Centrifuge Modeling of Settlement and Lateral Spreading with Comparisons to Numerical Analyses

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Overview

- Background of the Project
- Centrifuge Test Series
- Experimental Findings
- Numerical Analyses Methods
- Comparisons with Numerical Simulations
- Conclusions
Purposes of Project

- To study effects of liquefiable layer thickness, Dr, and ground motion characteristics on the amount of settlement and lateral spreading

- Perform initial validation studies on selected numerical procedures (e.g., SUMDES, OpenSEES)

- Provide data base on web for verification of analysis methods (http://cgm.engr.ucdavis.edu) (e.g., CYCLIC; Elgamal and Yang, UCSD)
Background

- A. Balakrishnan
  - 2 Centrifuge Tests
  - SUMDES

- K. K. Manda
  - 3 Centrifuge Tests
  - SUMDES

- S. Gajan
  - 1 Centrifuge Test
  - OpenSEES
  - Summary of Findings
General Model Configuration

PLAN

ELEVATION ON A - A
# Test Series

## Model Details

<table>
<thead>
<tr>
<th>Model Code</th>
<th>Model Details</th>
<th>Slope of Clay (C)</th>
<th>Slope of Sand (S)</th>
<th>Height of W.T. (H)</th>
<th>L and W</th>
</tr>
</thead>
<tbody>
<tr>
<td>C80</td>
<td>H1 = 0m</td>
<td>9.3%</td>
<td>3.3%</td>
<td>1.2m</td>
<td>L = 1.72m</td>
</tr>
<tr>
<td></td>
<td>Dr2 = 80%, H2 = 15</td>
<td></td>
<td></td>
<td></td>
<td>W = 0.69m</td>
</tr>
<tr>
<td>U50</td>
<td>Dr1 = 50%, H1 = 9m</td>
<td>9.0%</td>
<td>3.0%</td>
<td>1.2m</td>
<td>L = 1.72m</td>
</tr>
<tr>
<td></td>
<td>Dr2 = 80%, H2 = 6m</td>
<td></td>
<td></td>
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<td>W = 0.69m</td>
</tr>
<tr>
<td>U50_4.5</td>
<td>Dr1 = 50%, H1 = 4.5m</td>
<td>9.3%</td>
<td>3.3%</td>
<td>1.2m</td>
<td>L = 1.72m</td>
</tr>
<tr>
<td></td>
<td>Dr2 = 80%, H2 = 10.5m</td>
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<td></td>
<td></td>
<td>W = 0.69m</td>
</tr>
<tr>
<td>U50_4.5S</td>
<td>Dr1 = 50%, H1 = 4.5m</td>
<td>3.0%</td>
<td>3.0%</td>
<td>1.2m</td>
<td>L = 1.65m</td>
</tr>
<tr>
<td></td>
<td>Dr2 = 80%, H2 = 7.5m</td>
<td></td>
<td></td>
<td></td>
<td>W = 0.78m</td>
</tr>
<tr>
<td>U30_4.5</td>
<td>Dr1 = 30%, H1 = 4.5m</td>
<td>9.3%</td>
<td>3.3%</td>
<td>1.2m</td>
<td>L = 1.65m</td>
</tr>
<tr>
<td></td>
<td>Dr2 = 80%, H2 = 7.5m</td>
<td></td>
<td></td>
<td></td>
<td>W = 0.78m</td>
</tr>
<tr>
<td>U30_4.5M</td>
<td>Dr1 = 30%, H1 = 4.5m</td>
<td>9.3%</td>
<td>3.3%</td>
<td>-0.3~1.3m</td>
<td>L = 1.65m</td>
</tr>
<tr>
<td></td>
<td>Dr2 = 80%, H2 = 7.5m</td>
<td></td>
<td></td>
<td>(Variable)</td>
<td>W = 0.78m</td>
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</table>
Average Base Accelerations

(a) Small Step Wave
(b) Small Kobe
(c) Large Kobe
(d) Intermediate Kobe

(a) Small Step Wave
(b) Small Kobe
(c) Large Santa Cruz
(d) Intermediate Santa Cruz

U50_4.5
U30_4.5M
Accelration & Displacement Response Spectra of the Base Motions

(a) Spectral Acceleration (g) vs. Period (sec)
(b) Spectral Displacement (m) vs. Period (sec)

- C80
- U50
- U50_4.5
- U50_4.5S
- U30_4.5
- U30_4.5M
Instrument Locations
(U30_4.5M)
Experimental Observation

- **Pore Pressure (kPa)**
  - 0
  - 25
  - 50
  - 75
  - 100

- **Lat. Movement (m)**
  - 0
  - 1
  - 2

- **Settlement (m)**
  - -0.8
  - -0.4
  - 0.0

- **Acceleration (g)**
  - -0.5
  - 0.0
  - 0.5

- **Abutment (L21)**
  - South river bank relative to base (L26 - L33)

