl. regional, interpretations of behavior, and functional form of models

Next Steps Following Workshop

- **Collaborative PEER-funded Research Projects**
- *Next Generation Liquefaction Susceptibility Database and Modelling*; PI: Jonathan P. Stewart, Co-PI: Scott J. Brandenberg
- *Next Generation Liquefaction Susceptibility Database*: *Expansion of the Laboratory Component to Leverage Pacific Northwest Soils*
- Two-year projects with partial student support
- Will seek to directly address research needs identified in the PEER Workshop on Liquefaction Susceptibility and integrate findings into the broader NGL effort

[Application of PEER Research in NGL]

Current Probabilistic NGL Formulation

- Traditional Approach:

  Manifestation = triggering, M = T

  P[T|M] = 1.0

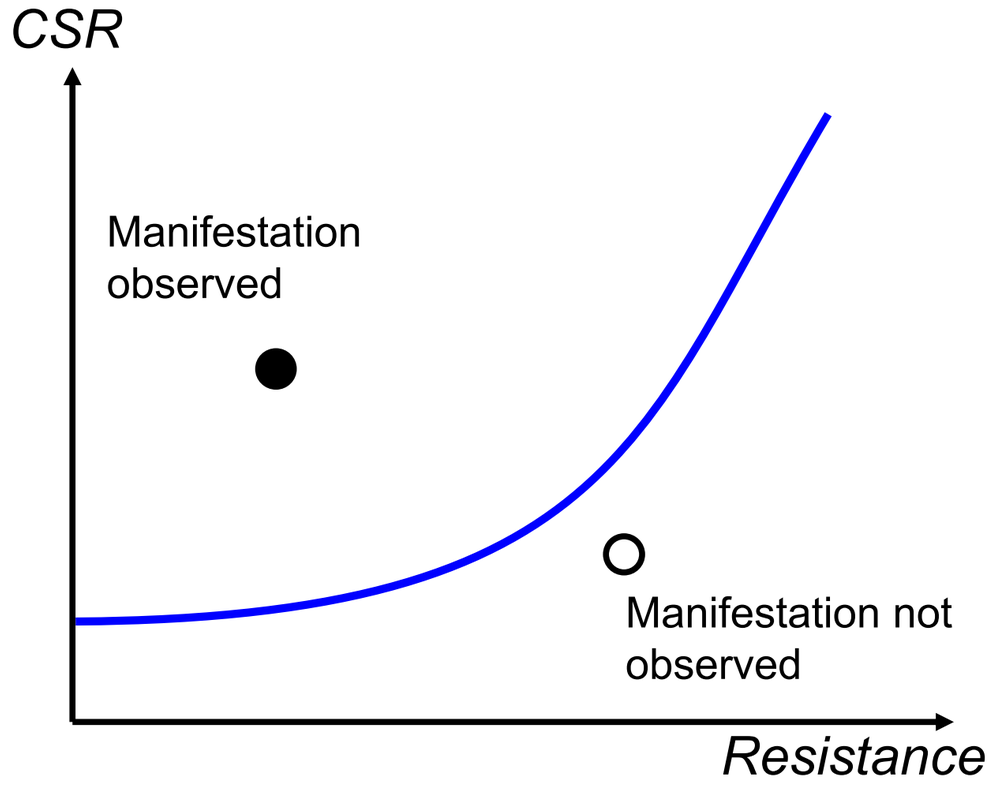
  P[NT|M] = 0.0

  No manifestation = no triggering, NM = NT

  P[T|NM] = 0.0

  P[NT|NM] = 1.0

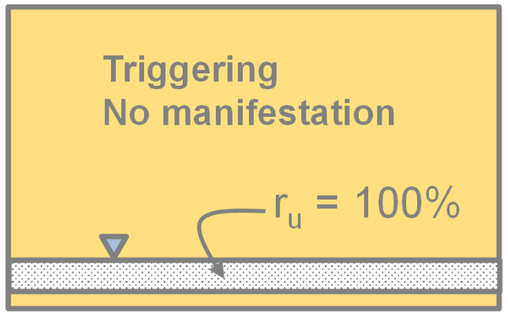
- NGL Modeling Approach
  - Probabilistic (similar to recent models)
  - Uses a triggering “prior” probability → laboratory-based
  - Manifestation models → case histories
  - Update of “prior”

