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Some Challenges & Opportunities in the Field of Geotechnical & Soil-Structure-Interaction

-

(Geo-Structures)

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Overview

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- Outstanding Questions in Soil Liquefaction
  - Laboratory vs. Field Behaviors
  - ~~System Response of Interlayered Soil Deposits~~
  - Partial Drainage and Multidirectional Loading
  - Liquefaction of Gravelly Soils
- Combined Loading on Deep Foundations (SSI Knowledge Gap)
  - Torsional response of deep foundations
  - Combined loading: torsional, lateral (axial?)

Outstanding Questions in Soil Liquefaction

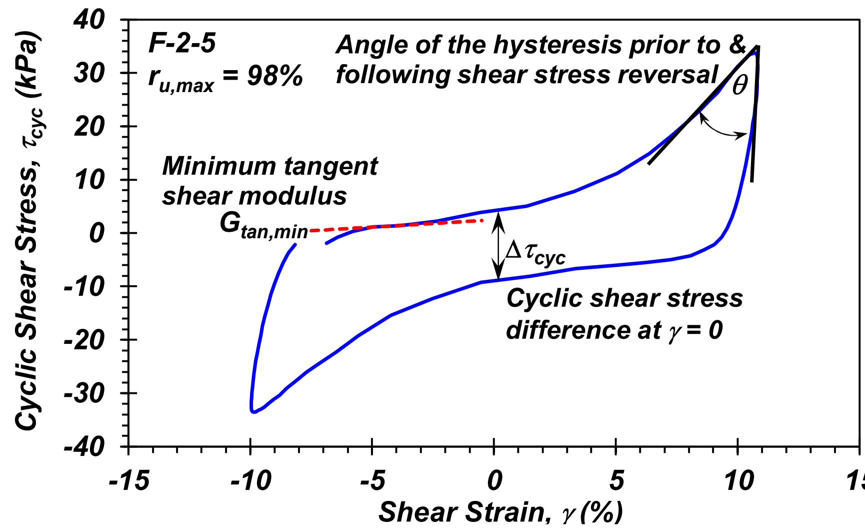
Laboratory vs. Field Response

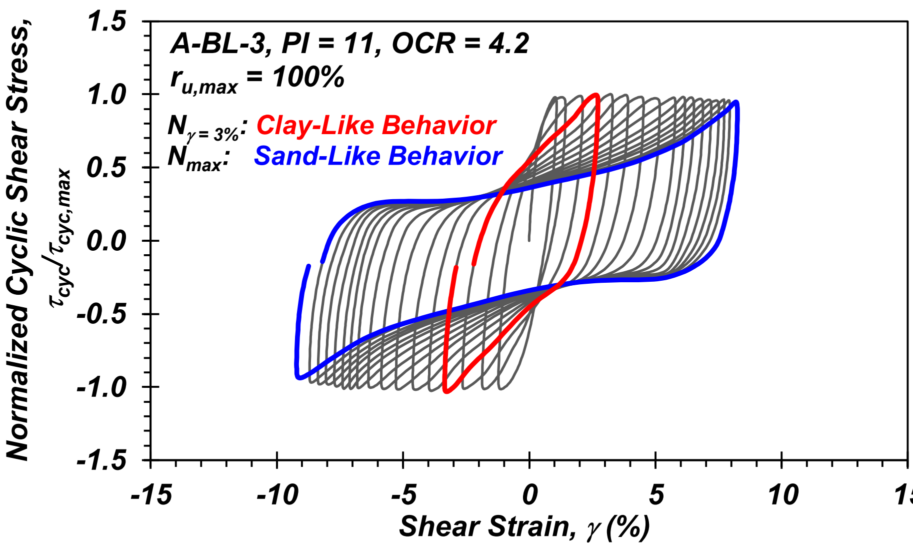
Linking Hysteretic Behavior to Liquefaction Susceptibility

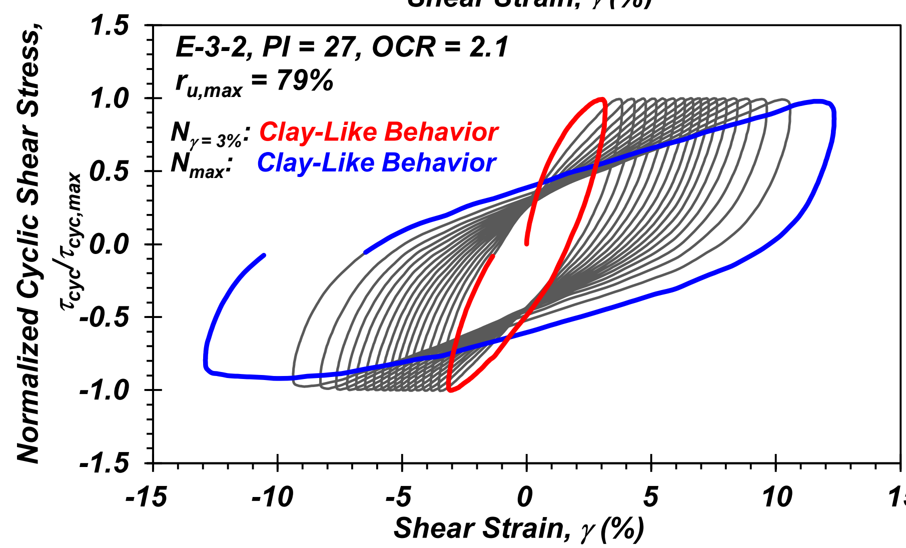
Stuedlein et al. (2023a)

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





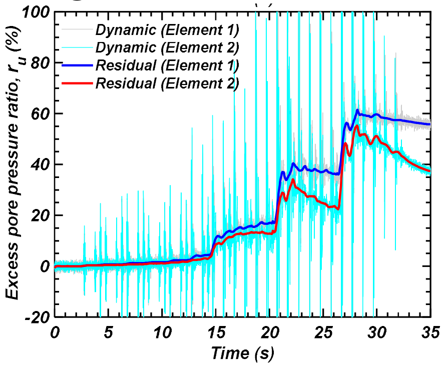


Laboratory vs. Field Response

Observed Field Behavior

Field Response?

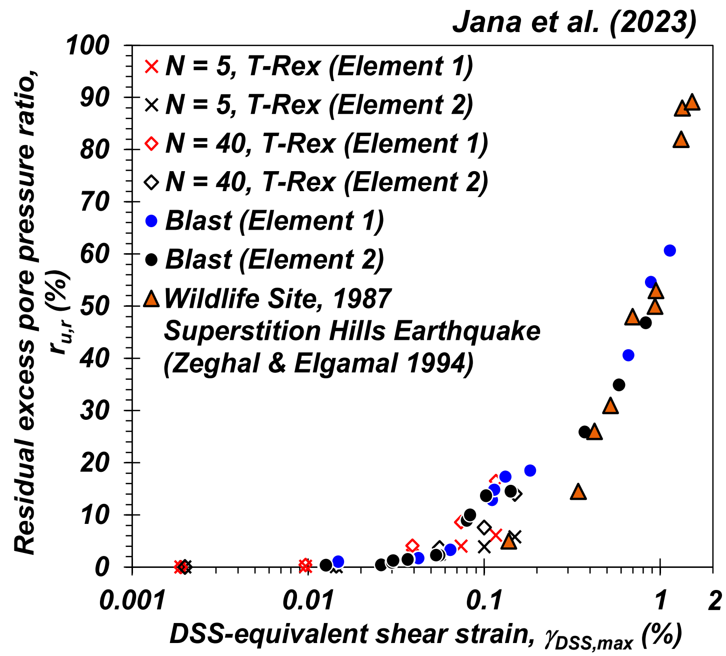
- Specimens derived from the OSU Blast Array at Port of Longview, WA (Jana et al. 2023a)
  - Instrument array facilitates computation of stresses and strains with linkage to excess pore pressure generation
  - Loaded using "T-Rex" (NHERI@UTEXAS), $\gamma_{max} \approx 0.15\%$
  - Loaded using controlled blasting, $\gamma_{max} \approx 1.15\%$
- Goal: link laboratory and field responses