- **South Central (P21)**

- **Ave. Base**

- **Time 5 seconds/tick mark**

**U50_4.5.**
Accelerations

(a) C80 A46
(b) U50 A46
(c) U50_4.5 A46
(d) U50_4.5S A46
(e) U30_4.5 A46
(f) U30_4.5M A46
Accelerations & PWP

U50

Pore pressure (kPa)

U30_4.5M

Pore pressure (kPa)
Evaluation of Shear Stresses

\[
\tau(z,t) = \int_0^z \rho \ddot{u} \, dz
\]

\[
\tau_i(t) = \tau_{i-1}(t) + \rho \frac{\ddot{u}_{i-1} + \ddot{u}_i}{2} \Delta z_{i-1}, \quad i = 2, 3, \ldots
\]

Elgamal et. al. (1996)
Calculation of Permanent Shear Displacements

- Measured from LVDT
- Calculated from ACC

- From LVDT, $D_d(t)$
- From ACC, $D_a(t)$

$fc = 0.3\, \text{Hz}, \, \text{Order} = 5$
Shear Stress – Shear Disp. Loops

- **σ'\(_{v0}\) = 16.8 kPa**
  - **ΔH = 2.19 m**
  - At Interface

- **σ'\(_{v0}\) = 32.0 kPa**
  - **ΔH = 1.35 m**
  - In Sand Layer

- **σ'\(_{v0}\) = 16.8 kPa**
  - **ΔH = 2.04 m**
  - At Interface

- **σ'\(_{v0}\) = 30.7 kPa**
  - **ΔH = 1.77 m**
  - In Sand Layer

(c) at interface
(d) in sand layer
Deformed Shapes of the Models

(a) C80

(b) U50

(c) U50_4.5

(d) U50_4.5S

(e) U30_4.5

(f) U30_4.5M
Deformations along the Depth

Settlement Beneath the Abutment (m)

Depth in Sand (m)

0.0 0.5 1.0

0 1.5 2.0 2.5 3.0

C80 U50 U50_4.5 U50_4.5S U30_4.5 U30_4.5M

Lateral Displacement (m)

C80 U50 U50_4.5 U50_4.5S U30_4.5 U30_4.5M

Depth in Sand (m)
Deformation Index (DI)

- To combine the effects of Density, Thickness and Depth

\[ DI (z) = \int_{z}^{\text{rigid base}} (1 - Dr)^2 \, dz \]

\[ DI (z) = \sum_{z} H_i (1 - Dr_i)^2 \]

For example, at the mid point of the Dr = 30% layer in U30_4.5,

\[ DI (2.25 \, m) = 2.25 \, m \, (1.0-0.3)^2 + 7.5 \, m \, (1.0-0.8)^2 = 1.40 \, m. \]
Deformation Index - Settlement

Points are labelled with peak base acceleration

- Large events
- Intermediate events
- Small events

$a_{\text{max}} = 0.8 \text{ g}$
Volumetric Strains

![Graph showing volumetric strains vs. relative density and peak base acceleration.]

- Peak base acceleration (g)
  - 0.0
  - 0.2
  - 0.4
  - 0.6
  - 0.8
  - 1.0
  - 1.2

- Vol. Strain = 7.5%
  - 4.0%
  - 2.0%
  - 0.5%

- Dr (%)
  - 20
  - 40
  - 60
  - 80

- Vertical Strain
  - 0.00
  - 0.05
  - 0.10
  - 0.15

- Notations for materials:
  - C80
  - U50
  - U50_4.5
  - U50_4.5S
  - U30_4.5
  - U30_4.5M
Volumetric Strain Contours

\[\text{Dr}_0 = \frac{e_{\text{max}} - e_0}{e_{\text{max}} - e_{\text{min}}} \quad \text{and} \quad \varepsilon_{v100} = \frac{e_0 - e_{\text{min}}}{1 + e_0}\]

to be

\[\varepsilon_{v100} = \left(1 - \frac{\text{Dr}_0}{\text{Dr}_0}\right) \frac{e_{\text{max}} - e_0}{1 + e_0}\]
Volumetric Strain Contours

\[ \tau_{av} = 0.65 \frac{a_{max}}{\sigma_0} \sigma_0 \gamma_d \]

\[ a_{base\_max} = g \]

\[ N1_{60} := C_{ER} \cdot C_N \cdot N \]

\[ Dr := 21 \left[ \frac{N}{(\sigma_0)^1 + 0.7} \right]^{\frac{1}{2}} \]

Tokimatsu and Seed (1987)
Volumetric Strain - Comparison

Tokimatsu and Seed (1987)
Finite Element Analysis

- 1-D Finite Element Analyses
  - SUMDES
  - OpenSEES
1-D Assumptions and Simplifications

