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Lecture #4b
Ground Improvement Techniques for Soil Liquefaction of Sands & Silty Sands
– *Vibro Stone Columns*

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Acknowledgments: T. Shenthan, R. Nashed; MCEER, FHWA

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Organized by Prof. A. Balasubramaniam

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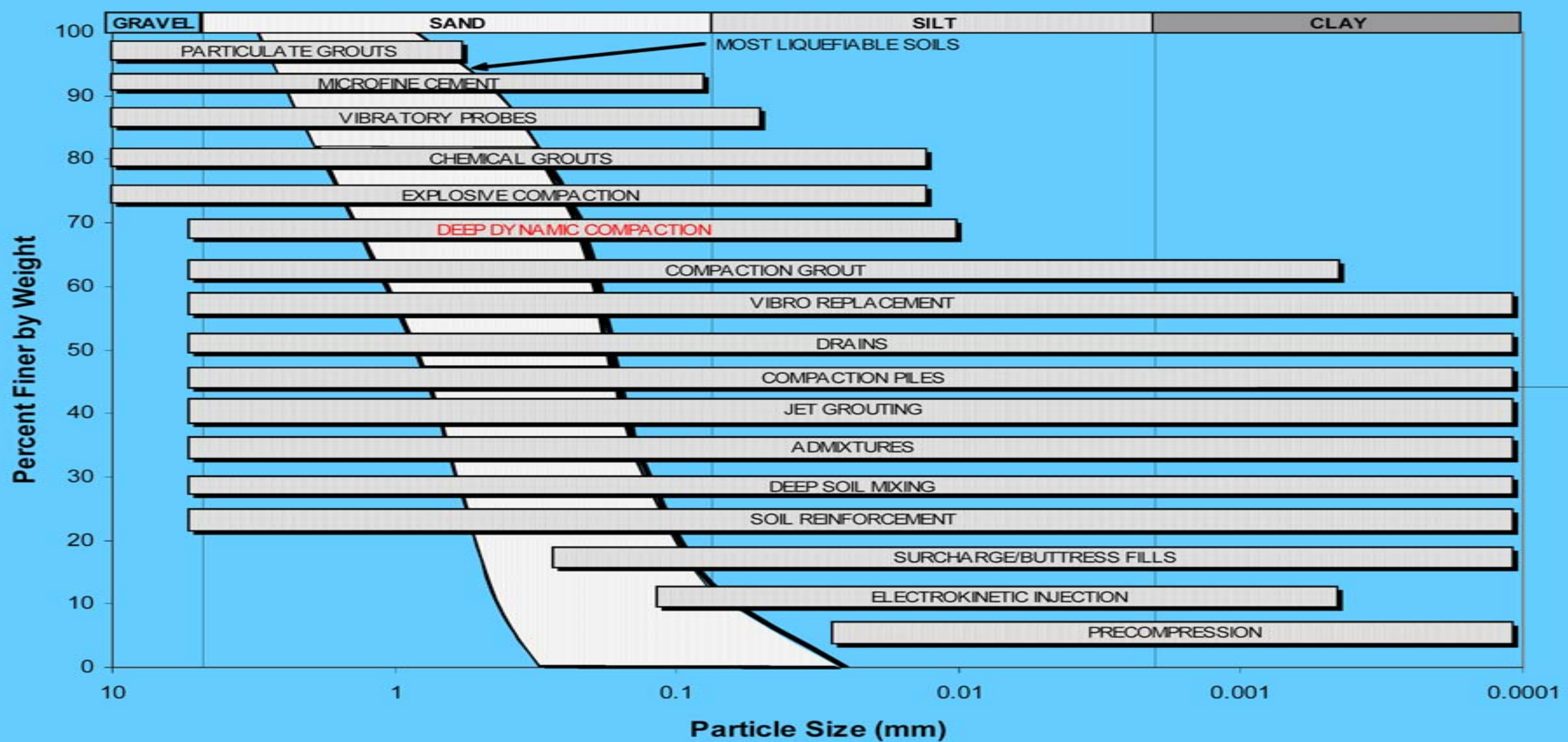
Problem

- Many earthquake-induced highway/bridge failures have occurred in **sands and silty soil sites**
  - Past research mainly focused on clean sands. However, silty soils do liquefy and cause liquefaction-induced hazards
- Understand **Liquefaction & Post-Liquefaction Behavior** of Silty Soils as compared to Clean Sands
  - Silty soils behave much differently from clean sands, and are low permeable
- Develop Modified **Densification methods & Design Guidelines** to Mitigate Liquefaction in silty soils
  - Traditional densification/drainage based ground improvement methods are not readily applicable for silty soils, and need modifications

Outline of Presentation

- Background
- Recent Advances
- Current Design Practice
- Objectives
- SC Simulation Model
- Field Comparisons
- Design Guidelines
- Design Example
- Conclusions

Grain Size Ranges & Suitability of Improvement Methods



Mitchell (1981)

Stone Column Construction

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Vibroprobe

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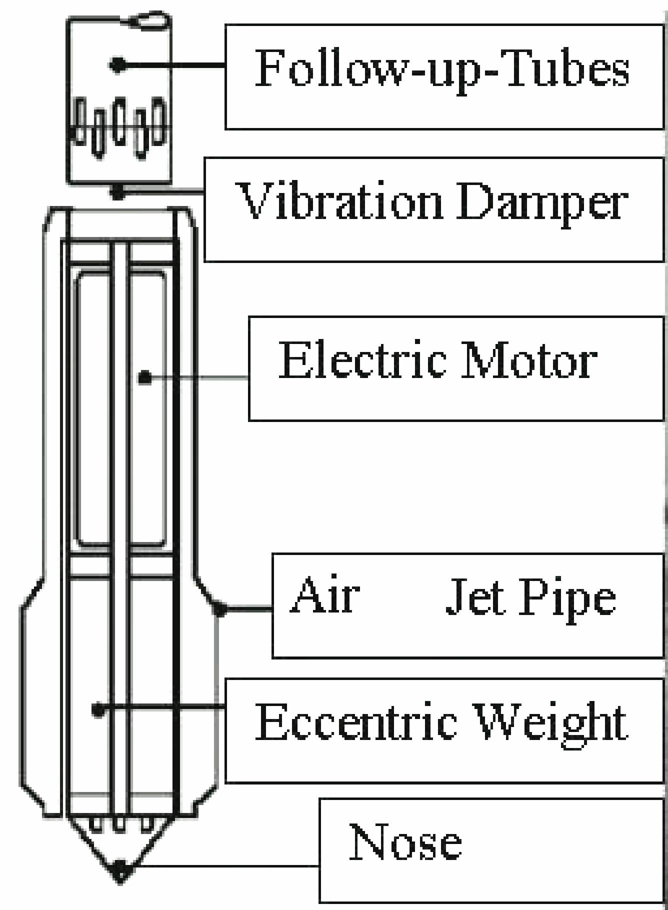

Cross Section Through a Vibroprobe

Vibrator

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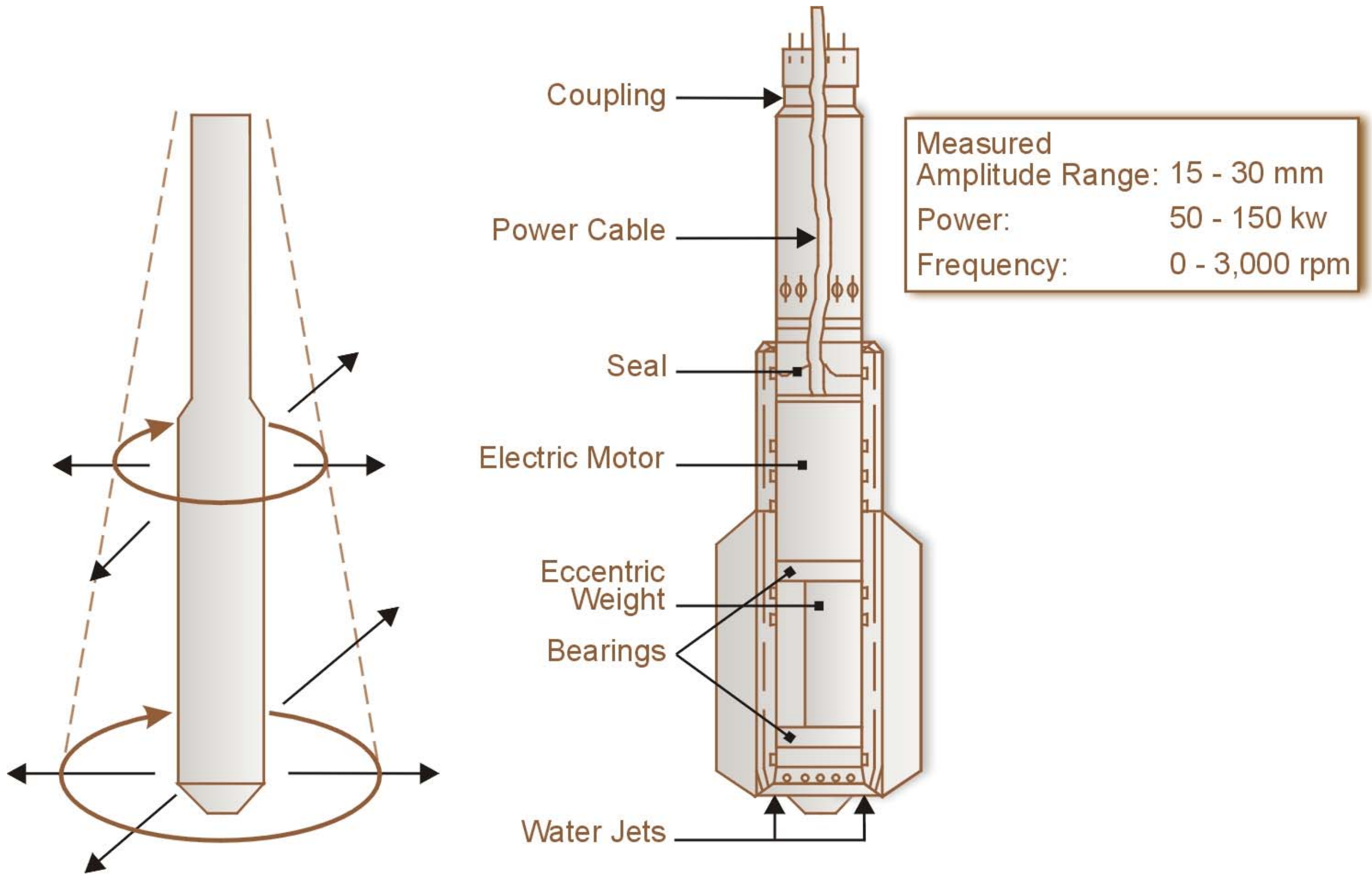

