Canada

USA

Seismic liquefaction CPT-based methods

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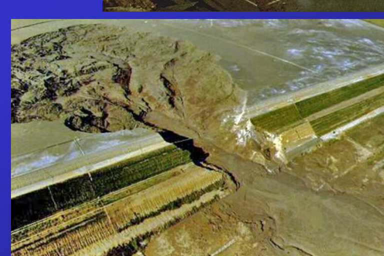
Vancouver

VGS 2014

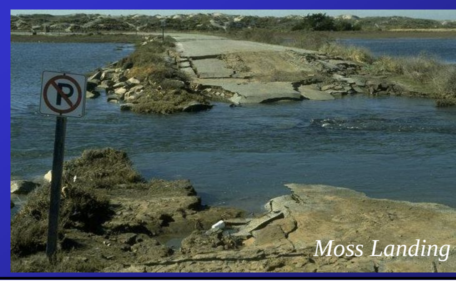
Definitions of Liquefaction

- Cyclic (seismic) Liquefaction
  - Zero effective stress (during cyclic loading)
- Flow (static) Liquefaction
  - Strain softening response

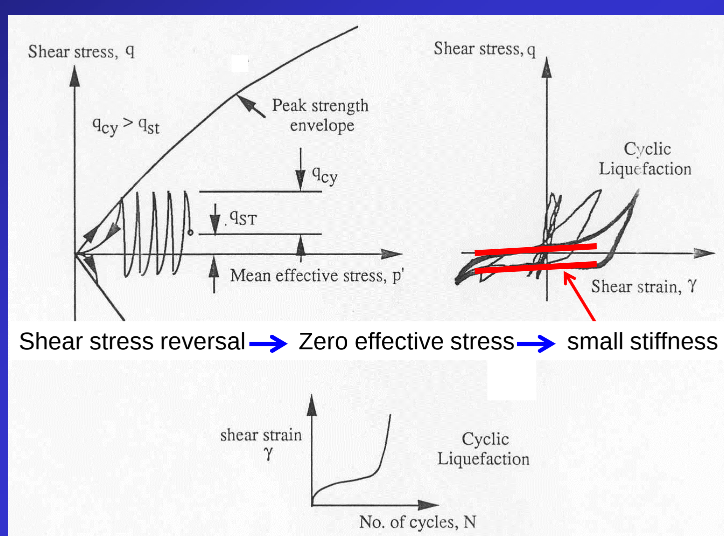


Cyclic (seismic) Liquefaction

- 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

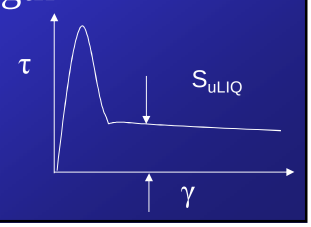


Cyclic Liquefaction – Lab Evidence

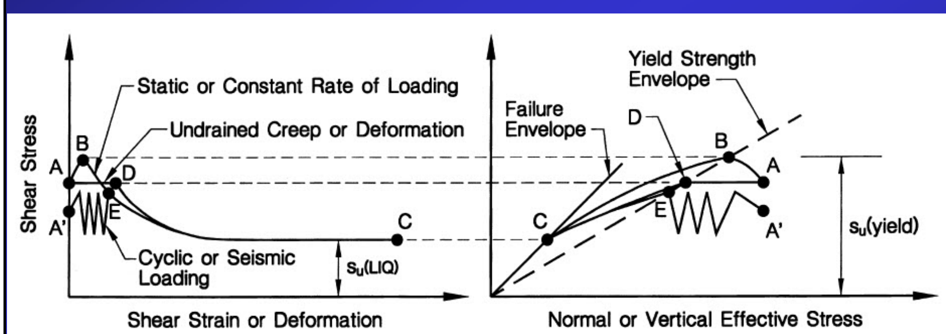


Flow (static) Liquefaction

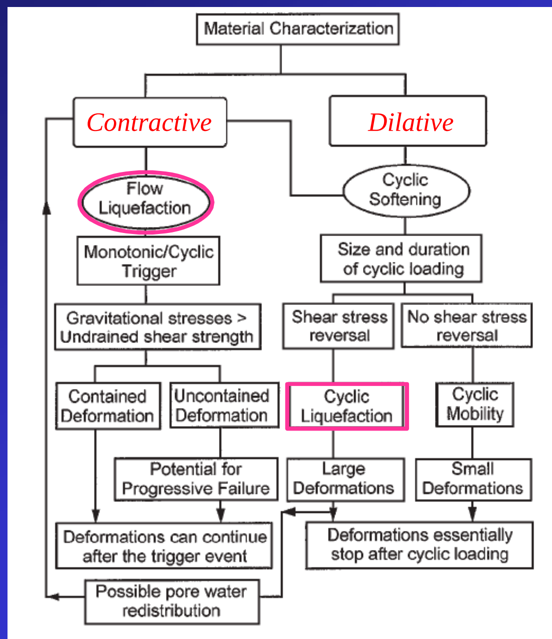
- Strain softening (*contractive*) response in undrained shear
- Trigger mechanism required
  - cyclic or static
- Static shear stress greater than minimum (liquefied) undrained shear strength
- Kinematic mechanism required
  - Uncontained flow
  - Contained deformation



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

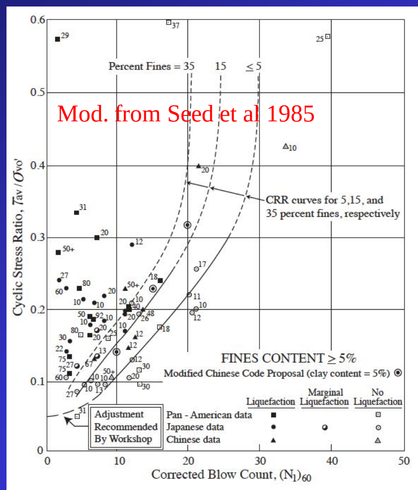
What level of sophistication is appropriate for SI & analyses?

