Seismic liquefaction
CPT-based methods

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Definitions of Liquefaction

• **Cyclic (seismic) Liquefaction**
  – Zero effective stress (during cyclic loading)

• **Flow (static) Liquefaction**
  – Strain softening response
Cyclic (seismic) Liquefaction

- Zero effective stress due to undrained cyclic loading
- Shear stress reversal
  - Level or gently sloping ground
- Controlled by size and duration of cyclic loading
- Large deformations possible

Cyclic Liquefaction – Lab Evidence

Shear stress reversal → Zero effective stress → small stiffness
Flow (static) Liquefaction

• Strain softening (contractive) response in undrained shear
• Trigger mechanism required
  – cyclic or static
• Static shear stress greater than minimum (liquefied) undrained shear strength
• Kinematic mechanism required
  – Uncontained flow
  – Contained deformation

Schematic undrained response of saturated, contractive sandy soil

After Olson & Stark, 2003
**Flow chart to evaluate liquefaction**

Terms ‘Contractive’ and ‘Dilative’ apply at large strains

After Robertson, 1994

**What level of sophistication is appropriate for SI & analyses?**

- **GOOD**: Precedent & local experience
- **SIMPLE**: Design objectives
- **LOW**: Level of geotechnical risk
- **LOW**: Potential for cost savings

- **Traditional Methods**: "Simplified"
- **Advanced Methods**: "Complex"
‘Simplified Procedure’ – Cyclic Liq.

Following the 1964 earthquakes in Alaska and Niigata the “Simplified Procedure” was developed by Seed & Idriss (1971) for evaluating seismic demand and liquefaction resistance of sands based on case histories (liq. & non-liq. cases).

Origin of CPT-based methods

All methods have similar origins:

Case histories (each summarized to 1 data point)

- $\text{CSR}_{7.5,\sigma' = 1} = 0.65 \left( \frac{a_{\text{max}}}{g} \right) \left( \frac{\sigma_v}{\sigma_v'} \right) r_d / \text{MSF} * K_\sigma$
- Normalization ($q_{cIN}$) and ‘fines’ correction to get normalized clean sand equivalent ($q_{cIN,cs}$ or $Q_{tn,cs}$)

Each method made different assumptions for: $r_d$, MSF, $K_\sigma$

normalization of $q_c$ & ‘fines correction’
Updated database > 250 sites

Holocene-age, uncemented, silica-based soil (~NC)  
After Boulanger & Idriss, 2014

Magnitude Scaling Factor (MSF)

No documented Liq case histories for $M < 5.8$

$N_{lq}$ of 30, $q_{c1Ncs} = 175$

$N_{lq}$ of 20, $q_{c1Ncs} = 133$

$N_{lq}$ of 10, $q_{c1Ncs} = 84$

Liq case histories $q_{c1Ncs} < 150$ (mean ~ 80)

Youd et al (NCEER, 2001)

B&I, 2014

Modified from Boulanger & Idriss, 2014
$I_c = \left( \frac{3.47 - \log Q}{2} \right)^2 + (\log F + 1.22)^2)^{0.5}$

( Modified from Jefferies & Davies, 1993 )

$I_c$ is an index of soil behaviour

Function primarily of Soil Compressibility

**CPT SBTn Index, $I_c$**

**Soil Behaviour Type Index, $I_c$**

$SANDS$

Increasing compressibility

$CLAYS$

$\text{Updated database on SBTn chart}$

All cases have CPT SBTn $I_c < 2.6$

Data base shows that when $I_c > 2.6$

predominately fine grained ‘clay-like’ soil

Data after Boulanger & Idriss, 2014
Susceptibility to cyclic liquefaction

Seed et al., 2003

Bray & Sancio, 2006

CPT SBT

Behavior Characteristics

Sand-like $I_c = 2.6(+/-)$

Clay-like

Physical Characteristics

Transition from sand to clay-like behavior

Transition from sand to clay-like behavior

SBT from CPT

Plasticity Index as function of SBT $I_c$

Boundary between sand-like and clay-like soils is $7 < PI < 12$

When $I_c < 2.60$
95% samples NP
84% have PI < 12%

Data from Cetin & Ozan, 2009

Robertson, 2014
**SBT $I_c$ cut-off?**

- Robertson & Wride (1997) suggested that $I_c = 2.6$ was a reasonable value to ‘cut-off’ clay-like soils from analysis, but when $I_c > 2.6$ samples should be obtained and soils with $I_c > 2.6$ and $F_r < 1\%$ should also be evaluated.

