San Diego Regional Chapter
Earthquake Engineering Research Institute

Seismic liquefaction CPT-based methods

Peter K. Robertson

EERI 2014

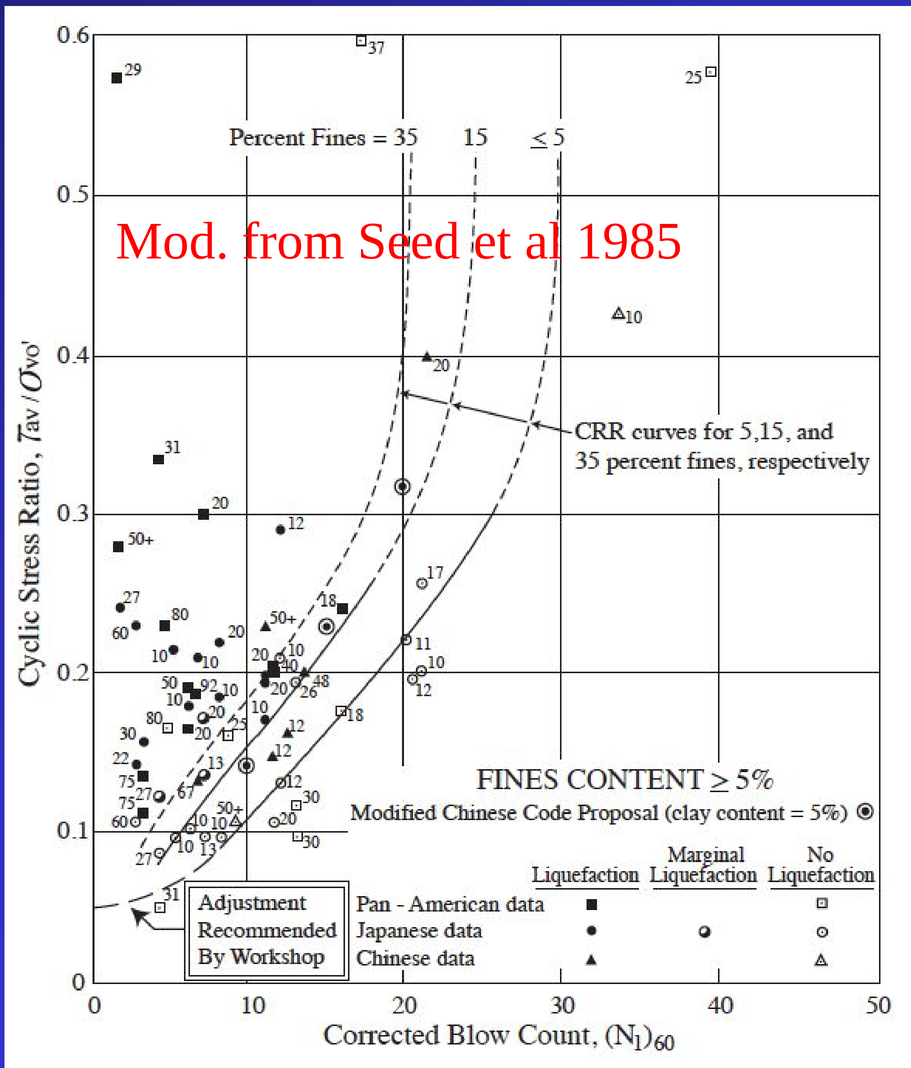
What level of sophistication is appropriate for SI & analyses?

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)

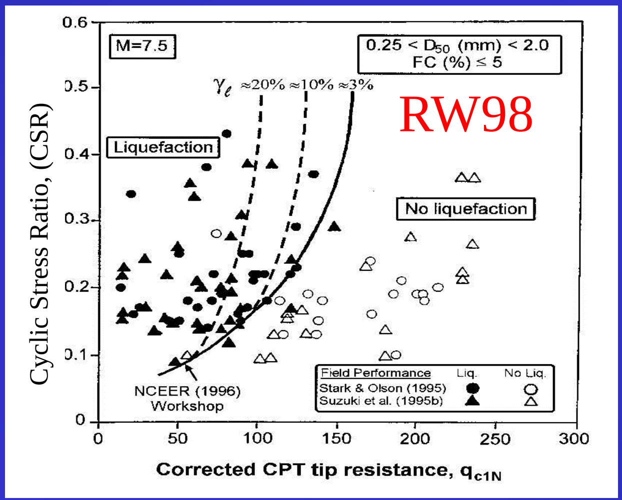
Origin of CPT-based methods

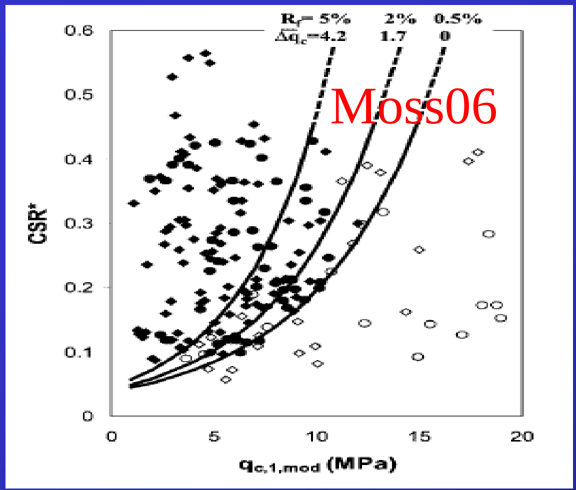
All methods have similar origins:

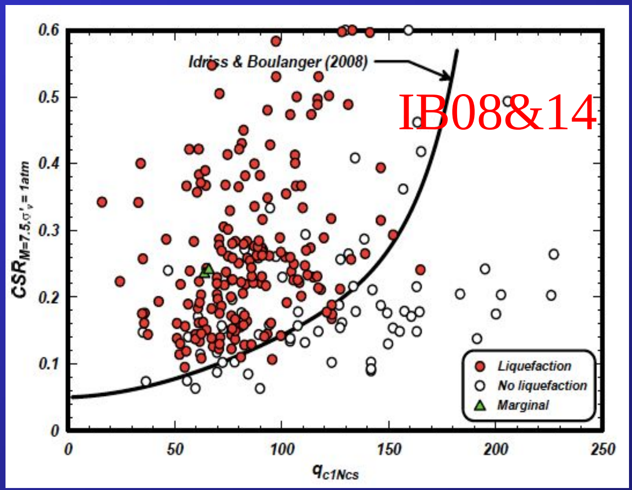
Case histories (each summarized to 1 data point)

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

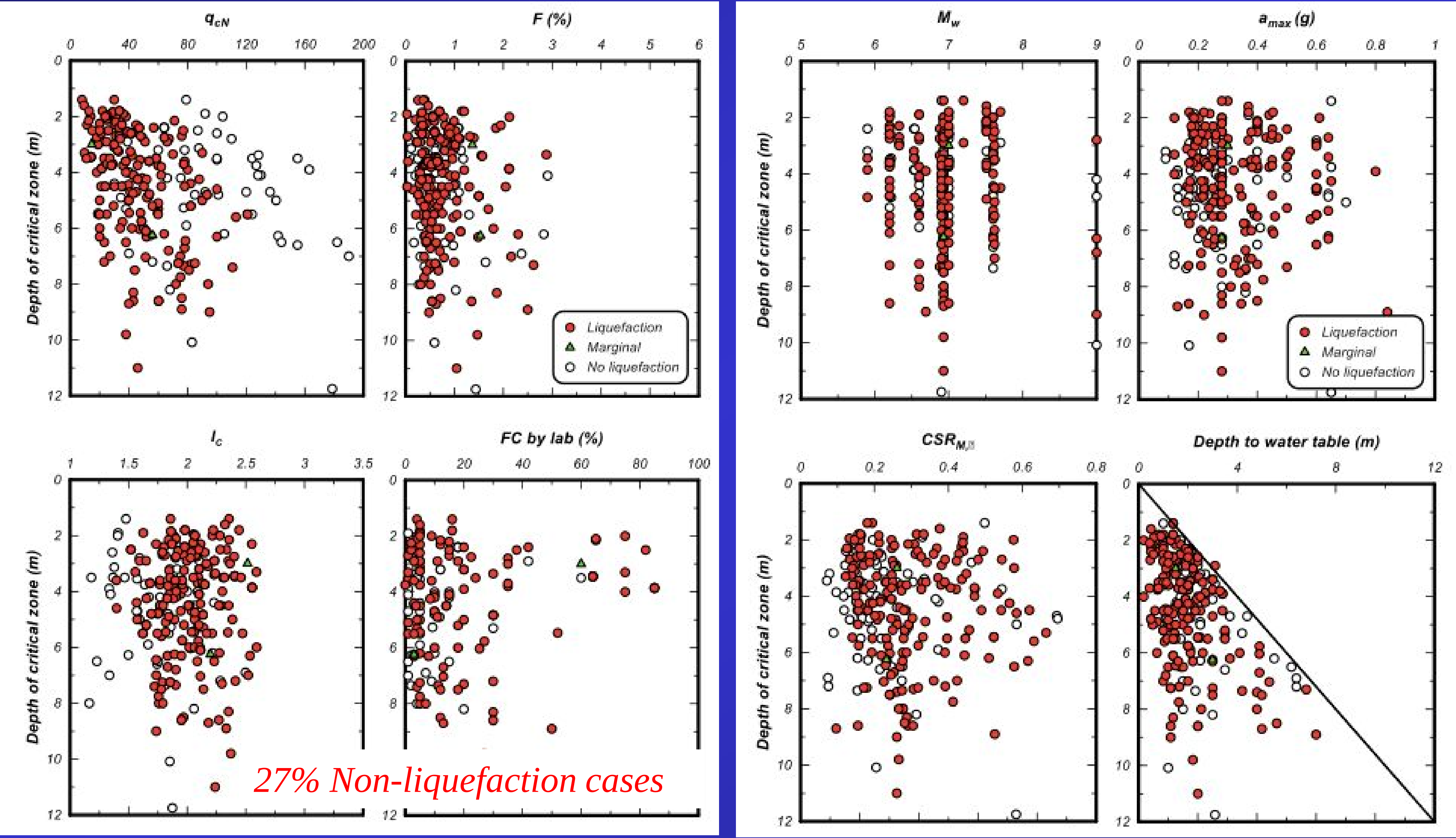
Each method made different assumptions for: *r_d, MSF, K_σ, normalization of q_c & 'fines correction'*