GOOD	**Precedent & local experience**	*POOR*
SIMPLE	**Design objectives**	*COMPLEX*
LOW	**Level of geotechnical risk**	*HIGH*
LOW	**Potential for cost savings**	*HIGH*

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)

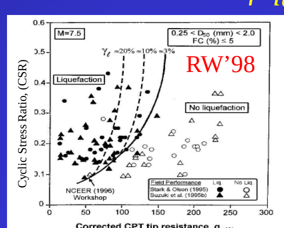
Origin of CPT-based methods

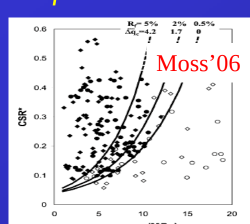
All methods have similar origins:

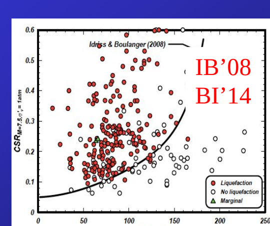
Case histories (each summarized to 1 data point)

- $CSR_{7.5,\sigma'=1} = 0.65\ (a_{max}/g)\ (\sigma_v/\sigma'_v)\ r_d\ /\ MSF\ *\ K_\sigma$
- Normalization (q_{c1N}) and ‘fines’ correction to get normalized *clean sand equivalent* ($q_{c1N,cs}$ *or* $Q_{tn,cs}$)

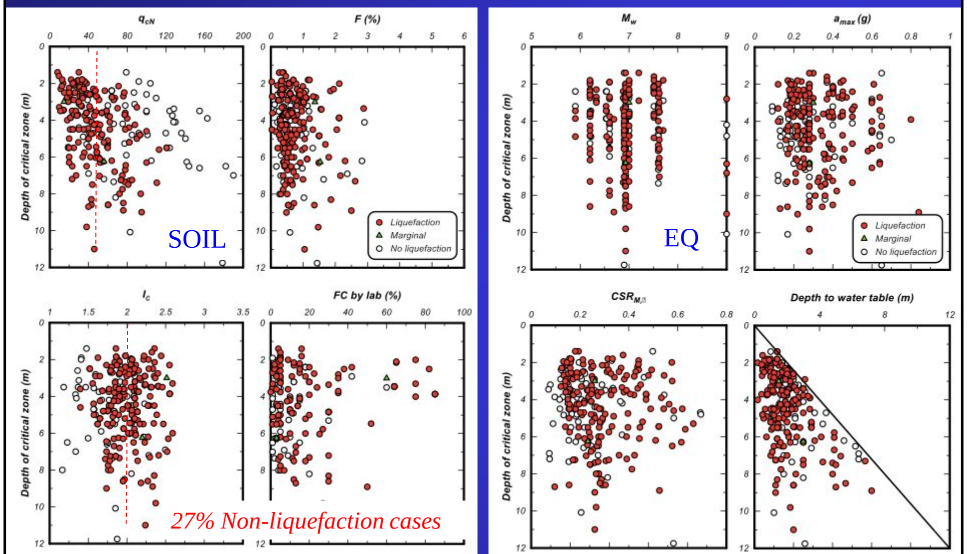
Each method made different assumptions for: *r_d, MSF, K_σ, normalization of q_c & ‘fines correction’*







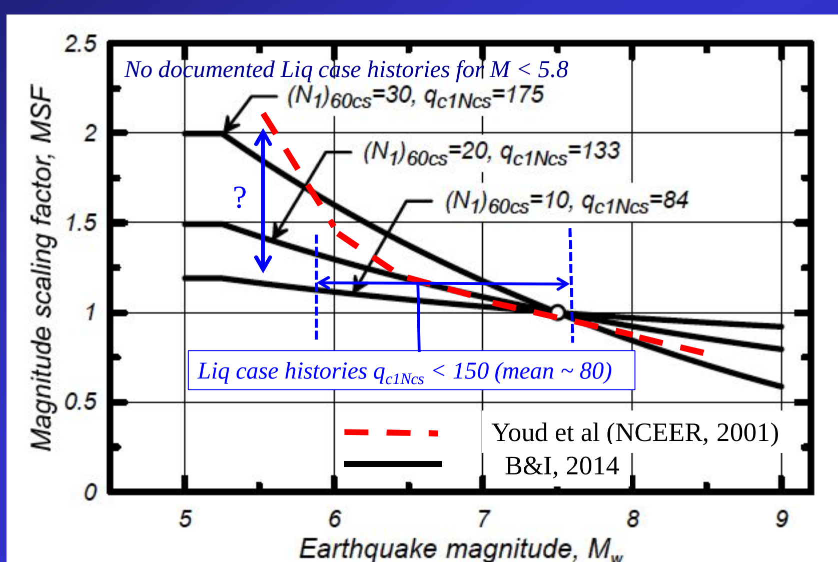
Updated database > 250 sites



Holocene-age, uncemented, silica-based soil (~NC)

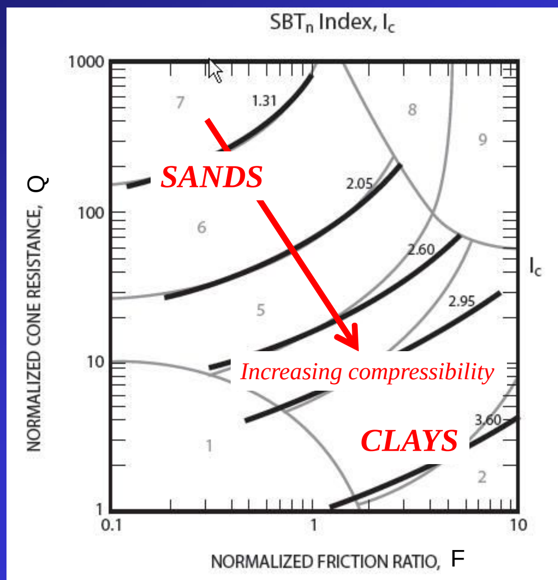
After Boulanger & Idriss, 2014

Magnitude Scaling Factor (MSF)



