Evaluation of soil liquefaction using the CPT – Part 1

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Webinar #7

2013



GUIDE TO
CONE PENETRATION
TESTING

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What is Soil Liquefaction?

- Loss of strength and/or stiffness due to undrained loading
- Major factor in earthquakes
  - Sand boils
  - Ground cracks
  - Slumping of embankments
  - Lateral spreading
  - Ground oscillations
- Flow slides
  - Statically or dynamically triggered

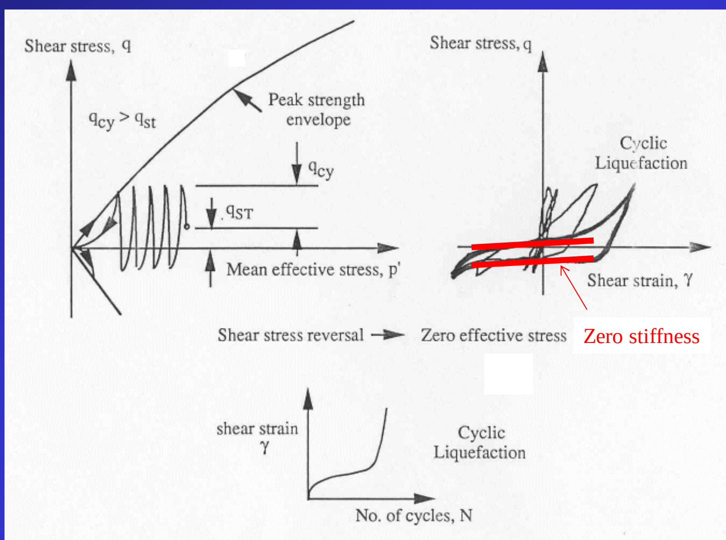
Definitions of Liquefaction

- Cyclic (seismic) Liquefaction
  - *Zero effective stress* *(during cyclic loading)*
- Flow (static) Liquefaction
  - *Strain softening response*
  - *Part 2*

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



Simplified Procedure

- Following the 1964 earthquakes in Alaska and Niigata, Japan, the "Simplified Procedure" was developed by Seed & Idriss (1971) for evaluating seismic demand and liquefaction resistance of sands
- $CSR = 0.65\ (a_{max}/g)\ (\sigma_v/\sigma'_v)\ r_d$
- CRR = fn of penetration resistance (SPT & CPT)
- NCEER Workshop (1996/7) to develop consensus update paper (Youd et al, 2001)

Liquefaction - Level Ground Sites

Sites defined as:

Level ground, gently sloping (< 5 degrees) or level with nearby steep slope or free-face

Sequence to evaluate (cyclic) liquefaction:

1. Evaluate susceptibility to cyclic liquefaction
2. Evaluate triggering of cyclic liquefaction
3. Evaluate post-earthquake deformations

Sand-like and Clay-like soils

Sand-like soils

- Fine-grained soils that are essentially non-plastic and behave very similar to sands
- Cyclic resistance within framework based on in-situ tests

Clay-like soils

- Clays and plastic silts that are more easily sampled, are less affected by sampling disturbance and exhibit stress-history normalized strength properties.
- Cyclic resistance estimated based on in-situ testing, laboratory testing and empirical correlations based on undrained shear strength

Evaluate Susceptibility to Liquefaction

Sand-like behavior

- Plasticity Index (PI) < 10 *(between 7 to17)*
- Liquid Limit (LL) < 37
- Natural water content (w_c) > 0.8 (LL).

Clay-like behavior

- Plasticity Index (PI) > 12
- Can experience cyclic deformations (softening).

Criteria based on classification tests on disturbed samples

Controlled by soil plasticity

(amount and type of clay minerals)

There is a transition from sand-like to clay-like response

Susceptibility to cyclic liquefaction

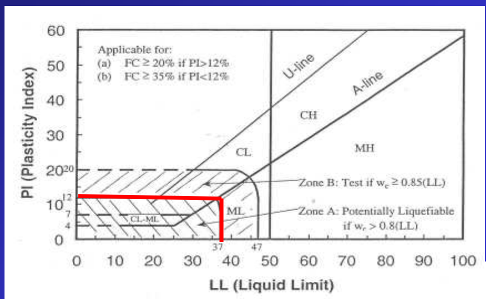
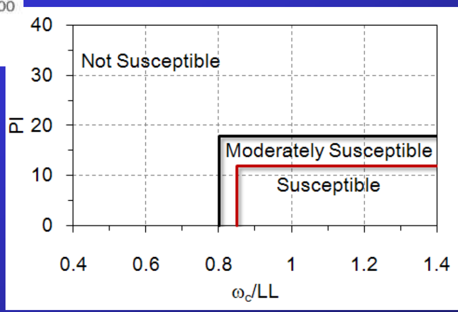


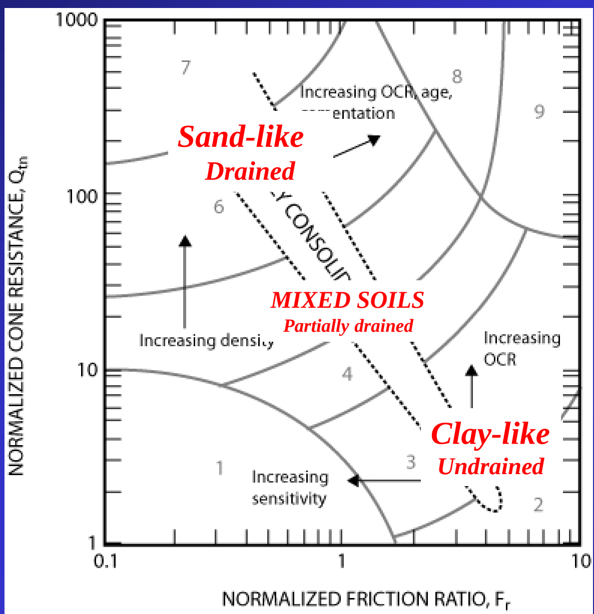
Fig 4: Recommendations Regarding Assessment of "Liquefiable" Soil Types

Seed et al, 2003



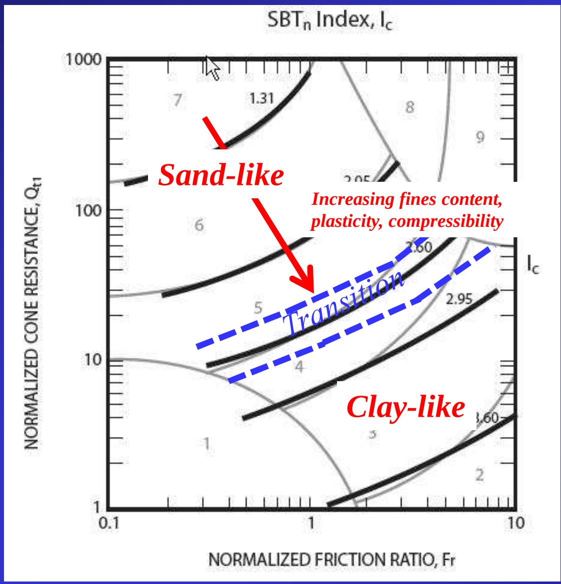
Bray & Sancio, 2006

CPT Soil Behaviour Type SBT



CPT SBT based on in-situ soil behavior - not the same as classification based Atterberg Limits and grain size carried out on disturbed samples

CPT SBT Index, I_c



Soil Behavior Type Index, I_c

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

Function primarily of Soil Compressibility

Compressibility linked to fines content and soil plasticity

CPT Normalization

- Early normalization based on theory for clays

$$Q = (q_t - \sigma_v) / \sigma'_v$$

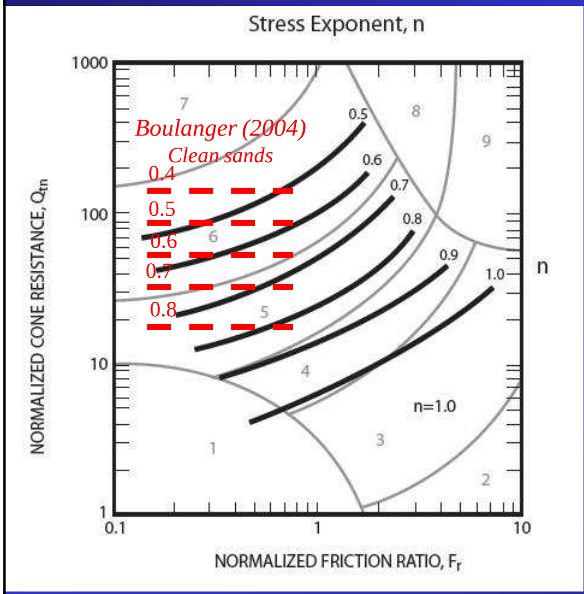
- Recently normalization based on soil type, density and stress level

$$Q_{tn} = [(q_t - \sigma_v)/p_a] \, (p_a/\sigma'_v)^n \quad [= q_{c1N}]$$

Where:

$(q_t - \sigma_v)/p_a$ = dimensionless net cone resistance,
$(p_a/\sigma'_v)^n$ = stress normalization factor (C_N)
n = stress exponent that varies with soil type (SBT *Ic*), density & stress level
p_a = atmospheric pressure in same units as q_t and σ_v

CPT Normalization



$Q_{tn} = [(q_t - \sigma_v)/p_a] (p_a/\sigma'_{vo})^n$

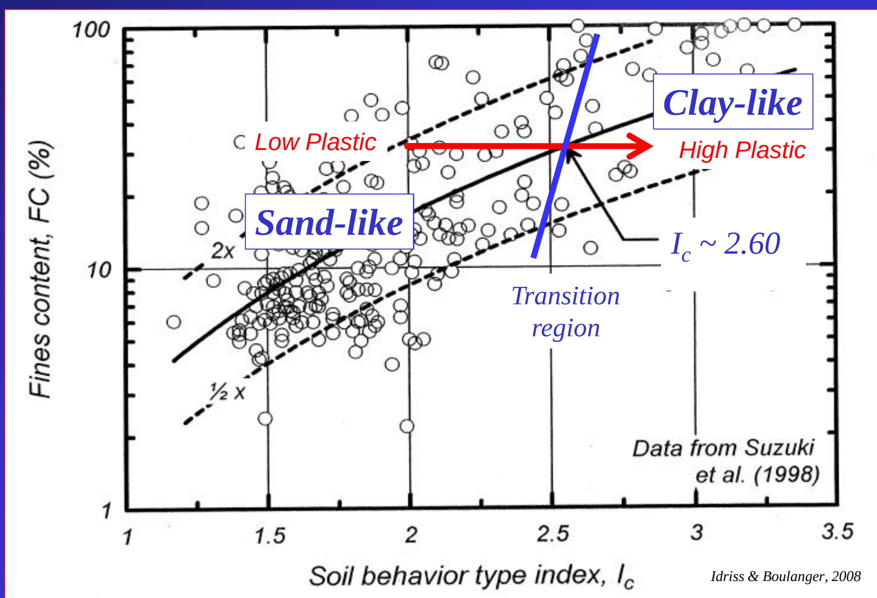
$n = 0.381 (I_c) + 0.05 (\sigma'_{vo}/p_a) - 0.15$

where $n \leq 1.0$
(Robertson, 2009)

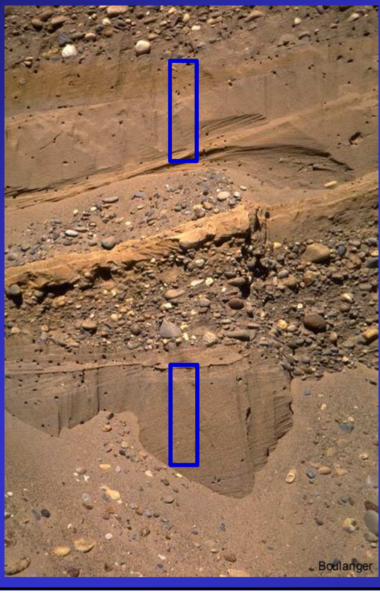
Jefferies & Been (2006) assume n =1.0 for all soils

If stress normalization correct - no need for any further stress level correction (e.g. K_σ)

SBT from CPT



Challenges with sampling

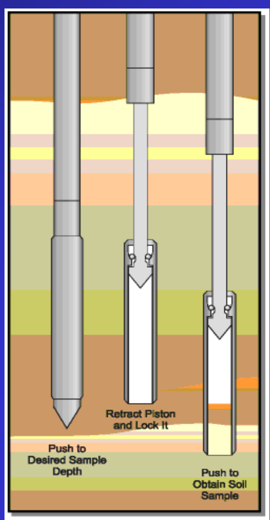


Problem with corrections based on 'fines content':

- soil behaviour not controlled only by fines content
- random sampling every 1.5 m (~5 ft) – will get a limited view of actual soil conditions

Better to select sampling depth based on adjacent CPT

Direct Push (CPT) Soil Sampler

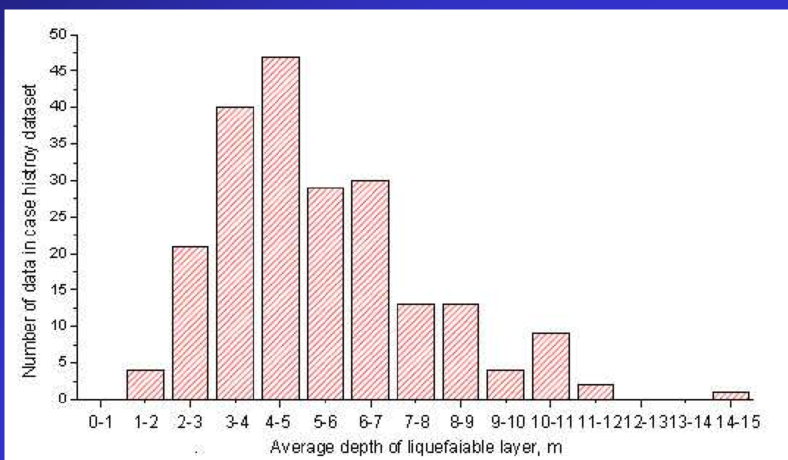


Direct push soil sampler used with CPT pushing equipment

Case history field observations

- Holocene age, clean sand deposits (K_o ~ 0.5)
- Level or gently sloping ground
- Corrected to magnitude M = 7.5 earthquake
- Depth range 1 to 15m
  - 95% < 10m
- Surface observations of liquefaction
- Average CPT values

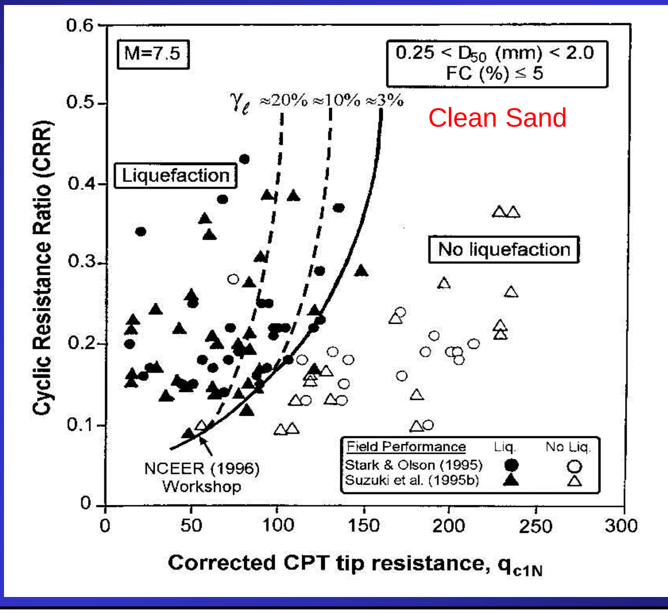
Database – depth of liquefaction



No case histories at depths > 15m
Possible that 'liquefaction' may have occurred > 15m but no surface effects

CPT Method – $CRR_{7.5}$

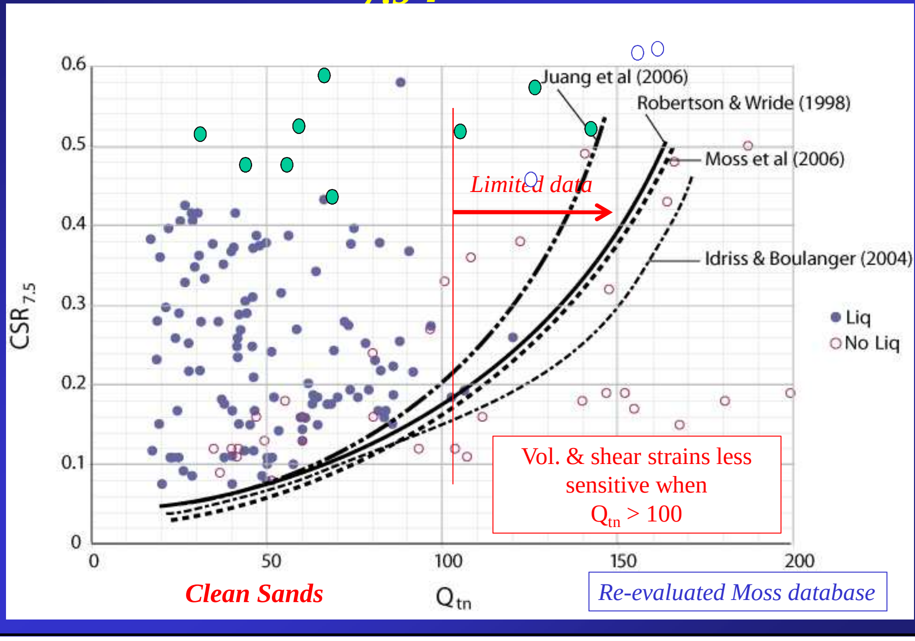
(Robertson & Wride, 1998)