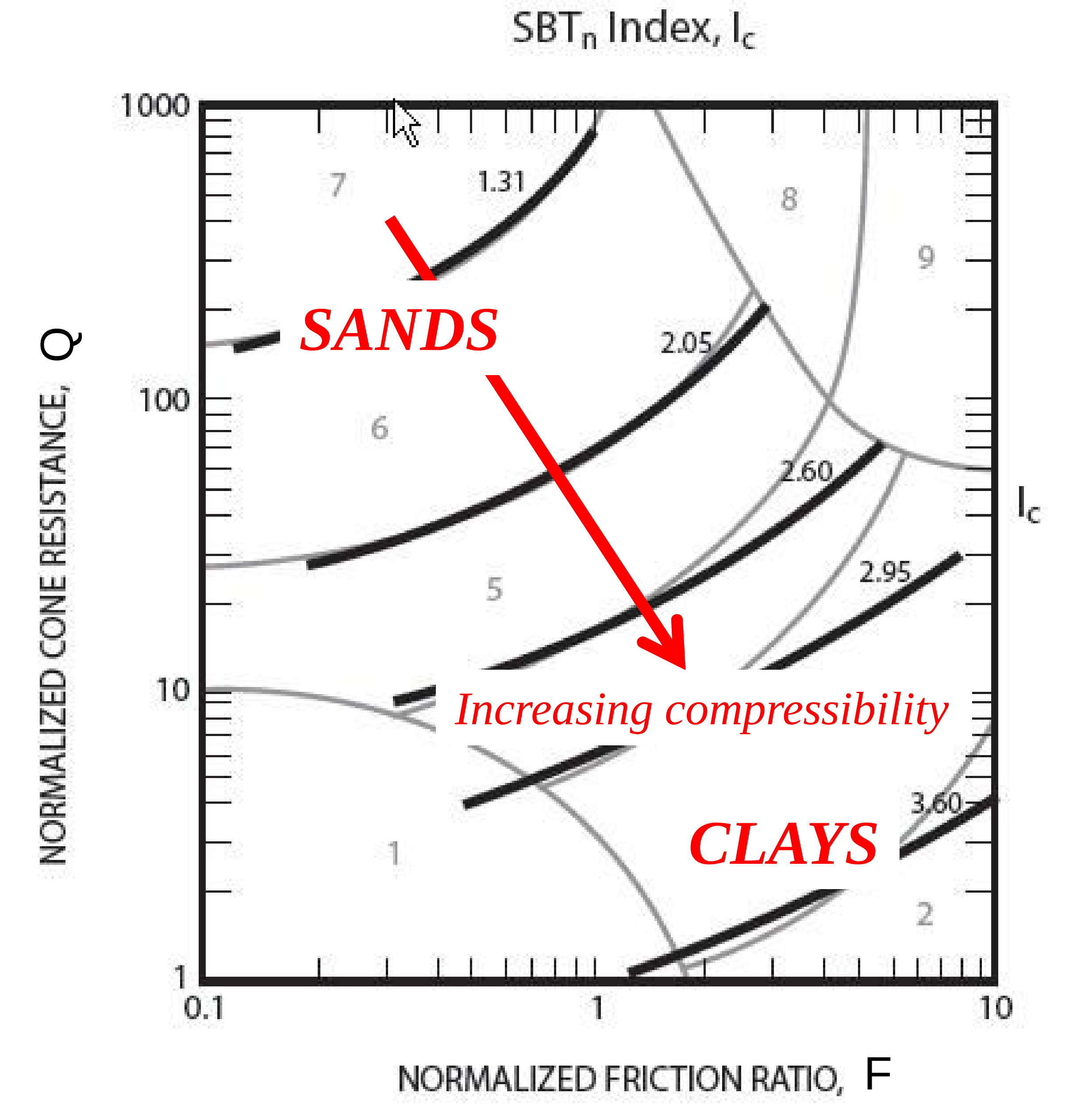
Updated database > 250 sites



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

After Boulanger & Idriss, 2014

CPT SBTn Index, I_c



Soil Behavior Type Index, I_c

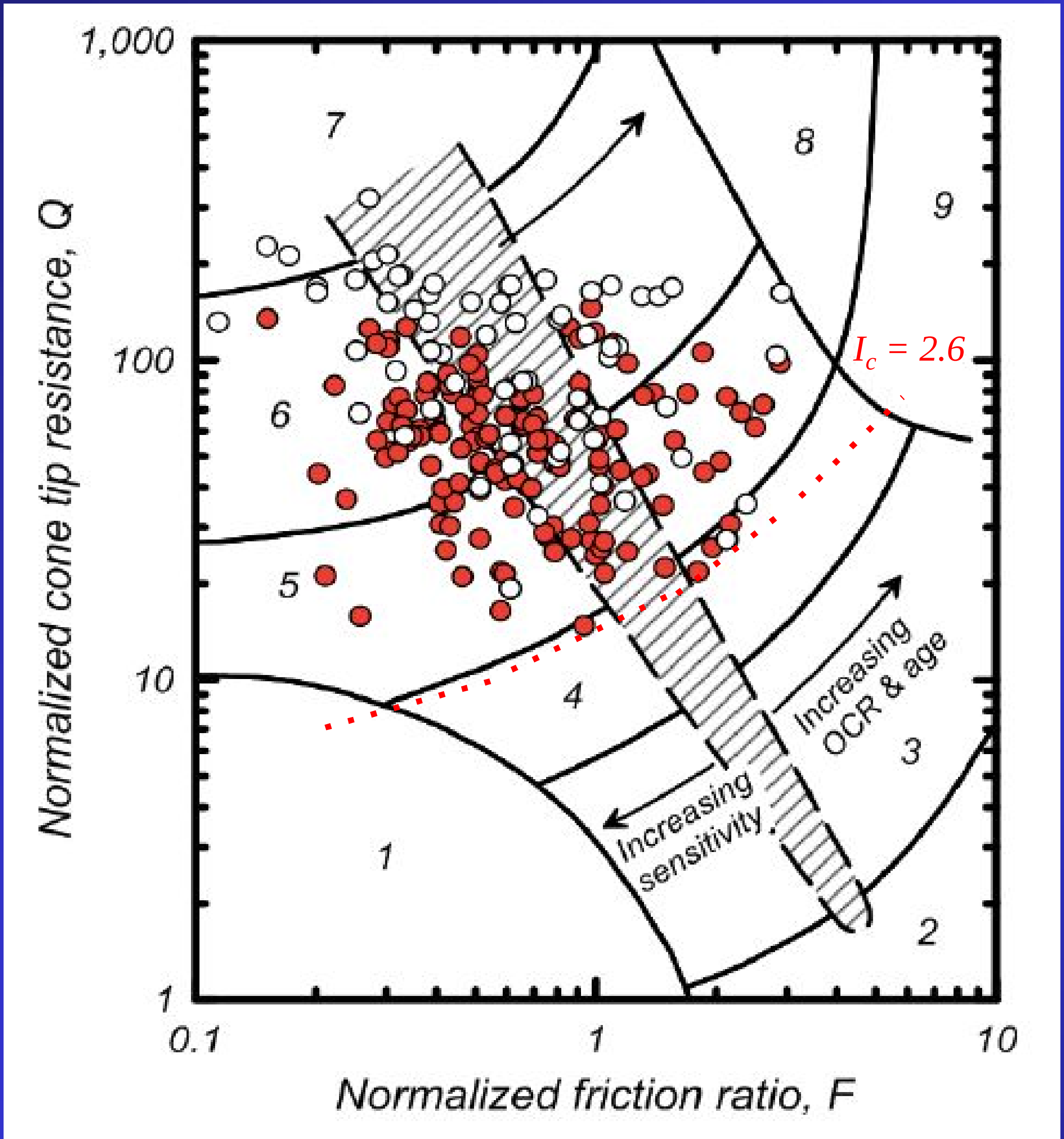
$I_c = [(3.47 - \log Q)^2 + (\log F + 1.22)^2]^{0.5}$

