Assessing effects of Liquefaction

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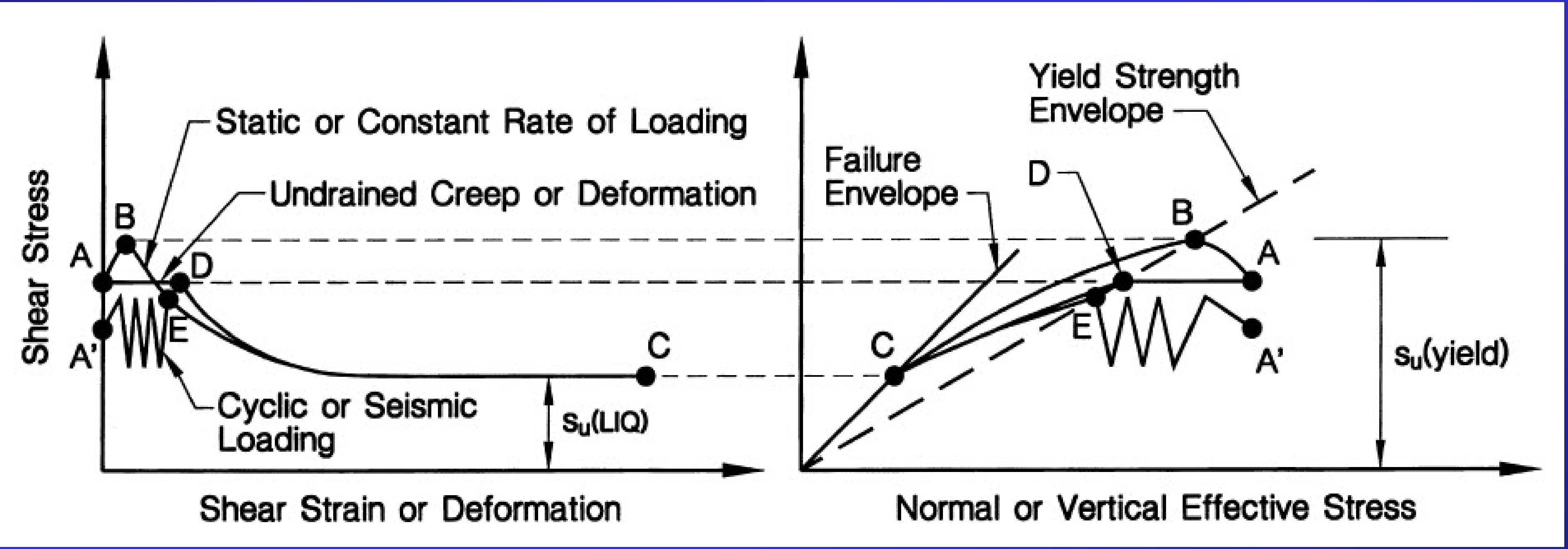
2016

Flow (static) Liquefaction



After Olson & Stark, 2003

Case histories – flow liquefaction

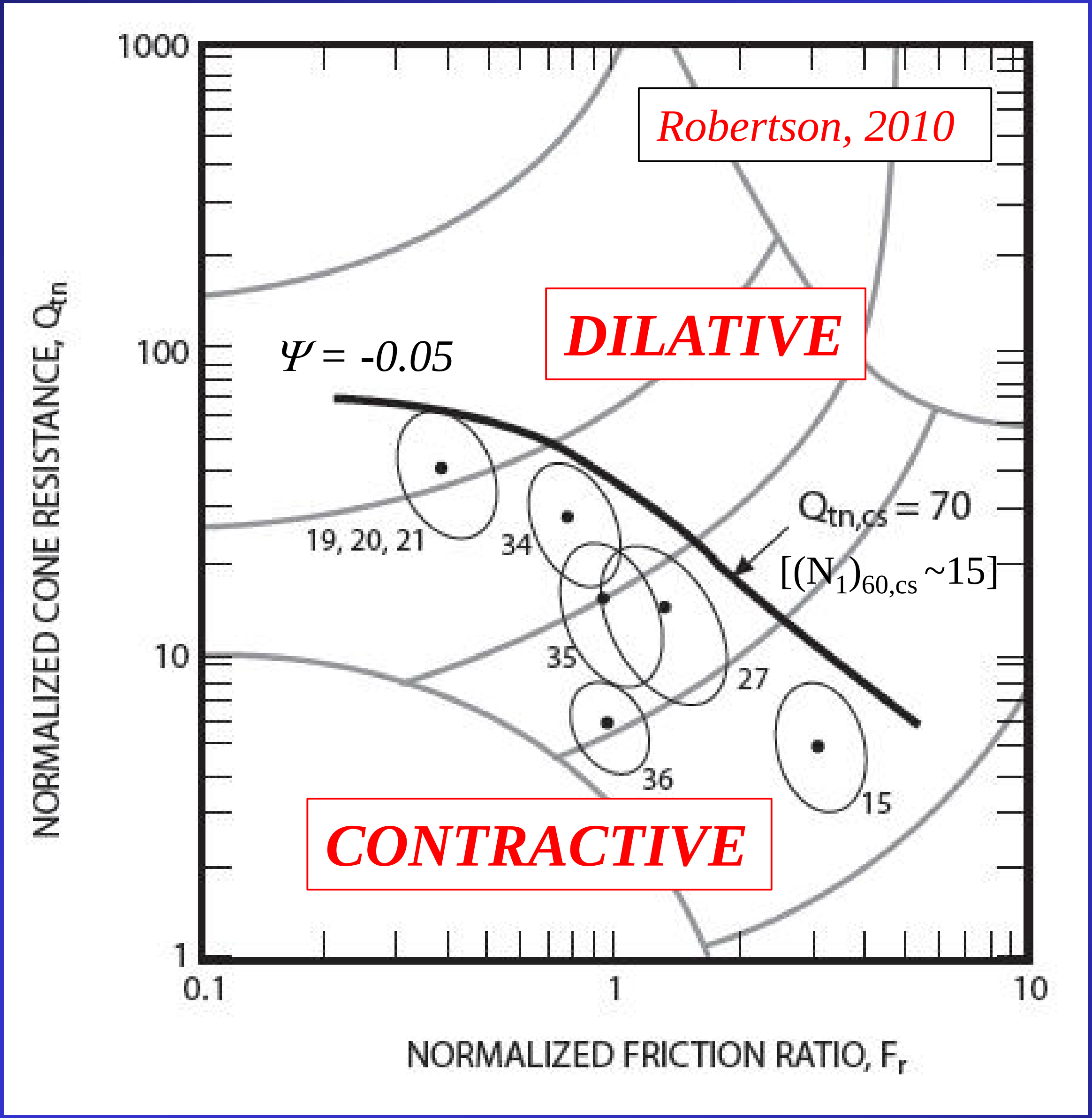
- *Common soil features:*
  - Very young age
  - Non-plastic or low-plastic
  - Uncemented
  - Silica-based sandy soil
  - Little or no stress history ($K_o \sim 0.5$)
  - Very loose *(contractive)*

