Seminar for the California Geoprofessionals Association

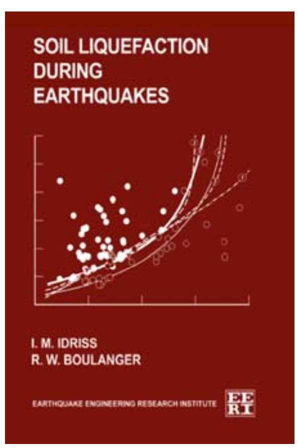
Soil Liquefaction During Earthquakes – The Cliffs Notes Version

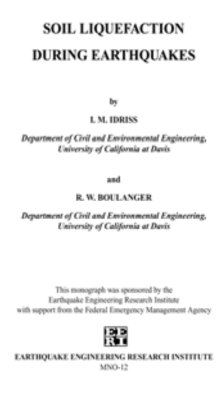
Irvine, California
June 11, 2009

Ross W. Boulanger

This seminar is based on:

- ***Materials from the Monograph (MNO-12) published by EERI in 2008, and***
- ***Materials presented at the EERI Seminars by I. M. Idriss & R. W. Boulanger in Pasadena, St. Louis, San Francisco & Seattle, on March 9, 11, 16 &18, 2009, respectively.***




SOIL LIQUEFACTION
DURING EARTHQUAKES

by

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Plot summary

- ***Fundamentals of liquefaction behavior***
  - ***Avoid confusion by being explicit with definitions.***
  - ***The role of excess pore pressure diffusion.***
- ***Triggering of liquefaction***
  - ***New SPT and CPT curves: How they compare to others and when the differences can be important for you.***
- ***Residual shear strength***
  - ***New recommendations that include consideration of void redistribution effects.***
- ***Lateral spreading and post-liquefaction settlements***
  - ***Making decisions from incomplete information.***
- ***Cyclic softening of clays and plastic silts***
  - ***Choosing appropriate engineering procedures.***

Fundamentals of liquefaction behavior

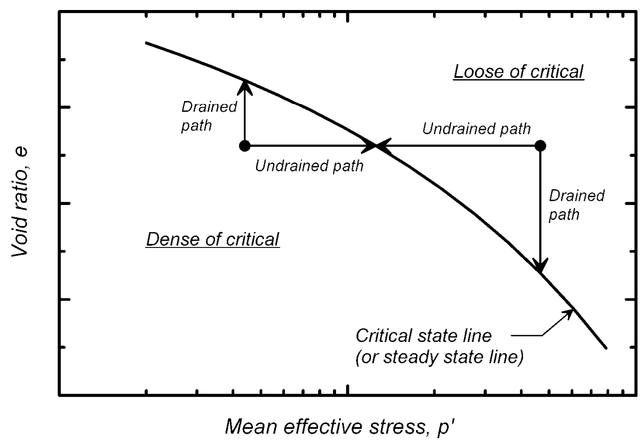


Figure 8. Stress paths for monotonic drained loading with constant p' and undrained loading (constant volume shearing) of saturated loose-of-critical and dense-of-critical sands

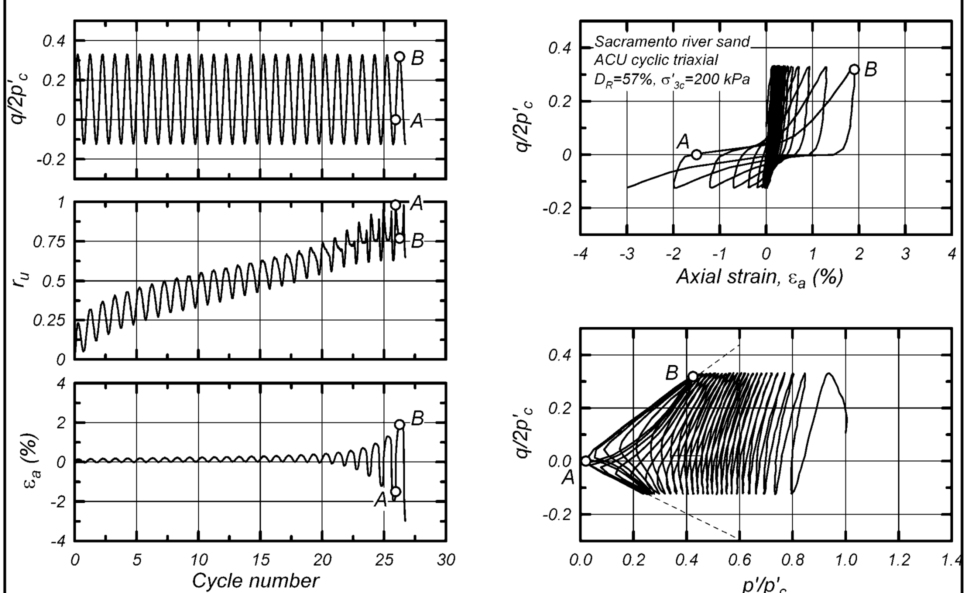


Figure 16. Undrained cyclic triaxial test (test from Boulanger & Truman 1996).

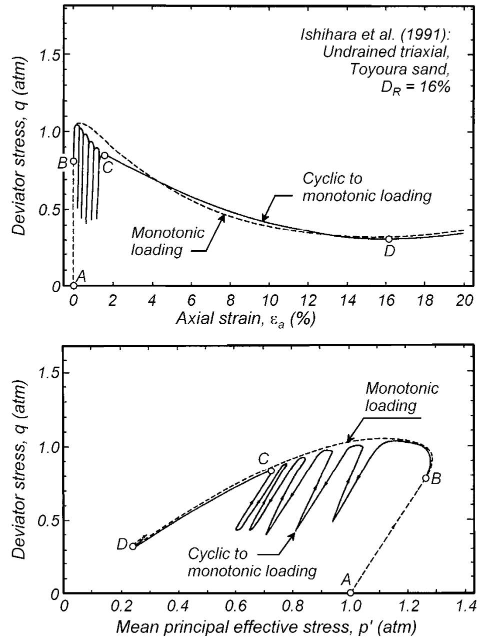


Figure 17. Undrained monotonic versus cyclic-to-monotonic loading for loose-of-critical sand (after Ishihara et al. 1991)

