Liquefaction: Additional issues
Ahmed Elgamal

This presentation consists of two parts:
Section 1
Liquefaction of fine grained soils and cyclic softening in silts and clays
Section 2
Empirical relationship for prediction of Lateral Spreading
Liquefaction of fine grained soils and cyclic softening in silts and clays

Main References


**Notation**

\[ w_c = \text{Water content} = \frac{\text{weight of water}}{\text{weight of soil}} \% \]

\[ LL = \text{Liquid Limit} = w_c \text{ at which soil starts acting like a liquid} \]

\[ PL = \text{Plastic Limit} = w_c \text{ at which the soil starts to exhibit plastic behavior} \]

\[ PI = \text{Plasticity Index} = LL - PL = \text{range of } w_c \text{ when soil exhibits plasticity} \]

\[ e = \text{void ratio} = \frac{\text{volume of voids}}{\text{volume of solids}} \]

\[ s_u = \text{Undrained shear strength} \]

\[ OCR = \text{Overconsolidation Ratio} \]

**Notes:**

1. Low \( PI \) implies low or lack of significant cohesion
2. High \( PI \) implies presence of significant cohesion
3. Higher \( e \) implies looser soil samples with lower shear resistance, more susceptibility to liquefaction, and higher potential for post-liquefaction settlement (permanent volumetric strain). For a given soil, these effects are judged more precisely based on the Relative Density \[ D_r = \frac{(e_{max} - e)}{(e_{max} - e_{min})} \% \]
Highlights

Based on post-earthquake reconnaissance and related soil-testing and analysis:

The “Chinese Criteria” about liquefaction resistance of fine grained soils is not correct. It is based on % clay content with no regard to its plasticity (PI) which makes all the difference.

If relatively non-plastic, saturated fine grained soils can build-up significant excess pore water pressure and liquefy.

Cyclic loading of soft clays degrades strength and softens the shear resistance potentially leading to large objectionable deformations.

Sand-type excess pore-pressure build-up likely for scenarios of $w_c / LL > 0.85$ and $PI < \text{ or equal } 12$; being relatively non-plastic soils (some suggest $PI < \text{ or equal } 7$) ….. These soils exhibit a cyclic mobility-type response …

Clay-type softening behavior likely for soil with $w_c / LL > 0.8$ and $18 > PI > 12$ (some suggest $PI > 7$) …. gradual reduction in shear stiffness and strength …

For PI > 18 soils tested at low confining pressure, potential for loss of shear resistance was minimal, but significant deformation is possible under strong shaking conditions.

Bray and Sancio suggest $PI$ rather than % $fines$ to account for higher Liquefaction resistance

A procedure similar to the Liquefaction Cyclic Stress Approach (described earlier) has been developed for cyclic clay softening scenarios (Boulanger + Idriss).
Figure from Bray and Sancio (2006) showing Chinese data left of the A-line indicating a significant level of plasticity (a key issue that was overlooked when the Chinese Criteria was formulated). Note: CL = Clays of Low Plasticity, CH = Clays of High Plasticity, ML = Silts of Low Plasticity, CH = Silts of High Plasticity.

Seed and Idriss (1982) stated that clayey soils could be susceptible to liquefaction only if all three of the following conditions are met: 1) percent of particles less than 0.005 mm <15%, 2) LL < 35, and 3) $\frac{w_c}{LL} > 0.9$. Due to its origin, this standard is known as the “Chinese criteria.”
Fig. 5. Results of a slow cyclic triaxial test (loading frequency of 0.005 Hz) on Specimen F7-P3A (ML, PI=0, e=0.76): (a) deviator stress versus number of load cycles; (b) excess pore water pressure versus number of load cycles; (c) axial strain versus number of load cycles; (d) deviator stress versus axial strain; and (e) deviator stress versus mean effective confining stress

Ref.: Bray and Sancio (2006)
Observed cyclic mobility response in fine grained soils

Fig. 9. Results of a cyclic simple shear test ($f=1$ Hz) on Specimen G4-P3 (ML, PI=0, $e=0.83$): (a) shear stress versus number of load cycles; (b) lateral effective stress versus number of load cycles; (c) shear strain versus number of load cycles; (d) shear stress versus mean effective stress; and (e) shear stress versus shear strain

Ref.: Bray and Sancio (2006)

Course notes: Ahmed Elgamal, Universidad Nacional de San Juan, Argentina, April, 2014
Fig. 6. Stress-strain relationship for the first cycle of loading (fine line) and the cycle at which \(-3\%\) axial strain is reached (thick line) for four specimens of increasing plasticity. The tests were performed on soils initially isotropically consolidated to an effective stress of 50 kPa.