Vibrator Motion

Vibrator Schematic

Vibro Compaction

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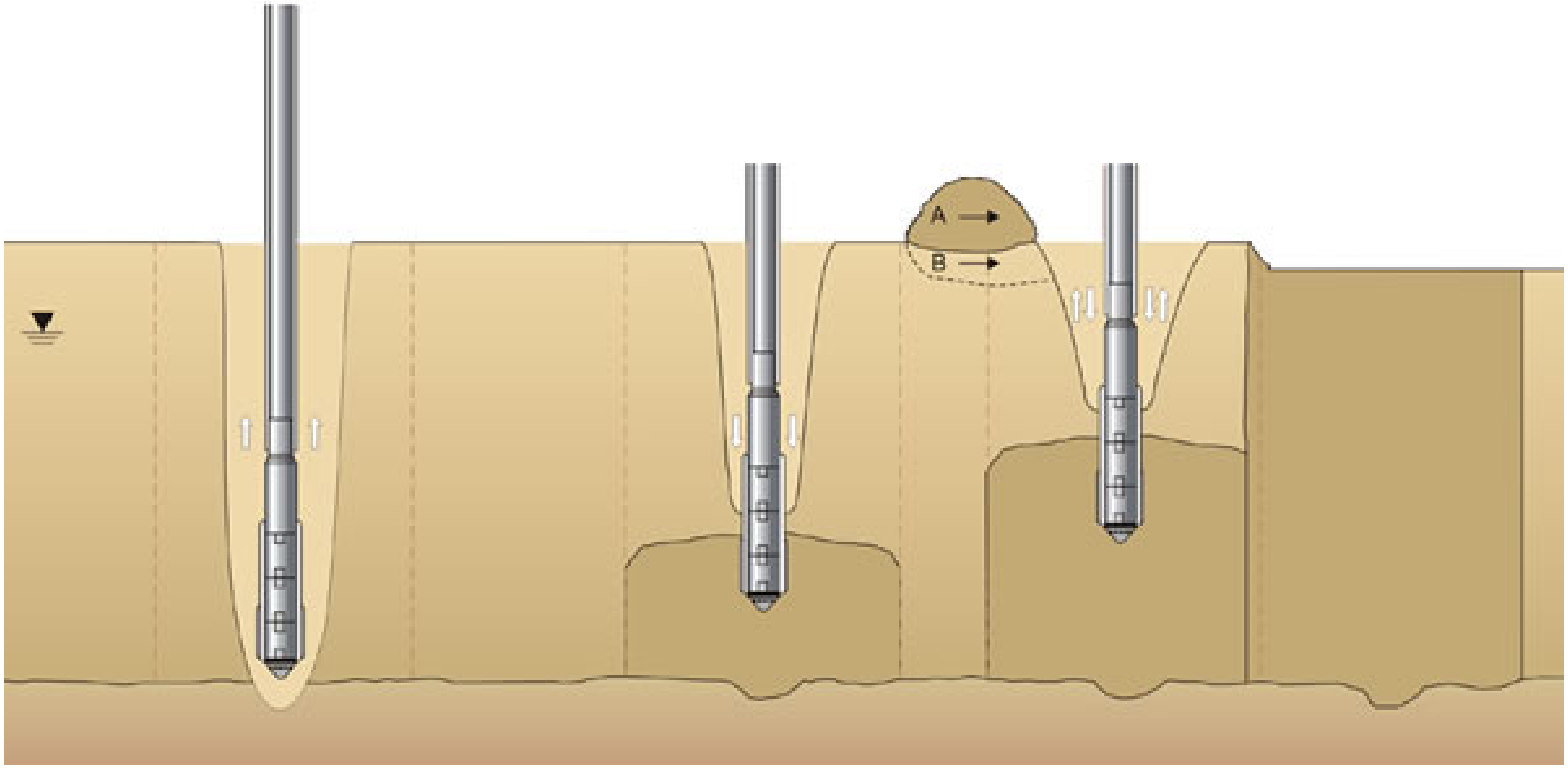
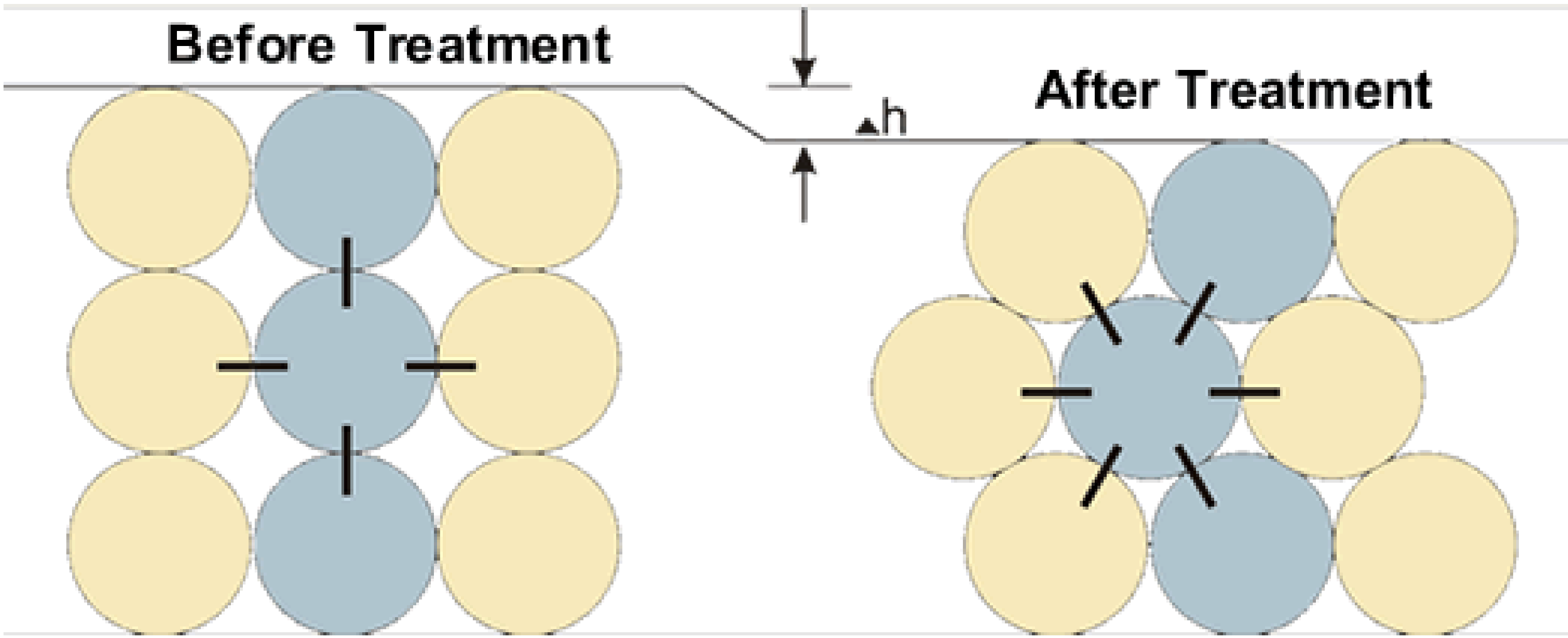


Vibro Systems

Vibro Systems are…

- **used to solve a wide range of static, dynamic and seismic foundation problems through the use of depth vibrators to densify and/or reinforce the soils in situ.**

Vibro Compaction



Vibro Techniques Use…

- specially-designed, poker-type depth vibrators. Extension tubes are added to allow penetration to treatment depths in excess of 100 feet below working grade. The vibrator assembly is typically supported from a standard crane or purpose-built hydraulic crawler crane. Treatment is accomplished over a two to three foot depth interval and the vibrator is then raised to the next level.

Vibro Techniques Use… (Cont'd)

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- This procedure is repeated over the entire depth of treatment. Vibro techniques offer a technically proven and cost effective alternate to deep foundations, allowing a variety of structures to be supported on shallow spread footings.

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Benefits of Vibro Technologies

- Increased bearing capacity
- Increased shear resistance
- Reduced settlement
- Mitigation of liquefaction and lateral spreading
- Uniformity of site after treatment
- Achievement of the specific degree of improvement required by the project
- Cost and time savings over conventional systems
- Can be applied close to existing structures
- In situ treatment, thus avoiding excavation and replacement

Important Vibro-Compaction Soil Parameters

- Ground type and gradation
- Relative density

Range of Soils Treated By Vibro Technologies

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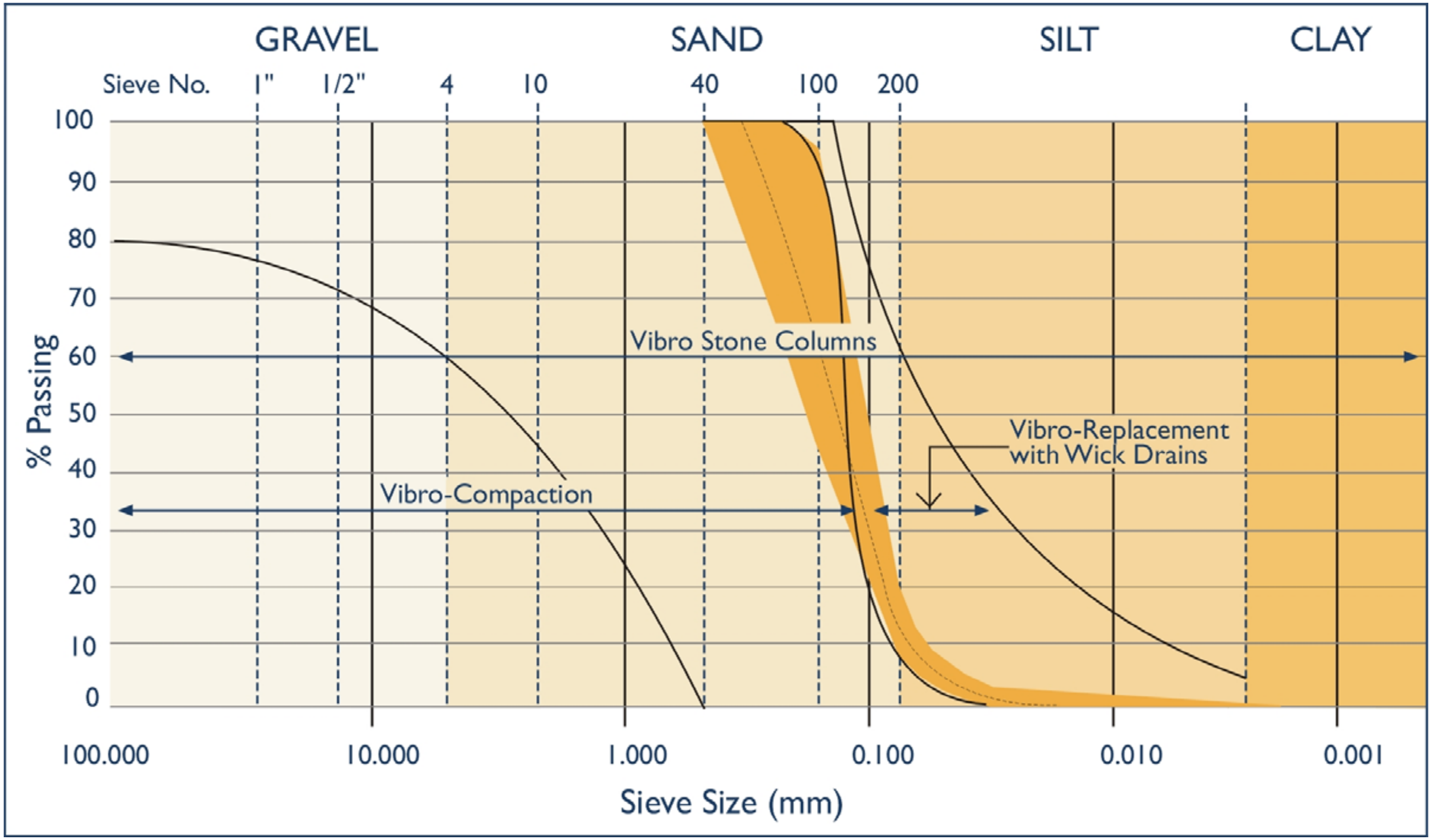
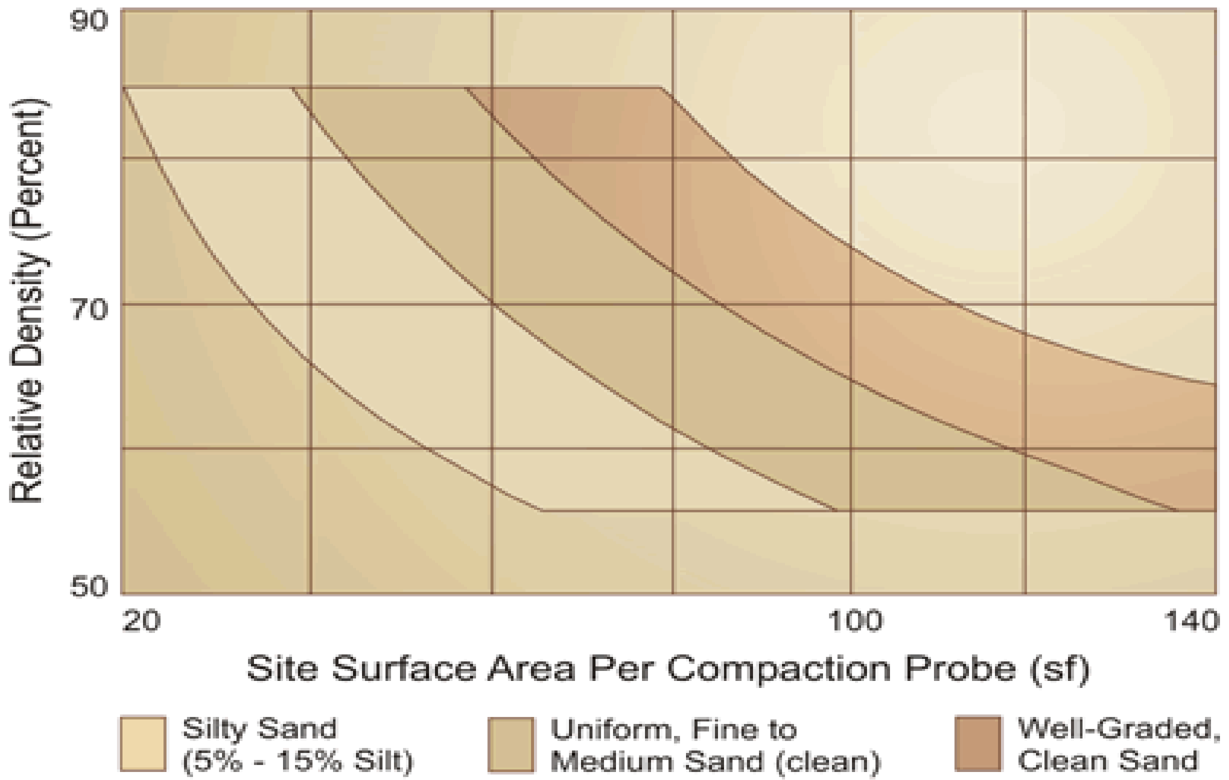


Expected Results

Ground Type	Relative Effectiveness
Sands	Excellent
Silty Sands	Marginal to Good
Silts	Poor
Clays	Not Applicable
Mine Spoils	Good (if clean granular)
Dumped Fill	Dependent On Nature of Fill
Garbage	Not Applicable

Vibro Compaction Effectiveness



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Vibro-Compaction Design Steps

- Perform site investigation
  soil gradation important
- Calculate predicted settlements
  Problem understood
- Establish compaction requirements
  Sufficient densification to reduce settlement and/or prevent liquefaction
- Develop appropriate Vibro-Compaction approach
  Treat entire site or just footing?
- Establish testing criteria
  Relative density, SPT, CPT, PMT, etc.