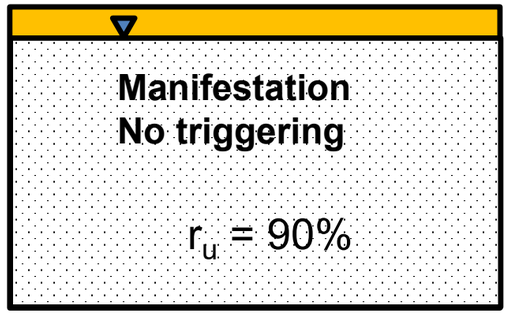


Current Probabilistic NGL Formulation

- Approach: allows rational consideration of:

No Manifestation ≠ No Triggering	P[NT|NM] < 1.0	P[T|NM] > 0.0
Manifestation ≠ Triggering	P[T|M] < 1.0	P[NT|M] > 0.0





- Current functional form:

$$P[T \mid M] = \frac{P[M \mid T]P[T]}{P[M]} = \frac{P[M \mid T]P[T]}{P[M \mid T]P[T] + P[M \mid NT]\left(1 - P[T]\right)}$$

Need three probabilities:

- Probability of manifestation given triggering, $P[M|T]$
- Probability of manifestation without triggering, $P[M|NT]$

} Probabilistic manifestation model; informed by case histories in the NGL Database

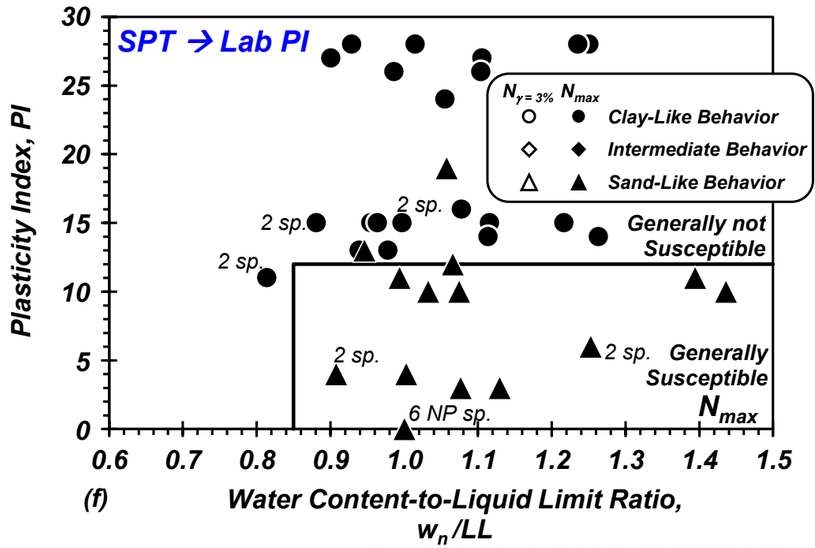
- Probability of triggering before incorporation of case history data, $P[T]$ - prior probability

Updated Probabilistic NGL Formulation

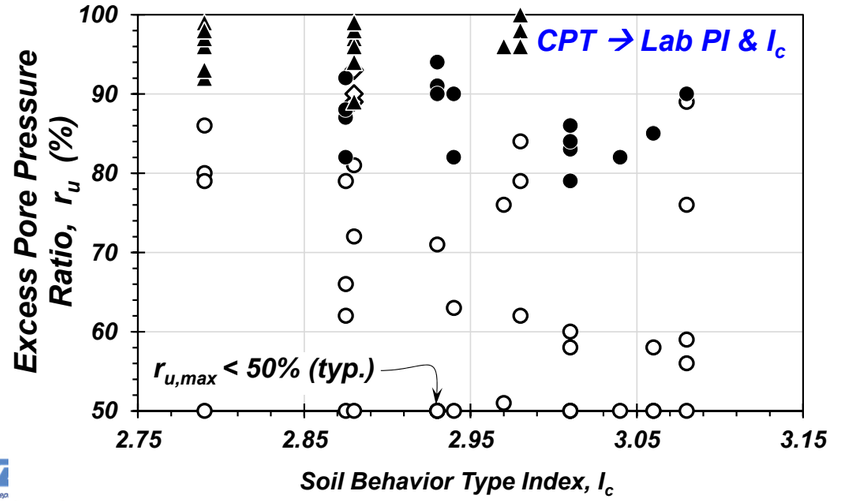
- Previously, the laboratory-based "prior" assumed $P[S] = 1.0$
- Characterize probability of liquefaction susceptibility, $P[S]$:
  - SPT-based triggering: *PI*
  - CPT-based triggering: *PI* and CPT I_c

