Lecture #2a
Soil Liquefaction & Liquefaction Screening

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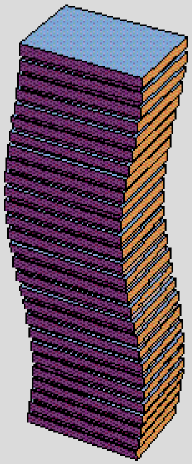
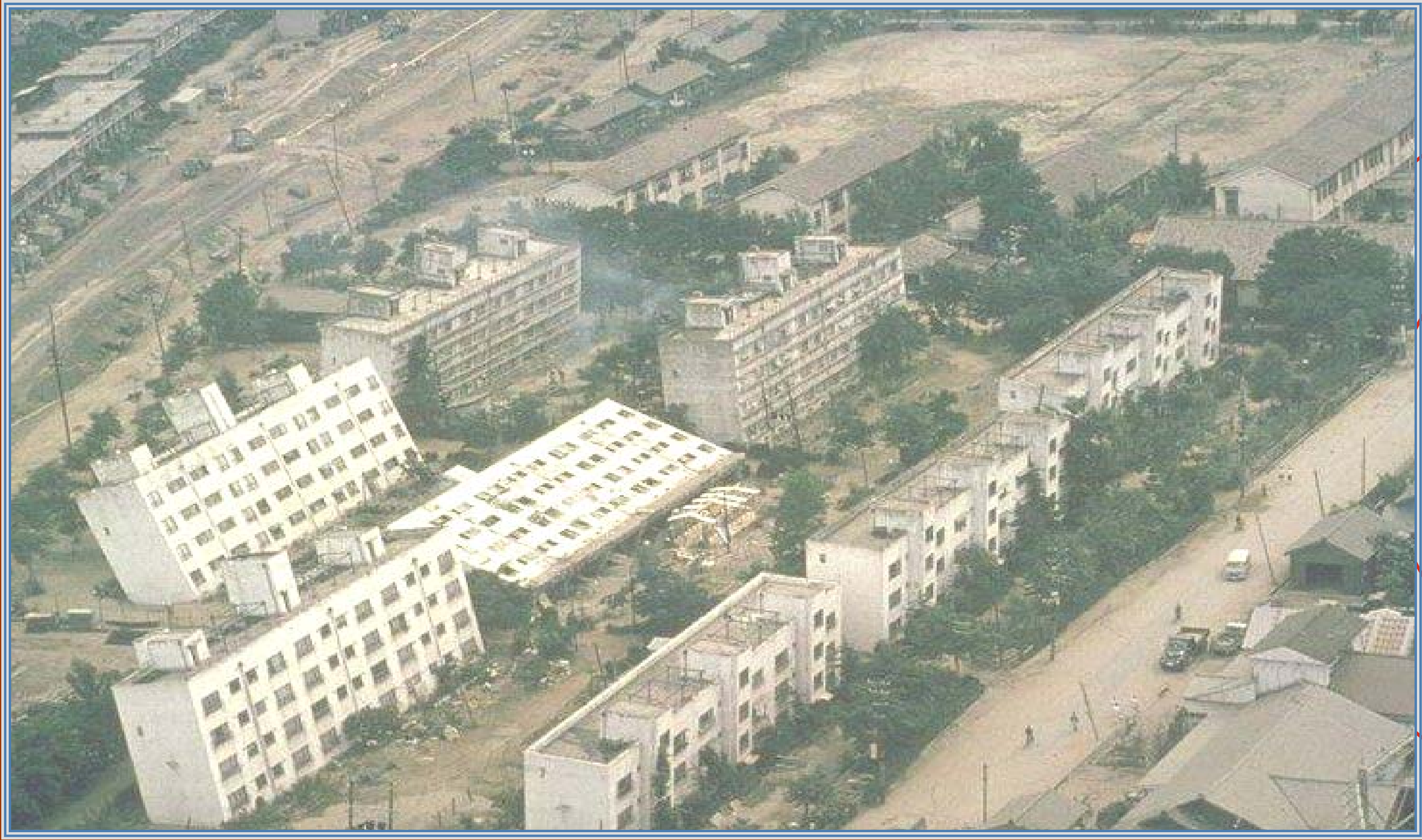
Organized by Prof. A. Balasubramaniam

Presentation Overview



1. Case Histories
2. Liquefaction Phenomena
3. Cyclic Strength
4. Evolution of Liquefaction Screening
5. Current Screening Methods
6. Limitations



Bearing Capacity Failure of Kawagishi-cho Apartments

1989 Loma Prieta Earthquake, USA

Sandboils in the Bay Area

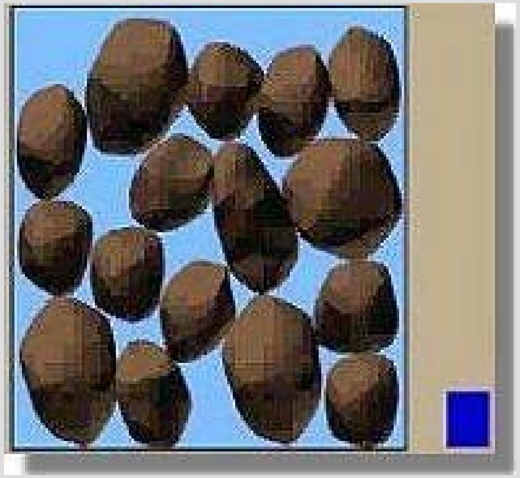
1995 Kobe Earthquake, Japan

Collapse of Hanshin Express way

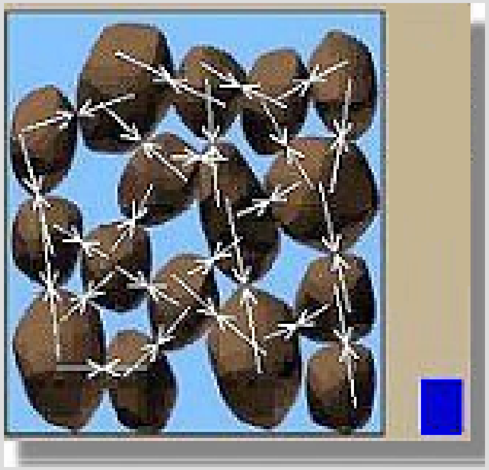
1995 La Conchita Flow Landslide, California

Flow Liquefaction Failure

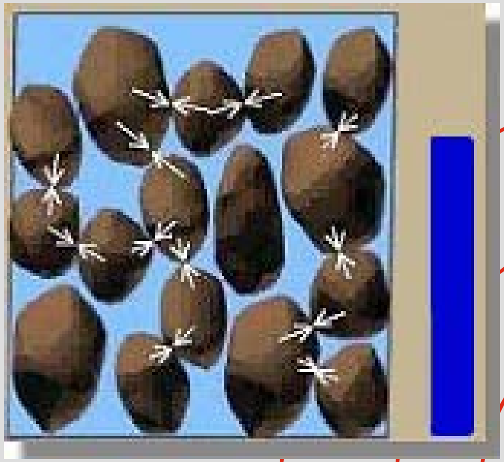
Liquefaction



Soil particles before liquefaction



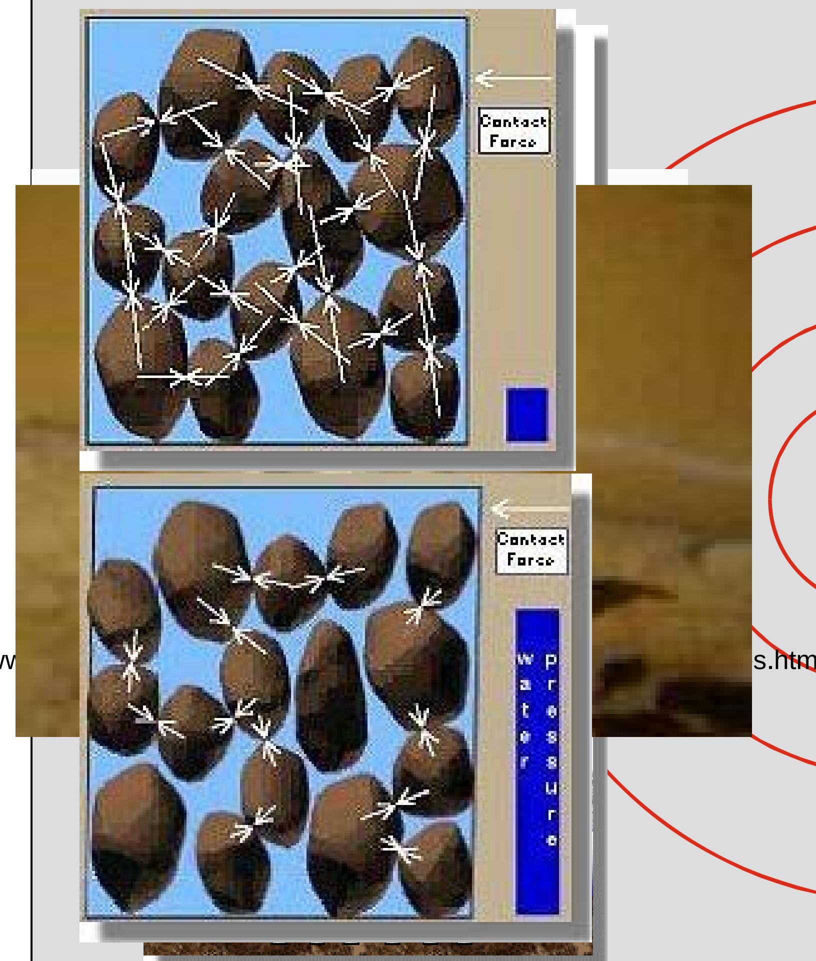
Contact forces between individual soil grains



Soil particles after liquefaction

Liquefaction

- The phenomenon
  - Occurs in saturated soils
  - Strength and stiffness properties greatly reduced
- The logic
  - Pore pressure increases
  - Effective shear stress reaches near zero
  - Large deformations occur
- Examples of damages
  - Pile Failure
  - Overturning of structures



Understanding Soil Liquefaction at a Soil Element Level

- For Clean sands

1. Monotonic Loading

2. Cyclic Loading

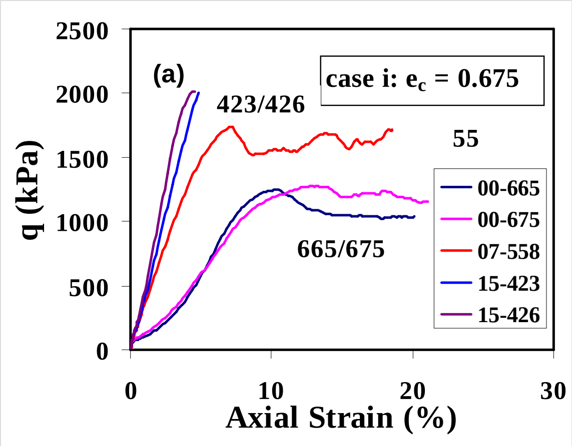
Laboratory Characterization – Liquefaction Resistance

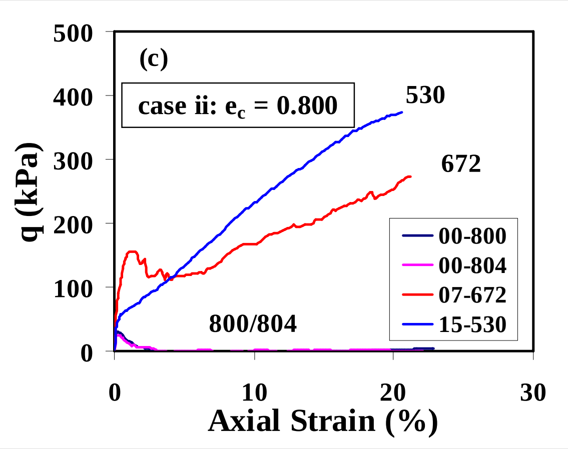
Typical Monotonic Undrained Shear Response of Sands