Q & F normalized CPT parameters

Function primarily of Soil Compressibility

Robertson, 2014

Updated database on SBTn chart

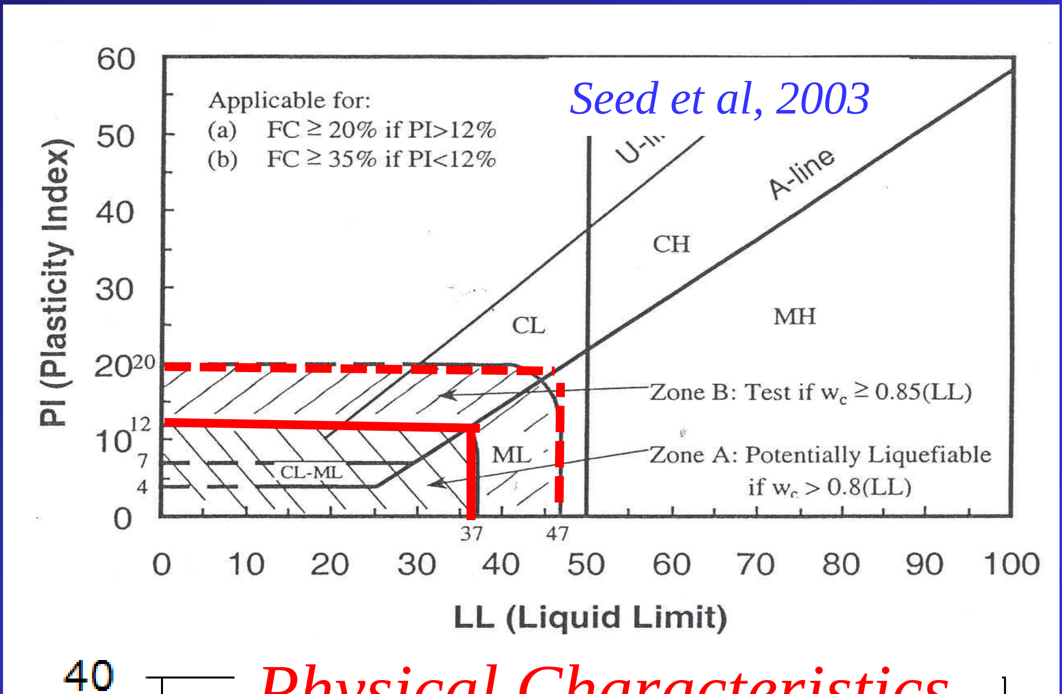


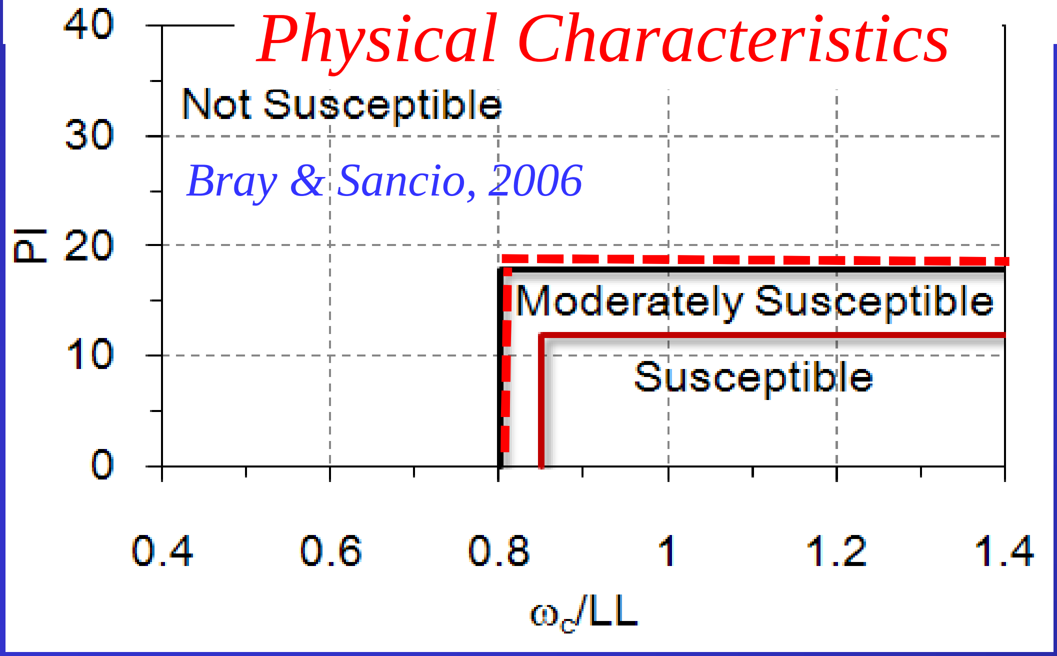
All cases have CPT SBTn $I_c < 2.6$

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

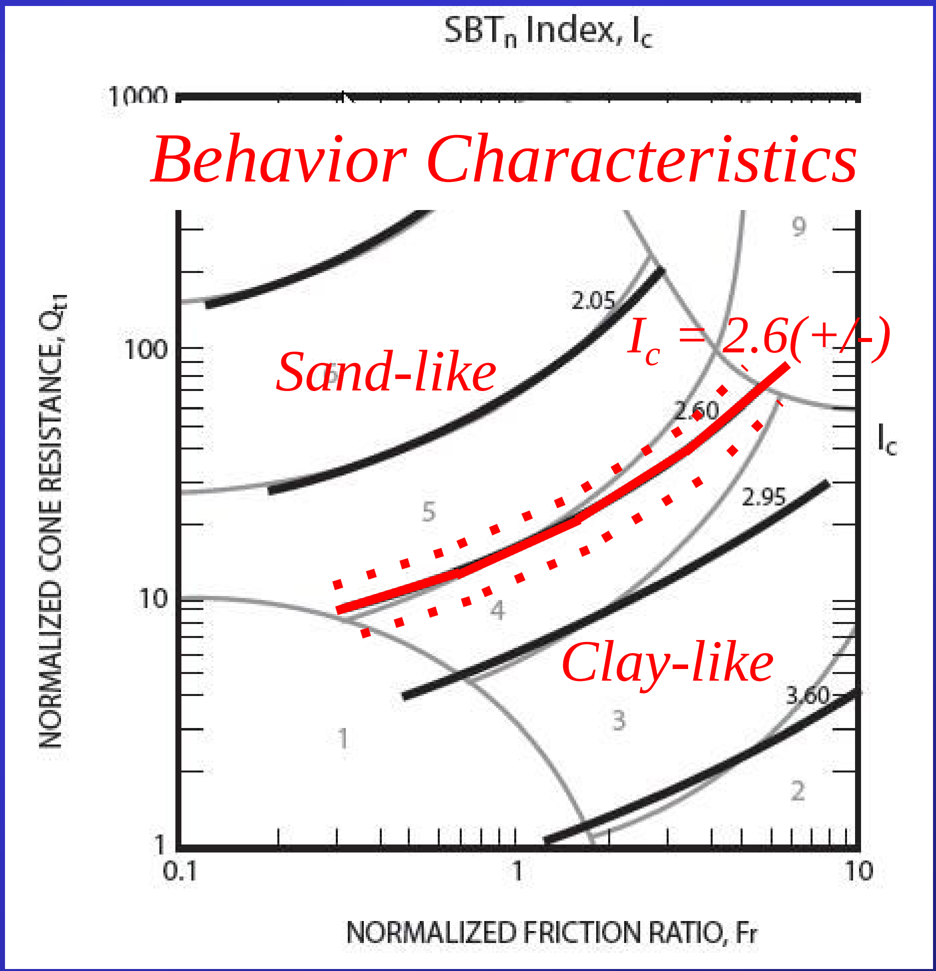
Data after Boulanger & Idriss, 2014

Susceptibility to cyclic liquefaction



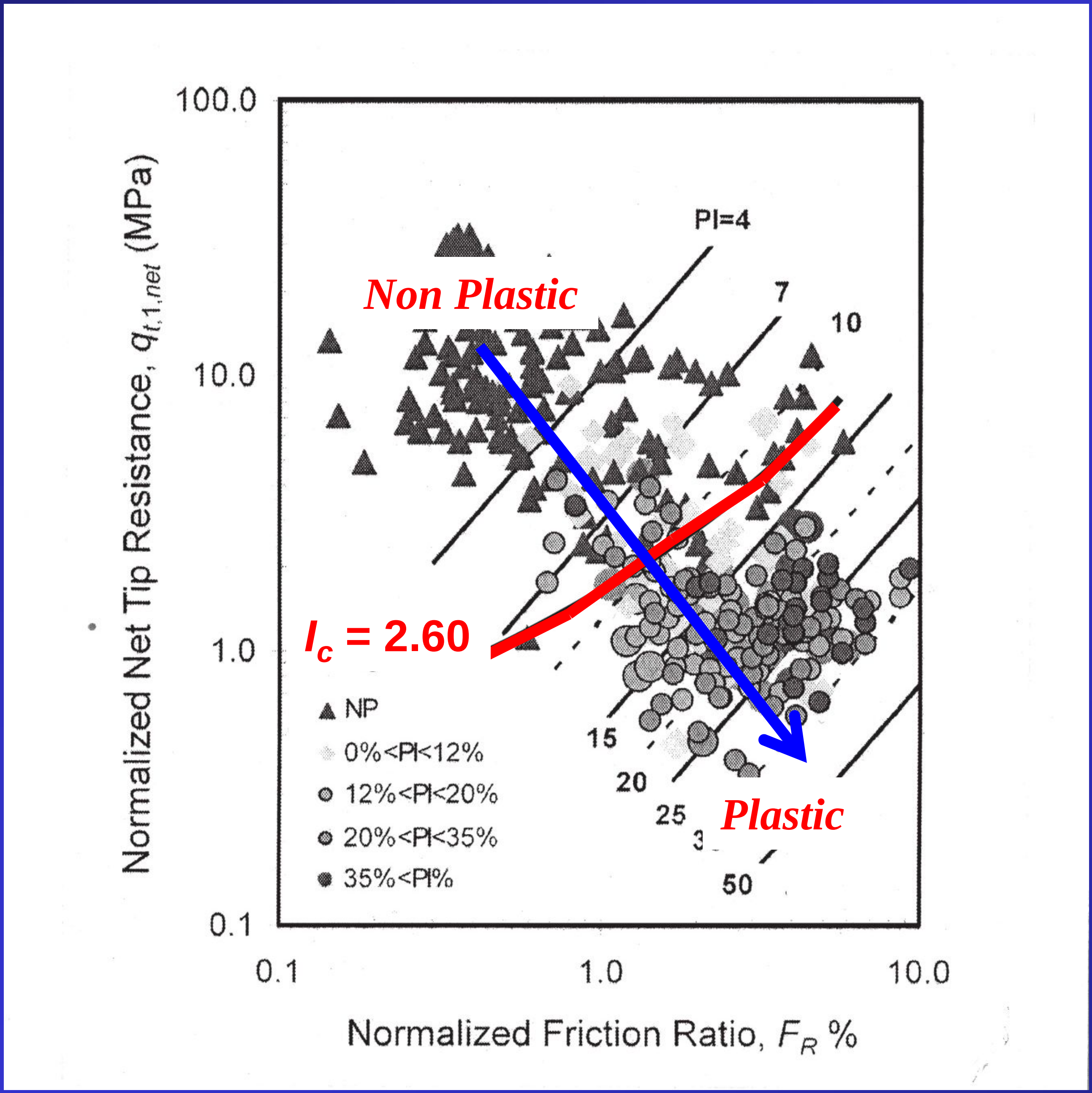


CPT SBT



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 PI ~ 10

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

Data from Cetin & Ozan, 2009

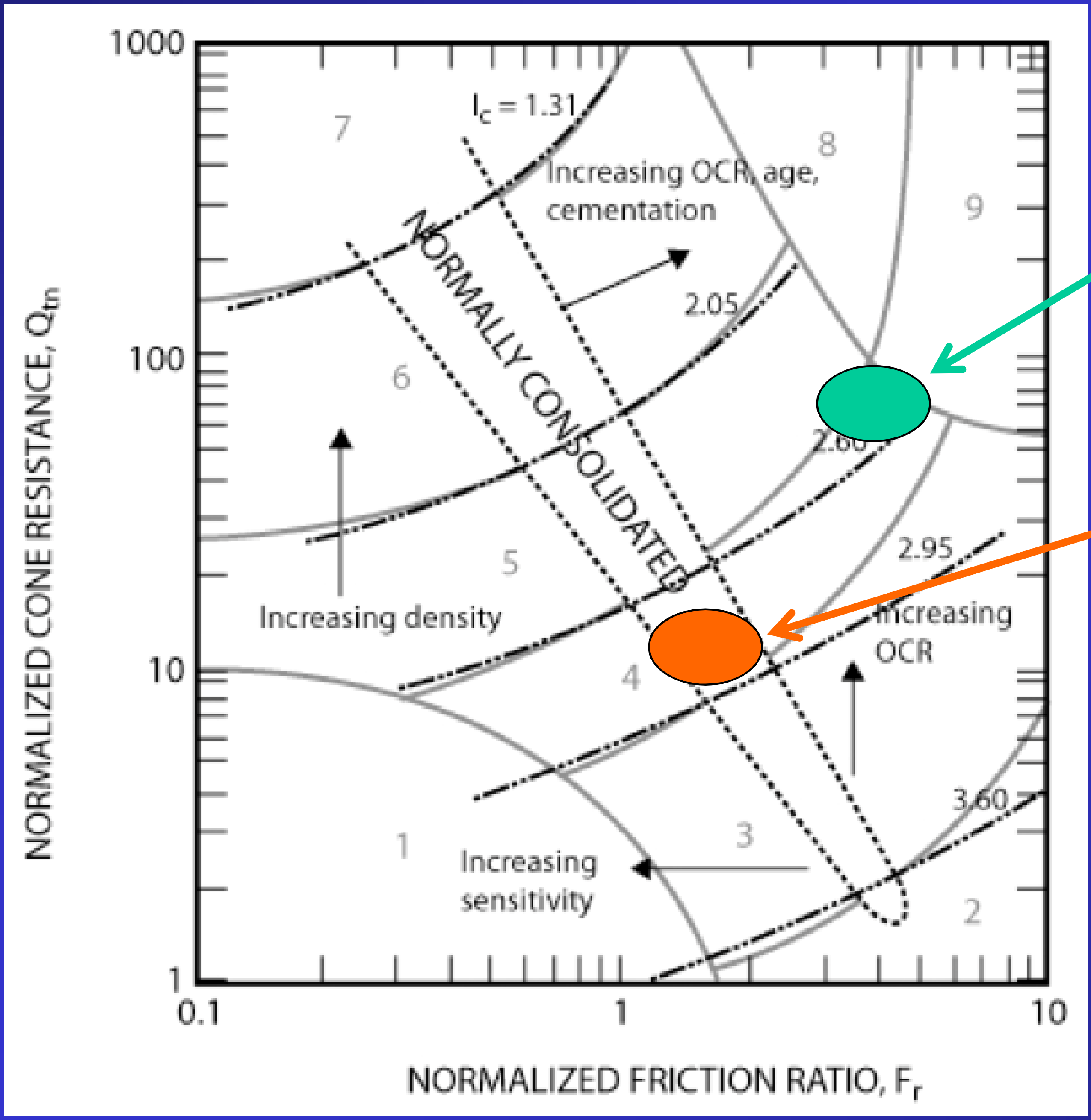
Robertson, 2014

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

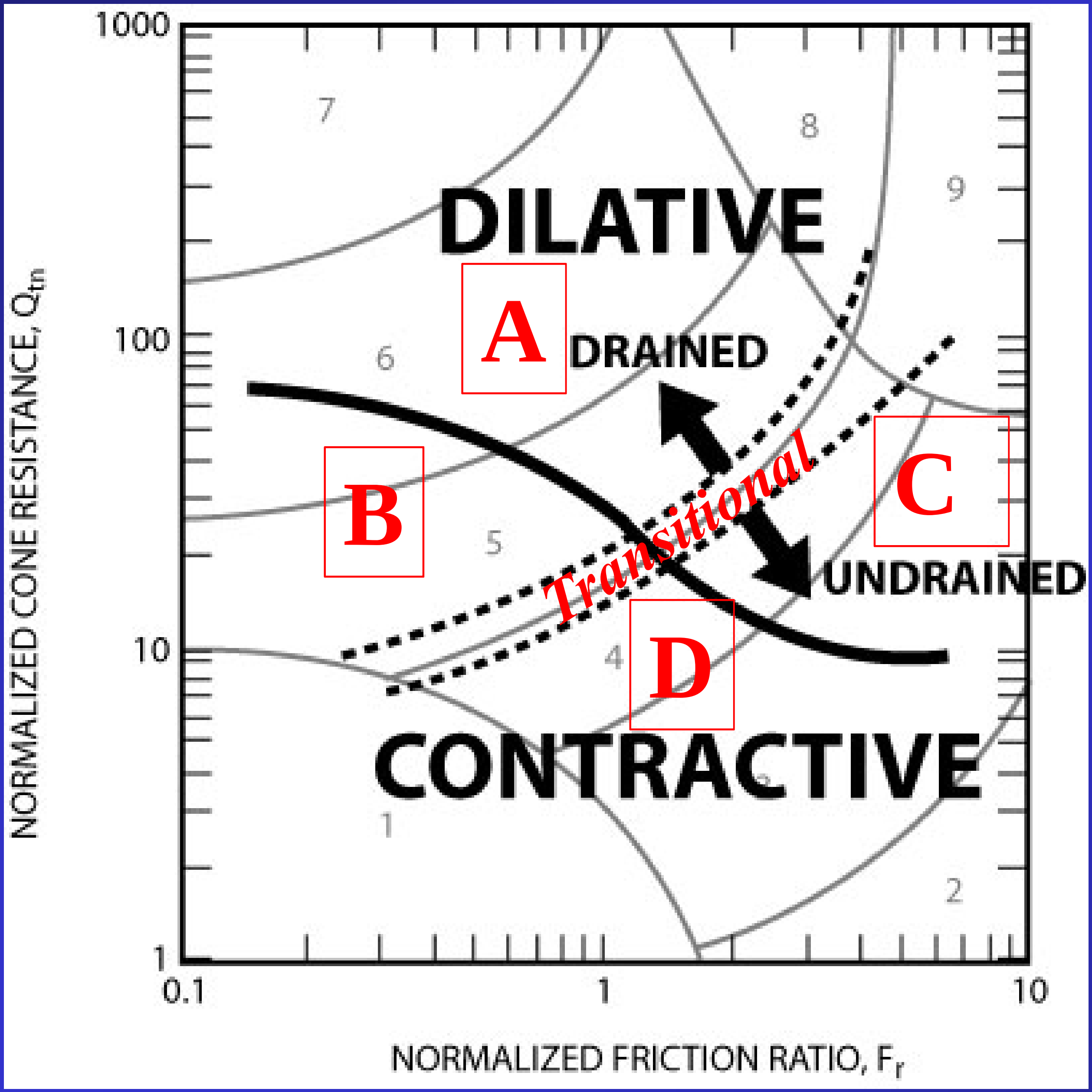