  } Susceptibility defined using hysteretic behavior & strength normalization
- Evaluate sensitivity $P[S]$ models to soils with differing fines contents, and fines of differing plasticity
- Functional form of model:

$$P[T|M,S] = \frac{P[M|T] \cdot \boxed{P[T|S] \cdot P[S]}}{P[M|T] \cdot P[T|S] \cdot P[S] + P[M|NT] \cdot (1 - \boxed{P[T|S]P[S]})}$$



Stuedlein et al. (2023) JGGE 149(1)

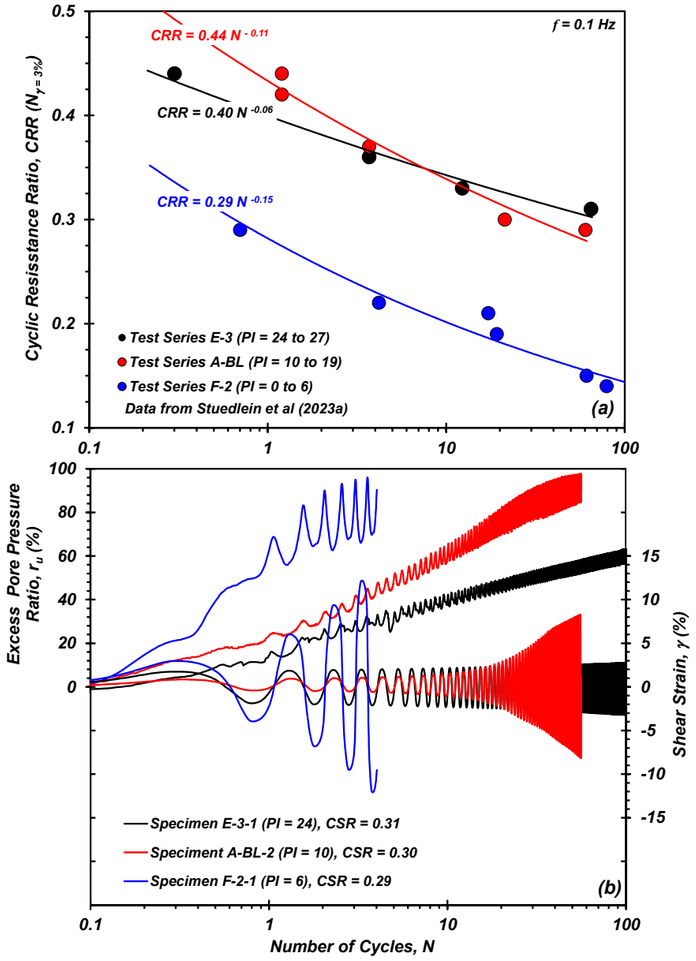


Stuedlein & Evans (2022) PEER Workshop

[Cyclic Resistance Models for Transitional Soils]