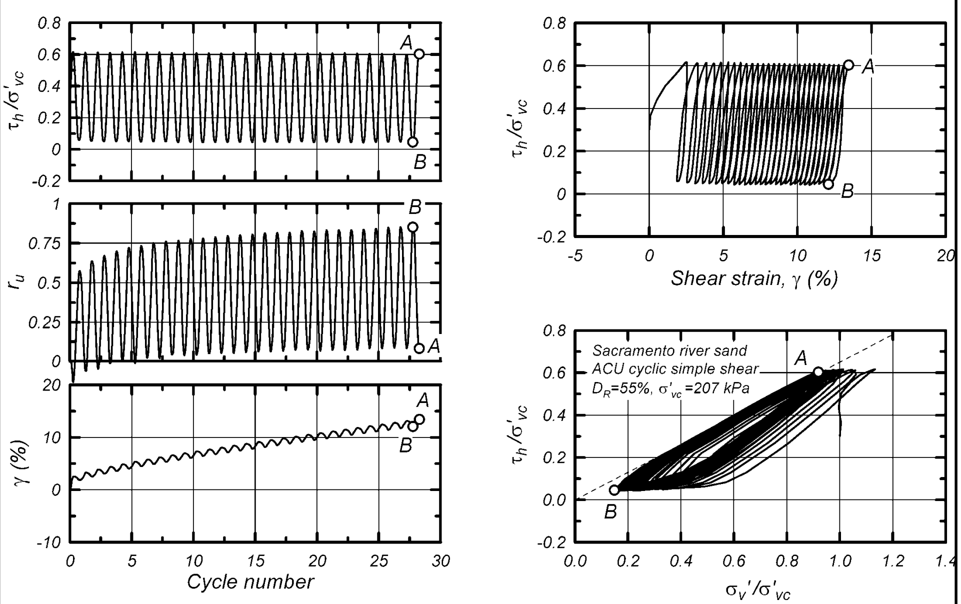
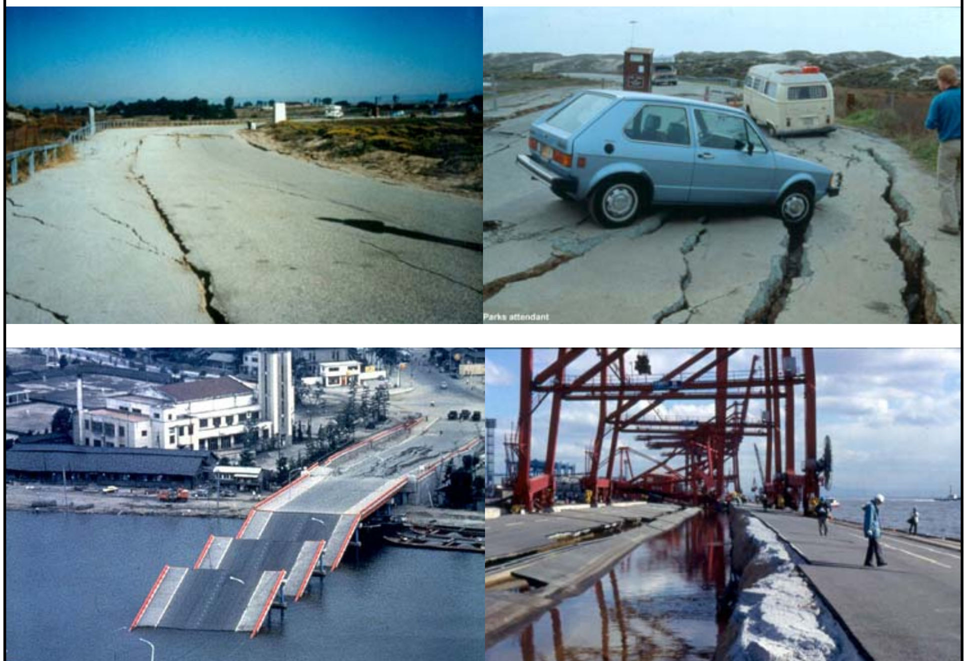


Figure 27. Undrained cyclic simple shear loading with an initial static shear stress ratio of 0.31 (test from Boulanger et al. 1991).



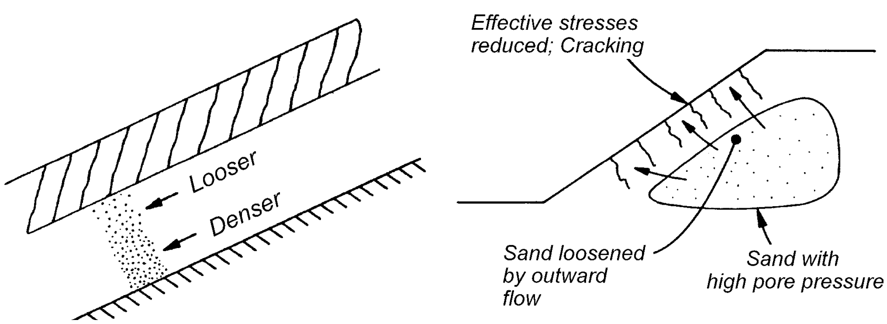


Figure 43. Two mechanisms by which void redistribution contributes to instability after earthquake-induced liquefaction (NRC1985, Whitman 1985)

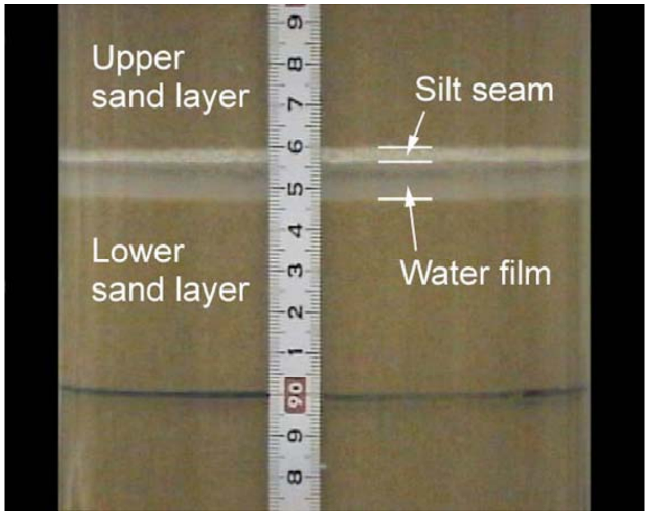


Figure 44. A water film that formed beneath a silt seam in a cylindrical column of saturated sand after liquefaction (Kokusho 1999)

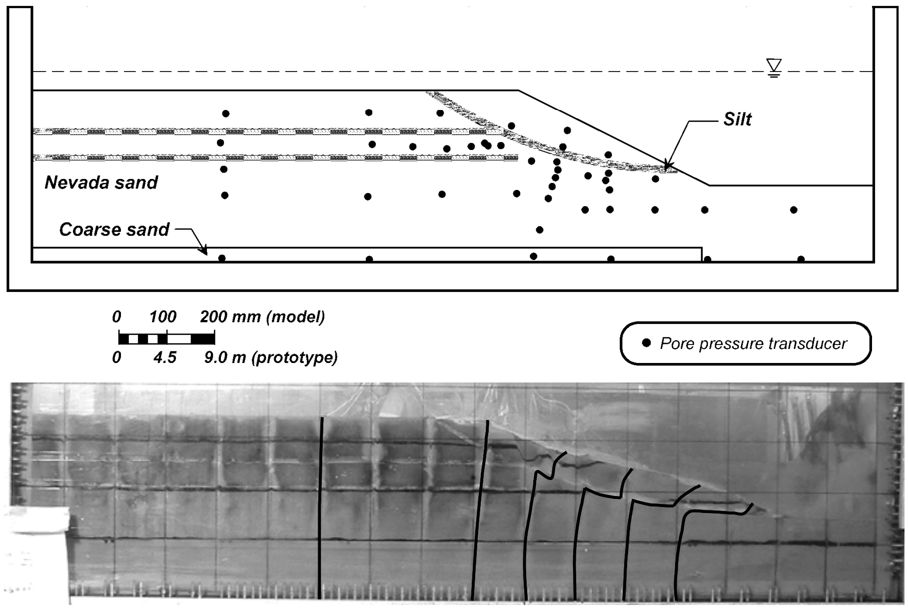


Figure 45. Localization of shear deformations along a lower-permeability interlayer within a saturated sand slope (Malvick et al. 2008)

