Cyclic Behavior of Soils

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Cyclic Shearing of Sands
Dry Sand

Diagram showing the cyclic shearing process with stages labeled as Initial State, Initial State of Shearing, Large Strain Shearing, and Unloading.
Triaxial Undrained Monotonic Shearing

CIUC tests

Critical State
Toyoura Sand

Ishihara

Ishihara
Critical State

Ishihara

LCC vs. CSL

Pestana and Whittle
Discussion about the State parameter $\Psi$

![Diagram showing the definition of state parameter $\Psi$.]

Fig. 2. Definition of state parameter $\psi$

Been, 1985

Critical State
Toyoura Sand

![Diagram showing the critical state behavior of Toyoura Sand.]

Ishihara
Discussion about the State Parameter \( I_s \)

\[
I_s = \frac{(e_{\text{crit}} - e)}{(e_{\text{crit}} - e_{\text{ci}})}
\]

<table>
<thead>
<tr>
<th>State</th>
<th>Behaviour</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_s &lt; 0 )</td>
<td>Entirely collapsible behaviour—no residual strength</td>
</tr>
<tr>
<td>( 0 &lt; I_s &lt; 1 )</td>
<td>Partially collapsible behaviour—with or without peak conditions occurring before critical state conditions</td>
</tr>
<tr>
<td>( I_s &gt; 1 )</td>
<td>Peak and critical state conditions occurring simultaneously at large strains</td>
</tr>
</tbody>
</table>

Phase Transformation

CIUC(L)

Toyora Sand

Verdugo
Phase Transformation

 Been, 1985

Friction Angle

 Fig. 15. $\phi - \phi_0$ as a function of state parameter

 Been, 1985
Cyclic Loading

Cyclic Shearing of Sands

Undrained cyclic DSS test,
Medium Density Nevada Sand

Kammerer et al, 2002
Cyclic Shearing of Sands

- Liquefaction is the situation where the effective stress of the soil is reduced significantly during cyclic loading due to the contractive tendency of medium to loose sands

Niigata, 1964
Kobe Port Damages, 1995

Liquefaction Potential

- Number of Cycles to Liquefaction (Monterey Sand)

Wu, 2002
Multiaxial Cyclic Response
Applied Shear Stress Paths

Multi-axial Cyclic Response

Kammerer
Applied Shear Stress

Stresses (Plan View)

Dr=61%, CSRmax=0.45

Kammerer

Experimental Results

Dr=61%, CSRmax=0.45

Kammerer
Multi-axial Cyclic Response

Effect of Fines on CSL
Effect of Fines on CSL

Experiments

 CSL Based on Integranular Voids Ratio

Bouckovalas et al
Effect of pre-consolidation

Ishihara

Effect of Sample Preparation

Mullis et al. 1977
Cyclic Shearing of Sands

• Shear Behavior for a given sand depends on:
  – Voids ratio
  – Stress State
  – Percentage of fines
  – Anisotropy/ Soil Structure/ Placement method
  – Over-consolidation ratio
  – Mode of shearing

Clays – Chinese Criteria

• Fine-grained soils are susceptible to this type of behavior if they satisfy the criteria shown in the table below.
  – Fraction finer than 0.005 mm< 15%
  – Liquid Limit, LL ≤ 35%
  – Natural water content > 0.9 LL
  – Liquidity Index ≤ 0.75
“Chinese Criteria”

NON-LIQUEFIABLE SOIL:
• $w < 0.87LL$ or $LL > 33.5$
• or Clay fraction > 20%
• or Plasticity Index > 13

POTENTIALLY LIQUEFIABLE SOIL IF:
• Clay fraction (0.005 mm) is less than 20%
• Plasticity Index is less than or equal to 13.

Chinese Criteria Adapted to ASTM Definitions of Soil Properties (Perlea, Koester and Prakash, 1999)

Prakash & Puri, 2003

Clays

Idriss and Boulanger, 2004
Clays

Idriss and Boulanger, 2004

Estimation of Liquefaction Risk
Liquefaction Risk

• Historically, sands were considered to be the only type of soil susceptible to liquefaction, but liquefaction has also been observed in gravel and silt.

• Strain-softening of fine grained soils can produce effects similar to those of liquefaction.

• Liquefaction susceptibility depends on particle shape. Soil deposits with rounded particles are more susceptible to liquefaction than soils with angular particles.

Wang, 1979

Liquefaction Risk

• Saturated soil deposits that have been created by sedimentation in rivers and lakes (fluvial or alluvial deposits), deposition of debris or eroded material (colluvial deposits), or deposits formed by wind action (aeolian deposits) can be very liquefaction susceptible.

• Man-made soil deposits, particularly those created by the process of hydraulic filling, may also be susceptible to liquefaction.
Cyclic Stress Ratio

\[ CSR = 0.65 \left( \frac{\sigma_{w} \theta_{w}}{\sigma_{w0}} \right) r_d \]

Not to be used for depths more than 20m!!

Seed and Idriss, 1971

Cyclic Stress Ratio, \( r_d \)

Idriss, 1999
Number of Equivalent Cycles vs Earthquake Magnitude

Idriss and Boulanger, 2004

Liquefaction Curves

Idriss and Boulanger, 2004
Magnitude Scaling Factor
(Scale to M=7.5)

\[ MSF = \frac{CSR_M}{CSR_{M=7.5}} \]

Idriss and Boulanger, 2004

Overburden Correction Factor Kσ

\[ K'_\sigma = \frac{CRR_{σ'_2}=kg/cm^2}{CRR_{σ_1}=kg/cm^2} \]

Idriss and Boulanger, 2004
Clean Sands

Idriss and Boulanger, 2004

Effect of Fines

\[
\frac{(N_{10})_{30} - (N_{10})_{50}}{\Delta (N_{10})} = 1.63 \times \left( \frac{9.7}{PC} \right) \left( \frac{15.7}{PC} \right)
\]

Idriss and Boulanger, 2004
SPT vs. CPT

Idriss and Boulanger, 2004

Evaluation of Liquefaction Risk through Vs measurements

- Useful for sites difficult to penetrate

Andrus & Stokoe, 2000
Evaluation of Liquefaction Risk through Vs measurements

Andrus & Stokoe, 2000
Evaluation of Liquefaction Risk through Vs measurements

Andrus & Stokoe, 2000
SPT, CPT, Vs

• Change of Dr from 30% to 80% would:
  – Increase SPT by a factor of 7.1
  – Increase CPT by a factor of 3.3
  – Increase Vs by a factor of 1.4

• Vs measurements useful to define lower, upper bounds, and uncertain regions
• Recommended use of SPT and CPT relations

Mitigation of Liquefaction Risk
Mitigation of Liquefaction Risk

- Vibroflotation
- Vibroreplacement

Mitigation of Liquefaction Risk

- Dynamic Compaction
Mitigation of Liquefaction Risk

- Stone Columns

Mitigation of Liquefaction Risk

- Drainage techniques (Stone Columns, PV-drains)
Mitigation of Liquefaction Risk

- Colloidal Silica Grouting

Gallagher, 2004