Exceptions



Very stiff OC clay

NC non-plastic silt

Generalized CPT Soil Behaviour Type



CPT Soil Behaviour

A: Coarse-grain-dilative

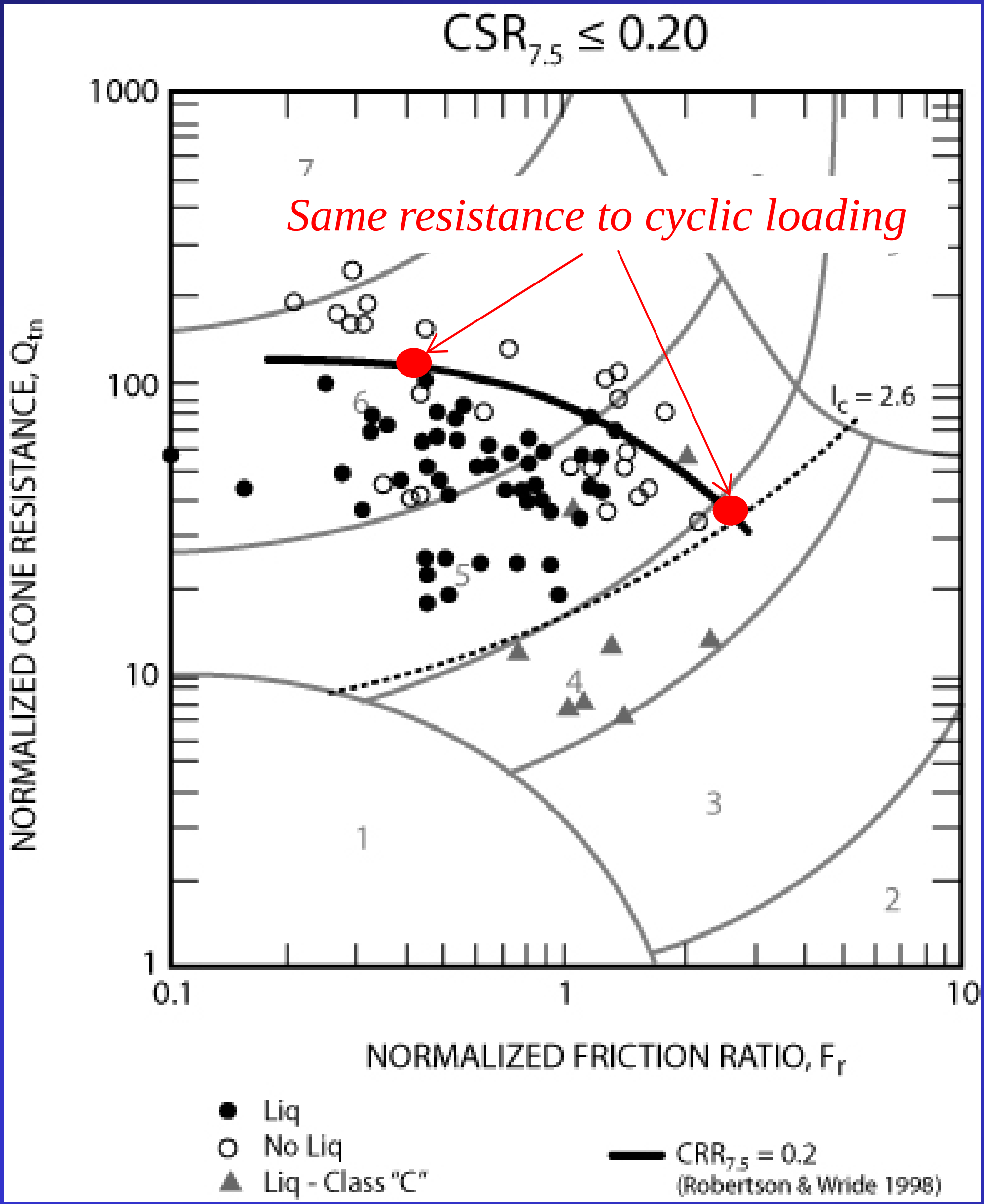
B: Coarse-grain-contractive

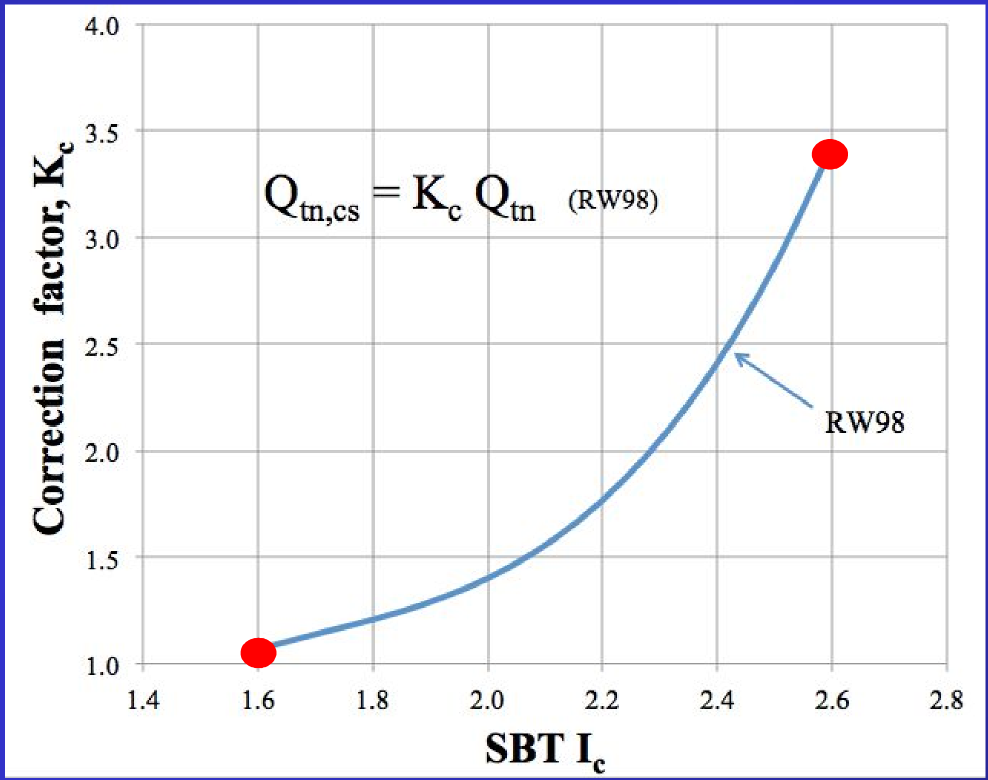
C: Fine-grain-dilative

D: Fine-grain-contractive

Robertson, 2012

CPT clean sand equivalent





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

Robertson 2009

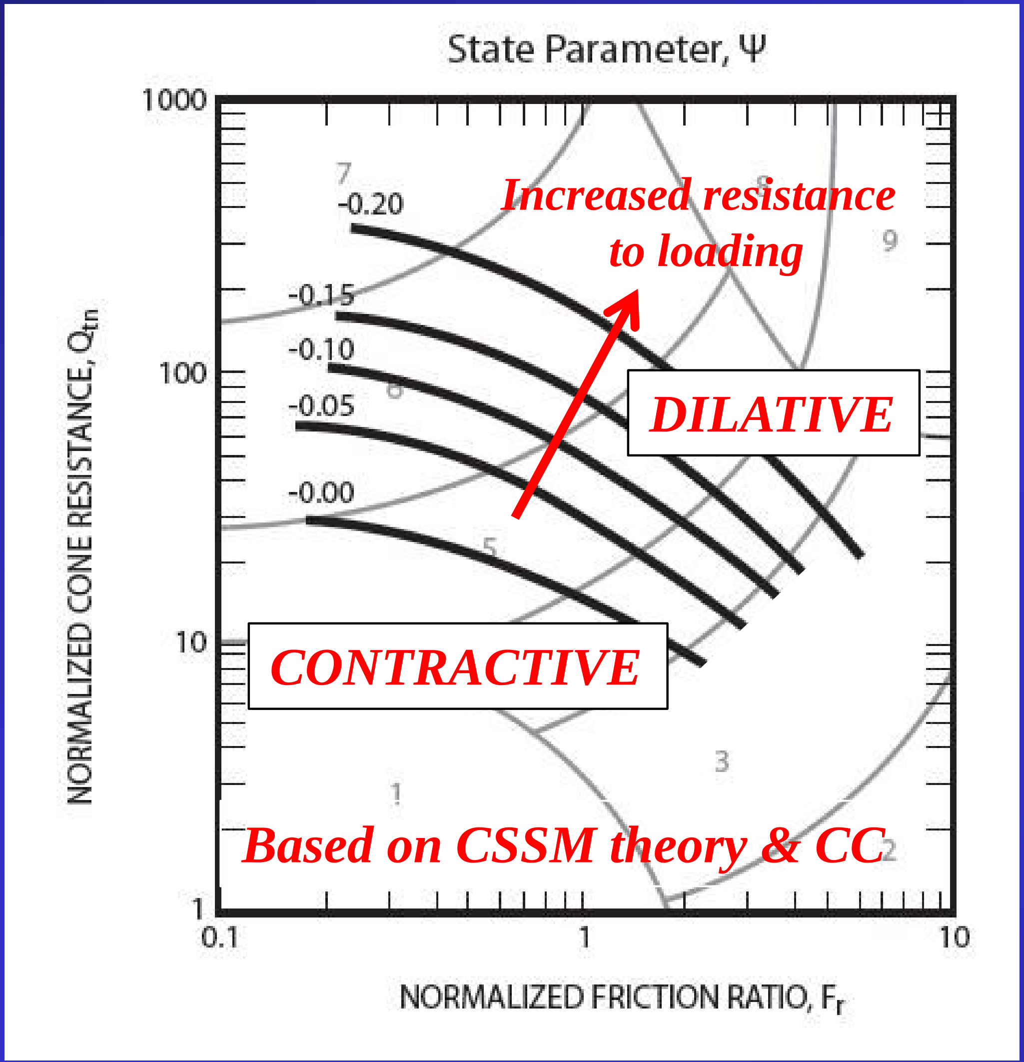
CPT-based "fines" correction

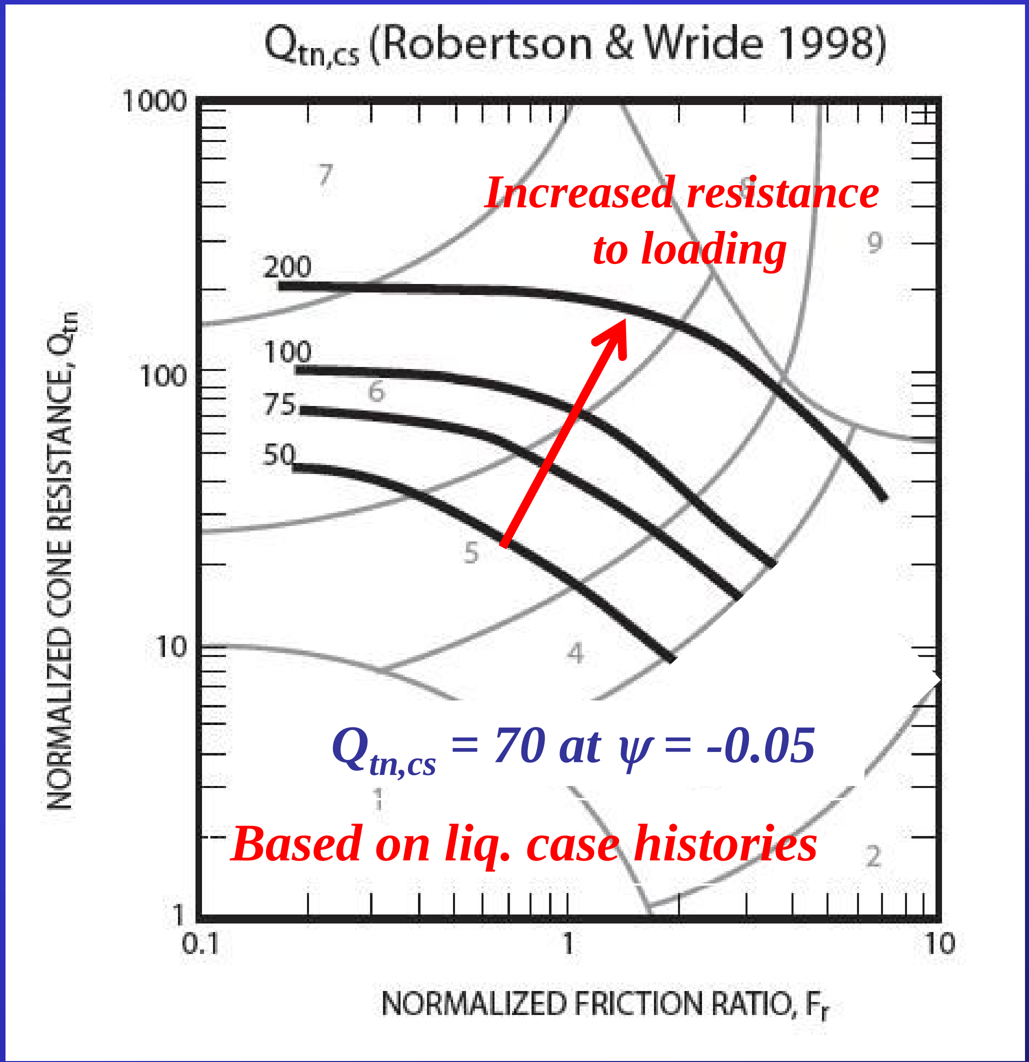
- ***Fines content*** is a ***physical characteristic*** obtained on ***disturbed samples***, that has a ***weak link*** to in-situ behavior. Application of a correction based on fines content introduces added uncertainty.