- Youd et al (2001-NCEER) suggested $I_c > 2.4$ samples should be evaluated.

*Whenever soils plot in the region close to $I_c = 2.6$ it is advisable to evaluate susceptibility using other criteria and modify selected cut-off.*

**Exceptions**

- Very stiff OC clay
- NC low-plastic silt

Challenge linking SBT with traditional ‘geologic’ terms, such as ‘sand’.
Generalized CPT Soil Behaviour Type

CPT Soil Behaviour

CGD: Coarse-grain-Dilative (mostly drained)
CGC: Coarse-grain-Contractive (mostly drained)
FGD: Fine-grain-Dilative (mostly undrained)
FGC: Fine-grain-Contractive (mostly undrained)

Modified from Robertson, 2012

CPT clean sand equivalent, $Q_{tn,cs}$

Clean sand equivalent normalized cone resistance, $Q_{tn,cs}$ based on soil behaviour type index, $I_c$

Robertson 2009
**CPT-based correction to** $Q_{tn,cs}$

- **Fines content** is a physical characteristic obtained on disturbed samples, that has a weak link to in-situ behaviour. Application of a correction based on fines content introduces added uncertainty.

- **CPT SBT $I_c$** is a behaviour characteristic, that has a strong and direct link to in-situ behaviour.

**How reliable is a correction based on $I_c$?**

**Is there a theoretical basis for the correction?**

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**Theoretical framework**

**State parameter and** $Q_{tn,cs}$

- Based on CSSM theory, CC, samples
- Increased resistance to loading
- Updated from Plewes et al. 1992

- Young, uncemented, silica-based soils
- $\psi \sim 0.56 - 0.33 \log Q_{tn,cs}$

- Contractive
- Dilative

- $K_o \sim 0.5$

- $Q_{tn,cs} = 70$ at $\psi = -0.05$

- Based on liq. case histories

- Robertson & Wride 1998

Robertson, 2012
Case histories – flow liquefaction

Case histories with CPT
Nerlerk (sand) – 19, 20, 21
Jamuna (sand) - 34
Fraser River (silty sand) - 27
Sullivan mines (silty tailings) - 35
Northern Canada (silty clay) – 36
L. San Fernando Dam (silt) – 15

CPT data in critical layers +/- 1 sd.

All case histories plot in ‘contractive’ portion of CPT SBT chart

After Robertson, 2010

Shearwave Velocity Approach

Liquefaction:
100 < $V_{s1} < 230$ m/s

No liquefaction:
$V_{s1} > 250$ m/s

Young, uncemented soils

Almost no influence due to fines
- can use as a check on CPT ‘fines’ correction

After Kayen et al., 2013

Kayen et al., 2013
Estimated $V_s$ based on CPT

Soils with same $V_{s1}$ have similar (small strain) behavior

*Young (Holocene-age) uncemented soils*

Based on large database (>1,000 data points)

Robertson, 2009
Example $V_s$ measured vs estimated

Example - young, uncemented soils – downtown San Francisco

Compare CPT and $V_{s1}$

Comparison between $V_{s1}$-based trigger curves by Kayen et al (2013) and the CPT-based trigger curves by Robertson and Wride (1998) using the correlation between CPT-$V_{s1}$ proposed by Robertson (2009).

Single, unique $I_c$-based correction provides excellent fit to large $V_s$ data base.
**Modified $I_c$ correction**

Small change to $K_c-I_c$ relationship to get very good agreement

Current correction slightly conservative at high $I_c$

**Fines content correction**

Complex ‘additive’ correction based on ‘measured’ fines content
- Little theoretical basis
- Little justification for ‘additive’ form

After Boulanger and Idriss, 2014
Large scatter partly due to difference between 'physical' and 'behaviour' measurement

B & I (2014) recommend

"using $C_{FC} = -0.29, 0$ and $0.29$ to evaluate the sensitivity to FC estimates"  
This can result in large uncertainty

Most case histories have low PI fines with mean $I_c \sim 2.0$

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**Consequences of Liquefaction**