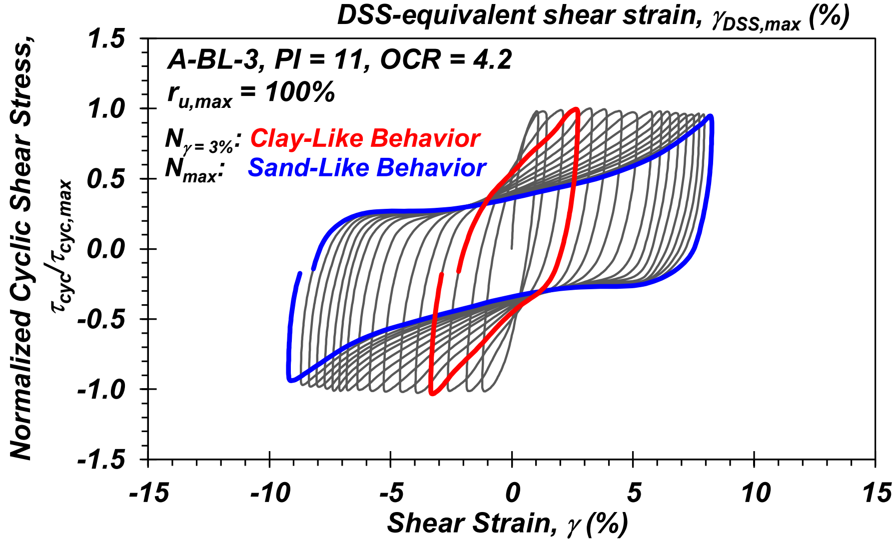


Laboratory vs. Field Response

Observed Field Behavior

- *In-situ* variation in residual excess pore pressure with shear strain; response similar to silty sand deposit @ Wildlife Site
- Large-strain "sand-like" cyclic behavior in CDSS linked to smaller strain liquefaction tendency
- Evidence suggests that:
  - Liquefaction of these transitional, low plasticity silts in the field is likely if loaded sufficiently
  - Ultimate hysteretic behavior ($\gamma > 5\%$) in CDSS is necessary to reveal the liquefaction potential (susceptibility)
  - Liquefaction in the field may occur at smaller strains than that implied by stress-controlled CDSS tests
- **LHPOST6 + laminar container may be used to prepare identical specimens (lab & container) to interrogate mis-match between laboratory and field**





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Partial Drainage & Multi-directional Shaking

Instrumentation Techniques

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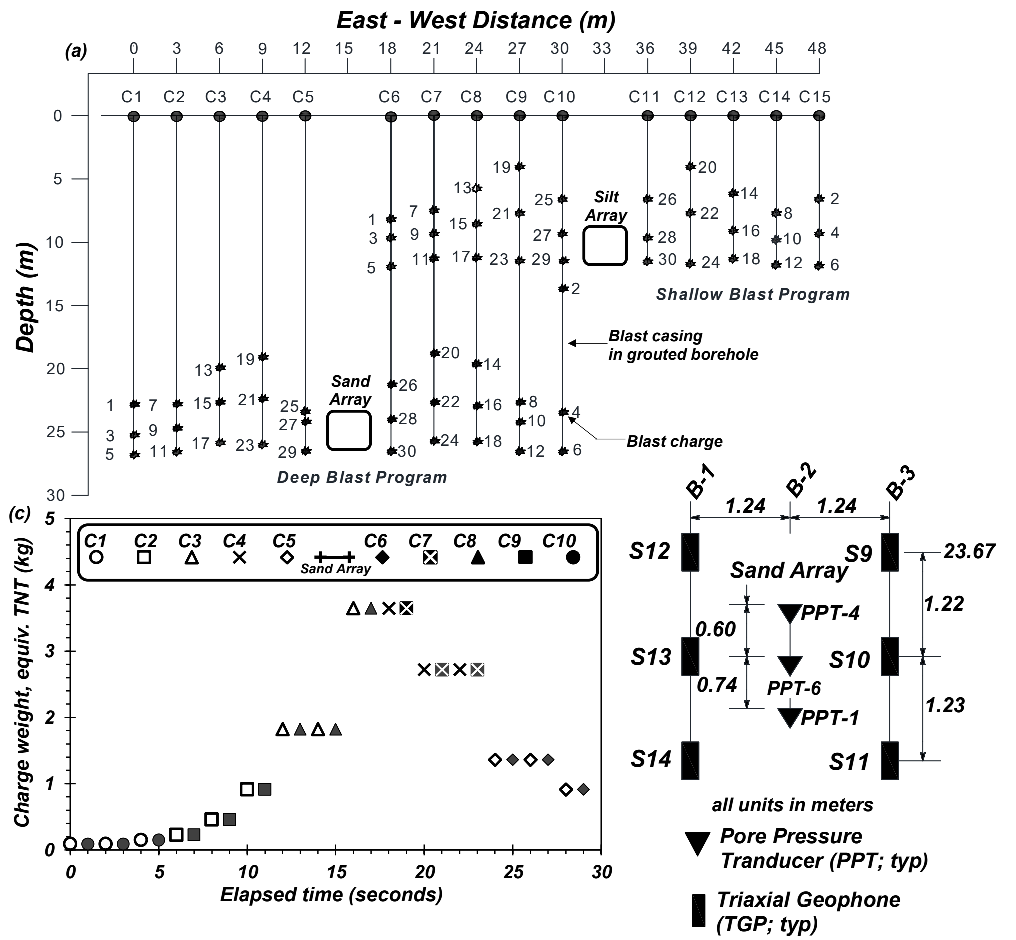
- Full-scale, in-situ dynamic testing has demonstrated the viability of our instrumentation techniques
  - –Velocity transducers placed to form “nodes” of a physical “finite” element
  - –Piezometers placed at mid-points of elements to measure pore pressure
- Shear waves generated through detonation of explosives
- Shear strains through differentiation of displacement time histories
- Shear stresses through velocity time histories & V_s
- Shear modulus & damping



(Stuedlein et al. 2023b)

Field Experiments

Controlled Blasting @ Depth of ~25 m

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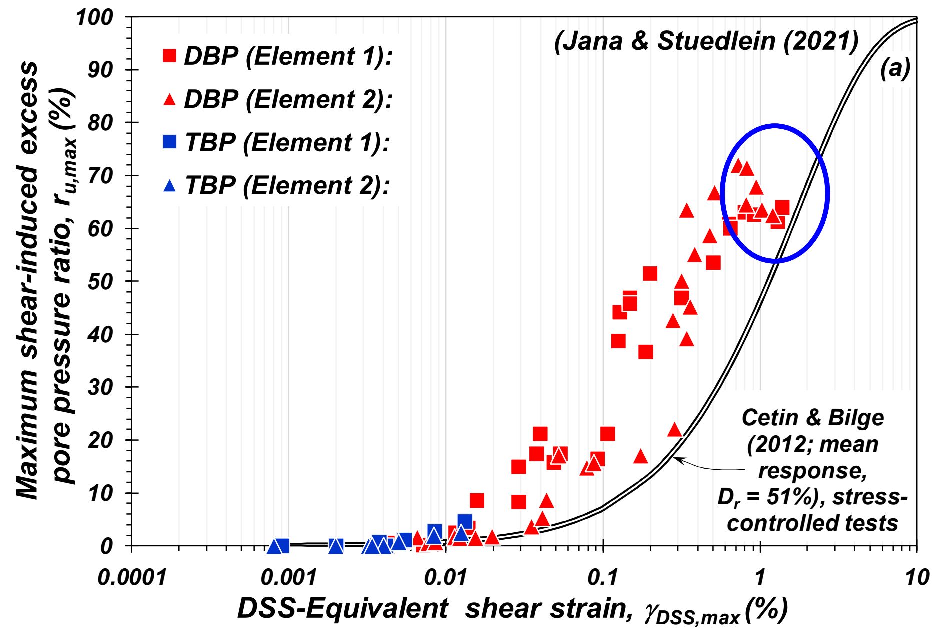
Key Observations (TBP & DBP)