Stava, Italy, 1985; 268 deaths, 190,000m^3

- *Common instability features:*
  - Some triggered by very minor disturbance
  - Failures tend to occur without warning
  - Failures tend to be progressive & rapid
  - Observation approach not valid

TVA – Kingston, 2008

Case histories – flow liquefaction



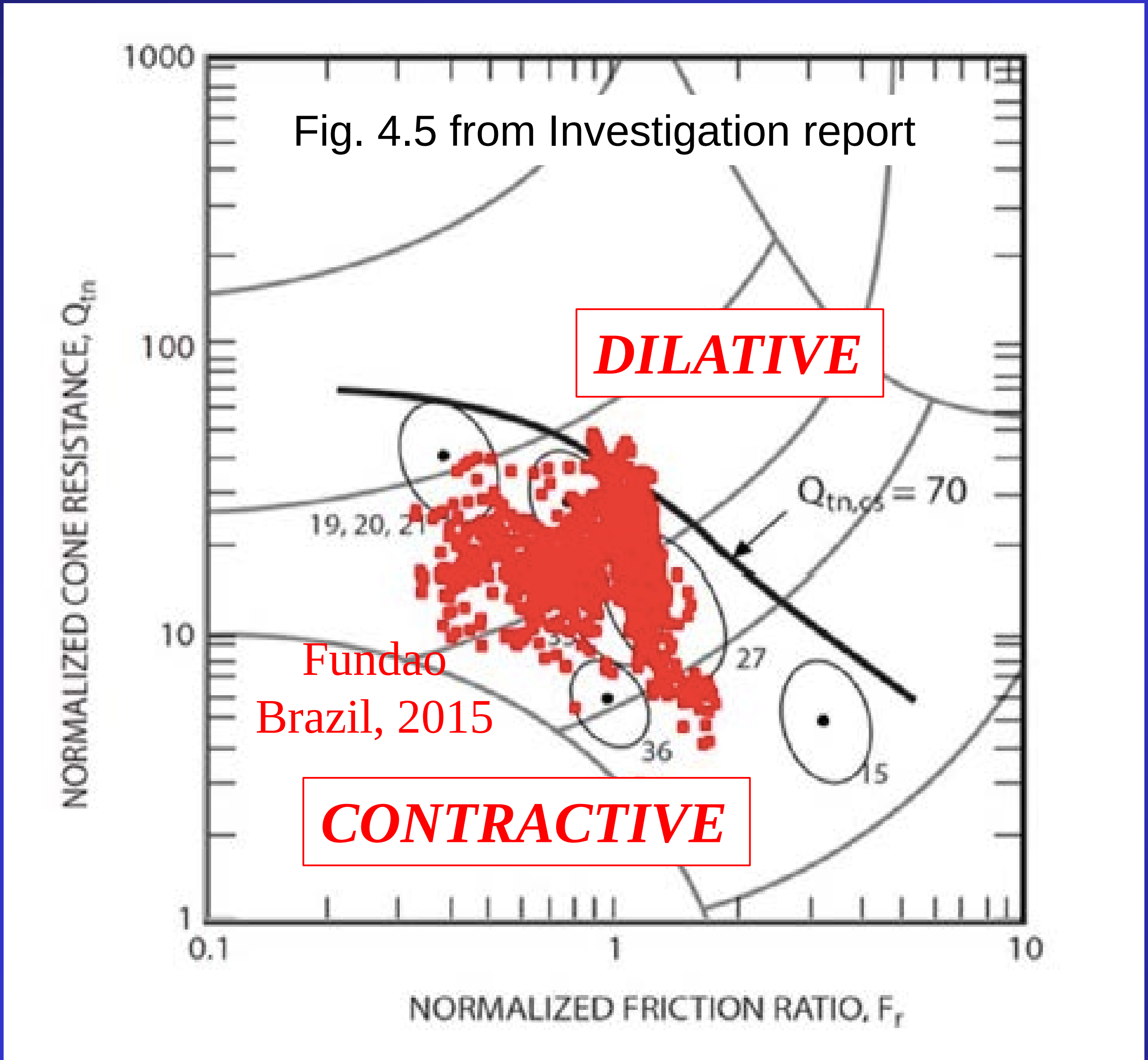
Case histories with CPT

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 flow liq. case histories plot in 'contractive' portion of CPT SBT chart
Good theoretical support via State Parameter