- ***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 $Q_{tn,cs}$

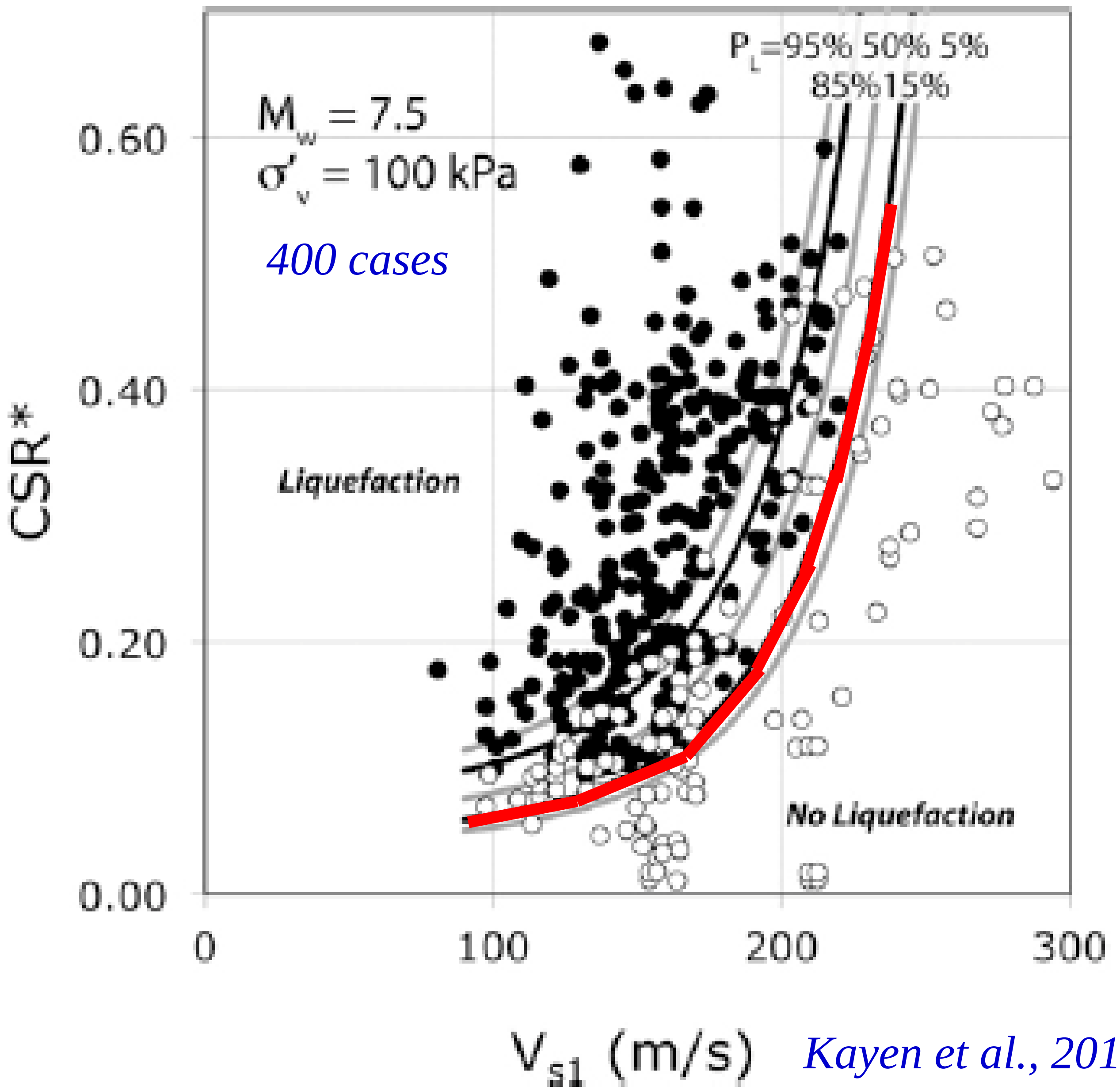




$\psi \sim 0.56 - 0.33 \log Q_{tn,cs}$

Robertson, 2012

Shearwave Velocity Approach



Kayen et al., 2013

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

Compare CPT and V_{s1}

Robertson & Wride, (1998) CPT-based liquefaction triggering method for young, uncemented sandy soils (I_c < 2.6):

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

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

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

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

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

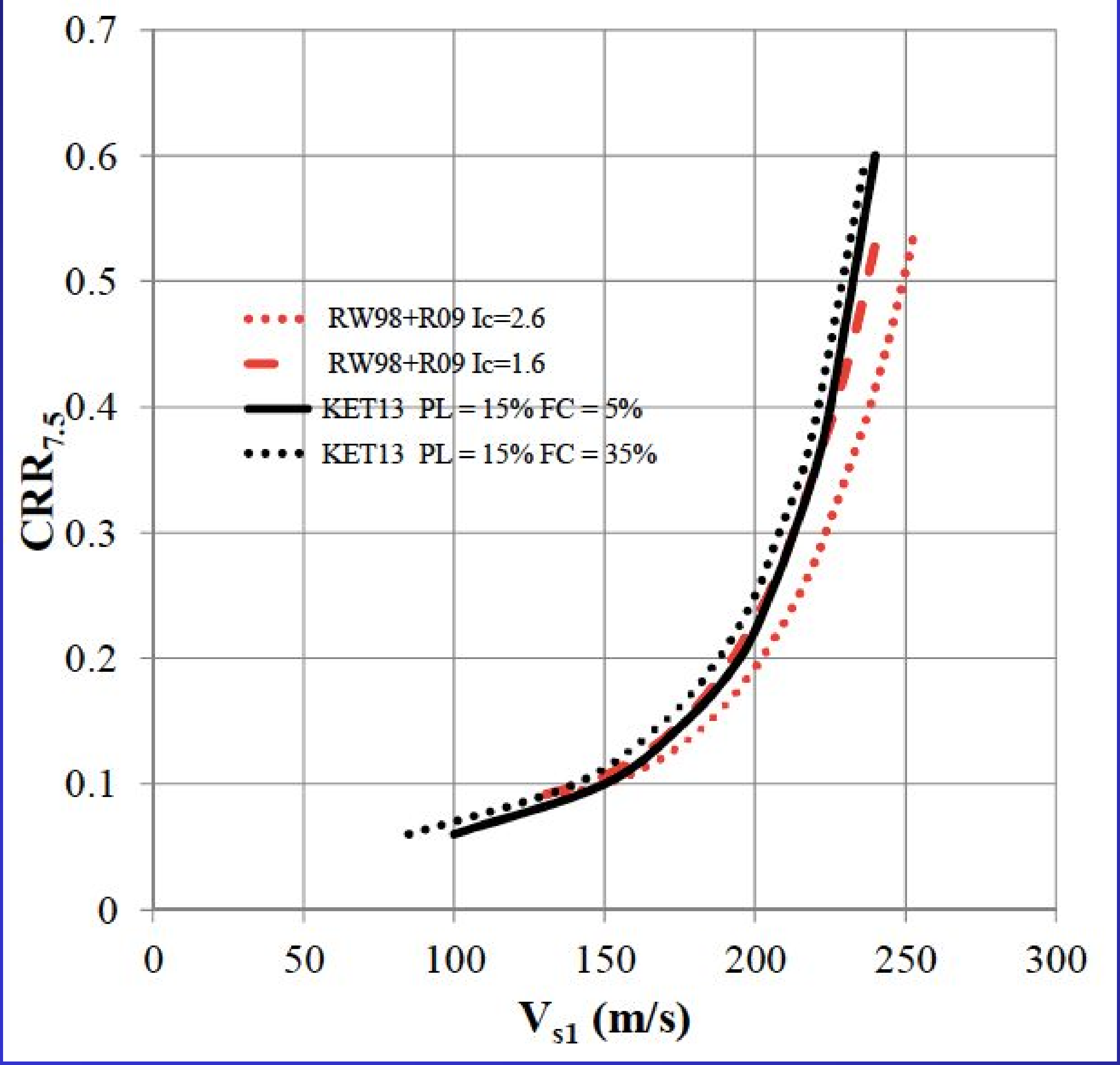
$$\alpha_{vs} = 10^{(0.55\ Ic\ +\ 1.68)}$$

Therefore: $Q_{tn,cs} = (K_c/\alpha_{vs})\ (V_{s1})^2$

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

- For clean sands (FC < 5%), I_c = 1.6, then α_{vs} = 363.078 and K_c = 1.0659
- For silty sands (FC ~35%), I_c = 2.6, then α_{vs} = 1288.25 and K_c = 3.4267

