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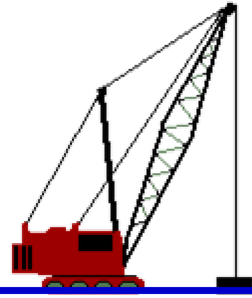

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Lecture #4a
Ground Improvement Techniques for Soil Liquefaction of Sands & Silty Sands
- *Deep Dynamic Compaction*

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

Workshop on Earthquakes and Soil Liquefaction, Griffith University, Australia, December 14, 2007
Organized by Prof. A. Balasubramaniam

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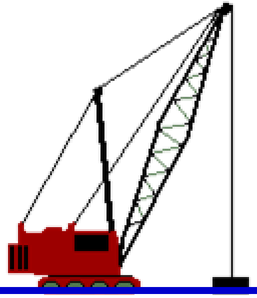

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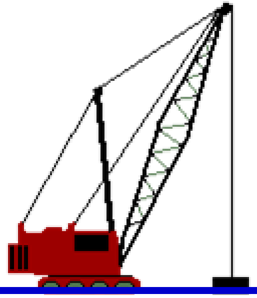
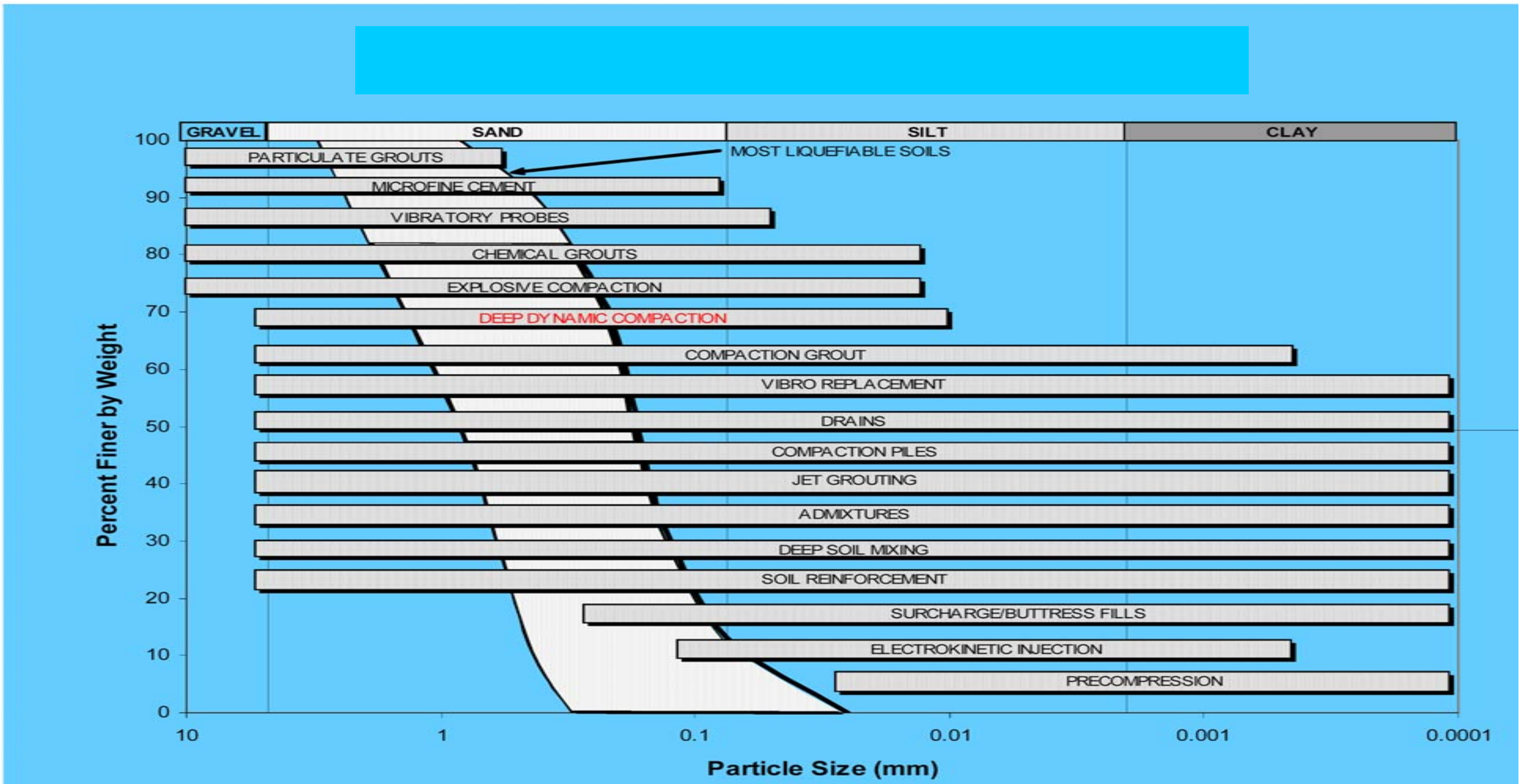
Outline of Presentation

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



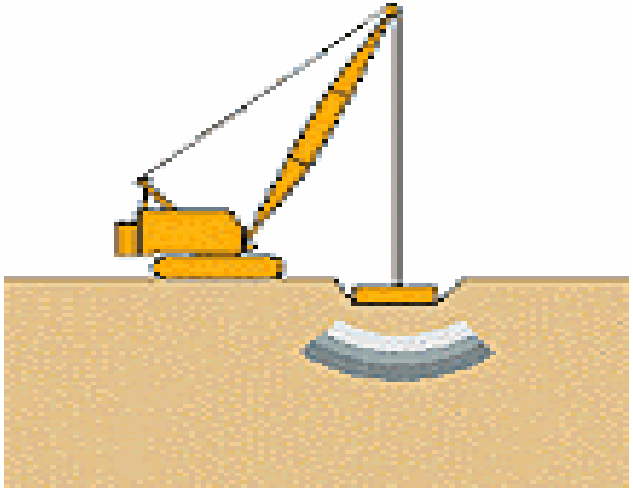
Grain Size Ranges & Suitability of Improvement Methods



Mitchell (1981)

Dynamic Compaction

- Simple and economical.
- Pounder (5 to 35 Mg).
- Falling Height (10 to 40 m).



W/O Wick Drains

(For Sand Deposits with Little or No Fines)

Dynamic Compaction

Impact using falling heavy weights to densify soils at depth.

- Advantages:
  - Simple and Economical.
  - Suitable for sands.
- Disadvantages:
  - Limited Influence Depth.
  - Site Disturbance.
  - Limitations in silty sands.