Vibro-Compaction Quality Control

- Compaction point locations
- Resistance level as measured by amp meter (Vibrator draws more current in denser soils.)
- Quantity of fill added or reduction in site level

Vibro-Compaction Acceptance Testing

- Standard Penetration Test (SPT)
- Cone Penetrometer Test (CPT)
- Pressuremeter Test (PMT)
- Dilatometer Test (DMT)
- Load test

Limitations of SC in – Low permeable Silty Soils

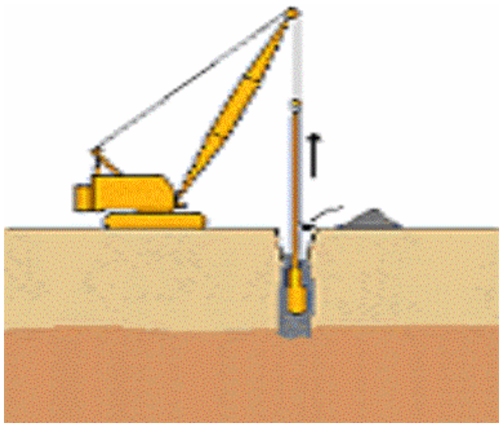
Limitation

- Rapid increase in pore pressure
- Very Slow Dissipation
- Limiting Energy transmitted into the soil
- Little densification

Solution

- Enhance Drainage during Installation
- Increase Energy transmitted
- Increased/Repeated Densification

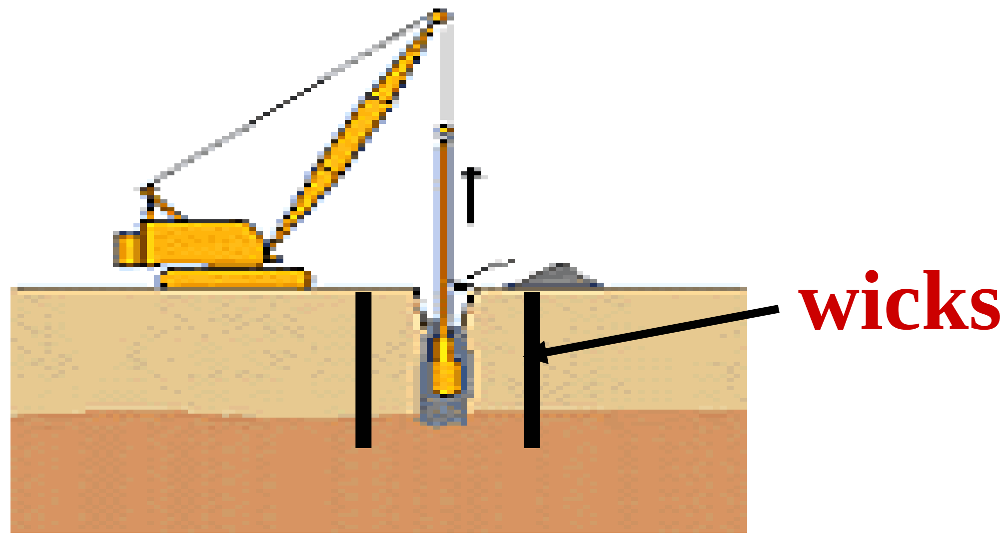
Vibro Stone Columns



- Suitable in Open space conditions
- Design is Empirical

Composite Stone Column

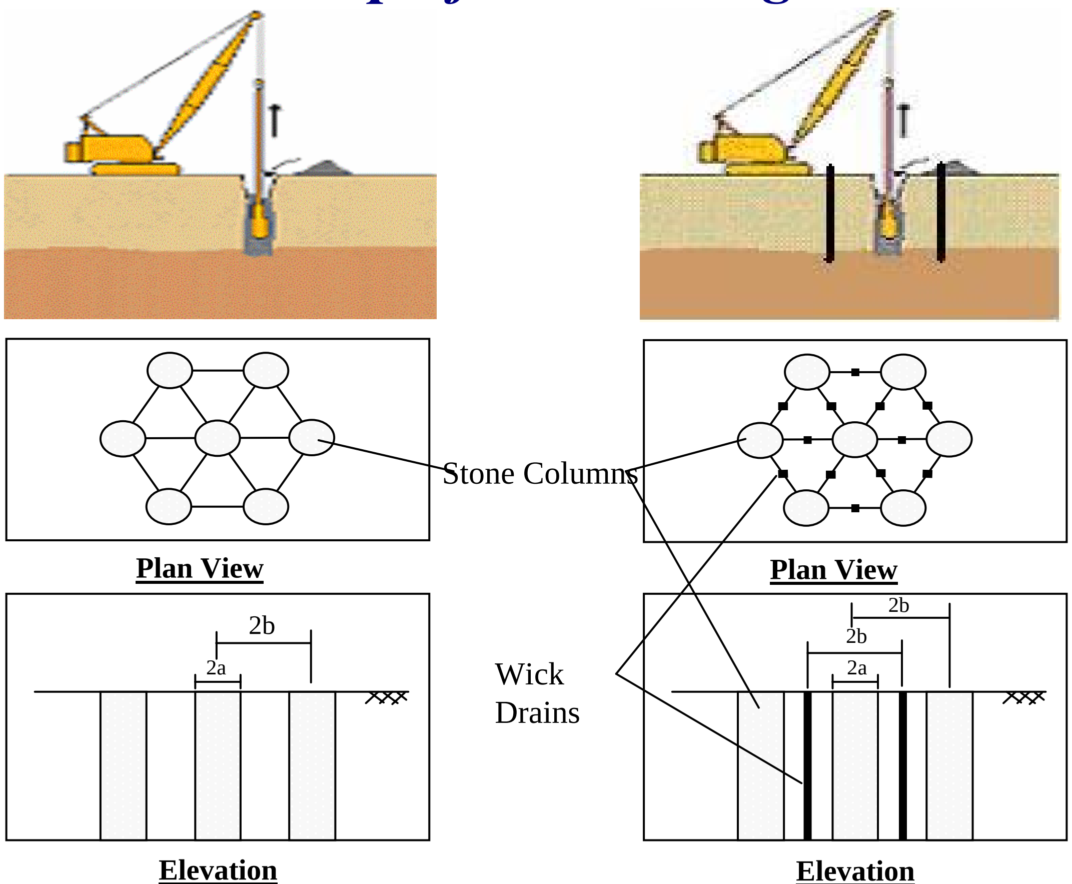
- for Silty soils



– Supplementary wick drains
  - Enhance Drainage & Densification in Silty Soils

Stone Columns
& Wick Drains

- For Liquefaction Mitigation



W/O Wick Drains
(For Sand Deposits with Little or No Fines)

W Wick Drains
(For Non-Plastic Silty Deposits)

Soil Densification – Stone Column

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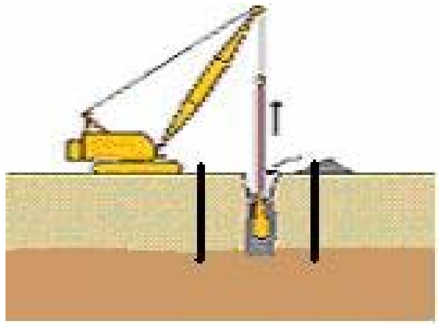
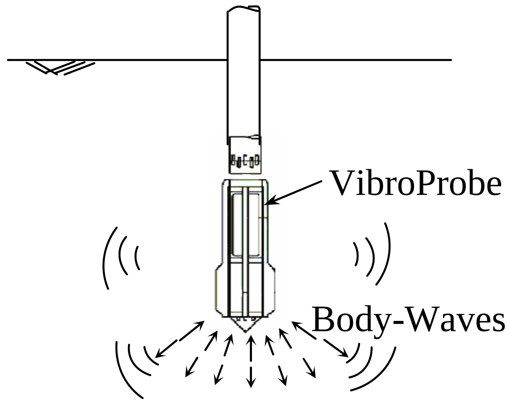
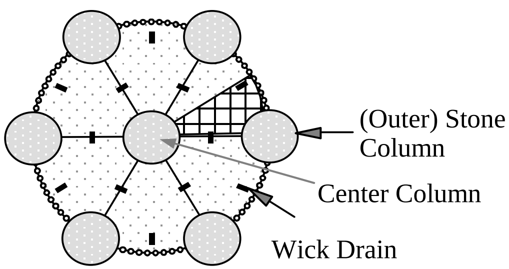
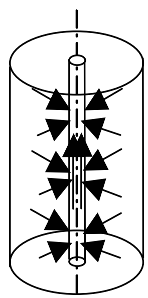


Vibratory energy delivery

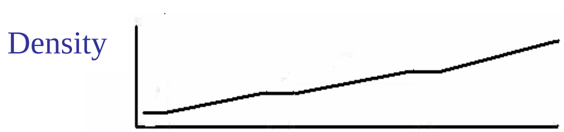


Energy dissipation &
Pore pressure generation





Pore pressure dissipation (with wick drains)



Densification & increase in
liquefaction resistance

Stone Column w/ Wick Drains

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– Test Section: San Diego: Silt

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Goal

Develop an improved remediation technique and design method to mitigate liquefaction hazards in silty soils using stone columns

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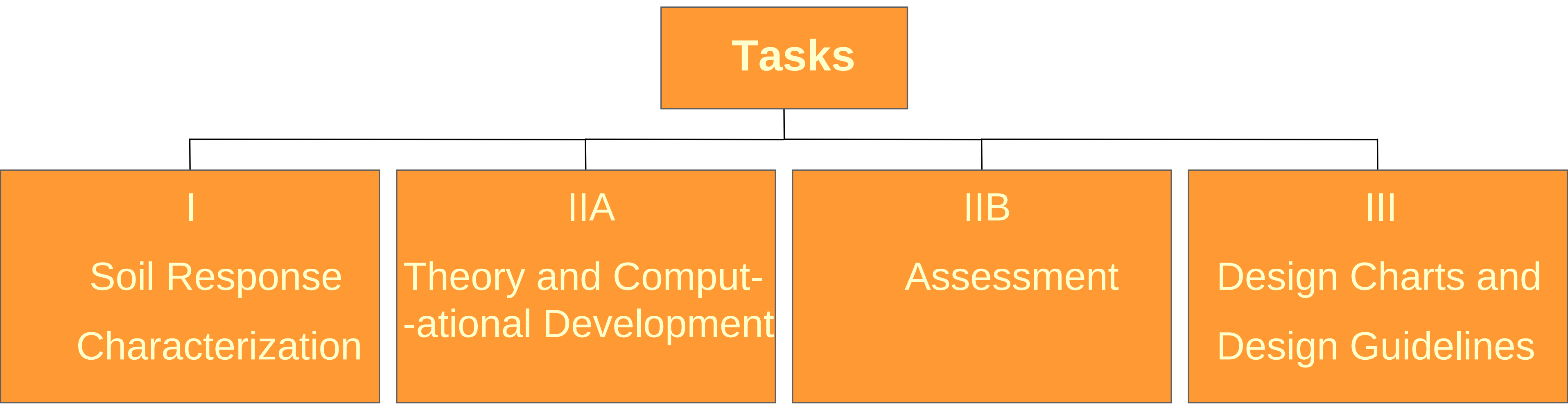
Why Stone Columns?

Benefits of Stone Columns

- **Drainage**
  During Installation, and During Earthq.
- **Densification**
  During Installation
- **Reinforcing Elements**
  -Reduces the Sh. Stress Felt by the Surr. Soil During Earthq.-

What is Needed?



Task I

Soil Response Characterization (Experimental Study)

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- Cyclic Strength and Liquefaction Behavior of Silty Soils
- Pore Pressure Generation, Post-Liquefaction Dissipation, and Densification
- Hydraulic Conductivity, Compressibility, Coefficient of Consolidation

Task IIA

Theory and Computational Development

- Pore Pressure Generation
  - Energy Dissipation & Pore Pressure Generation
  - Cavity Expansion & Pore Pressure Generation

- Pore Pressure Dissipation & Densification

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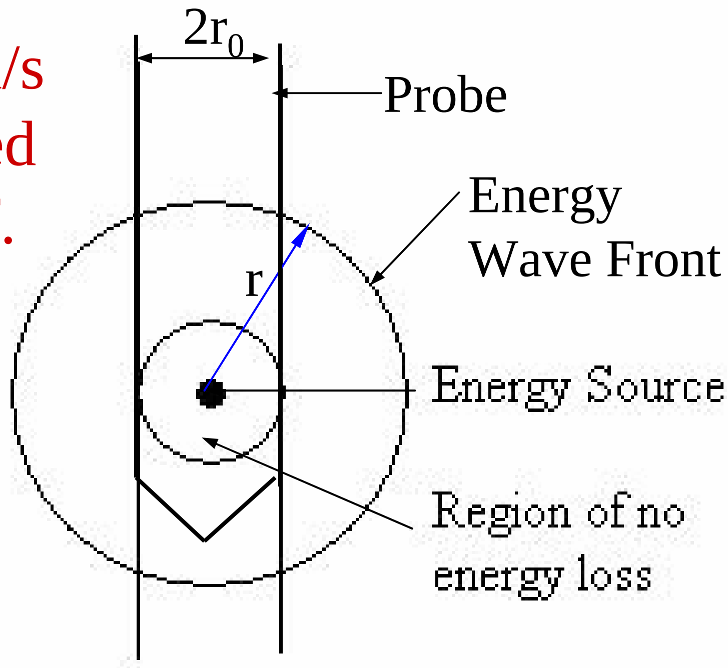
Energy Dissipation & Pore Pressure Generation

Simplified Energy Attenuation Model

$$W = \frac{W_0}{4\pi r^2} Exp\left[-2\alpha(r - r_0)\right]$$

W=Energy/unit area/s
W0=Energy Imparted
α=Attenuation Coef.



