Lecture #3c
Effects of Fines on Liquefaction Resistance & CPT Resistance

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Organized by Prof. A. Balasubramaniam

PROBLEM

➢ Many earthquake-induced liquefaction and lateral spreading have occurred in silty soil sites. There is a need to understand Liquefaction Behavior of Silty Soils as compared to Clean Sands.

➢ Current Liquefaction Screening Technique for sands and non-plastic silty soils is highly empirical

- Current empirical charts are based on field observation from sand and silty sand sites and data on clean sands (NCEER 1997).
- The rationale for these methods for silty soils is not fully understood
- High uncertainty in these methods

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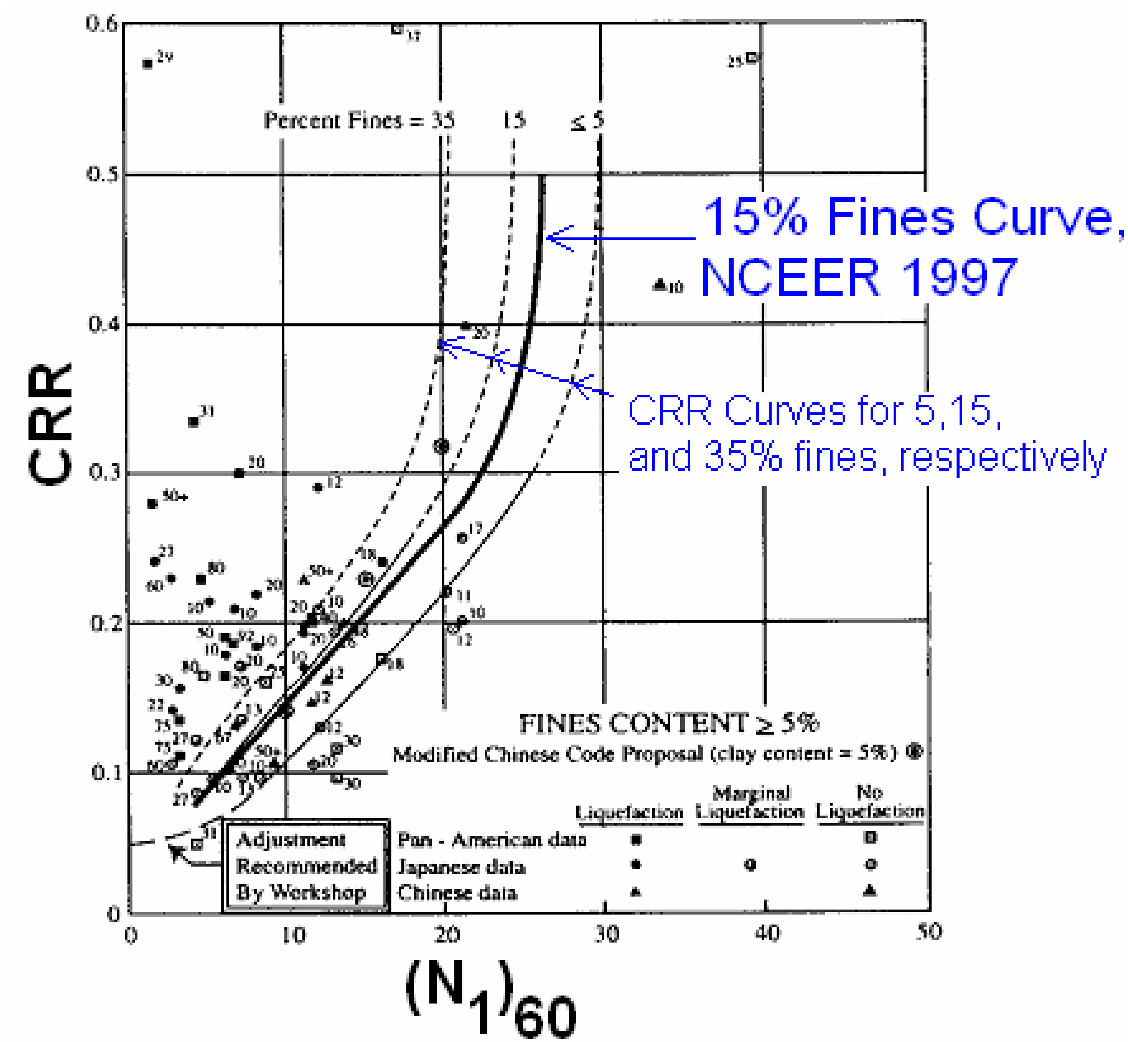
Current Liquefaction Screening Methods

Method	Resistance ($CRR_{7.5}$)	*x*	Factor of Safety
SPT $(N_1)_{60}$	$[a+cx+ex^2+gx^3]/[1+bx+dx^2+fx^3+hx^4]$	$(N_1)_{60cs} = \alpha + \beta (N_1)_{60}$	
CPT q_{c1N}	$0.833[x/1000]+0.05$ for $x<50$ $93[x/1000]^3+0.08$ for $50<x<160$	$(q_{c1N})_{cs} = K_c\, q_{c1N}$	$(CRR_{7.5}/CSR)MSF$
S-wave V_{s1}	$r(V_{s1}/100)^2 + s[1/(V_{s1c}-V_{s1})-1/V_{s1c}]$	V_{s1}	

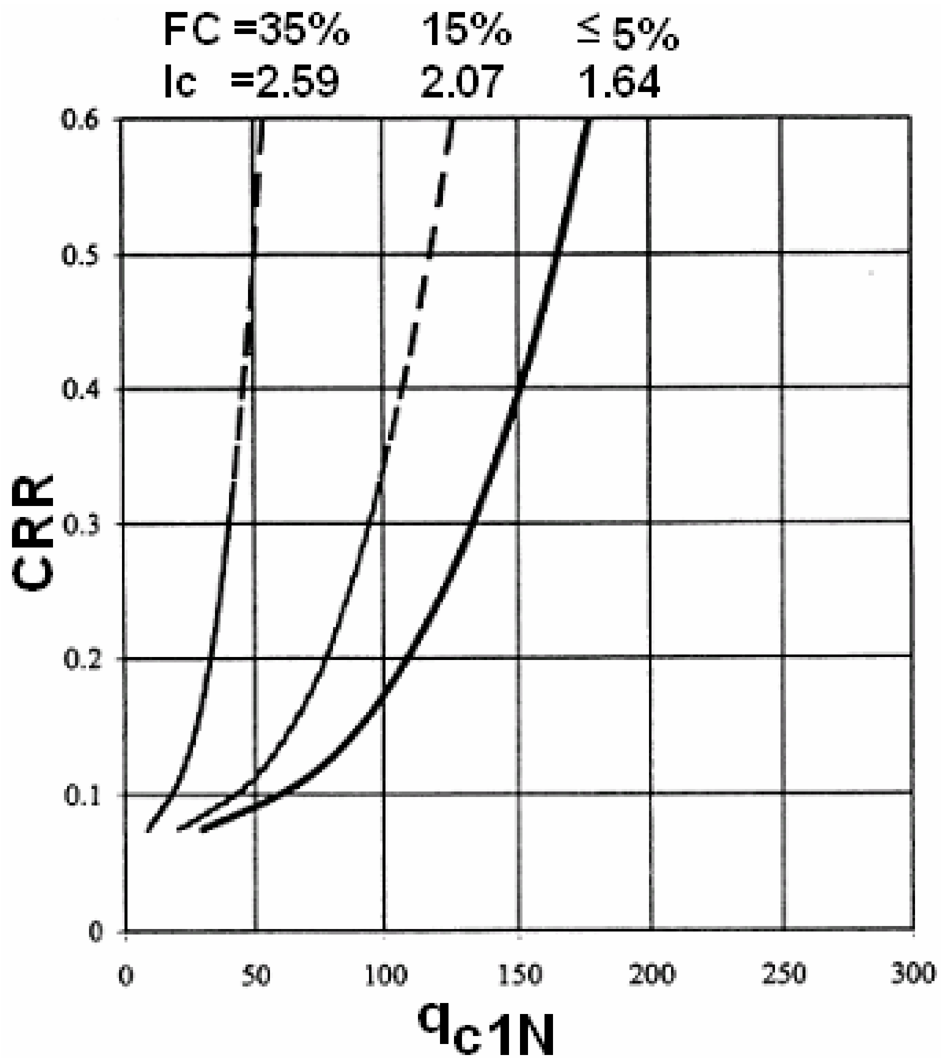
α, β, K_c, V_{s1c} = silt content dependent

SPT Method



(Youd and Idriss, 2001)

CPT Method



(Robertson and Wride, 1998)

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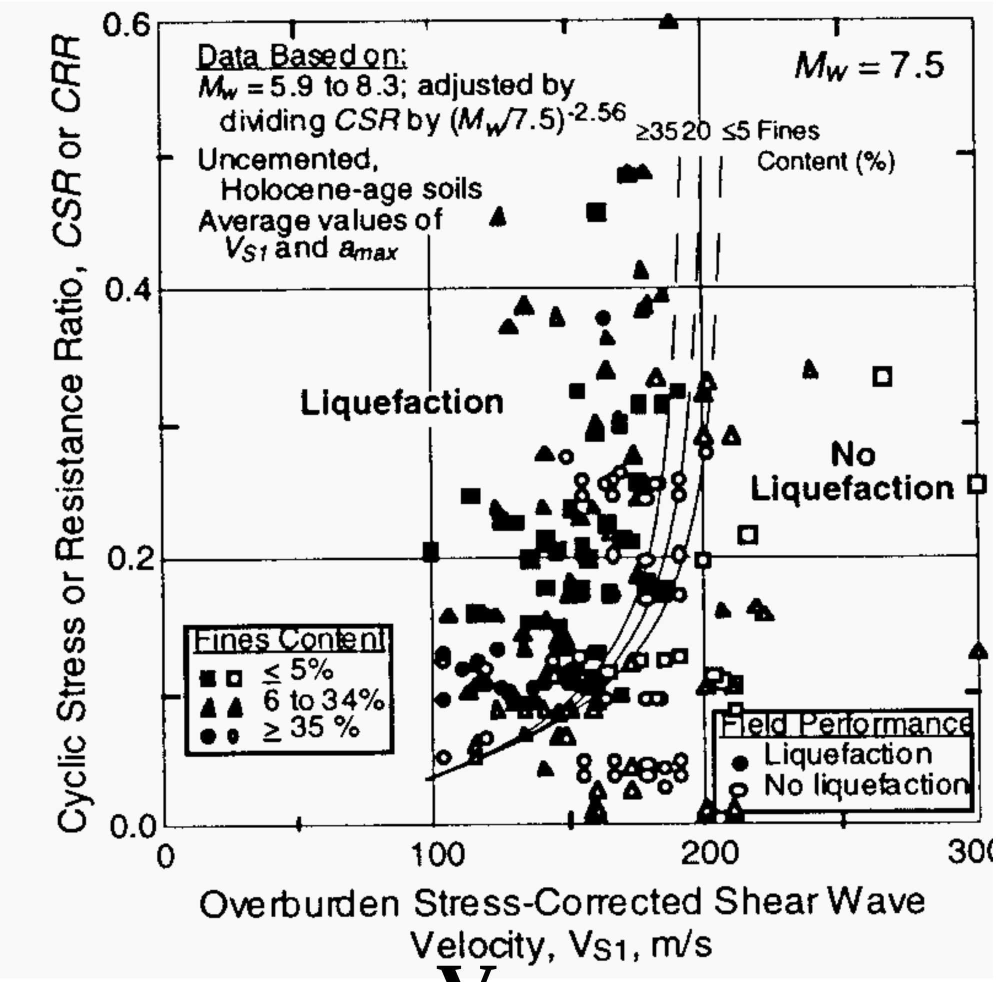
S-Wave Method

CRR



V_{s1}

(Andrus and Stokoe et al. 2000)

LIQUEFACTION SCREENING QUESTIONS

- Why SPT/CPT/V_s charts
  - depend on silt content ?
  - not affected by silt content > 35% ?