DC Equipment

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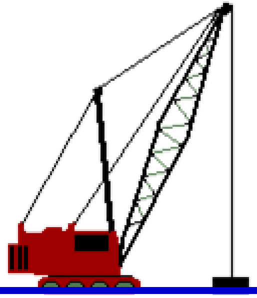

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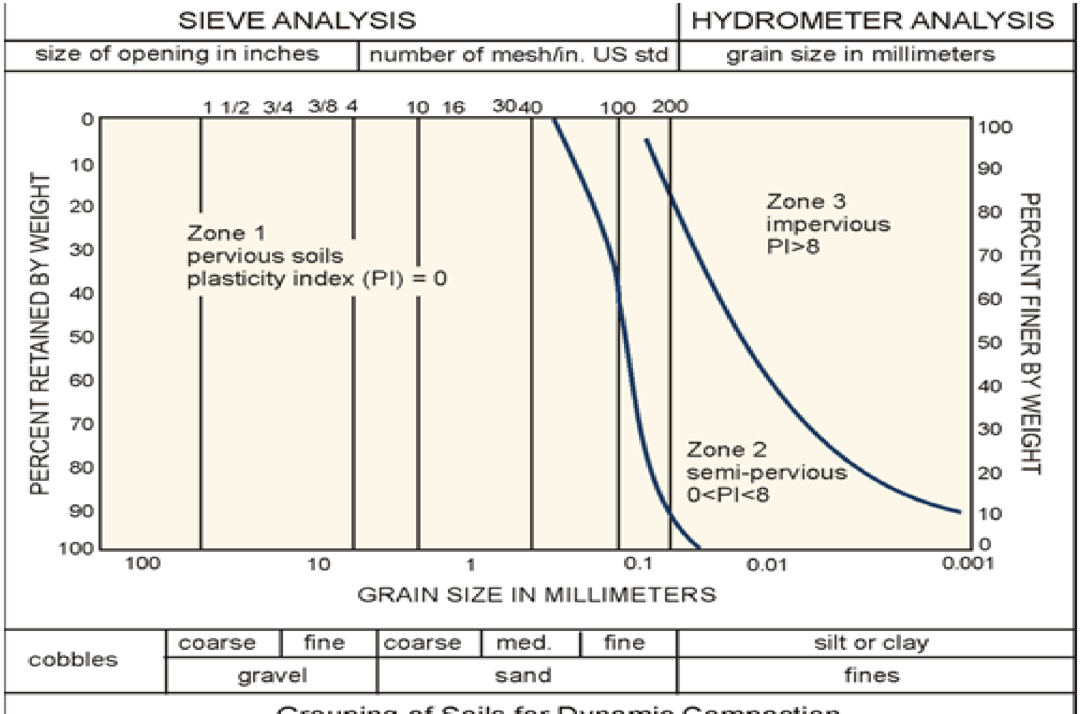
Soil Types & Dynamic Compaction



Grouping of Soils for Dynamic Compaction

- Zone 1: Most favorable.
- Zone 2: Only if excess pore pressures dissipate.
- Zone 3: Not recommended.

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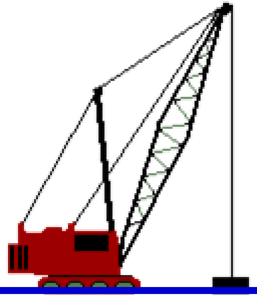

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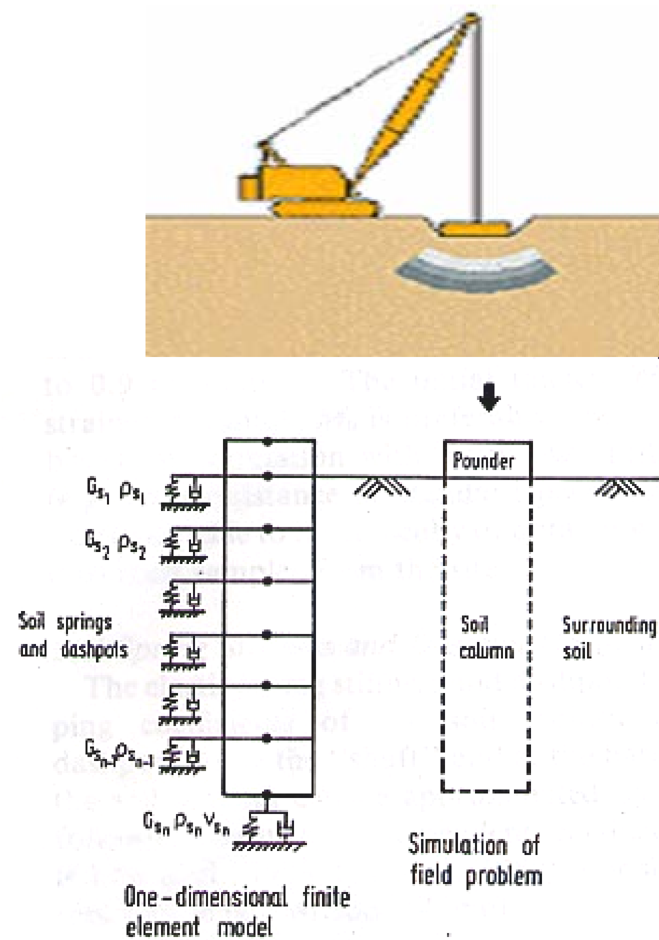
Dynamic Compaction Applications

- Densify Soils
- Reduce foundation settlements
- Reduce seismic subsidence
- Permit construction on fills
- Densify garbage dumps
- Improve mine spoils
- Induce settlements in collapsible soils

Densification Mechanism & Modeling



- **Densification:**

  High-induced intergranular stresses by shockwave.

- **Simulation:**

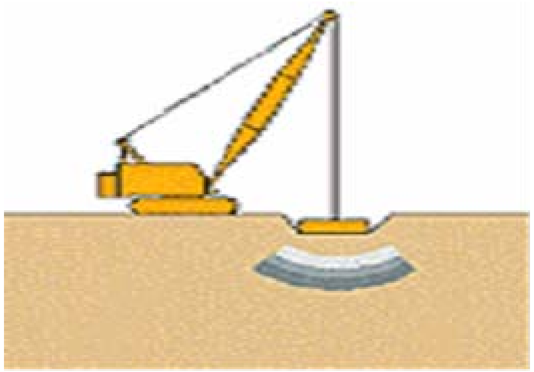
  1-D column model (drained)

  - Dry soils.
  - Free-draining saturated sands.
  - Saturated silty soils. (No)

Densification Mechanism in Saturated Sands

❖ <u>Densification:</u>

Liquefaction & Dissipation of pore pressures and associated densification.



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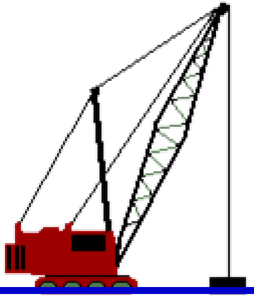

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Parameters
Affecting Densification by D.C.

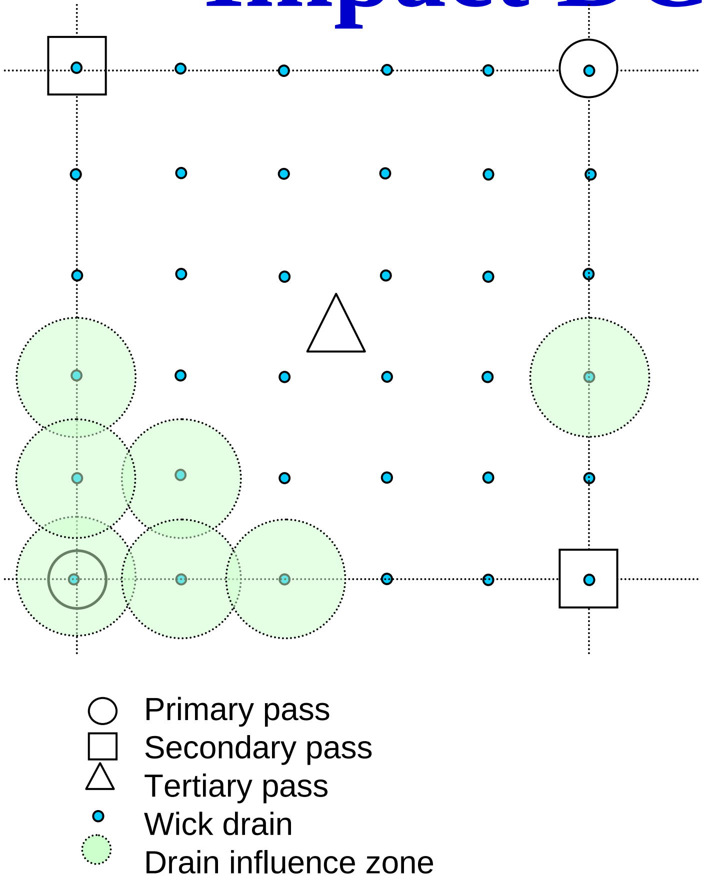
Site Specific Conditions

- Hydraulic conductivity *k* and fines content *FC*.
- Pre-compaction density *pre-Dr*.
- Layering, etc.