Shear Strain *vs.* Excess Pore Pressure



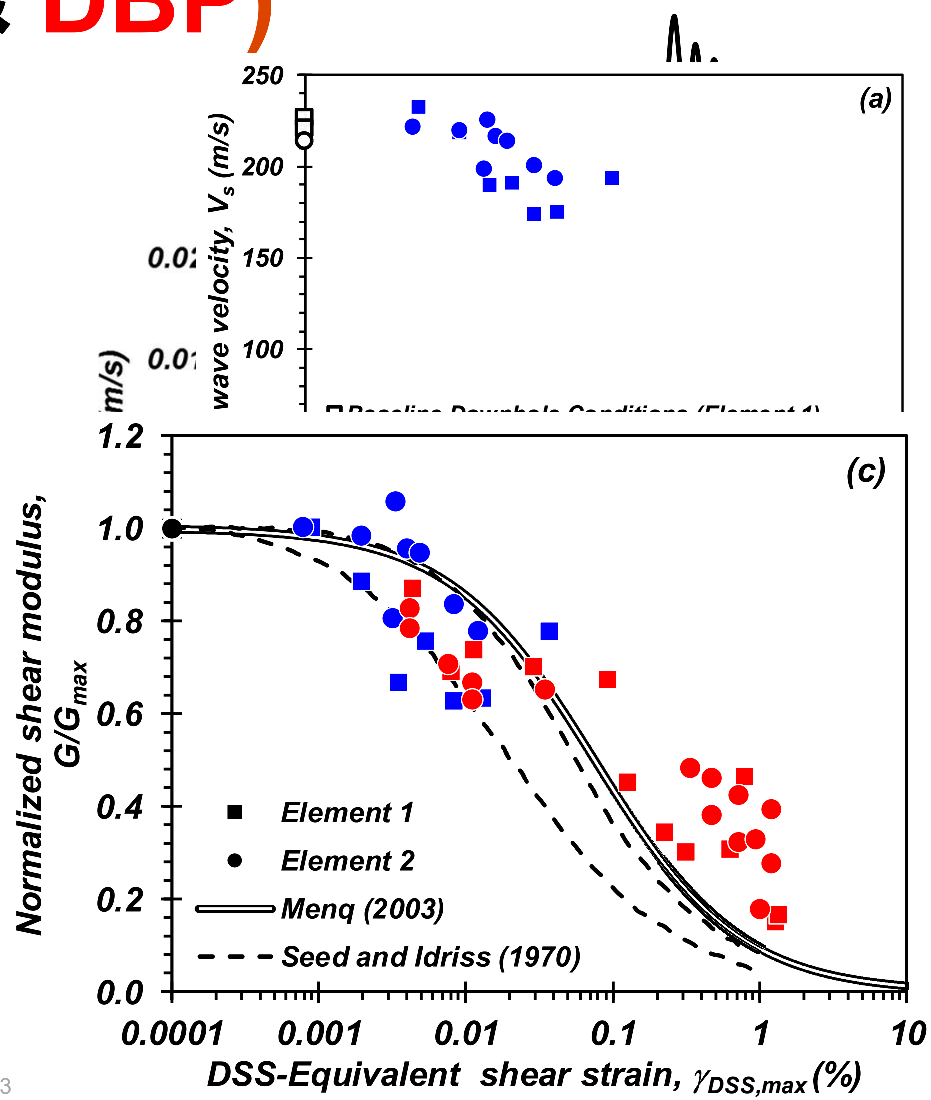
- Maximum excess pore pressure, $r_{u,max}$, occurs at smaller γ_{max} than implied by EPWP model for sands (C&B 2012)
- Drainage towards end of DBP inhibits larger $r_{u,max}$
- Strain-controlled CDSS data confirm γ-r_u relationship at v. small & large strains, until drainage initiates

Key Observations (TBP & DBP)

Shear Modulus Reduction with Shear Strain

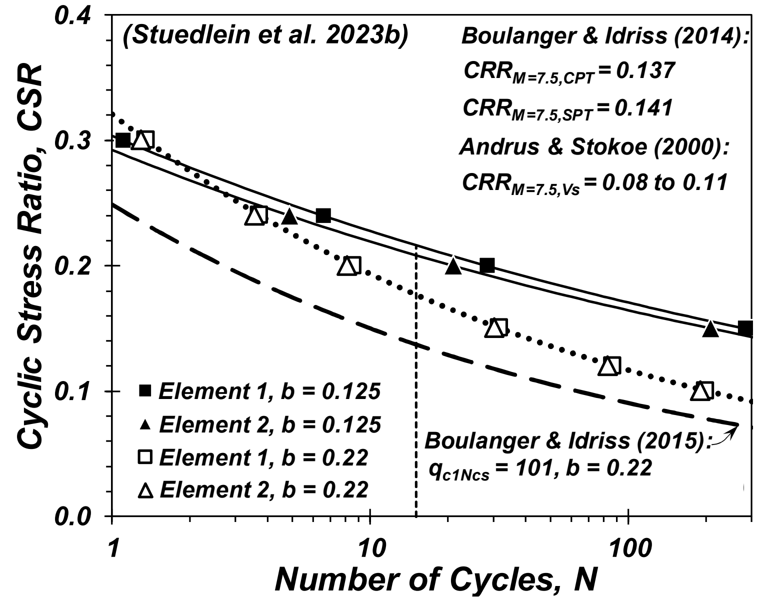
- Baseline V_s established through downhole and cross-hole (blast) tests (TBP), and downhole (DBP)
- Shear wave velocity calculated for each charge as the waveform passes through the array
- V_s is matched with its corresponding shear strain
- Shear modulus deduced: $G_{max}, G = \rho \cdot V_s^2$
  - Initial loss of stiffness consistent with previously-reported laboratory data
  - Effects of multi-directional loading?
  - Large strain response indicative of field ***drainage***

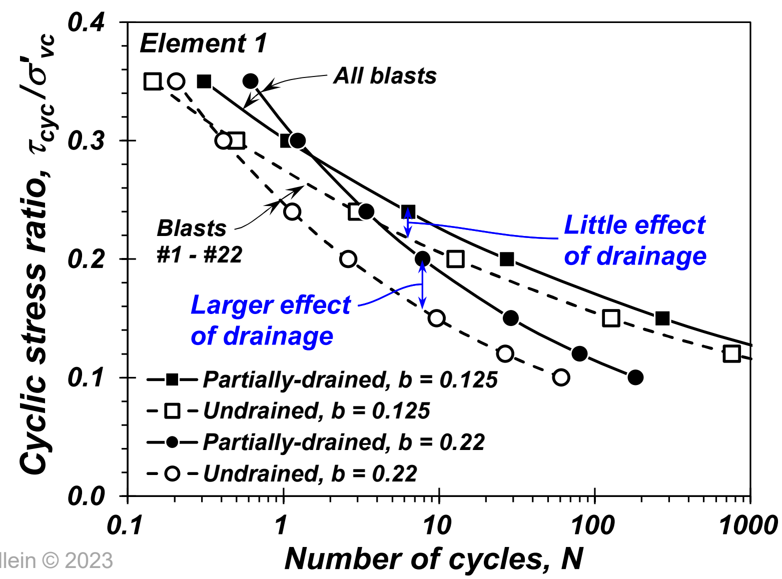
(Jana & Stuedlein (2021)