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Dissipated Energy

$$w = W_0 \frac{\alpha}{2\pi r^2} Exp\left[-2\alpha\left(r - r_0\right)\right]$$

w=Dissipated Energy/unit Volume/s

W_0 depends on soil strength.

As pore pressure increases, strength decreases.

$$w = W_0 \frac{\alpha}{2\pi r^2} Exp\left[-2\alpha\left(r - r_0\right)\right].Exp\left[-\beta\left(r_u\right)_{av}\right]$$

r_u=Pore Pressure Ratio=$\Delta u_e/\sigma_0'$

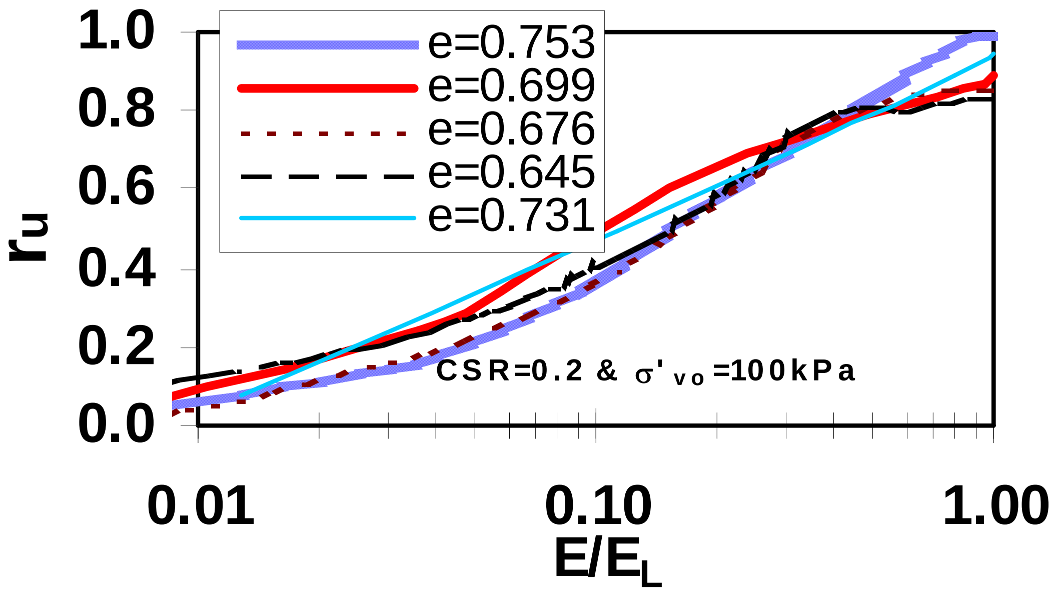
u_e=Excess Pore Pressure; σ_0'=Initial Effective Confining Pressure

β=Constant

W_0=Probe Efficiency * Power Rating

Energy-Based Liquefaction Model

$$\mathbf{r_u} = 0.5\mathbf{Log}_{10}\left(100\mathbf{E}/\mathbf{E_L}\right)$$



E=Cumulative Dissipated Energy

E_L=Energy to Cause Liquefaction

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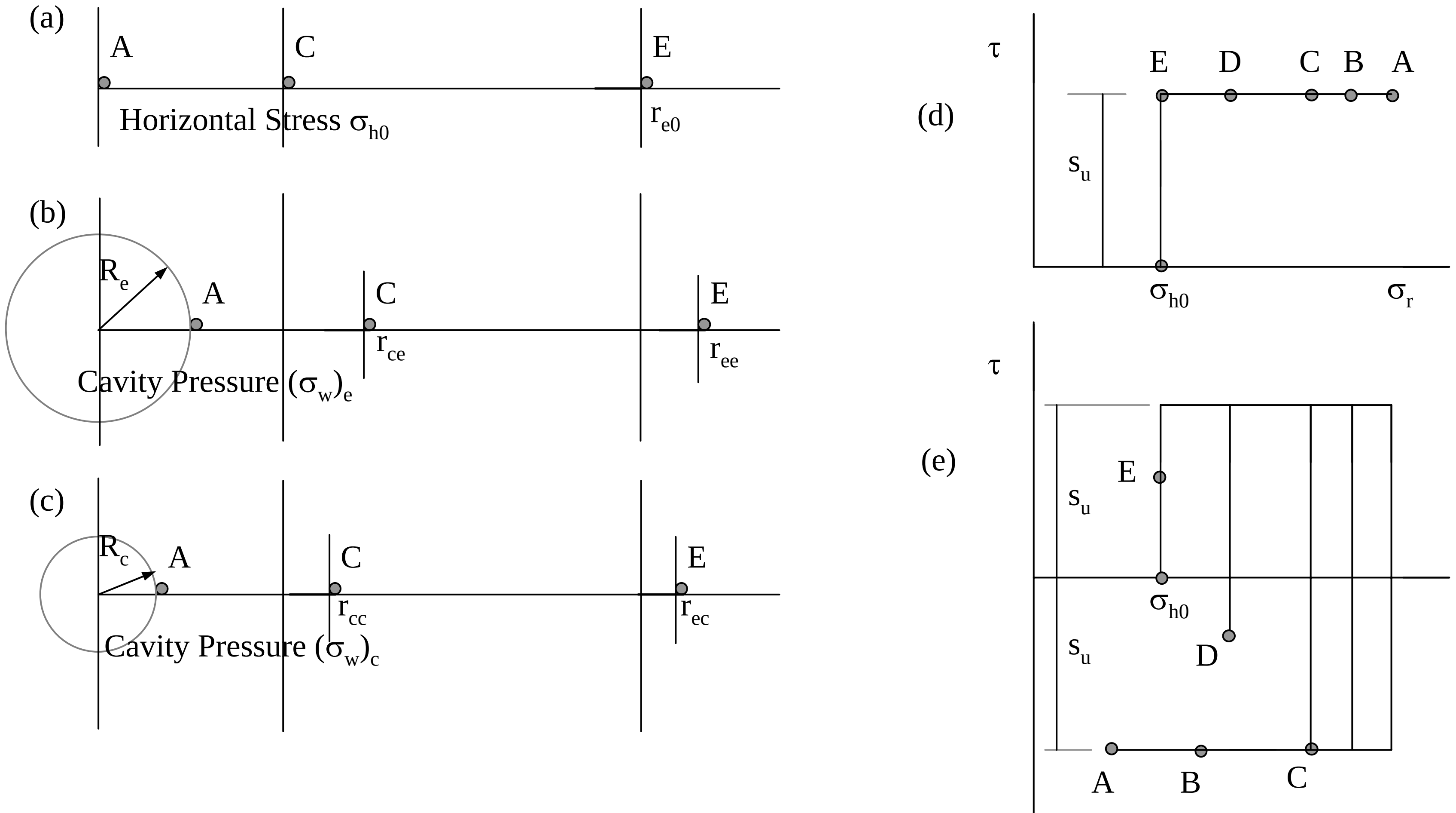
Cavity Expansion & Pore Pressure Generation

Cavity Expansion

During Stone Column Installation



Definition of Radii Used in Analysis, and Stress States Around the Vibratory Probe

Pore Pressure Due to Cavity Expansion

$$u_e = 2S_u \ln\left[\frac{r_{ee}}{r}\right] + u_{sh} \qquad for \qquad r \le r_{ee}$$

$$0 \qquad for \qquad r > r_{ee}$$

Pore Pressure Due to Cavity Contraction

$$u_e = 0.5\left(\sigma_r(r) + \sigma_\theta(r) - 2\sigma_{h0}\right) + u_{sh} \qquad for \qquad r \le r_{cc}$$

$$0.5\left(\sigma_r(r) + \sigma_\theta(r) - 2\sigma_{h0}\right) \qquad for \qquad r > r_{cc}$$

$$r_{ee} = R_e \sqrt{I_r}$$

$$r_{cc} = R_c \sqrt{\frac{\exp\left\{\frac{2}{I_r}\right\} - 1}{\exp\left\{2\ln\left[\frac{R_e}{R_c}\right]\right\} - 1}}$$

I_r=Rigidity Index=G/S_u

u_{sh} =Shear Induced Pore Pressure

Shear Induced Pore Pressure

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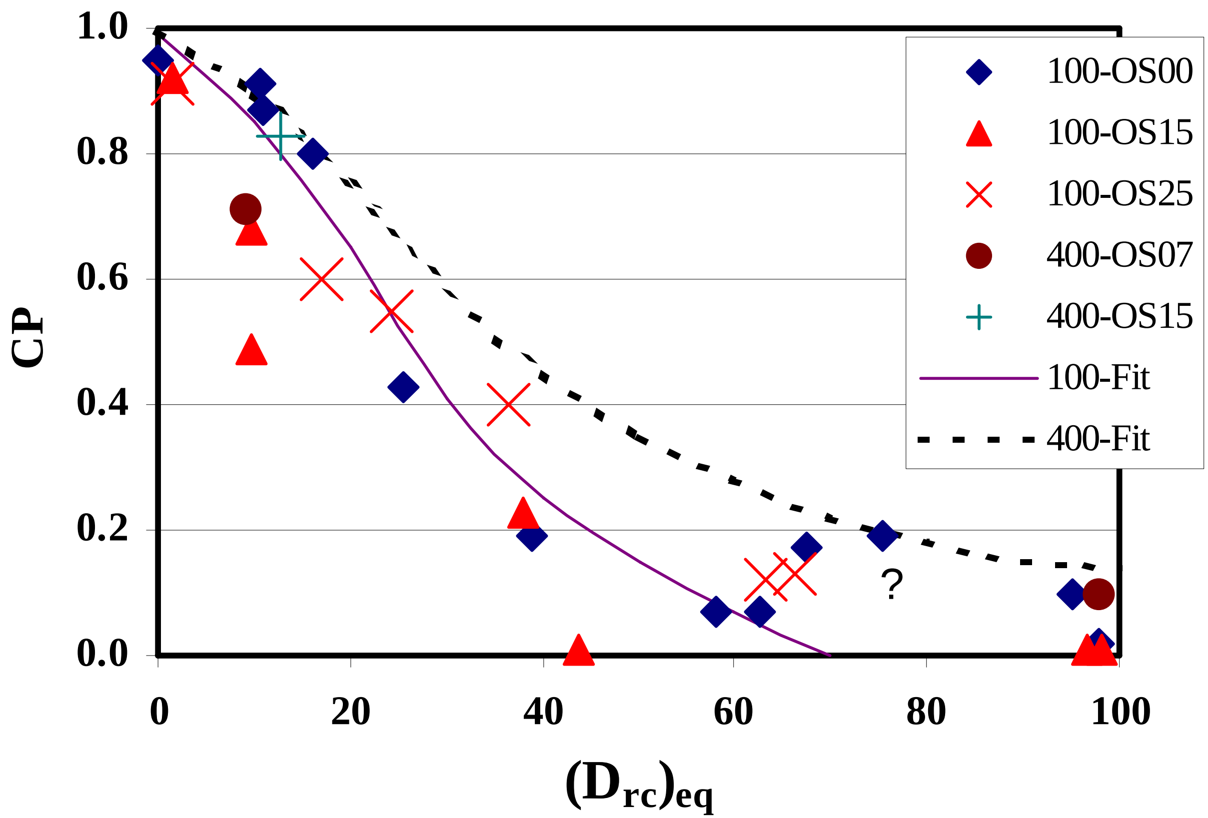
$$u_{sh} = CP * \sigma_0^{'}$$

CP=Collapse Potential



Pore Pressure Dissipation

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Governing Equation

$$\frac{\partial u}{\partial t}=\frac{k_h}{\gamma_w m_v}\left(\frac{\partial^2 u}{\partial r^2}+\frac{1}{r}\frac{\partial u}{\partial r}+\frac{1}{r^2}\frac{\partial^2 u}{\partial \theta^2}\right)+\frac{k_v}{\gamma_w m_v}\frac{\partial^2 u}{\partial z^2}+\frac{\partial u_g}{\partial t}$$

- k_h & k_v = horizontal and vertical hydraulic conductivities, respectively
- m_v = coefficient of volume compressibility
- u = pore pressure
- u_g = pore pressure generated
- γ_w = unit weight of water

Densification

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$$\varepsilon_v = \int m_v . d\sigma'$$