D.C. Operational Parameters

- Energy per impact.
- No. of impacts.
- Time cycle between impacts.
- Impact grid pattern.
- Impact print spacing.

Impact DC Grid Pattern



Typically involves

- **Weights of 10 to 30 tons**
- **Drop heights of 50 to 100 ft**
- **Impact grids of 7 x 7 ft to 20 x 20 ft**

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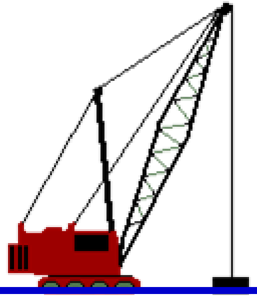

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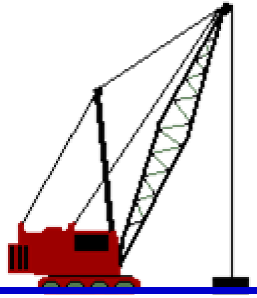
Important Factors

- **Effective Depth --** Maximum depth of ground improvement
- **Zone of Major Densification --** About upper 2/3 of effective depth
- **Energy Level --** Energy per blow (weight times drop height)
- **Energy Intensity Factor --** Involves energy level, spacing, and number of blows

Soil Types, Energy Levels & Degree of Improvement

Type of Deposit	Applied Energy Normally Used	Improvement Expected
Pervious coarse grained soil -- Zone 1	20-25 txm/m^3	Excellent
Semi-pervious fine grained soil -- Zone 2	25-35 txm/m^3	Moderate to Good
Zone 3	Not Applicable	Not applicable
Landfills	60-110 txm/m^3	Excellent

Note: Standard Proctor energy equals 60.5 txm/m^3; 1 txm/m^3 = .10255 $ton\text{-}ft/ft^3$



Important Design Steps

- Perform site investigation
- Develop settlement influence diagrams
- Develop initial Dynamic Compaction program
- Develop numerical performance prediction
- Develop QA/QC plans

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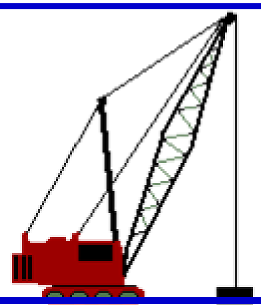

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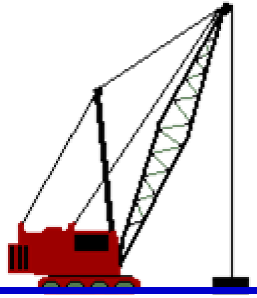
Current Design Practice - Empirical

$$d_{\max} = n\sqrt{WH}$$

Soil Type	Degree of Saturation	Recommended n value*
Pervious soil deposits – Granular soil	High	0.5
	Low	0.5 to 0.6
Semi-pervious soil deposits – Primarily silts with plasticity index < 8	High	0.35 to 0.4
	Low	0.4 to 0.5
Impervious soil deposits –Primarily clayey soils with plasticity index > 8	High	Not recommended
	Low	0.35 to 0.4 Soils should be at water content less than the plastic limit

*Cumulative energy 1~ 3 MJ/m^2 (FHWA 1995)

- Use Past experience.
- Use Field trials for design.



Current Design Practice – Typical Energy Intensity

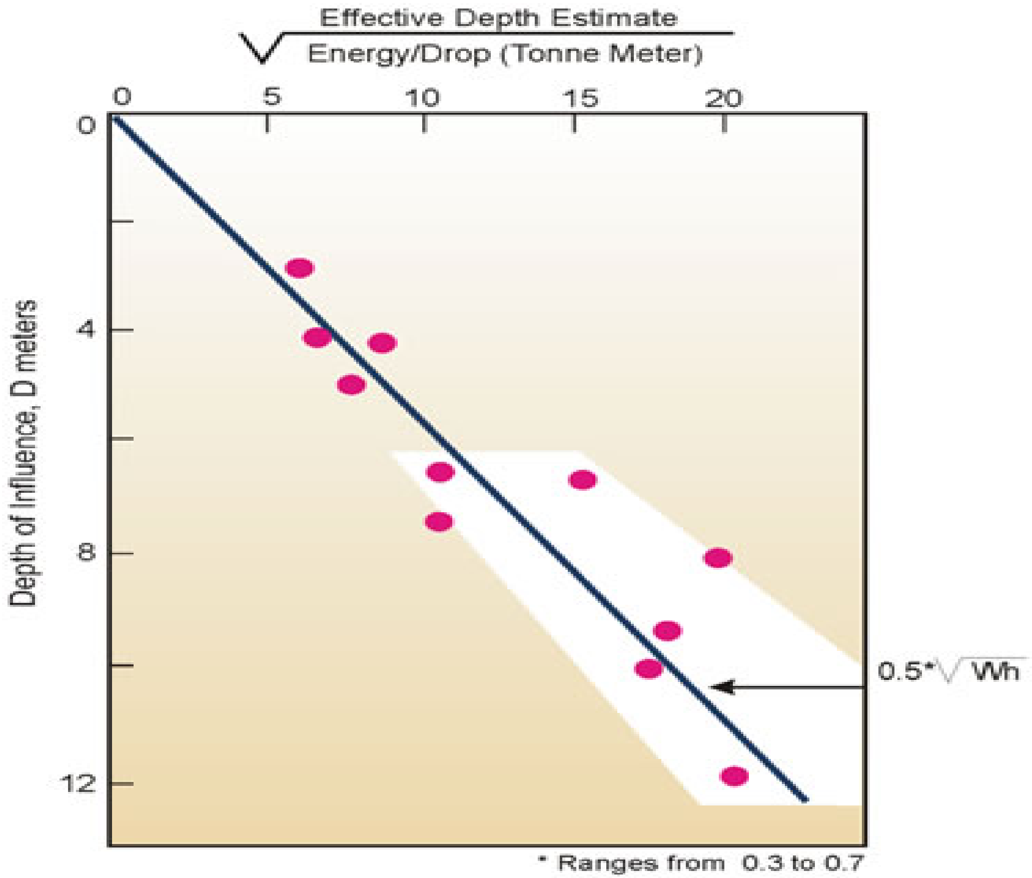
$$E = \frac{N_I W H P}{S^2 d_{\max}}$$

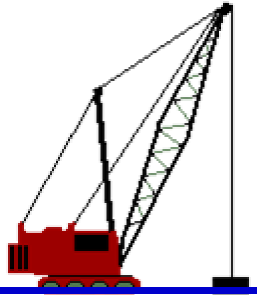
Type of deposit	Applied Energy (E) (K J/m^3)	Percent Standard Proctor Energy
Pervious coarse grained soils	200 to 250	33 to 41
Semipervious fine grained soils and clay fills above the water table	250 to 350	41 to 60
Landfills	600 to 1100	100 to 180

* Standard Proctor energy equals 600 KJ/m^3 (FHWA 1995)

Applied energy guidelines

Depth of Improvement





Important Dynamic Compaction Construction Conditions

- Minimum 100-150 ft clearance from any structure
- Review site for vibration sensitivity

