Session 2: Triggering of Liquefaction

Plenary Speaker: Geoff Martin  
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University of Southern California

- What are the primary deficiencies in the simplified method for evaluation of liquefaction potential, and how they can be improved?
- What is the role of other triggering evaluation procedures in current practice and in the future?

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Historical Developments

- Triggering: Laboratory Cyclic Simple Shear Tests

Stress Controlled Test  
(Peacock and Seed, 1968)  

Strain Controlled Test  
(Bhatia et al, 1980)
Historical Developments

- Laboratory Test Based Liquefaction Strength – Issues for Use in Design (Seed, 1979):
  - Sample preparation methods (given Dr)
  - Field sample disturbance
  - Influence of in situ k_0
  - Influence of prior seismic strains and multi-direction loading
  - Influence of sample age

Influence of Dr and k_0 (Seed, 1979)

Influence of Strain History (Finn 1970)

- Liquefaction Strength (Cyclic Resistance Ratios CRR) Based on Field Case Histories:

Recommended CRR Curves from SPT Data
(M=7.5) (Youd and Idriss, 1997)
Historical Developments

- Liquefaction Strength (Cyclic Resistance Ratios CRR) Based on Field Case Histories:
  - CPT Correlation Chart (Robertson and Wride, 1998)
  - Shear Wave Velocity Correlation Chart (Andrus and Stokoe, 2000)

Historical Developments

- Representative Triggering Analysis from an SPT Borings
  - Example Analysis (After Idriss and Boulanger, 2008)
CPT: Better Evaluation of Complex Stratigraphy

Complex Stratigraphy– Triggering Interpretation is Difficult

- Post Liquefaction Settlement Reflects Changes in Sand Structure from large Shear Strain Response

Stress Controlled Undrained Cyclic Simple Shear Test (Dr=60%)

Limiting Shear Strains (after Seed, 1976)

Design Chart (after Tokimatsu and Seed, 1987)
Low Plasticity Sandy Silt: Need for Laboratory Tests

Schematics of the transition from sand-like to clay-like behavior for fine-grained soils with increasing PI, and the recommended guidelines for practice.

Cyclic Simple Shear Test Results: U.C. Berkeley Laboratory

Load/Unload Behavior

Mechanism of Pore Pressure Increase

DESRA: Constitutive Model

- Relationship between Volume Reduction during Drained Tests and Pore-Water Pressure Increase in Undrained Tests

Martin, Finn & Seed (1975)
Fundamentals of Liquefaction under Cyclic Loading, ASCE J.GED, May.

\[ \Delta \mu = \mu \cdot \Delta \varepsilon_{vd} \]

Liquefaction will occur when: \( \varepsilon_{vd} = \varepsilon_{VR} \)
Non-Uniform Load Cycle Simulations

After Martin et al., 1975
After Bhatia et al., 1980

DESRA: Program Development – 1977/78

- Coupled Nonlinear Dynamic Analysis and Pore Pressure Response – A Mechanistic Triggering Analysis

- 1D Analysis - Vertically propagating shear waves
- Layered soil profile converted to lumped mass system connected with nonlinear springs with inherent hysteretic damping
- Differential equation of motion

\[ [M]\ddot{x} + [C]\dot{x} + [K]x = -[M] \ddot{u}_g(t) \]

solved numerically in time domain
- Typically use 2% viscous damping
**Dissipation/Redistribution of Pore-Water Pressure**

- Pore-water pressure in undrained layers of sand during earthquake will not be in instantaneous equilibrium.
- Continuous re-distribution take place under gradients established and possibly dissipation.
- The equation below must be solved numerically in conjunction with equation of motion to continually update values of pore-water pressure.

\[
\frac{\partial u}{\partial t} = E_r \frac{\partial}{\partial z} \left( k \frac{\partial u}{\partial z} \right) + E_r \frac{\partial \varepsilon_{vd}}{\partial t}
\]

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**DESRA: Program Development – 1977/78 (Continued)**

- Hyperbolic Nonlinear Backbone Curve Replaced by Iwan Model
- Hysteresis Loops from Iwan Model
- Development of Backbone Curve from Shear Modulus Reduction Curves

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**DESRAMUSC: Modifications to DESRA**

- Hyperbolic Nonlinear Backbone Curve Replaced by Iwan Model
DESRA: Practical Site Liquefaction Application

- Housing Development Site, M7 Design Earthquake, PGA 0.25 g


DESRA: Practical Site Liquefaction Application (continued)

- Acceleration Time History
- Representative Pore Pressure Time History
- DESRA Pore Pressure Response vs. SPT F.O.S.
Liquefaction Study Report
Recommended LRFD guidelines for the seismic design of highway bridges

DESRAMUSIC: Practical Site Liquefaction Application (continued)

- Liquefaction Study Report
  NCHRP Project 12-49
  MCEER Report-03-SP08.

- Site Response Studied for M6.5, 7.0, and 7.5 Earthquakes
  PGA = 0.24g
  (475-yr Return Period)

Soil Profile - Washington Site
DESRAMUSC: Practical Site Liquefaction Application (continued)

- Simplified Liquefaction Potential Evaluation

- Backbone Curve Construction

- Liquefaction Strength Curve

- Representative DESRAMUSC Parameters

- Stress Ratio

- Number of Cycle

- Shear Strain (%)

- Backbone Curve Construction
DESRAMUSC: Practical Site Liquefaction Application (continued)

Acceleration Time Histories and Spectra

Pore Pressure Time Histories

<table>
<thead>
<tr>
<th>Elevation</th>
<th>Soil Type</th>
<th>Cyclic Resett. Ratio CRR</th>
<th>Res. Strength B_u</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.0</td>
<td>1. Sand</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.0</td>
<td>2. Soft Clay</td>
<td></td>
<td>0.15</td>
</tr>
<tr>
<td>-15.0</td>
<td>3. Sand</td>
<td></td>
<td>0.2</td>
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<tr>
<td>-20.0</td>
<td>4. Sand</td>
<td></td>
<td>0.3</td>
</tr>
<tr>
<td>-25.0</td>
<td>5. Sand</td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>-30.0</td>
<td>6. Sand</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>-35.0</td>
<td>7. Soft Clay</td>
<td></td>
<td>0.6</td>
</tr>
<tr>
<td>-40.0</td>
<td>8. Sand</td>
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<td>9. Sand</td>
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<td>0.8</td>
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<tr>
<td>-50.0</td>
<td>10. Sand</td>
<td></td>
<td>0.9</td>
</tr>
<tr>
<td>-55.0</td>
<td>11. Soft Clay</td>
<td></td>
<td>1.0</td>
</tr>
</tbody>
</table>

-100.0
Shear Stress-Strain Hysteresis Loops

Maximum Shear Strains
Summary

- Deficiencies in Simplified Method for Determining Triggering:
  - Unable to reflect influence of pore-water pressure increases and potential redistribution in complex stratigraphy
  - Unable to reliably establish potential for post earthquake deformation/settlement in complex stratigraphy
  - Unable to reflect influence of site-specific acceleration time histories on triggering

- Triggering evaluations are more reliably assessed using effective stress site response analyses using site specific acceleration time histories

Summary (Continued)

- Role of other Triggering Evaluation Procedures
  - Current simplified methods to determine CRR (SPT, CPT, $V_s$) dominate current practice, but are best used in conjunction with each other where possible
  - A potential simplified cyclic strain based method may have some merit
  - Studies of the role of site-specific effective stress site response analyses to evaluate both triggering and post liquefaction deformations, seem the best way forward to eliminate uncertainties in current simplified methods for design
  - Future role of laboratory cyclic tests?