- What Controls
  - Penetration Resistance - q_{c1N} and $(N_1)_{60}$?
  - Liquefaction Resistance – CRR ?

- How to account for effects of silt content on CRR – Penetration Resistance Relationships ?

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OBJECTIVES

- Synthesize current knowledge, site observations, and experience in silty soils
- Understand and Contrast Liquefaction of Silty Soils and Sands
- Understand Factors Affecting Penetration Resistances
- Understand relationship between penetration resistance and liquefaction resistance
- Develop Advanced Methods and Guidelines for Liquefaction Screening

Outline

- Experimental Study
  - Effects of fines on Liquefaction Resistance
- Numerical study
  - to simulate cone penetration in a soil
  - to find the effect of hydraulic conductivity (k) and compressibility (m_v) on pore pressures and cone penetration resistance in soils

- Laminar box liquefaction experiments and cone penetration tests (CPT) on clean sands

- Develop Advanced Methods and Guidelines for Liquefaction Screening

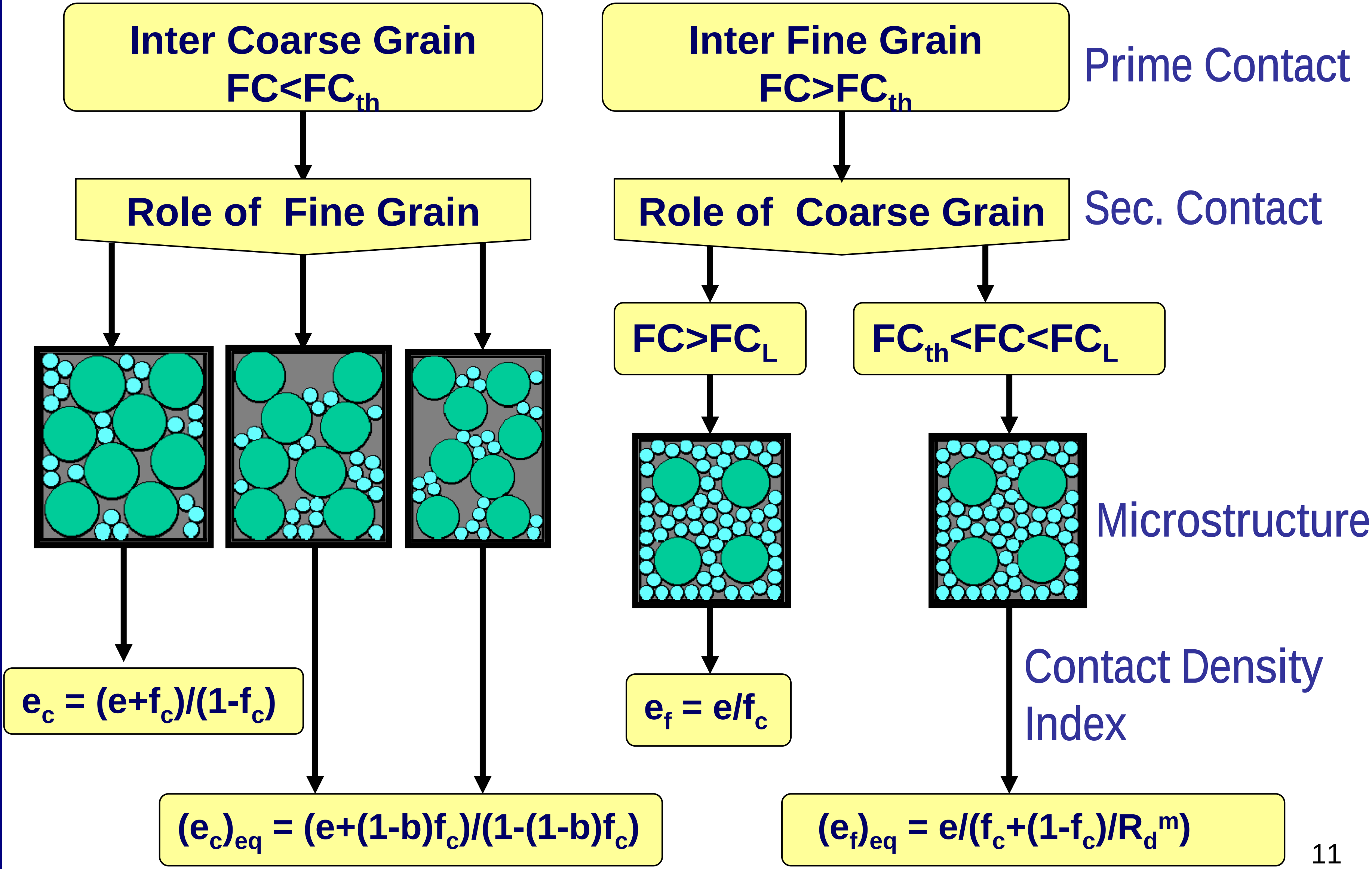
WORKING HYPOTHESIS

- Liquefaction resistance depends primarily on;
  - Inter-grain Contact Density
  - Contact density depends on e and fines content (FC)

- Permeability and compressibility depend on fines content, soil gradation, soil mineral

- Penetration Resistance depends primarily on;
  - Inter-grain Contact Density
  - C_v
  - Instrument Geometry
  - Penetration rate

MIX CLASSIFICATION



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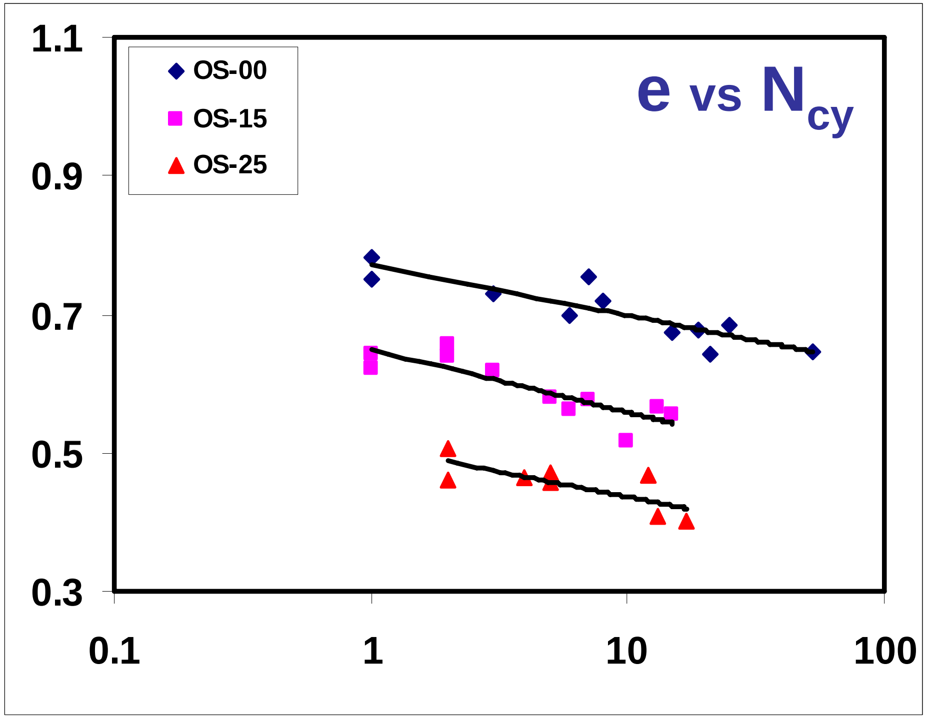
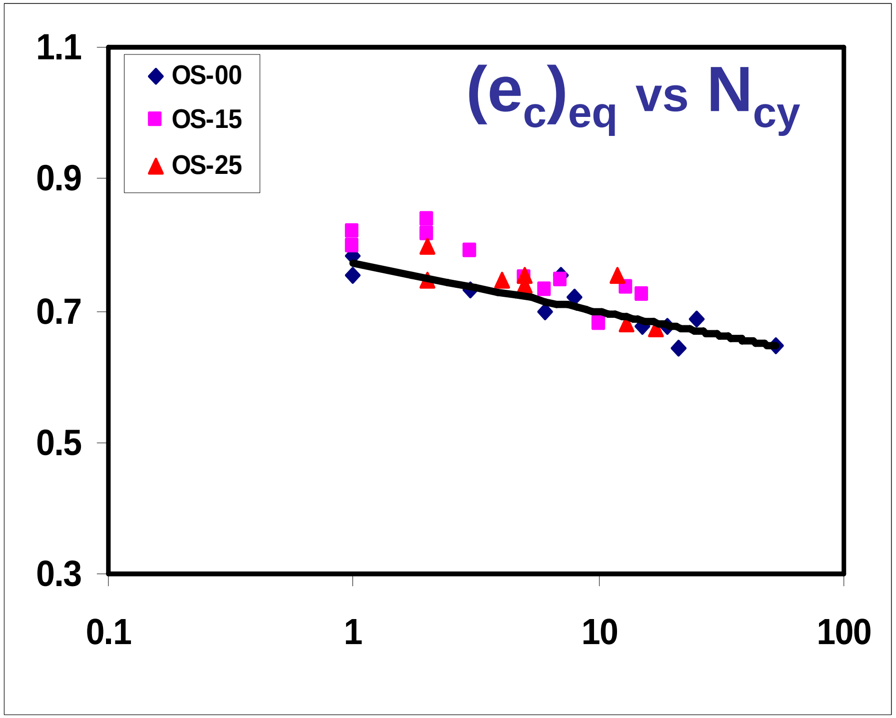
Effect of Fines Content on Cyclic Shear Strength