Re-evaluation of case histories

- Moss (2003) CPT expanded database (Robertson 2009 re-evaluated data based on continuous digital data):
  - re-evaluated selection of ‘average’ values to represent critical layer
- Focused on key sites where average values close to boundary line
- Class C (non-standard/mechanical cones) data removed (poor quality f_s values)
- Continuous results should be used to evaluate CPT-based methods
  - application (software) based on continuous results

$CRR_{7.5}$ from CPT

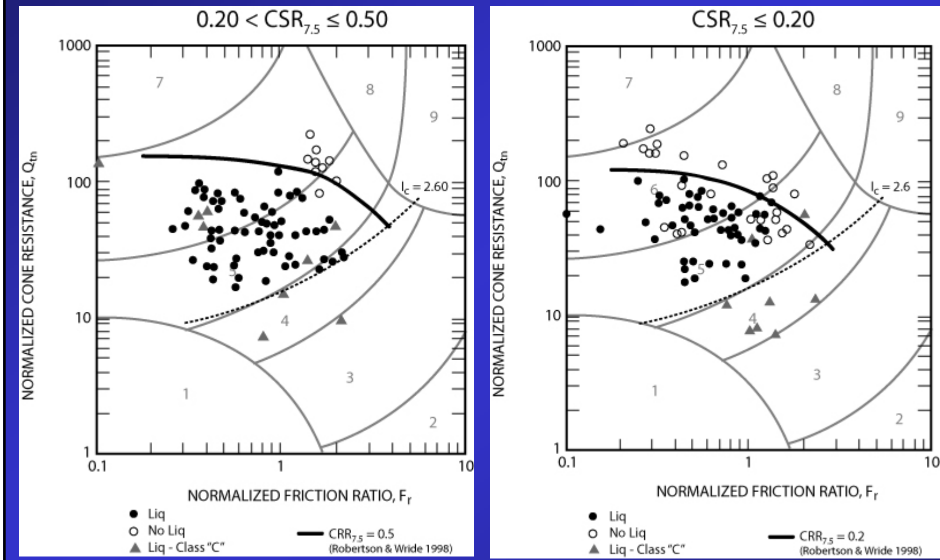


Seismic liq. – case histories

- Based on the early work of Seed & Idriss (1971) penetration resistance (SPT & CPT) has been used to evaluate the '*state*' of sandy soils to evaluate the potential for liquefaction based on extensive case histories
- Concept of "*clean sand equivalent*" ($Q_{tn,cs}$) is used to extend liq. evaluation to wider range of sandy soils (Robertson & Wride, 1998)

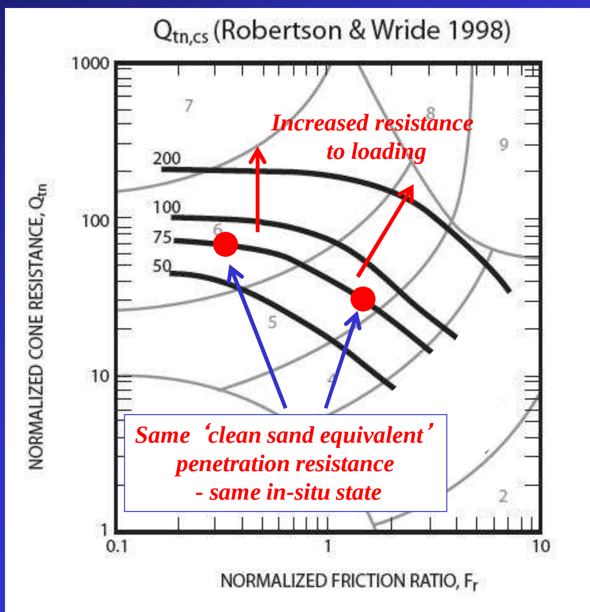
$$Q_{tn,cs} = K_c \, Q_{tn} \qquad [K_c = fn\,(I_c)]$$

Case Histories



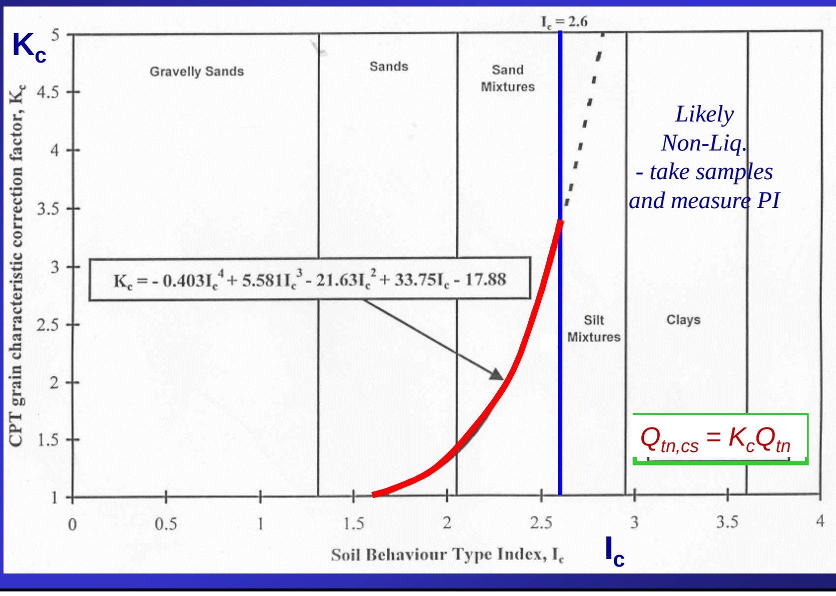
Modified Moss database

Clean sand equivalent, $Q_{tn,cs}$

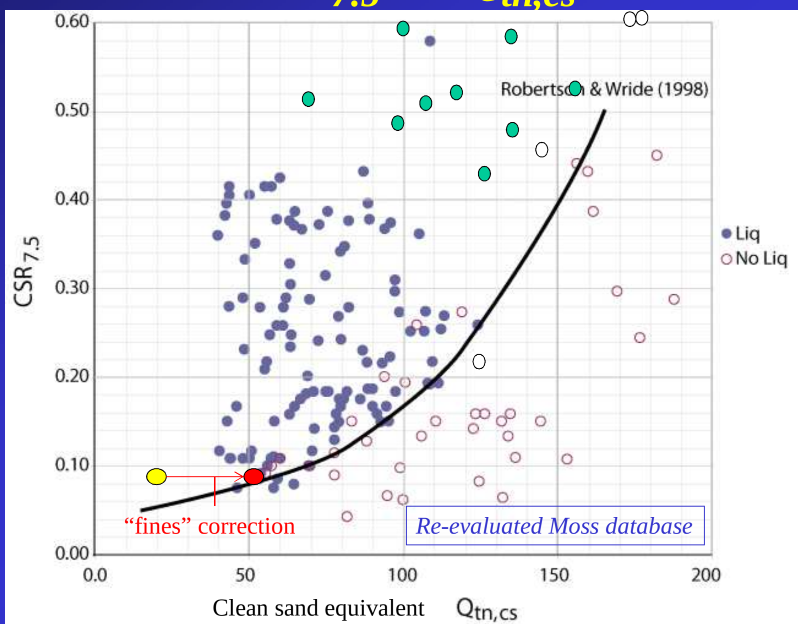


Soils with same 'clean sand equivalent' $Q_{tn,cs}$ have similar behavior

Clean sand correction, $Q_{tn,cs}$ ($q_{c1N,cs}$)



$CRR_{7.5}$ vs $Q_{tn,cs}$



CPT–based method summary

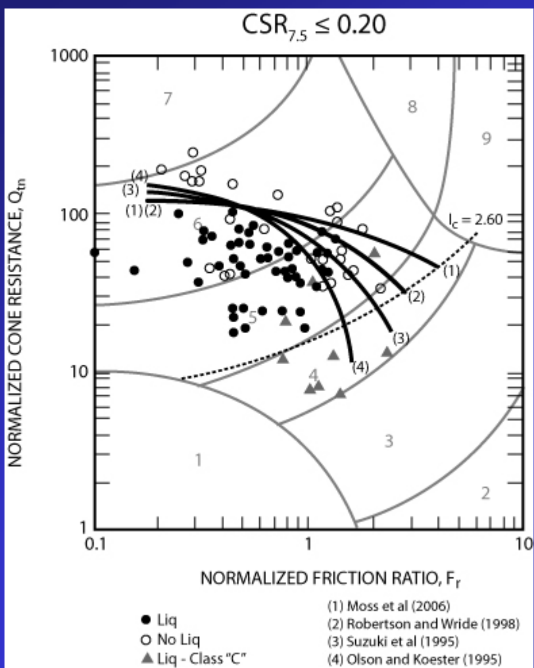
- Calculate $CSR_{7.5}$ for design earthquake
  - $CSR_{7.5} = 0.65\ (\sigma_v/\sigma'_v)(a_{max}/g)\ r_d\ (1/MSF)$
- Normalize CPT data, Q_{tn} & F
- Calculate soil behavior type index, I_c
- Calculate CPT 'clean sand equivalent', $Q_{tn,cs}$
- Determine $CRR_{7.5}$
- Factor of Safety, $FS = (CRR_{7.5}/CSR_{7.5})$
- Plot profiles of CRR and FS