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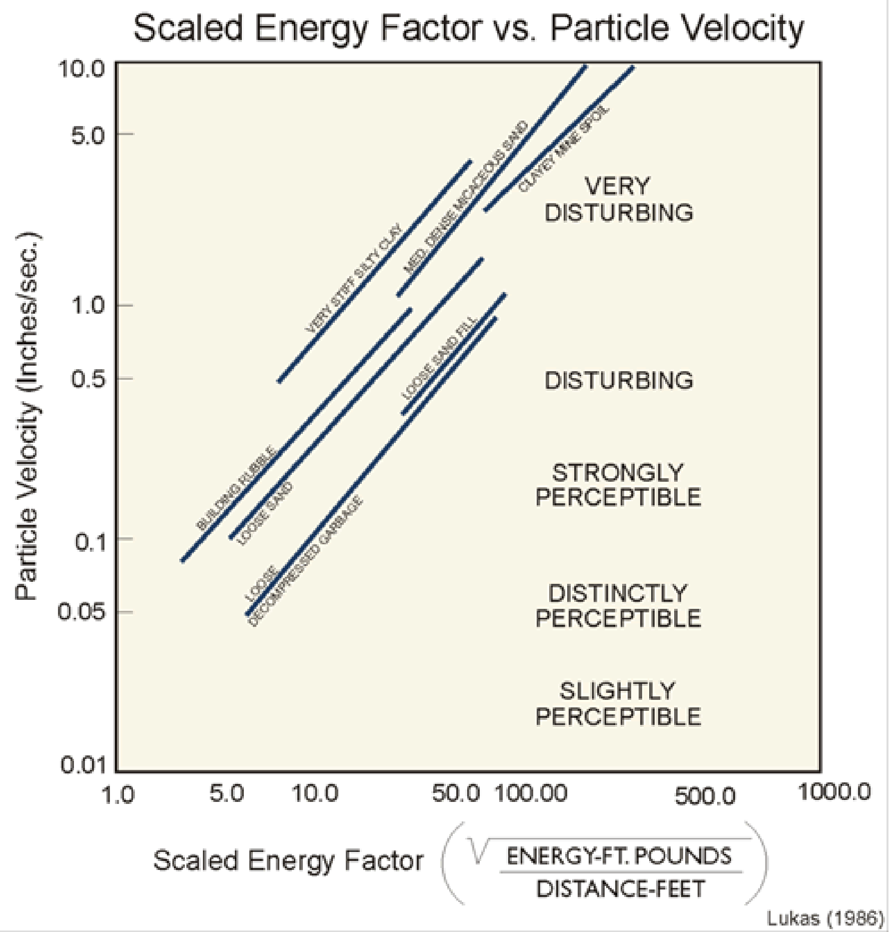
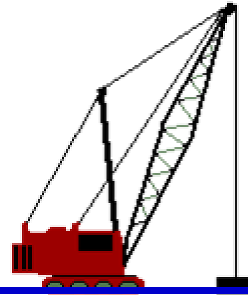
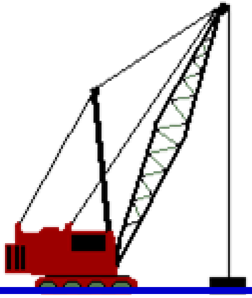
Construction Vibration Control





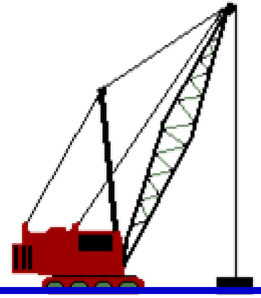
Dynamic Compaction Quality Control

- Crater depths (map)
- Surface elevation monitoring
- Decrease in depth of weight penetration with successive drops
- Pore pressures
- Geophysical monitoring



Dynamic Compaction Acceptance Testing

- Large-Scale Load Test (where CPT & SPT are unreliable i.e. construction rubble and cobbles)
- Standard Penetration Test (SPT)
- Cone Penetrometer Test (CPT)
- Pressuremeter Test (PMT)
- Dilatometer Test (DMT)
- Shear-Wave Velocity Profile



Limitations of DC - in Silty Soils

Limited Densification

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

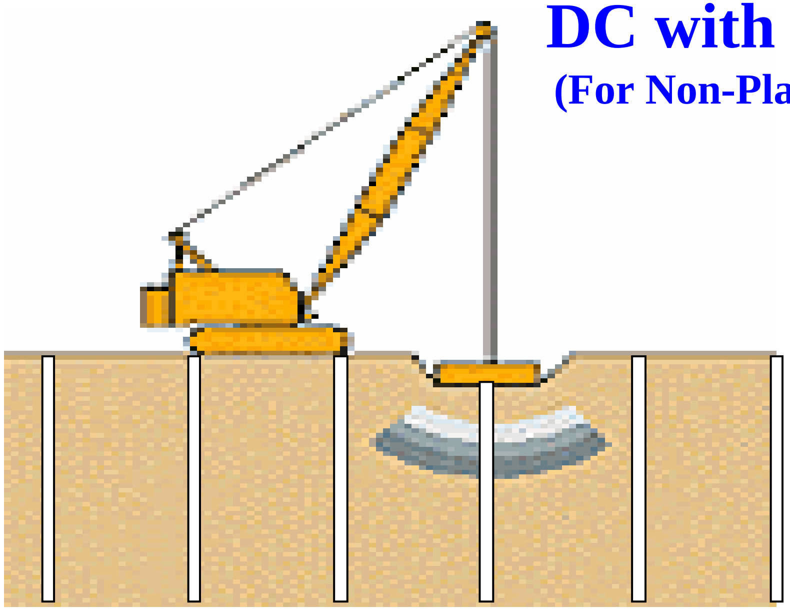
Solution

- Enhance Drainage during Installation using wicks
- Increase Energy transmitted to cause soil liquefaction
- Increased/Repeated Densification
- **Increase Resistance to Liquefaction**

Recent Advances

DC with Wick Drains

(For Non-Plastic Silty Deposits)



Supplementary Wick Drains

- Enhance densification during compaction in Silty Soils
- **Design is Empirical**

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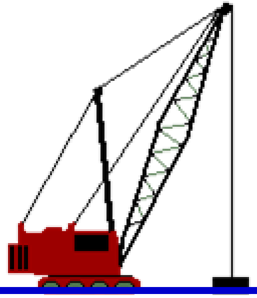