Silt Content < 25%



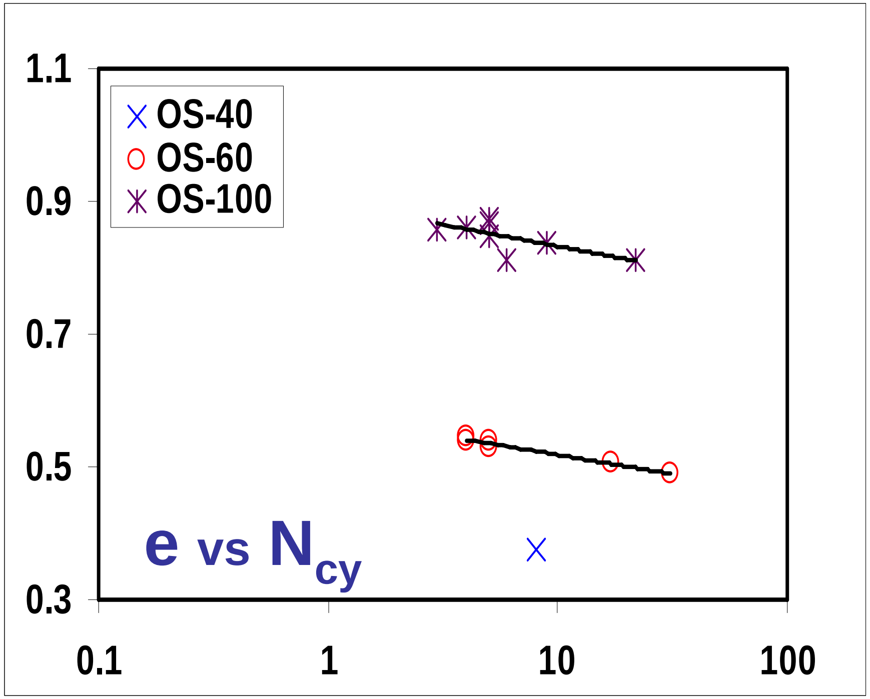


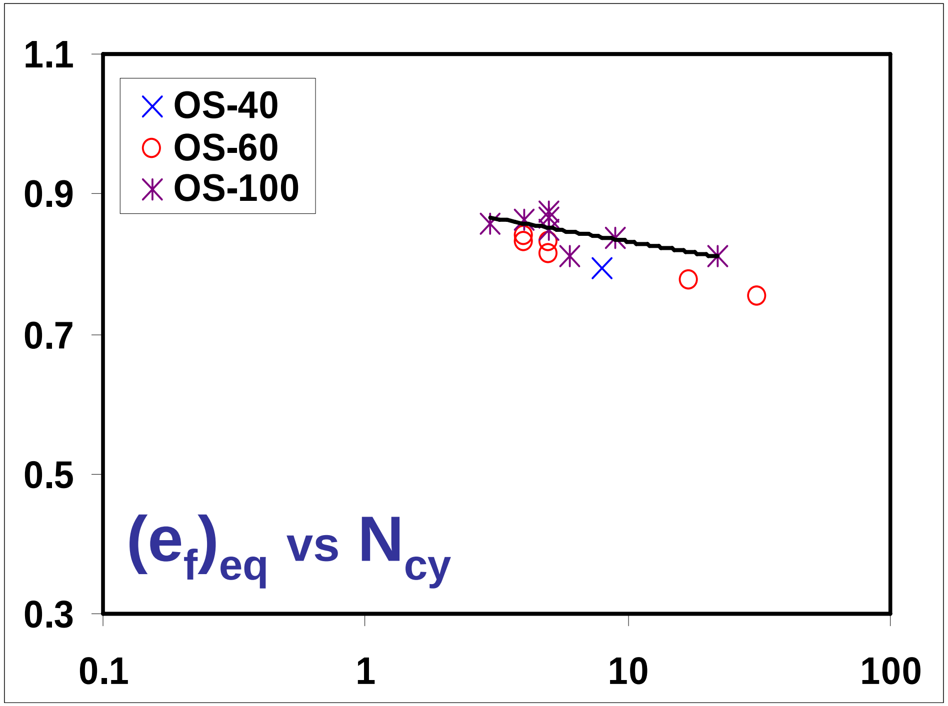
$(e_c)_{eq}$ correlates with N_{cy}

(Thevanayagam et al. 1999, 2001)

Effect of Fines Content on Cyclic Shear Strength

Silt Content > 25%





$(e_f)_{eq}$ correlates with N_{cy}

(Thevanayagam et al. 1999, 2001)

Effect of Fines Content on Strain-Energy

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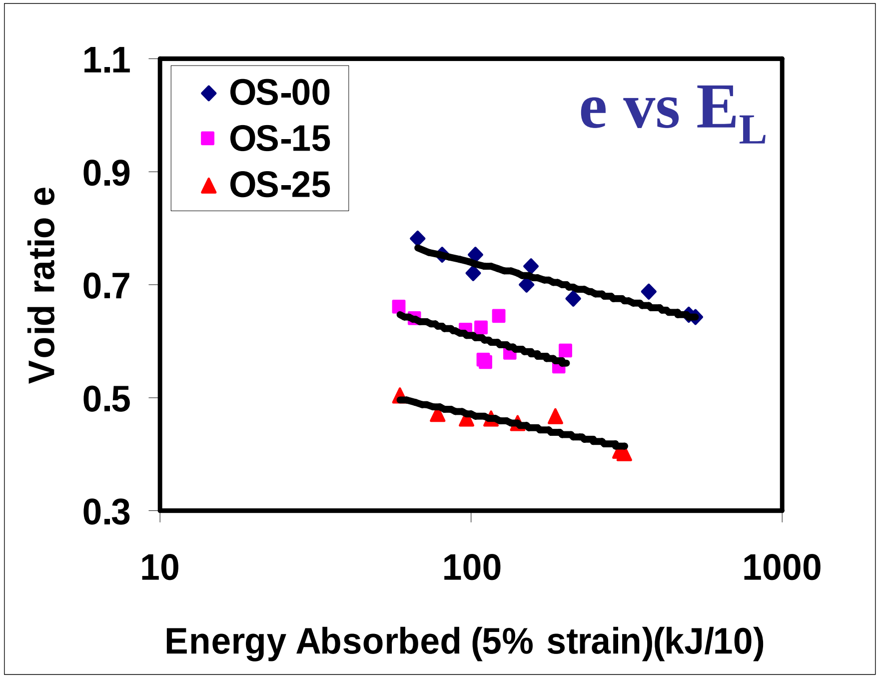
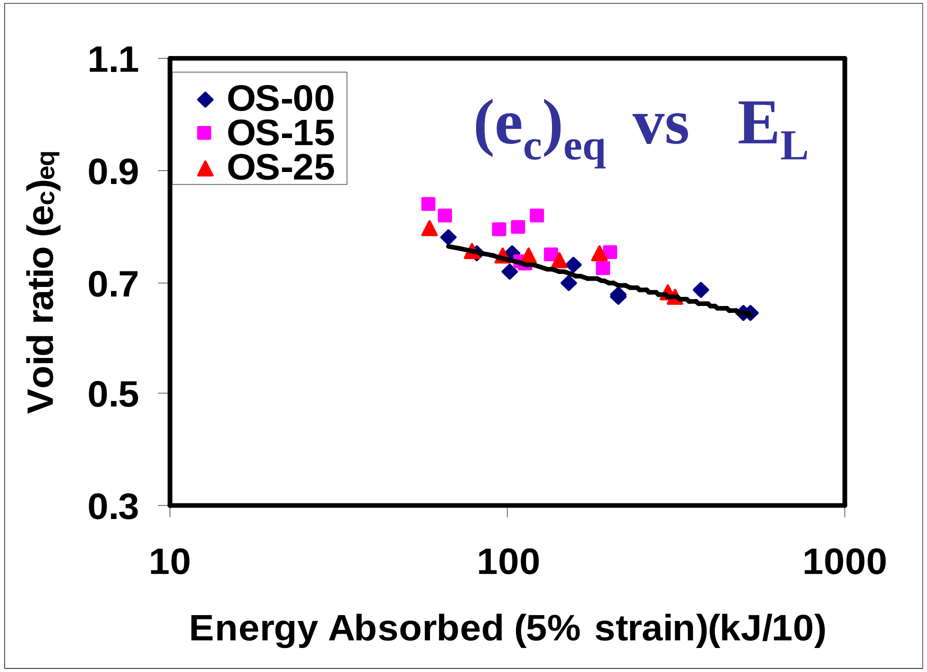
Silt Content < 25%





$(e_c)_{eq}$ correlates with E_L

(Thevanayagam et al. 2003)

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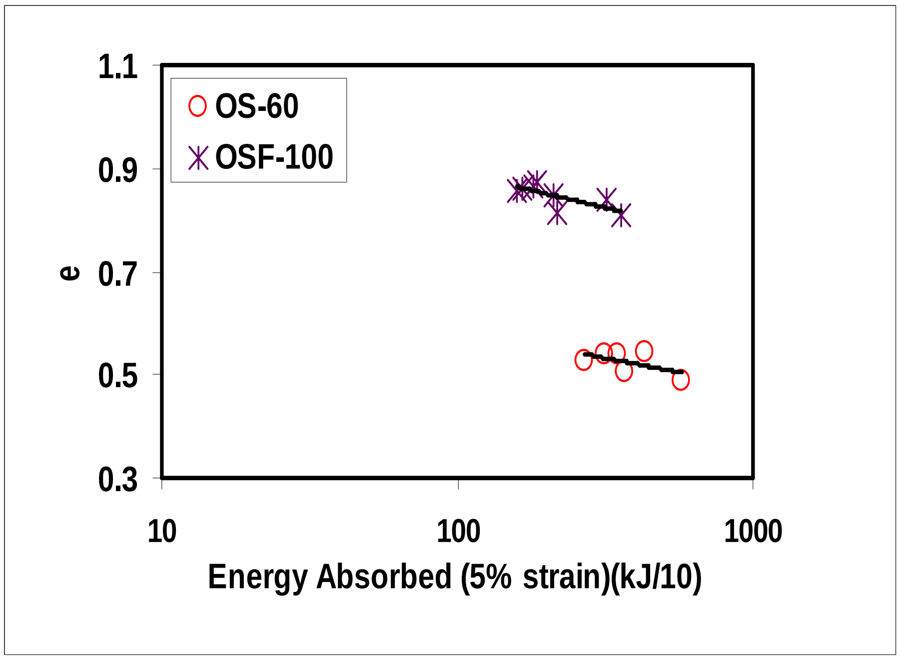
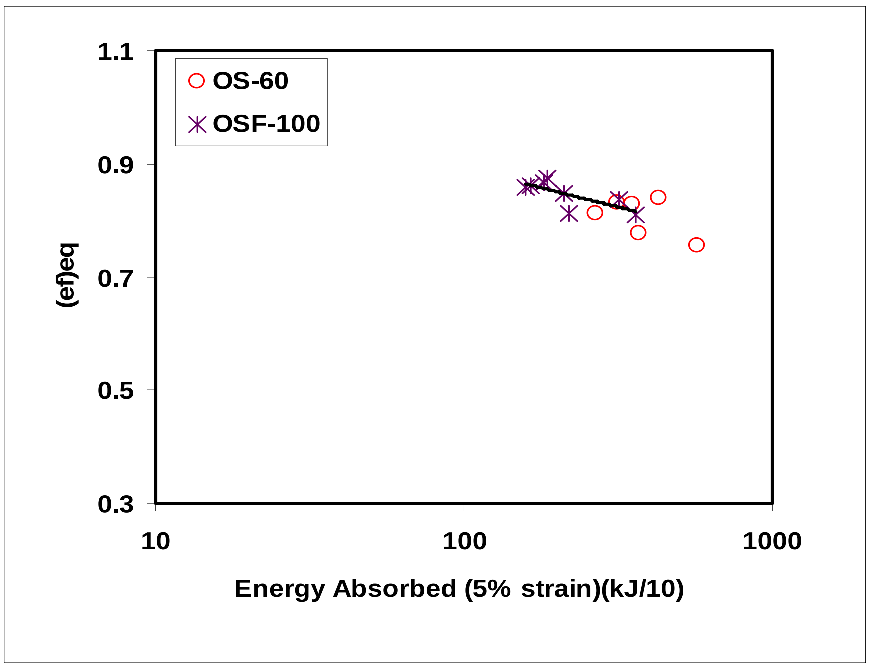
Effect of Fines Content on Strain-Energy

Silt Content > 25%





$(e_f)_{eq}$ correlates with E_L

(Thevanayagam et al. 2003)