Outstanding Questions in Soil Liquefaction

- In-situ cyclic resistance > case history-based triggering estimates (*upper right figure*)
- Effects of drainage has been documented; partial drainage increases resistance (*lower right figure*)
- What are the effects of multidirectional shaking?
  - Blast-induced S-waves produce 2D or 3D shaking
  - Effect on cyclic resistance mixed – *needs further study*
- Blasting → 3D excess pore pressure field (?)
- Does partial drainage occur in the field?
  - Possible for long-duration (CSZ) earthquakes
  - *Need to confirm effects on shear modulus, amplification*
- **Propose construction of bidirectional laminar box to fully leverage LHPOST6 capabilities**





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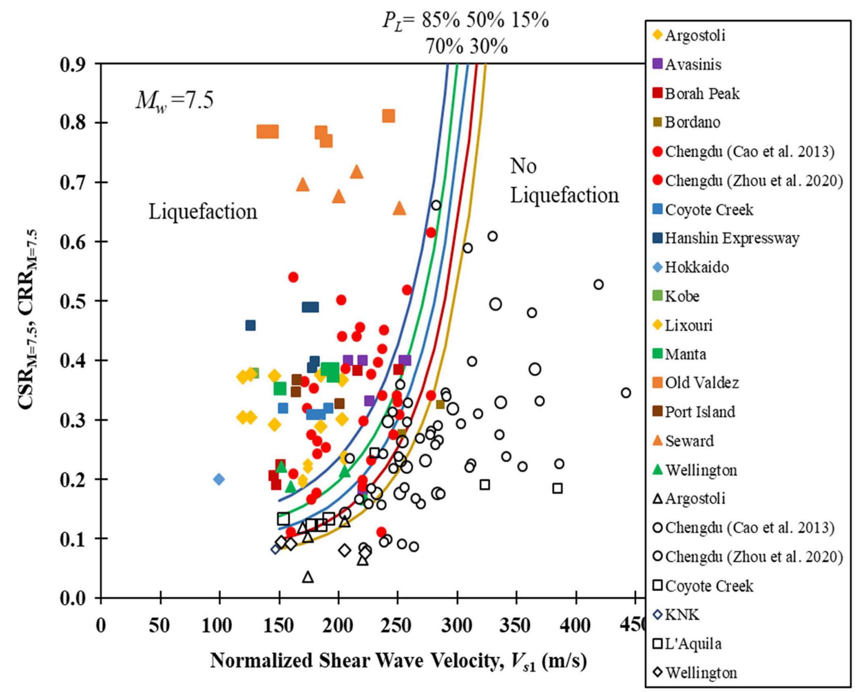
Liquefaction of Gravels

Liquefaction of Gravels

Concerns

- The coupled fluid-mechanical seismic response of natural, native gravelly soils *in-situ* has never been observed in a controlled experimental setting
- Penetrometer-based estimates of cyclic resistance
  - DPT – small penetrometer relative to some gravel sizes
  - BPT or iBPT: relies on correlations to SPT (?), not widely-available, $$$
- Uncertainties with V_s-based methods
  - New case history-based V_s liquefaction model available – great..!
  - But what about those gravels that liquefied without surface manifestation? Epistemic uncertainty in model?



Rollins et al. (2022)

Liquefaction of Gravels

Concerns, Variables, Hypothesis

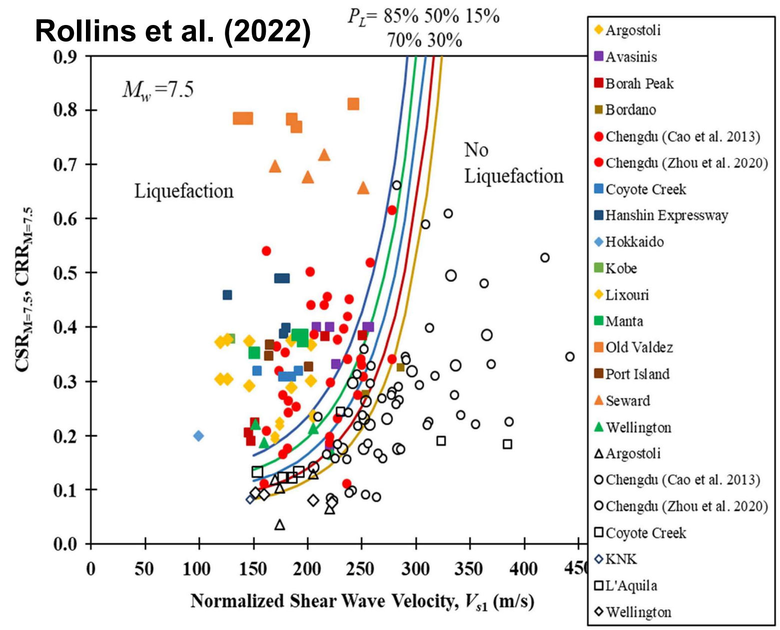
- Epistemic uncertainty → reducible uncertainty
- Penetration resistance *can* account for effects of gradation through blow count, but subject to partial drainage when fine sand, silts, and clays comprise the matrix between large particles
- Gradation is key:
  - Poorly-graded gravels drain fast, but exhibit large void ratios and have lower V_s as a result; when capped, drainage is prohibited
  - Well-graded gravels cannot drain fast, but exhibit small void ratios, have larger V_s, and larger cyclic resistance as a result
- Demonstration via the cyclic strain approach

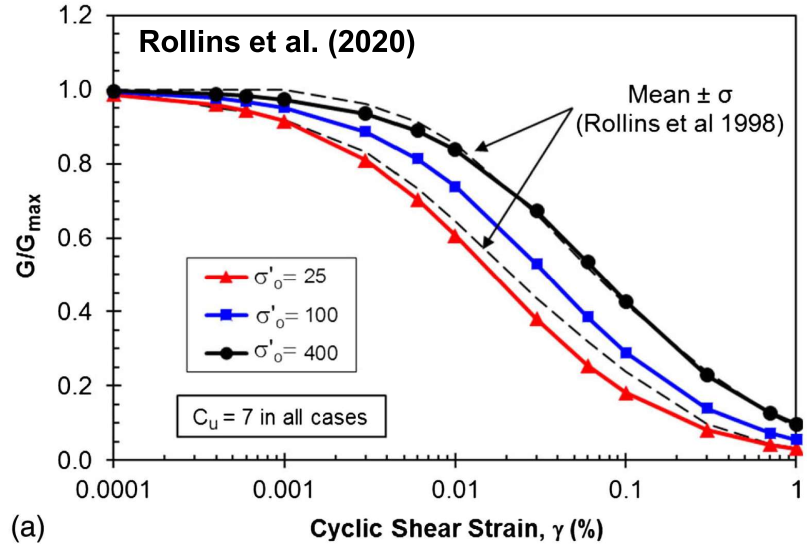
Liquefaction of Gravels

Cyclic Strain Approach

- Proposed in discussion to Rollins et al. (2022)
- Set *CRR* from V_s-based triggering model equal to that expected from shear modulus degradation → probabilistic shear strain to trigger liquefaction, $\gamma_{cl}(P_L)$
- Allows coefficient of uniformity, C_u to be included in liquefaction triggering analyses

$$CRR = \exp\left(\frac{3.88*10^{-7}*V_{s1}^3 - 1.6*M_w - \ln\left(\frac{1-P_L}{P_L}\right)}{4.95}\right) \qquad \frac{G_{cl}}{G_{max}} = \frac{1}{1+\left(\frac{\gamma_{cl}}{\gamma_r}\right)^{0.84}}$$