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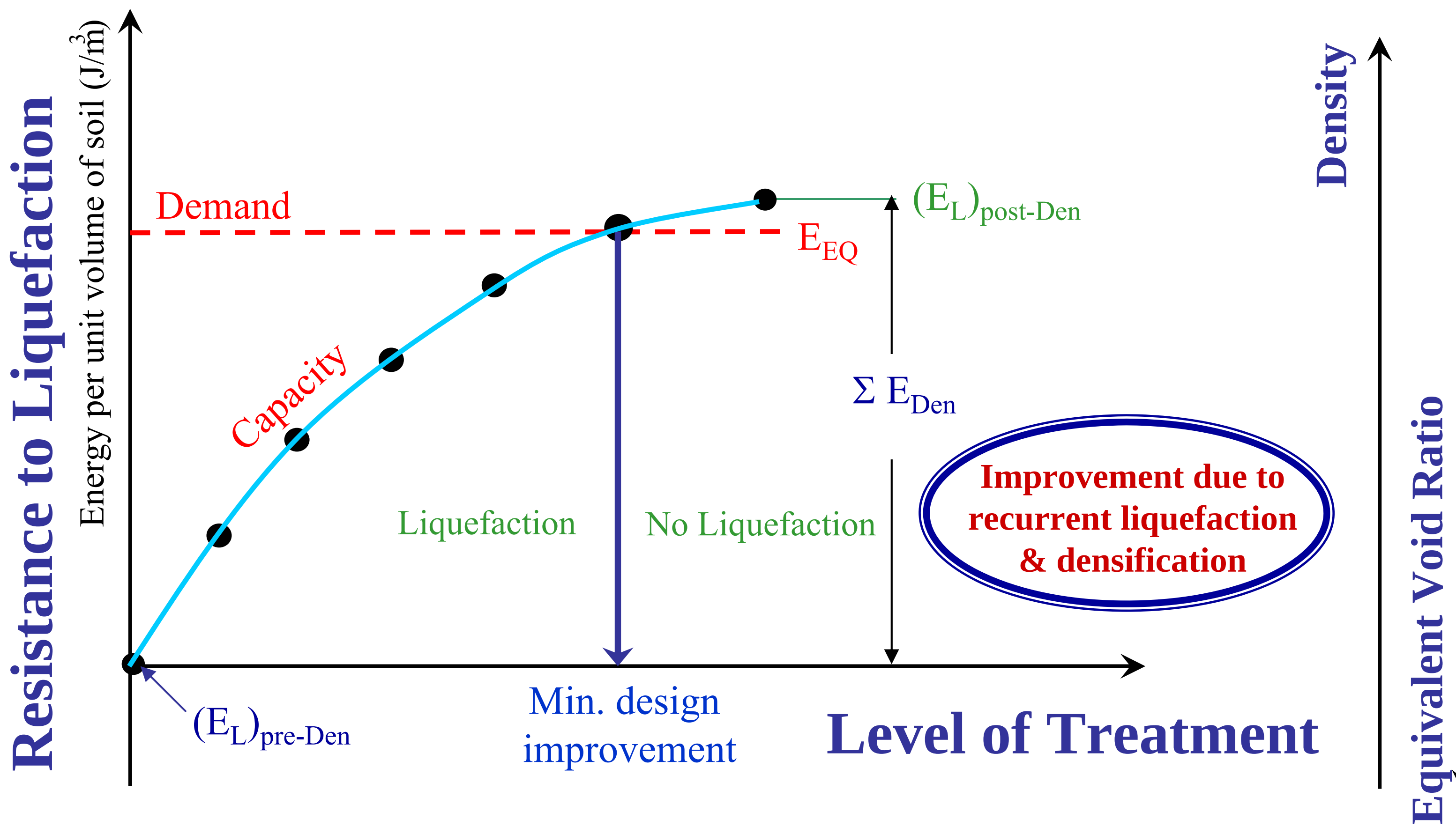
Recent Research @UB – (R. Nashed)

- Develop numerical model to simulate and analyze soil densification during DC processes.
- Identify parameters controlling post-improvement soil density.
- Verify the model by comparing with field data
- Develop design guidelines for densification of silty soils.

Energy-Based Liquefaction Mitigation Design



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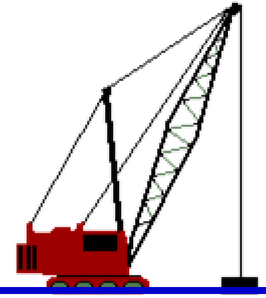

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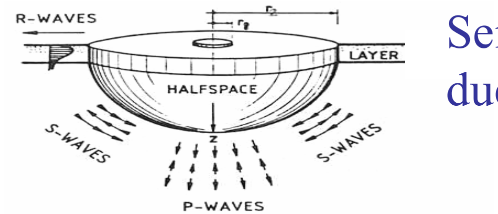
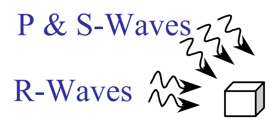
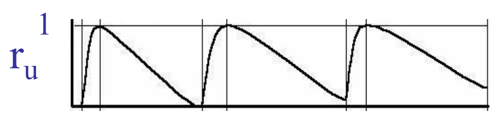
DC Densification Process

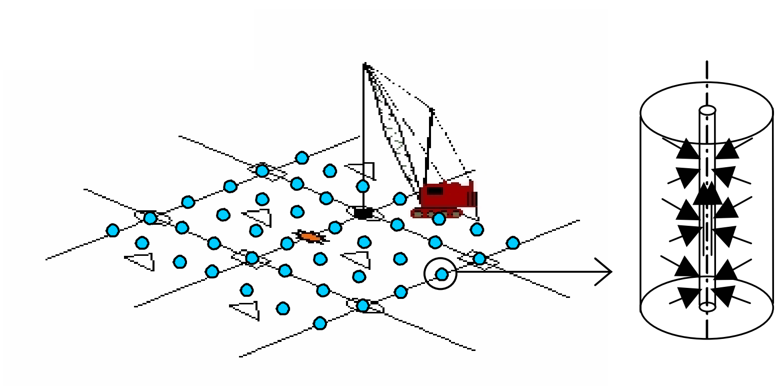


Seismic waves induced due to surface impact

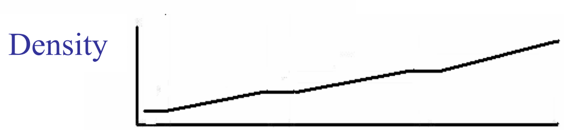


Energy dissipation & pore pressure generation

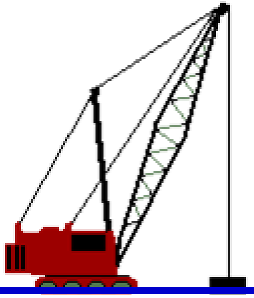




Pore pressure dissipation



Densification & increase in liquefaction resistance



Dynamic Compaction Numerical Simulations

- Vibratory Energy
  - Radiation & Attenuation Relations
  - Dissipation & Pore Pressure Generation
- Pore Pressure Dissipation
- Soil Densification

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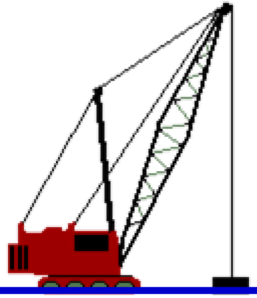

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METHODS

An analytical technique was developed to simulate the process based on:

- ❖Mechanics of energy dissipation in soil due to surface impact.
- ❖Attenuation relationships to estimate the energy dissipated in the soil.
- ❖Experimental data based on energy principles to estimate generated pore pressures.
- ❖Coupled consolidation equations to quantify densification.

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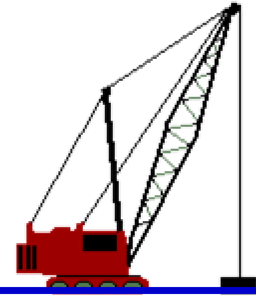

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Governing Equations

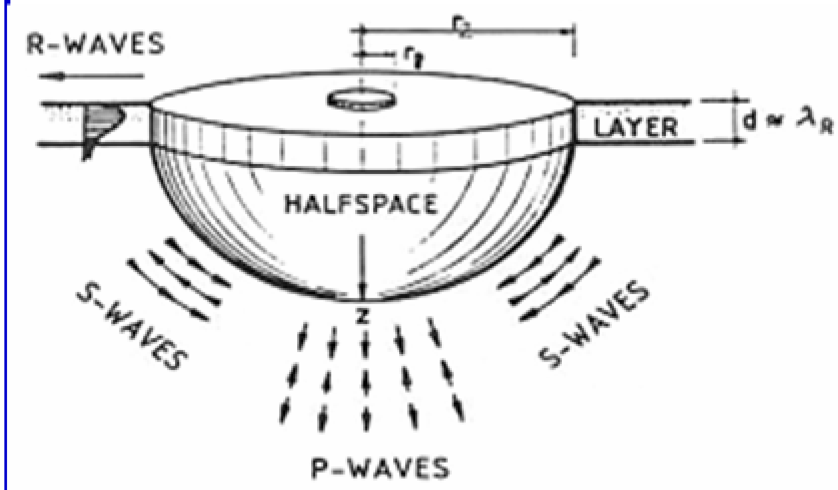
$$\frac{du}{dt} = C_r \left(\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r} \right) + C_v \frac{\partial^2 u}{\partial z^2} + \frac{\partial u_g}{\partial t}$$