Case histories – flow liquefaction



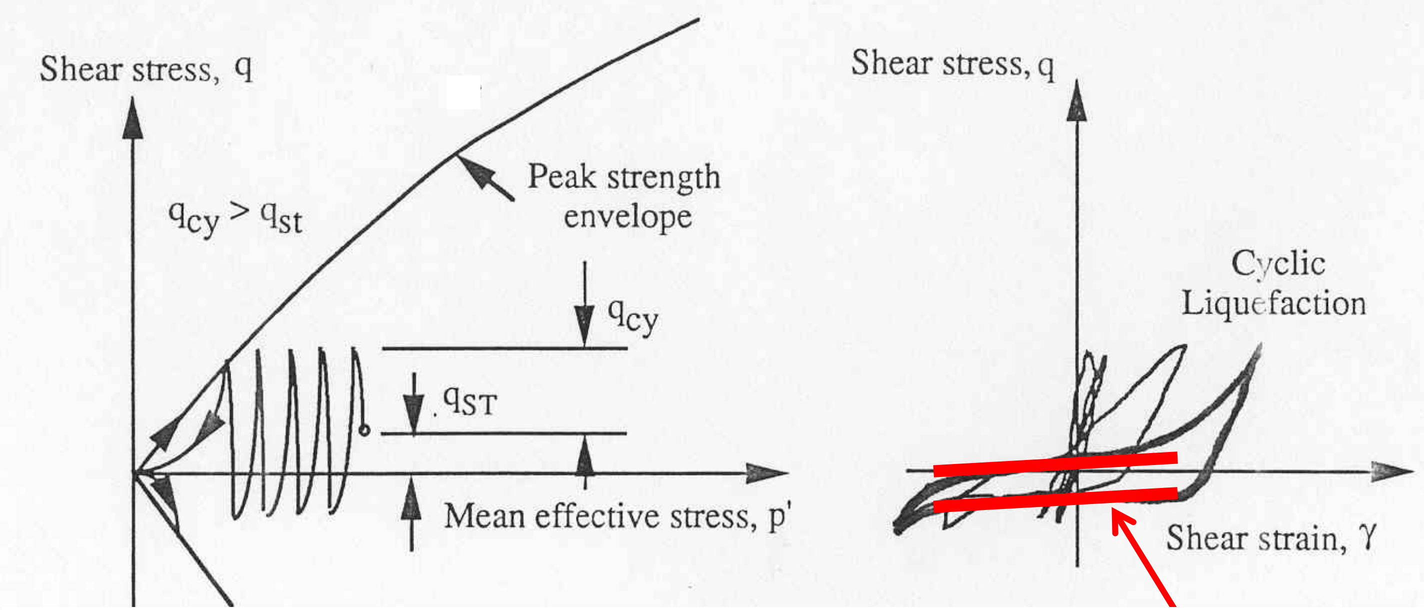
Fundao tailings dam failure Brazil, Nov. 2015

19 deaths

> 60x10^6 m^3 flowed > 600km

http://fundaoinvestigation.com/

Cyclic Liquefaction – Lab Evidence



Shear stress reversal → Zero effective stress → small stiffness

Loose sands can reach zero effective stress
Dense sands dilate before reaching zero effective stress
Clays can experience some softening, but do not reach zero effective stress

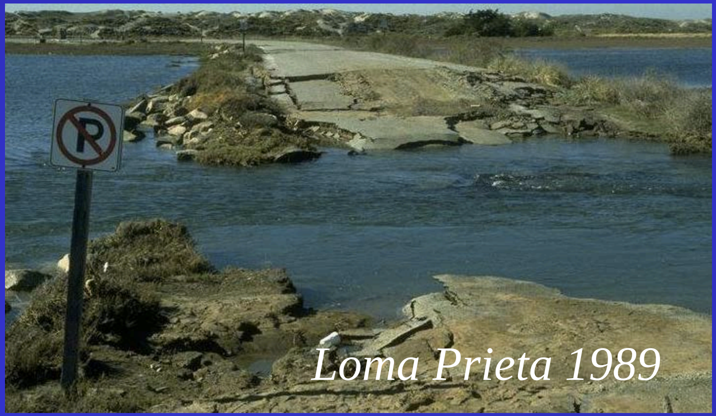
Case histories – cyclic liquefaction

Common soil features

Young (Holocene-age)
Non- plastic or low-plastic
Uncemented
Silica-based sandy soil
Little or no stress history (K_o ~ 0.5)

Database

Mostly 6.0 < M < 7.6
Bias 'liq' sites (>70%)
Shallow depth z < 12m
Mostly ~level ground