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Working Hypothesis

- Liquefaction resistance depends primarily on;
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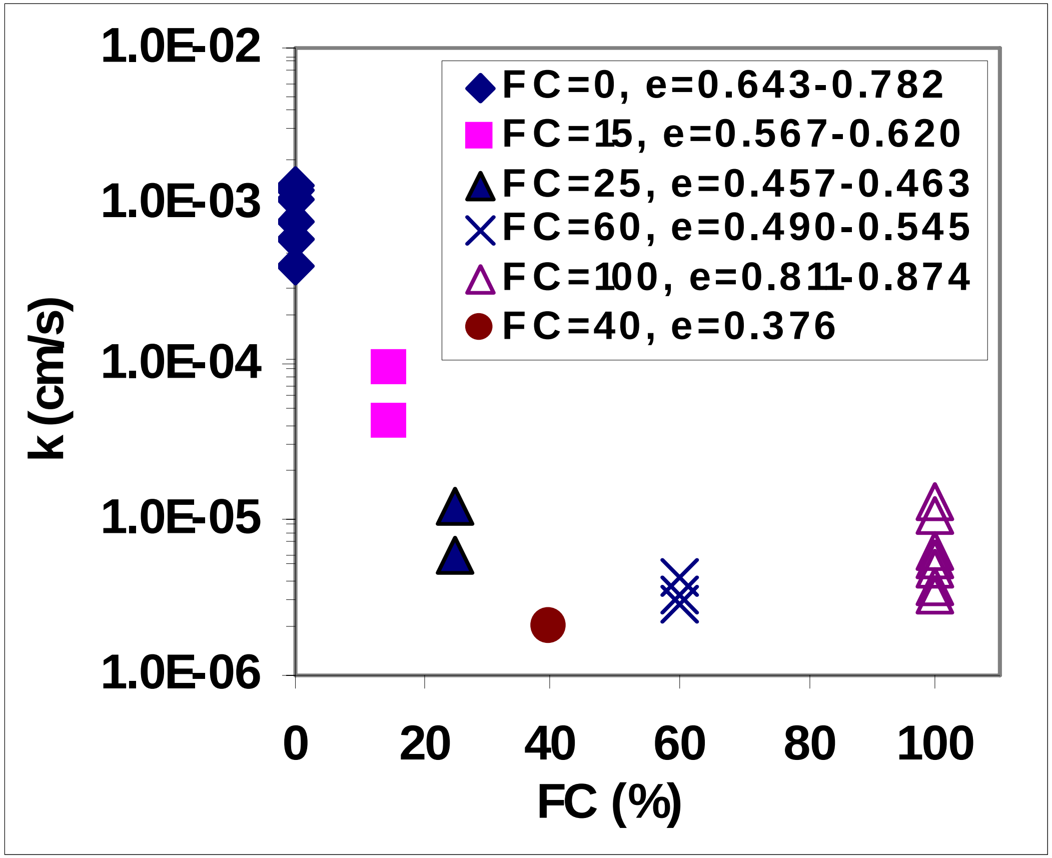
- Permeability and compressibility depend on silt content, soil gradation, soil mineral

- Penetration Resistance depends primarily on;
  - Inter-grain Contact Density
  - C_v
  - Instrument Geometry
  - Penetration rate

Permeability (k)



(Thevanayagam and Martin, 2001)

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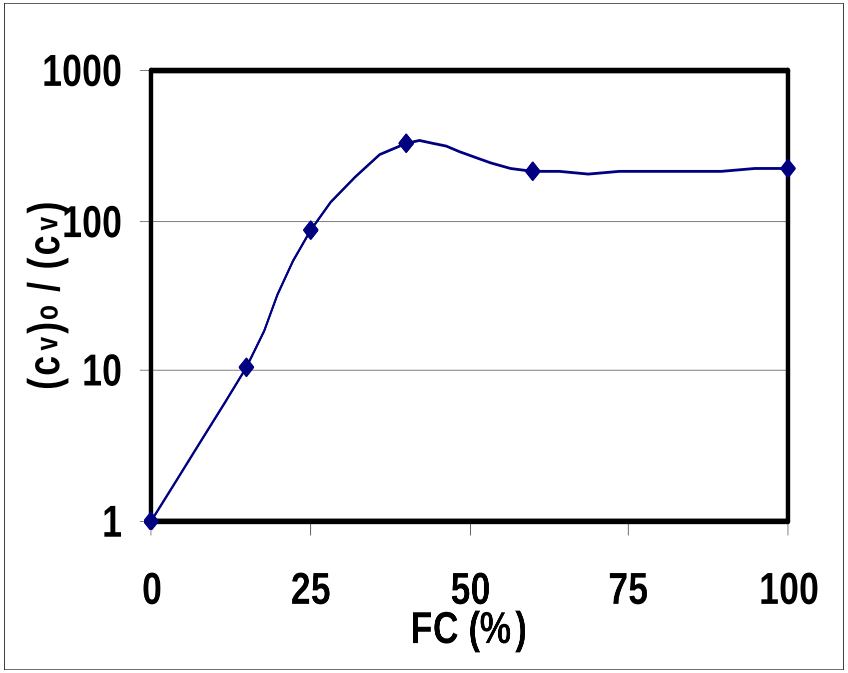
Coefficient of Consolidation (c_v)



(Thevanayagam and Martin, 2001)

C_v →
- Decreases up to FC_{th}, about 30-40% Silt content
- Unaffected by Silt content > FC_{th}
- Not much dependent on contact density

Findings

At the same contact density indices between sand and silt-mixes;

- Some difference in compressibility (m_v)
- Major difference in coefficient of consolidation (c_v) and permeability (k)

↓

C_v depends on FC and k

(Thevanayagam and Martin, 2001)

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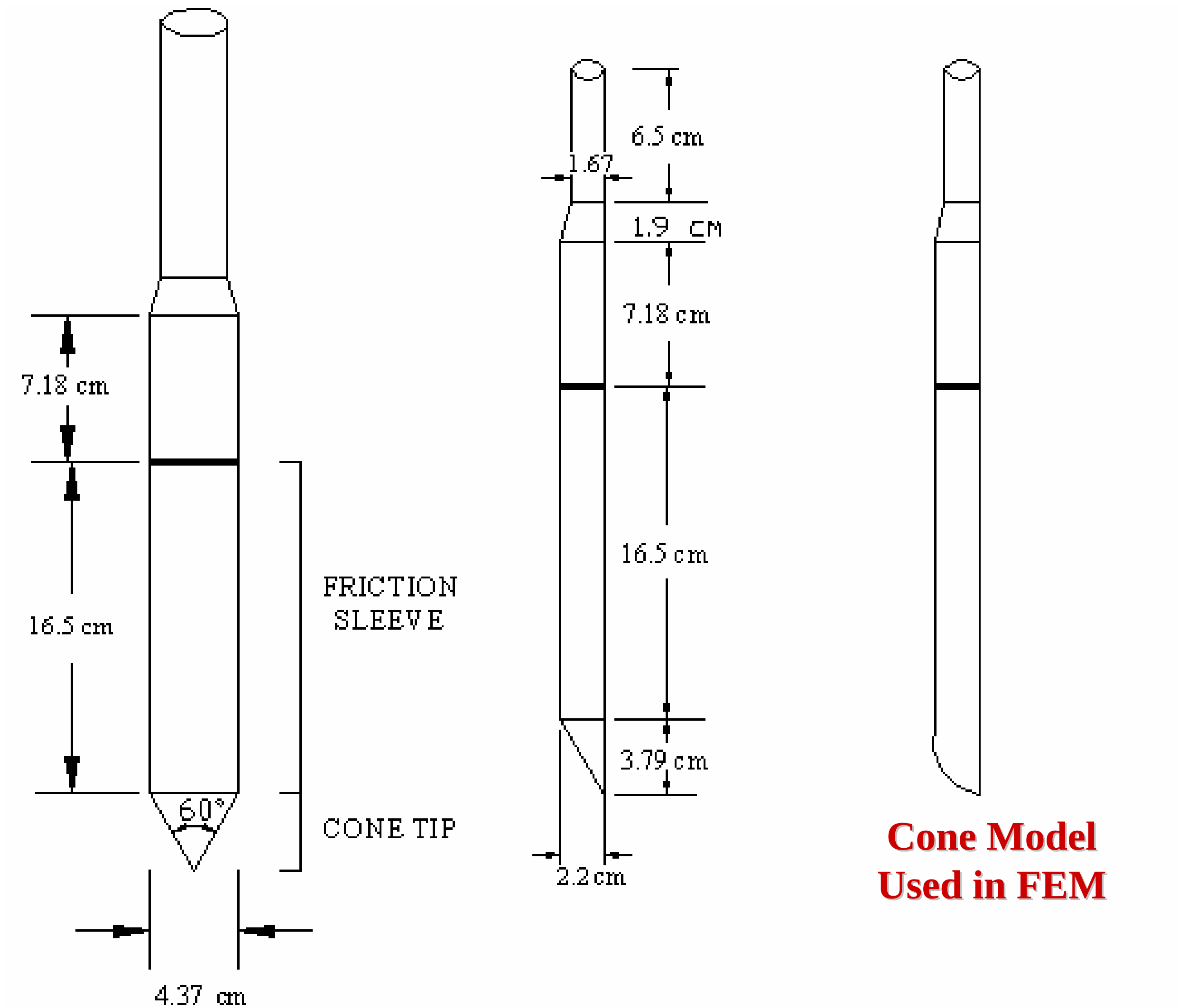
Effects of permeability and compressibility on

- Excess Pore Pressure response around the cone tip
- Cone penetration resistance