- 3-D problem
  - South side can be simplified to 2-D

- Effect of river channel

- Effect of the slope of free surface
  - Away from the soil column considered

- Boundary effects
  - Flexible shear beam containers

- 1-D small strain simulations
  - cannot capture the effect of change of geometry as large deformations occur
SUMDES - Li et al. (1992)

- Sites Under Multi Directional Earthquake Shaking

- Horizontally layered sites subjected to multi directional earthquake shaking

- Nonlinear effective stress principle, fully coupled with pore pressure generation and dissipation

- Includes five different constitutive models

- Modified by Balakrisnan (2000) to include the effect of ground slope
Constitutive Model - SUMDES

Model Parameters

\[ \Phi, G_0, \kappa, \lambda, R_p / R_f, h_p, b, h_r, d, k_r \]
OpenSEES

- Open System for Earthquake Engineering Simulations – PEER

- Multi Yield Models (Yang and Elgamal, 2000)
  - PressureDependMultiYield (for sands)
  - PressureIndepependMultiYield (for clays)
  - FluidSolidPorous (for saturated soils under undrained loading conditions)

- Capable of doing 3-D analysis

- Fully undrained models
  - Pore pressure dissipations could not be simulated
Constitutive Model - OpenSEES
### Model Parameters - OpenSEES

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<tbody>
<tr>
<td></td>
<td>Nevada Sand</td>
<td>Bay Mud</td>
</tr>
<tr>
<td></td>
<td>Dr = 40%</td>
<td>Dr = 80%</td>
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<tr>
<td>Reference shear modulus (Mpa)</td>
<td>31.36</td>
<td>45.0</td>
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<td>Reference mean pressure (kPa)</td>
<td>80.0</td>
<td>80.0</td>
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<td>Pressure dependence coefficient</td>
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<td>0.5</td>
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<td>Friction angle (degrees)</td>
<td>32.3</td>
<td>38.0</td>
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<tr>
<td>Phase transformation angle (degrees)</td>
<td>26.5</td>
<td>28.0</td>
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<td>Contraction parameter 1</td>
<td>0.17</td>
<td>0.07</td>
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<td>Contraction parameter 2</td>
<td>-0.05</td>
<td>-0.03</td>
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<td>Dilation parameter 1</td>
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<td>Dilation parameter 2</td>
<td>130.0</td>
<td>130.0</td>
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<tr>
<td>Liquefaction parameter 1 (kPa)</td>
<td>10.0</td>
<td>5.0</td>
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<td>Liquefaction parameter 2 (%)</td>
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<td>Liquefaction parameter 3</td>
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<td>3.0</td>
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<tr>
<td>Liquefaction parameter 4</td>
<td>1.0</td>
<td>0.005</td>
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</tbody>
</table>
Soil Elements

- Accelerometer
- Pore pressure transducer
Comparisons with SUMDES

Comparison of Centrifuge results of test U50_4.5 with predictions from SUMDES
Comparisons with OpenSEES

Comparison of Centrifuge results of test U50_4.5 with predictions from OpenSEES
Shear Stress – Shear Disp. Loops (C80)

(a) At interface

Centrifuge

$\sigma'_{v_0} = 16.8 \text{ kPa}$

$\Delta H = 2.19 \text{ m}$

SUMDES

OpenSEES

(b) In sand layer

Centrifuge

$\sigma'_{v_0} = 32.0 \text{ kPa}$

$\Delta H = 1.35 \text{ m}$

SUMDES

OpenSEES
Lateral Movement Profiles

Lateral Displacement (m)

Depth in Sand (m)

U30_4.5

U30_4.5M

U50_4.5

U50_4.5S

C80

U50
Conclusions

- Excellent repeatability of centrifuge tests
- Transmitted acceleration spikes are dictated by the displacement spectra
- Lateral movement of the clay seems to be insensitive to the underlying sand layer thickness and density
- As the degree of improvement increases,
  - soil stiffness increases
  - more dilative acceleration spikes
  - more negative pore pressure spikes and early dissipation
- Deformations of the sand depend on both the density and thickness of the layer
- Deformation Index (DI) combines the effects of both density and thickness on settlement and lateral movement of sand
Conclusions (cont…)

- Measured volumetric strains of sands enable estimation of volumetric strain contours in (PBA - Dr) plot
- A thick medium dense sand layer may present more severe liquefaction consequences than thin loose layers
- Numerical simulations show reasonable agreement for acceleration, pore pressure and lateral movements
- Dilative behavior of sand is not well predicted by the simulations
- Settlements are under predicted by the simulations
- Permeability of the sand should be specified as a function of pore pressure ratio
Acknowledgements

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