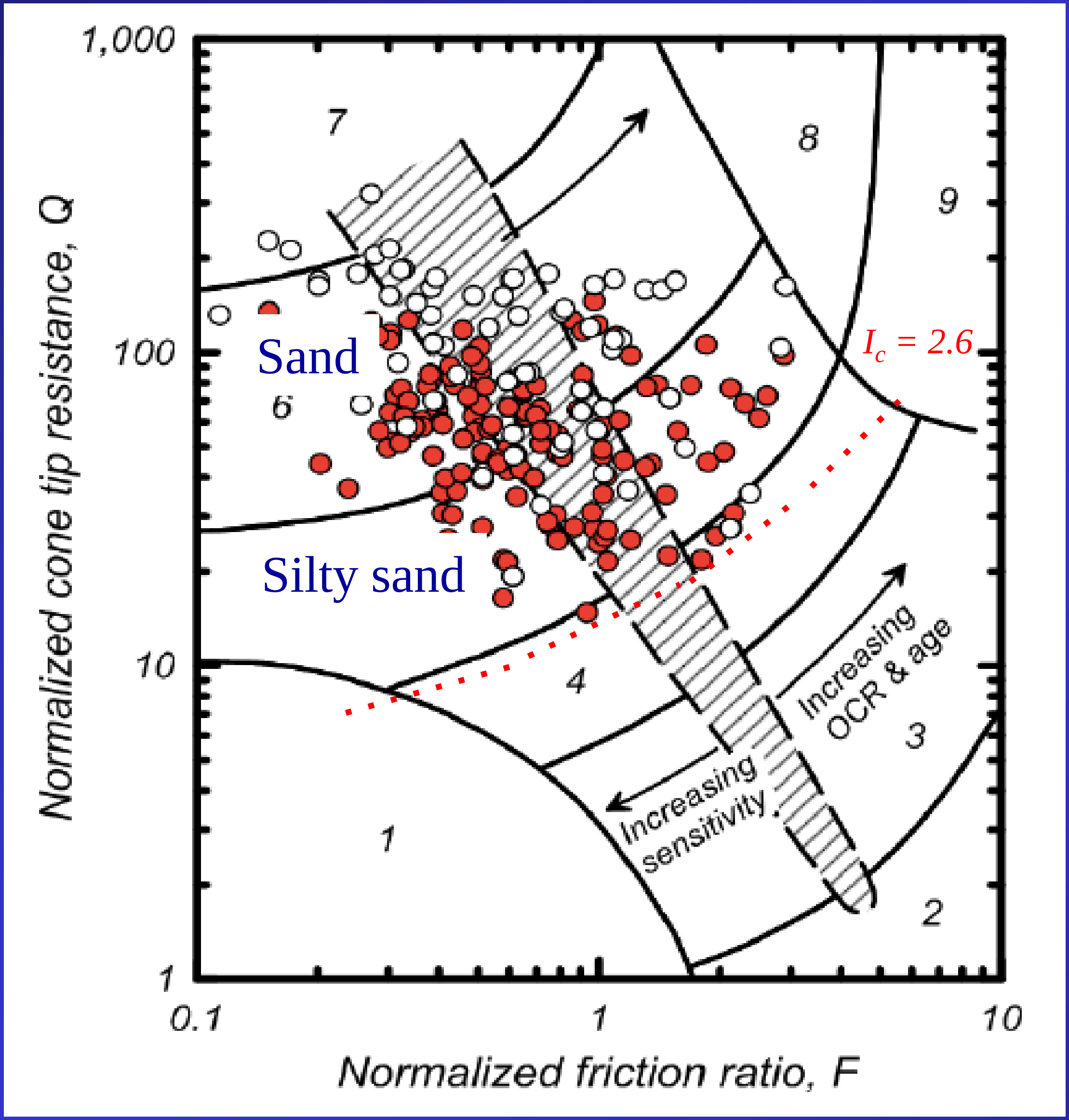


Loma Prieta 1989

Kobe 1995

Christchurch 2010

Case histories – cyclic liquefaction



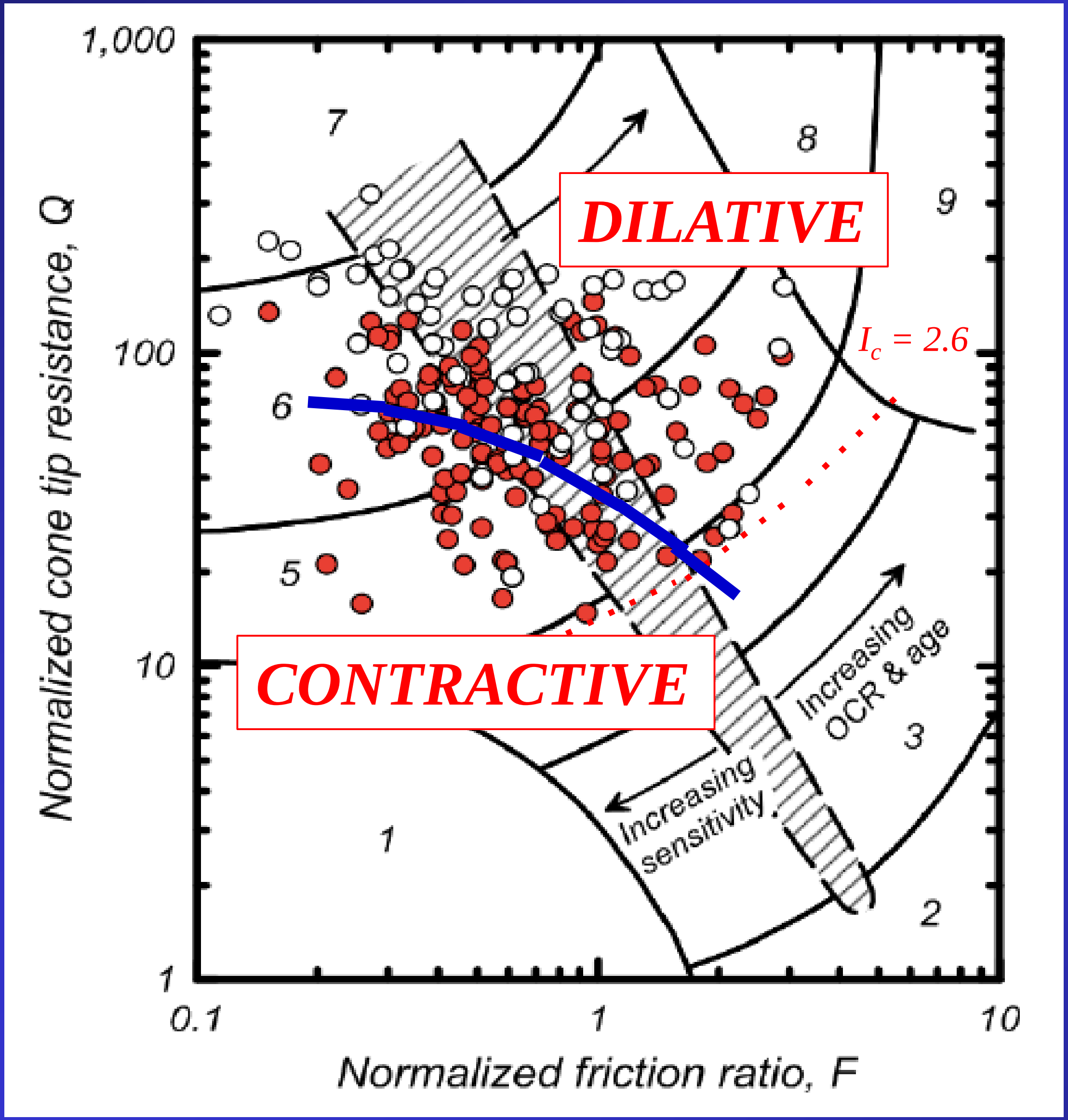
Significant growth in CPT database (>250 cases)