Cone Model Used in FEM



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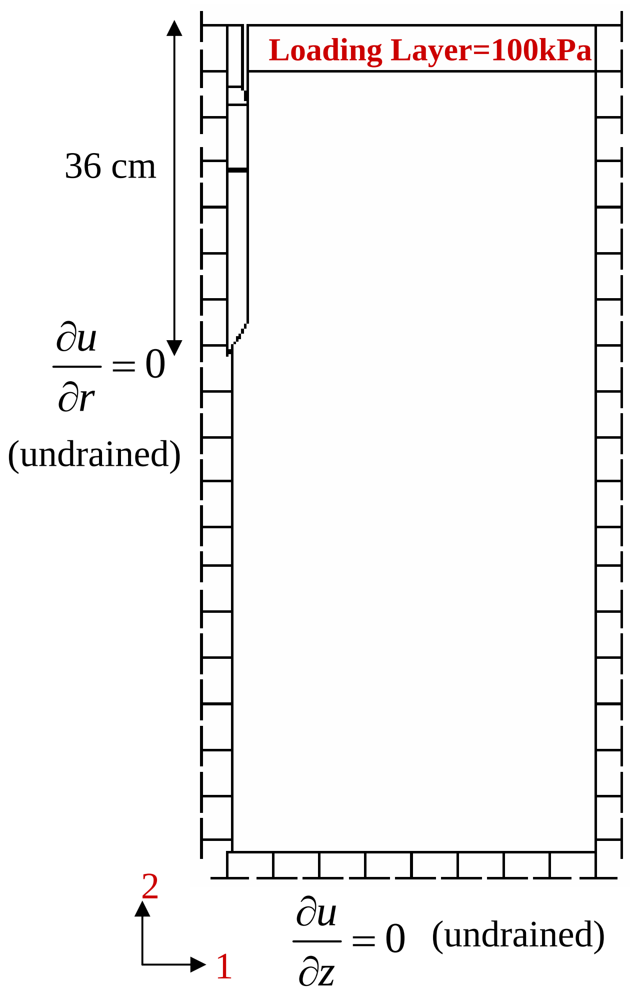
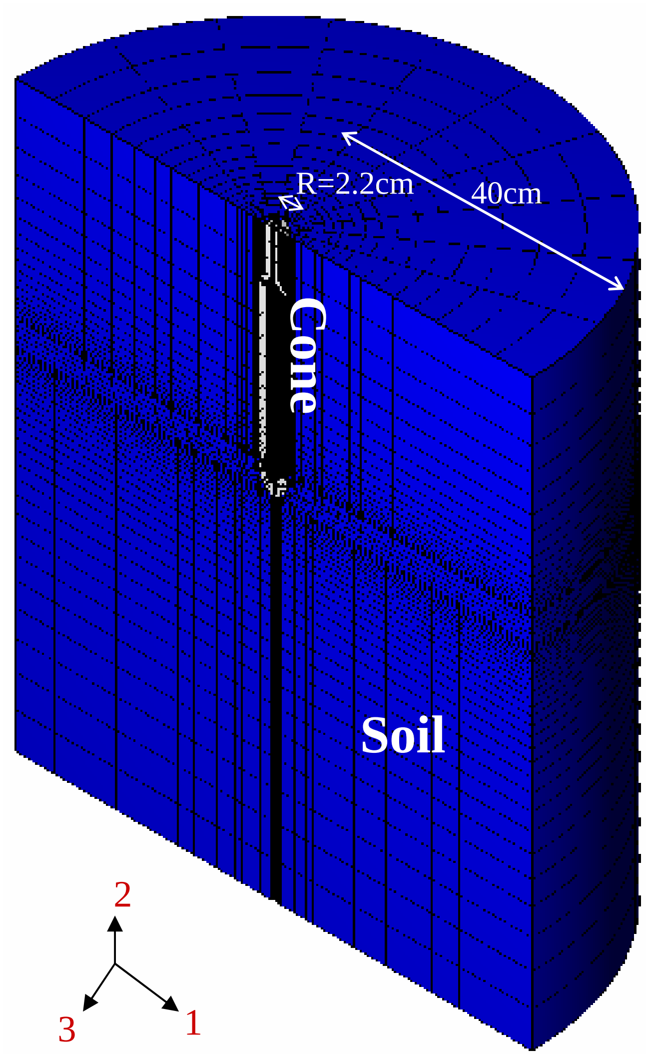
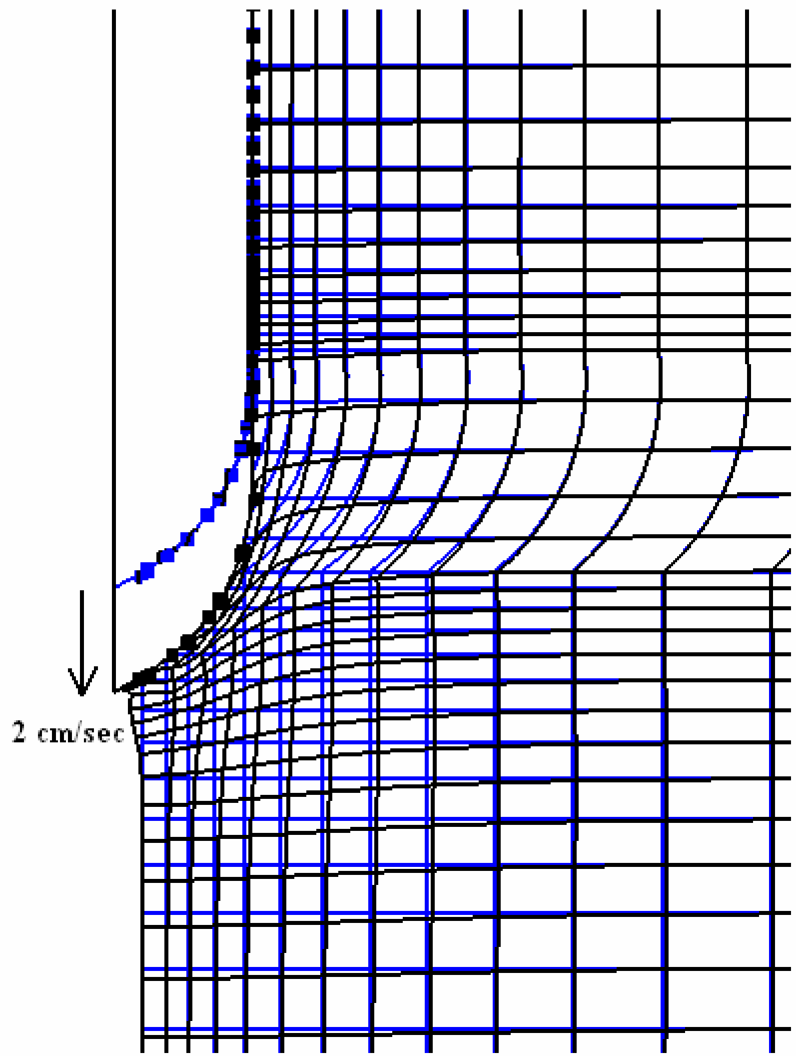
FEM Mesh



Penetration rate=2cm/sec

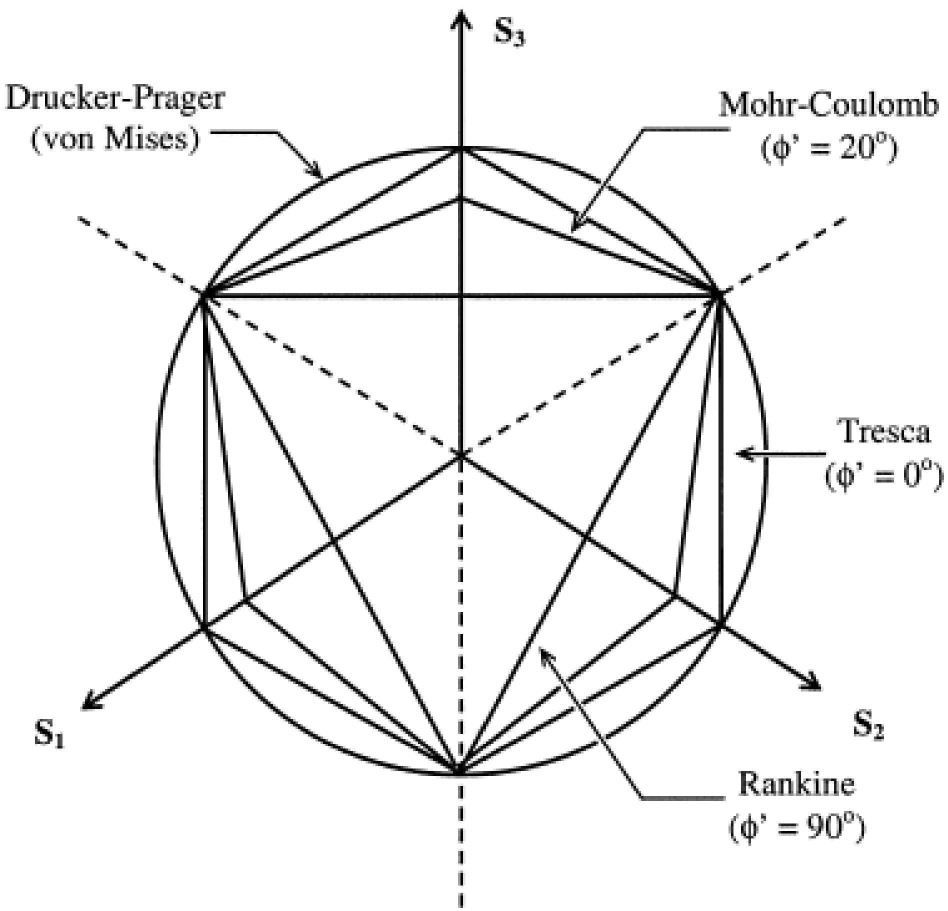


Finite Element Model



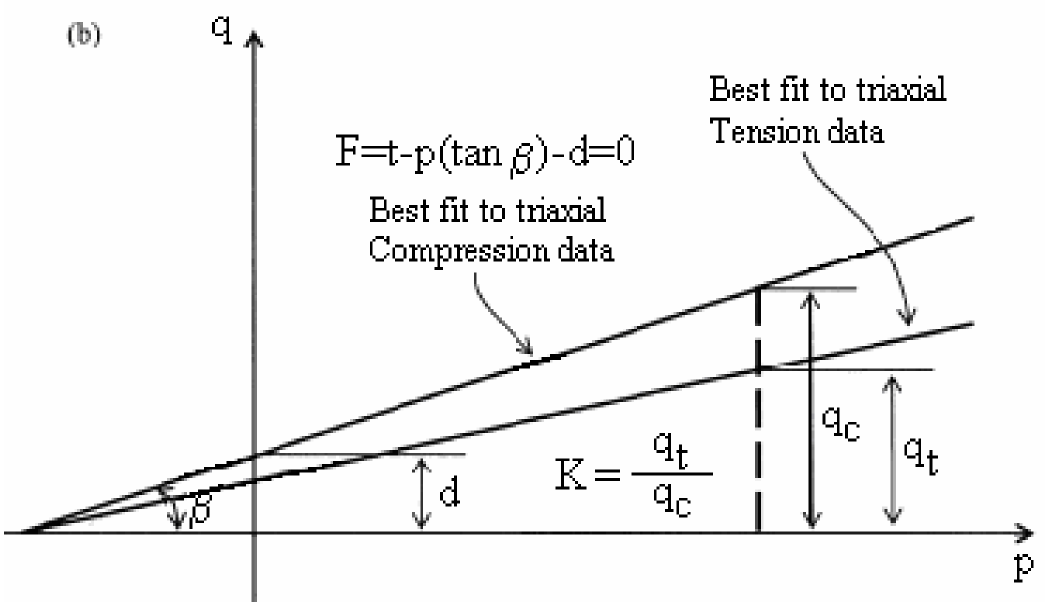
- Penetration rate 2 cm/s
- The area close to cone tip is under very large strain. Therefore to model the soil, a non-linear material constitutive model is used.

Soil Model (Drucker-Prager Model)



- **Elastic Paramaters**
- **Yield Criterion**
- **Hardening Rule**

Soil Model (Drucker-Prager Model)



$$F = t - (p \tan \beta) - d = 0$$

$$t = \frac{1}{2} q \left[1 + \frac{1}{K} - (1 - \frac{1}{K})(\frac{r}{q})^3 \right]$$

$$q = \tau_{oct} = \sqrt{\frac{2}{9}(I_1^{\,2} + 3I_2)} = \sqrt{\frac{2}{3} J_2}$$

$$p = \sigma_{oct} = \frac{1}{3} I_1$$

Model parameters obtained from undrained monotonic triaxial tests.

Time Stepping and Accuracy

- Step 1: Equalizes geostatic loading
- Step 2: Small time increments for non-linear analysis

$$\Delta t \geq \frac{1}{6}\frac{(\Delta l)^2}{\theta c}$$

(Vermeer and Verruijt 1981)

Δt=Time increment

Δl=Typical element dimension

θ=represents the type of approximation chosen for the behavior of the excess pore pressure

c=coefficient of consolidation

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Normalized Penetration Rate (T) – Dependent Excess Pore Pressures and Cone Resistance

$$T = \frac{vd}{c_h}$$

- v = penetration rate (2cm/s : ASTM D3441)
- d = cone diameter (instrument geometry)
- c_h= coefficient of consolidation