Take home points

- ***"Liquefaction" means different things to different people – use more specific technical terms to avoid confusion in technical discussions.***
- ***Critical state soil mechanics is a useful tool for appreciating the different behaviors of various soils over a range of densities and confining stresses.***
- ***In situ shear strengths can be affected by the diffusion of excess pore pressures during and after shaking.***

Triggering of liquefaction

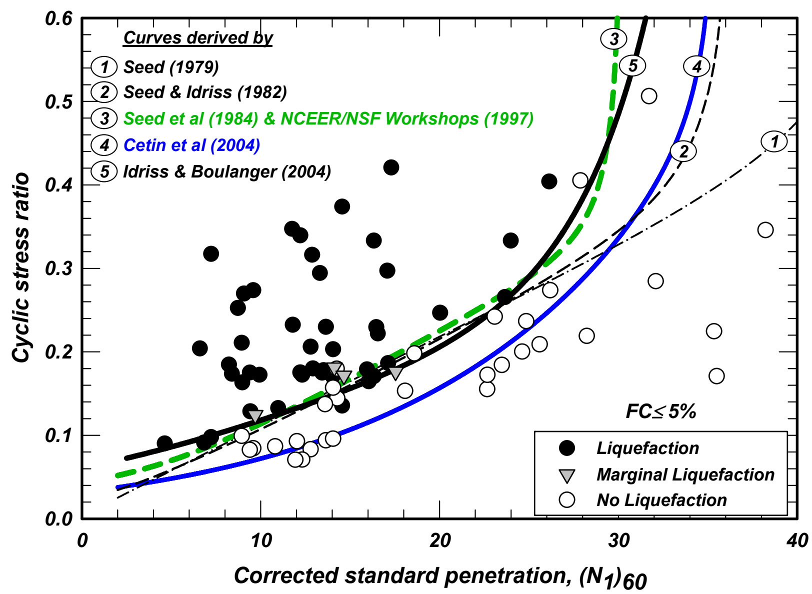
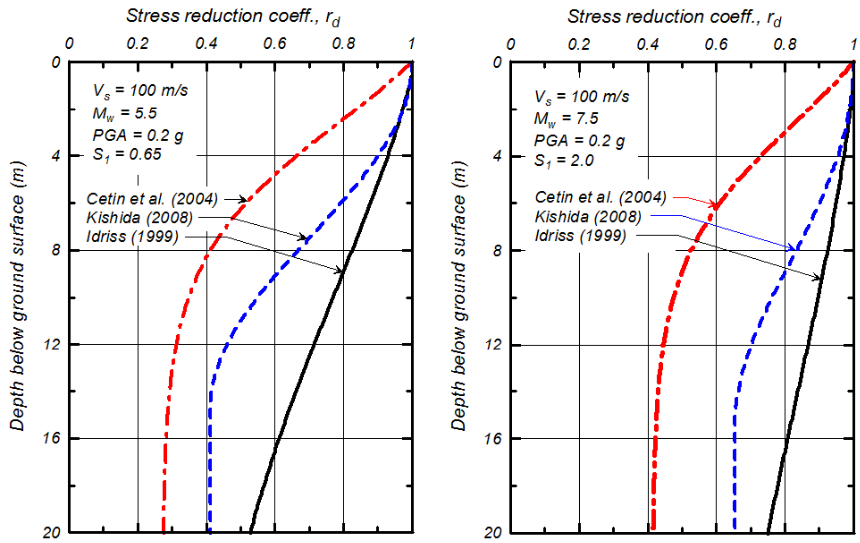
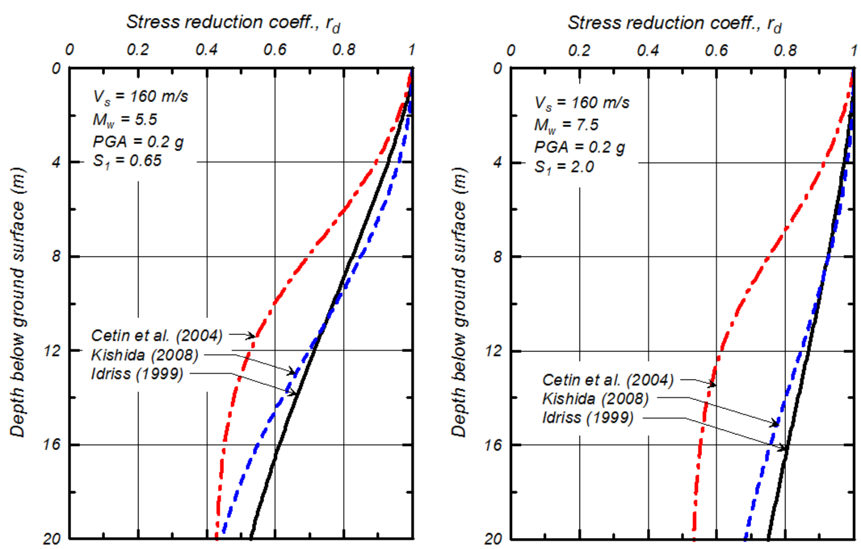


Figure 66 – Curves relating CRR to $(N_1)_{60}$ for clean sands with $M = 7½$ and $\sigma'_{vc} = 1$ atm.

A primary contributor to the differences between Cetin et al, NCEER and Idriss & Boulanger is the differences in r_d.