Recent Controversy

- After NCEER Workshop, some researchers wanted to 'update/modify' the NCEER Simplified Method
  - Seed (Cetin – SPT; Moss – CPT)
  - Idriss & Boulanger (SPT & CPT)
- Each changed CSR (case histories) that resulted in a change to CRR – but, in general, little change to FS (in region of database, z < 12m)
- Important to apply all elements of a method – do not mix & match

Factors resulting in recent changes

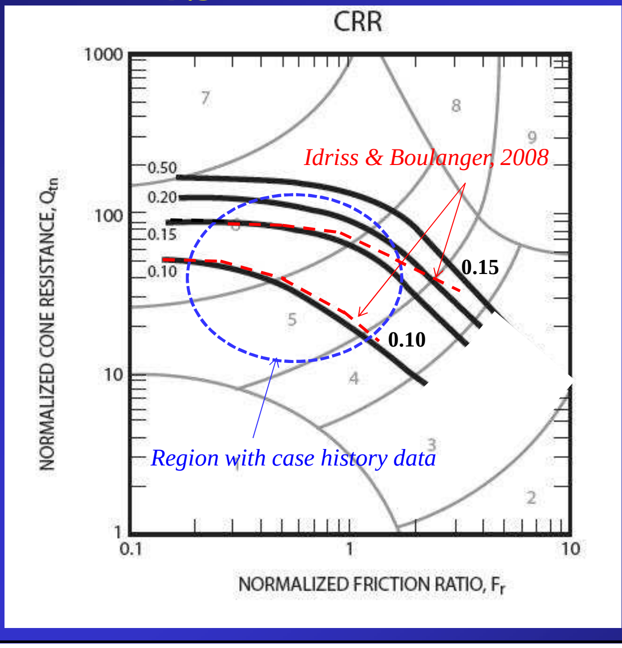
- Observed 'liquefaction' – surface effects
  - Possible false negatives (e.g. sites with some liquefaction but no surface effects)
- Evaluation of CSR
  - Estimation of GWL, σ_v & σ'_v
  - Estimation of depth reduction factor, r_d
    - Changes in r_d is largest factor – moves data points – moves CRR line
- Stress Reduction factor, K_σ (database z < 12m)
  - NCEER (2001) $K_\sigma = 1.0$
  - Seed (Moss) et al (2006) K_σ </= 1.5
  - I&B (2008) K_σ </= 1.1



Comparison clean sand equivalent correction

1. *Moss et al, 2006*
2. *Robertson & Wride, 1998*
3. *Suzuki et al 1995*
4. *Olson & Koester, 1995*

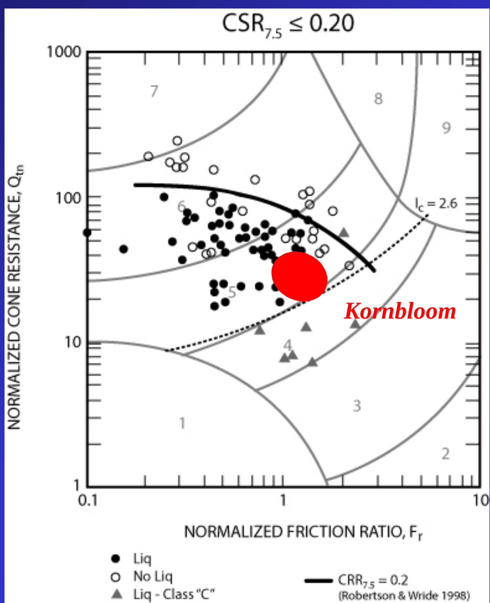
$CRR_{7.5}$ contours (I&B vs NCEER)



Idriss & Boulanger (2008) CPT-based method uses a 'fines content' correction.

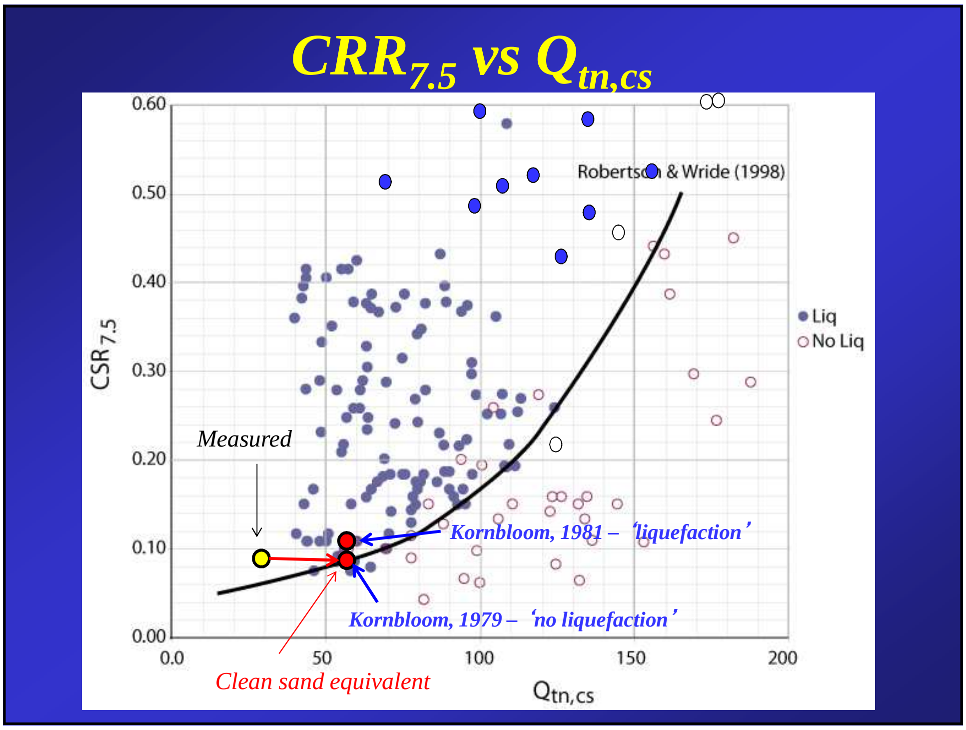
Comparison based on conversion from fines content to CPT SBT I_c

Kornbloom (Imperial Valley)

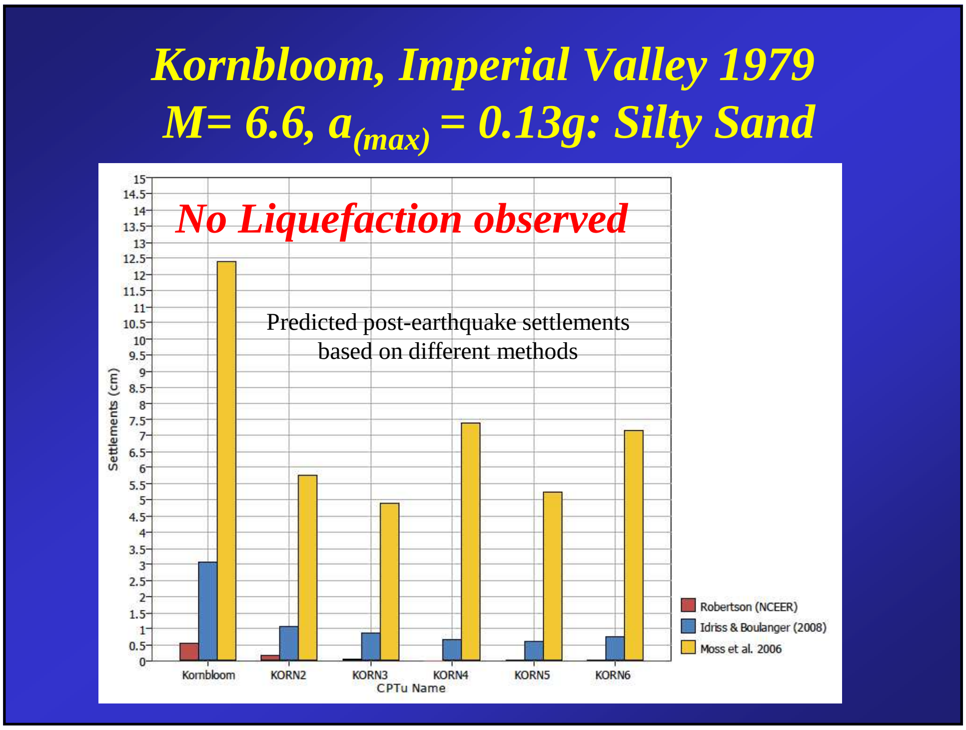


- **1981 Westmorland EQ**
  - M = 6.0, $a_{(max)} = 0.19g$ (CSR = 0.09-0.11)
  - Liquefaction observed (sand boils, surface movement)
  - Silty sand deposit (i.e. large 'correction' to clean sand equivalent)
- **1979 Imperial Valley EQ**
  - M = 6.6, $a_{(max)} = 0.13g$ (CSR = 0.08-0.09)
  - No liquefaction observed (no sand boils, etc.)