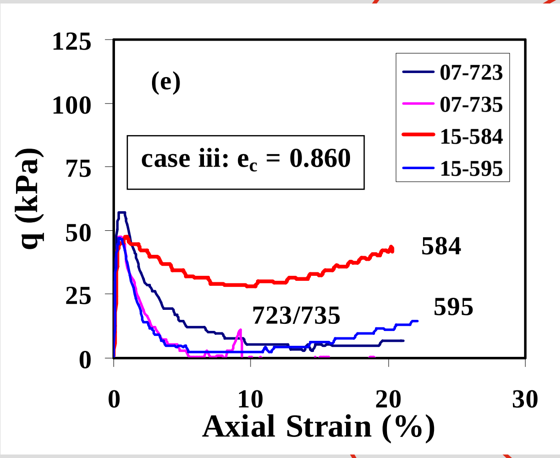
Dense (Dilative)

Med. Dense

Loose (Contractive)

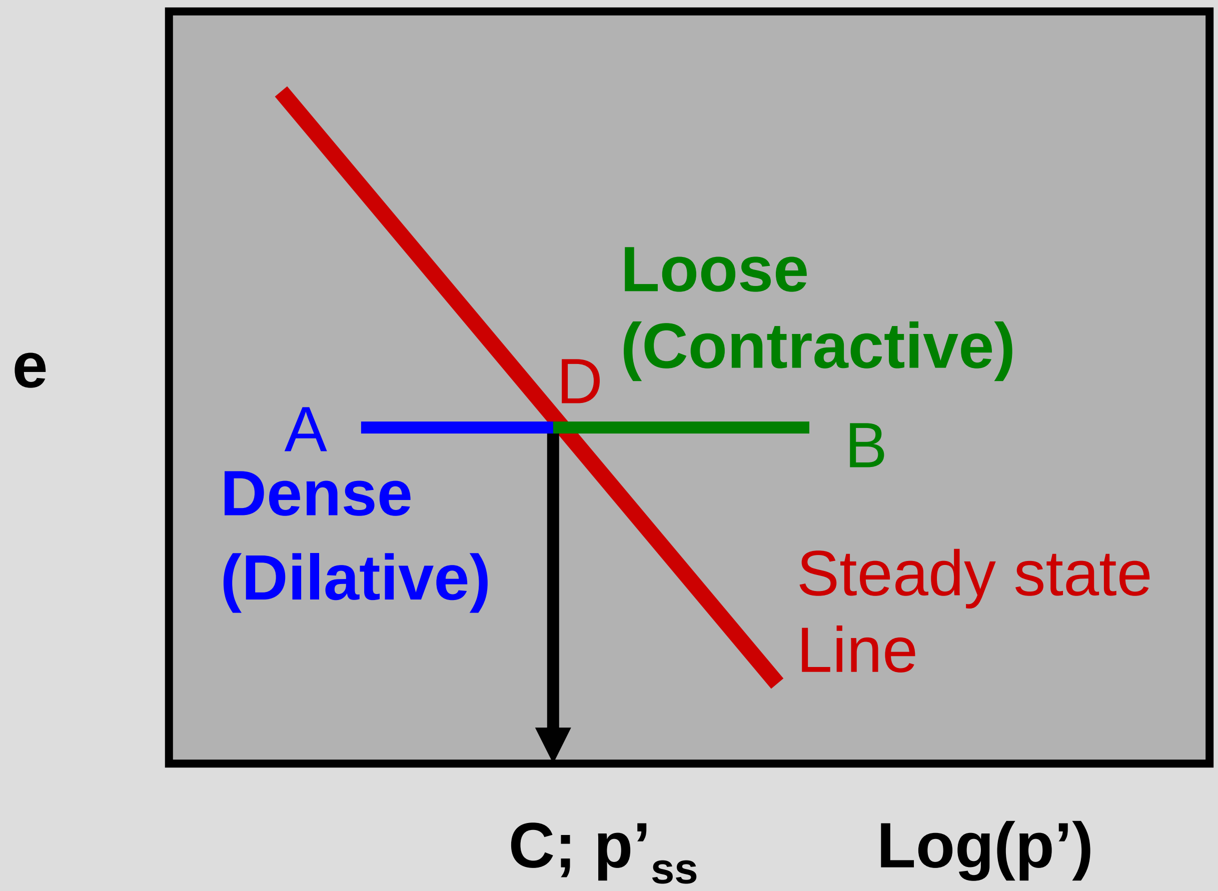






Conf. Stress = 100kPa = Constant

Typical Monotonic Undrained Shear Response of Sands & Steady State Concept

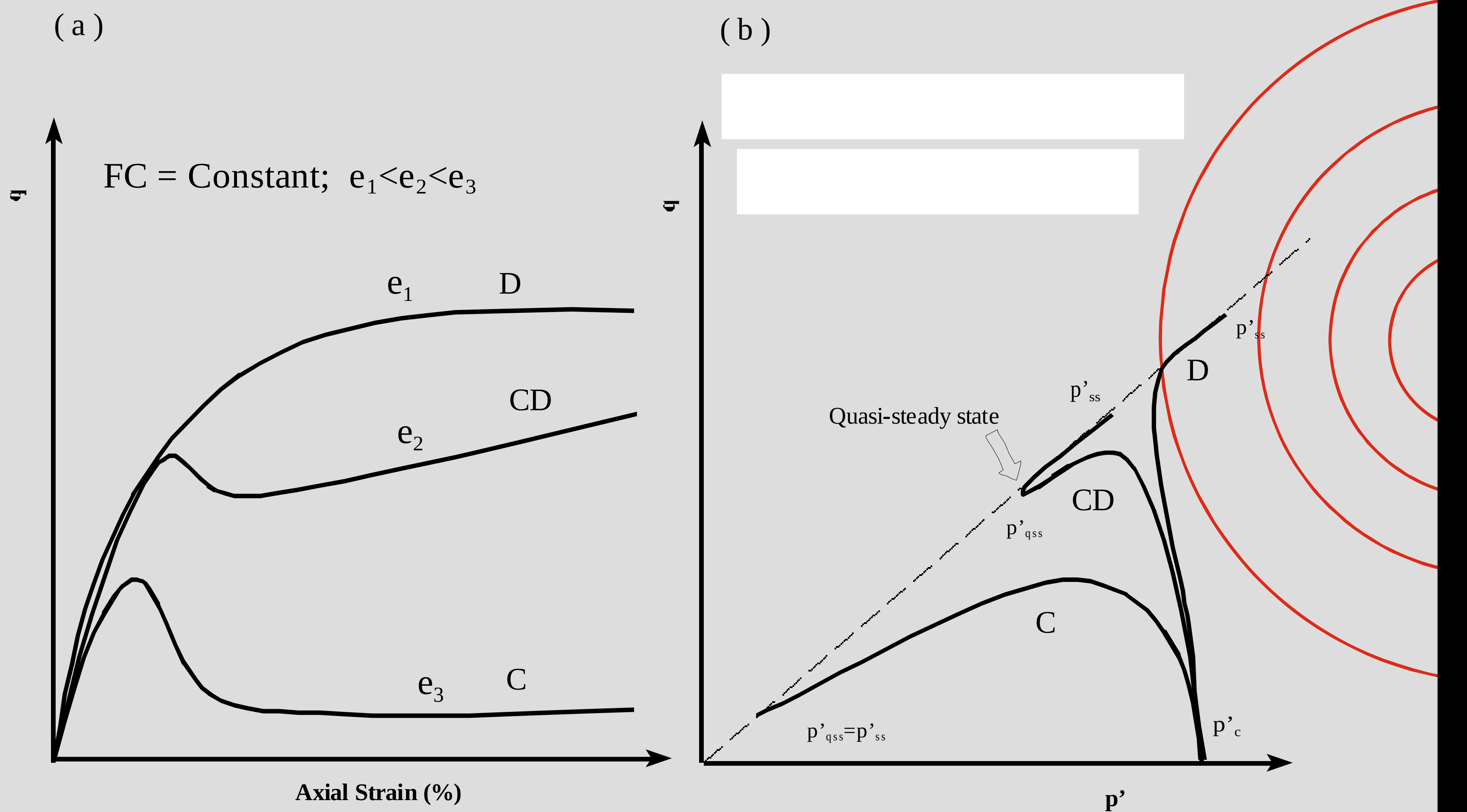


What is Steady State Strength?

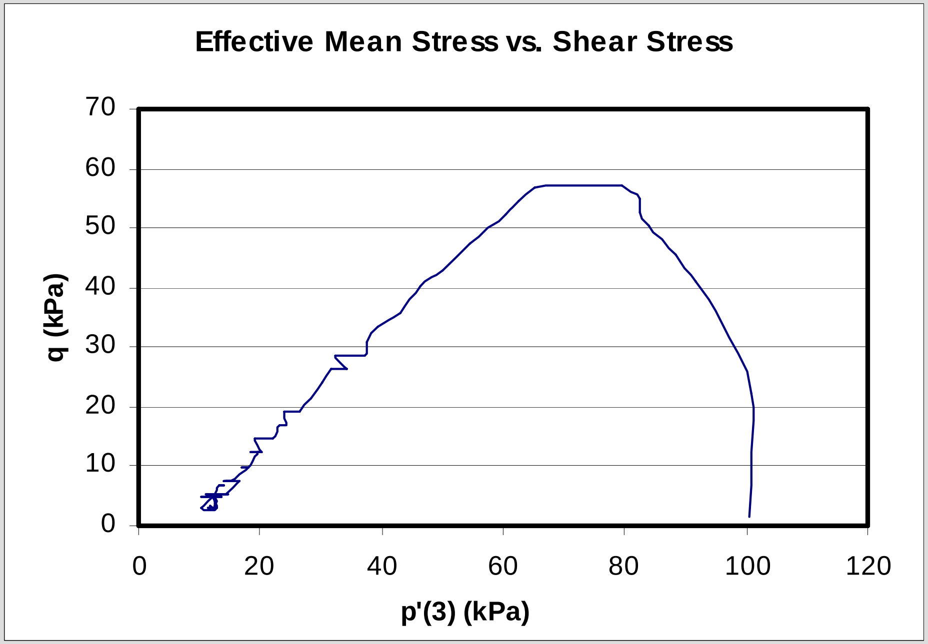
Undrained strength at which the soil deforms at a constant void ratio at constant velocity.

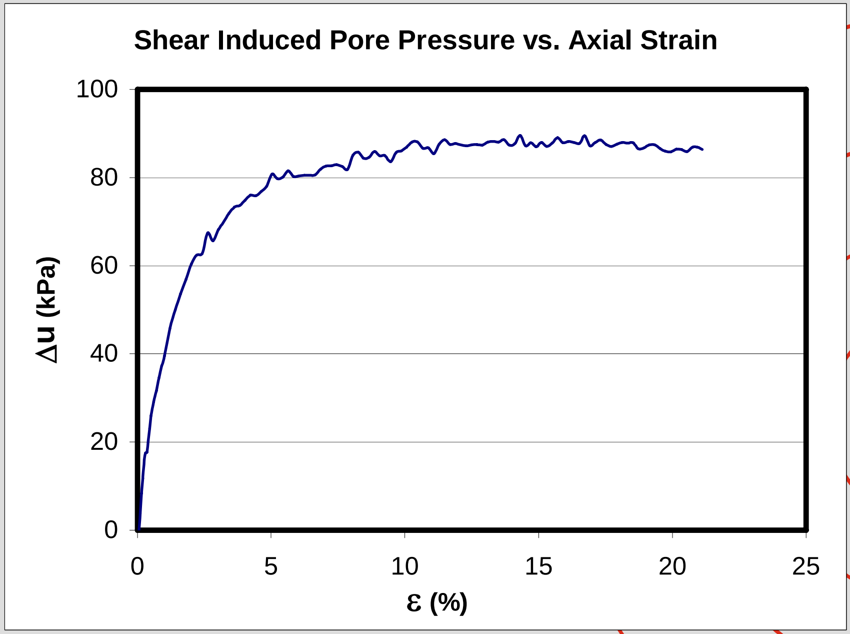
Depends on void ratio.