Other notable sources of differences are:

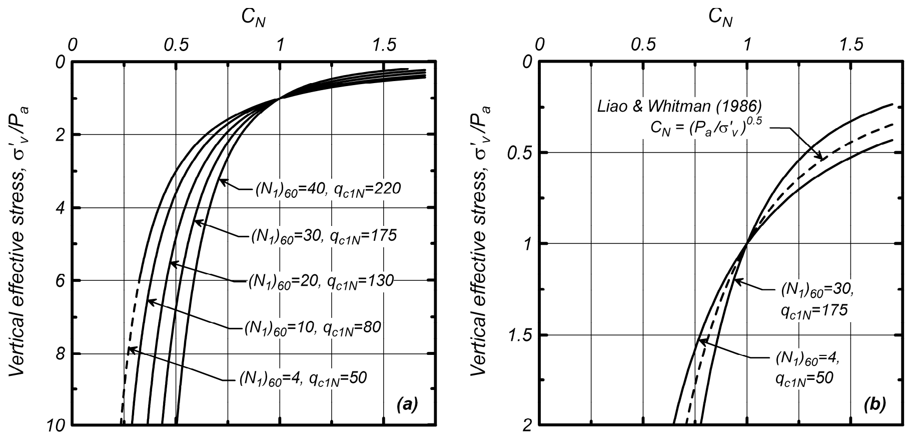


Figure 60 – Overburden normalization factor C_N: (a) dependence on denseness, and (b) simpler approximations often used at shallower depths.

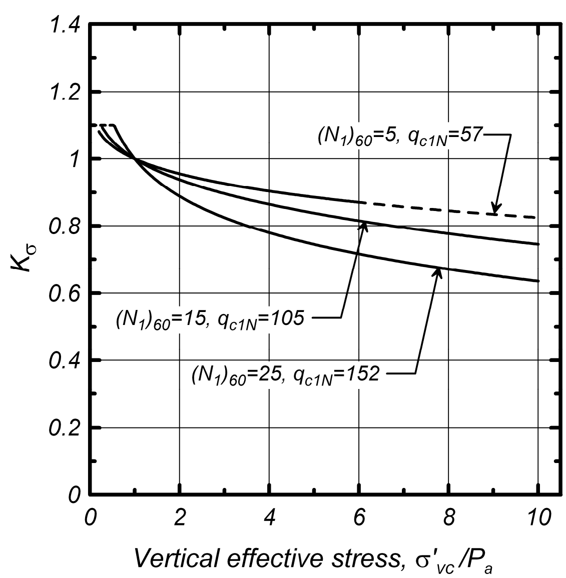


Figure 64 – K_σ relationships derived from ξ_R relationships (from Boulanger and Idriss 2004).

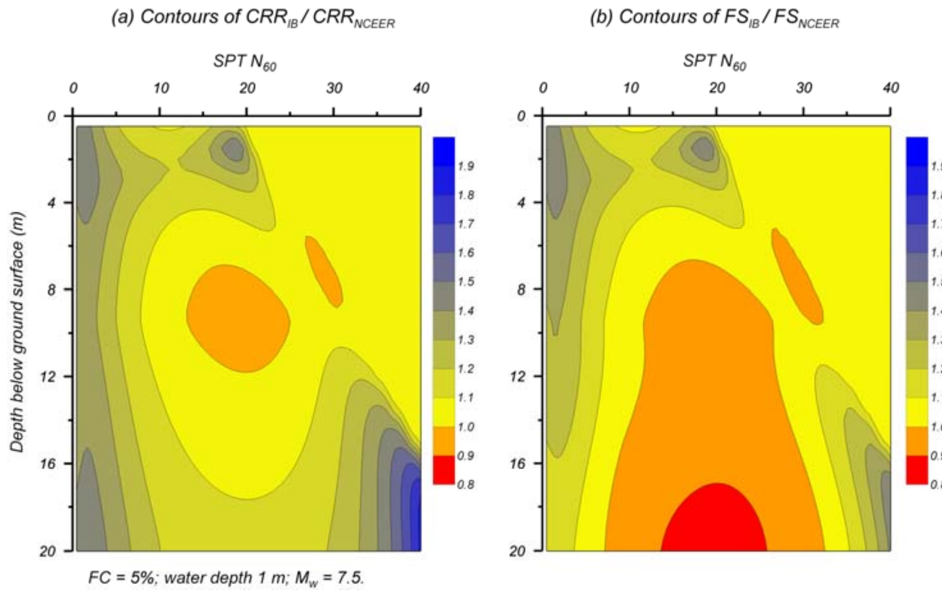


Figure 69 – Comparison of liquefaction procedures by Idriss and Boulanger (2006) to those from the NCEER/NSF workshop (Youd et al. 2001): (a) ratio of CRR values, and (b) ratio of FS_{liq}

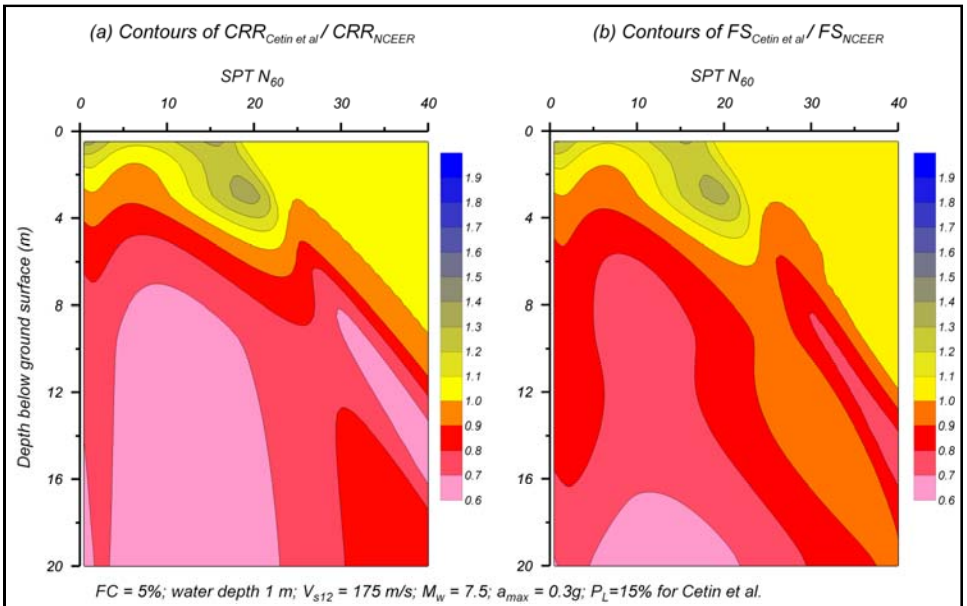


Figure 70 – Comparison of liquefaction procedures by Cetin et al. (2004) to those from the NCEER/NSF workshop (Youd et al. 2001): (a) ratio of CRR values, and (b) ratio of FS_{liq}