6 CPT's at site



$CRR_{7.5}$ vs $Q_{tn,cs}$
0.60
0.50
0.40
0.30
0.20
0.10
0.00
CSR 7.5
0.0
50
100
150
200
Qtn,cs
Robertson & Wride (1998)
Liq
No Liq
Measured
Kornbloom, 1981 – 'liquefaction'
Kornbloom, 1979 – 'no liquefaction'
Clean sand equivalent



Kornbloom, Imperial Valley 1979
M= 6.6, $a_{(max)}$ = 0.13g: Silty Sand
No Liquefaction observed
Predicted post-earthquake settlements based on different methods
Settlements (cm)
CPTu Name
Kornbloom
KORN2
KORN3
KORN4
KORN5
KORN6
Robertson (NCEER)
Idriss & Boulanger (2008)
Moss et al. 2006

Comparison of CPT-based methods

- Different CSR & CRR values, but similar Factor of Safety (FS) (within +/-30%)
- Similar damage potential (i.e. similar LPI and post-earthquake deformations)
- Variation within margin of uncertainty:
  - data scatter, local variations in soil properties, uncertainty in some parameters (e.g. unit weight, GWL), estimates of seismicity, etc….
  - Provided data are within database limits

Probability of Liquefaction

Juang et al., (2011) related Factor of Safety (FS) to the probability of liquefaction (PL) for the R&W CPT (NCEER) method using:

$$PL = 1 / (1 + (FS/0.9)^6)$$

When FS = 1, PL = 35% (i.e. slightly conservative)

Similarity for Sand & Clay

In many respects clays are similar to sands:

- Loose sand ⇨ normally consolidated (NC) clay
  - 'loose' sand and NC clay both contract in shear
- Dense sand ⇨ over consolidated (OC) clay
  - 'dense' sand and OC clay both dilate in shear
- Both can defined by their 'STATE'
  - Sands in terms of D_r or Ψ
  - Clays in terms of *OCR*

Cyclic Softening (deformation) of Clays

$$\mathbf{CRR_{7.5} = 0.8\ (s_u/\sigma'_{vo})\ K_\alpha}$$

$$\mathbf{CRR_{7.5} = 0.18\ (OCR)^{0.8}\ K_\alpha}$$

Where:

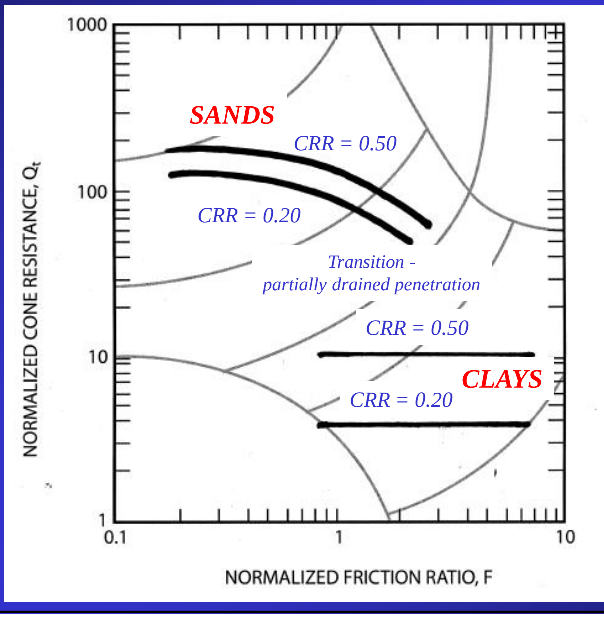
s_u/σ'_{vo} undrained shear strength ratio for the appropriate direction of loading (typically direct simple shear).

K_α correction factor to account to static shear stress.

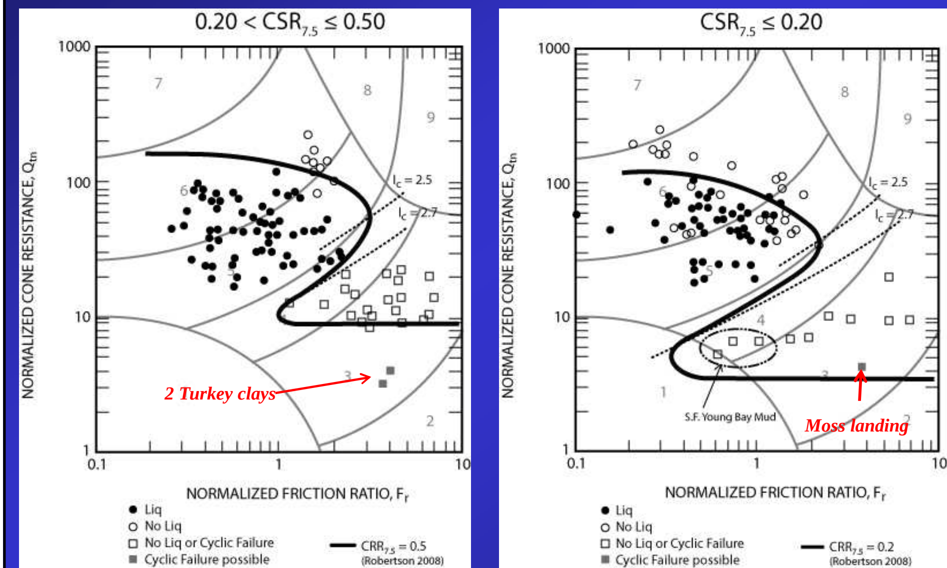
For seismic loading where CSR < 0.6, cyclic softening (deformation) is possible only in normally to lightly overconsolidated (OCR < 4) clay-like soils

Controlled by peak undrained strength (s_u)
-that can be estimated directly from CPT

$CRR_{7.5}$ Contours – sands & clays



$CRR_{7.5}$ Case Histories



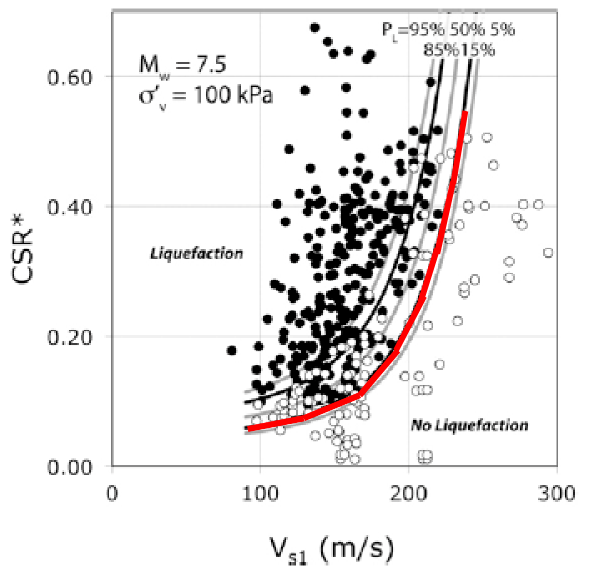
Expanded database to include 'clay' deposits

Seismic CPT (SCPT)

- Geophone incorporated into standard CPT
- Downhole seismic method
- Shear wave velocity, V_s, measured every 1 meter
- Shear wave velocity measured in same soil as cone penetration resistance, q_c
- Simple and reliable technique

$G_o = \rho \cdot V_s^2$ $\rho = \gamma / g$

Shearwave Velocity Approach



Liquefaction:

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

No liquefaction:

$V_{s1} > 250$ m/s

Kayen et al., 2013

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 (Part 2)*

Factors that can affect liquefaction-induced deformations

- Soil Characteristics
  - relative density (state), fines content, plasticity, age, degree of saturation, cementation, prior stress & strain history, in-situ stress state, depositional environment
- Earthquake Characteristics
  - level and duration of shaking, frequency content of motions
- Site Characteristics
  - topography, geometry, stratigraphy, lateral variability, static piezometric profile, hydraulic conductivity, pore water & void re-distribution
- Other factors
  - 3-D effects, ground cracking effects, low permeable surface layer, near by foundations

Post Earthquake Deformations

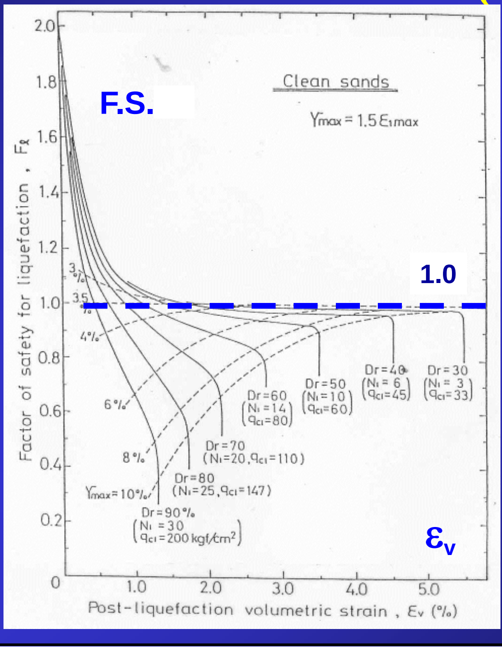
- Estimating deformations in sandy soils is difficult (even under static loading)
- For low to moderate risk projects semi-empirical models are common & appropriate
  - CPT-based methods provide continuous profiles of volumetric & shear strain
- For high risk projects numerical analyses can be appropriate, if initial screening indicates a need