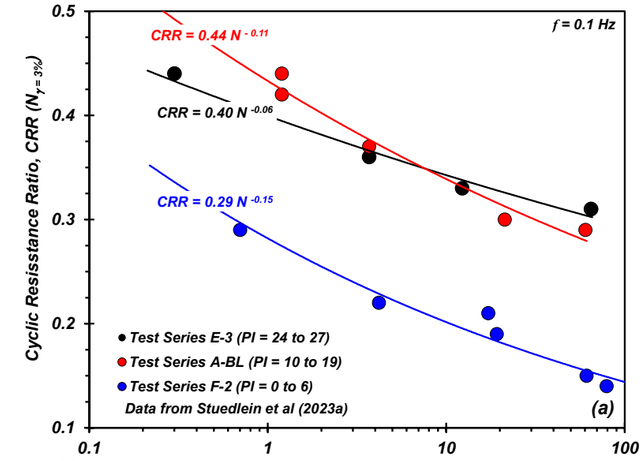
2023/01: Motivation

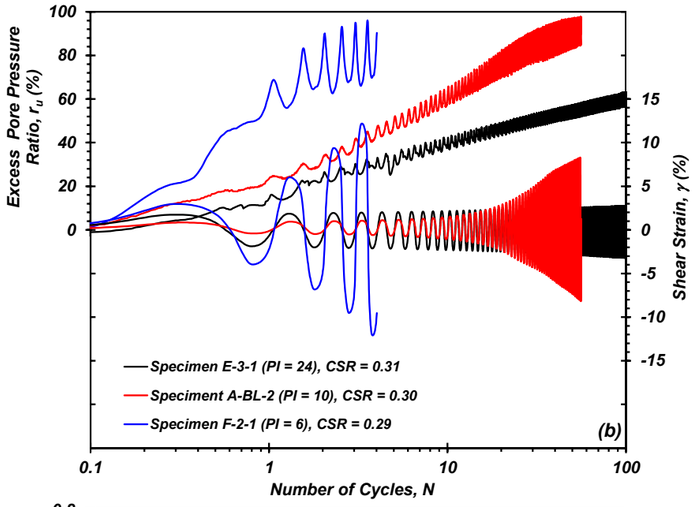
- Transitional soils: silty a/o clayey sands, sandy silts, silts, clayey silts
- Cyclic resistance estimates for transitional silts are challenging
  - Low-plasticity silts with CPT I_c < 2.6 not well-represented in pre-NGL liquefaction case history databases
  - Soils with I_c ≥ 2.6 often excluded from pre-NGL databases
  - Penetration resistance affected by partial drainage
- Transitional soils exhibit a clear, though uncertain, transition in soil behavior (i.e., “sand-like”, “clay-like”) and cyclic resistance

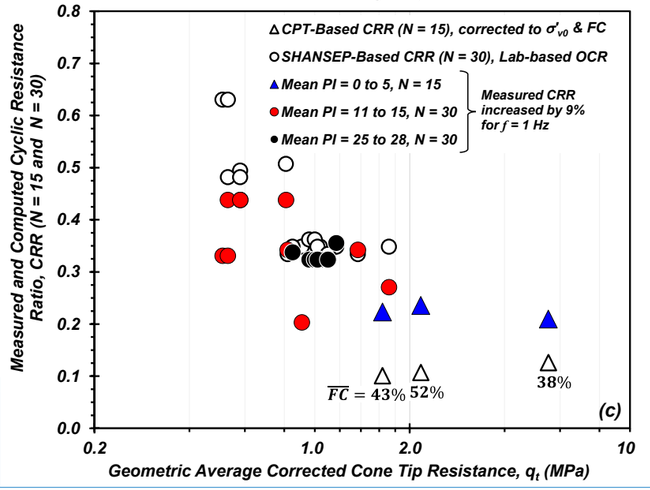


2023/01: Motivation

- Example “Clay-like” soils (●, cyclic softening-susceptible)
  - *PI* = 24 to 27, *FC* ≥ 97%, I_c = 2.94 to 3.06
  - SHANSEP-based cyclic resistance estimates are excellent
- Example “Sand-like” soils (▲, liquefaction-susceptible)
  - *PI* = 0 to 5, *FC* = 38 to 52%, I_c = 2.79 to 3.08, q_{c1Ncs} = 66 to 96
  - CPT-based cyclic resistance underestimates actual by 50%$^+$
- Example Transitional soils (●, liquefaction-susceptible)
  - *PI* = 11 to 15, *FC* ≳ 80%, I_c = 2.46 to 2.99
  - CPT-based cyclic resistances inapplicable
  - SHANSEP-based cyclic resistances poor; non-parallel CSL and NCL lines