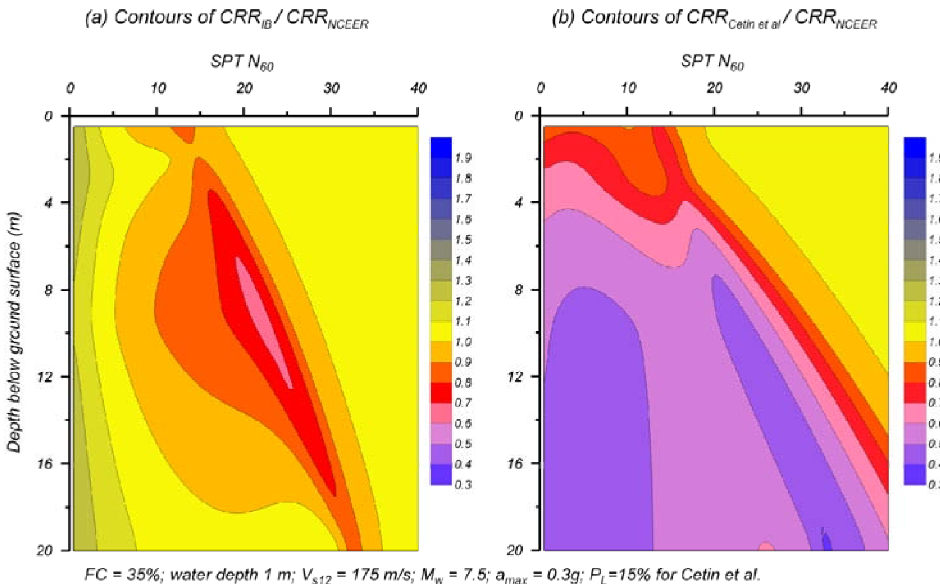


Figure 76 – Comparison of liquefaction analysis procedures from Idriss and Boulanger (2006), Cetin et al. (2004), and NCEER/NSF (Youd et al. 2001) for FC=35%.

Is there a depth, like 50 ft (or 15 m) below which we don't need to consider liquefaction as being possible?

EERI seminar participants

Influence of depth on liquefaction:

- ***Mechanisms affecting:***
  - ***Soil strengths***
  - ***Seismic loads***
  - ***Consequences***
- ***Empirical observations – must have a theoretical basis for understanding how our experiences from one site may relate to another.***
- ***Limitations in how analysis methods handle the role of depth.***

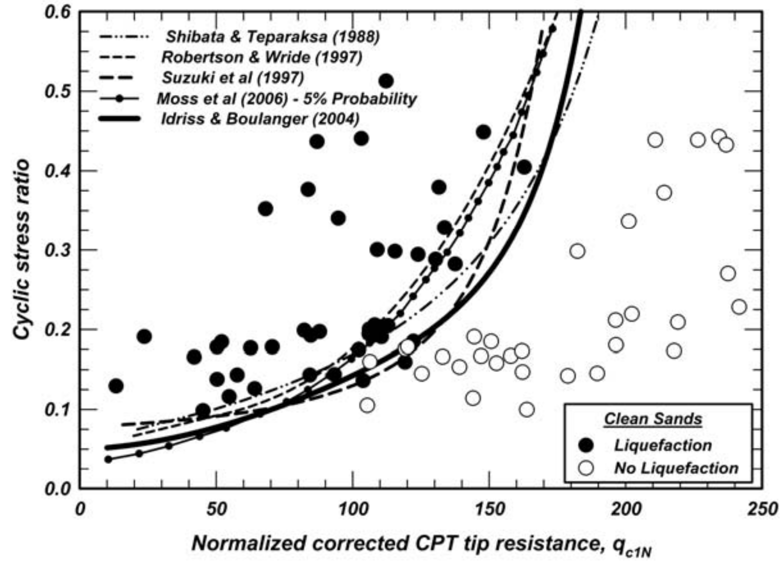


Figure 67 – Curves relating CRR to q_{c1N} for clean sands with M = 7½ and = 1 atm

Adjustment for fines content (FC)

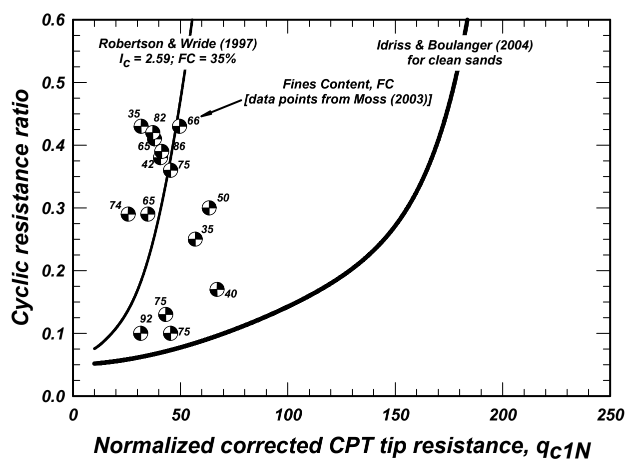


Figure 77 (a) – Comparison of field case histories for cohesionless soils with high fines content and the curves proposed by (a) Robertson & Wride (1997) for soils with I_c = 2.59 (apparent FC = 35%)

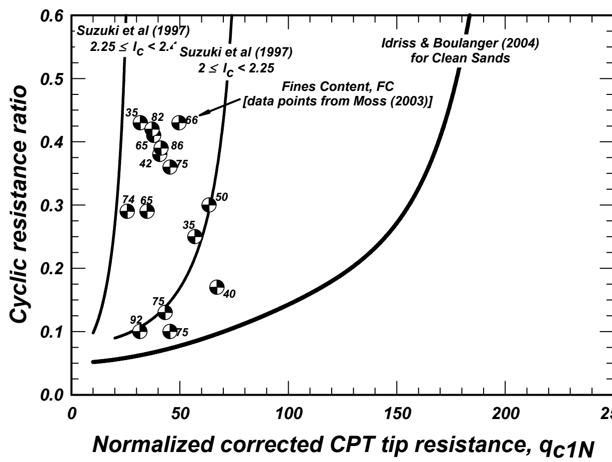


Figure 77 (b) – Comparison of field case histories for cohesionless soils with high fines content and the curves proposed by (b) Suzuki et al (1997) for I_c values of 2.0 – 2.4