Trigger curves well established

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

Data after Boulanger & Idriss, 2014

Cyclic Liq. Case Histories

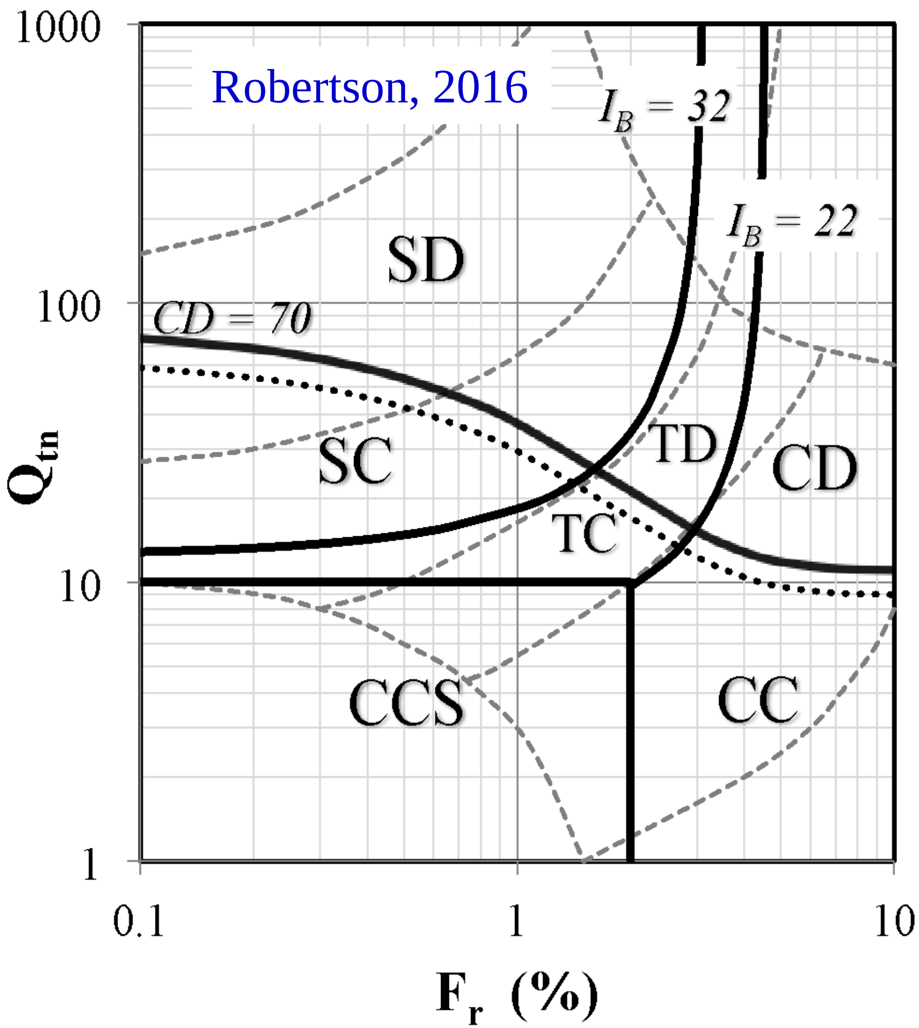


Many cyclic liquefaction case histories are in the ‘dilative’ SBT region.

Soils that are ‘dilative’ at large strain can develop positive pore pressures at smaller strains and experience cyclic liquefaction (softening), but deformations tend to be smaller

Data after Boulanger & Idriss, 2014

Updated SBTn Charts



Behavior Descriptions

Soil Behaviour Type

1: CCS Clay-like - Contractive - Sensitive
2: CC Clay-like - Contractive
3: CD Clay-like - Dilative
4: TC Transitional - Contractive
5: TD Transitional - Dilative
6: SC Sand-like - Contractive
7: SD Sand-like - Dilative

$$CD = (Q_{tn} - 11)(1 + 0.06F_r)^{17}$$

$$I_B = 100(Q_{tn} + 10)/(70 + Q_{tn}F_r)$$

Applies primarily to young, uncemented, silica-based soils

Liquefaction Case Histories

- Dominated by (*'ideal'*) soils that are: very young, uncemented silica-based sandy soils (& essentially normally consolidated)
- In many parts of the world soils are either older and/or lightly cemented or have different mineralogy (e.g. high mica or carbonate content): i.e. soils with *'microstructure'* – current methods tend to be too conservative
  - *Macrostructure* (layering, fissuring, etc.)
  - *Microstructure* (particle scale – aging, bonding, etc.)