- **Post-earthquake settlement** caused by reconsolidation of liquefied soils, plus possible loss of ground (ejected) and localized shear induced movements from adjacent footings, etc.
- **Lateral spreading** due to ground geometry
- **Loss of shear strength**, leading to instability of slopes and embankments – strain softening response – *flow liquefaction*
**Predicting post-EQ settlement**

- Based on summation of vol. strains (*Zhang et al., 2002*) using FS from selected method
- Many factors affect actual settlement:
  - Site characteristics (stratigraphy, buildings, ejecta, etc.)
  - EQ characteristics (duration, frequency, etc.)
  - Soil characteristics (age, stress history, fines, etc.)
- No ‘correct’ answer (many variables)
- Useful *index* on expected performance

**Challenges estimating vertical settlements**

- Liquefied soil
- Liquefied soil
- Liquefied soil
**Transition zone**

CPT data in ‘transition’ when cone is moving from one soil type to another when there is significant difference in soil stiffness/strength (e.g. soft clay to sand)

CPT data within transition zone will be misinterpreted

*In interlayered deposits this can result in excessive conservatism*

Ahmadi & Robertson, 2005

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**Transition zone detection**

Based on rate of change of $I_c$ near boundary of $I_c = 2.60$

Can be very important for liquefaction analysis

“CLiq” software
www.geologismiki.gr
Depth of liquefaction

Ishihara (1985) showed that surface damage from liquefaction is influenced by thickness of liquefied layer and thickness of non-liquefied surface layer.

Cetin et al (2009) proposed simple weighting of vol. strain with depth to produce similar results.

Example

Christchurch KAN-19 $M_w = 7.1$, $a_{(\text{max})} = 0.23g$ Minor liquefaction, estimated settlement ~2cm
Transition zones - example

Christchurch KAN-19 $M_w = 7.1$, $a_{(max)} = 0.23\text{g}$ Minor liquefaction, estimated settlement ~2cm

Transition & weighting - example

Christchurch KAN-19 $M_w = 7.1$, $a_{(max)} = 0.23\text{g}$ Minor liquefaction, estimated settlement ~2cm
Sensitivity analysis

Removing transition zones and weighting vol. strains with depth reduces conservatism and generally gets closer to case history performance – unless sand ejecta has played a role for very shallow liq.

Recent Christchurch NZ Cases

- Green et al (2014) identified 25 high quality case history sites from Christchurch NZ
- Detailed site and digital CPT data available
- Each site experienced several earthquakes
  - 2 major earthquakes for 50 cases
  - Sept 2010 $M = 7.1$ & Feb 2011 $M = 6.2$
- Each site categorized by damage
**Christchurch (NZ) Experience**

Green et al., 2014 (data)
41 reliable cases – average values for each category

**Predicted 1-D Settlement**
All methods are conservative
B&I’14 – most conservative (mostly due to new MSF)
RW’98 – less conservative
(Note: change from previous version of slide for Moss06)

Newer methods appear to be getting more conservative?

**Regions of potential liquefaction**

**Coarse-grained soils** - Evaluate potential behavior using CPT-based case-history liquefaction correlations.

**CGD** Cyclic liquefaction possible depending on level and duration of cyclic loading.

**CGC** Cyclic & flow liquefaction possible depending on soil sensitivity, loading and ground geometry.

**Fine-grained soils** - Evaluate potential behavior based on in-situ and laboratory test measurements

**FGD** Cyclic softening possible depending on level and duration of cyclic loading.

**FGC** Cyclic softening and flow liquefaction possible depending on soil sensitivity, loading and ground geometry

Modified from Robertson, 2009
Summary

• Each method is a ‘package deal’ – can not mix and match

• All methods are conservative – some more conservative than others (helpful to compare)

• Similar predictions for many case histories
  – esp. where liq. clearly occurred (in clean sands)
  – less so for sites where liq. was not observed

• Different extrapolation into regions with no case history data (e.g. \( z > 12 \text{m} \) and \( M_w < 7.0 \))

  Caution required if extrapolated beyond database

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Summary

• Recommend removing transition zones
  – \textit{CLiq provides auto feature to remove}

• Recommend ‘weighting’ strains with depth
  – \textit{CLiq provides simple ‘weighting’ feature}

• Adjust \( I_c \) cut-off, if needed

• Recommend sensitivity analysis to evaluate sensitivity of output (deformation) to main variables (e.g. EQ load, etc.)

• Often no single answer – requires some judgment
  – complex problem with ‘simplified’ method
Questions?