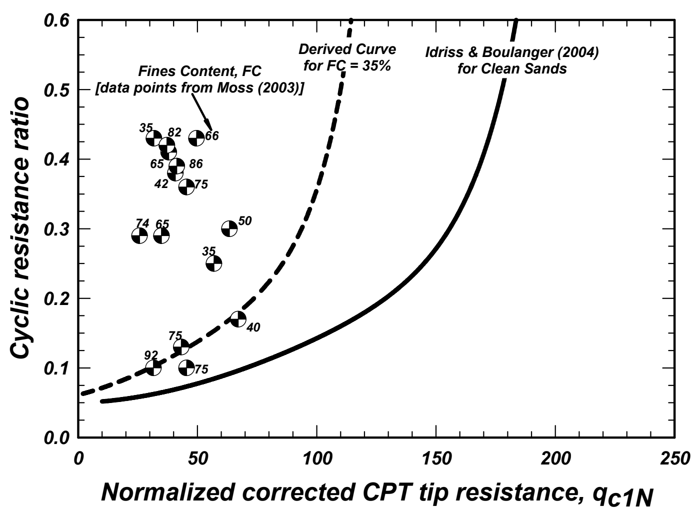


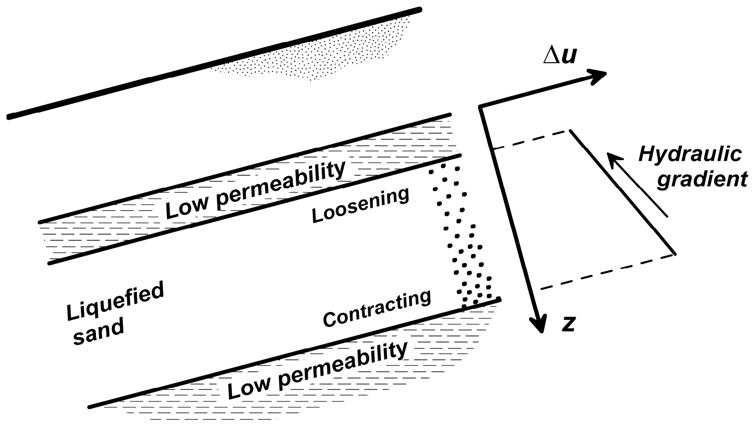
Figure 79 – Comparison of field case histories for cohesionless soils with high fines content and a curve recommended for cohesionless soils with FC = 35%

Take home points

- Curves relating CRR to $(N_1)_{60}$ for clean sands and sands with non-plastic fines have largely stabilized.
- Curves relating CRR to q_{c1N} for clean sands are stabilizing, but the effects of fines content are subject to further refinements.
- Extrapolation of liquefaction correlations to depths larger than are covered empirically requires a sound theoretical basis.

Consequences of liquefaction:

Residual Shear Strength



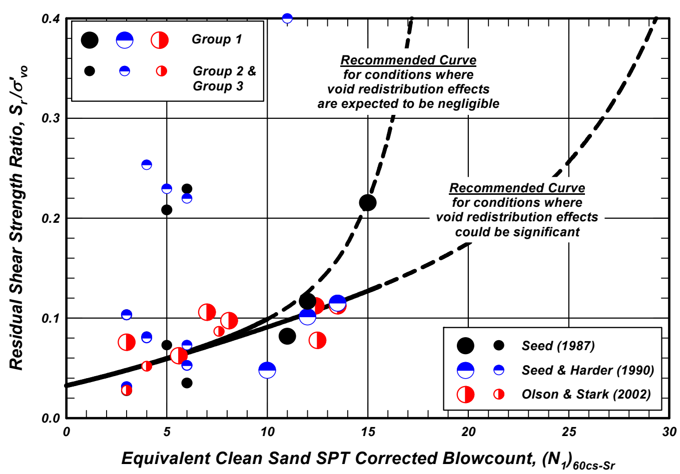


Figure 89 – Normalized residual shear strength ratio of liquefied sand versus equivalent clean-sand, corrected SPT blow count based on case histories published by Seed (1987), Seed and Harder (1990), and Olson and Stark (2002)

Take home points

- ***An understanding of strength loss mechanisms is provided by laboratory testing and physical modeling studies.***
- ***Case histories implicitly account for void redistribution.***
- ***The relationships presented in the Monograph reflect the current understanding and capabilities for modeling this phenomenon.***
- ***More work in this area is needed.***

Consequences of liquefaction:

Lateral spreading and post-liquefaction reconsolidation settlements

Lateral spreading analyses

- ***Approaches***
  - ***Empirical***
  - ***Newmark sliding block analyses***
  - ***Integrate potential strains versus depth***
  - ***Nonlinear dynamic analyses***
- ***None capture all the physical phenomena.***
- ***Site characterization is a major source of uncertainty.***

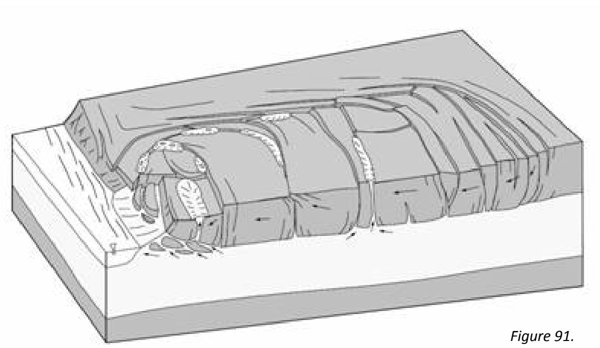


Figure 91.
From Rausch 1997

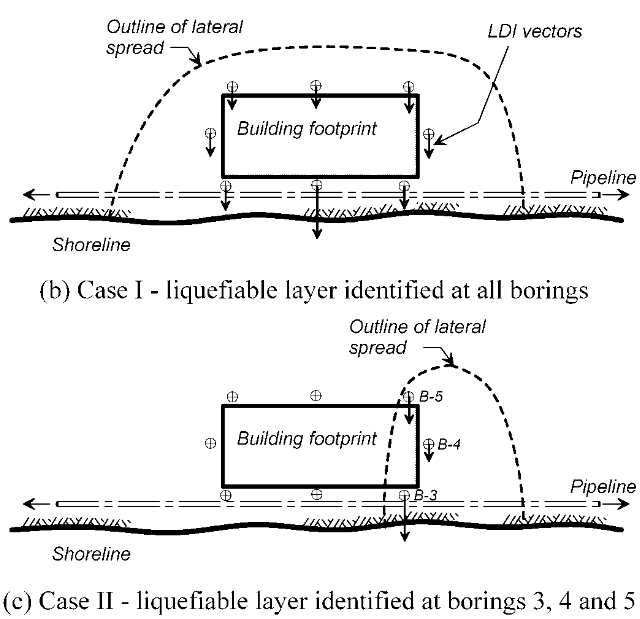
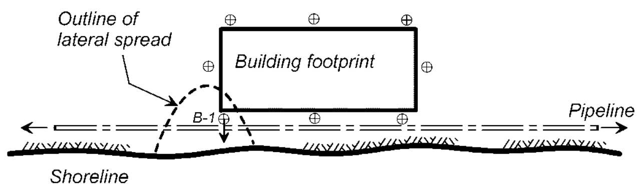
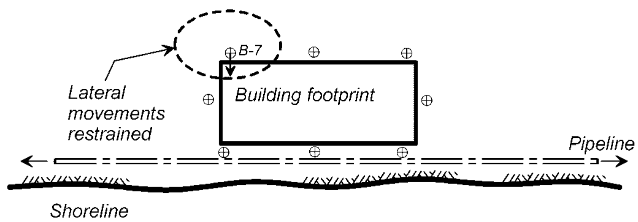