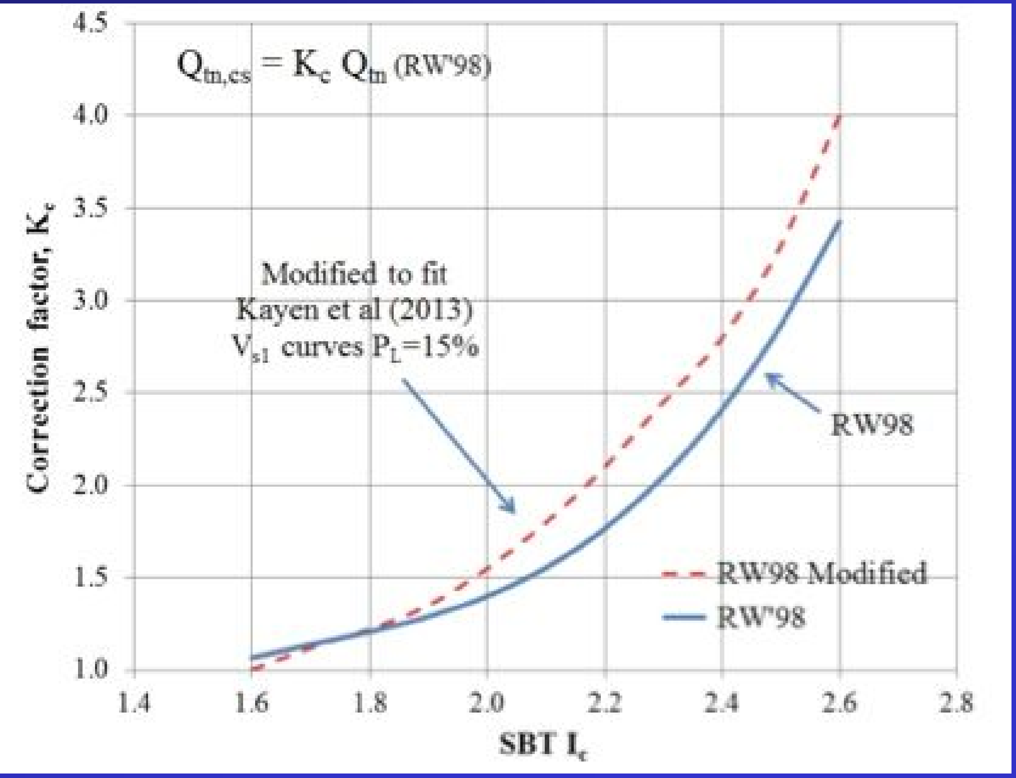
Compare CPT and V_{s1}

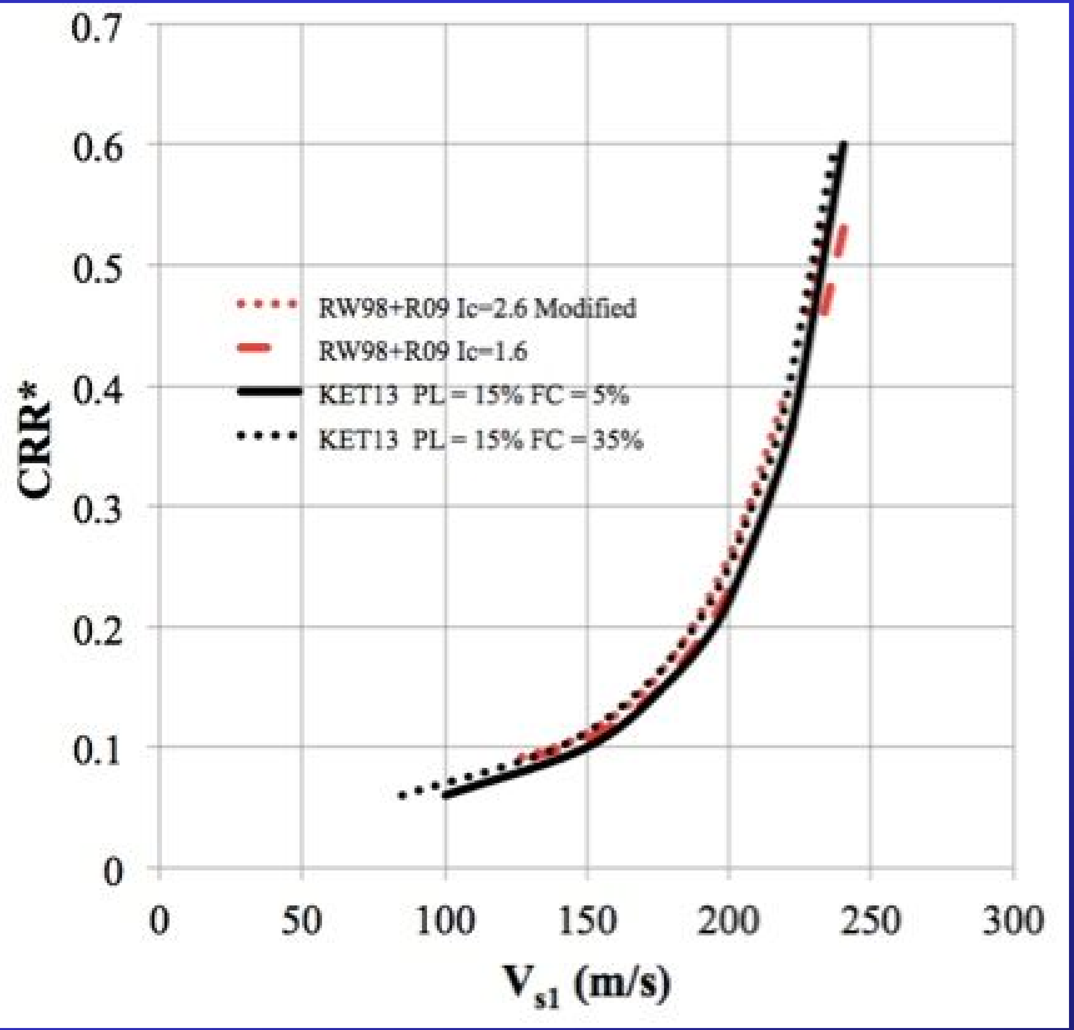


Comparison between V_{s1}-based trigger curves by *Kayen et al (2013)* and the CPT-based trigger curves by *Robertson and Wride (1998)* using the correlation between CPT-V_{s1} proposed by *Robertson (2009)*

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

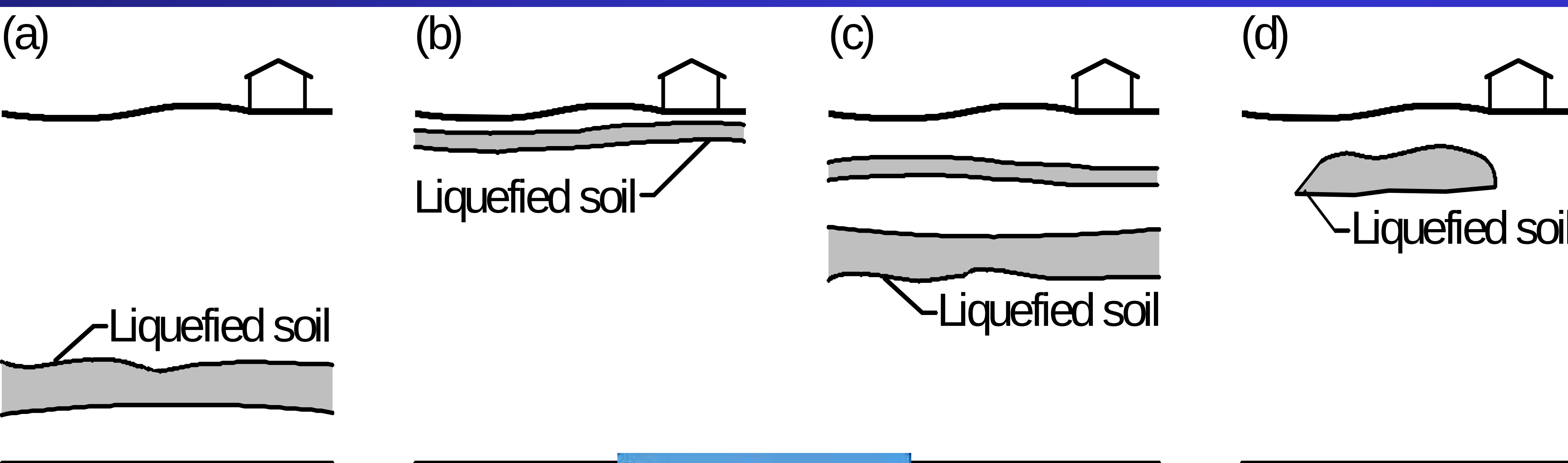
Consequences of Liquefaction

- *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*

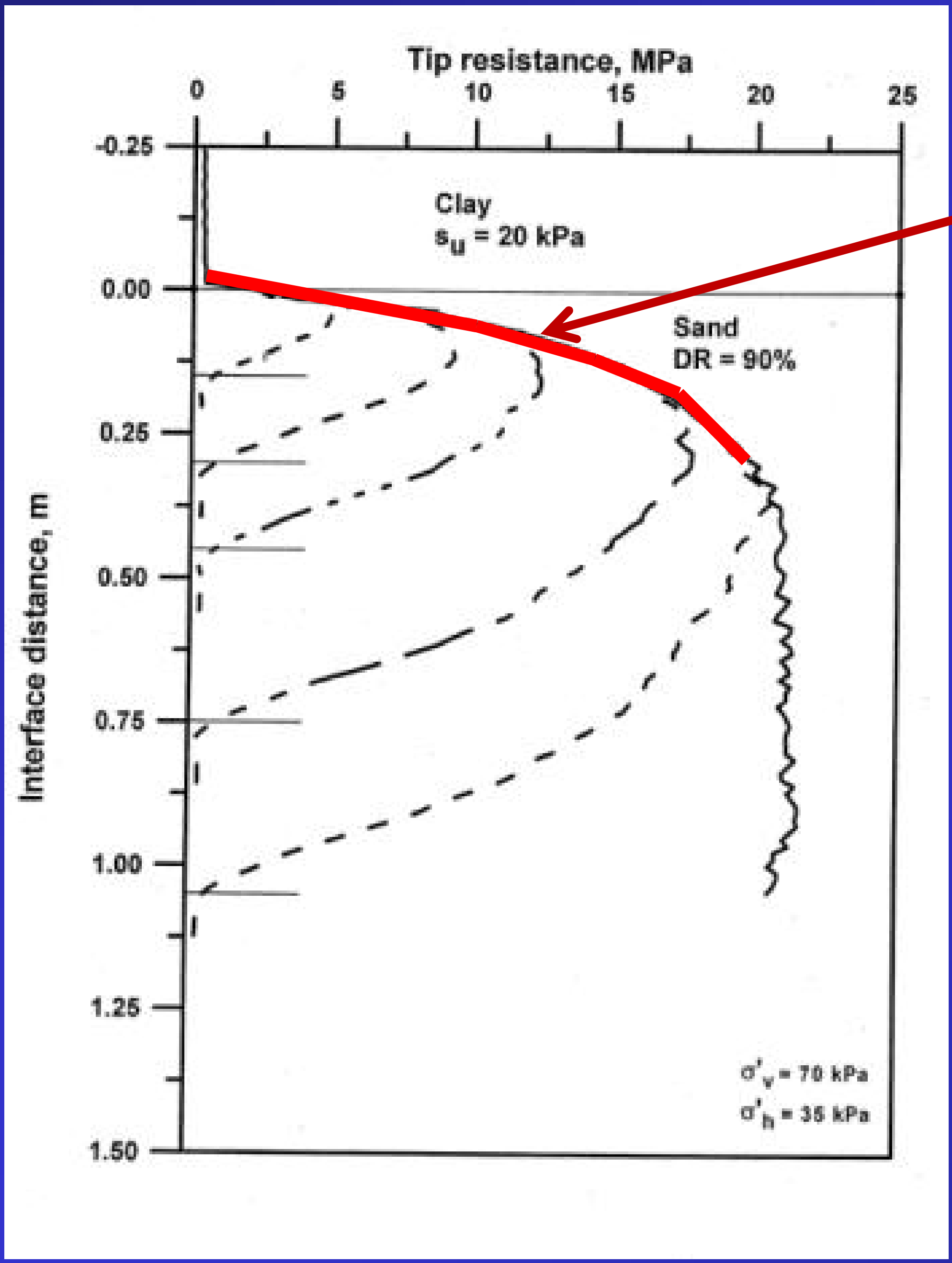
Predicting post-EQ settlement

- 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



Transition zone

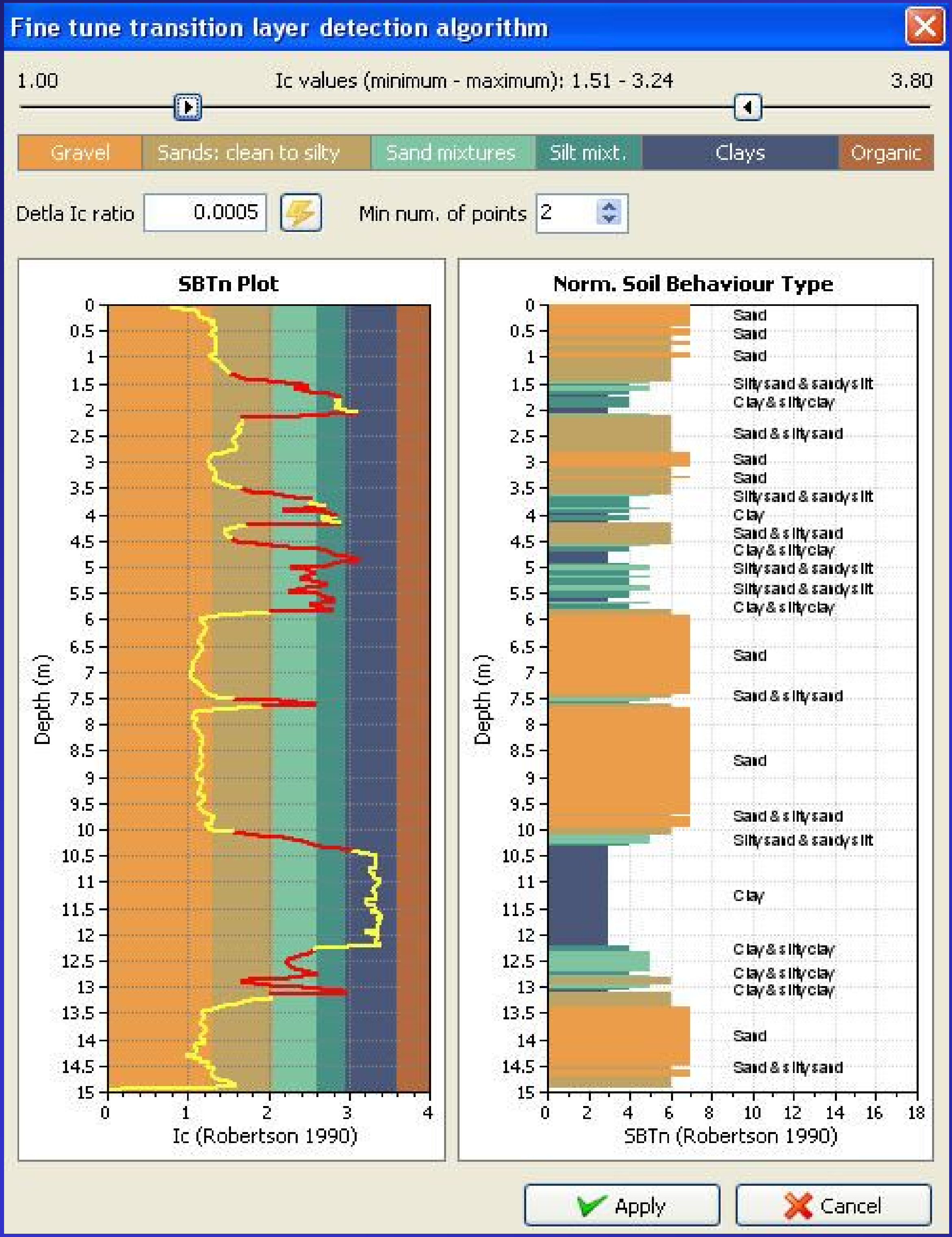


CPT data in 'transition' when cone is moving from one soil type to another when there is significant difference in soil stiffness/strength (e.g. soft clay to sand)