CPT-based post earthquake deformations

(Zhang, Robertson & Brachman, 2002 & 2004)

- Based on extensive laboratory test results
  - Ishihara and Yoshimine (1992)
- Links CPT and factor of safety to volumetric & shear strains for clean sands
- Apply CPT ‘*clean sand equivalent*’ approach to get profiles of volumetric & shear strains and hence, displacements
- Calibrated with case histories

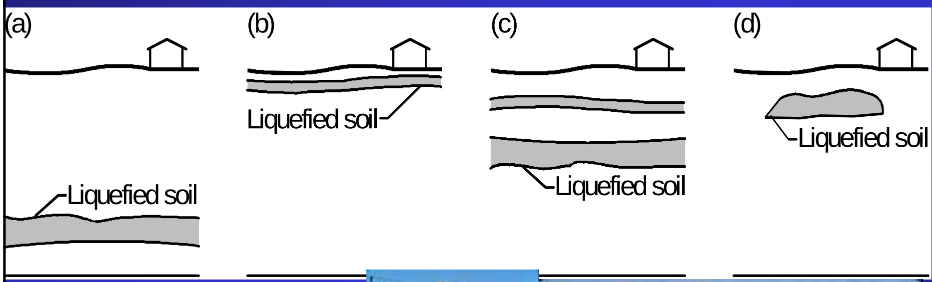
Ishihara and Yoshimine (1992)



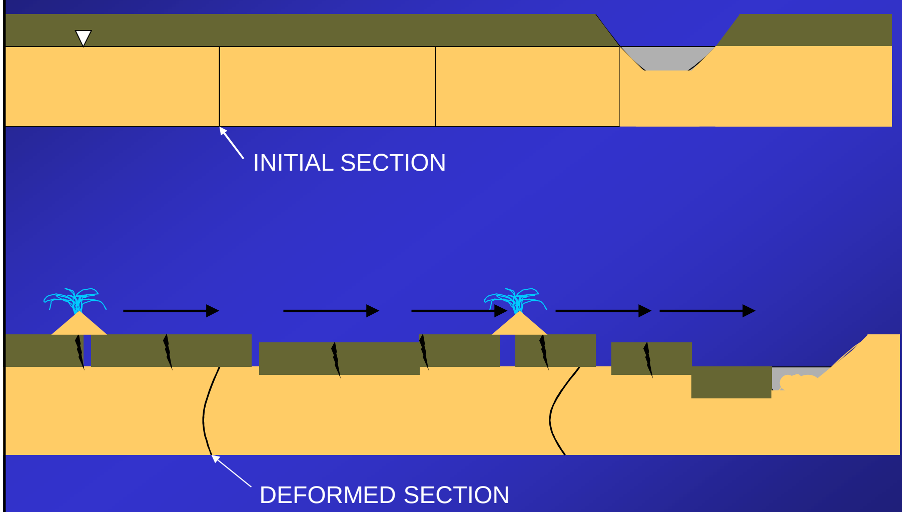
Evaluation of CPT Settlements

- Zhang et al. (2000) showed:
  - Good results when applied to Marina District (1998) and Treasure Island (1998) case histories
  - Importance of thin layers and transition zones
  - Importance of other factors (3-D, depth, proximity to footings, ejected soil, etc.)
- Lee et al. (2000) showed:
  - Good results when applied to Taiwan (1999) case histories

Challenges estimating vertical settlements



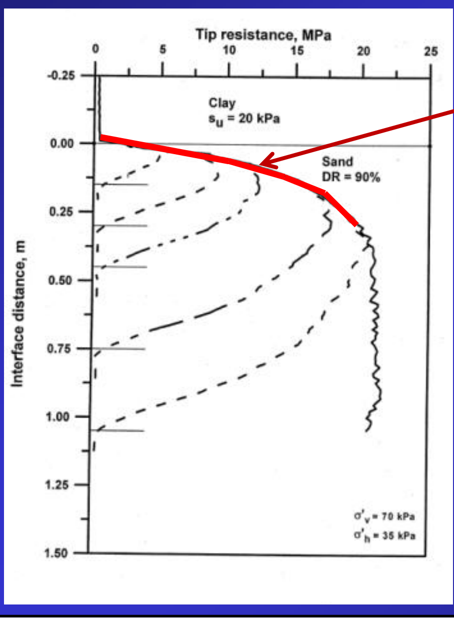
Lateral Spreading



Evaluation of Lateral Spread Approach

- D. Chu & J. Stewart (2006) showed that Zhang et al (2004) CPT and Youd et al (2002) SPT methods produced good results (slight over-predictions).
- Layers below base elevation of free face (z > 2H) should not be included.

Transition zone

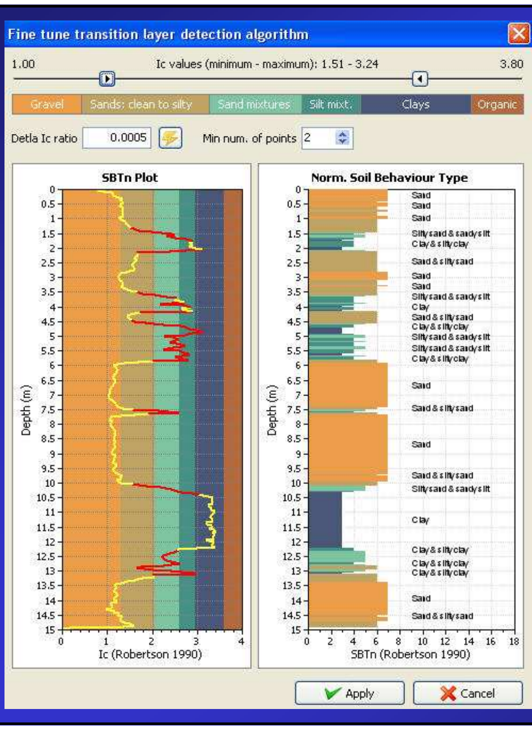


CPT data in 'transition' when cone is moving from one soil type to another when there is significant difference in soil stiffness/strength (e.g. soft clay to sand)

CPT data within transition zone will be misinterpreted

In interlayered deposits this can result in excessive conservatism

Ahmadi & Robertson, 2005



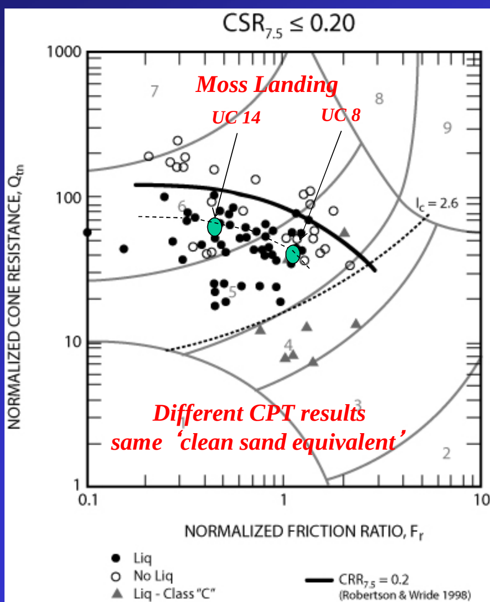
Transition zone detection

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

Example - Moss Landing



Moss Landing Examples

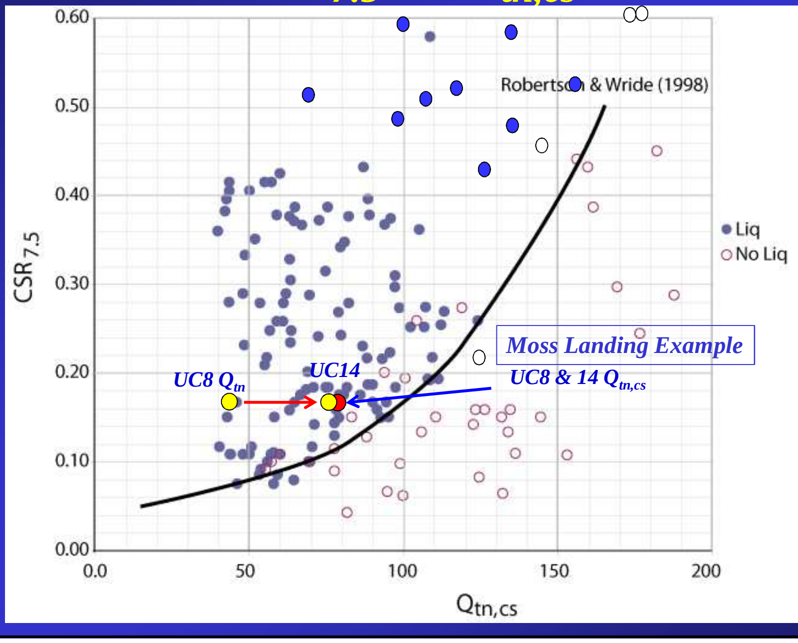
UC 14 State Beach site
Clean sand
($FC < 5\%$, $I_c < 1.6$)