Modified from Boulanger & Idriss, 2014

CPT SBTn Index, I_c



Soil Behaviour Type Index, I_c

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

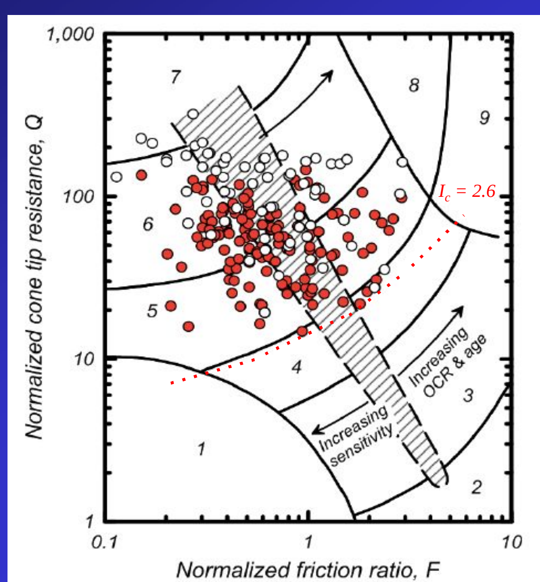
(Modified from Jefferies & Davies, 1993)

I_c is an index of soil behaviour

Function primarily of Soil Compressibility

Robertson, 2014

Updated database on SBTn chart

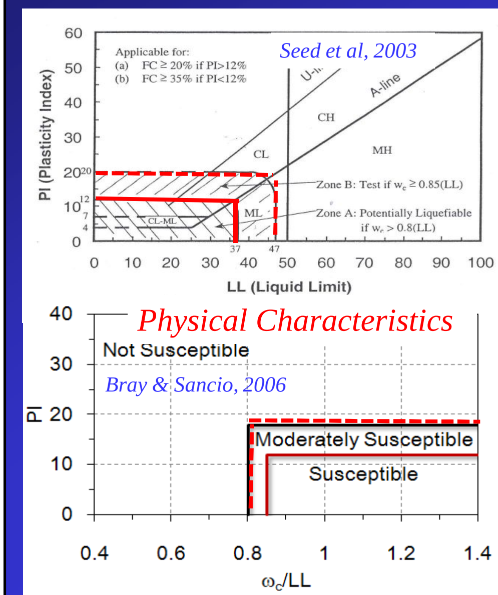


All cases have CPT SBTn $I_c < 2.6$

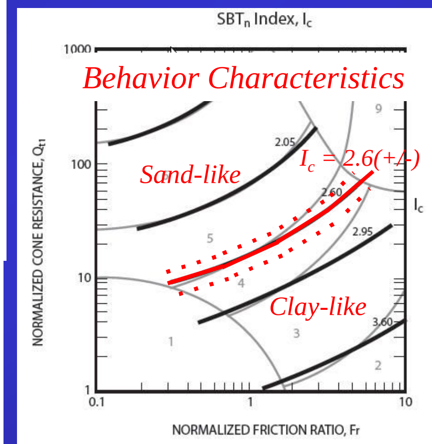
Data base shows that when $I_c > 2.6$ predominately fine grained 'clay-like' soil

Data after Boulanger & Idriss, 2014

Susceptibility to cyclic liquefaction

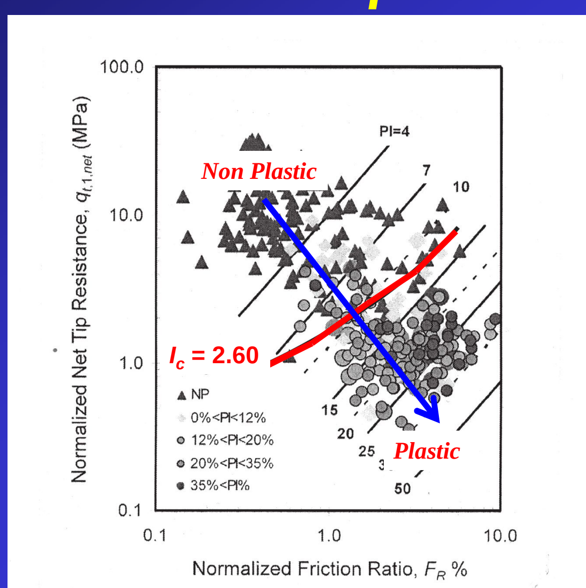


CPT SBT



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

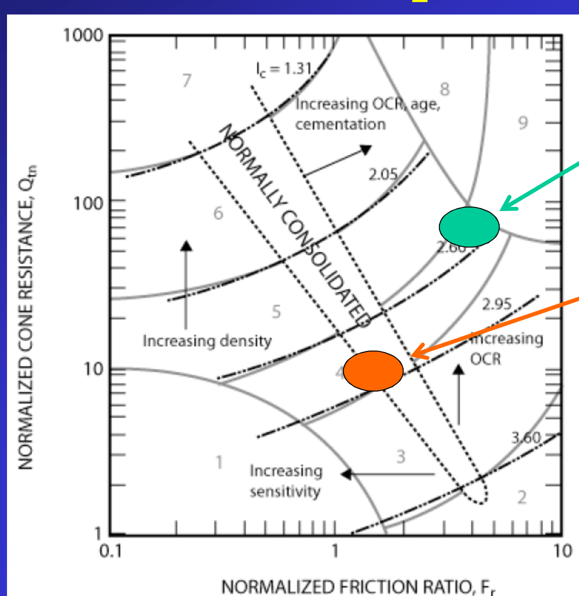
Robertson, 2014

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

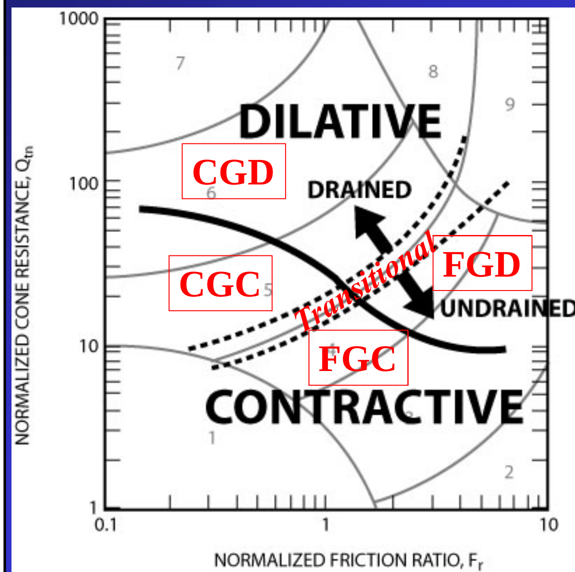


Very stiff OC clay

NC low-plastic silt

Challenge linking SBT with traditional 'geologic' terms, such as 'sand'