Monotonic
Undrained Shear Response



Static Liquefaction

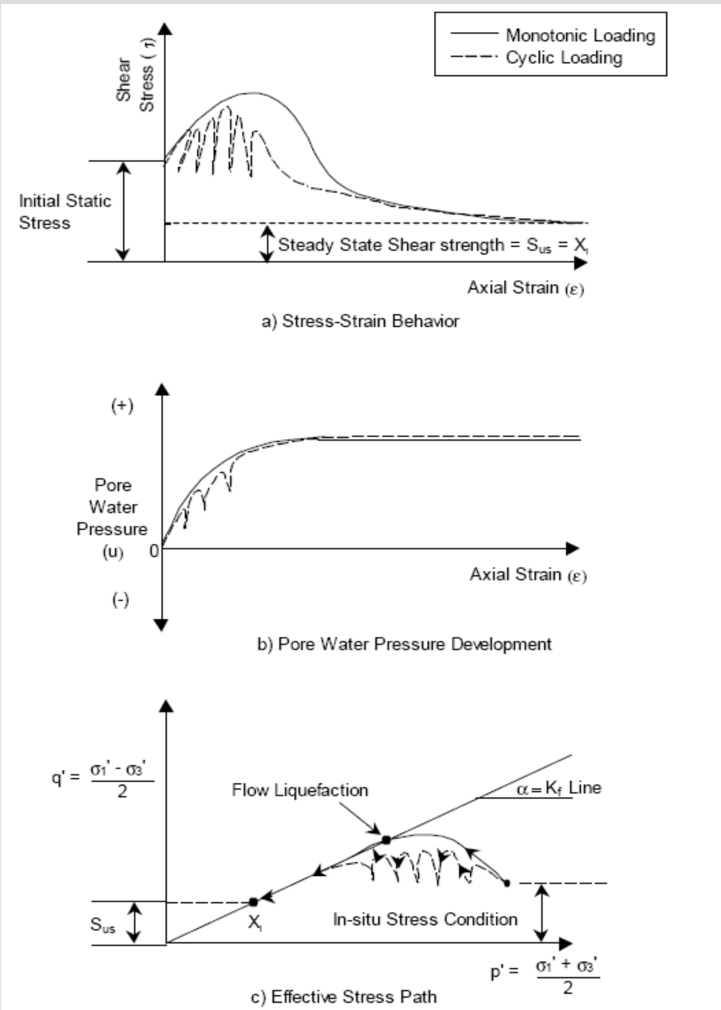




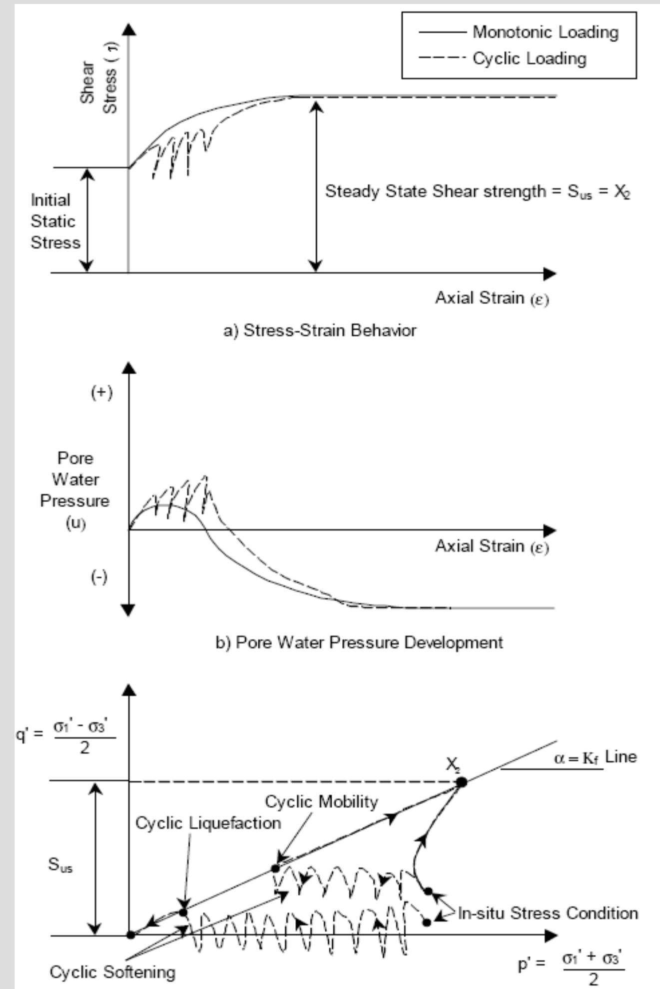
- Loss of stiffness and increase in pore water pressure during undrained shear.
- May result in large lateral deformation or flow of soil

Typical Soil response & Steady State Strength

Contractive Soil



Dilative Soil



How to design against static liquefaction?

1. What is the strength of “liquefied” soil?

   -Steady state strength approach

2. What factors are at play in the “field” that affect “residual” strength of the soil?

   -Residual strength approach

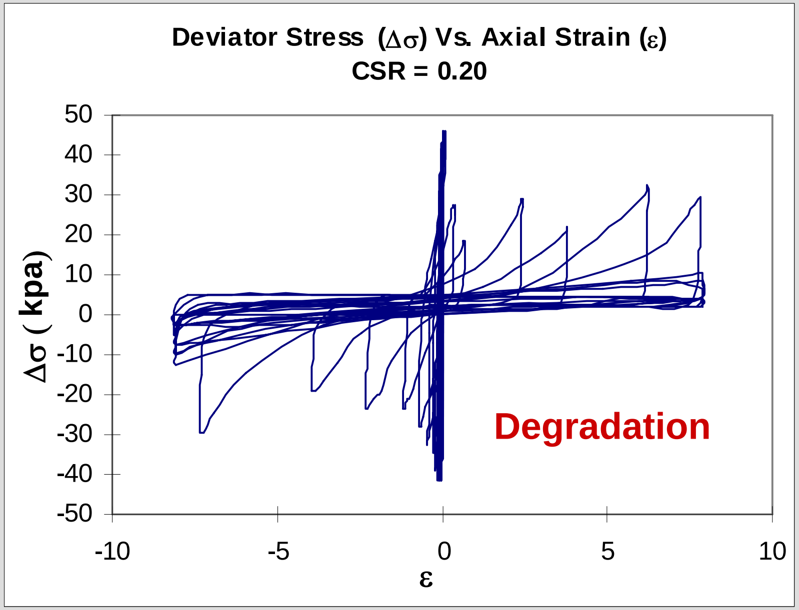
3. Other approaches

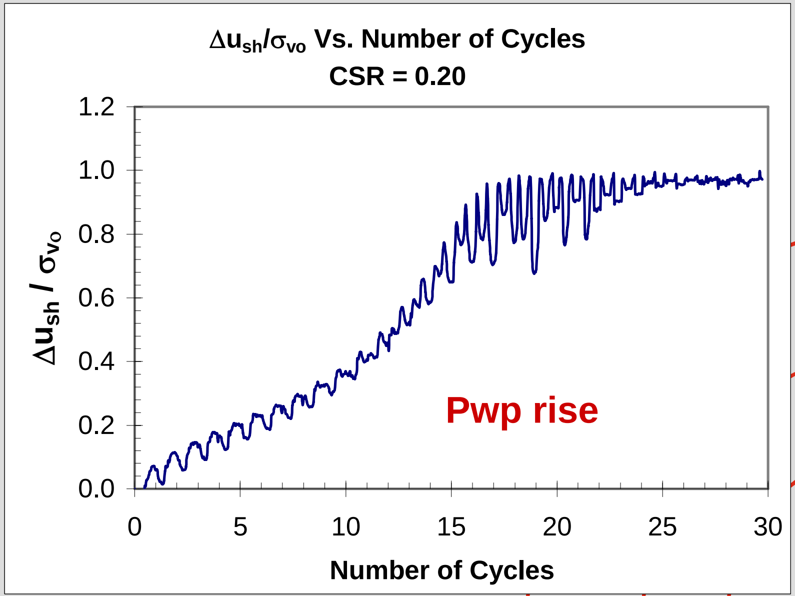
Understanding Soil Liquefaction at a Soil Element Level