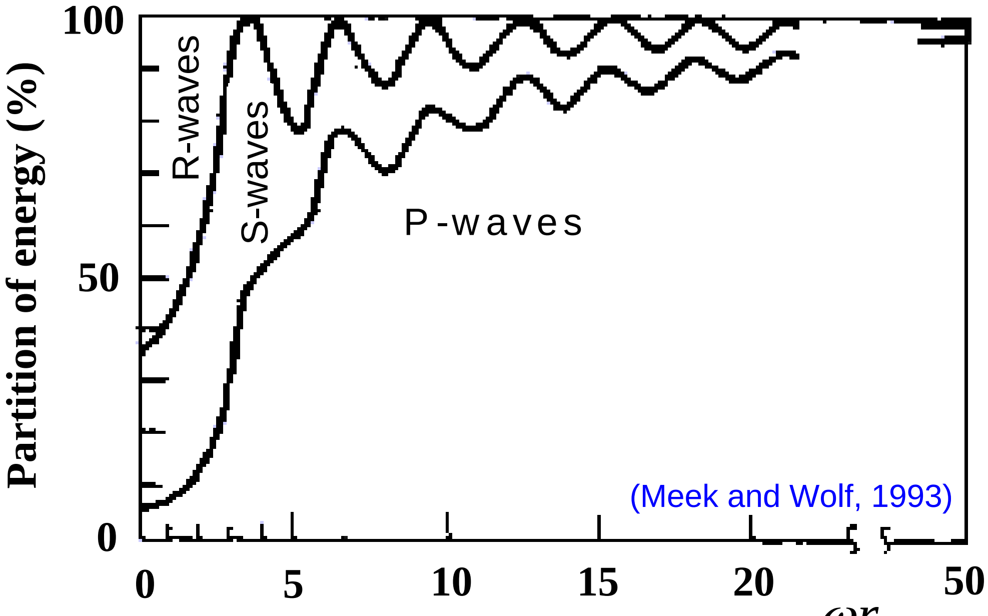
$$\varepsilon_v = \int m_v . d\sigma'$$

where,

- u = pore pressure
- t = time
- C_r & C_v = radial and vertical coefficients of consolidation, respectively
- r = radial distance
- u_g = pore pressure generated due to surface impact
- γ_w = unit weight of water
- ε_v = Volumetric Strain
- m_v = Volume Compressibility (stress and density dependent)

Partition of Energy





$$a_0 = \frac{\omega r_0}{v_s}$$

- ❖ Rayleigh wave: 67%
- ❖ Body wave: 33%

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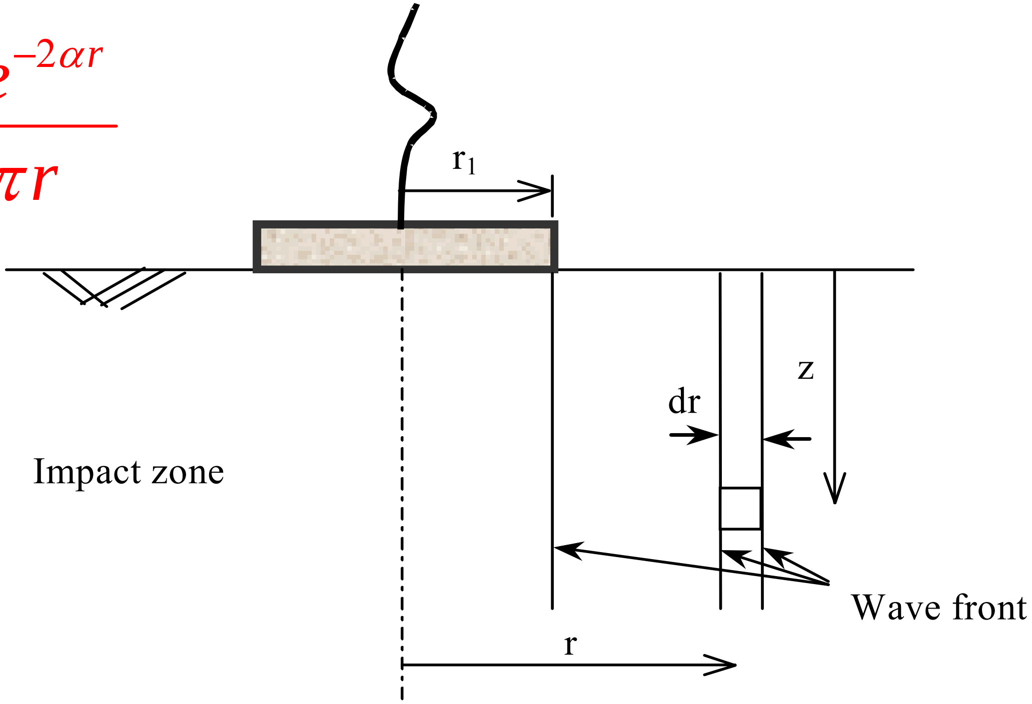
Energy Dissipated/ unit volume Due to Impact

- Rayleigh wave:

$$w_R(r,z) = F(0.67WH)\frac{\alpha e^{-2\alpha r}}{\pi r}$$



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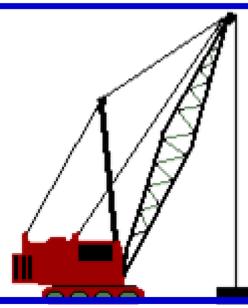

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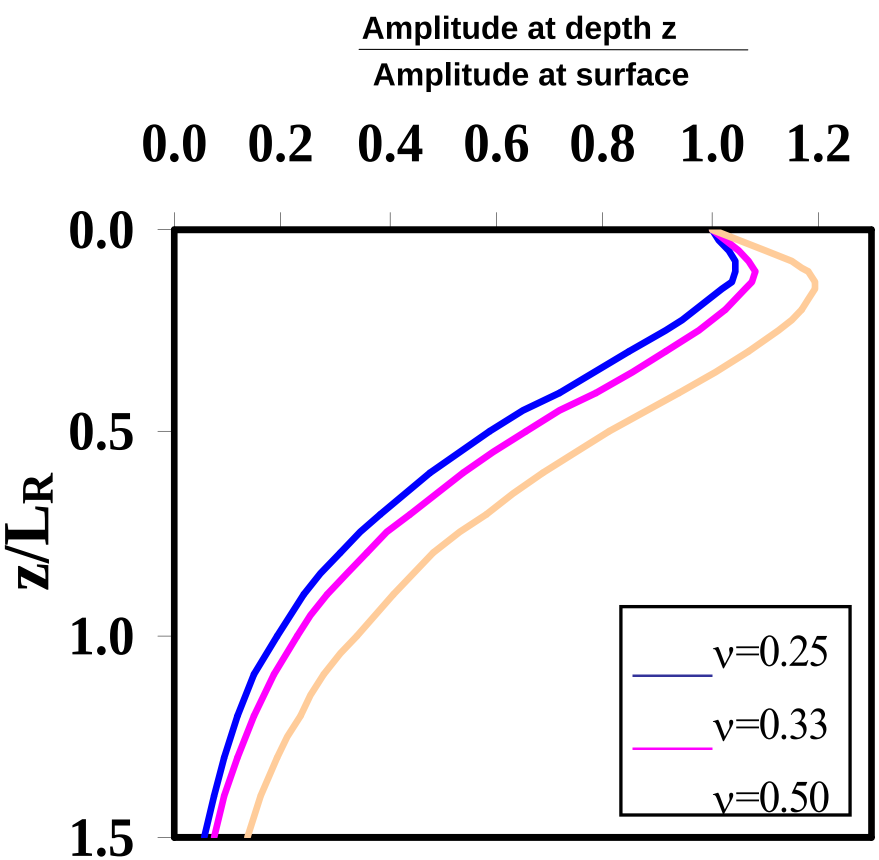
Rayleigh Wave Attenuation With Depth

$$w_R(r,z) = F(0.67WH)\frac{\alpha e^{-2\alpha r}}{\pi r}$$

$$F = \frac{f^2\left(\frac{z}{L_R}\right)}{\int_0^\infty f^2\left(\frac{z}{L_R}\right)dz}$$