UC 8 Marine Lab site
Silty sand
(FC ~20% , I_c ~ 2.2)

Both had post-earthquake settlements and lateral spreading

Database based on 'average' values within critical layer

$CRR_{7.5}$ vs $Q_{tn,cs}$



Moss Landing State Beach

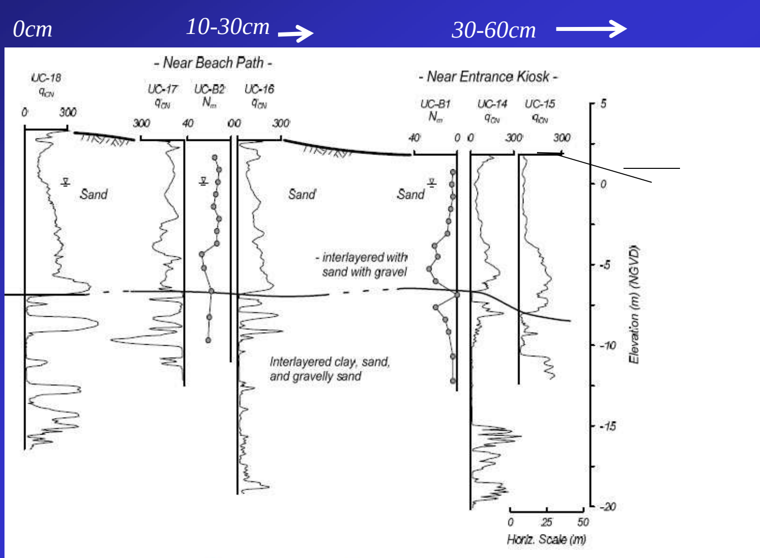
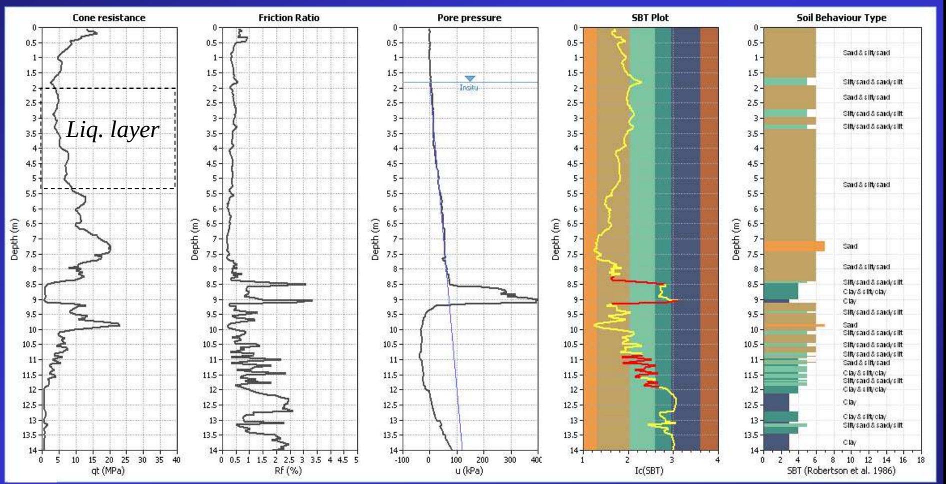


Figure 3.2: Profile at the Moss Landing State Beach (Boulanger et al. 1997)