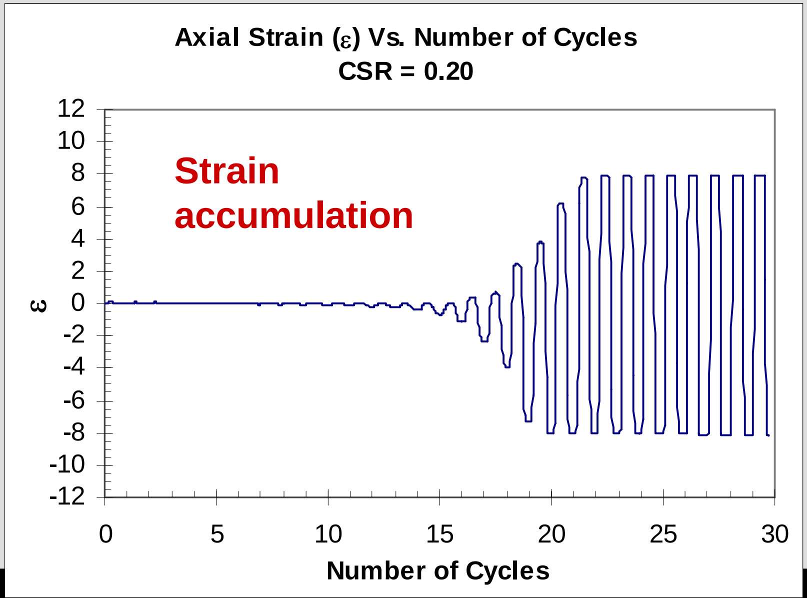
1. Monotonic Loading

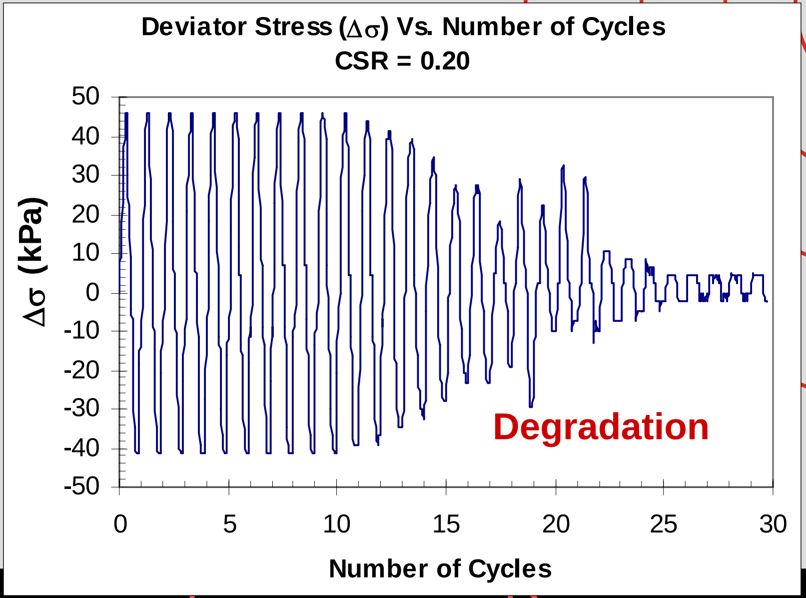
2. Cyclic Loading

Undrained Cyclic Shear & Liquefaction

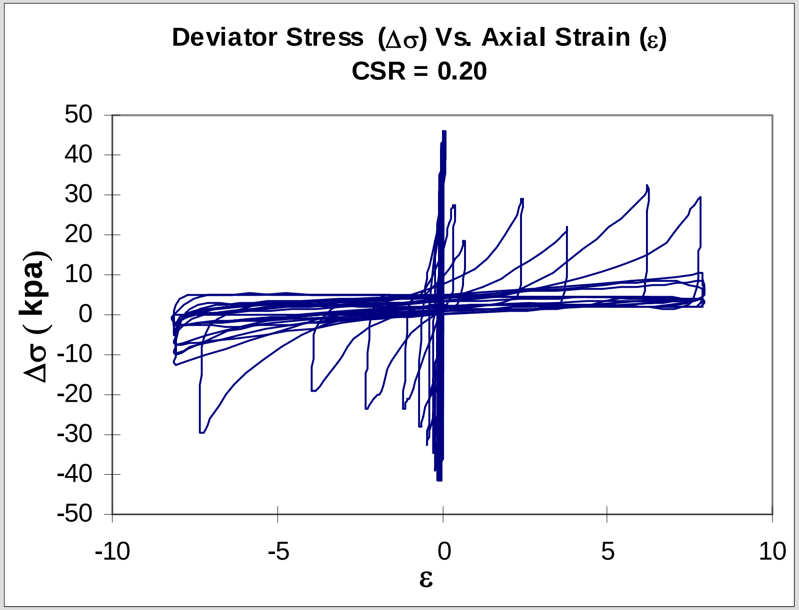


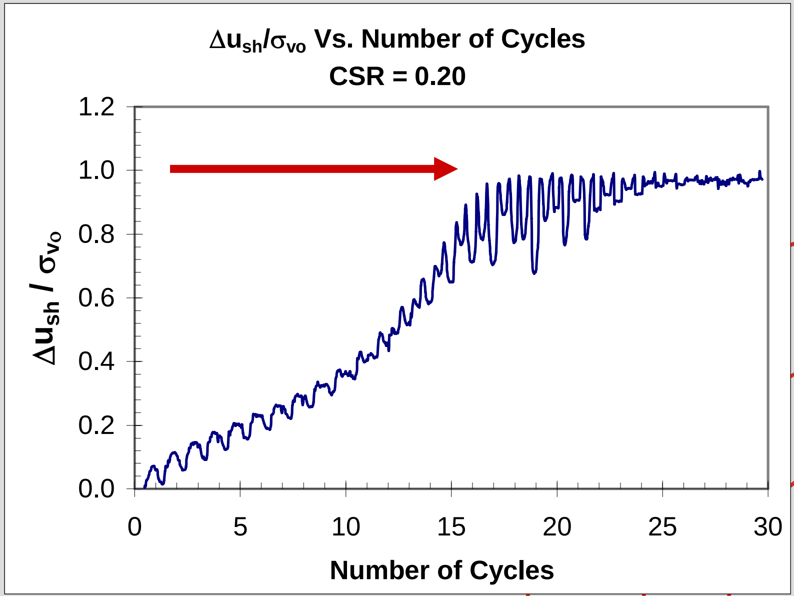


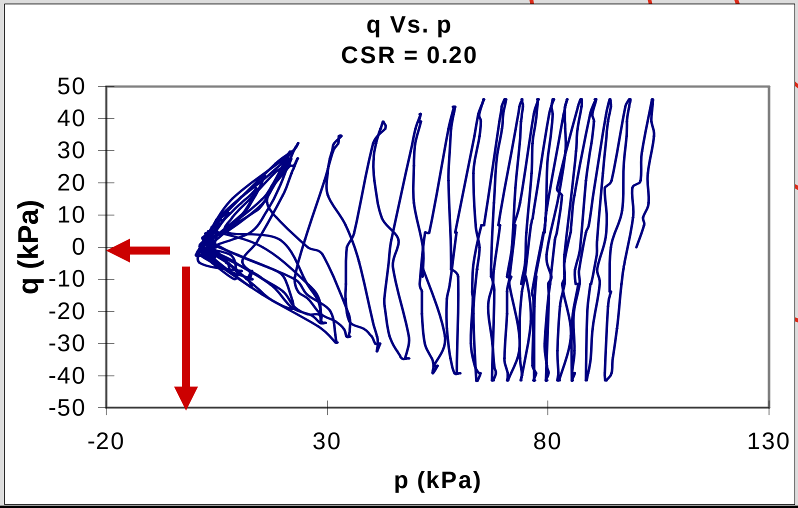




Cyclic Liquefaction

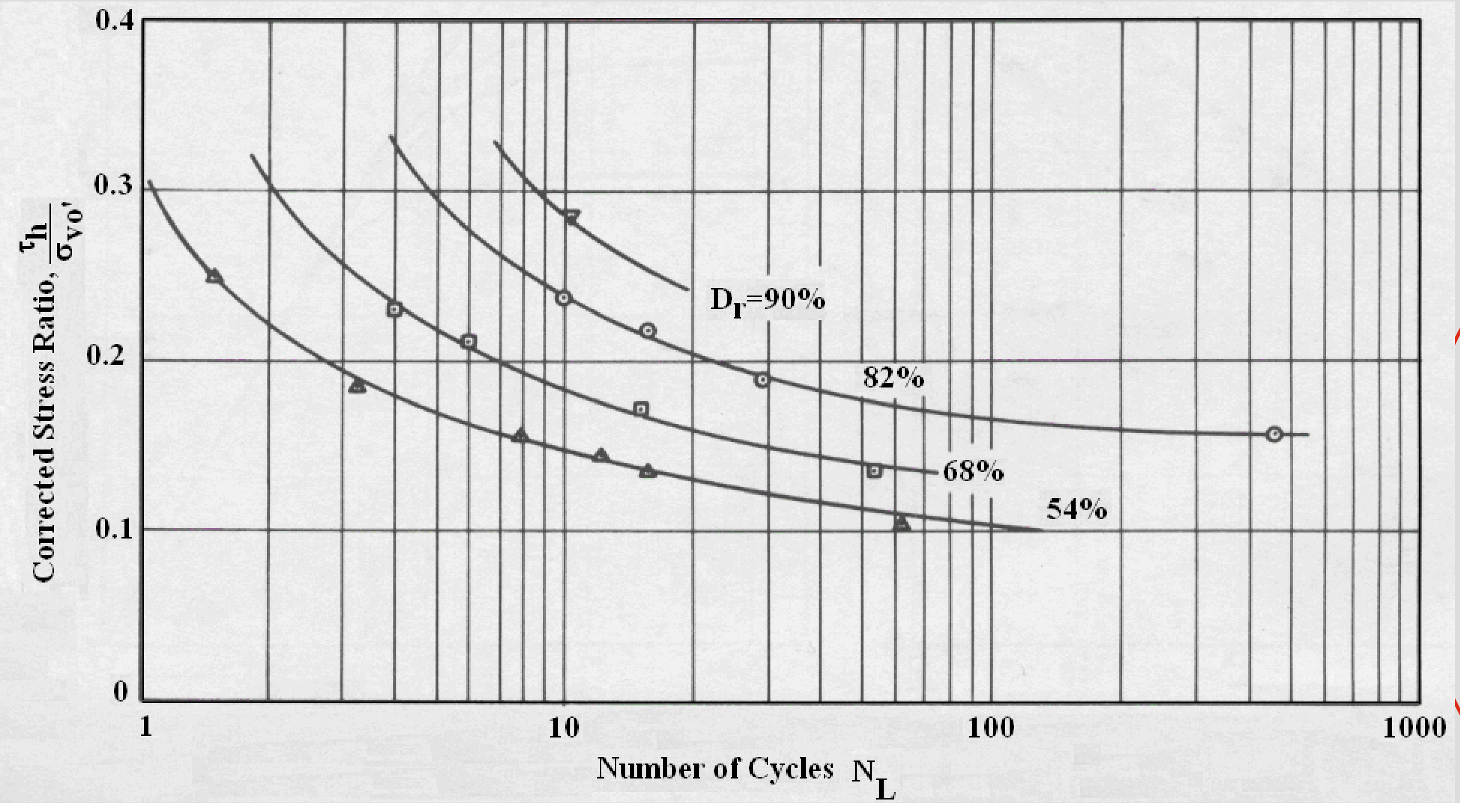






Degradation of stiffness, increase in excess pore pressure, reduction in effective stress near zero,
Increase in cyclic strains.

What is Cyclic Strength?



Cyclic Strength = Cyclic Stress Ratio (CSR) required to cause "Liquefaction" in a sand at a given Dr at a specified No. of Cycles

- Also Called Cyclic Resistance Ratio - CRR

Main Factors Affecting Liquefaction Resistance

- Size, shape, and gradation spectrum of soil particles
- Initial Relative density
- Stress levels
- Previous strain history
- Period of loading
- Fabric
- Fines content
- Drainage characteristics
- Vibration characteristics
- Trapped air
- Others

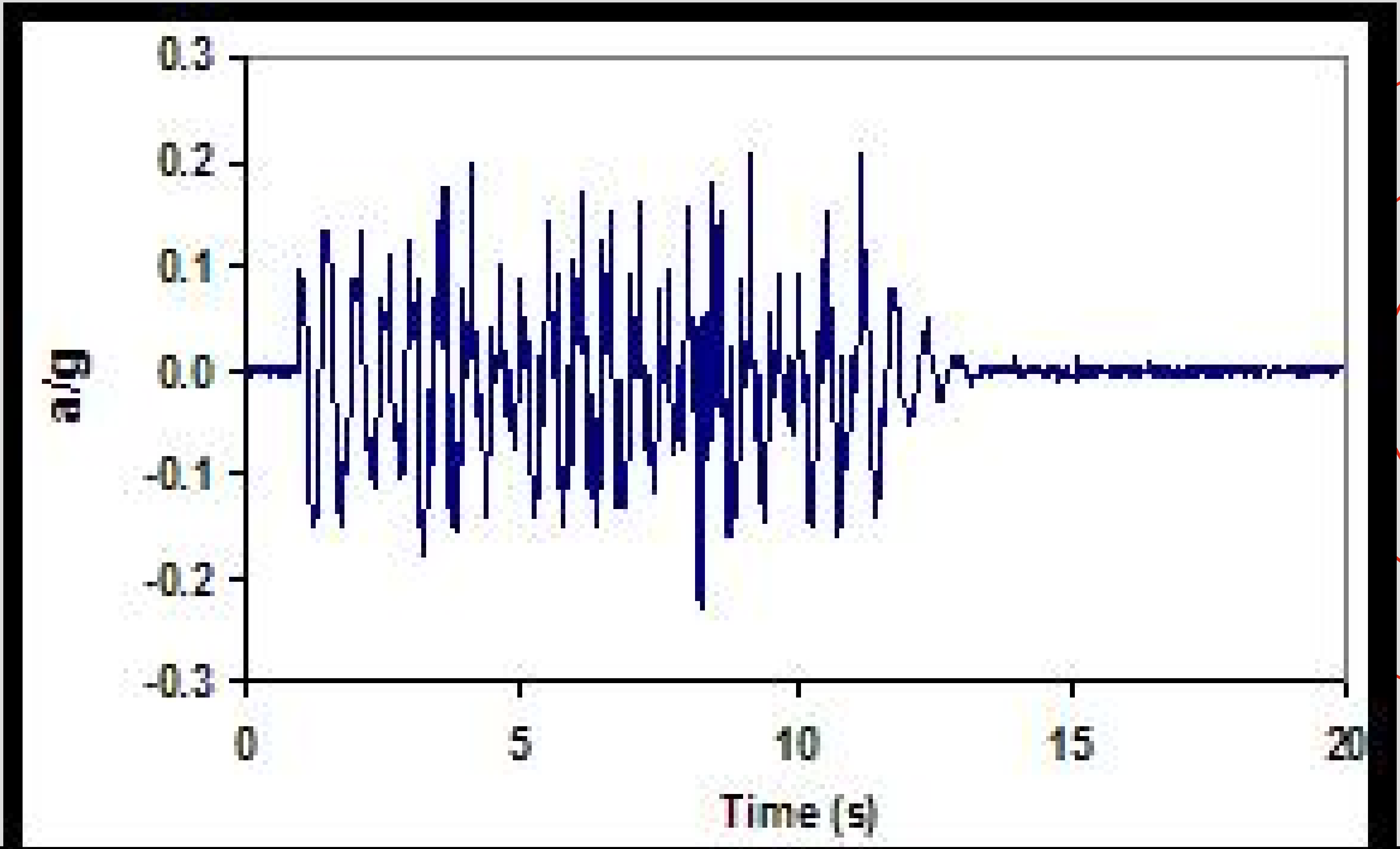
Stress Approach to Liquefaction Evaluation

1. Liquefaction Resistance of Soil
   - Cyclic Strength Ratio (CRR), N_L & D_r

2. Cyclic Loading from an earthquake
   - Cyclic Stress Ratio (CSR) & Equivalent No. of Cycle (N_{cy})
   - How to determine CSR & N_{cy} (Next 2 slides)