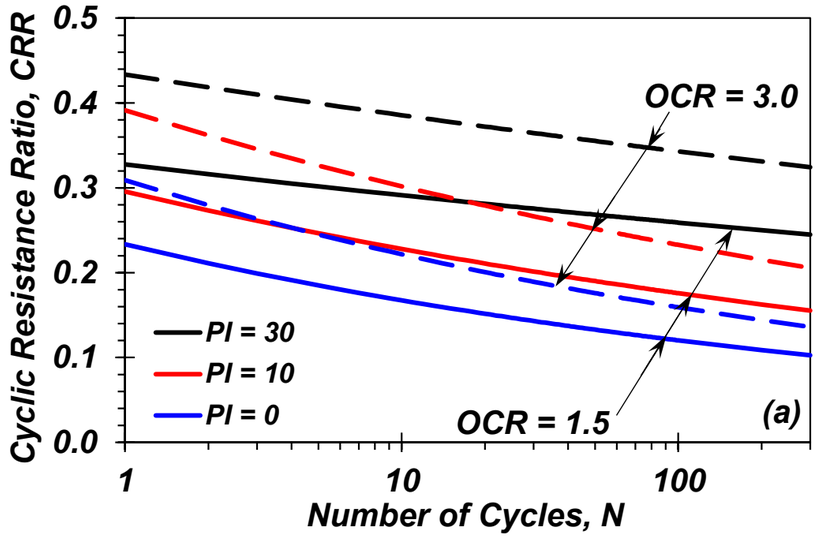
2023/01: Project Outcome

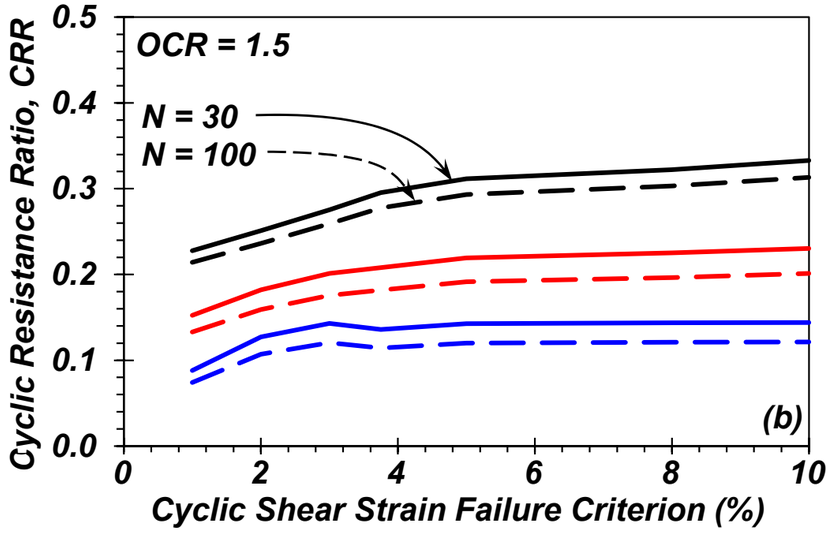
- Shear strain-dependent cyclic resistance model for transitional silts for 1% ≤ γ ≤ 10% :

$$CRR^*(\gamma) = c_0 \cdot (PI + 1)^{c_1} \cdot OCR^{c_2} \cdot N^{-b^*}$$

$$b^* = a_0 \cdot (PI + 1) + a_1$$

- Trained on laboratory CDSS specimens from good-to-high quality samples
- Captures transition in cyclic resistance with plasticity and stress history, independent of susceptibility determinations
- Accompanied by N_{eq} and magnitude scaling factor models specifically for subduction zone earthquakes





2023/01: Applications

- Preliminary assessments of cyclic failure (e.g., 30% design level):
  - Estimate N_{eq} and $N_{eq} \pm \sigma$ for a given M_w
  - Compute $CRR^*(\gamma)$ given N_{eq} and M_w; fully-compatible with PBEE framework
  - Assess $FS_{cyclic\ failure}$ and need for cyclic testing program to improve understanding of risk of cyclic failure and/or mitigation strategies
- Planning cyclic testing programs:
  - Select seismic hazard(s) to consider, $M_{w,i}$
  - Estimate N_{eq} and $N_{eq} \pm \sigma$ for a given M_w, set termination criterion for test specimens
  - Conduct post-cyclic tests to appraise hazard-specific consequences
- Calibration of constitutive models for nonlinear dynamic analyses:
  - Ground response analysis
  - Deformation analysis (OpenSees, FLAC, etc.)

[Concluding Remarks]

Concluding Remarks

- PEER-funded research serving to advance critical areas in soil liquefaction / cyclic softening
  - Cyclic resistance for transitional soils (2023/01)
  - Clarifying perspectives on liquefaction susceptibility (2023/02)
  - Expanding the NGL Database to support susceptibility models (initiating Fa23)
  - Development of NGL liquefaction susceptibility models (initiating Fa23)
- Next Generation Liquefaction Project
  - NGL Database continues to expand w/r/t field cases, lab data, and tools for querying data
  - Multiple community modeling teams on differing timelines
  - Supporting NGL studies to tackle outstanding model components
  - SMT continues to improve probabilistic model, unpacking triggering from susceptibility and manifestation