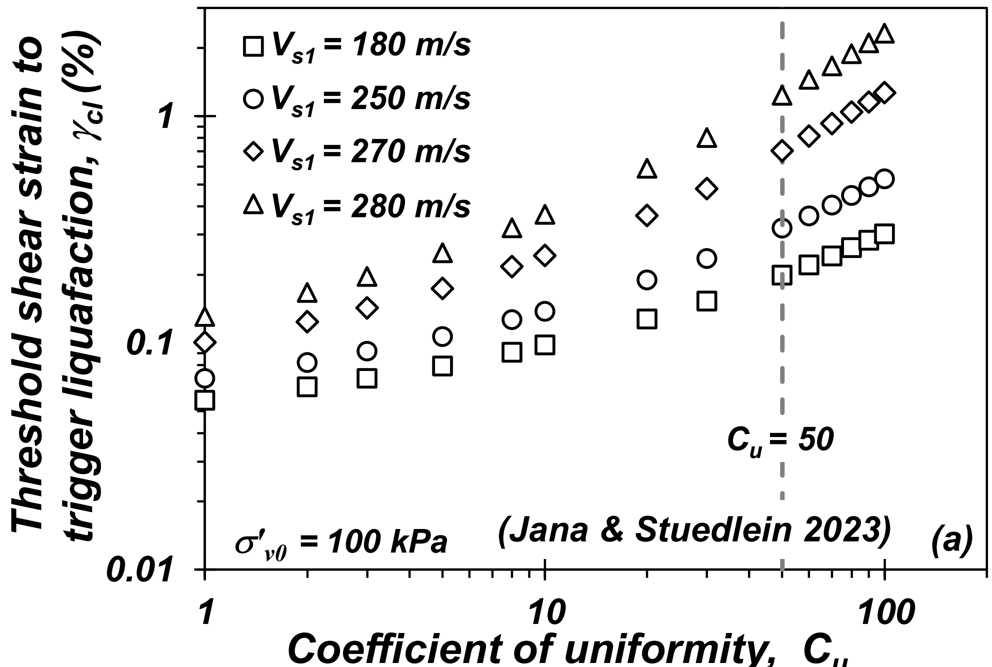


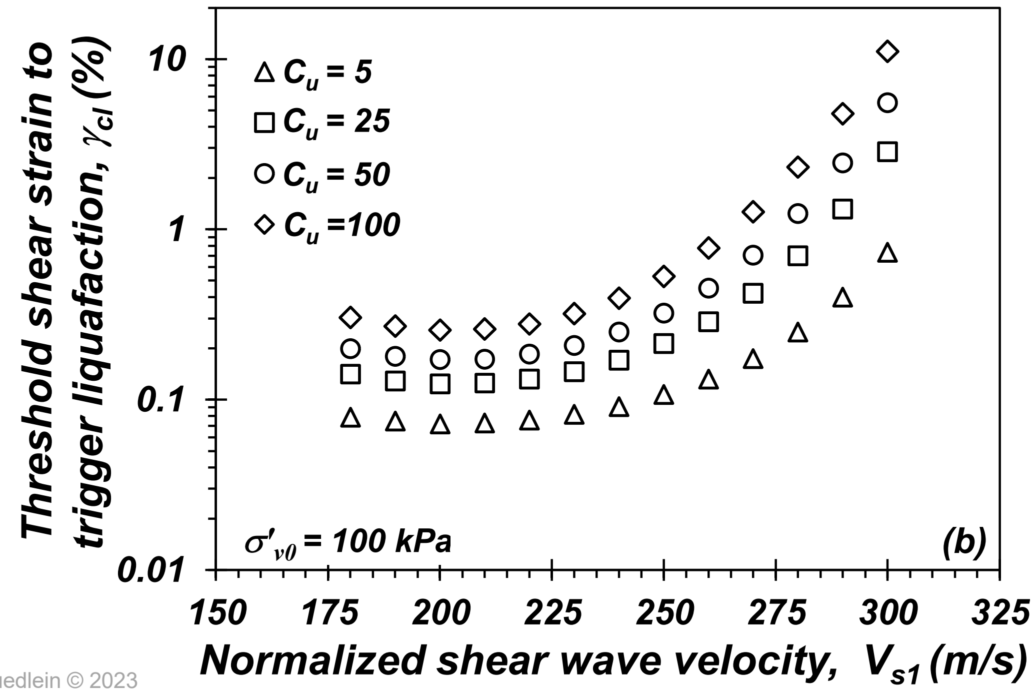
(a)

Liquefaction of Gravels

Proposed Cyclic Strain Approach (Jana & Stuedlein 2023)

$$\gamma_{cl} = \exp\left(\frac{3.88*10^{-7}V_{s1}^3 - 1.6M_w - \ln\left(\frac{1-P_L}{P_L}\right)}{4.95}\right)\left[\frac{\frac{\sqrt{\sigma'_{v0}}}{0.1*\rho*V_{s1}^2}}{1+\left\{\frac{\gamma_{cl}}{0.0046(C_u)^{-0.197}(\sigma'_0)^{0.52}}\right\}^{0.84}}\right]$$





Liquefaction of Gravels

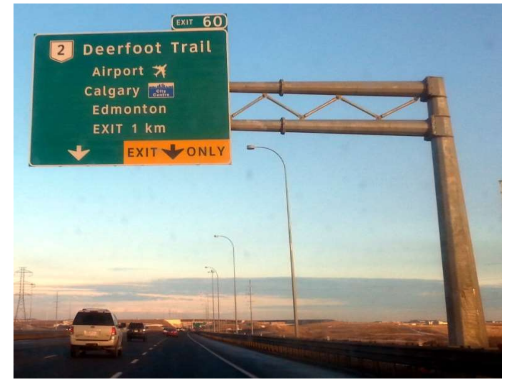
Proposed Cyclic Strain Approach (Jana & Stuedlein 2023)

- Deterministic γ_{max} can be computed directly
- We determined C_u and γ_{max} for 70 of 174 case histories
- For all liquefaction ("Yes") cases, except 3, $\gamma_{max} > \gamma_{cl}$
- For all "No" cases, except 5, $\gamma_{max} < \gamma_{cl}$ (effect of capping layer?)
- γ_{max} for 1964 Anchorage EQ very large for lateral spreading and flow slide case histories (sometimes exceeding 1,000%)
- ***We can measure γ_{max} in-situ or in a laminar container***
- *Thus, we can directly test our cyclic strain-based approach*

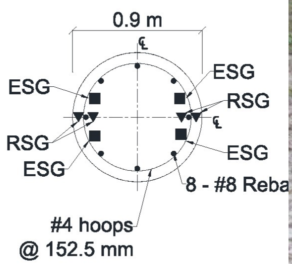
Combined Loading on Deep Foundations

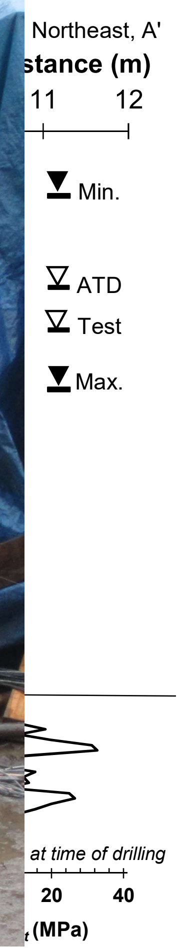
Combined Loading on Deep Foundations

- Axial-lateral-torsional loadings
- Sources of combined loadings:
  - Mast arm signal- and signage poles (gravity, wind)
  - Near and offshore structures (berthing/mooring loadings)
  - Skewed bridges (seismic)
  - Asymmetric buildings (wind, seismic)
- These loadings can be extreme and are uncertain
- Resistance..? ODOT-funded study shed some light on this topic