Challenges

- How to identify and quantify the existence of soil microstructure?
- How to incorporated microstructure into current liquefaction evaluation methods?
  - Increased resistance to triggering
  - Influence on effects of liquefaction

Recent developments

- *Shear wave velocity - V_s (small strain measure)*
  - – controlled mainly by: state (relative density & OCR), effective stresses, age and cementation
- *CPT tip resistance - q_t (large strain measure)*
  - – controlled mainly by: state (relative density & OCR), effective stresses, and to lesser degree by age and cementation

Strong relationship between q_t and V_s, but depends mainly on *microstructure*

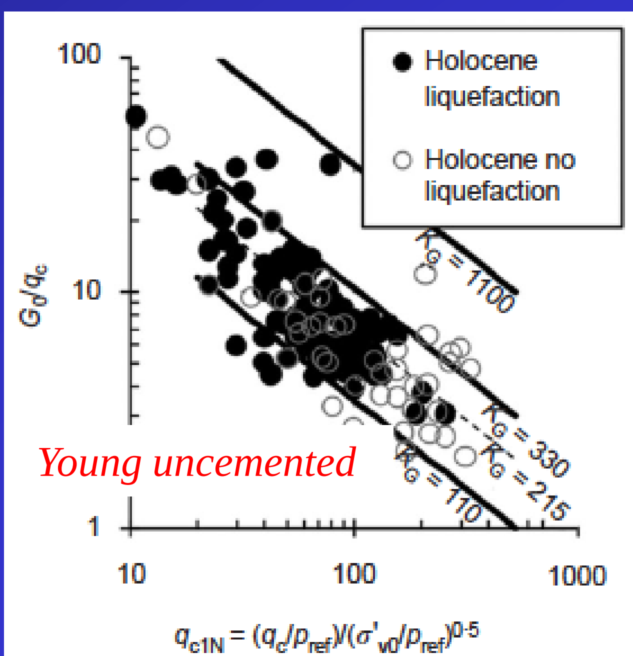
(i.e. age and cementation)

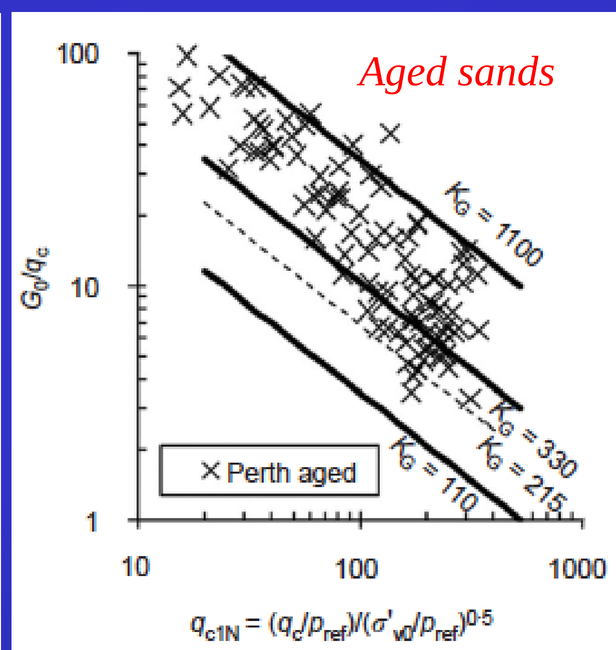
Normalized Rigidity Index K_G

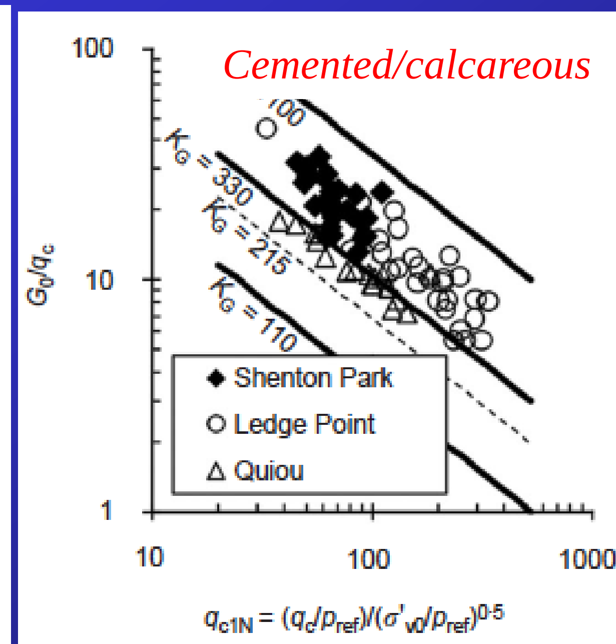
Normalized Rigidity Index, K_G *(Schneider & Moss, 2011)*