Generalized CPT Soil Behaviour Type

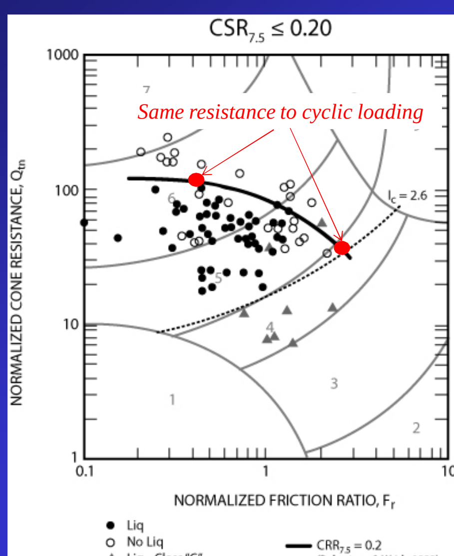


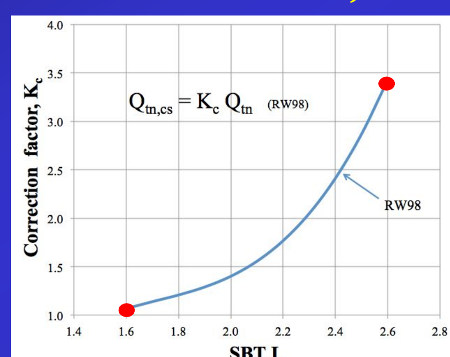
CPT Soil Behaviour

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, $Q_{tn,cs}$





Robertson 2009

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

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

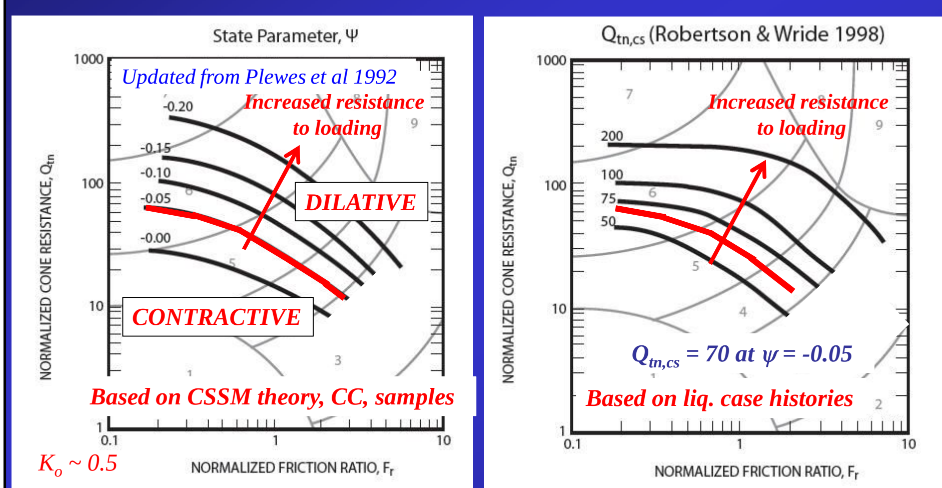
- ***Fines content*** is a ***physical characteristic*** obtained on ***disturbed samples***, that has a ***weak link*** to in-situ behaviour. Application of a correction based on fines content introduces added uncertainty.

- ***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?

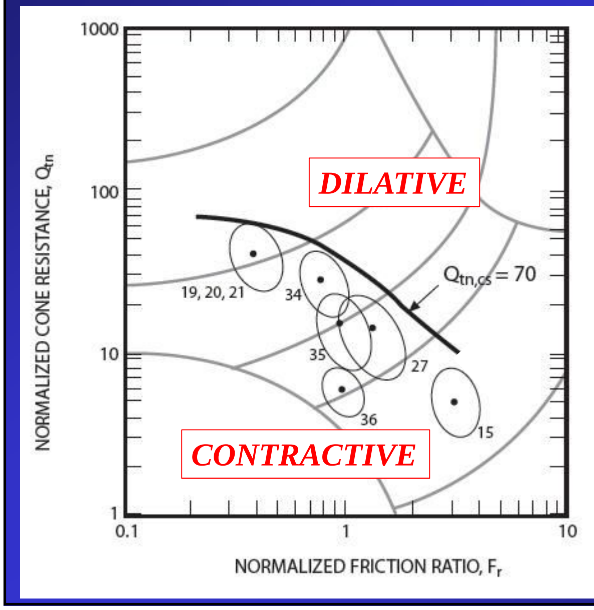
Is there a theoretical basis for the correction?

Theoretical framework State parameter and $Q_{tn,cs}$



Young, uncemented, silica-based soils $\psi \sim 0.56 - 0.33 \log Q_{tn,cs}$ *Robertson, 2012*

Case histories – flow liquefaction



Case histories with CPT

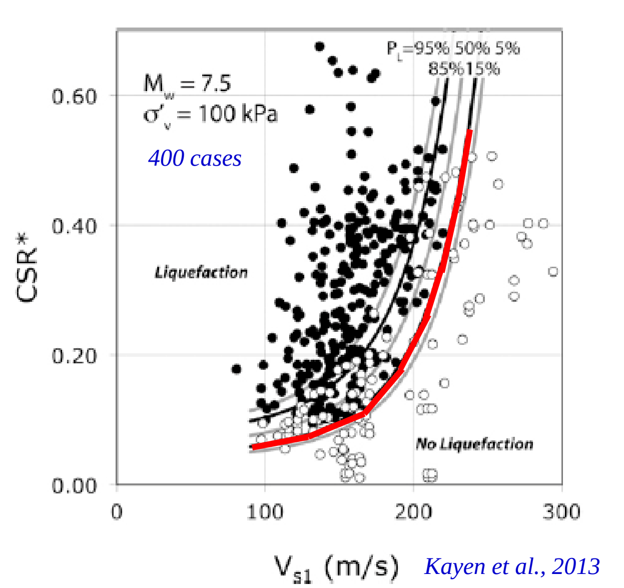
Nerlerk (sand) – 19,20,21
Jamuna (sand) - 34
Fraser River (silty sand) - 27
Sullivan mines (silty tailings) - 35
Northern Canada (silty clay) – 36
L. San Fernado Dam (silt) – 15