CPT data within transition zone will be misinterpreted

In interlayered deposits this can result in excessive conservatism

Ahmadi & Robertson, 2005



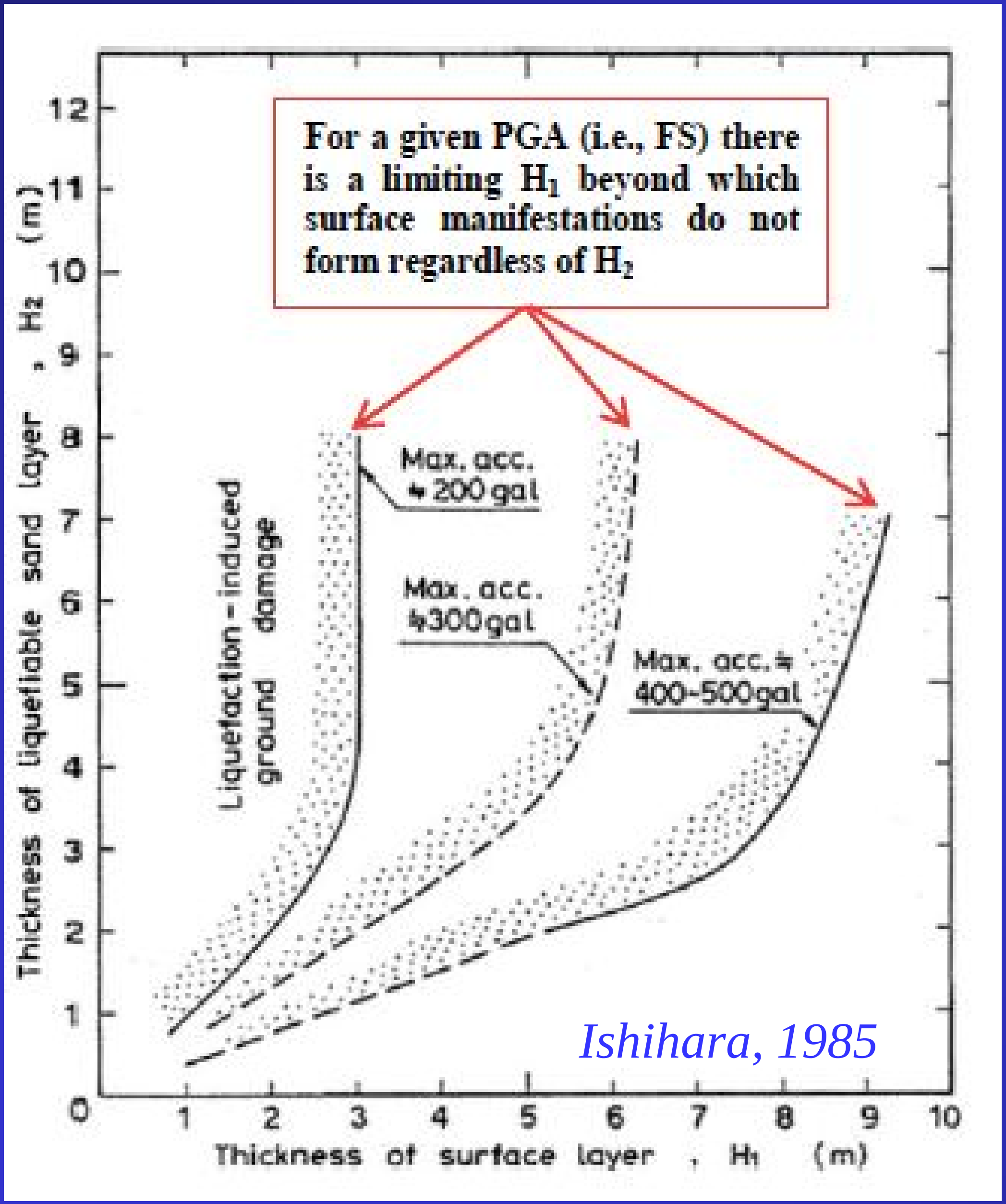
Transition zone detection

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

Very important for liquefaction analysis

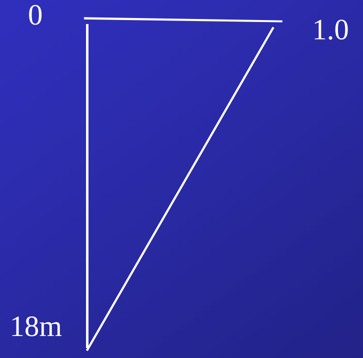
"CLiq" software
www.geologismiki.gr

Depth of liquefaction

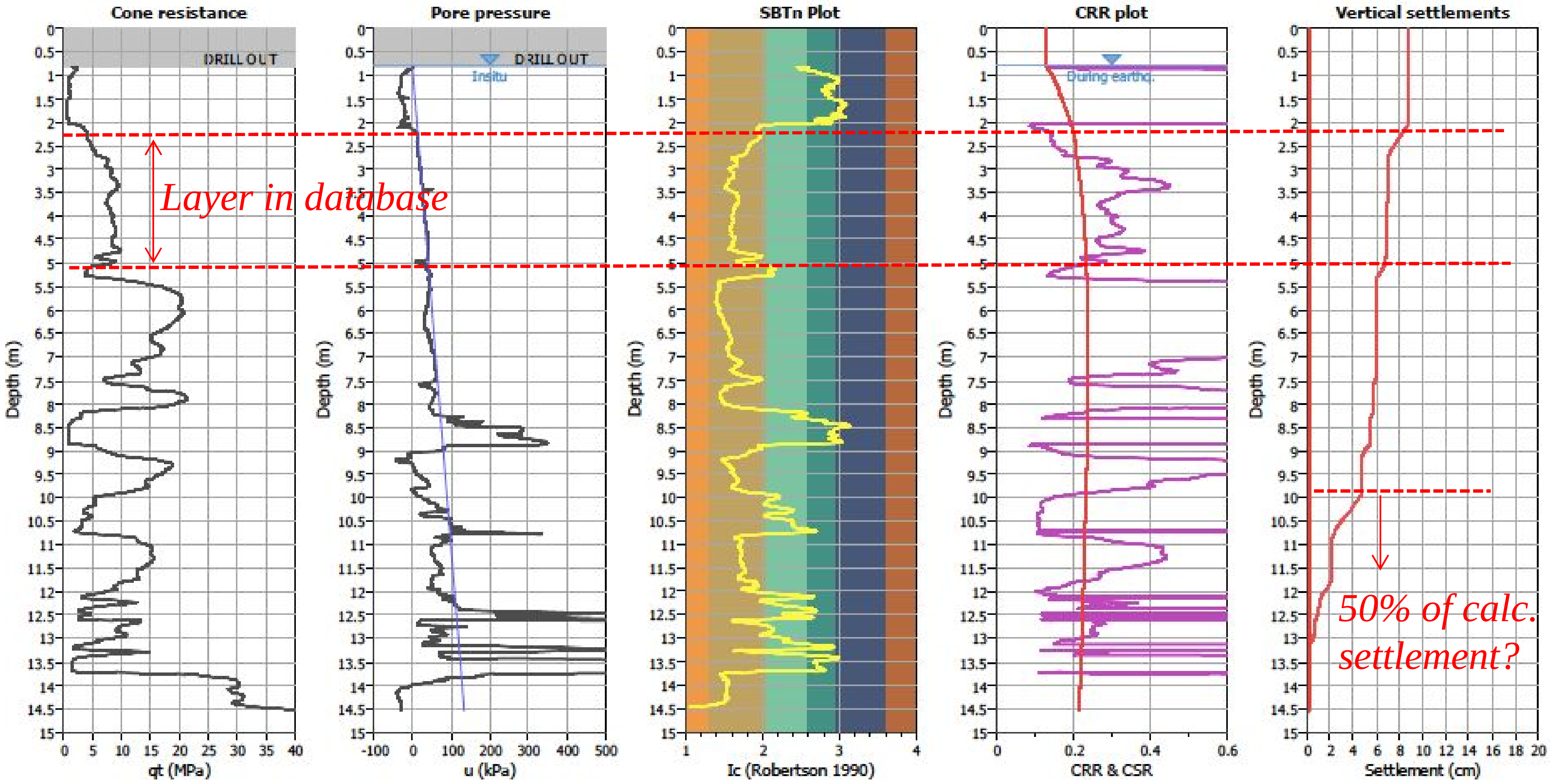


Ishihara (1985) showed that surface damage from liquefaction is influenced by thickness of liquefied layer and thickness of non-liquefied surface layer.