Ref.: Bray and Sancio (2006)
Fig. 13. Graphical representation of the proposed liquefaction susceptibility criteria: (a) isotropically consolidated CTX testing data from this study; (b) field data from Bray et al. (2004a); (c) Potrero Canyon field data from Bennett et al. (1998); (d) field data from Wang (1979); and (e) field data from Chu et al. (2004)
Cyclic reduction of shear stiffness and strength in saturated clay

Ref.: Boulanger and Idriss (2007)

Fig. 4. Stress-strain response and effective stress paths for Cloverdale clay during undrained slow cyclic loading (adapted from Zergoun and Vaid 1994, used with permission)
Fig. 1. Cyclic strength ratios to cause cyclic failure versus number of uniform loading cycles at a frequency of 1 Hz: (a) natural soils; (b) tailing materials

Ref.: Boulanger and Idriss (2007) 3% shear strain

Course notes: Ahmed Elgamal, Universidad Nacional de San Juan, Argentina, April, 2014
Slope shear stress impacts NC clay (OCR = 1) as acting stress nears shear strength (minimal impact on highly OC clays)

Fig. 6. $K_\alpha$ versus $\alpha$ for clay at various OCR

$$CRR_{M=7.5} = 0.18 \cdot OCR^{0.8} \cdot K_\alpha$$

Ref.: Boulanger and Idriss (2007)
### Appendix: Supplementary Materials

#### Unified Soil Classification

<table>
<thead>
<tr>
<th>Field Identification Procedures</th>
<th>Group Symbols</th>
<th>Typical Names</th>
<th>Information Required for Describing Soils</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide range in grain size and substantial amounts of all intermediate particle sizes</td>
<td>GW</td>
<td>Well graded gravels, gravel-sand mixtures, little or no fines</td>
<td>Give typical name, indicate approximate percentage of sand and gravel, max. size, angularity, surface condition, and hardness of the coarse grains; local or geological name and other pertinent descriptive information, and symbol in parentheses</td>
</tr>
<tr>
<td>Predominantly one size or a range of sizes with some intermediate sizes missing</td>
<td>GP</td>
<td>Poorly graded gravels, gravel-sand mixtures, little or no fines</td>
<td>For undisturbed soils add information on stratification, degree of compactness, cementation, moisture conditions and drainage characteristics</td>
</tr>
<tr>
<td>Non-plastic fines (for identification procedures see ML below)</td>
<td>GM</td>
<td>Silty gravel, poorly graded gravel-sand mixtures</td>
<td></td>
</tr>
<tr>
<td>Plastic fines (for identification procedures see CL below)</td>
<td>GC</td>
<td>Clayey gravels, poorly graded gravel-sand mixtures</td>
<td></td>
</tr>
<tr>
<td>Wide range in grain sizes and substantial amount of all intermediate particle sizes</td>
<td>SW</td>
<td>Well graded sands, gravelly sands, little or no fines</td>
<td></td>
</tr>
<tr>
<td>Predominantly one size or a range of sizes with some intermediate sizes missing</td>
<td>SP</td>
<td>Poorly graded sand, gravelly sands, little or no fines</td>
<td></td>
</tr>
<tr>
<td>Non-plastic fines (for identification procedures see CL below)</td>
<td>SM</td>
<td>Silty sand, poorly graded sand-silt mixtures</td>
<td></td>
</tr>
<tr>
<td>Plastic fines (for identification procedures see CL below)</td>
<td>SC</td>
<td>Clayey sand, poorly graded sand-clay mixtures</td>
<td></td>
</tr>
</tbody>
</table>