ε_v = Volumetric Strain

m_v Changes with Shear Induced Excess Pore Pressure

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Numerical Simulations

- Vibratory energy - Pore Pressure Generation, Dissipation, & Densification

- Cavity Expansion – Pore Pressure Generation, Dissipation, & Densification

Simulated Region

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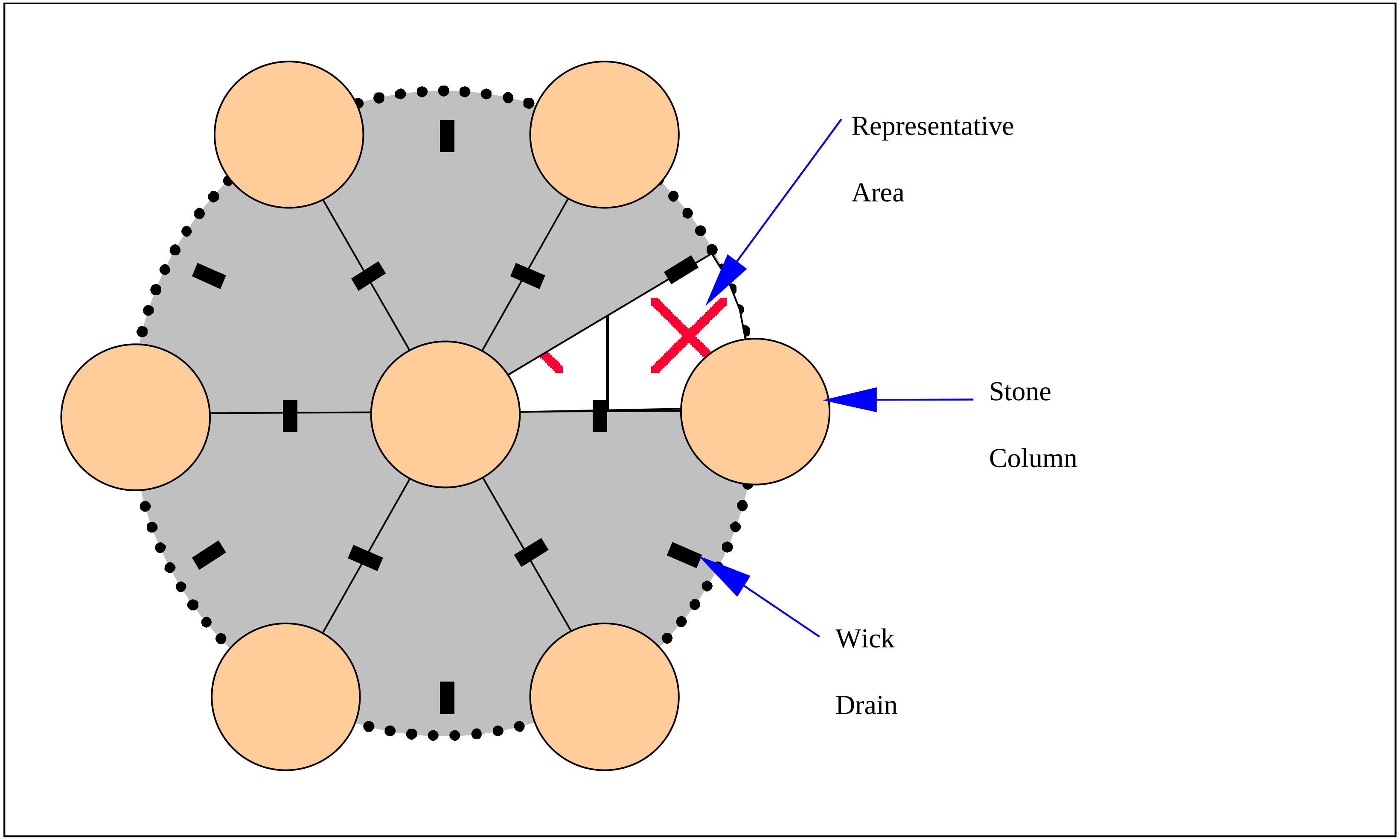
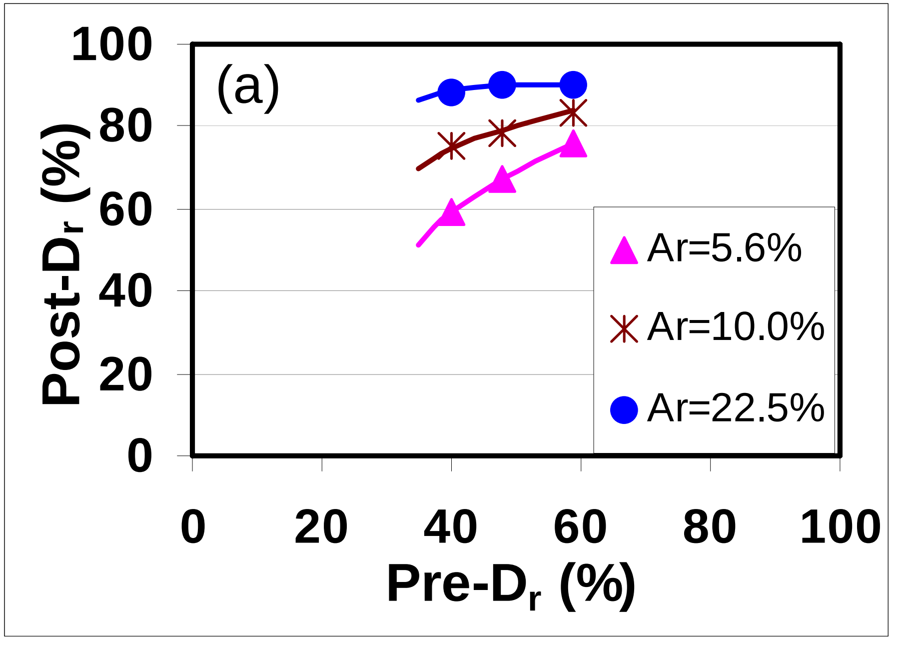
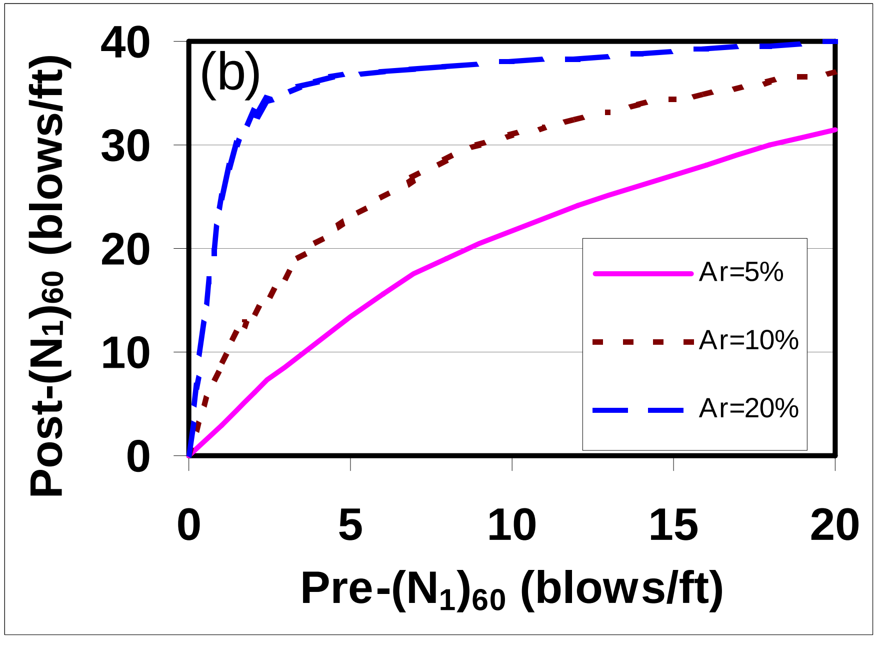


Densification Considering Vibratory Energy only

Simulation Results – Stone Columns: Sand





(a) This Study **(b) Field Data - Design Curves (Baez 1995)**

Effect of Initial Density & Spacing on Post-Improvement Densification

Simulation Results – Stone column & Wicks – Silty Soils

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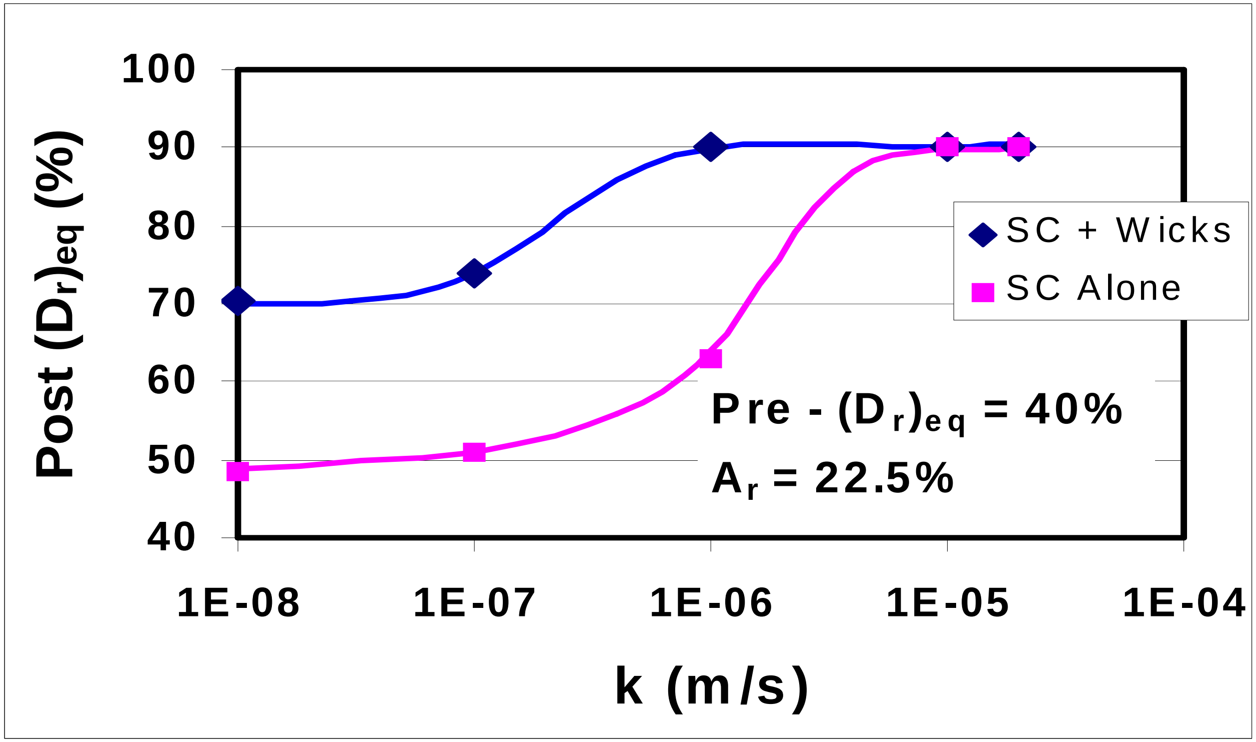
← Increasing Silt %



Effect of Silt Content (& k)

A_r = 22.5% - Small spacing, S=1.8m, D=0.9m

Simulation Results – Stone column & Wicks – Silty Soils

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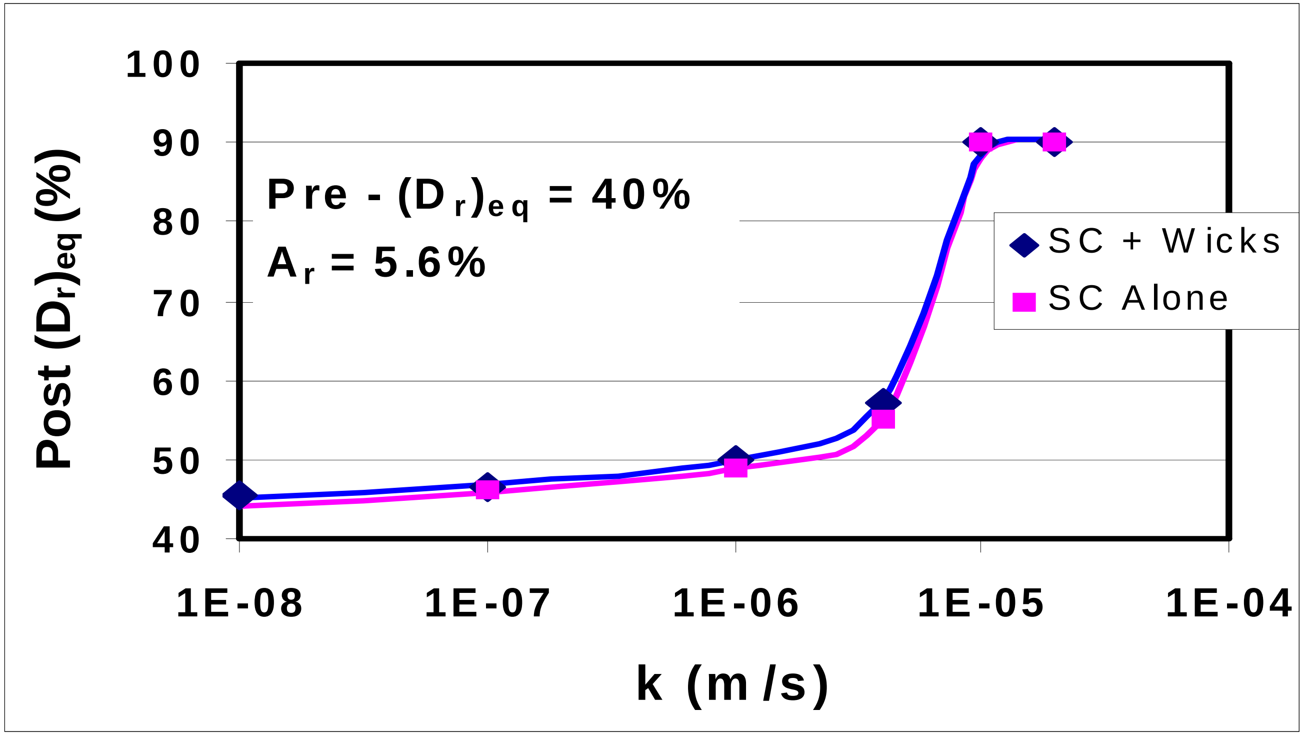

Effect of Silt Content (&k) on Densification

A_r = 5.6% (Large Spacing S=3.6m, D=0.9m)