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

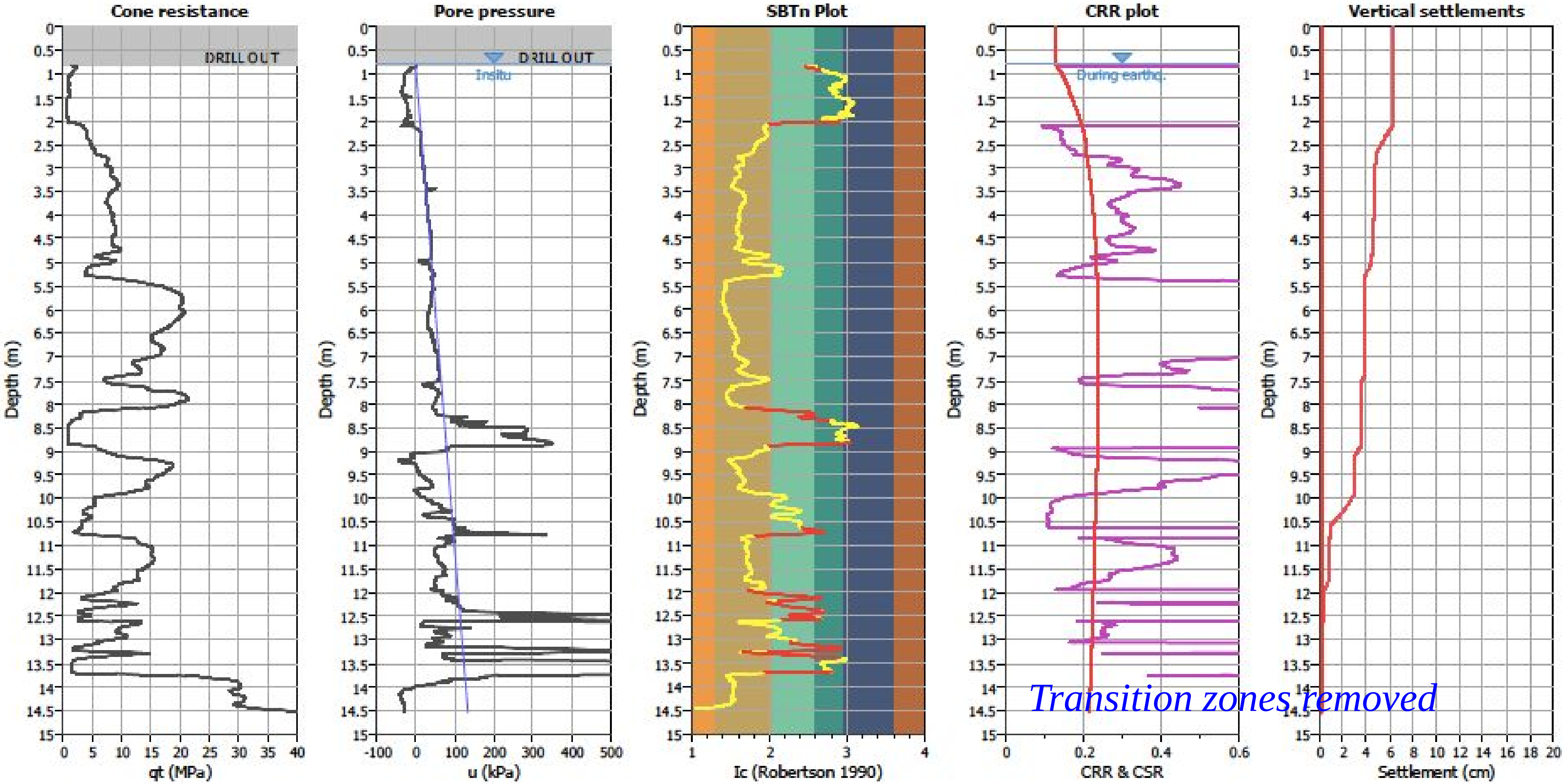


Example



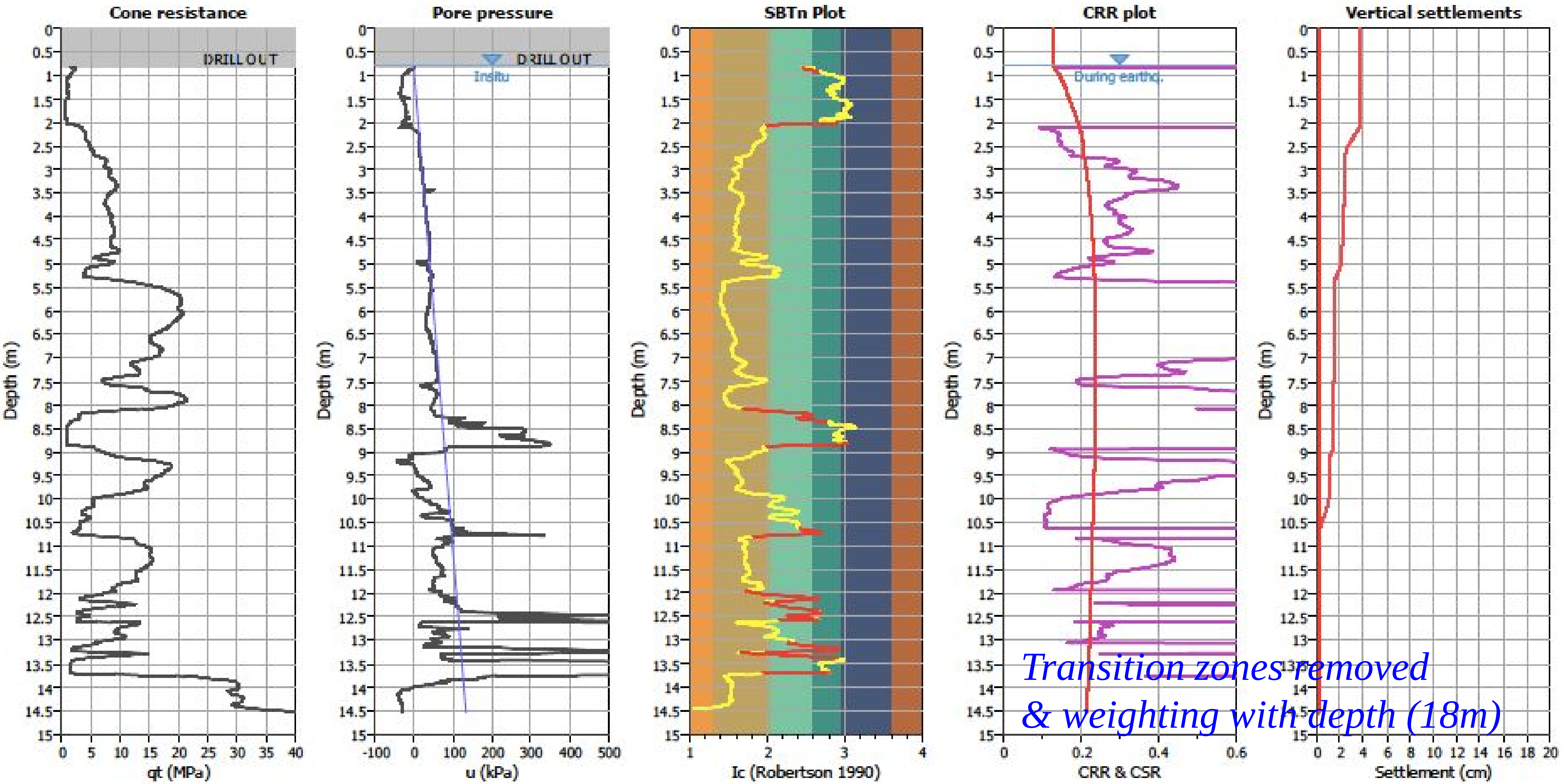
Christchurch KAN-19 M_w = 7.1, $a_{(max)}$ = 0.23g Minor liquefaction, estimated settlement ~2cm

Transition zones - example



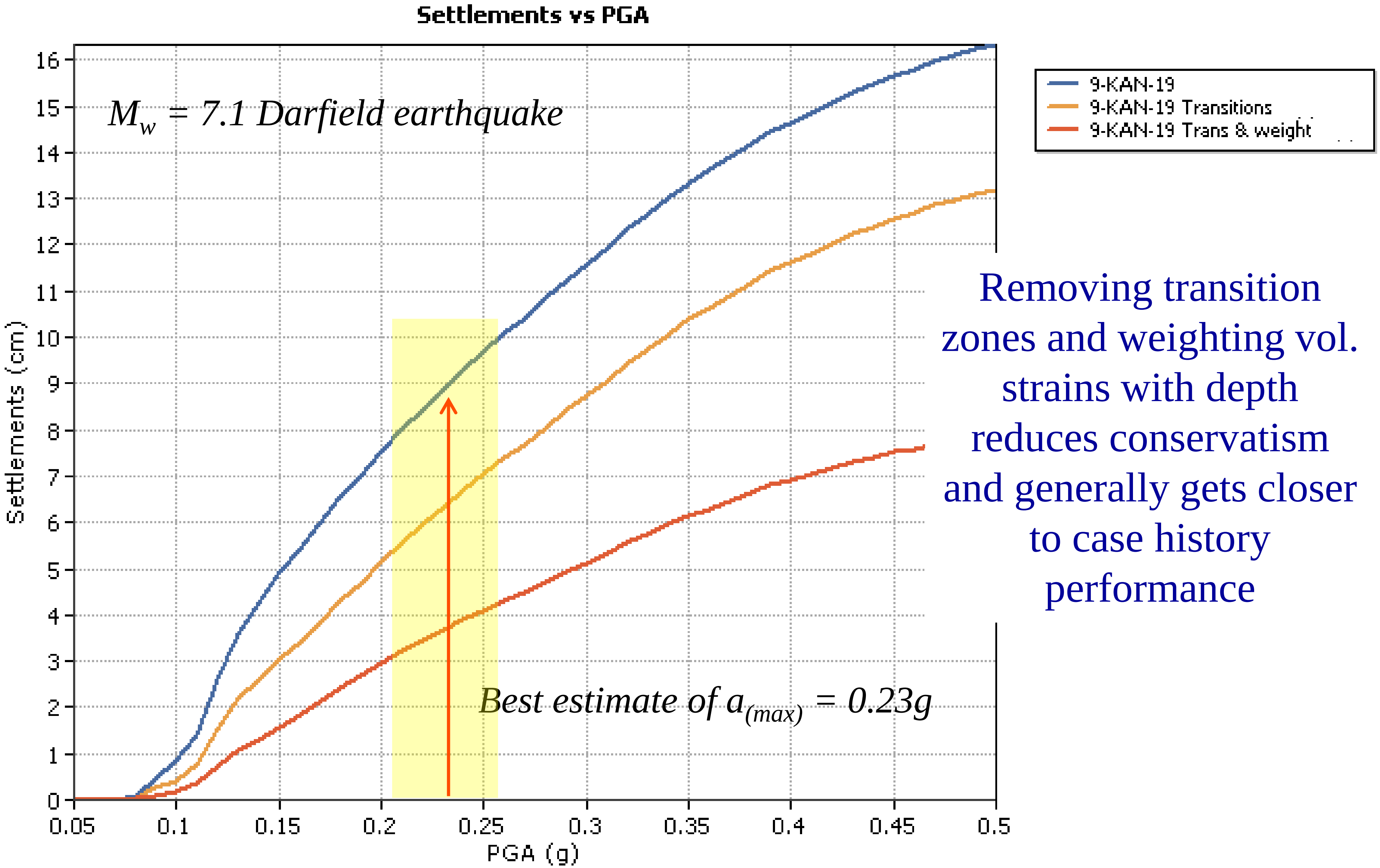
Christchurch KAN-19 $M_w = 7.1$, $a_{(max)} = 0.23g$ Minor liquefaction, estimated settlement ~2cm

Transition & weighting - example



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

Sensitivity analysis

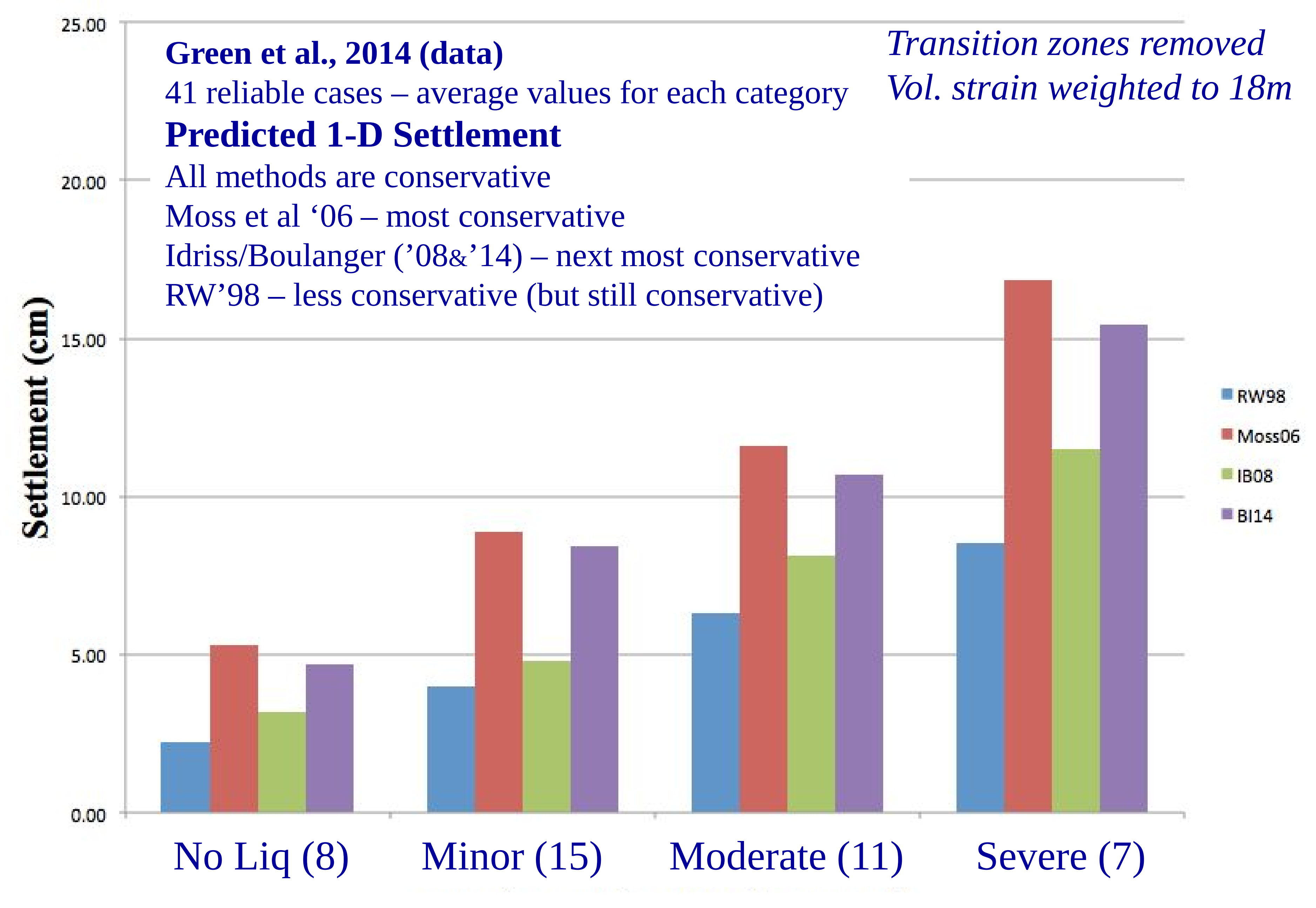


Removing transition zones and weighting vol. strains with depth reduces conservatism and generally gets closer to case history performance

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



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 '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*