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

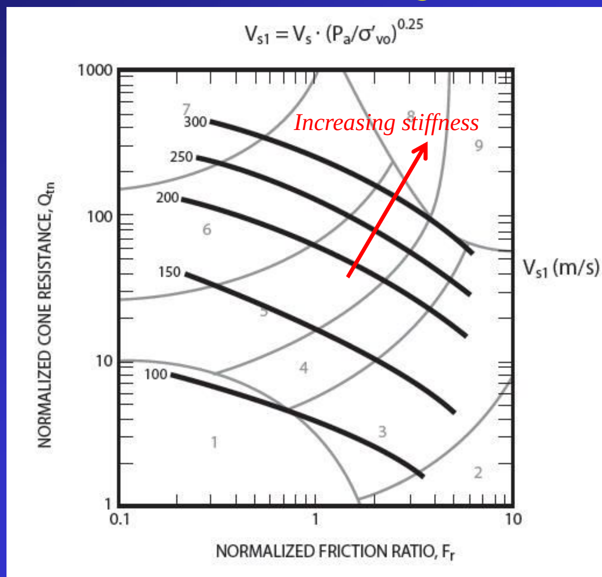
No liquefaction:

V_{s1} > 250 m/s

Young, uncemented soils

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

Estimated V_s based on CPT



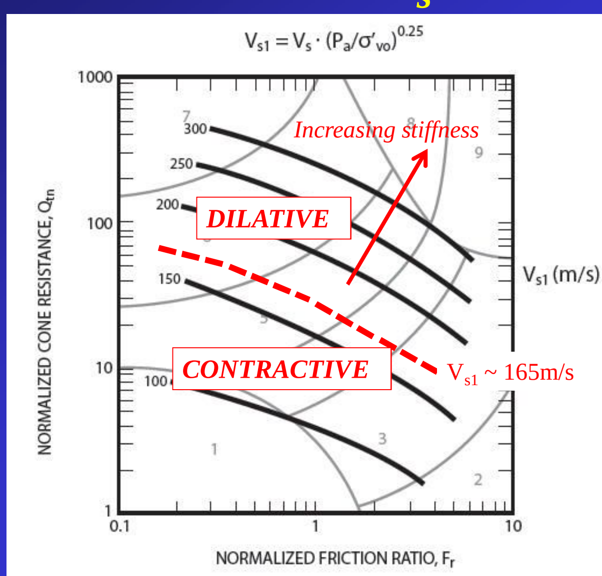
Soils with same V_{s1} have similar (small strain) behavior

Young (Holocene-age) uncemented soils

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

Robertson, 2009

Estimated V_s based on CPT



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

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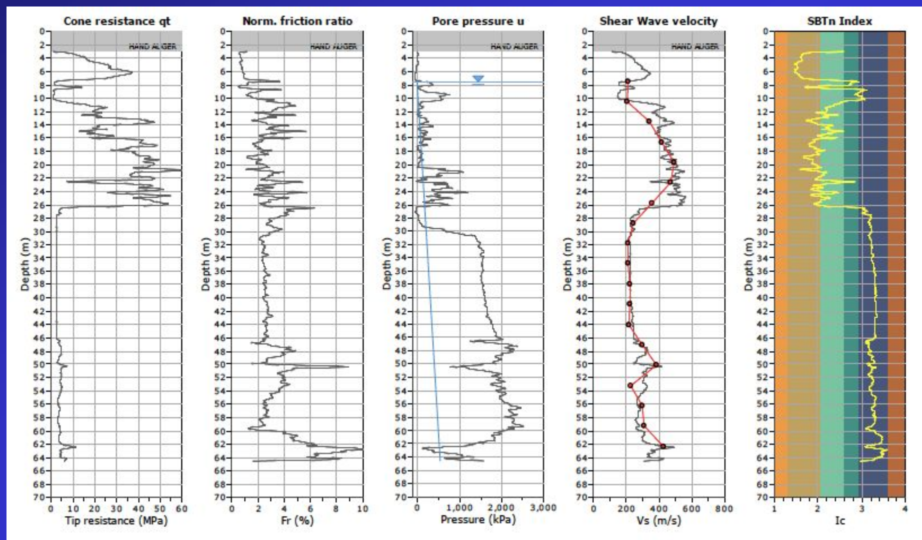
Based on large database (>1,000 data points)