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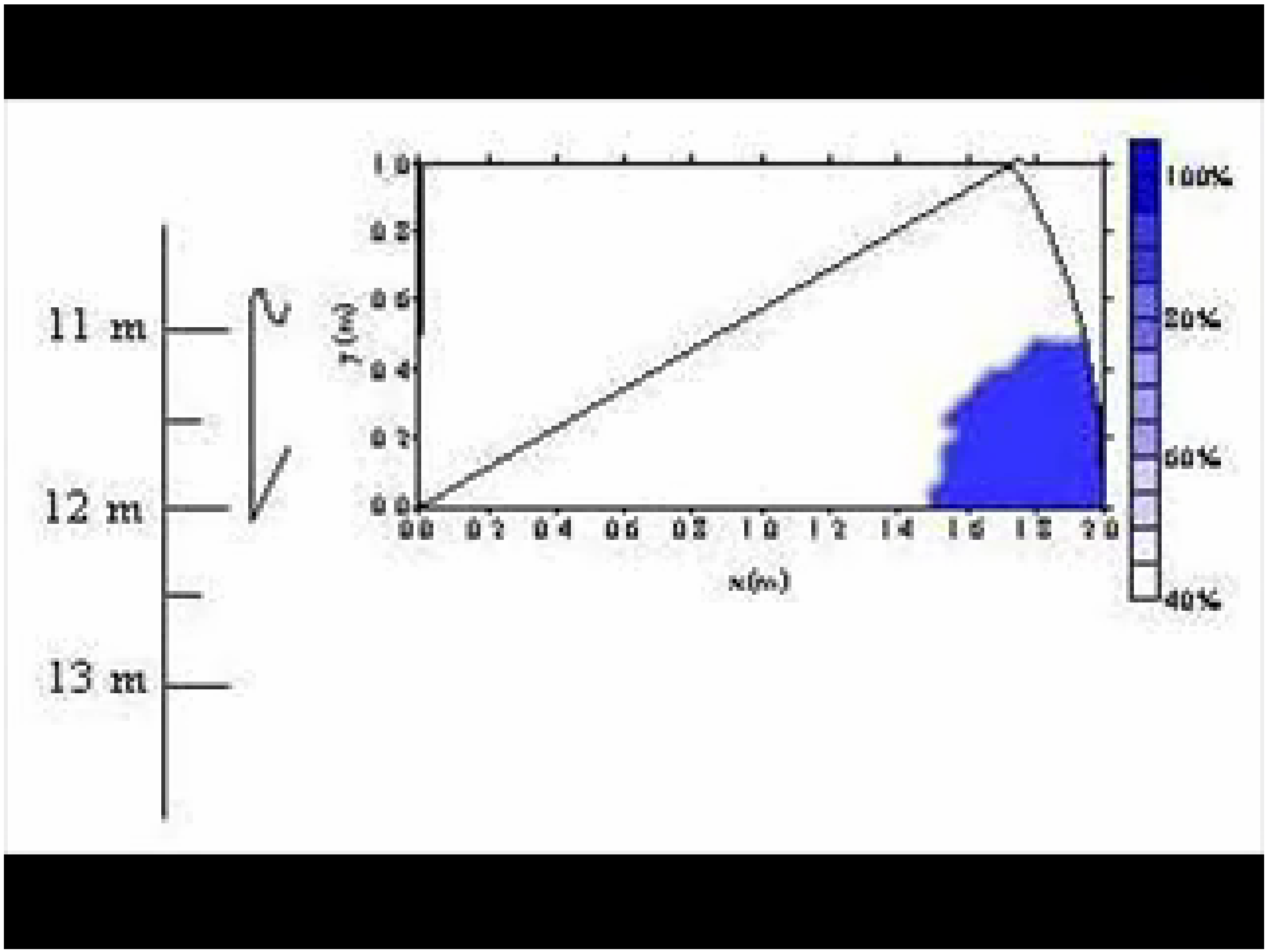
Changes in Soil Density during Stone Column Installation - Movie



Densification Due to Cavity Expansion

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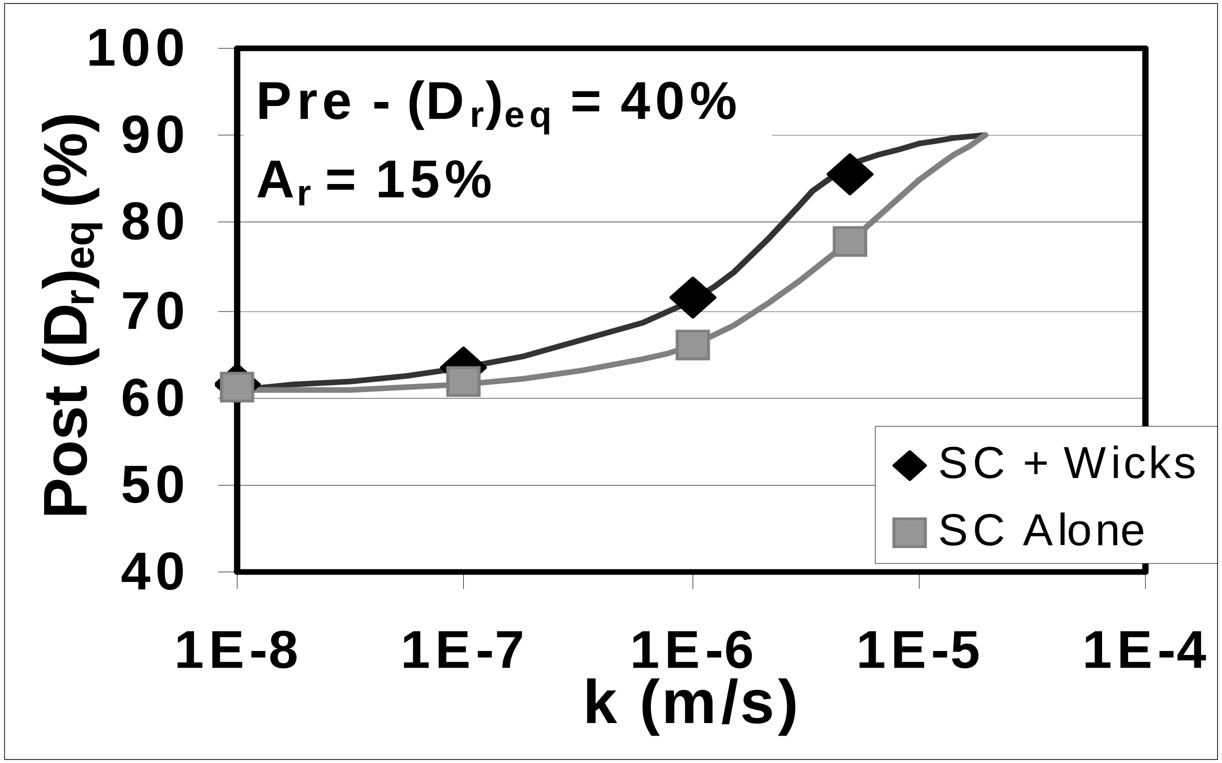
← Increasing Silt Content %



Effect of Cavity Expansion on densification may be significant

(S=2.3m, D=0.95m)

Summary

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- A numerical model to analyze densification of saturated silty soils during stone column installation has been developed.
- Post-improvement densities due to the coupled effect of both cavity expansion and vibratory energy should be higher than those obtained by considering either one individually. However, pore pressure generation due to cavity expansion would reduce the rate of vibratory energy imparted into the soil. Therefore the effect of cavity expansion has been qualitatively omitted in developing design charts.
- Silty soils up to k > 10^{-8} m/s can be densified using stone column & wick drains.
- Stone columns & wick drains are highly effective at Area replacement Ratio A_r > about 20% (small column spacing).
- Simulations (without wicks) agree with Field Data for sands.
- Simulations (with wicks) need to be verified using case histories or field test data.

Task IIB

Assessment

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- Case Histories
- Field Tests

Field Data Collection

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Past Records:

Monterey Site, CA:

Test section consisted of mostly clean sand; 0.9m diameter vibro stone columns were installed at about 5mx5m grids.

Salmon Lake Dam Site, CO:

Site consisted of mostly sandy silt with silt content more than 60%; vibro stone columns with supplementary wick drains were installed at triangular pattern.

Lopez Dam Site, CA:

Sections of the site consisted of silty sand, while most of the area consisted of sands; vibro stone columns were installed at triangular pattern.

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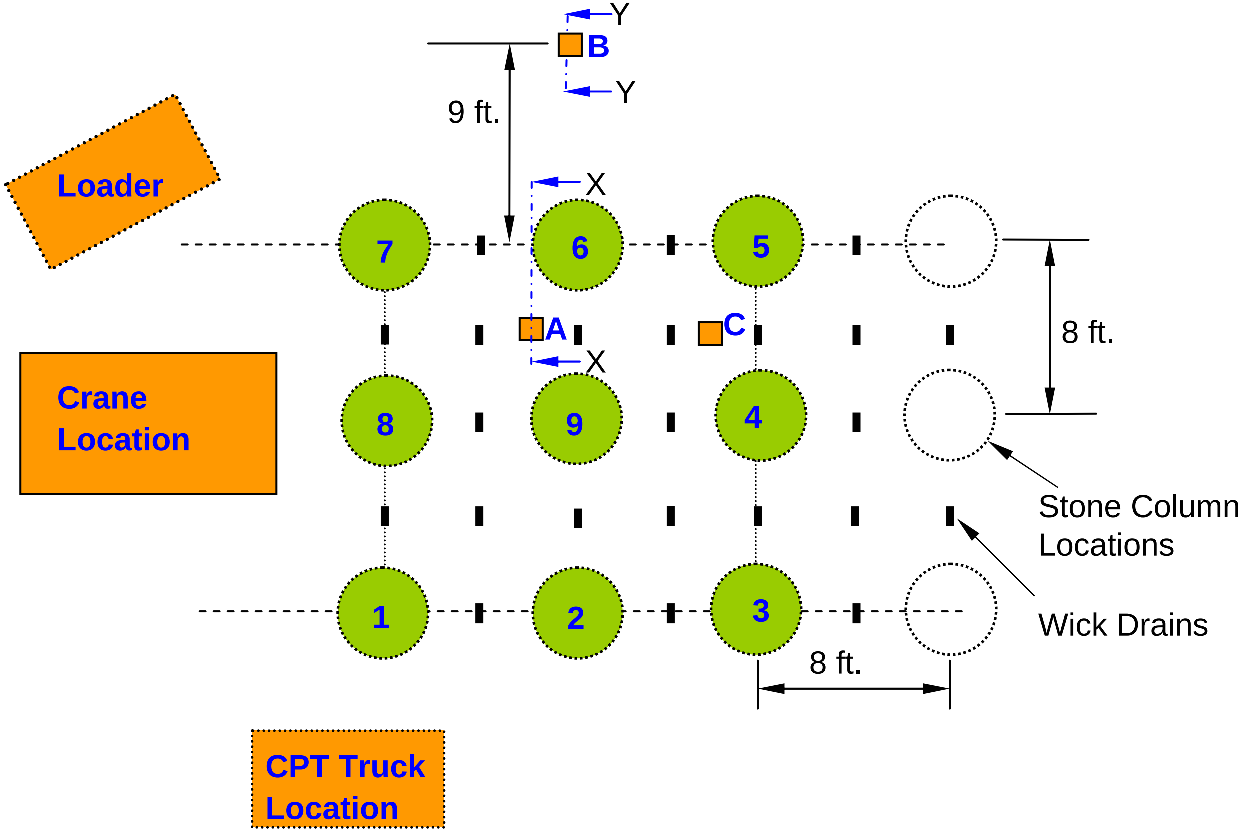
Field Test

Marina Del Ray, CA: Completed in April 2004

In collaboration with:

Hayward Baker, Inc. (and Advanced Geosolutions, Inc.), & UCLA

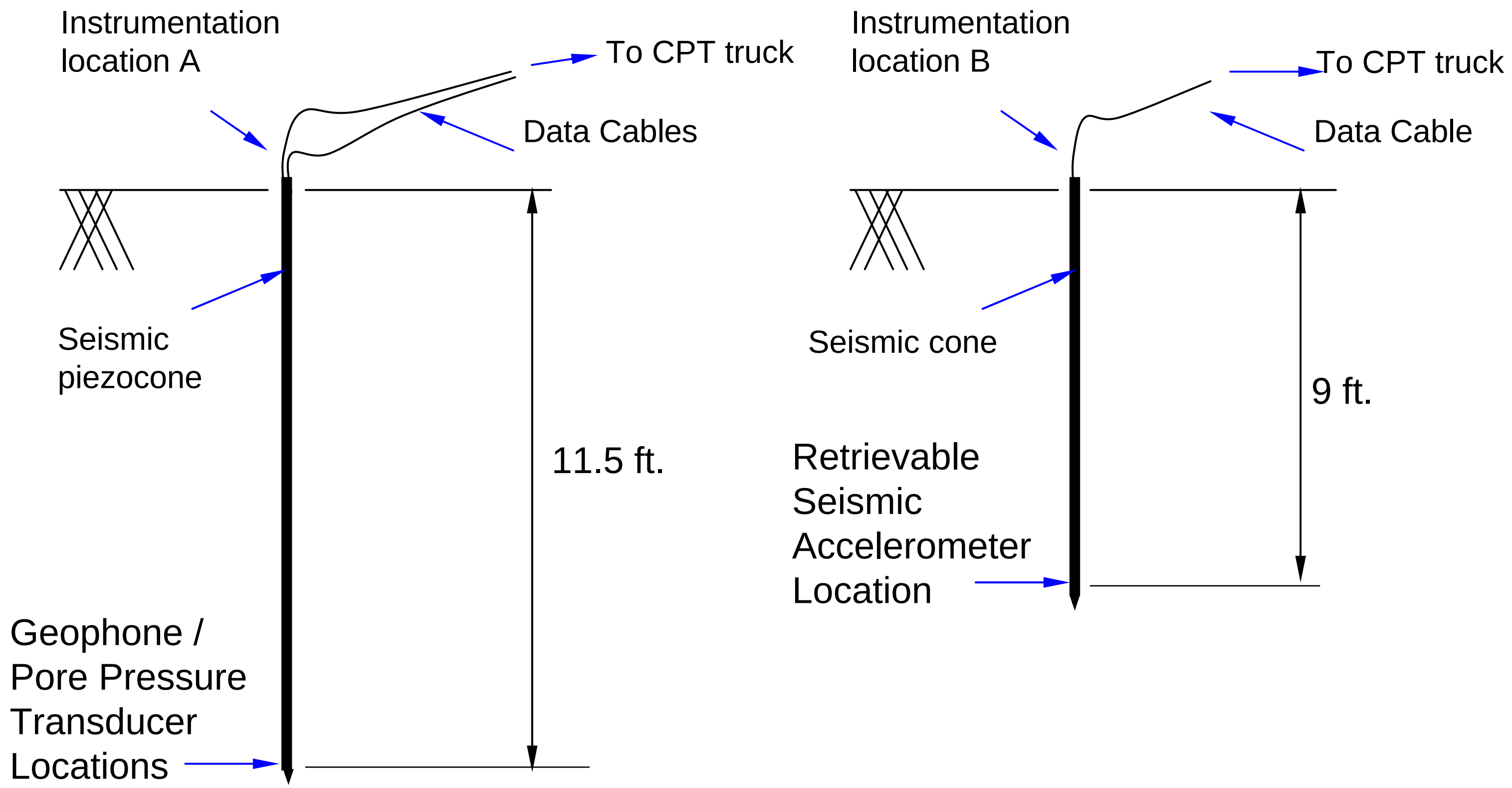
Field Data Collection



<u>Plan View</u>

Schematic Site Layout & Instrumentation Location – Marina Del Rey, CA

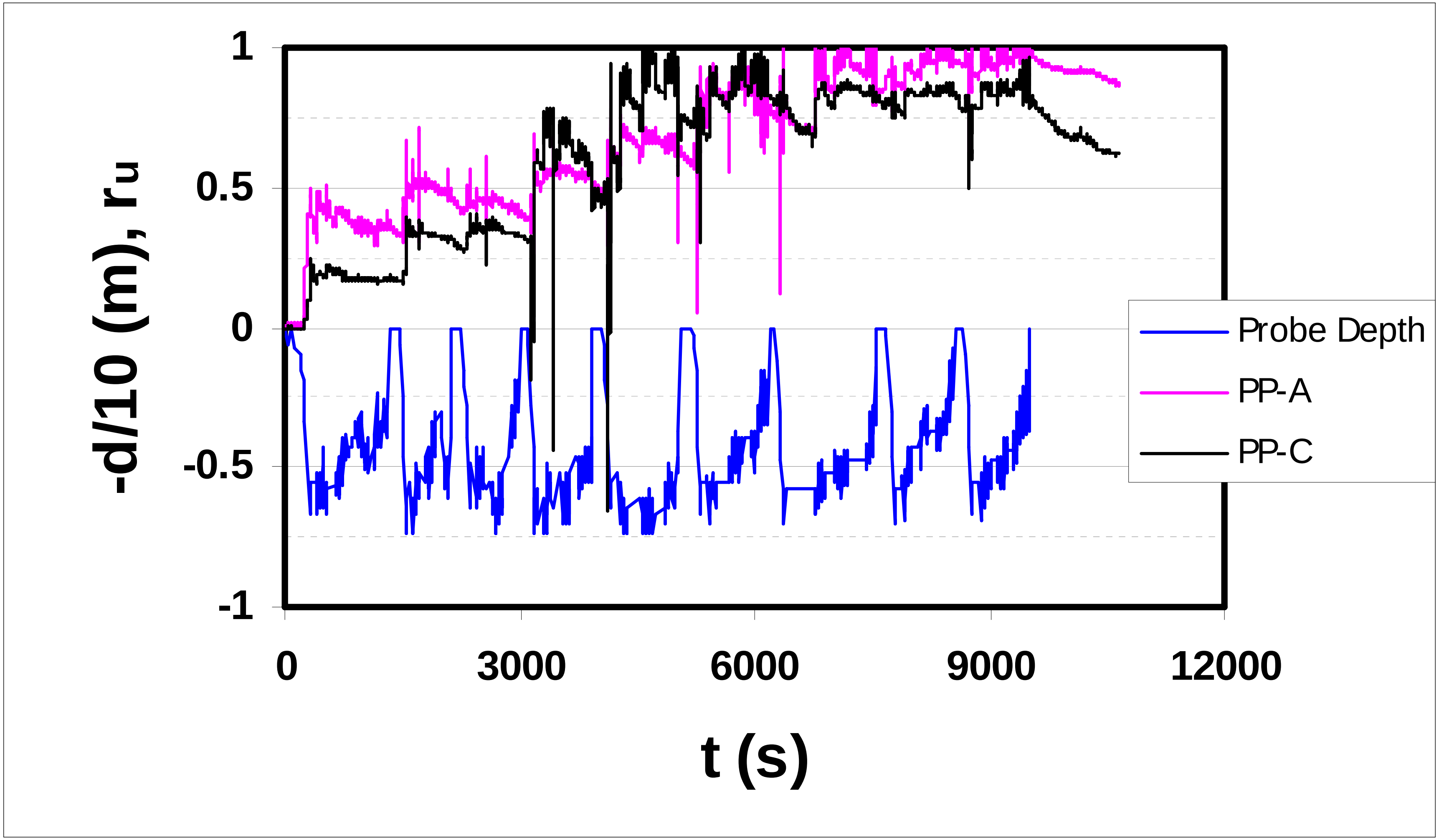
Field Data Collection



Schematic Profiles Through Instrumentation Locations A and B

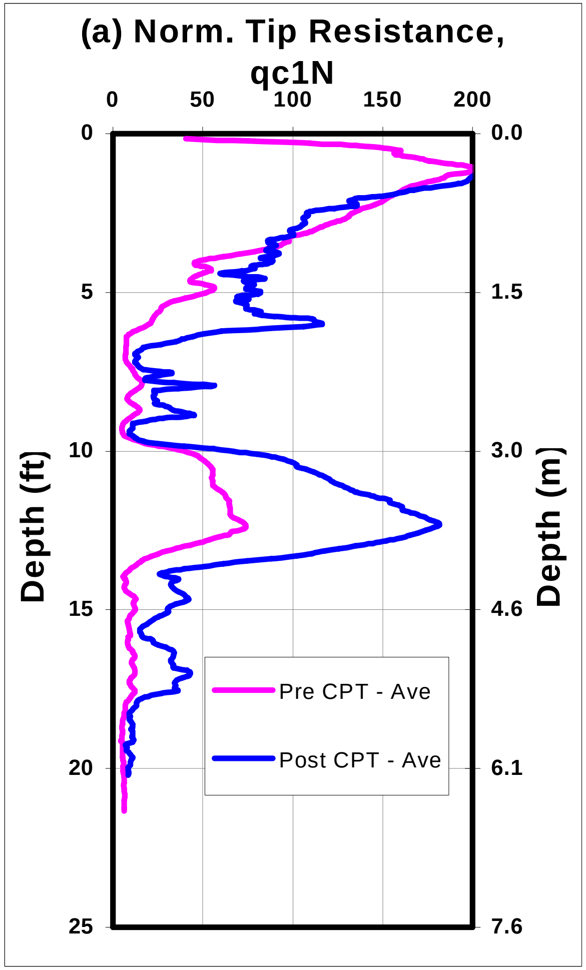
Pore Pressure Response at A & C

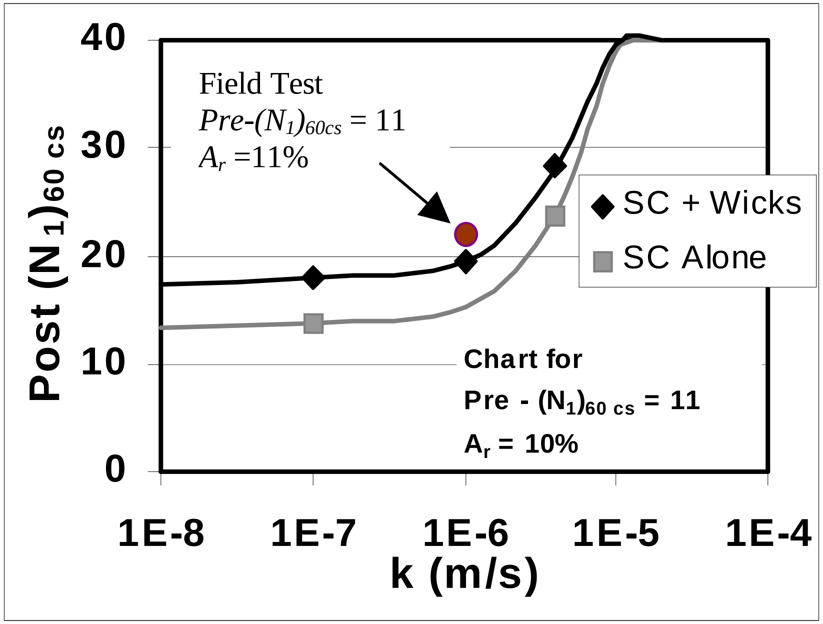
Marina del Ray, Los Angeles



Pore Pressure Response at A & C

Marina del Ray, Los Angeles





Finding

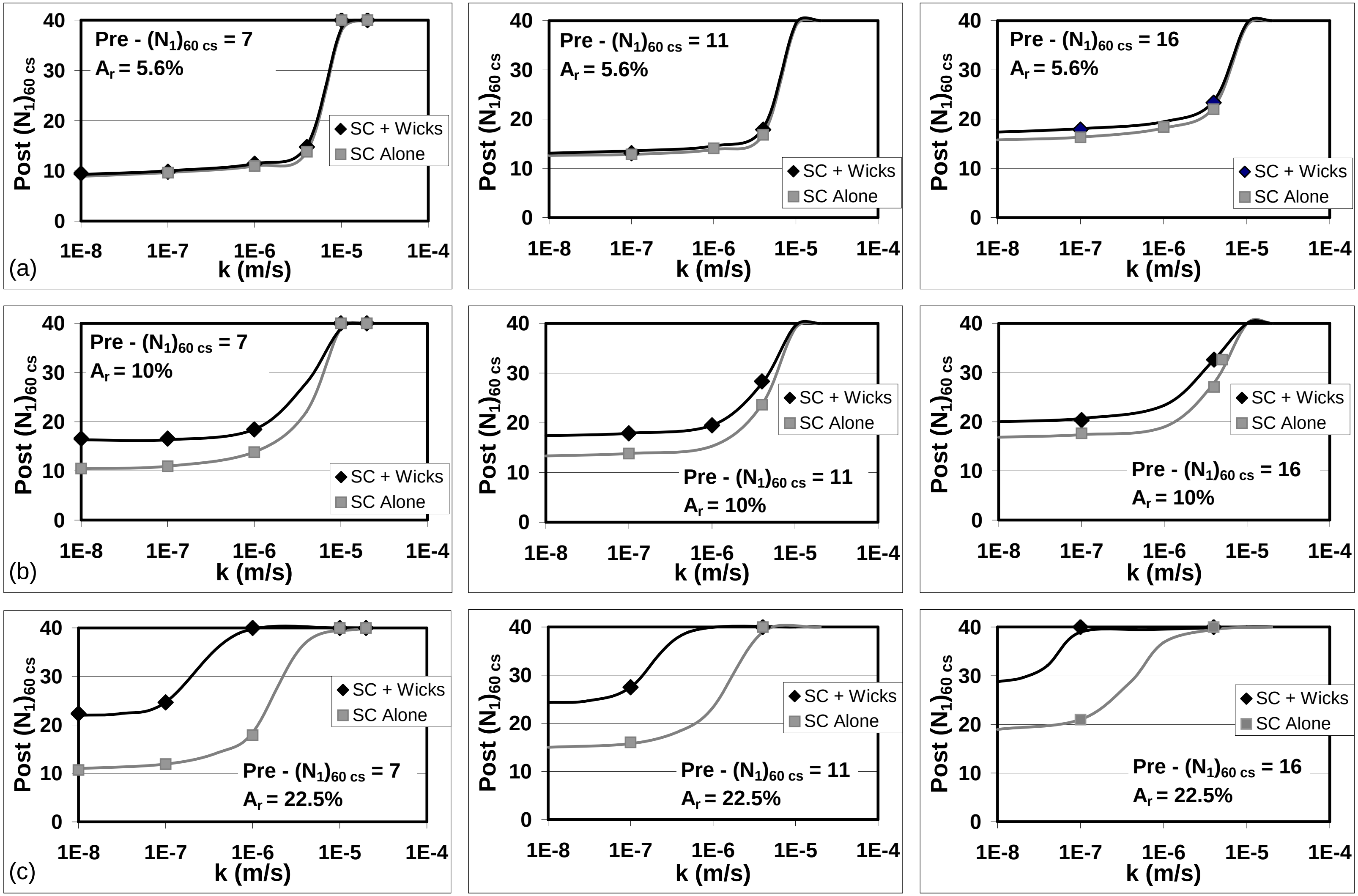
- **Simulations (w/ wicks) also agree with Field data**