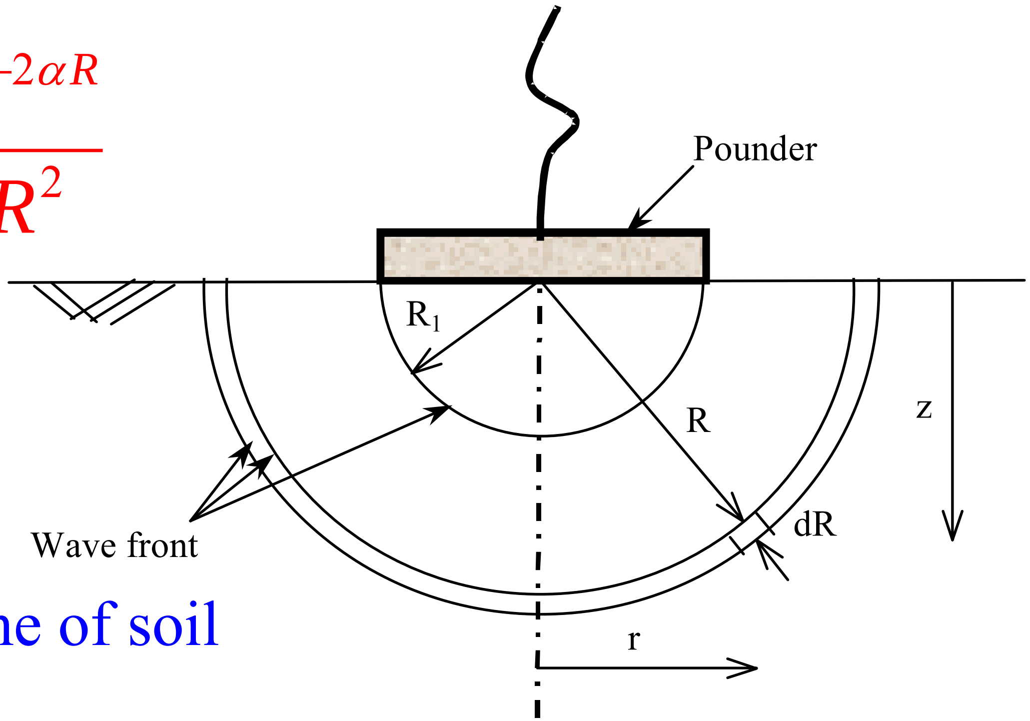
w: energy loss per unit volume of soil



Energy Dissipated/ unit volume Due to Impact

❖ Body wave:

$$w_B(r,z) = (0.33WH)\frac{\alpha e^{-2\alpha R}}{\pi R^2}$$



w: energy loss per unit volume of soil

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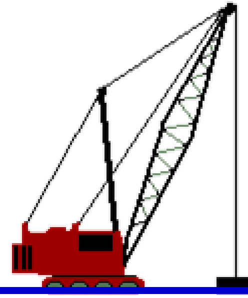

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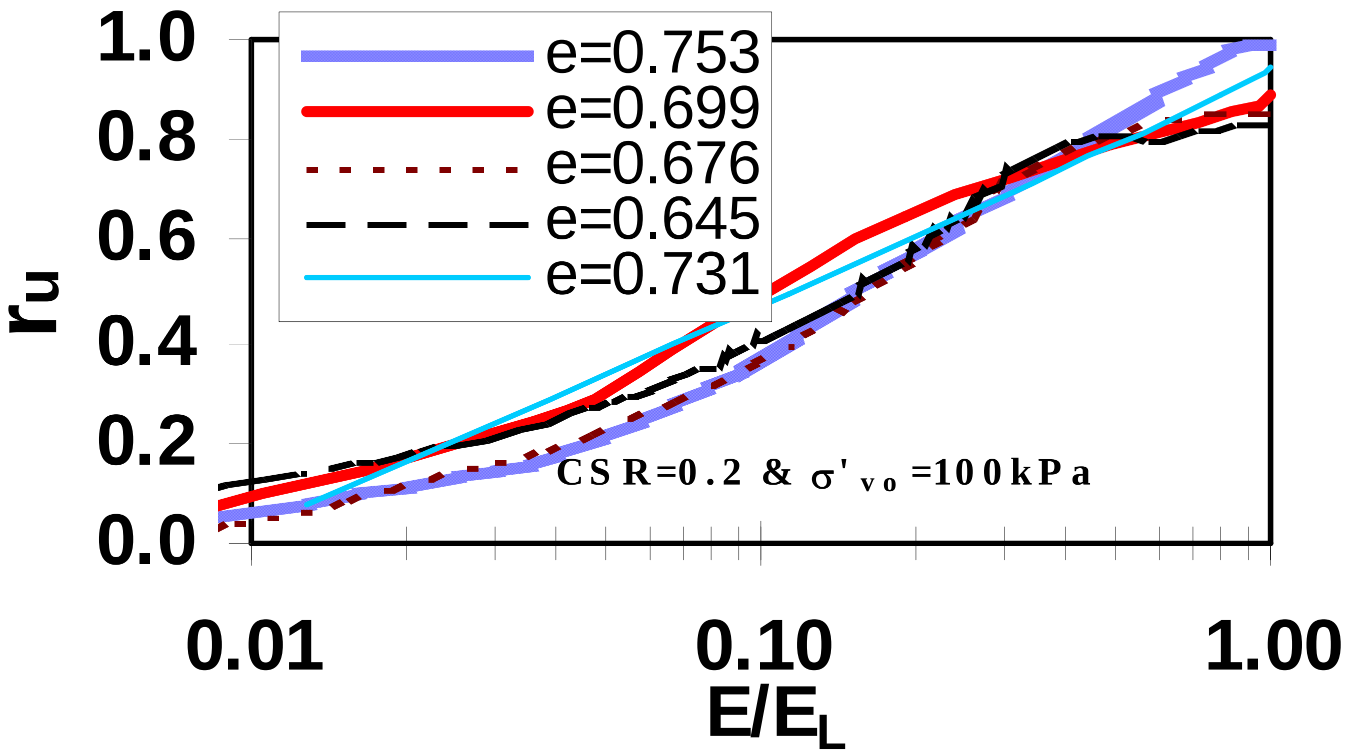
Material Damping Attenuation Coefficient

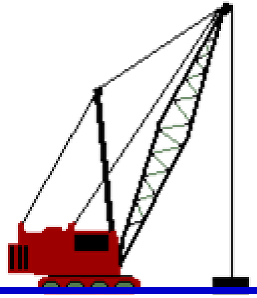
Class	α (m^{-1})		Soil
	5 Hz	50 Hz	
I	0.01 –0.03	0.1 – 0.3	Weak or soft soils (N < 5)
II	0.003 - 0.01	0.03 – 0.1	Competent soils (5 < N < 15)
III	0.0003 – 0.003	0.003 – 0.03	Hard soils (15 < N < 50)
IV	< 0.0003	< 0.003	Hard, competent rock (N > 50)

❖Field measurements of ground vibrations induced by dynamic compaction, ball dropping, and vibroflotation.