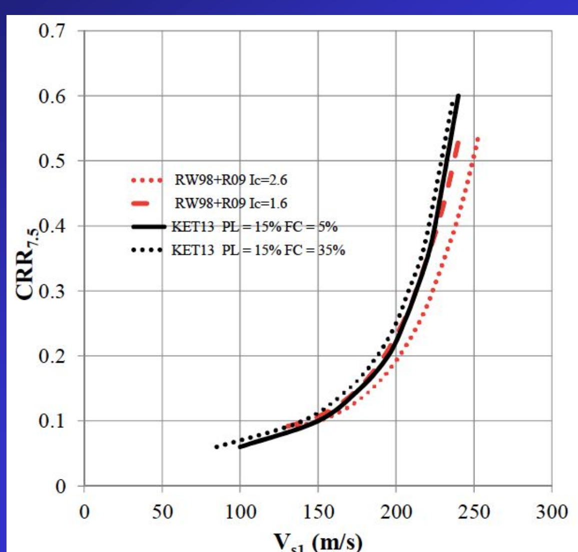
Robertson, 2009

Example V_s measured vs estimated



Example - young, uncemented soils – downtown San Francisco

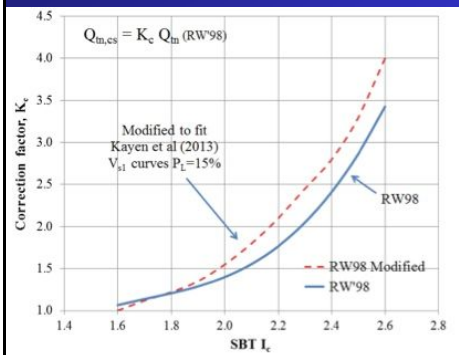
Compare CPT and V_{s1}

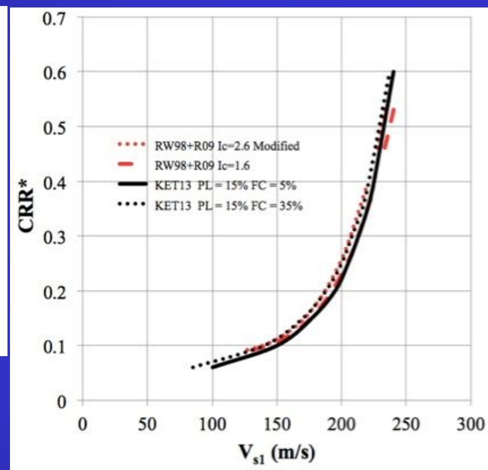


Comparison between V_{s1}-based trigger curves by *Kayen et al (2013)* and the CPT-based trigger curves by *Robertson and Wride (1998)* using the correlation between CPT-V_{s1} proposed by *Robertson (2009)*

Single, unique I_c-based correction provides excellent fit to large V_s data base