Task III

Design Charts

- Developed Design Charts for Sands and Silty Soils with Various Pre-Improvement Relative Densities
- Converted Relative Densities into Equivalent SPT Blow Counts to be In-Line with General Practice
- Developed Easy-to-Follow Design Guidelines

S. C. Design Charts



Design Charts for initial $(N_1)_{60cs}$ of 7, 11, & 16

S. C. Design Charts

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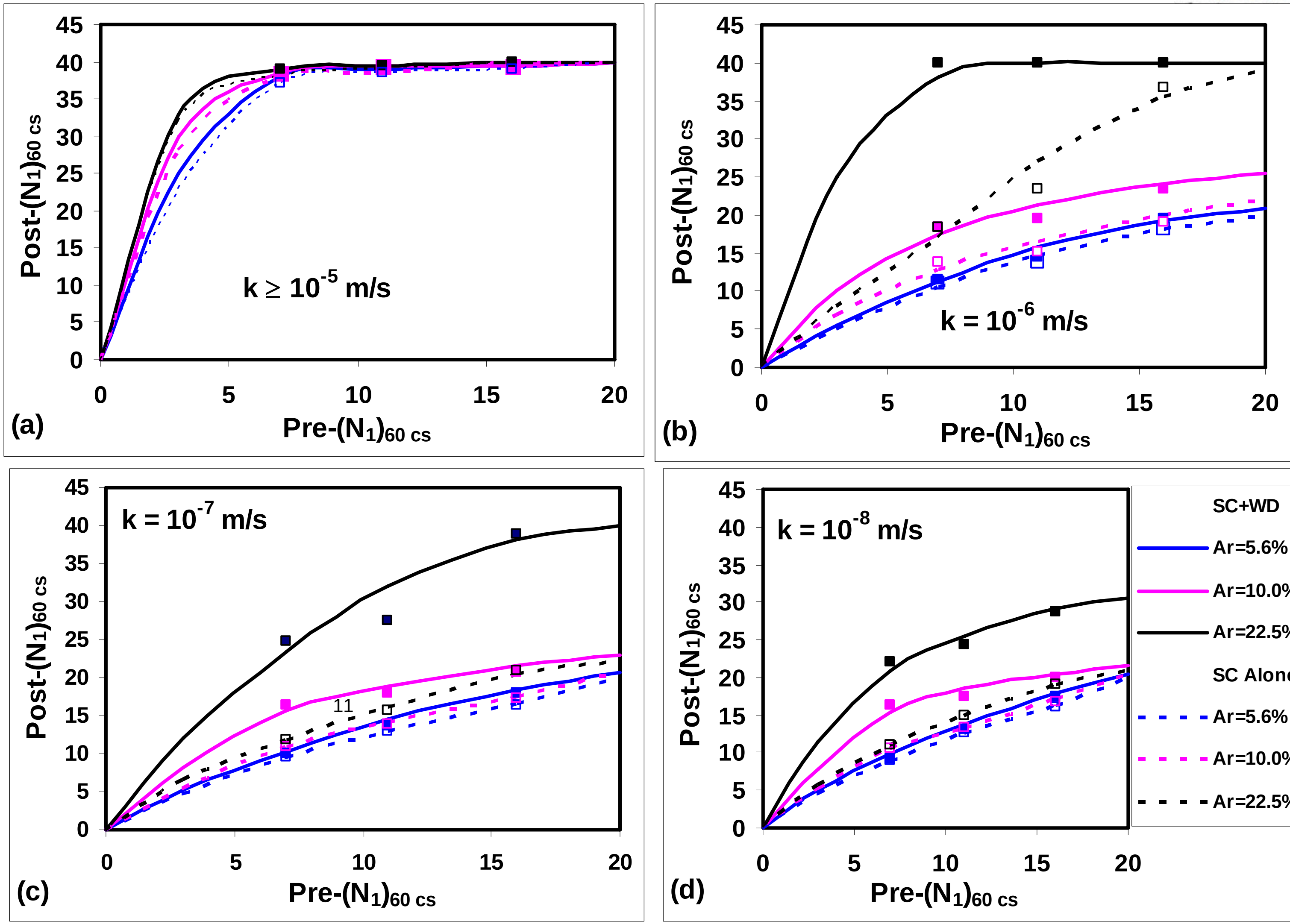


Design Charts for initial $(N_1)_{60cs}$ of 7, 11, & 16

A — **Required Improvement**

Min. $(N_1)_{60cs}$ or $(D_r)_{eq}$

↓

B — **Input Soil Parameters**

k , FC, avg. $(N_1)_{60cs}$
for the deposit to be improved
Find $(D_r)_{eq}$ from $(N_1)_{60cs}$

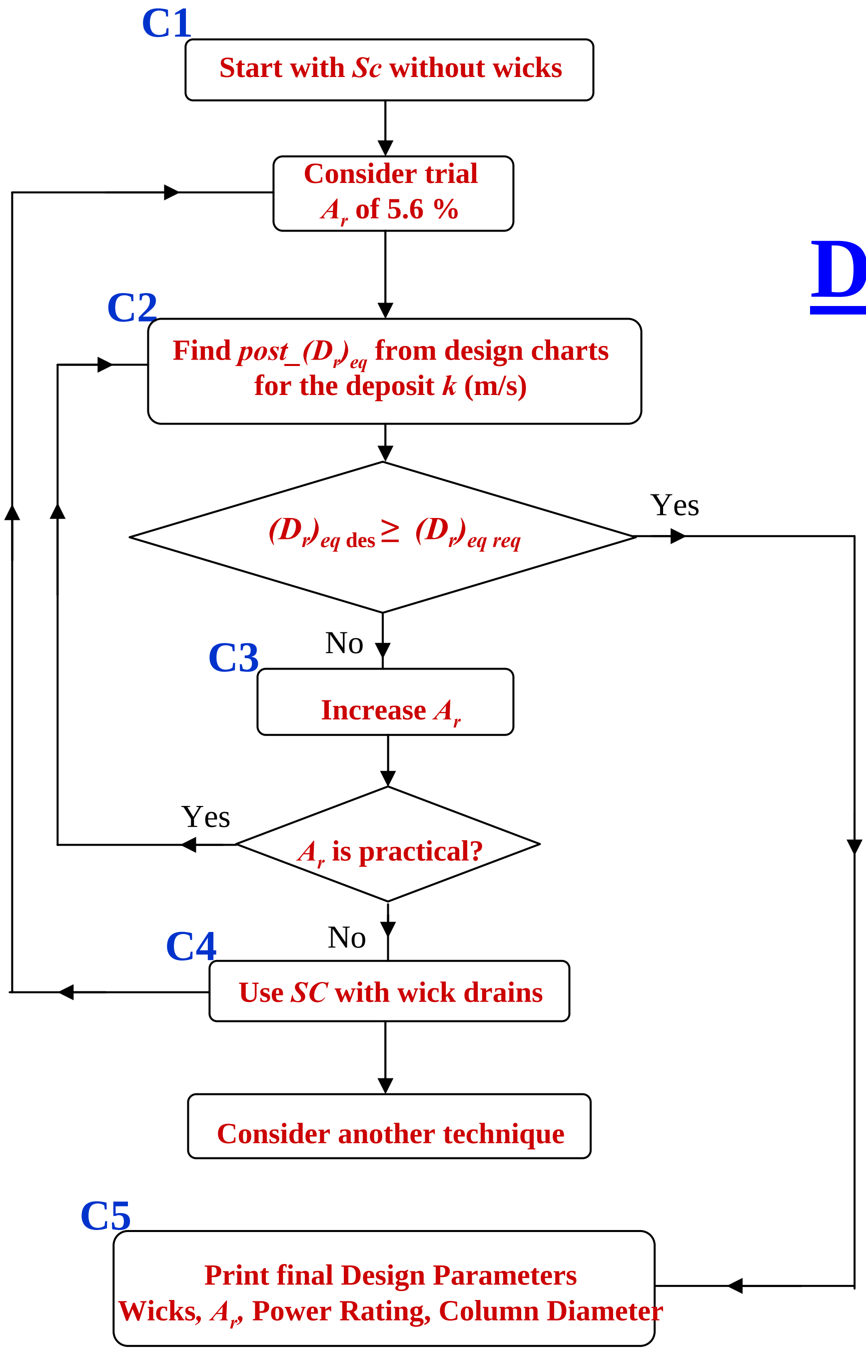
↓

C — **Design Process**

Determine Design Operational Parameters
Wicks, *Ar*, Power Rating,
Column Diameter

S. C. Design Steps

Design Process



Design Example

A. min $(Dr)_{eq}$ = 75 %

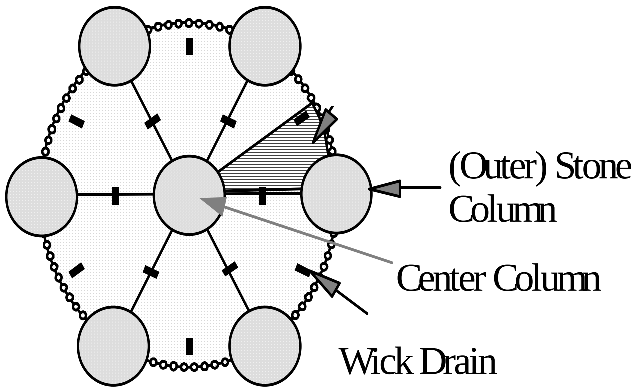
B. Input soil parameters

$k = 10^{-7}$ m/s; FC = 25 %; $(D_r)_{eq}$ = 40 %

C. Design Operational Parameters

A_r = 22.5 %, Power Rating 120 KW,

Column diameter 0.95 m



Trial #	wicks	A_r %	$(Dr)_{eq}$ %	Satisfy Req.?
1	No	5.6	47	No
2	No	10	49	No
3	No	22.5	52	No
4	Yes	5.6	48	No
5	Yes	10	61	No
6	Yes	22.5	75	Yes

S. C. Design Charts

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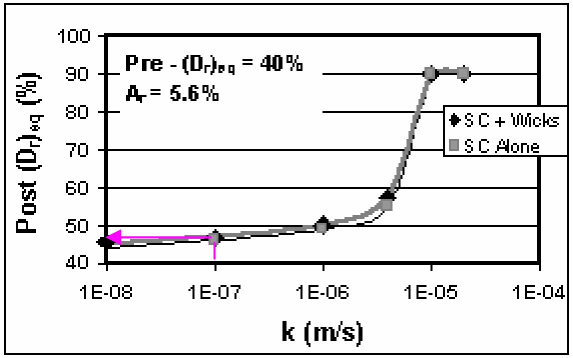

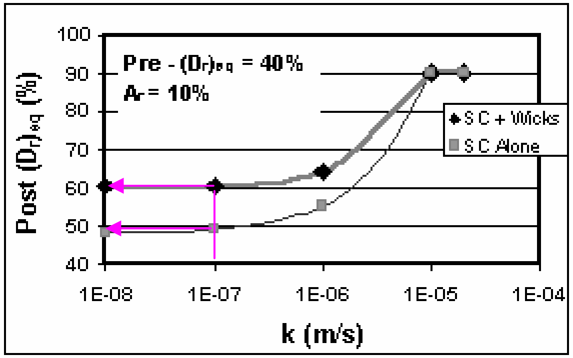

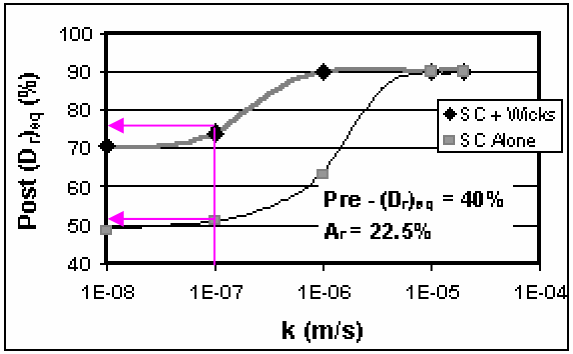

Design Charts for initial $(D_r)_{eq}$ = 40 %

Conclusion

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- A numerical model to analyze densification of saturated silty soils during stone column installation has been developed based on theoretical considerations and experimental results.
- Simulation results have been qualitatively (using past records) and quantitatively (using instrumented field study) verified using limited data.
- Based on the simulations and field study, design charts and design guidelines have been developed to design stone columns with or without wick drains for densifying sands and silty soils.

Further Study

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- Couple the effects of cavity expansion and vibratory energy.
- Refinements based on more field test data.
- Further research correlating field tests such as SPT and CPT with liquefaction and post-liquefaction characteristics.
- Further study in quantifying energy imparted in to the soil during ground improvement and corresponding improvement in liquefaction resistance.

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- **Shenthan, T. (2001) "Factors affecting liquefaction mitigation in silty soils using stone columns", MS Thesis, University at Buffalo, NY, 220p.**
- **Thevanayagam, S., Martin, G. R., and Shenthan, T. (2002), "Ground remediation for silty soils using composite stone columns", Annual Report for Research Year 2, MCEER Highway Project, FHWA Contract DTFH61-98-C-00094, p II109-118**
- **Thevanayagam, S., Martin, G. R., and Shenthan, T. (2003), "Ground remediation for silty soils using composite stone columns", Annual Report for Research Year 3, MCEER Highway Project, FHWA Contract DTFH61-98-C-00094, submitted Feb. 2003.**
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Thank You

Questions…