Figure 98. How LDI vectors may relate to the extent of lateral spreading

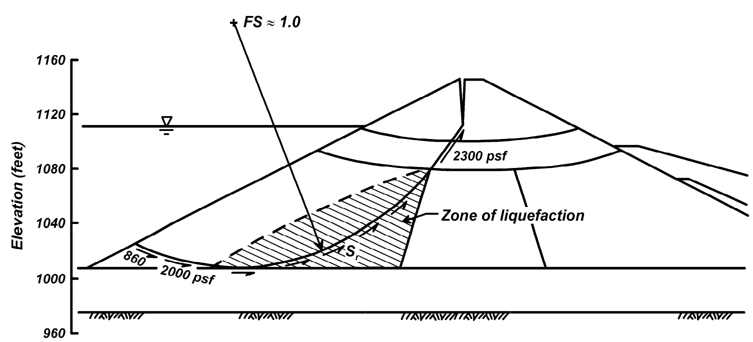


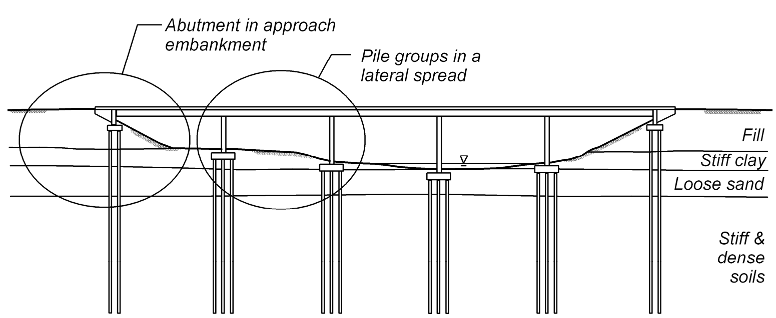
(d) Case III - liquefiable layer identified at boring 1 only



(e) Case IV - liquefiable layer identified at boring 7 only

Figure 98. How LDI vectors may relate to the extent of lateral spreading





Take home points

- ***Appropriate site characterization is essential for identifying and quantifying liquefaction hazards.***
- ***Simplified procedures for estimating liquefaction-induced ground deformations are inherently limited in their accuracy by the fact they cannot account for all the physical mechanisms or initial conditions.***
- ***The insights from various types of analyses, even if their accuracy is limited, can still guide effective decision making.***

Cyclic softening in clays and plastic silts

What is liquefaction & what is cyclic softening?

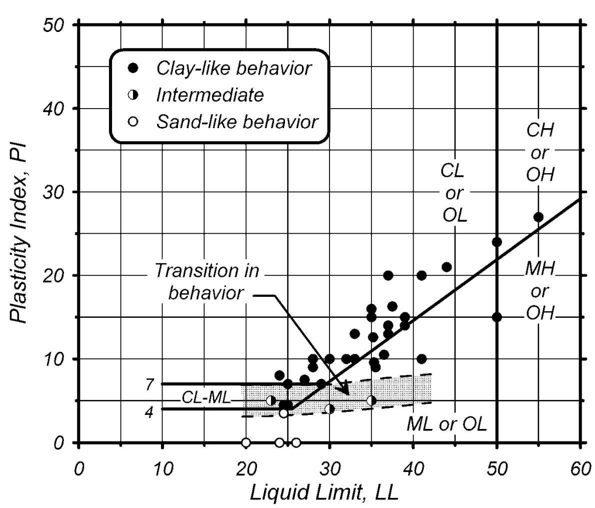
An interpretation problem

- ***Using "liquefaction" to describe ground failure in both sands and low-plasticity clays implies:***
  - ***a common behavior, and***
  - ***a common set of engineering procedures.***
- ***If a silt/clay is deemed "liquefiable", it is common to use SPT- and CPT-based liquefaction correlations***
  - ***E.g., NCEER/NSF workshop (e.g., Youd et al. 2001)***
  - ***Recommendations to sample and test "potentially liquefiable" silts/clays are often not heeded.***

Reposing the question

- ***Question:***
  - ***What is the best way to estimate the potential for strength loss & large strains in different types of fine-grained soils?***
  - ***Or, what types of fine-grained soils are best evaluated using procedures modified from those for sands, versus procedures modified from those for clays?***
- ***Terminology:***
  - ***"Sand-like" (or cohesionless) refers to soils that behave like sands in monotonic and cyclic undrained loading. Onset of strength loss and large strains is "liquefaction."***
  - ***"Clay-like" (or cohesive) refers to soils that behave like clays in monotonic and cyclic undrained loading. Onset of strength loss and large strains is "cyclic softening."***

Atterberg limits of fine-grained soils exhibiting sand-like versus clay-like behavior



- ***Distinguishes between soils whose seismic behaviors are best evaluated using different engineering procedures.***

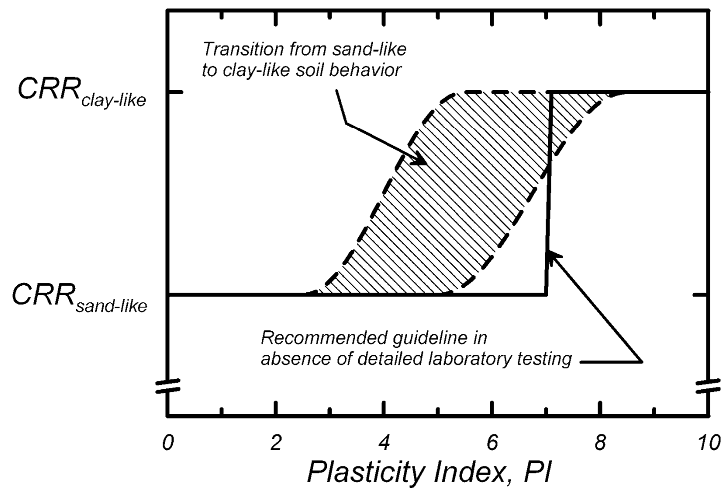


Figure 135. Schematic of transition from sand-like to clay-like behavior for fine-grained soils

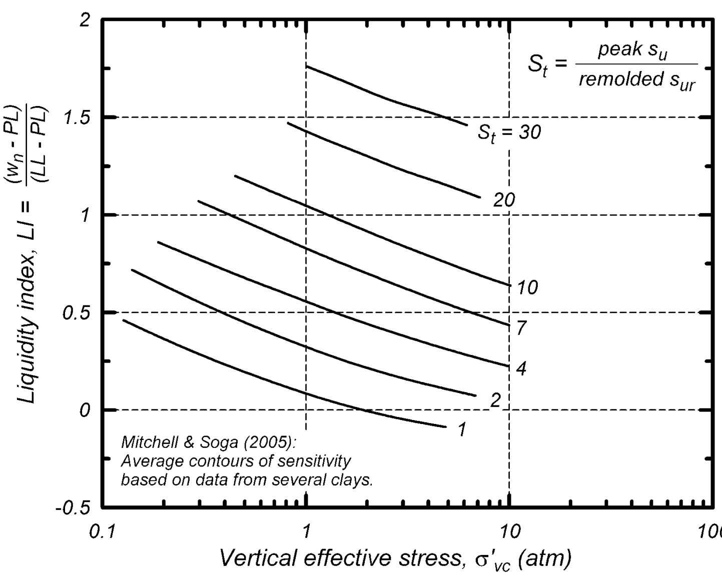
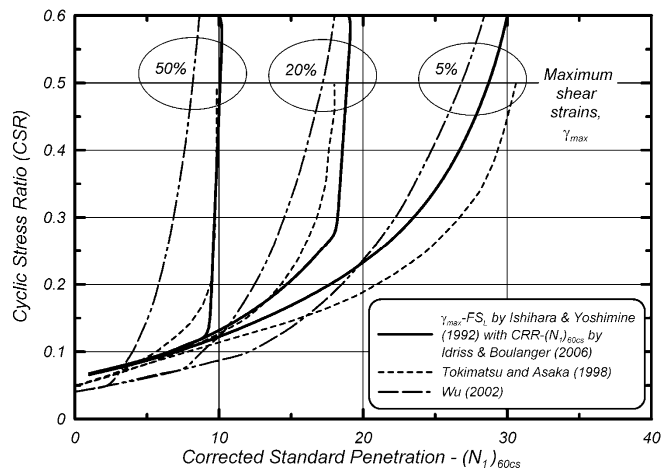