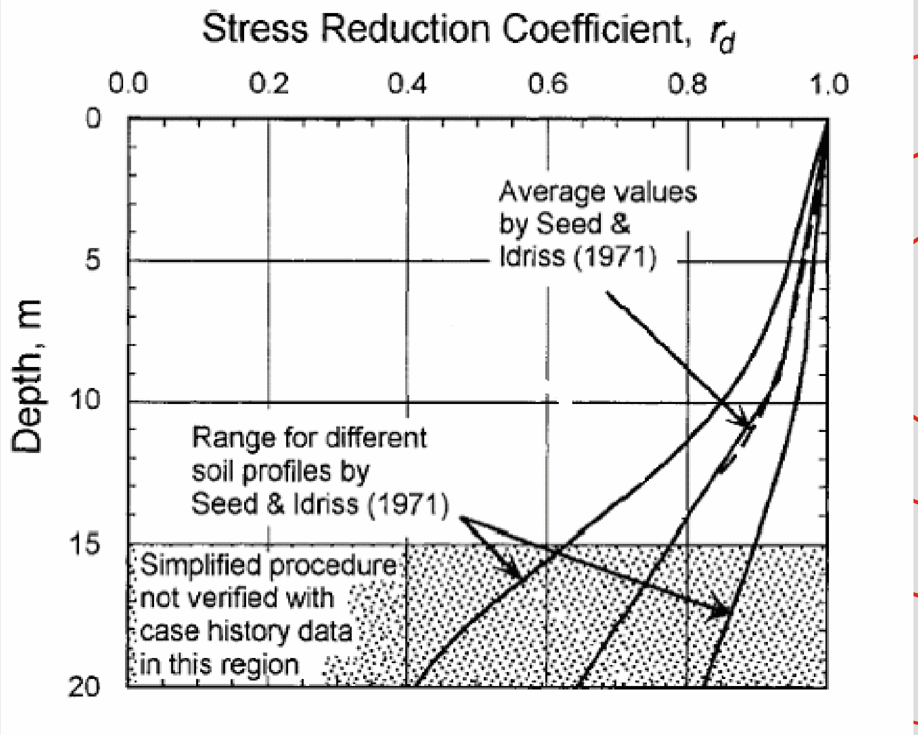
3. Liquafaction Potential
   - CRR (@ $N_L = N_{cy}$) > CSR .... No Liquefaction
   - CRR (@ $N_L = N_{cy}$) < CSR .... Liquefaction

Any Random Shaking may be reduced an equivalent stress cycle over an equivalent number of cycles



How to estimate Equivalent Cyclic stress ratio caused by an earthquake?

$$CSR = \left(\frac{\tau_{ave}}{\sigma'_{vo}}\right) = 0.65\frac{a_{max}}{g}\frac{\sigma_{vo}}{\sigma'_{vo}}r_d$$



a_{max} = peak ground acceleration
σ_{vo} = vert. overburden stress
σ'_{vo} = effective overburden stress
r_d = depth factor

(Seed and Idriss 1971)

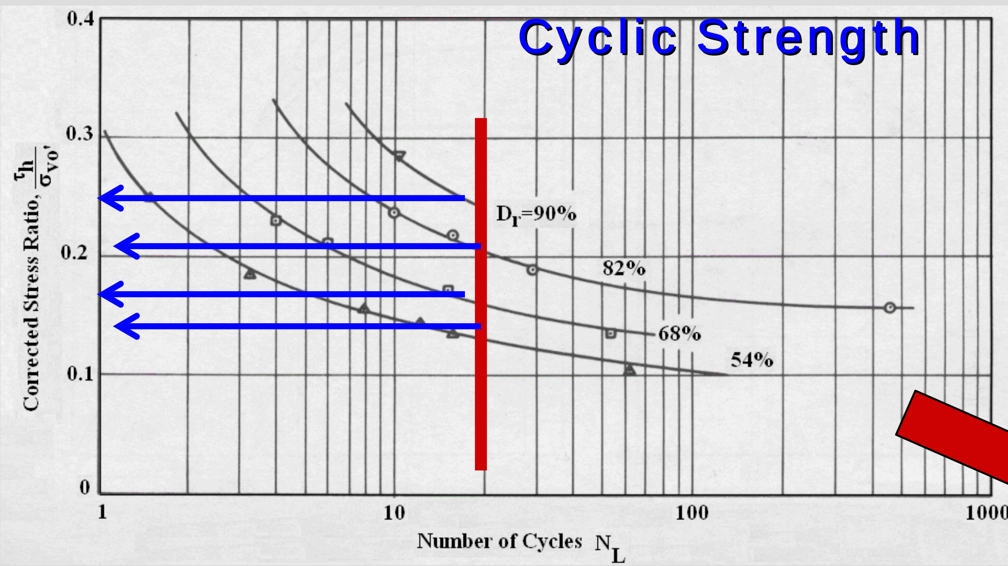
Other Approaches to Liquefaction Evaluation - TBA

1. Strain Approach

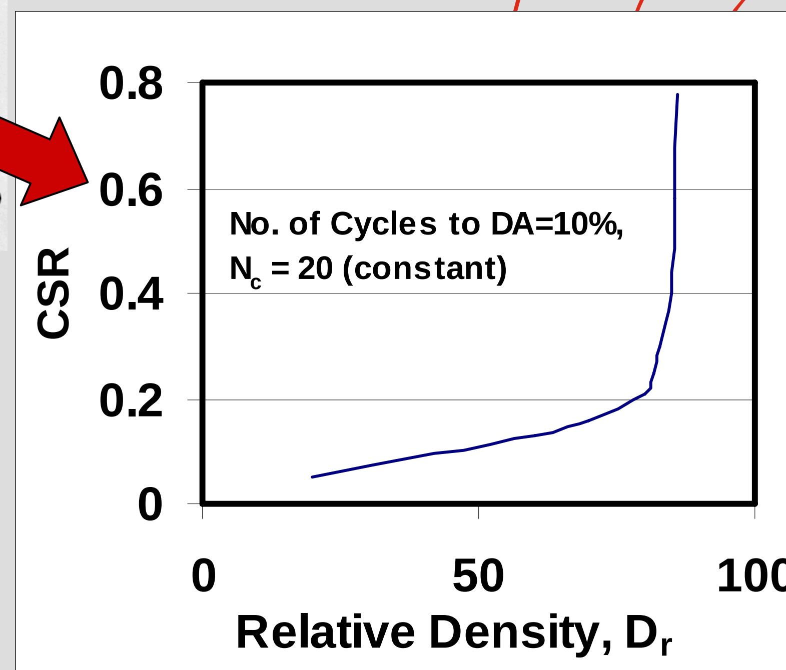
2. Energy Approach

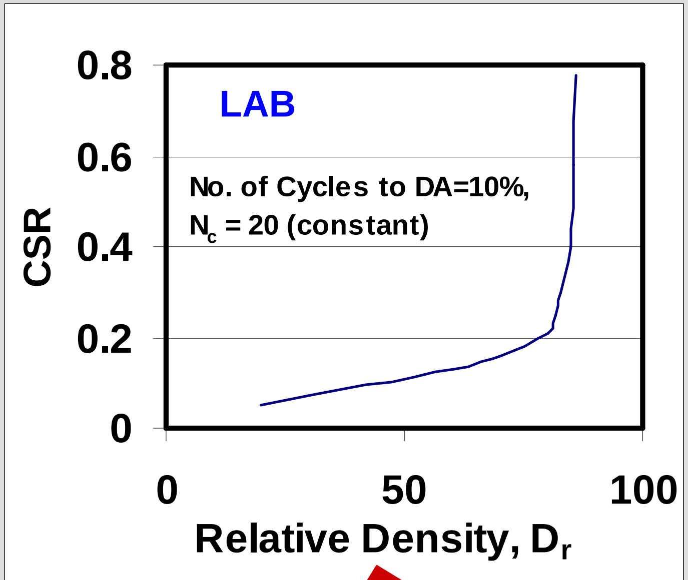
3. Numerical Approaches, etc.

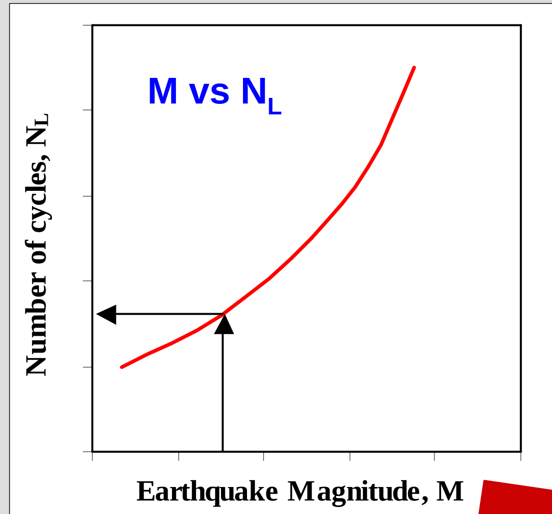
Evolution of stress approach towards Field Liquefaction Screening



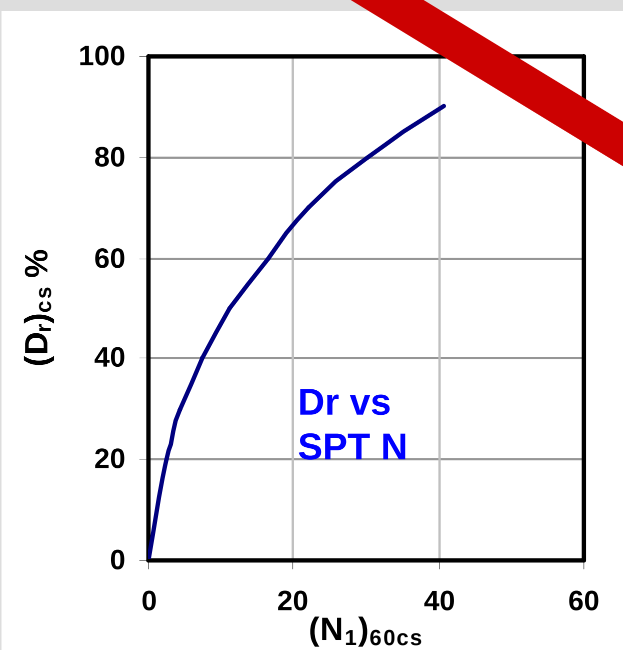
Mapping CSR vs N_L for a given D_r
To
CSR vs D_r for a given N_L