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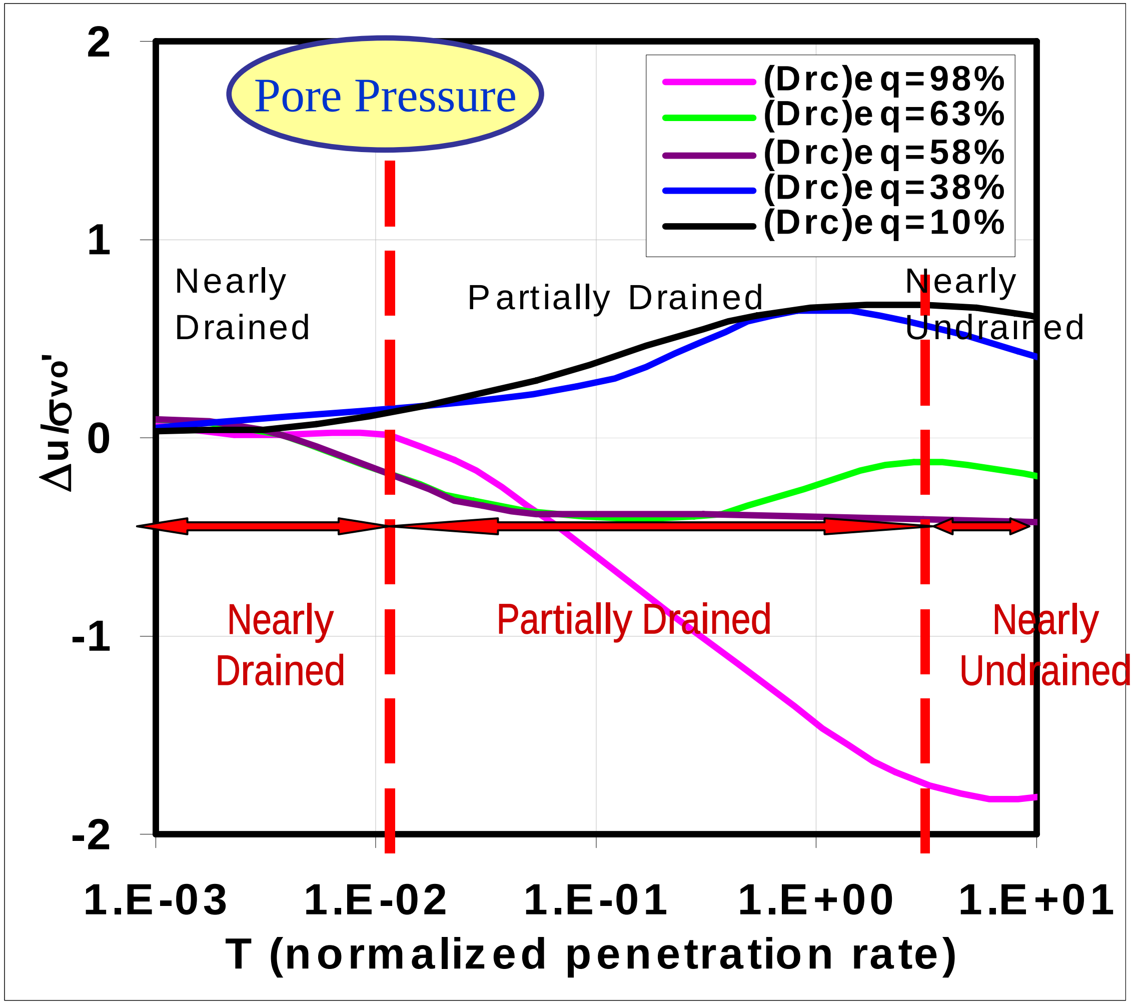
$\Delta u/\sigma_{vo}'$ vs normalized penetration rate



- Nearly '<u>drained</u>' response at Low T values (sands)
- <u>Partial</u> drainage around the cone at intermediate T (low silt content)
- Nearly '<u>undrained</u>' response at high T values (high silt content)

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Preliminary Analysis

Effect of k and C_v on excess pore pressure contours around the cone tip

- $(D_{rc})_{eq}$= 45%, $k=10^{-3}$ m/s → Dr=45%_k=10-31.wmv
- $(D_{rc})_{eq}$= 45%, $k=10^{-5}$ m/s → Dr=45%_k=10-51.wmv
- $(D_{rc})_{eq}$= 45%, $k=10^{-7}$ m/s → Dr=45%_k=10-71.wmv

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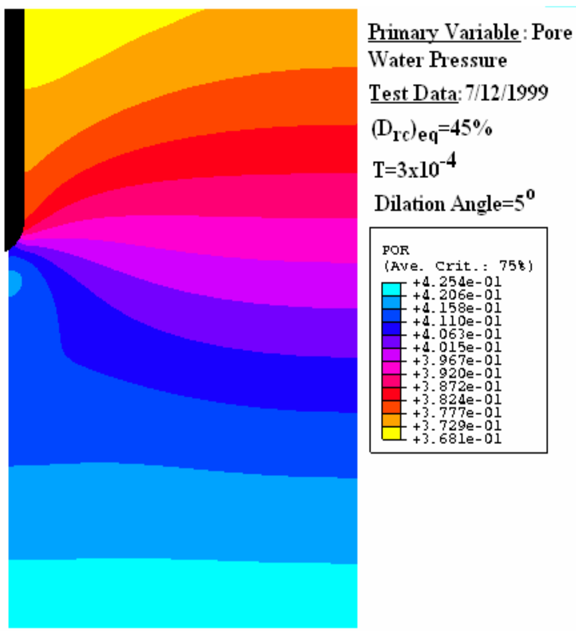
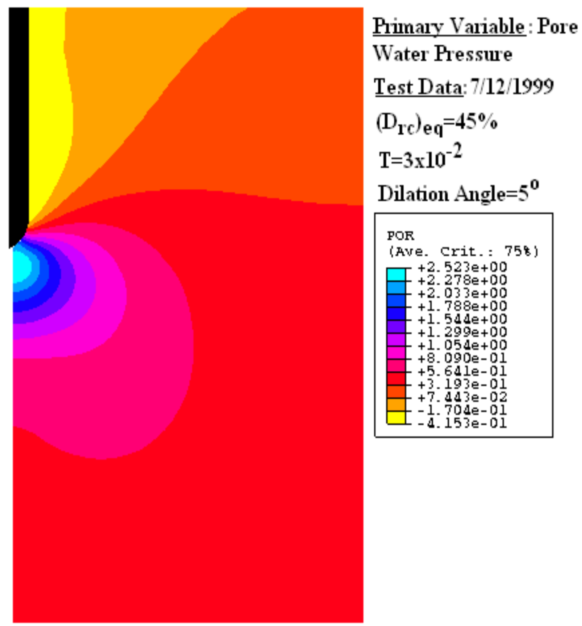
Effect of "T" on Pore Water Pressure

Same material properties for all, but k was varied from 10^{-3} to 10^{-7} m/s

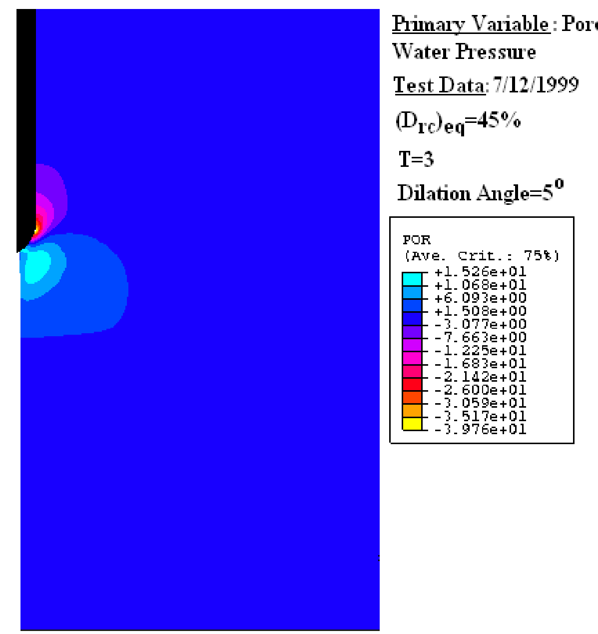
Pwp changed from negligible (drained) to significant (undrained)



T=3x10^{-4} (k=10^{-3} m/s)



T=3x10^{-2}, k=10^{-5} m/s



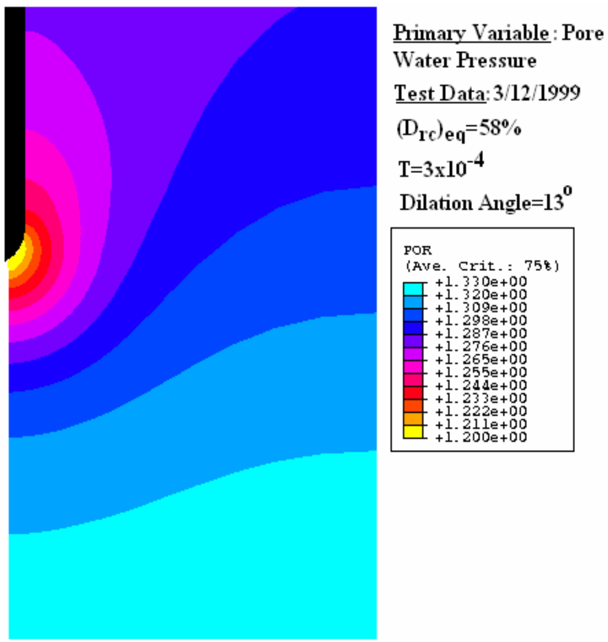
T=3, k=10^{-7} m/s

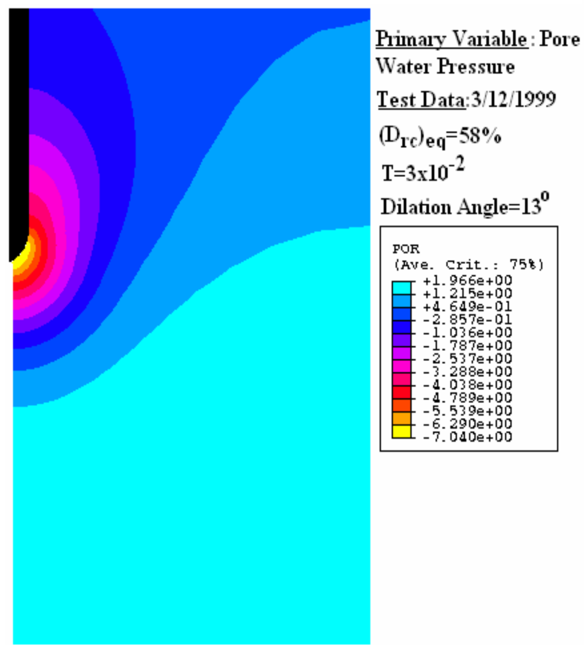
$(D_{rc})_{eq}$= 45%

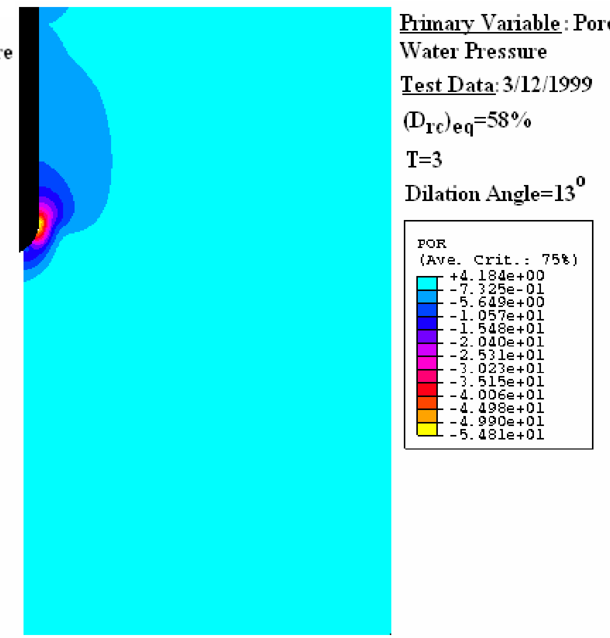
Effect of “T” on Pore Water Pressure

Same material properties for all, but k was varied from 10^{-3} to 10^{-7} m/s

Pwp changed from negligible (drained) to significant (undrained)







$T=3x10^{-4}$ ($k=10^{-3}$ m/s) | $T=3x10^{-2}$, $k=10^{-5}$ m/s | $T=3$, $k=10^{-7}$ m/s

