Seismic liquefaction
CPT-based methods

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What level of sophistication is appropriate for SI & analyses?

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“Simplified” — “Complex”
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)

- CSR$\text{CSR}_{7.5,\sigma'} = 0.65 \left( \frac{a_{\text{max}}}{g} \right) \left( \frac{\sigma_v}{\sigma'_v} \right) r_d / \text{MSF} \times K_\sigma$

- Normalization ($q_{c1N}$) and ‘fines’ correction to get normalized clean sand equivalent ($q_{c1N,cs}$ 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)

27% Non-liquefaction cases

After Boulanger & Idriss, 2014
Soil Behavior Type
Index, $I_c$

$I_c = [(3.47 – \log Q)^2 + (\log F+1.22)^2]^{0.5}$

$Q$ & $F$ normalized CPT parameters

Function primarily of Soil Compressibility

Robertson, 2014
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

Clay-like

Transition from sand to clay-like behavior
Plasticity Index as function of SBT $I_c$

Boundary between sand-like and clay-like soils is $\text{PI} \sim 10$

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 non-plastic silt
Generalized CPT Soil Behaviour Type

CPT Soil Behaviour

A: Coarse-grain-dilative
B: Coarse-grain-contractive
C: Fine-grain-dilative
D: Fine-grain-contractive

Robertson, 2012
CPT clean sand equivalent

Same resistance to cyclic loading

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

Robertson 2009

$Q_{tn,cs} = K_c Q_{tn}$ (RW98)
CPT-based “fines” correction

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

- **CPT SBT $I_c$** is an *in-situ behavioral index*, that has a *strong and direct link* to in-situ behavior.

*How reliable is a correction based on $I_c$?*
Theoretical framework
State parameter and $Q_{tn,cs}$

Based on liq. case histories
Based on CSSM theory & CC

Increased resistance to loading
DILATIVE

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

Based on liq. case histories

$\psi \sim 0.56 - 0.33 \log Q_{tn,cs}$

Robertson, 2012
Liquefaction:
$100 < V_{s1} < 230$ m/s

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

Young, uncemented soils

No $V_{s1}$ ‘fines’ correction
- can use as a check on CPT ‘fines’ correction

Kayen et al., 2013
Compare CPT and $V_{s1}$


$$CRR_{7.5} = 93 \left( \frac{Q_{tn,cs}}{1000} \right)^3 + 0.08$$

$$Q_{tn,cs} = K_c \frac{Q_{tn}}{1000}$$

$$K_c = 5.581 I_c^3 - 0.403 I_c^4 - 21.63 I_c^2 + 33.75 I_c - 17.88$$

Robertson (2009) proposed a relationship for young (Holocene-age) uncemented soils linking $V_{s1}$ to CPT normalized cone resistance, $Q_{tn}$:

$$V_{s1} = (\alpha_{vs} Q_{tn})^{0.5}$$

$$\alpha_{vs} = 10^{(0.55 I_c + 1.68)}$$

Therefore:

$$Q_{tn,cs} = \left( \frac{K_c}{\alpha_{vs}} \right) (V_{s1})^2$$

$$CRR_{7.5} = 93 \left[ \left( \frac{K_c}{\alpha_{vs}} \right) (V_{s1})^2 / 1000 \right]^3 + 0.08$$

- For clean sands ($FC < 5\%$), $I_c = 1.6$, then $\alpha_{vs} = 363.078$ and $K_c = 1.0659$
- For silty sands ($FC \sim 35\%$), $I_c = 2.6$, then $\alpha_{vs} = 1288.25$ and $K_c = 3.4267$
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 data base.
**Modified $I_c$ correction**

Small change to $K_c$-$I_c$ relationship to get perfect agreement

Current correction slightly conservative and high $I_c$
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, 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

(a) (b) (c) (d)

Liquefied soil

Liquefied soil

Liquefied soil
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
Transition zone detection

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

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

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

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

$M_w = 7.1$ Darfield earthquake

Removing transition zones and weighting vol. strains with depth reduces conservatism and generally gets closer to case history performance

Best estimate of $a_{(max)} = 0.23 \text{g}$
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
Moss et al ‘06 – most conservative
Idriss/Boulanger (’08&’14) – next most conservative
RW’98 – less conservative (but still conservative)

Transition zones removed
Vol. strain weighted to 18m
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
Summary

• Recommend removing transition zones
  – *CLiq* provides auto feature to remove

• Recommend ‘weighting’ strains with depth
  – *CLiq* provides ‘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*