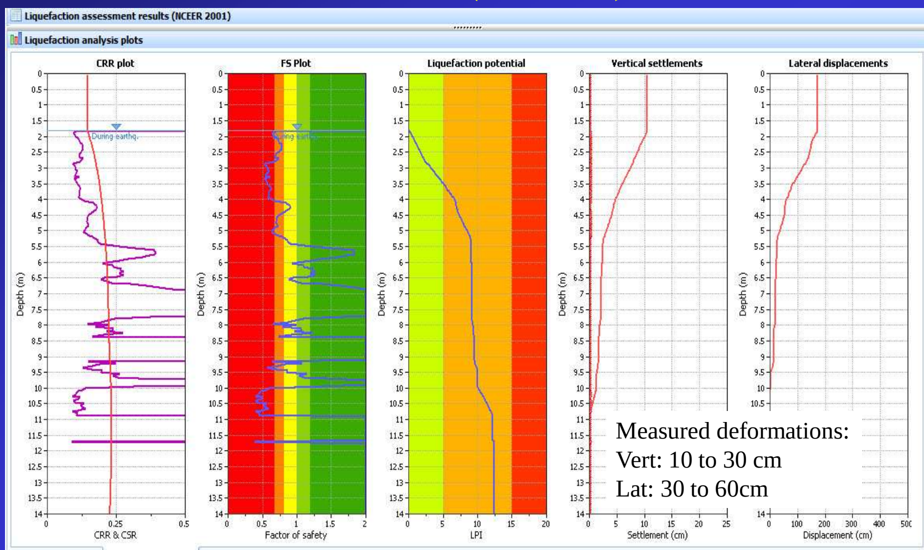
Moss Landing State Beach UC 14



Example in I&B 2008 Appendix B: L = 20m, H = 5m
$a_{(max)}$ = 0.28g, M = 6.9

Moss Landing UC 14

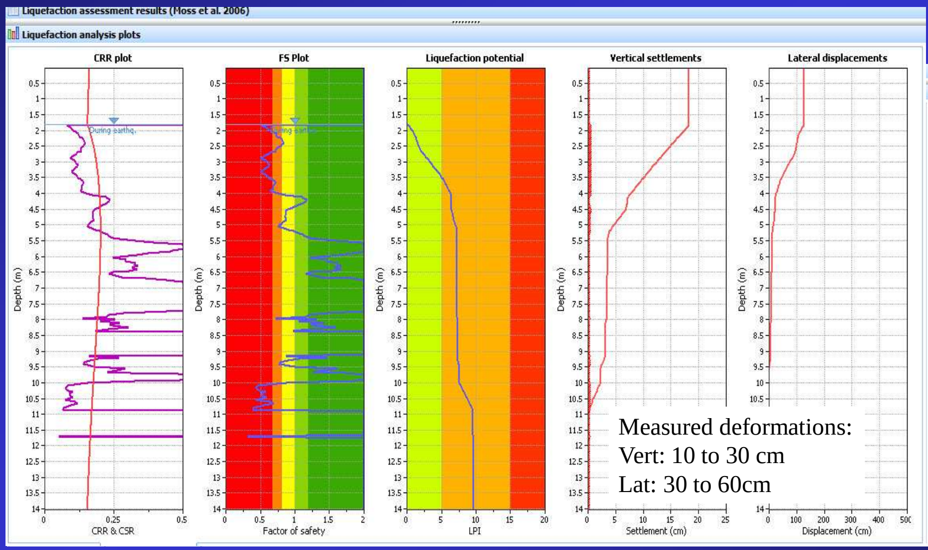
UC 14 NCEER (R&W) Method



Example in I&B 2008 Appendix B: L = 20m, H = 5m

Moss Landing UC 14

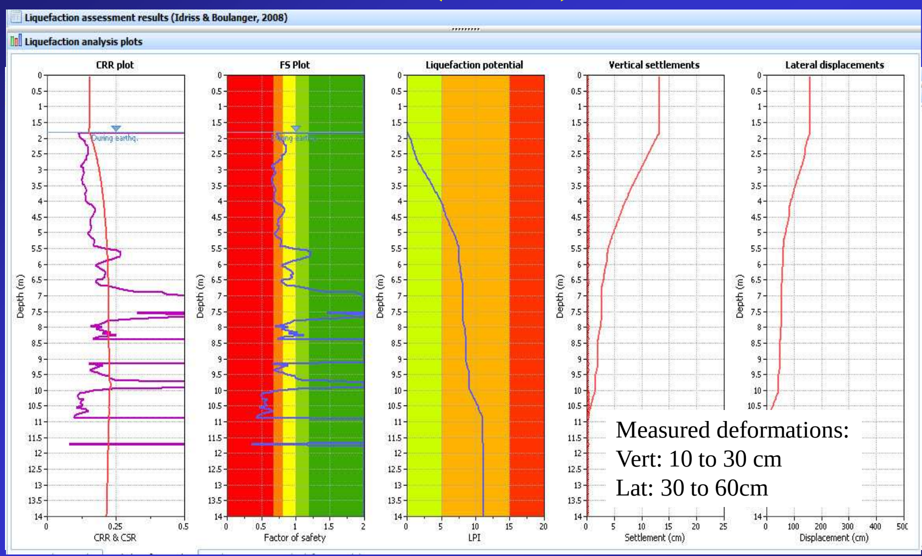
UC 14 Moss et al (2006)Method



Example in I&B 2008 Appendix B: L = 20m, H = 5m

Moss Landing UC 14

UC 14 I&B (2008) Method

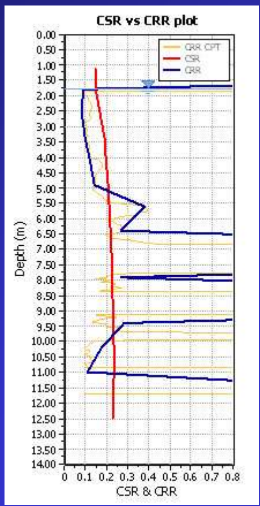


Example in I&B 2008 Appendix B: L = 20m, H = 5m

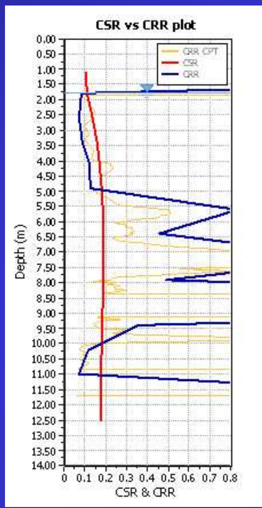
Moss Landing UC 14

Comparison of SPT & CPT methods

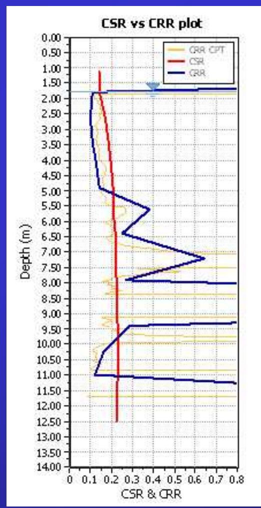
Moss Landing UC 14/UC B-1



NCEER, 2001



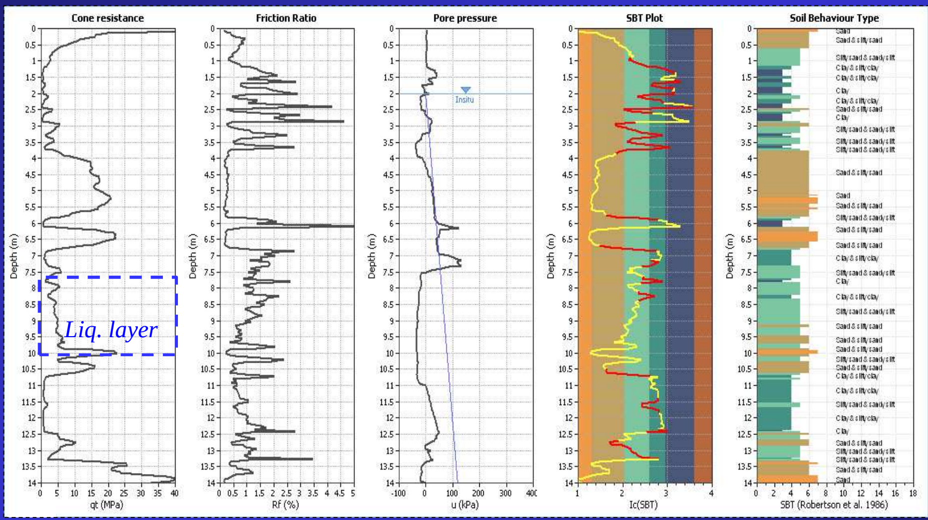
Cetin/Moss, 2006



I&B, 2008

Moss Landing - Lateral Spread

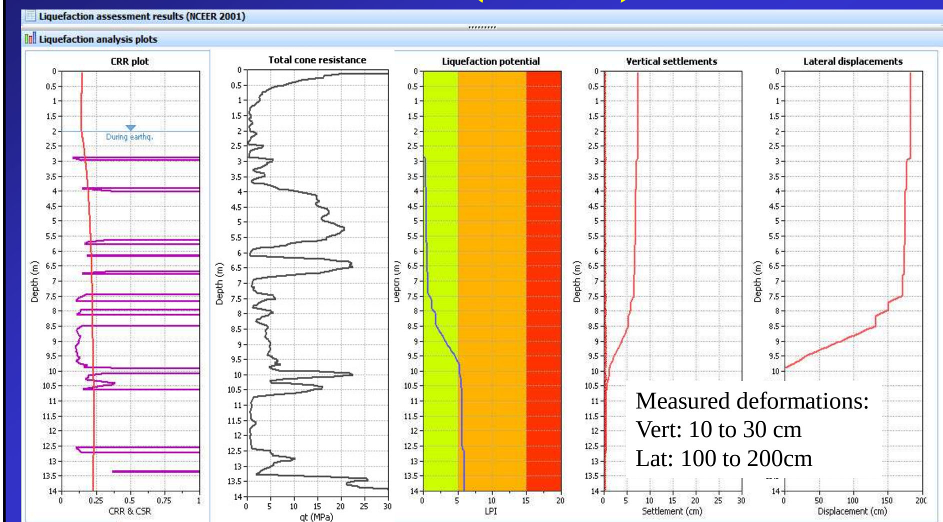
Moss Landing Marine Lab UC 8



L = 20m, H = 5m; $a_{(max)}$ = 0.28g, M = 6.9

Moss Landing UC 8

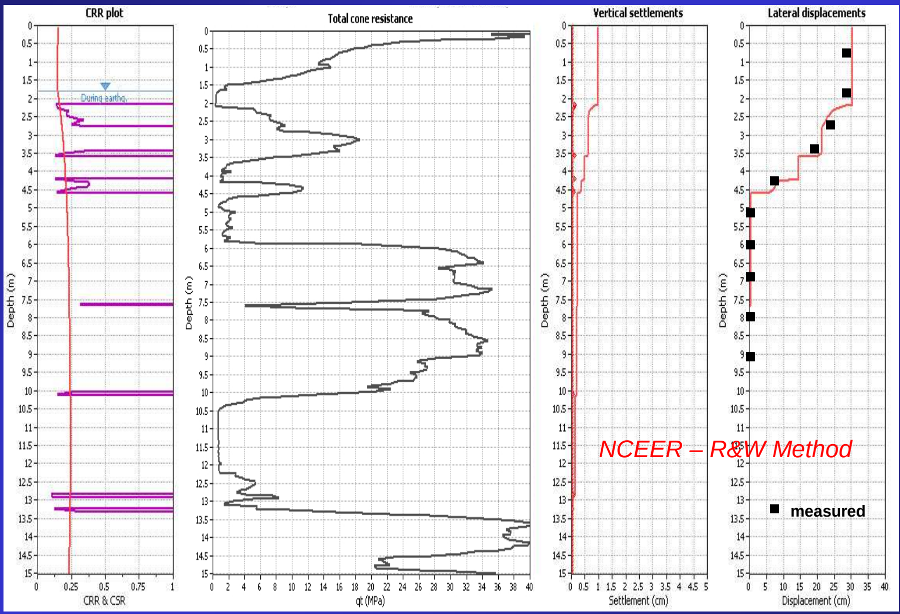
UC 8 NCEER (R&W) Method

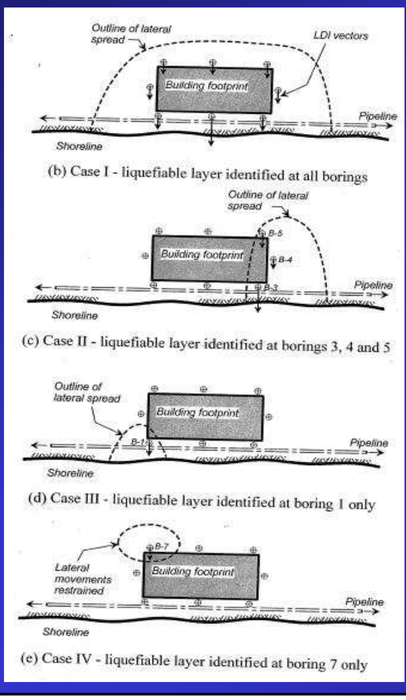


L = 20m, H = 5m

Moss Landing UC 8

Moss Landing – MBARI (UC4)





Schematic of how LDI vectors influence extent of lateral spreading

After Idriss & Boulanger, 2008

Summary

- Risk based approach useful to determine the level of characterization
- Evaluation of ground deformations a key element in performance-based design
- CPT provides continuous, repeatable profiles of ground characteristics in a cost effective manner
- Soil samples can be obtained with CPT equipment

Summary

- CPT can provide estimates of:
  - Potential for cyclic liquefaction & softening (*via CRR*)
  - Post earthquake settlement and lateral displacement profiles
  - Screening for flow liquefaction (strength loss)
- Updates on:
  - Stress normalization
  - Extended to include clay-like soils
    - No need for an *Ic* cut-off
  - Identification of transition zones
- Seismic CPT provides two independent methods to evaluate soil response in same soil