Figure 136. Relationship among sensitivity, LI, and effective consolidation stress (after Mitchell and Soga 2005)

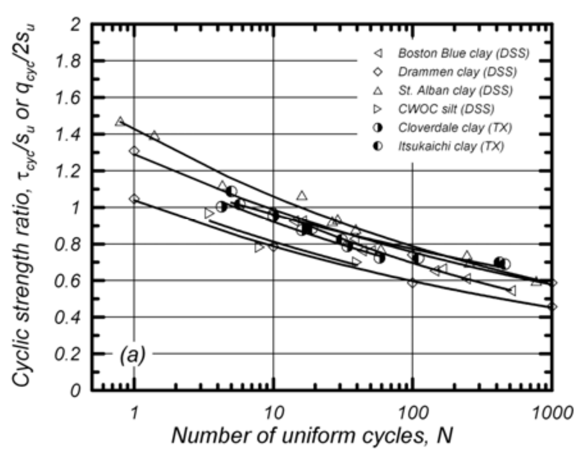
"Liquefaction" procedures for cohesionless soils

- ***Semi-empirical correlations based on in situ penetration tests.***
- ***Consequences depend on relative density (e.g., bad if loose, not so bad if dense).***



"Cyclic softening" procedures for cohesive soils

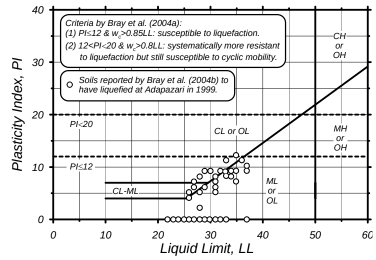
- ***Procedures based on estimation of undrained shear strength (e.g., may include correlations, in situ tests, lab tests).***
- ***Consequences depend on sensitivity (e.g., bad for quick clays, not so bad for insensitive clays; e.g., consider LI or w_n/LL).***

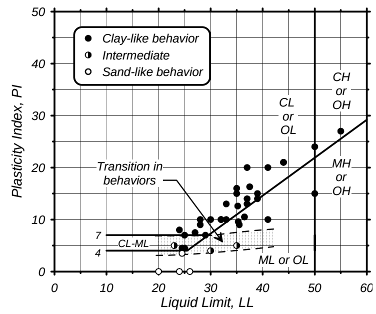


Comparing criteria – The common message

Boulanger & Idriss (2004, 2006) and Bray et al. (2004, 2006).

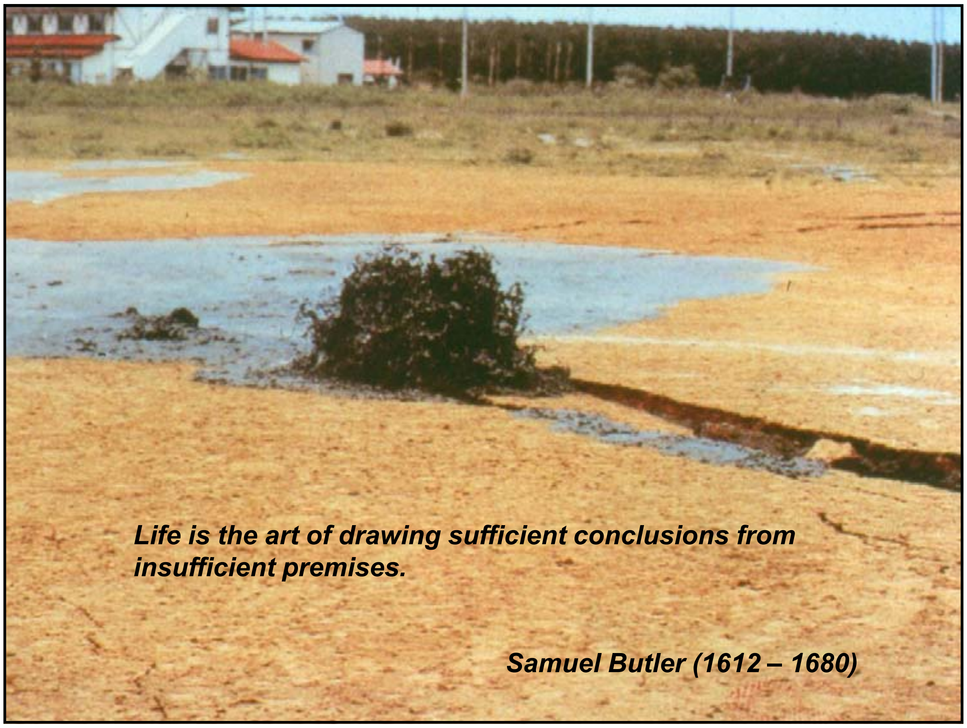
- ***PI < 4, no issue; Analyze using liquefaction correlations.***
- ***PI > 20, no issue; Analyze using procedures for clays.***
- ***4 ≤ PI ≤ 20***
  - ***Agree soil may develop high r_u, lose strength, & deform.***
  - ***Call it liquefaction, cyclic softening, or XYZ?***
  - ***Issue: How best to evaluate XYZ behavior?***





Take home points

- ***Do not use the Chinese Criteria.***
- ***Potential for <u>cyclic softening</u> of <u>clay-like</u> or <u>cohesive</u> fine-grained soils is best evaluated using procedures that are similar to, or build upon, established procedures for evaluating the monotonic undrained shear strength of such soils (e.g., Boulanger & Idriss 2004).***
- ***Fine-grained soils transition from behavior that is best analyzed as "clay-like" versus "sand-like" over a narrow range of PI values.***
- ***Fine-grained soils with PI≥7 are best analyzed as clay-like. These criteria may be refined on the basis of site specific testing.***


Life is the art of drawing sufficient conclusions from
insufficient premises.
Samuel Butler (1612 – 1680)