#### Identification Procedures on Fraction Smaller than No. 40 Sieve Size

<table>
<thead>
<tr>
<th>Sand and Clays</th>
<th>Liquid limit</th>
<th>Dry Strength (Crushing Characteristics)</th>
<th>Dilatancy (Reaction to Shaking)</th>
<th>Toughness (Consistency Near Plastic Limit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ML</td>
<td>Liquid limit</td>
<td>None to slight</td>
<td>Quick to slow</td>
<td>None</td>
</tr>
<tr>
<td>OL</td>
<td>Liquid limit</td>
<td>Medium to high</td>
<td>None to very slow</td>
<td>Medium</td>
</tr>
<tr>
<td>MN</td>
<td>Liquid limit</td>
<td>Slight to medium</td>
<td>Slow</td>
<td>Slight</td>
</tr>
<tr>
<td>VL</td>
<td>Liquid limit</td>
<td>Slight to medium</td>
<td>Slow to none</td>
<td>Slight to medium</td>
</tr>
<tr>
<td>CH</td>
<td>Liquid limit</td>
<td>High to very high</td>
<td>None</td>
<td>High</td>
</tr>
<tr>
<td>MH</td>
<td>Liquid limit</td>
<td>Medium to high</td>
<td>High to very low</td>
<td>Medium to high</td>
</tr>
<tr>
<td>PT</td>
<td>Liquid limit</td>
<td>Highly Organic</td>
<td>Ready identified by color, odor, spongy feel and frequently by fibrous texture</td>
<td></td>
</tr>
</tbody>
</table>

#### Laboratory Classification Criteria

- $C_u = \frac{D_{10}}{D_{60}}$: Greater than 4
- $C_c = \frac{D_{60}^2}{D_{10}}$: Between one and 3

**Examples**

- Silty sand gravelly, about 20% hard, angular gravel particle $\frac{1}{4}$ in maximum size, rounded and subangular sand grains coarse to fine, about 15% non-plastic fines with low dry strength, well compacted and most in place, alluvial sand. (SM)

#### Plasticity Chart

For laboratory classification of fine grained soils.

- **Plasticity index**
- **Comparing soils at equal liquid limit**
- **toughness and dry strength increase** with increasing plasticity index

---

Course notes: Ahmed Elgamal, Universidad Nacional de San Juan, Argentina, April, 2014
# Unified Soil Classification Including Identification and Description

<table>
<thead>
<tr>
<th>Field Identification Procedures</th>
<th>Group Symbols</th>
<th>Typical Names</th>
<th>Information Required for Describing Soils</th>
</tr>
</thead>
<tbody>
<tr>
<td>(excluding particles larger than 3 inches and basing fractions on stated weights)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wide range in grain size and substantial amounts of all intermediate particle sizes</td>
<td>GW</td>
<td>Well graded gravels, gravel-sand mixtures, little or no fines</td>
<td>Give typical name, indicate approximate percentage of sand and gravel, max. size, angularity, surface condition, and hardness of the coarse grains; local or geological name and other pertinent descriptive information, and symbol in parentheses</td>
</tr>
<tr>
<td>Predominantly one size or a range of sizes with same intermediate sizes missing</td>
<td>GP</td>
<td>Poorly graded gravels, gravel-sand mixtures, little or no fines</td>
<td>For undisturbed soils add information on stratification, degree of compactness, cementation, moisture conditions and drainage characteristics</td>
</tr>
<tr>
<td>Non-plastic fines (for identification procedures see ML below)</td>
<td>GM</td>
<td>Silty gravel, poorly graded gravel-sand silt mixtures</td>
<td></td>
</tr>
<tr>
<td>Plastic fines (for identification procedures see CL below)</td>
<td>GC</td>
<td>Clayey gravels, poorly graded gravel-sand clay mixtures</td>
<td></td>
</tr>
<tr>
<td>Wide range in grain sizes and substantial amount of all intermediate particle sizes</td>
<td>SW</td>
<td>Well graded sands, gravelly sands, little or no fines</td>
<td></td>
</tr>
<tr>
<td>Predominantly one size or a range of sizes with some intermediate sizes missing</td>
<td>SP</td>
<td>Poorly graded sand, gravelly sands, little or no fines</td>
<td></td>
</tr>
<tr>
<td>Non-plastic fines (for identification procedures see CL below)</td>
<td>SM</td>
<td>Silty sand, poorly graded sand-silt mixtures</td>
<td></td>
</tr>
<tr>
<td>Plastic fines (for identification procedures see CL below)</td>
<td>SC</td>
<td>Clayey sand, poorly graded sand-clay mixtures</td>
<td></td>
</tr>
</tbody>
</table>