$(D_{rc})_{eq}= 58\%$

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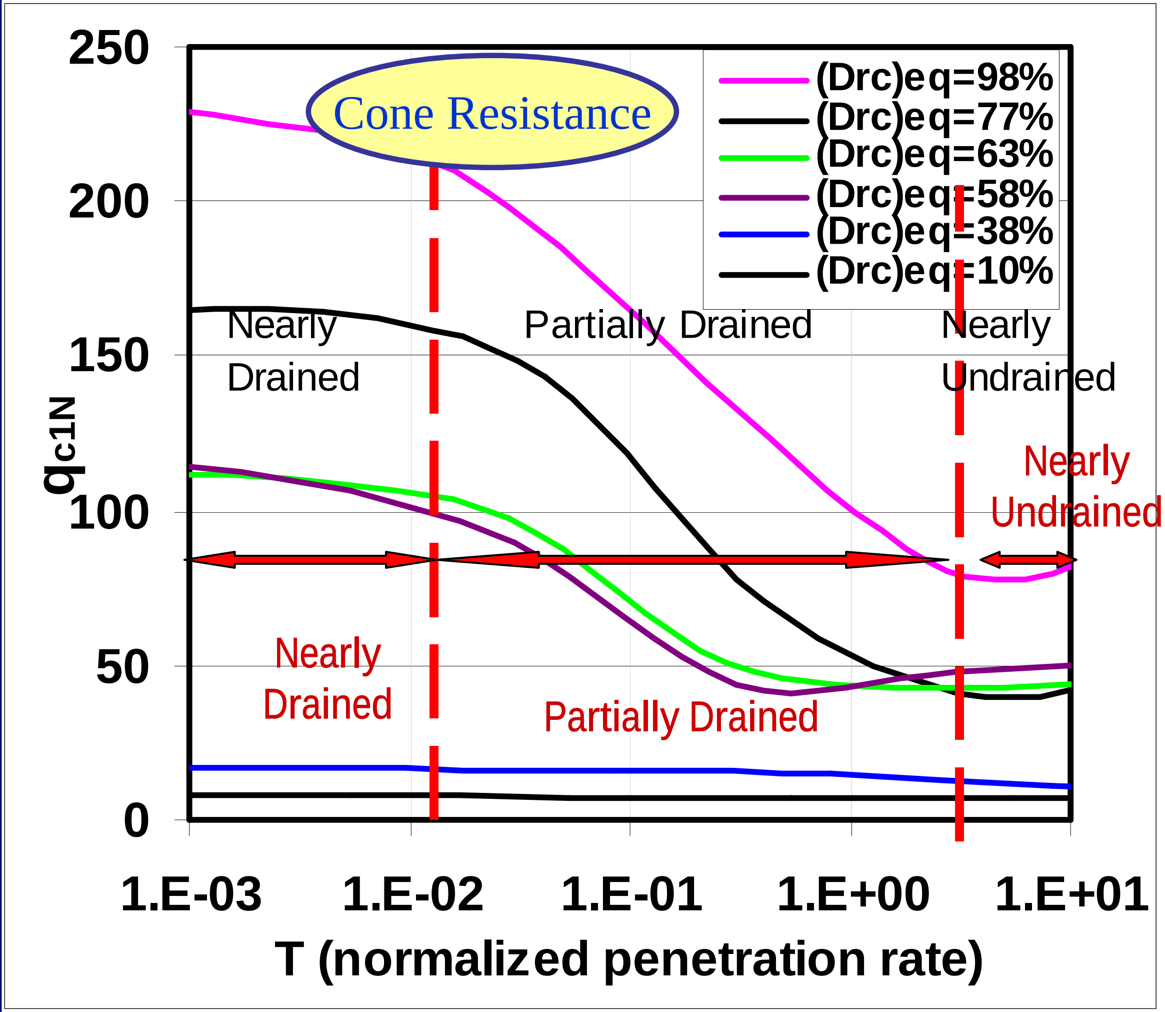
q_{c1N} vs normalized penetration rate



- Nearly '<u>drained</u>' response at Low T values (sands)
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Effects of fines content on

- $(CRR)_{field}$ versus Cone Penetration Resistance
- E_L/σ_c' versus Cone Penetration Resistance

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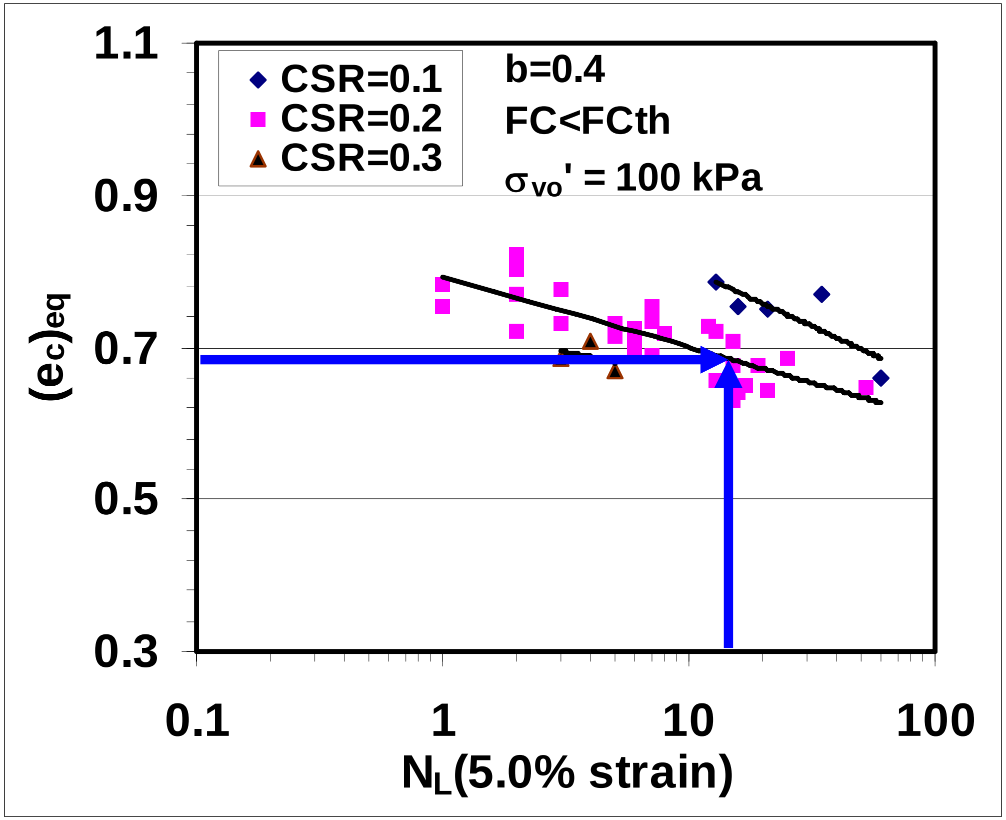
From Experimental Work



$(e_c)_{eq}$ & for 15cycles

↓

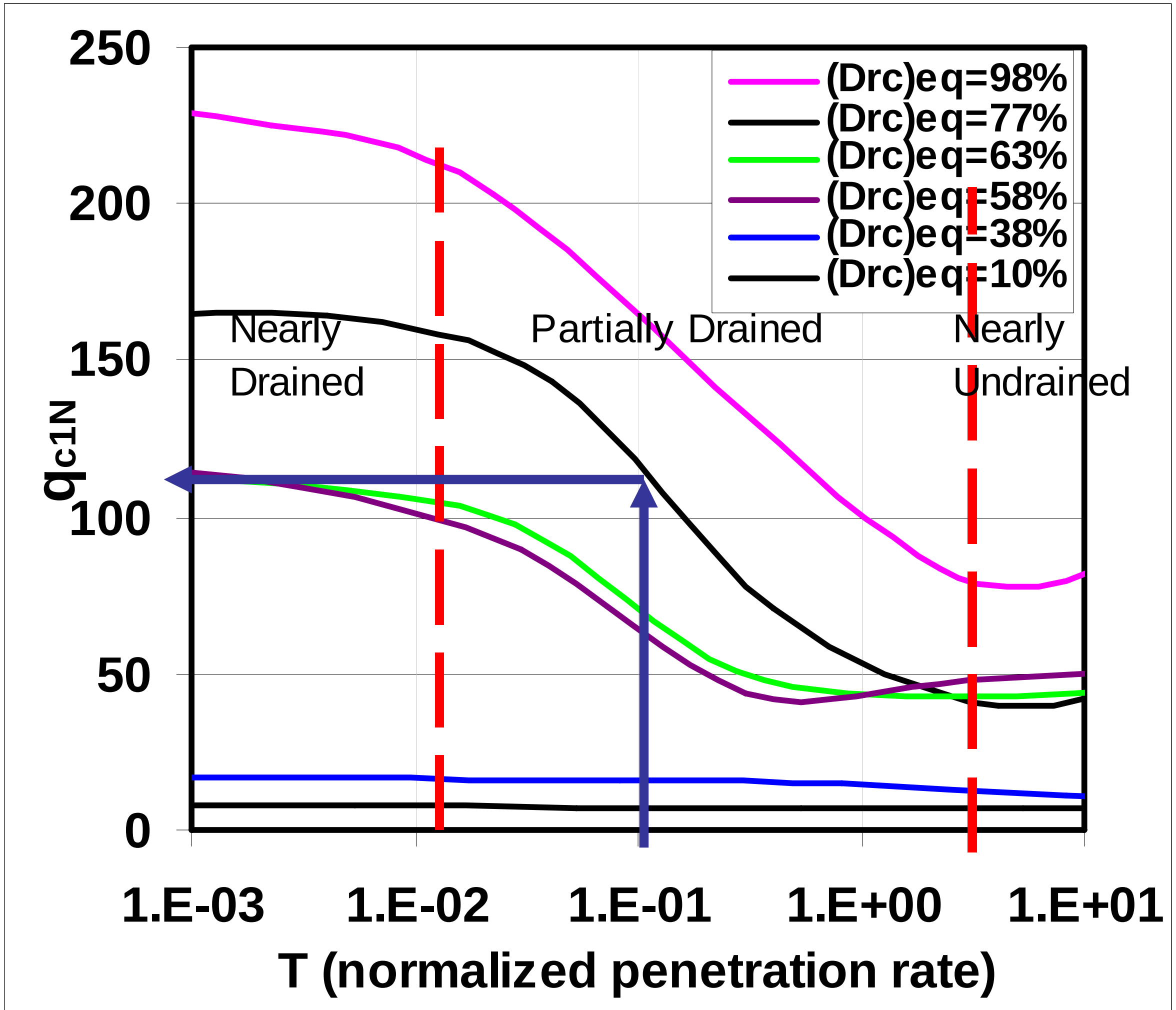
$(CRR)_{tx}$

↓

$$(CRR)_{field} = 0.9\frac{2(1+2K_o)}{3\sqrt{3}}(CRR)_{tx}$$

(Source : Castro (1975), Seed et al. (1978))