$$K_G = (G_o/q_t)(Q_{tn})^{0.7}$$

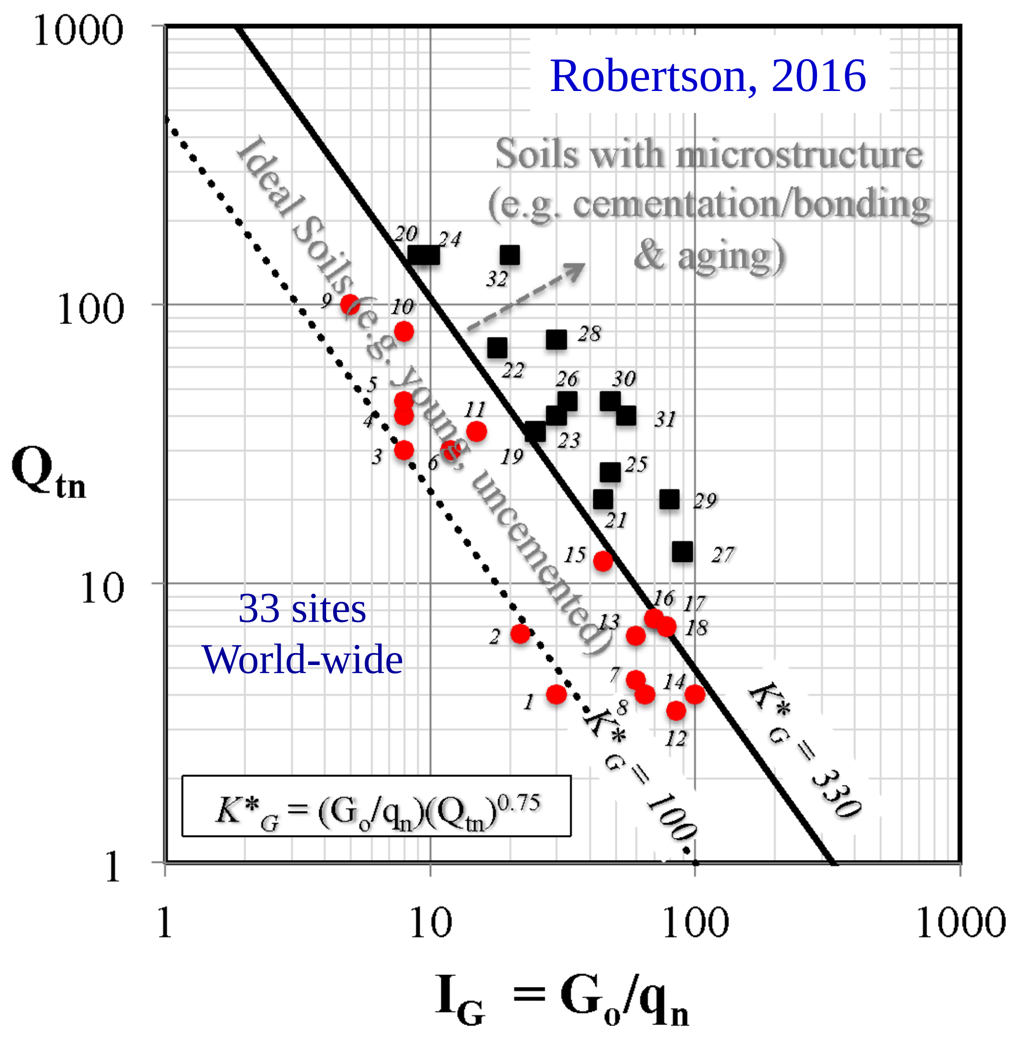
- If $K_G > 330$ aged and/or cemented
- If $K_G < 330$ young & uncemented (K_G ~200 for liq cases)







New G_o/q_n Chart



Average normalized rigidity index for young, uncemented silica-based soils:

$K^*_G = 200$

CRR for AGED soils

Andrus et al, 2009 + Hayati & Andrus, 2009

Based on MEVR *(Measure to Estimated V_s Ratio)*

$$MEVR = V_{s(measured)} / V_{s(estimated\ from\ CPT)}$$

–If MEVR > 1.0 aged (older)

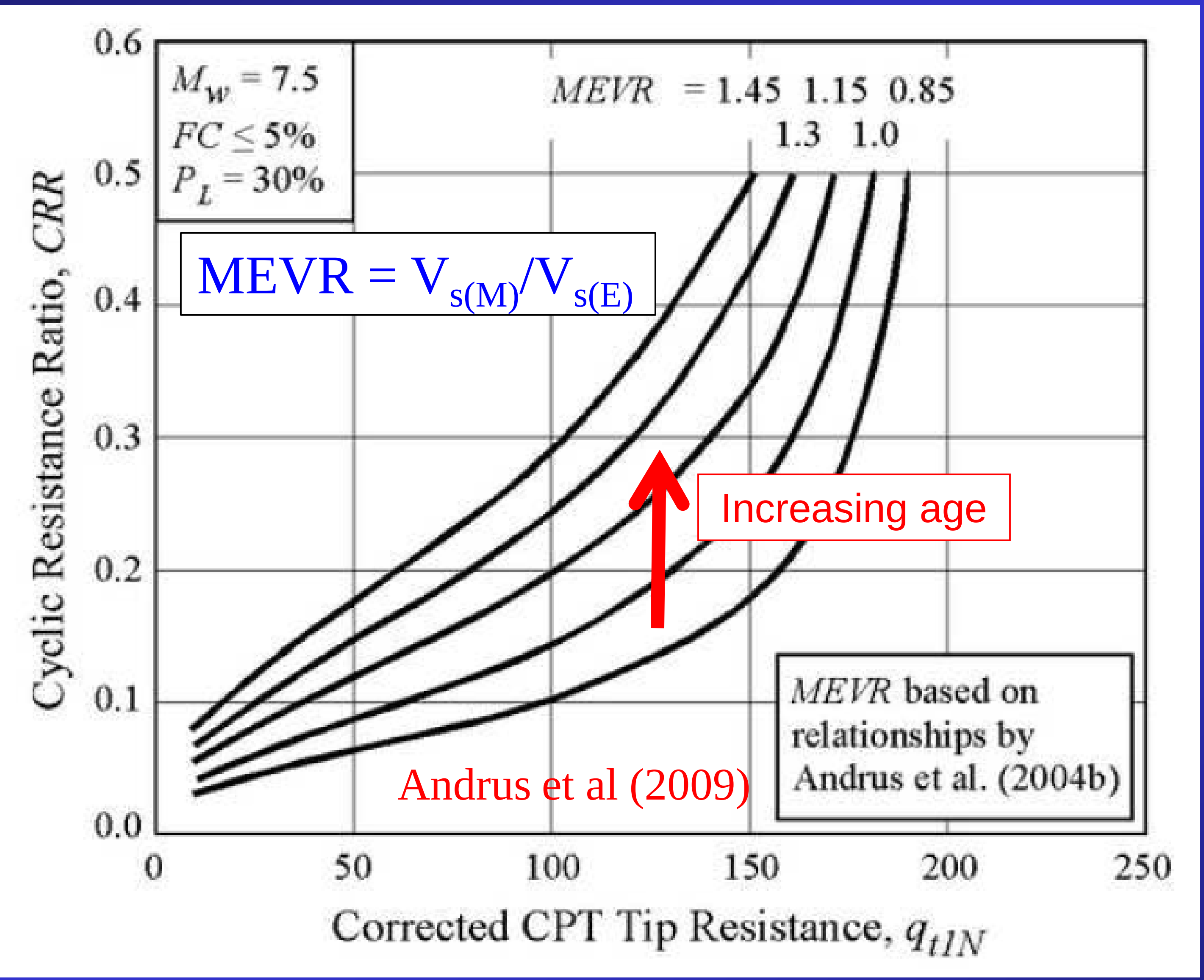
–If MEVR = 1.0 very young (~23 yrs)

$$CRR_{Deposit} = CRR\ K_{DR}$$

$$K_{DR} = 1.08\ MEVR - 0.08$$

Difference between *'geologic-age'* and *'behavior-age'*
e.g. past soil liquefaction events can re-set age clock?