Modified I_c correction

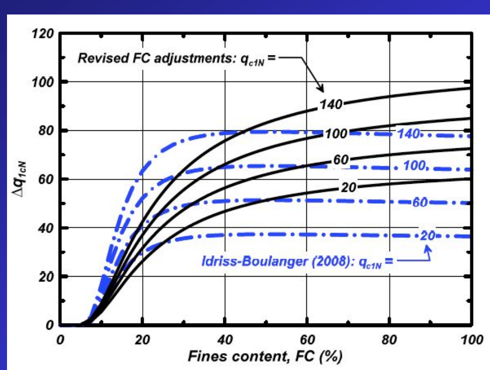




Small change to K_c-I_c relationship to get very good agreement

Current correction slightly conservative at high I_c

Fines content correction

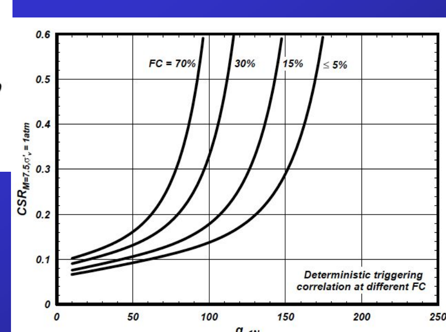


$$q_{c1N,cs} = q_{c1N} + \Delta q_{c1N}$$

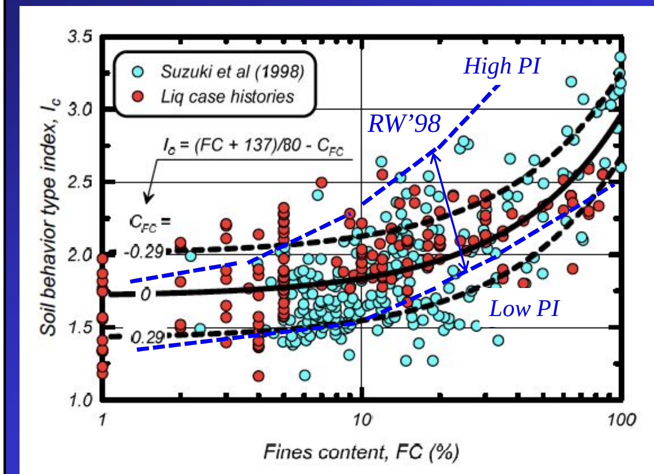
After Boulanger and Idriss, 2014

Complex 'additive' correction based on 'measured' fines content

- Little theoretical basis
- Little justification for 'additive' form



Fines content & SBT I_c



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 ~ 2.0

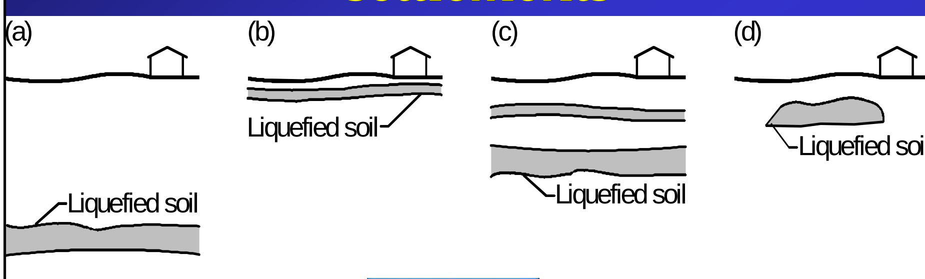
Consequences of Liquefaction

- *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*

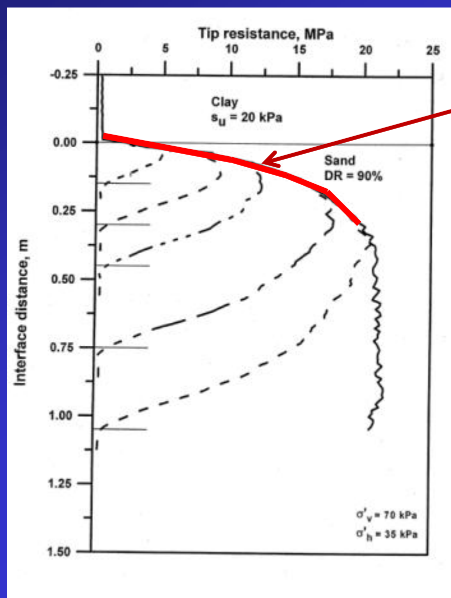
Predicting post-EQ settlement

- 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



Transition zone

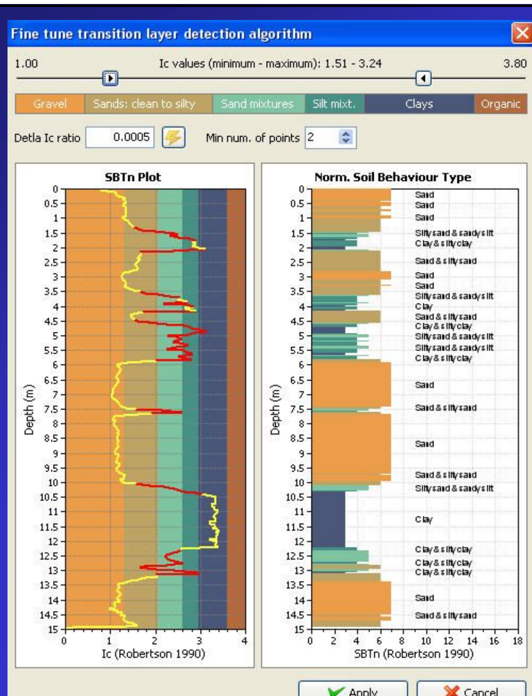


CPT data in 'transition' when cone is moving from one soil type to another when there is significant difference in soil stiffness/strength (e.g. soft clay to sand)

CPT data within transition zone will be misinterpreted

In interlayered deposits this can result in excessive conservatism

Ahmadi & Robertson, 2005



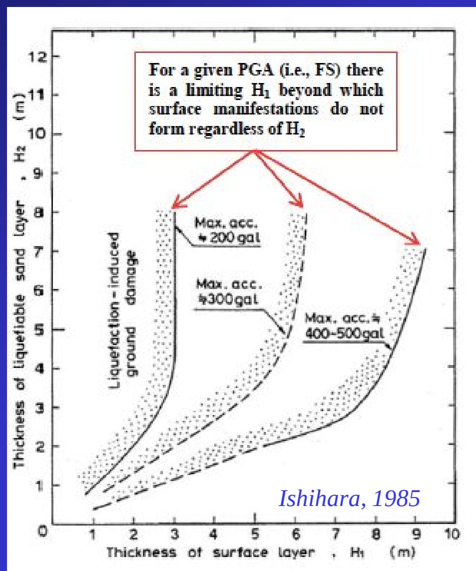
Transition zone detection

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

Can be very important for liquefaction analysis

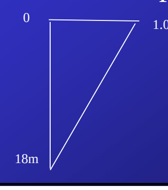
"CLiq" software
www.geologismiki.gr

Depth of liquefaction

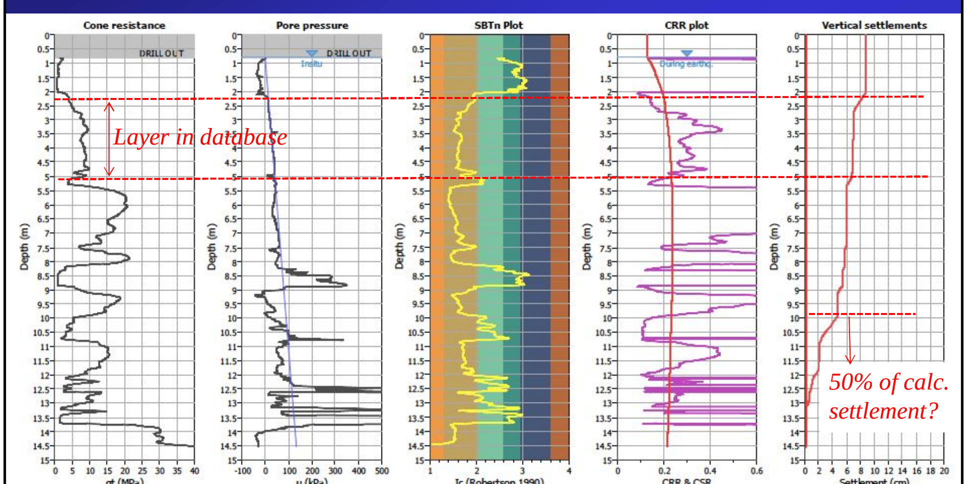


Ishihara (1985) showed that surface damage from liquefaction is influenced by thickness of liquefied layer and thickness of non-liquefied surface layer.