From Numerical Work

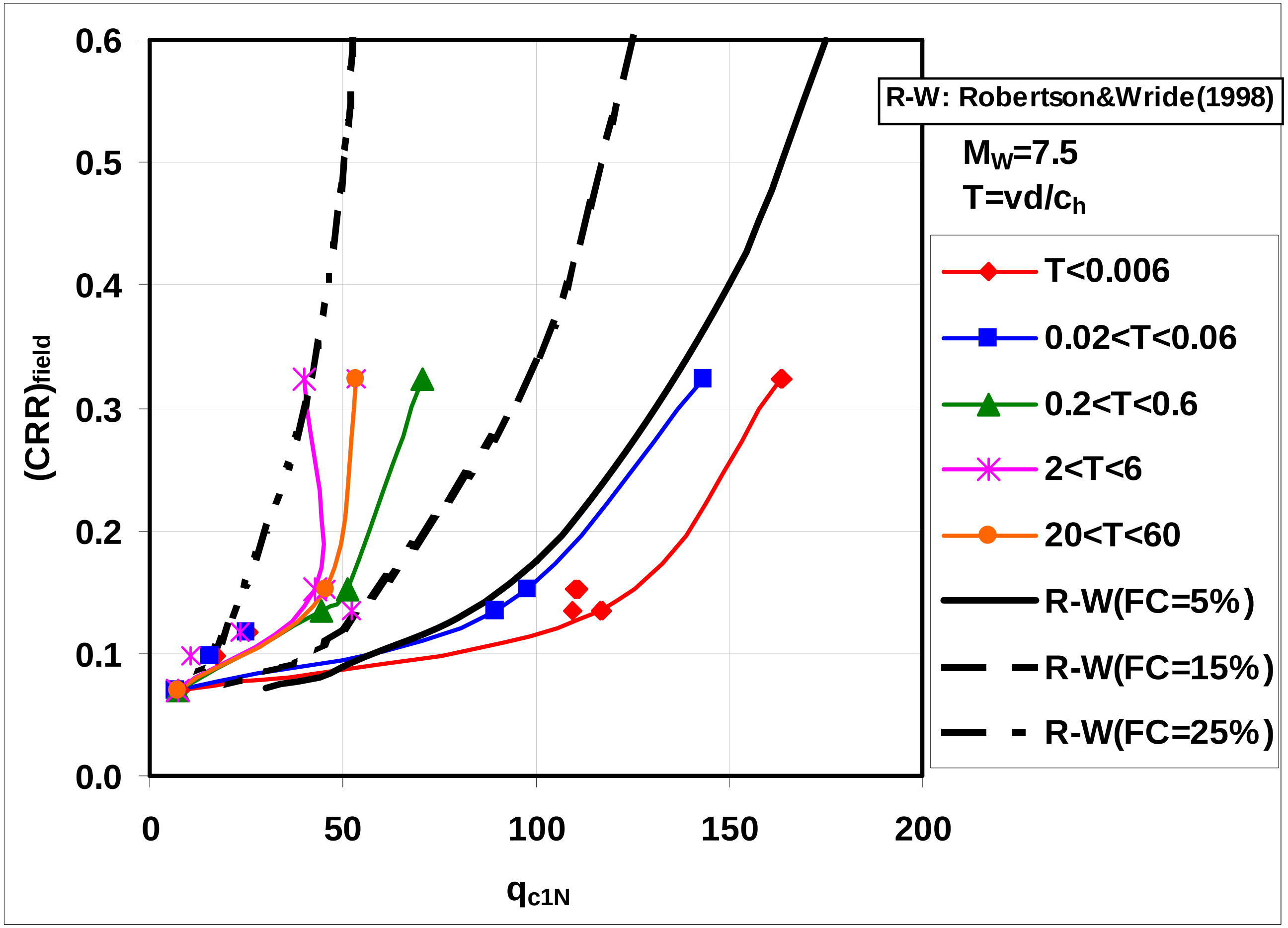


T & **for** $(D_{rc})_{eq}$

↓

q_{c1N}

Proposed Liquefaction Screening Based on CRR, q_{c1N} and T



$$T \uparrow = \frac{vd}{c_h \downarrow}$$

FC ↑

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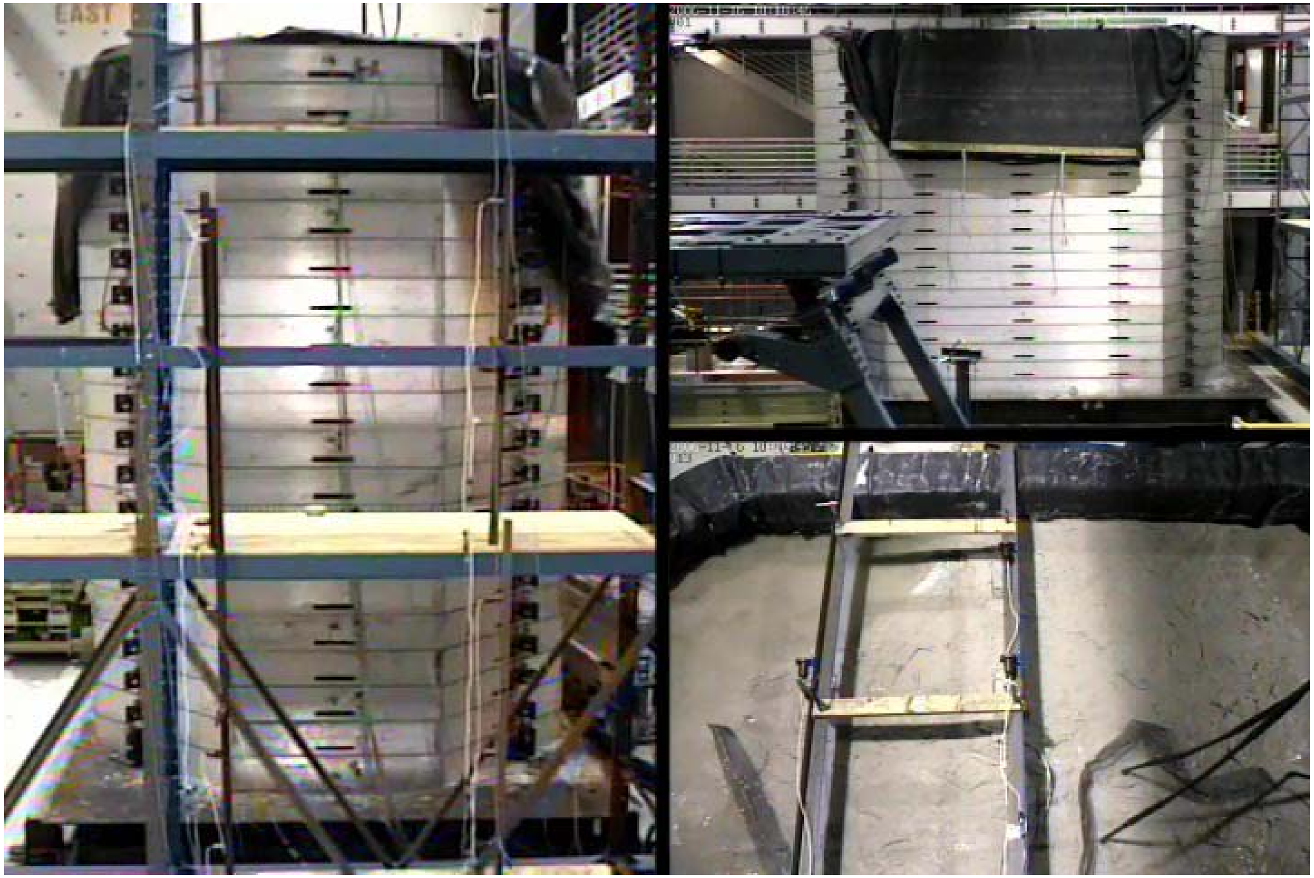
Large Scale Liquefaction Test
- Test LG0

(For video, click https://central.nees.org/?projid=122&loc=Public#)

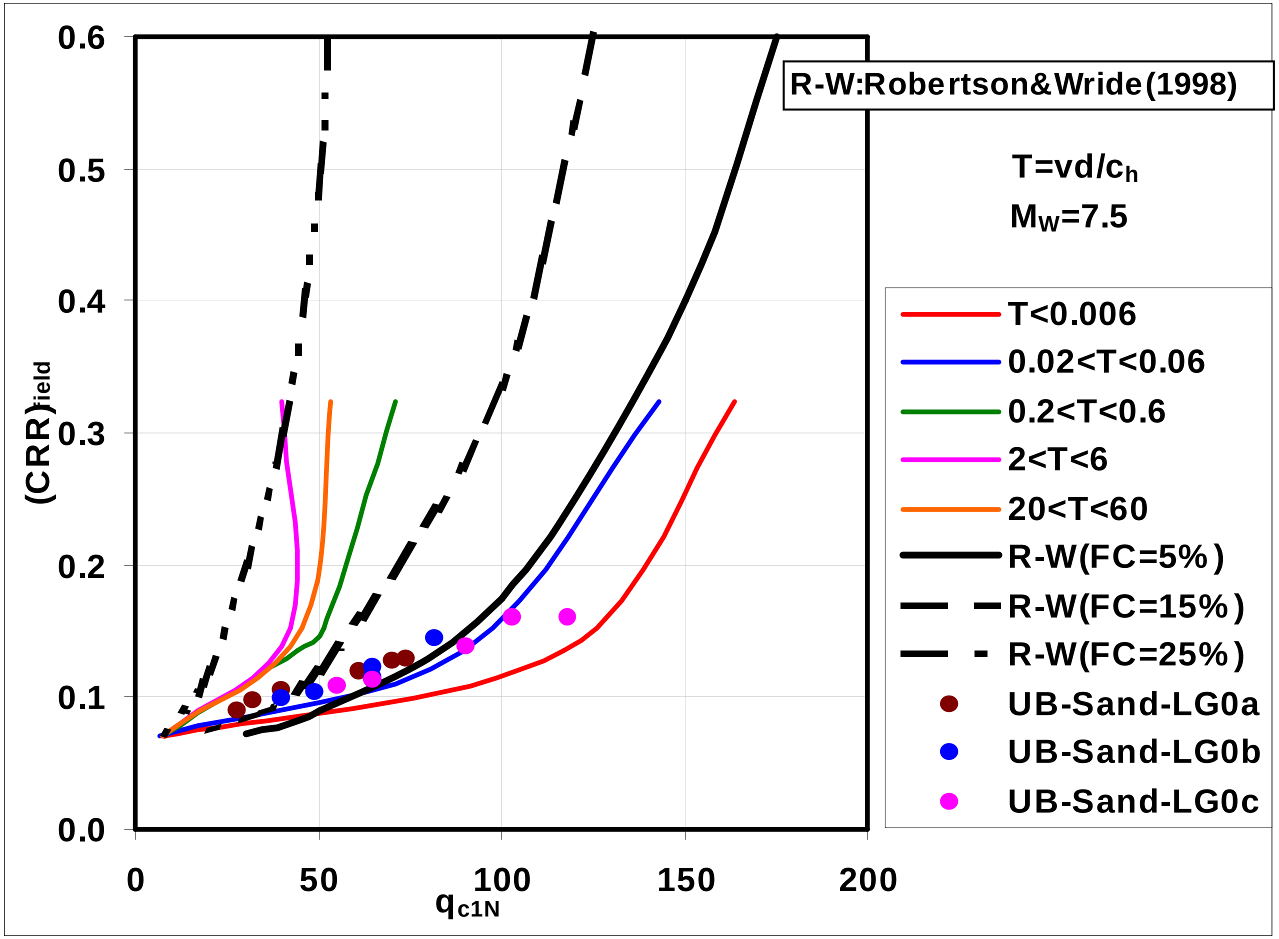


CPT tests before shaking tests

Shake tests to Liquefy soil

Compare CPT resistance to Liquefaction Resistance

$(CRR)_{field}$ - q_{c1N} – T Relationship



FINDINGS

1. CRR depends on Intergrain Contact Density
   - Contact density depends on e and silt content

2. Penetration Resistance depends primarily on
   - Intergrain Contact Density
   - Normalized Penetration Rate (T)
     - c_h
     - Instrument Geometry
     - Penetration rate

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FINDINGS

3. CRR versus Penetration Resistance is Dependent on

   - c_h, Cone geometry, size, and Penetration rate

4. CRR correlates with $\mathbf{q_{c1N}}$ & T

   - $T = vd/c_h$
   - c_h depends on silt content (and characteristics) and decreases up to a silt content of about 30-40%

5. CRR - q_{c1N} - T correlation is more rational than a mere silt-content dependent CRR-q_{c1N} – FC correlation, but requires further field validation and refinement

THANK YOU
Questions..?