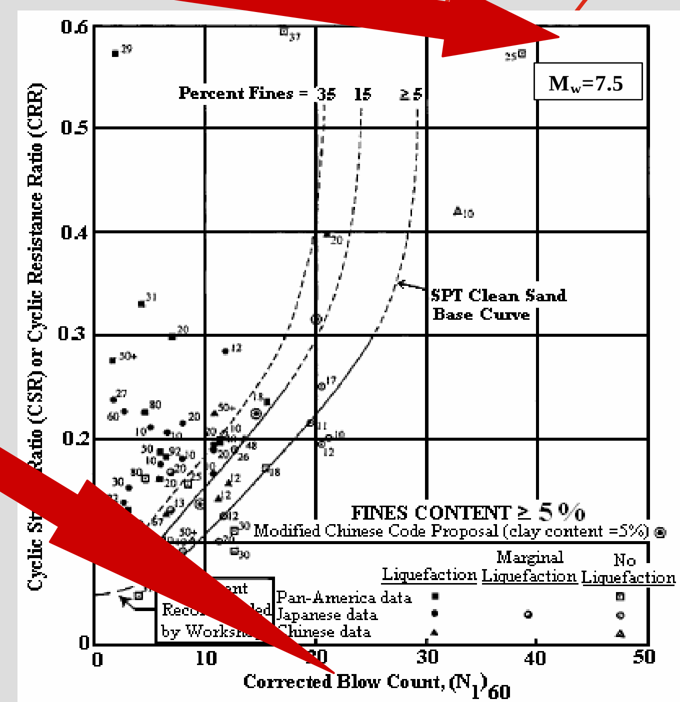




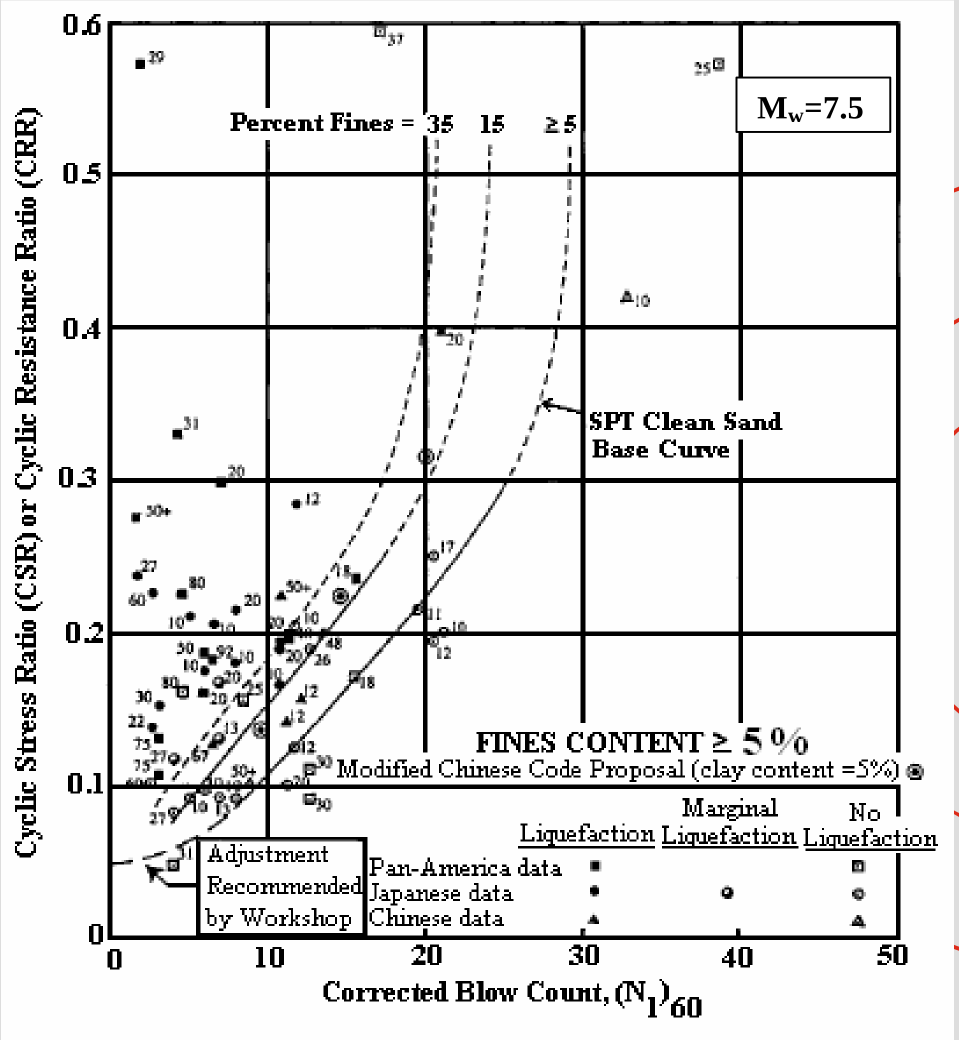
N_L
To
M (EQ magnitude)



CSR vs Dr
To
CSR vs $(N_1)_{60cs}$



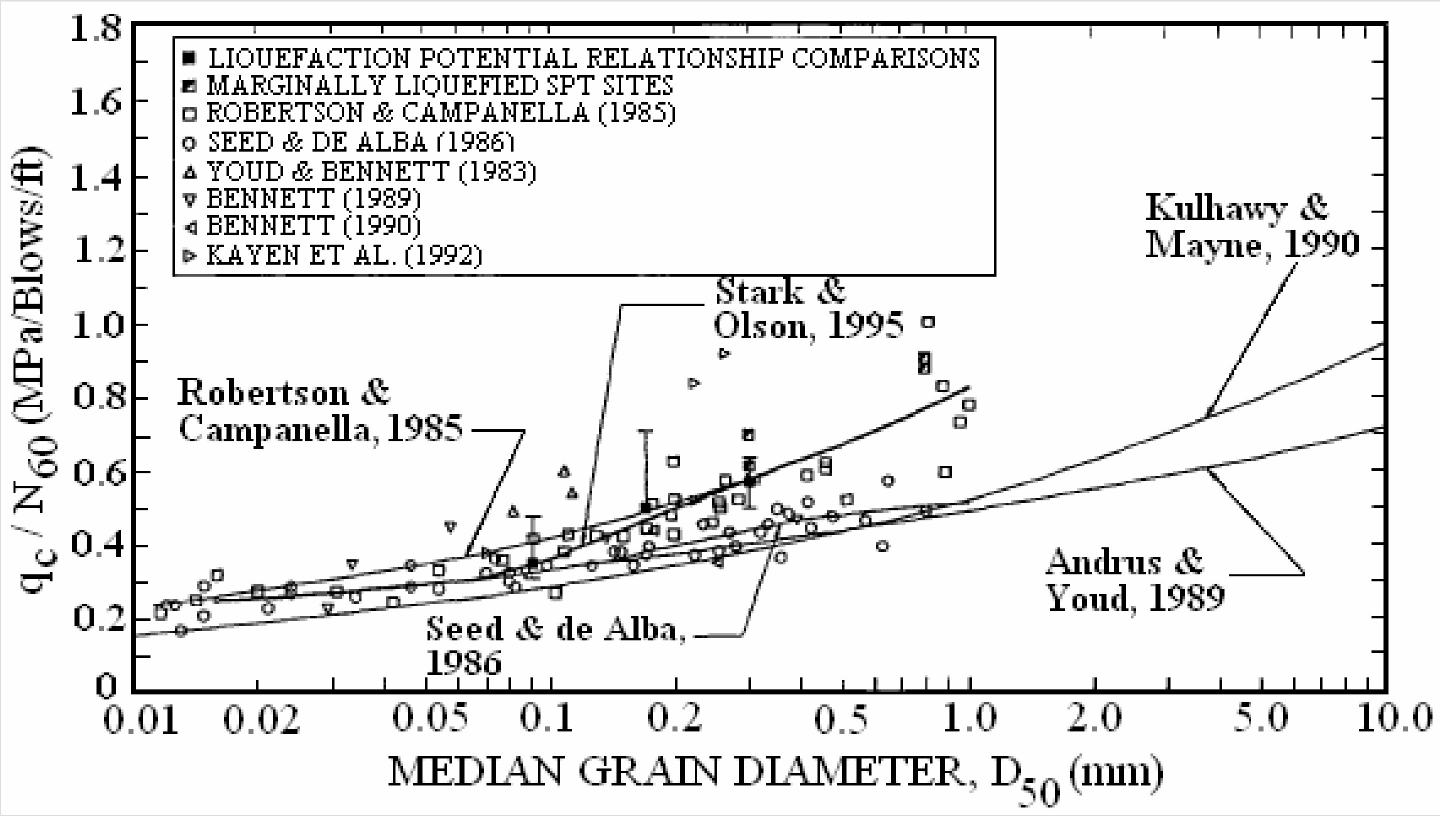
SPT-based Liquefaction Screening



Field data follows the trend expected for CRR vs $(N_1)_{60cs}$ deduced before

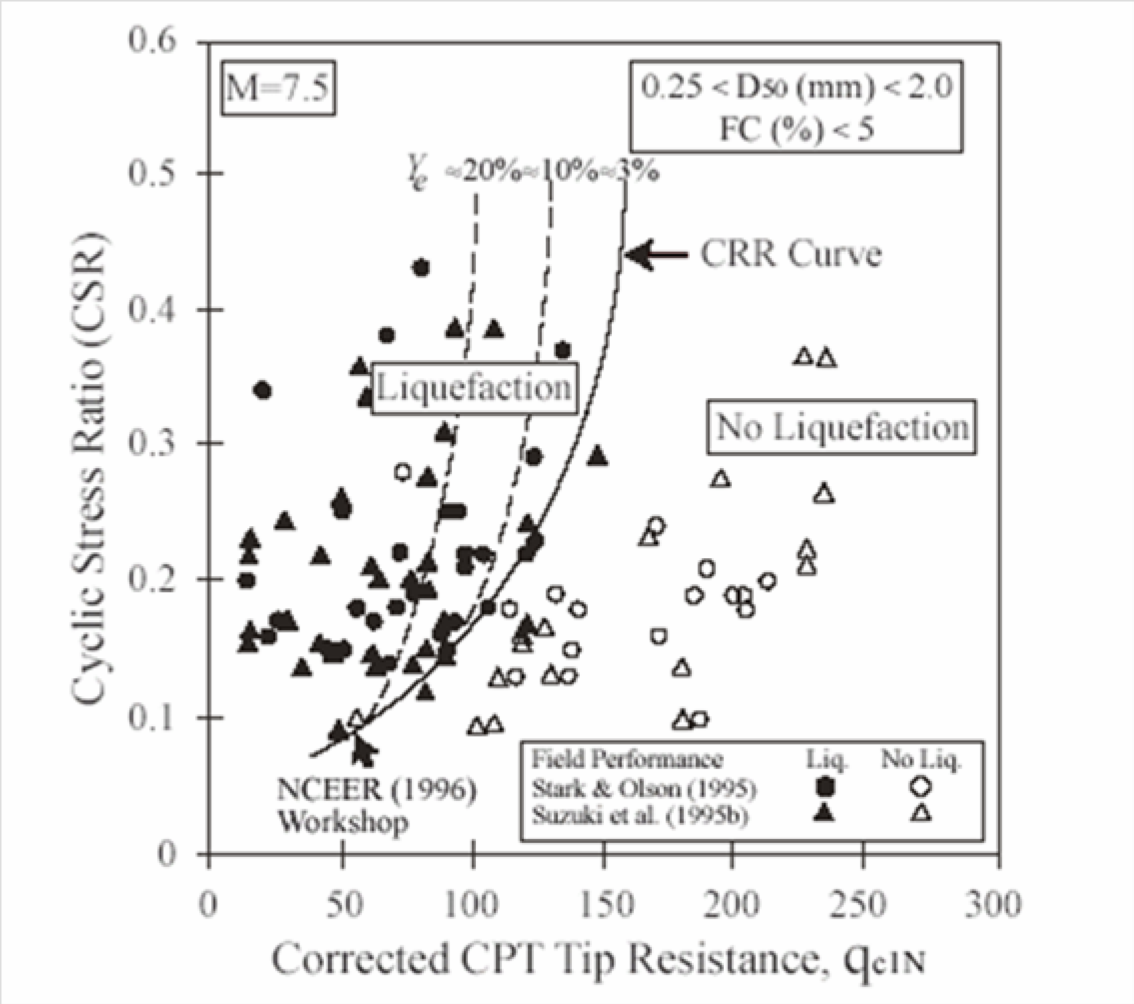
Data from Liquefaction Case Histories (Seed et al. 1983, Youd et al. 2001)