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

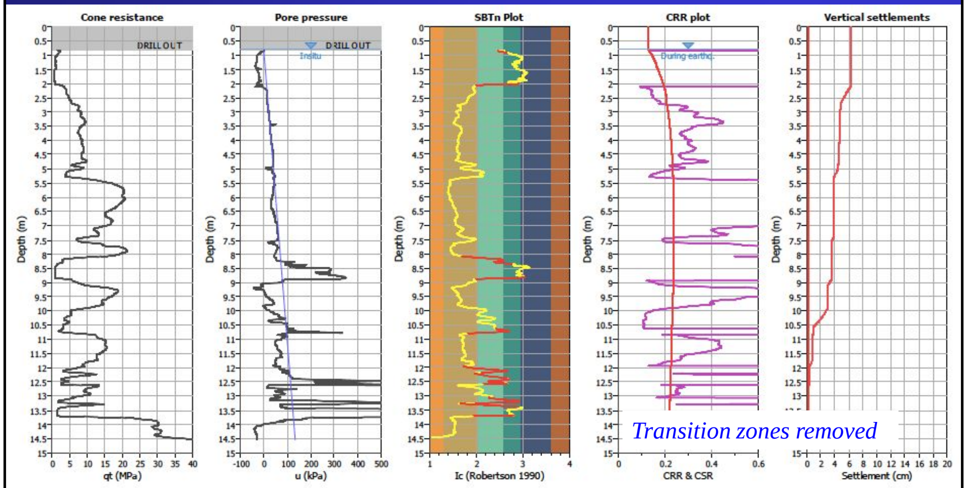


Example



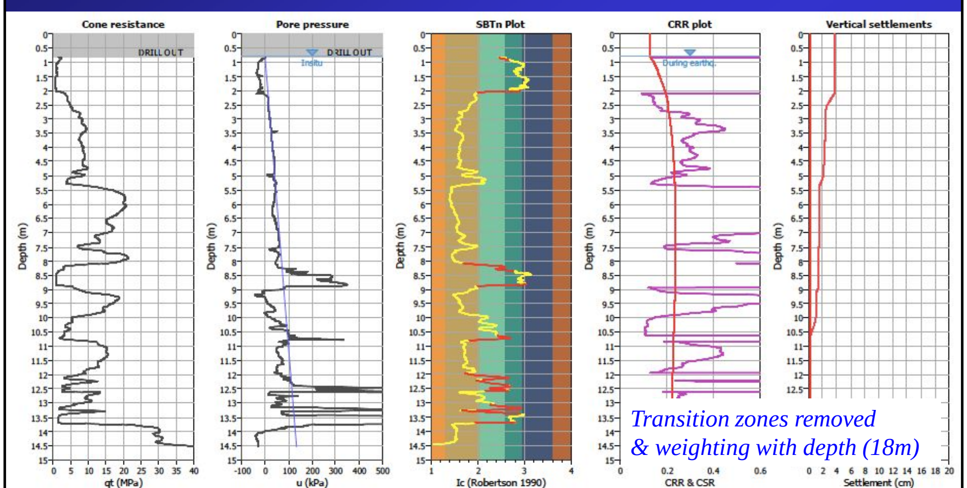
Christchurch KAN-19 M_w = 7.1, $a_{(max)}$ = 0.23g Minor liquefaction, estimated settlement ~2cm

Transition zones - example



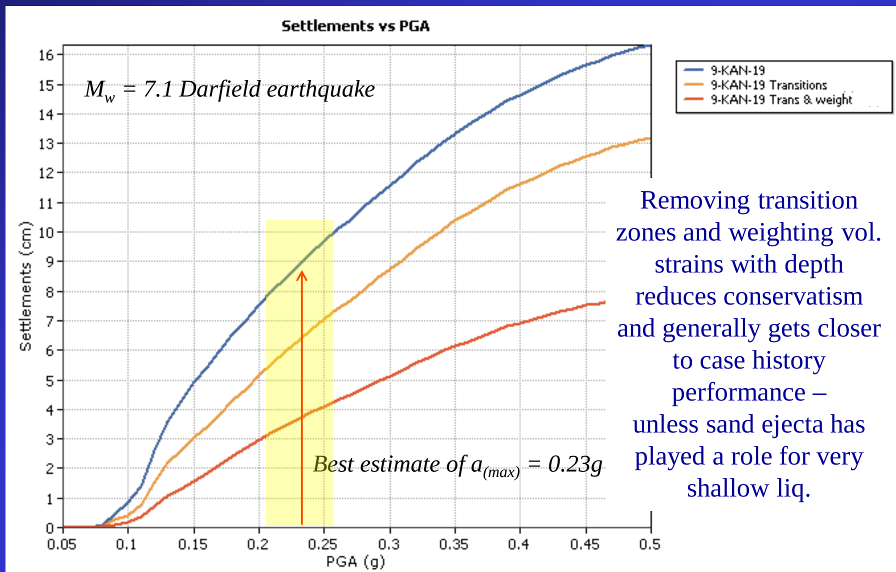
Christchurch KAN-19 M_w = 7.1, $a_{(max)}$ = 0.23g Minor liquefaction, estimated settlement ~2cm

Transition & weighting - example



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

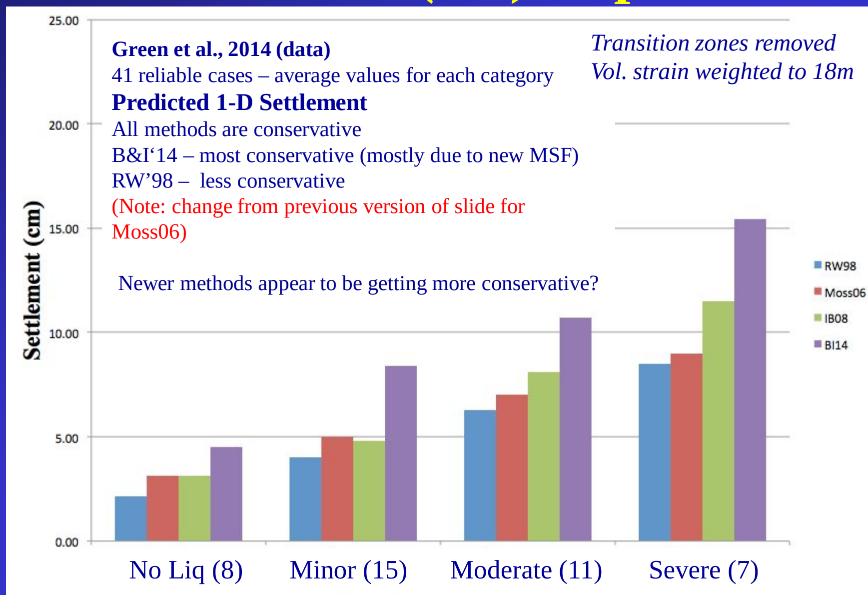
Sensitivity analysis



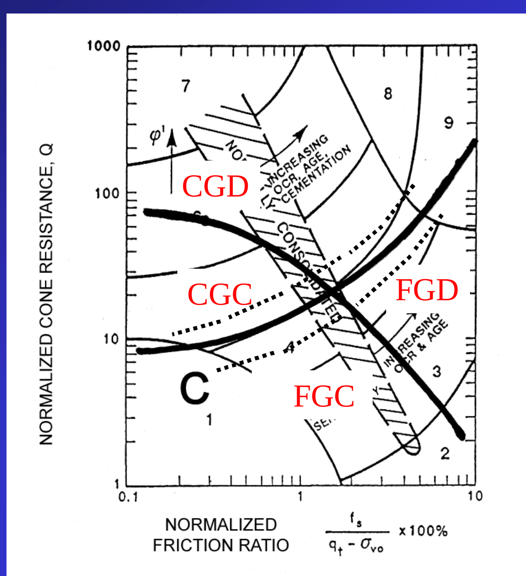
Recent Christchurch NZ Cases

- 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



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 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. $z > 12$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 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?