Some Challenges & Opportunities in the Field of Geotechnical & Soil-Structure-Interaction - (Geo-Structures)

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Overview

• 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

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

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Behavior</th>
<th>$r_{u,\text{max}}$ (%)</th>
<th>$G_{\text{tan,min}}/\tau_{\text{cyc,max}}$</th>
<th>$\Delta\tau_{\text{cyc}}/\tau_{\text{cyc,max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>F-2-6</td>
<td>Interm. Sand</td>
<td>93</td>
<td>99</td>
<td>10.12</td>
</tr>
</tbody>
</table>

Stuedlein et al. (2023a)
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
Partial Drainage & Multi-directional Shaking
Instrumentation Techniques

- 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

(Armin W. Stuedlein © 2023)
Field Experiments
Controlled Blasting @ Depth of ~25 m
Key Observations \((TBP \ & \ DBP)\)  
Shear Strain vs. Excess Pore Pressure

- Maximum excess pore pressure, \(r_{u,max}\), occurs at smaller \(\gamma_{max}\) 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 \(\gamma\sim r_u\) 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: $G_{\text{max}}, G = \rho \cdot V_s^2$
  - Initial loss of stiffness consistent with previously-reported laboratory data
  - Effects of multi-directional loading?
  - Large strain response indicative of field *drainage*
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
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 $\rightarrow$ 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 $\rightarrow$ probabilistic shear strain to trigger liquefaction, $\chi_{cl}(P_L)$
• Allows coefficient of uniformity, $C_u$ to be included in liquefaction triggering analyses

\[
CRR = \exp\left(\frac{3.88 \times 10^{-7} V_s^3 - 1.6 M_w - \ln\left(\frac{1-P_L}{P_L}\right)}{4.95}\right)
\]

\[
\frac{G_{cl}}{G_{max}} = \frac{1}{1 + \left(\frac{\chi_{cl}}{\chi_r}\right)^{0.84}}
\]

Rollins et al. (2020)
Mean $\pm \sigma$ (Rollins et al. 1998)

$C_u = 7$ in all cases
Liquefaction of Gravels

Proposed Cyclic Strain Approach (Jana & Stuedlein 2023)

\[
\gamma_{cl} = \exp\left(\frac{3.88 \times 10^{-7}V_{s1}^3 - 1.6M_w - \ln\left(\frac{1 - P_L}{P_L}\right)}{4.95}\right) \left[\sqrt{\frac{\sigma'_{\nu0}}{0.1 \rho V_{s1}^2}} \cdot \frac{V_{cl}}{0.0046(C_u)^{0.197}(\sigma'_n)^{0.52}}\right]^{0.84}
\]

Threshold shear strain to trigger liquafaction, \(\gamma_{cl}(\%)\)

- \(V_{s1} = 180 \text{ m/s}\)
- \(V_{s1} = 250 \text{ m/s}\)
- \(V_{s1} = 270 \text{ m/s}\)
- \(V_{s1} = 280 \text{ m/s}\)

<table>
<thead>
<tr>
<th>Coefficient of uniformity, (C_u)</th>
<th>(\sigma'_{\nu0} = 100 \text{ kPa})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(Jana &amp; Stuedlein 2023)</td>
</tr>
<tr>
<td>10</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

Threshold shear strain to trigger liquafaction, \(\gamma_{cl}(\%\)

- \(C_u = 5\)
- \(C_u = 25\)
- \(C_u = 50\)
- \(C_u = 100\)

\(\sigma'_{\nu0} = 100 \text{ kPa}\)

Normalized shear wave velocity, \(V_{s1}(\text{m/s})\)

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Liquefaction of Gravels
Proposed Cyclic Strain Approach (Jana & Stuedlein 2023)

- Deterministic $\gamma_{\text{max}}$ can be computed directly
- We determined $C_u$ and $\gamma_{\text{max}}$ for 70 of 174 case histories
- For all liquefaction ("Yes") cases, except 3, $\gamma_{\text{max}} > \gamma_{\text{cl}}$
- For all “No” cases, except 5, $\gamma_{\text{max}} < \gamma_{\text{cl}}$ (effect of capping layer?)
- $\gamma_{\text{max}}$ for 1964 Anchorage EQ very large for lateral spreading and flow slide case histories (sometimes exceeding 1,000%)

- **We can measure** $\gamma_{\text{max}}$ **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
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

- 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...!
• 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
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By others