Early Approach to CPT based Liquefaction Screening



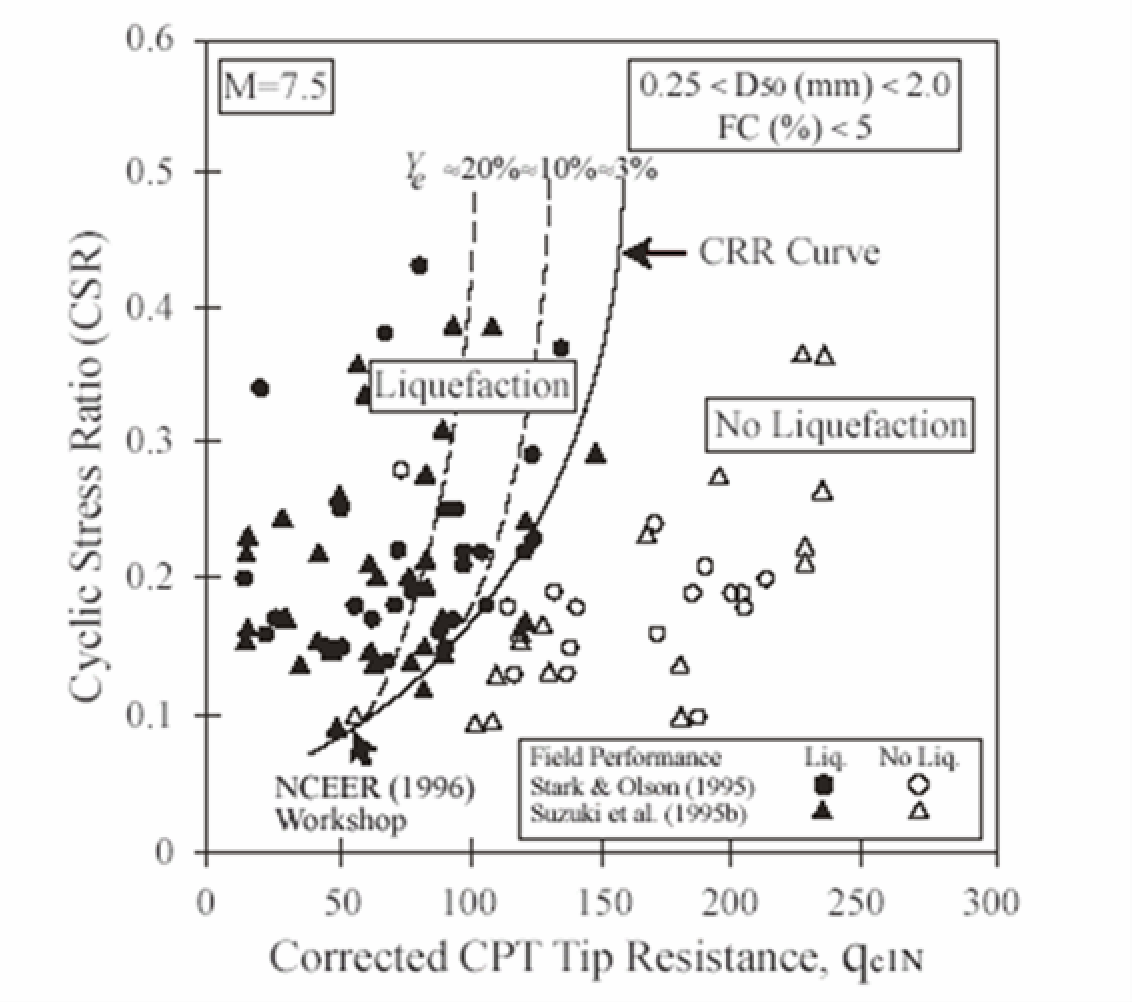
- **Conversion of CPT cone resistance to SPT resistance**
- **Then use SPT-Liquefaction Chart**

CPT Liquefaction Screening
- Based on Case History Data



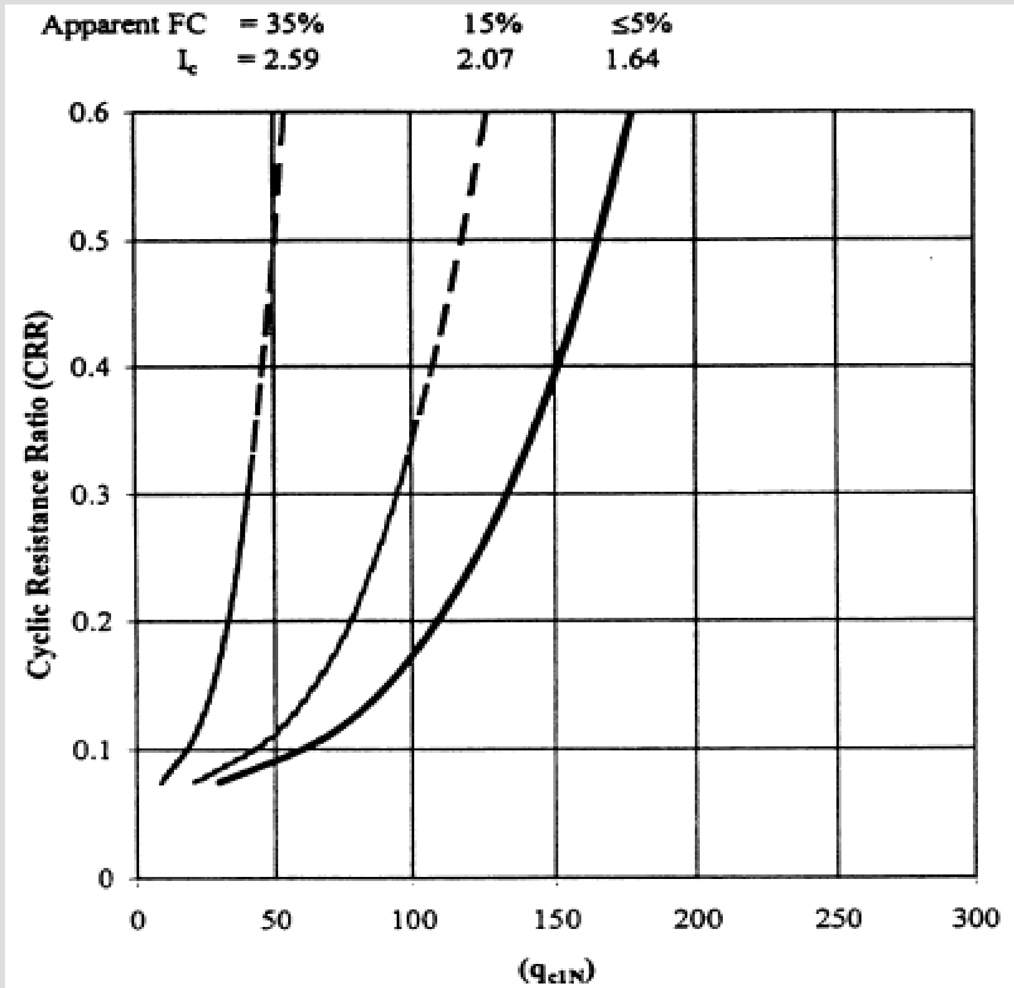
(NCEER 1997)

CPT Liquefaction Screening
- Based on Case History Data



(NCEER 1997)

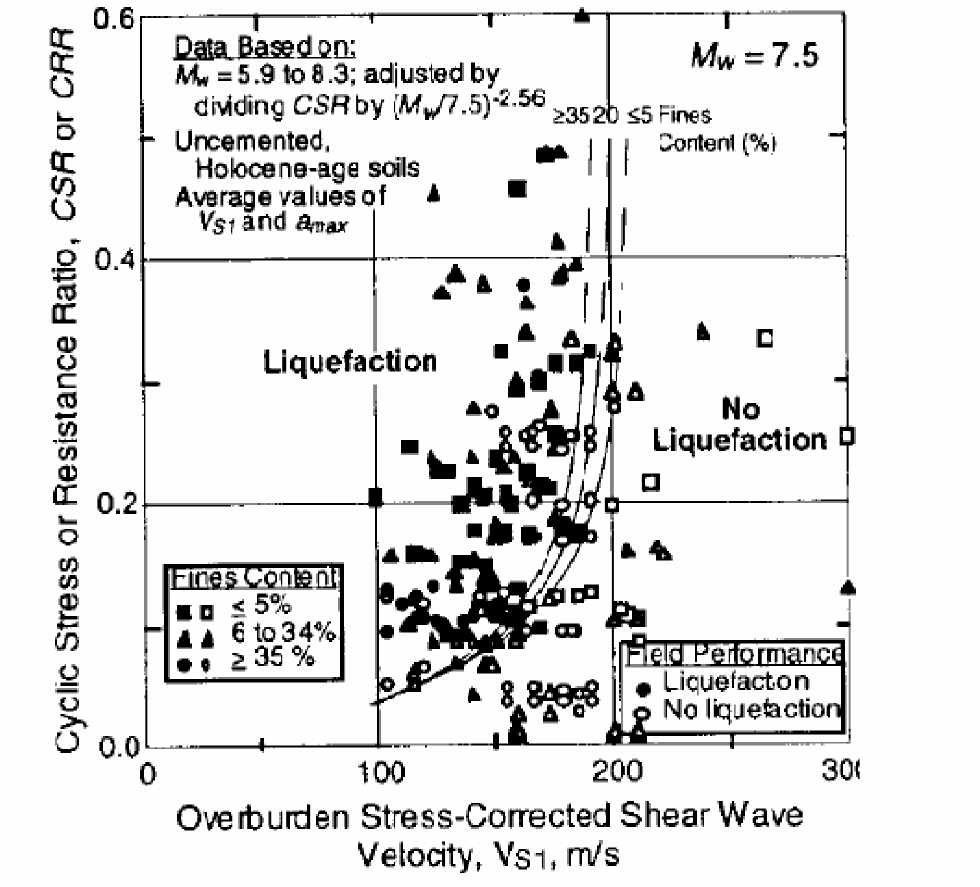
CPT Liquefaction Screening
- for sands and silty sands



Robertson and Wride 1998

Liquefaction Screening Based on Shear Wave Velocity v_s

Note: Shear wave velocity is related to relative density and confining stress



Shear wave velocity data from case histories **(Andrus and Stokoe 2000)**

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}	

$\alpha, \beta, K_c, V_{s1c}$ = silt content dependent

MSF – Magnitude Scaling Factor
Standard Value 1.0 for M=7.5

Table 2.2 MSF Values (NCEER Workshop 1996)

Earthquake Magnitude	Magnitude-Scaling Factor (MSF)	
	Idriss (1995)	Andrus and Stokoe (1997)
5.5	2.20	2.8
6.0	1.76	2.1
6.5	1.44	1.6
7.0	1.19	1.25
7.5	1.00	1.00
8.0	0.84	-
8.5	0.72	-

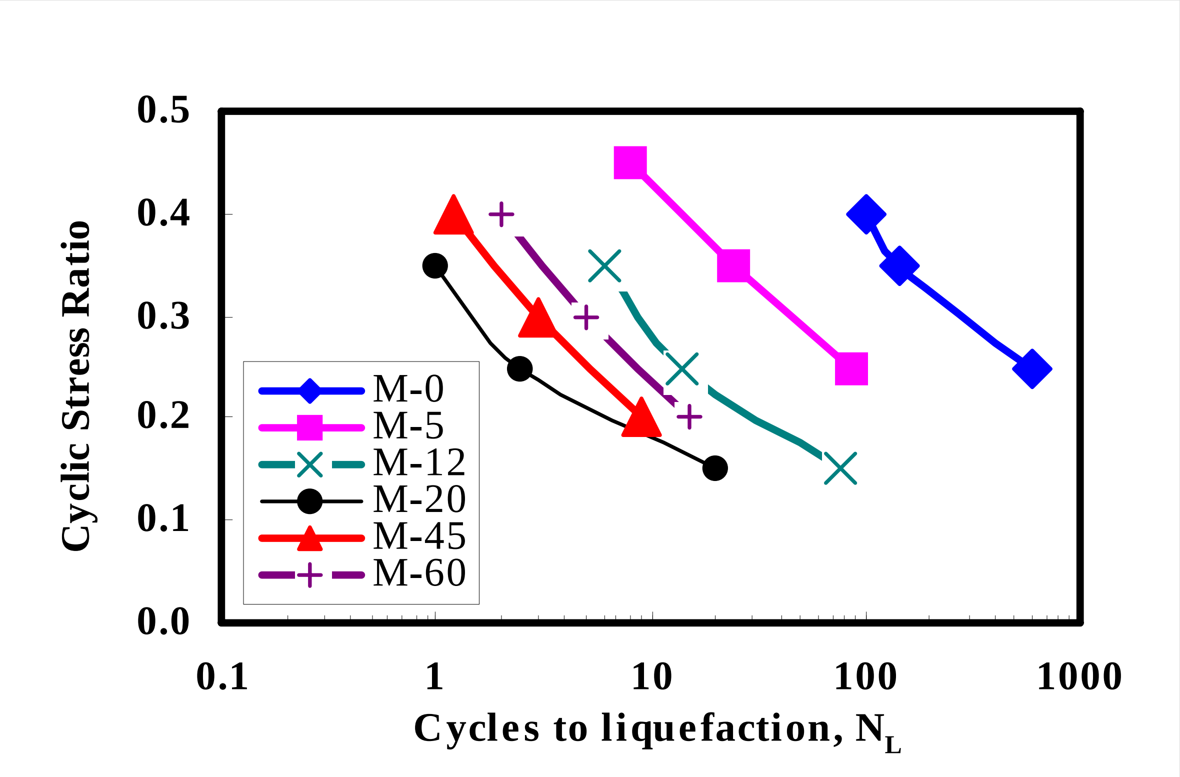
Examples – Liquefaction screening

TBA

Understanding Soil Liquefaction at a Soil Element Level

- For silty soils

Anomalous (?) or Inconsistent (?) Behavior of Cyclic Strength when Fines are added