| Identification Procedures on Fraction Smaller Than No 40 Sieve Size | | |
| Dry Strength (crushing characteristics) | Dilatancy (reaction to shaking) | Toughness (consistency near plastic limit) | |
| Silts and Clays | | | |
| Liquid limit less than 50 | | | |
| None to slight | Quick to slow | None | Inorganic silts and very fine sands, rock flour, silty or clayey fine sand with slight plasticity |
| Medium to high | None to very slow | Medium | Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays |
| Slight to medium | Slow | Slight | Organic silts and organic silt-clays of low plasticity |
| Slight to medium | Slow to none | Slight to medium | Inorganic silt, micaceous or diatomaceous fine sandy or silty soils, elastic silts |
| High to very high | None | High | Inorganic clays of high organic plasticity |
| Medium to high | None to very slow | Slight to medium | Organic clays of medium to high plasticity |
| Highly Organic Soils | | | |
| Readily identified by color, odor, spongy feel and frequently by fibrous texture | | | Clayey silt, brown, slightly plastic; small percentage of fine sand; numerous vertical root holes; firm and dry in place, loess, (ML) |

---

Course notes: Ahmed Elgamal, Universidad Nacional de San Juan, Argentina, April, 2014
Use grain size curve in identifying the fractions as given under field identification.

Determine percentages of gravel and sand from grain size curve. Depending on percentage of fines (fraction smaller than No. 200 sieve size) coarse grained soils are classified as follows:
- Less than 5%
- More than 12%
- 5% to 12%

GW, GP, SW, SP.
GM, GC, SM, SC.
Borderline cases requiring use of dual symbols.

PLASTICITY CHART

LABORATORY CLASSIFICATION OF GRANIZED SOILS

For laboratory classification of fine grained soils:

- Atterberg limits above "A" line or PI greater than 7
- Not meeting all gradation requirements for SW
- PI between 4 and 7

C_u = \frac{D_{10}}{D_{60}}

Greater than 6

Above "A" line with PI between one and 3

Above "A" line with PI between 4 and 7

Not meeting all gradation requirements for GW

C_c = \frac{(D_{10})^2}{D_{60}}

Greater than 4

Not meeting all gradation requirements for GW

C_c = \frac{(D_{10})^2}{D_{60}}

between one and 3
Additional Related References (Fine Grained Soils)


Wang, W. (1979). Some findings in soil liquefaction, Water Conservancy and Hydroelectric Power Scientific Research Institute, Beijing, China. (Chinese Criteria was derived based on the data in this ref.)


Lateral Spreading: Empirical Approach

Primary References


Additional Reference

Empirical MLR Procedure

1) Large Case History Data Set

2) Multi-Linear Regression Analysis (MLR)


New predictive equation is based on additional new data sets from US and Japan, and some corrections and modifications
Displacement Versus Distance From Free Face for Lateral Spread Displacements Generated in Niigata, Japan During 1994 Earthquake

Courtesy of Professor T. L. Youd
$D_H$ = horizontal displacement (m),

$M$ = moment magnitude,

$R$ = distance from seismic energy source (km),

$W$ = free face ratio = $(H/L)(100)$ in percent (see figure above),

$S$ = ground slope = $(Y/X)(100)$ in percent (see figure above),

$T_{15}$ = thickness of layer with $(N_1)_{60} < 15$ (m),

$F_{15}$ = fines content in $T_{15}$ layer (%),

$D_{50_{15}}$ = average mean grain size in $T_{15}$ layer (mm).
Recommended MLR Equations


Free face conditions:

\[
\log D_H = -18.084 + 1.581 M - 1.518 \log R^* - 0.011 R + 0.551 \log W \\
+ 0.547 \log T_{15} + 3.976 \log (100-F_{15}) - 0.923 \log (D_{50_{15}}+0.1)
\]

Ground slope conditions:

\[
\log D_H = -17.614 + 1.581 M - 1.518 \log R^* - 0.011 R + 0.343 \log S \\
+ 0.547 \log T_{15} + 3.976 \log (100-F_{15}) - 0.923 \log (D_{50_{15}}+0.1)
\]

where \( R^* = R+R_0 \) and \( R_0 = 10^{(0.89M-5.64)} \)

**Note:**

- This model is valid for coarse-grained sites (\( D_{50_{15}} \) up to 10mm for silty sediments)
- Predicted displacements greater than 6 m are poorly constrained by observational data and are highly uncertain

Course notes: Ahmed Elgamal, Universidad Nacional de San Juan, Argentina, April, 2014
Measured versus predicted displacements for Port and Rokko Islands, Japan showing that Bartlett and Youd Equations greatly under-predict displacements at coarse-grained sites (Youd et al. 1999).