Correction based on V_s (MEVR)

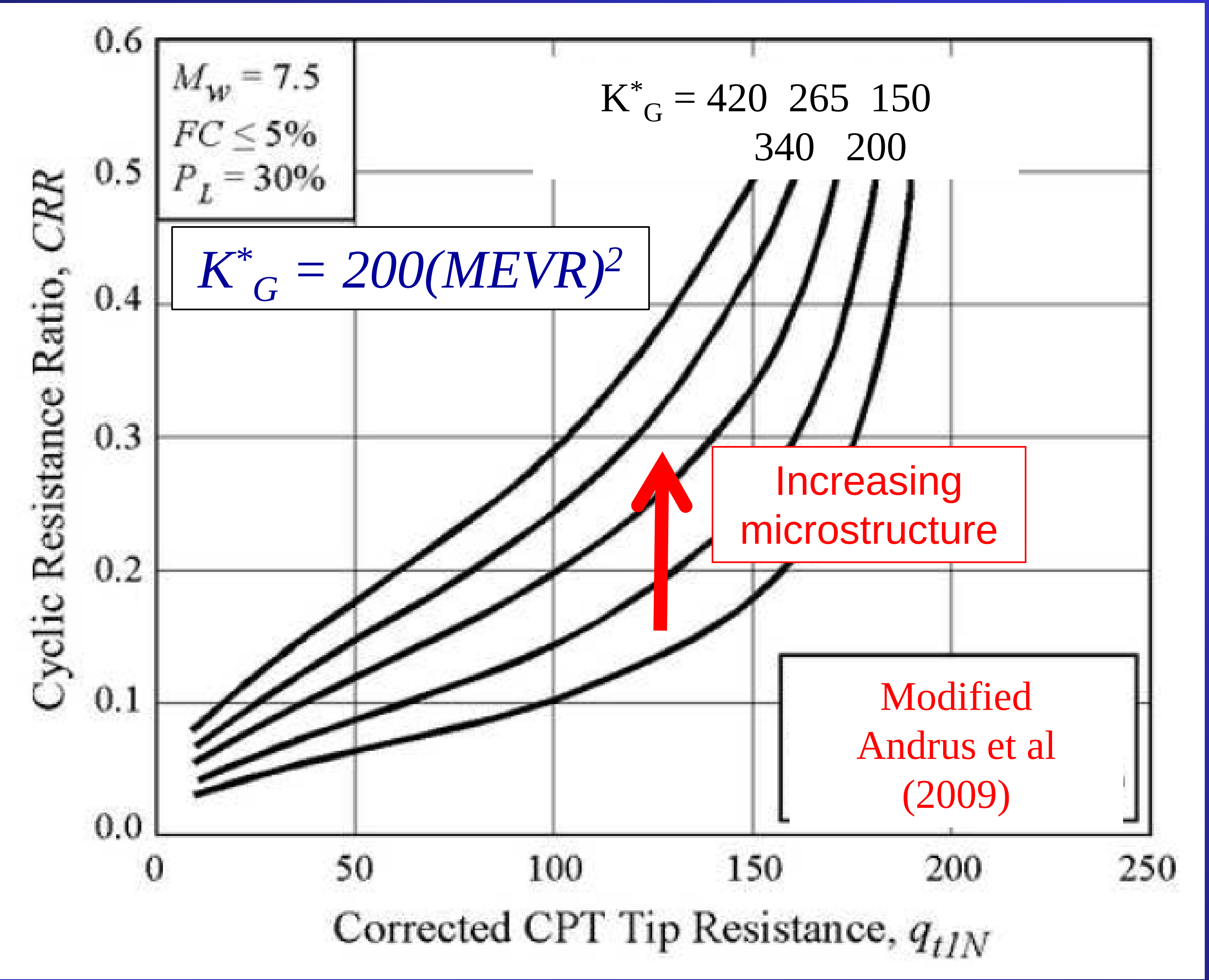


Age correction based on measured V_s

Estimate $V_{s(E)}$ from CPT

SCPT gives both CPT and V_s

Correction based on K^*_G



Microstructure correction based on measured K^*_G

If CPT and V_{s1} give different interpretation – which one is correct?

Main factors can be either aging or cementation

•V_{s1} generally correct for *aging* (Andrus et al 2009)

•If earthquake loading (CSR) exceeds threshold strain (estimated from G_o) – *cementation* may be destroyed and large strain response (Q_{tn}) may control (Schneider & Moss, 2011)

More research needed

Challenges

- Many soils around the word have some microstructure that influences their response to liquefaction
  - How do we identify these soils?
  - How do we adjust current liquefaction evaluation methods to account for microstructure?
- Need more case history data from sites were liquefaction did not occur or where deformations were small due to microstructure

Other challenges

- CPT data is near continuous
  - How to account for high level of detail?
    - Removal of transition zones
    - Fine tune 'I_c' cut-off for clay-like soils
- Depth effects on performance
  - How to reduce effect of liquefaction at depth relative to surface structures?
  - Weighting of strains with depth?