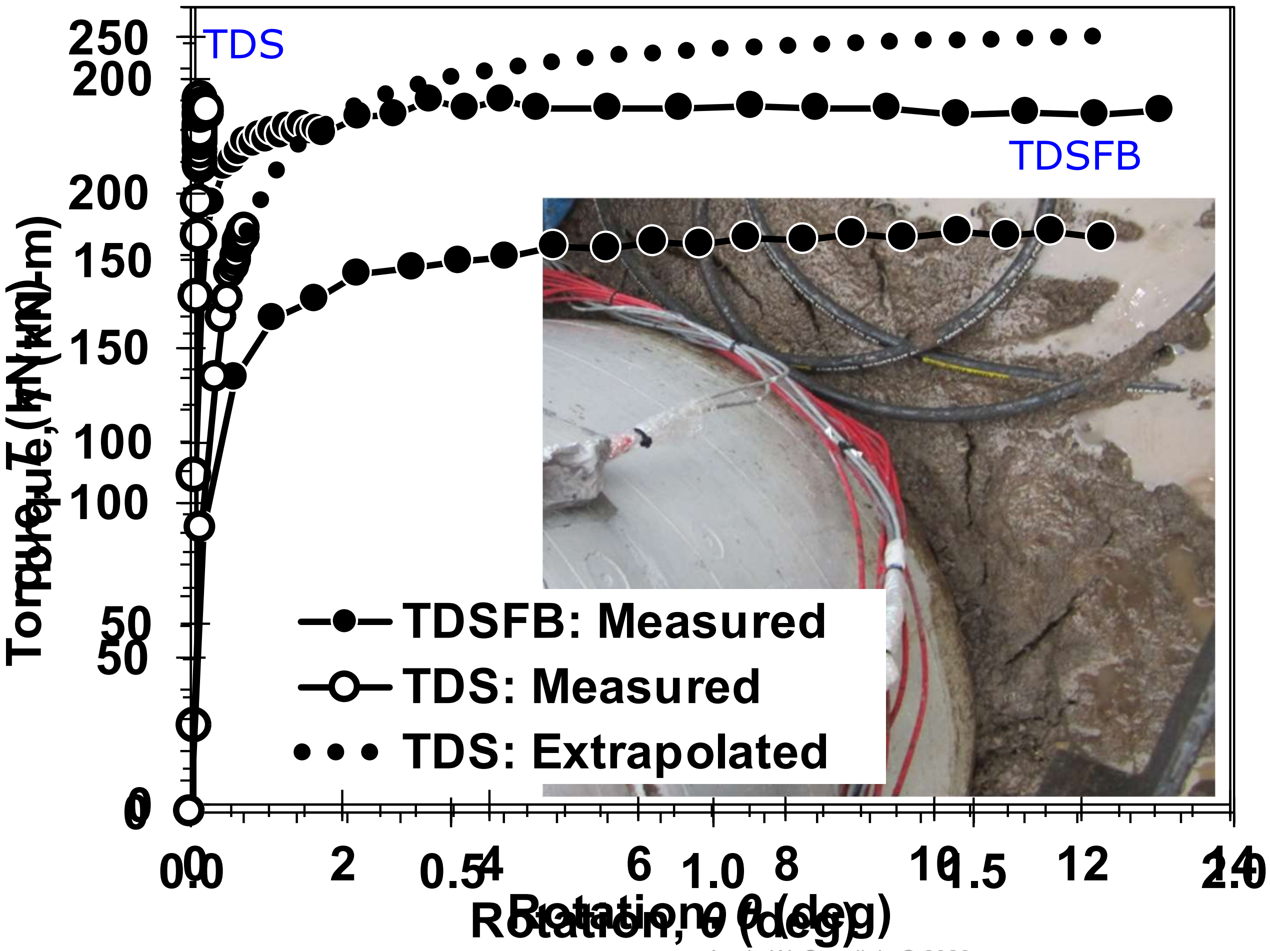
Instrumented, Full-scale Specimens





Quasi-Static Torsional Loading

Applied Rotation at Head vs. Developed Torque

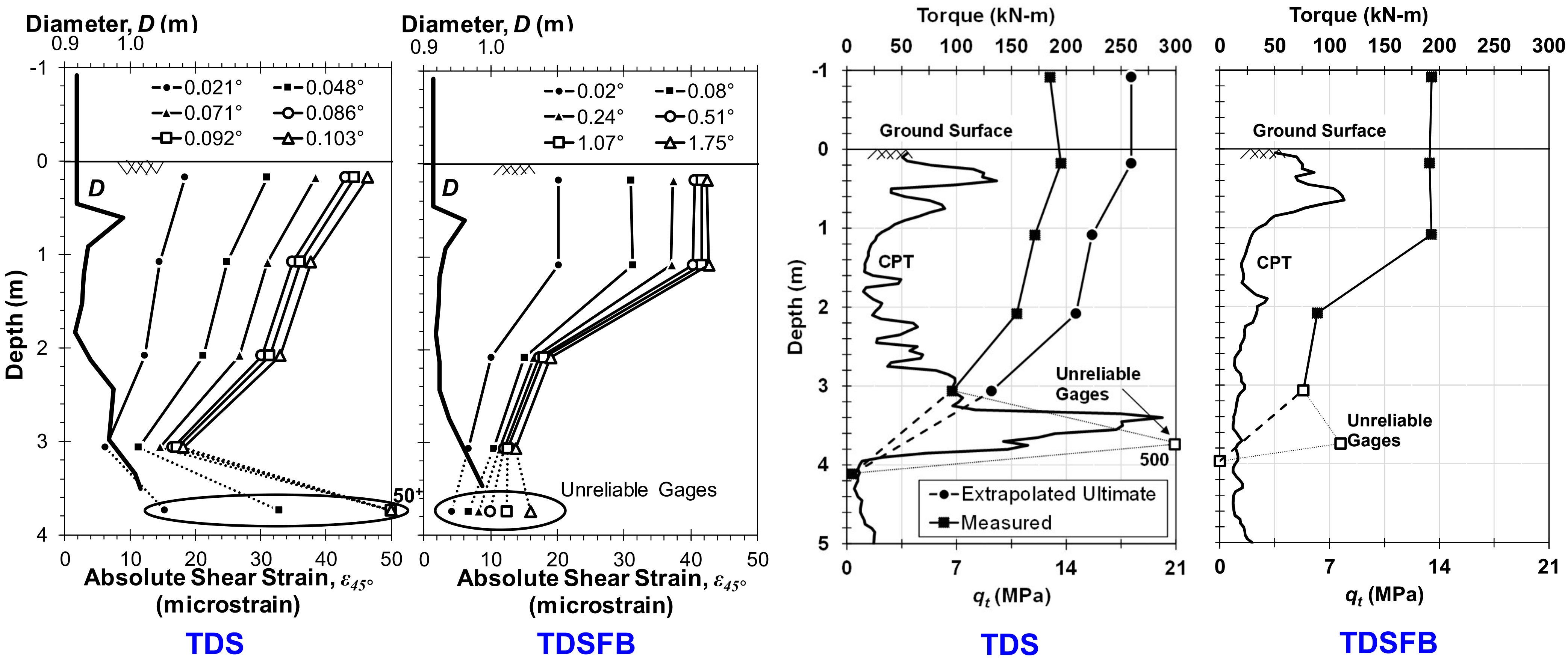


Take-away:

Torsional resistance is a "small" rotation (displacement) phenomenon

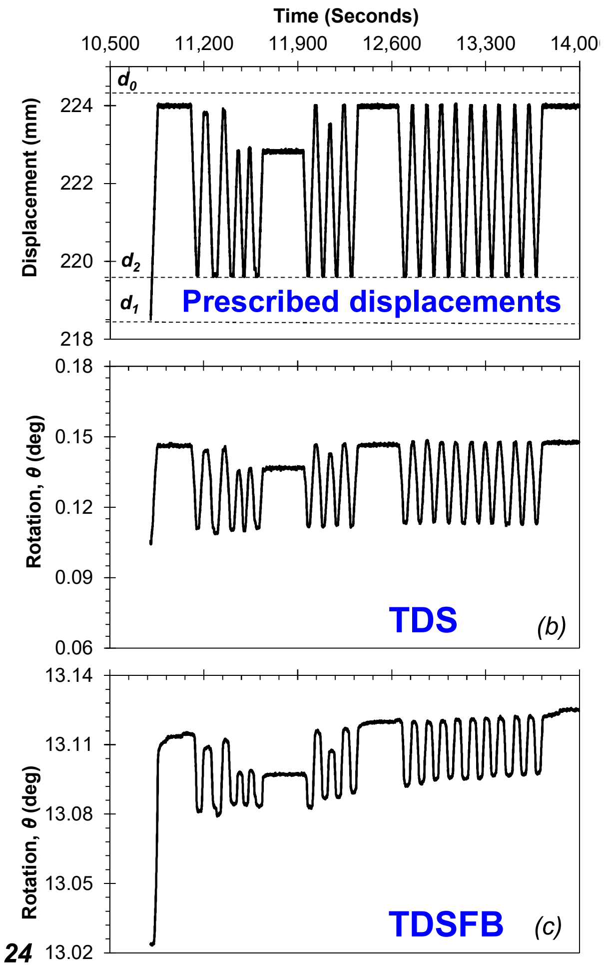
Quasi-Static Torsional Loading

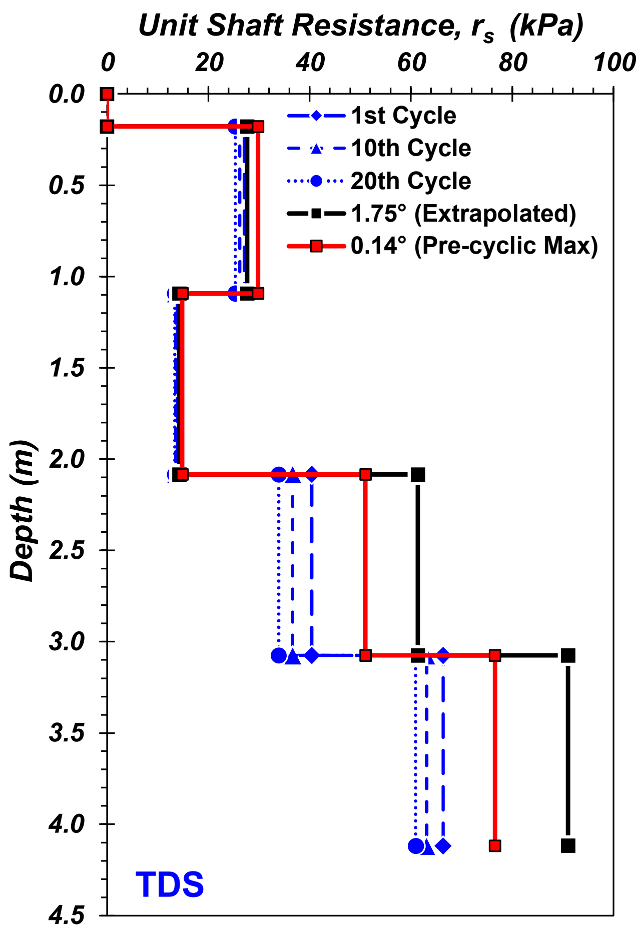
Distribution of Shear Strain & Torsional Load Transfer



Quasi-Static Cyclic Torsional Loading

Loading Protocol, Global Response, Unit Shaft Resistances



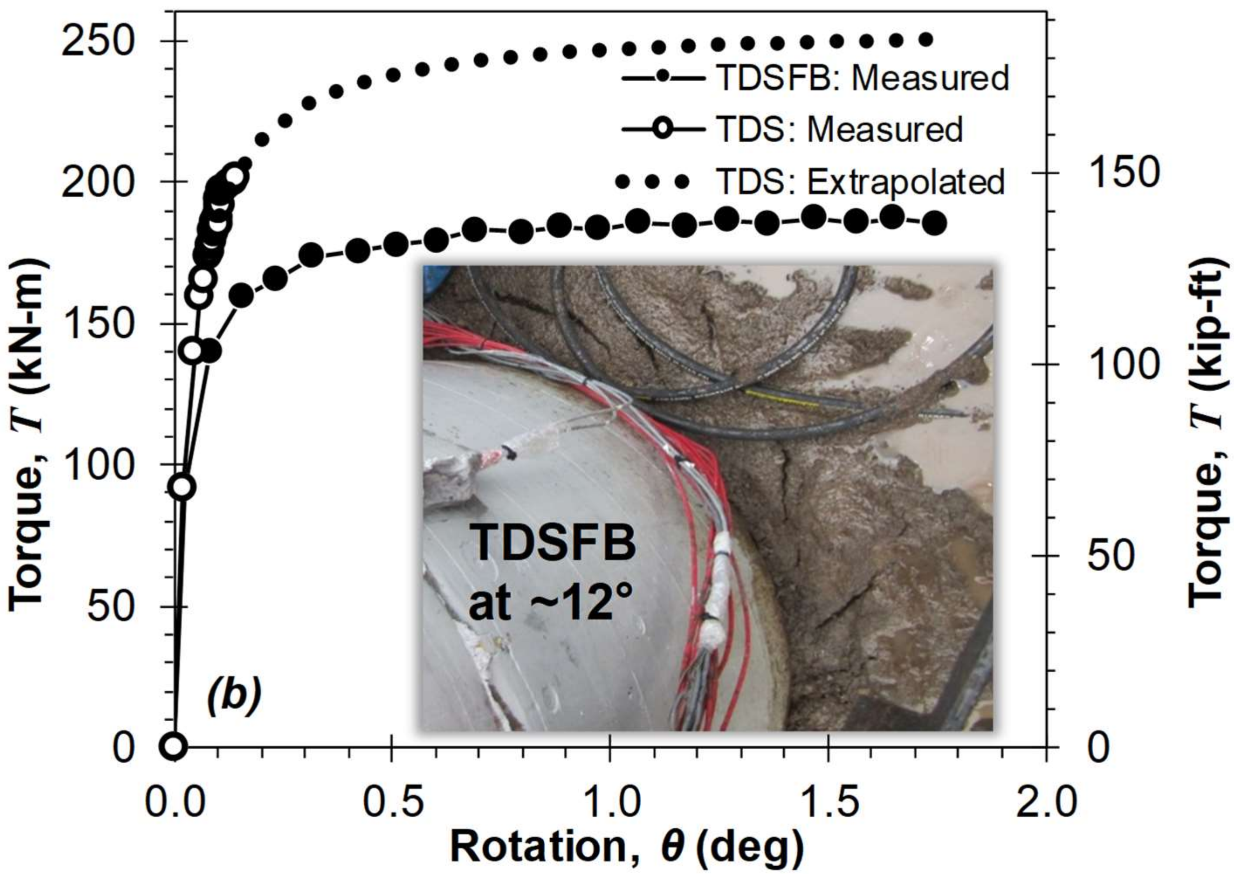


- No significant change in global torsional response with number of cycles
- Initial cyclic stiffness similar between both shafts, but post-yield stiffness for TDS 2x larger than for TDSFB due to dense sand layer
- Local response shows possible softening and/or friction fatigue

Combined Loading (*Incidental…*)

Recall:

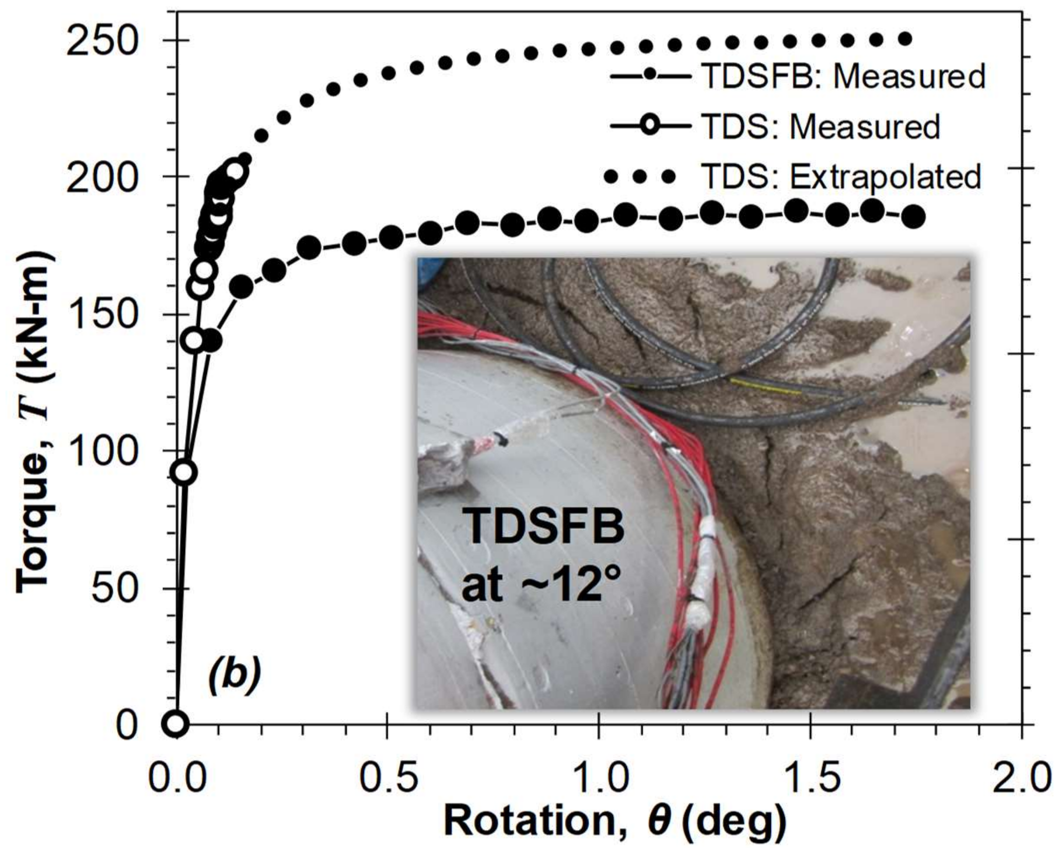
- Radial ground cracks opened next to TDSFB during torsional loading
- One shaft experienced “geotechnical failure”, the other did not…
- Differential mobilization of resistance under a displacement couple requires an induced lateral load for torsional equilibrium….
- Allows insight into effect of combined loading



Combined Loading

Significant Differences in Lateral Responses

- The initial response of TDS (no ground cracking) indicated little impact of combined loading
- Not so for TDSFB (with ground cracking)
- Torsional shear-induced cracks must first close prior to the generation of lateral resistance
- If torsional shear occurs prior to large lateral movements, then the lateral response will be soft.
- ***Consider torsional loading prior to near-fault velocity pulse…***



Very little rotation required to mobilize ultimate torsional resistance…!

Combined Loading

Bending Moment Profiles; Poorly-captured using 1D Methods

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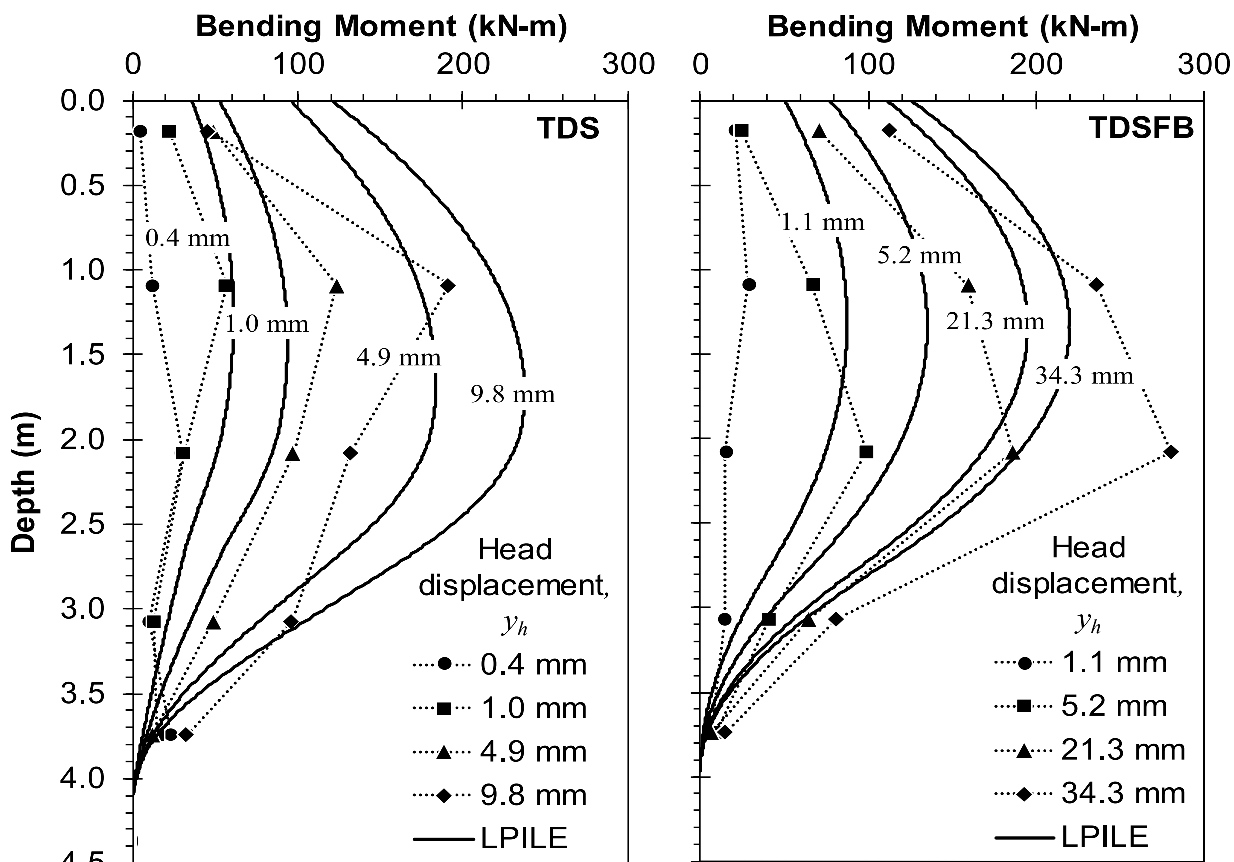
- Typical lateral loading simulation (e.g., L-Pile) cannot capture effect of combined flexure and torsional shear
- In case of TDSFB, the maximum bending moment was significantly under-predicted as a result
- **LHPOST6 + Laminar Box: apply controlled torsional, and inertial and kinematic lateral loading to study effects of combined loading, develop numerical methods for simulation**



Acknowledgements

- **Sponsors**
  - National Science Foundation
  - Port of Portland
  - Cascadia Lifelines Program
  - Oregon DOT
  - Pacific Earthquake Engineering Research Center

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