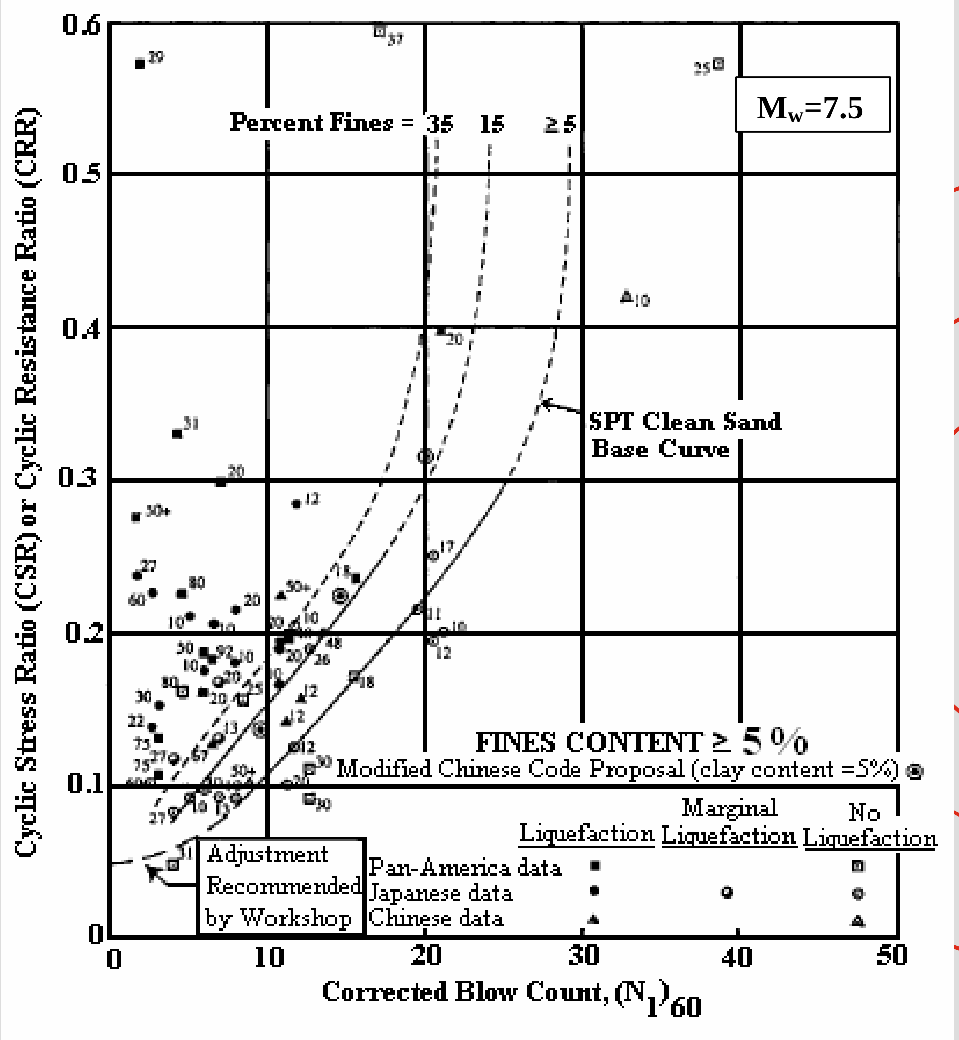
e=0.558=constant; Silt content varied from 0 to 60%; M-20=20% silt content by dry weight

SPT-based Liquefaction Screening

Is silty soil more resistant to liquefaction than sand?

Is this inconsistent with laboratory data?

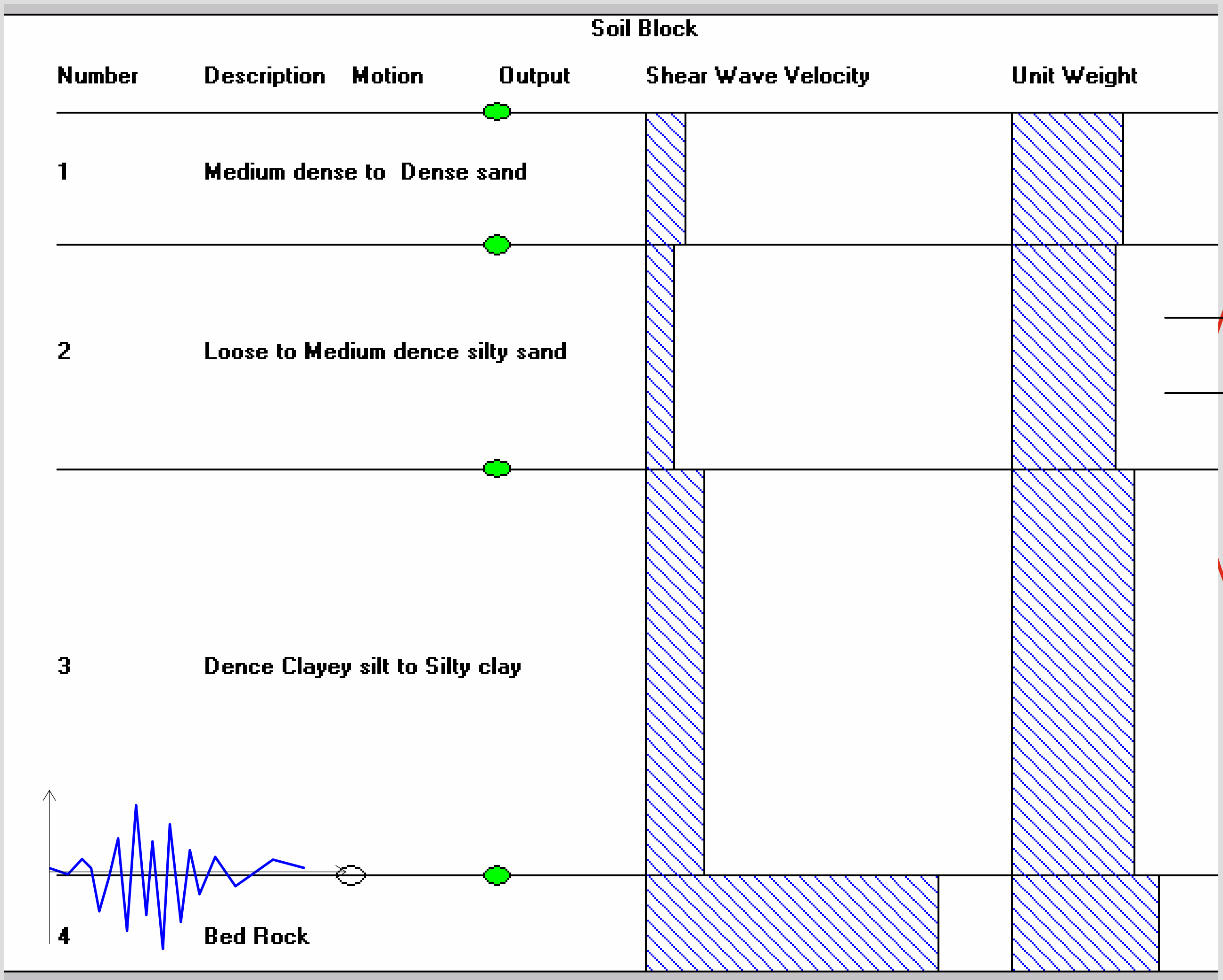
To be discussed later



Data from Liquefaction Case Histories (Seed et al. 1983, Youd et al. 2001)

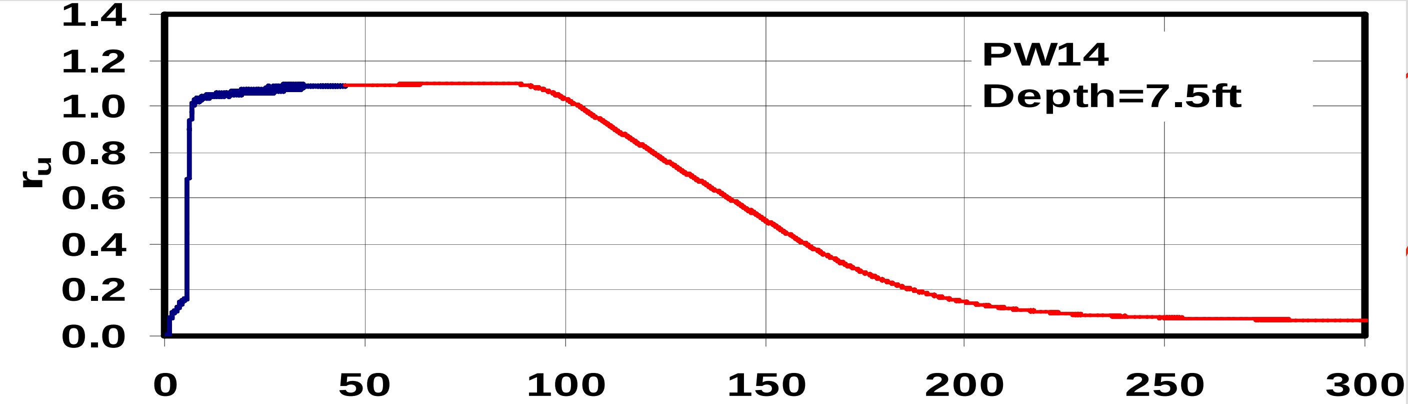
Understanding Soil Liquefaction at a Soil Deposit Level

Liquefaction in a Soil Deposit

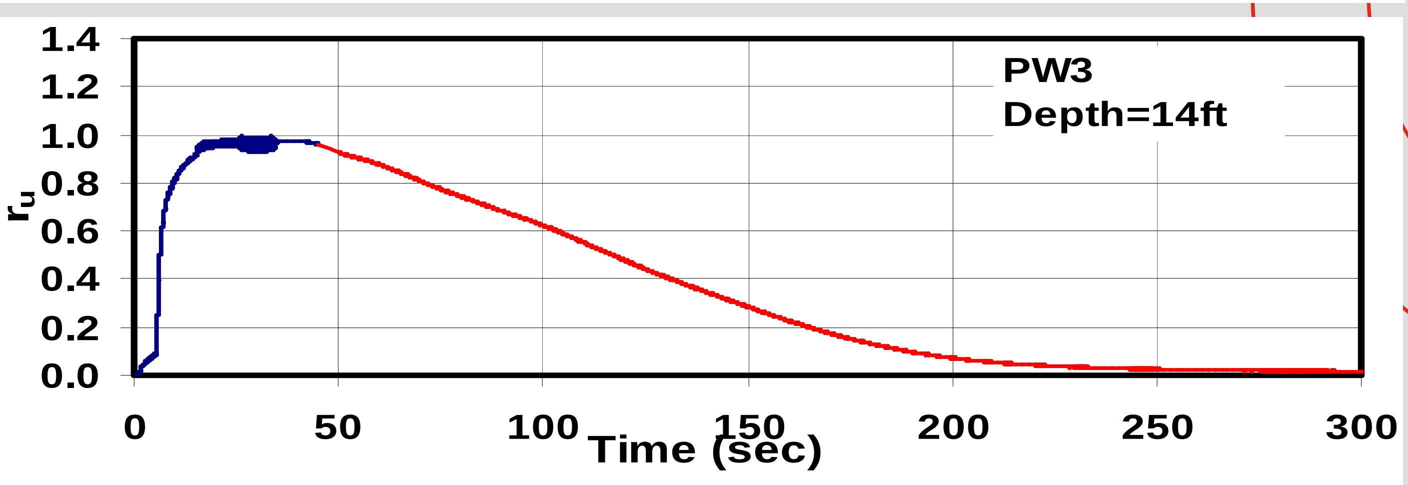


Undrained Laboratory Cyclic Pore Pressure Versus Field Pore Pressure Response

7.5ft



14ft



Effects of Macro Field response including effects of layers of sands, silty sands, etc.

How to perform liquefaction screening and How to design against liquefaction-induced failures
- to be discussed later

Thank You

Questions...