Energy-Based Liquefaction Model

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





Energy Dissipation – Pore pressure relationship

$$r_u = 0.5\log_{10}\left(100\frac{w_c}{w_L}\right), \quad \frac{w_c}{w_L}\rangle 0.05$$

(Thevanayagam et al. 2002)

Pore pressure Dissipation

$$\frac{du}{dt} = C_r\left(\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r}\right) + C_v\frac{\partial^2 u}{\partial z^2} + \frac{\partial u_g}{\partial t}$$

Densification

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

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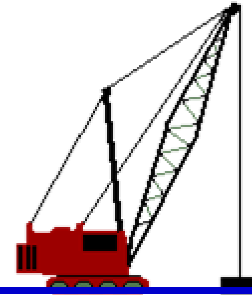

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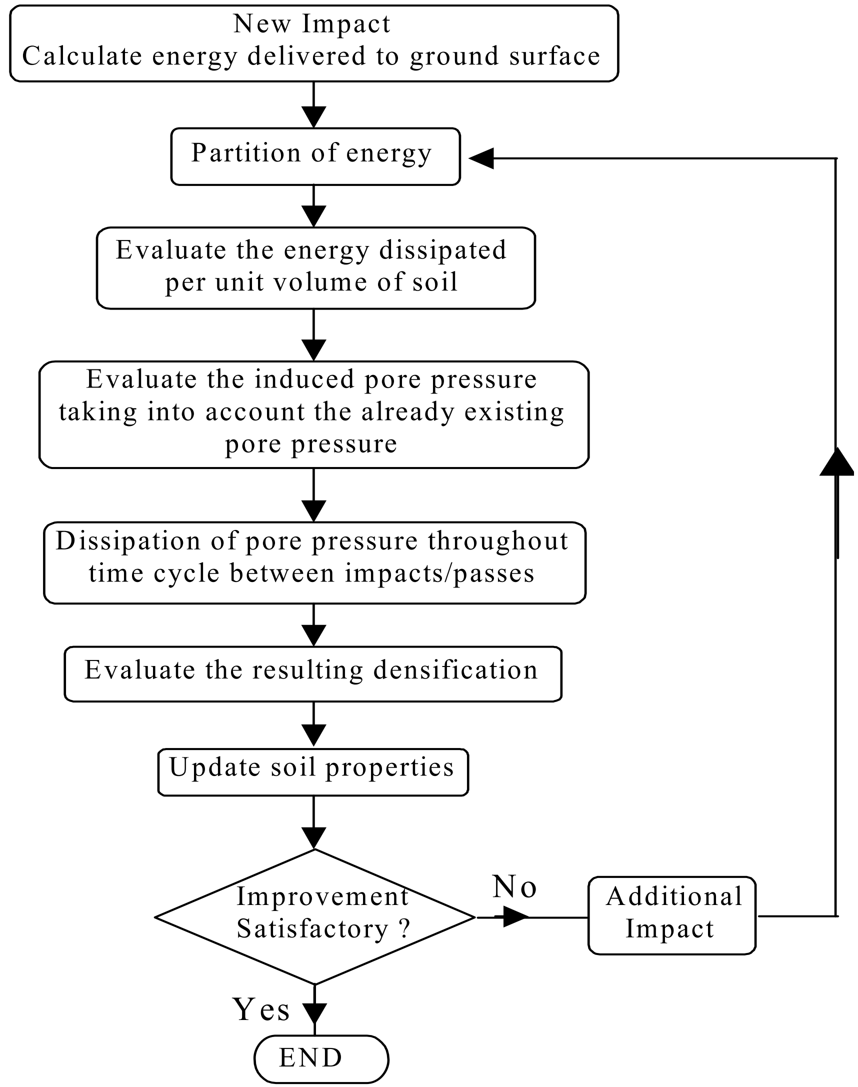
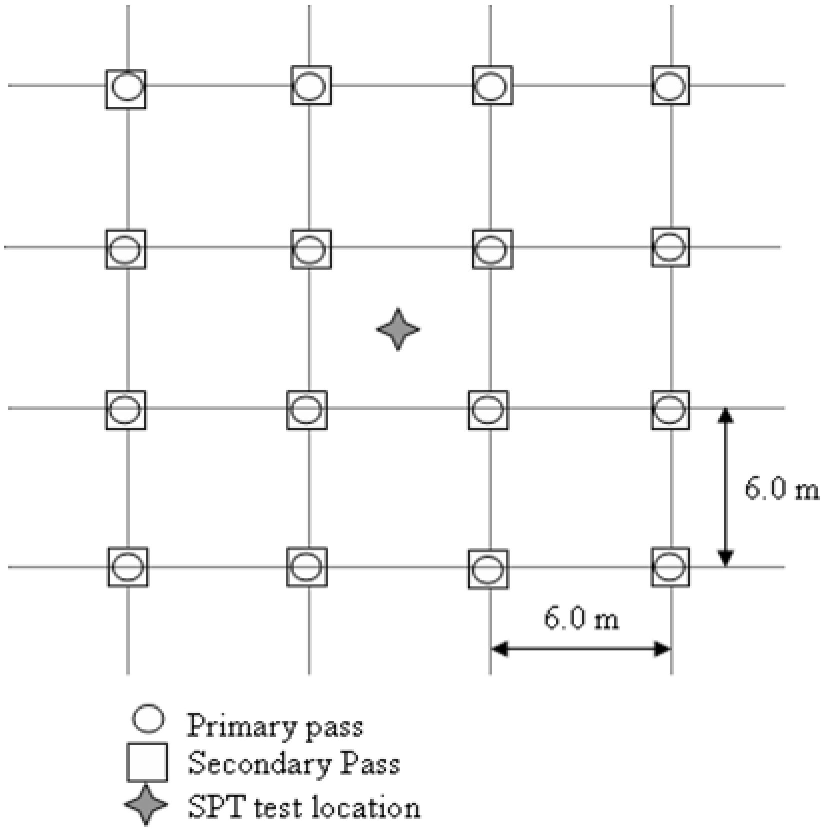
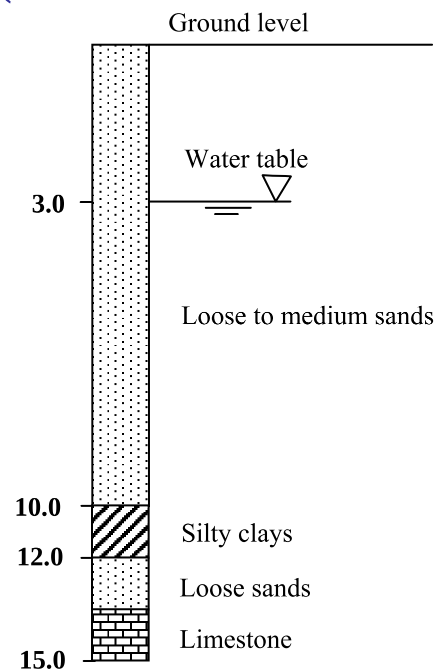
Modeling DC Processes



Field Comparisons – Sand

Kampung Pakar Site, Malaysia (Sand w/o wick drains)





Impact Parameters	1st pass	2nd Pass
Pounder weight (tonne)	15.0	15.0
Drop height (m)	20.0	25.0
No. of impacts at each grid point	10	6

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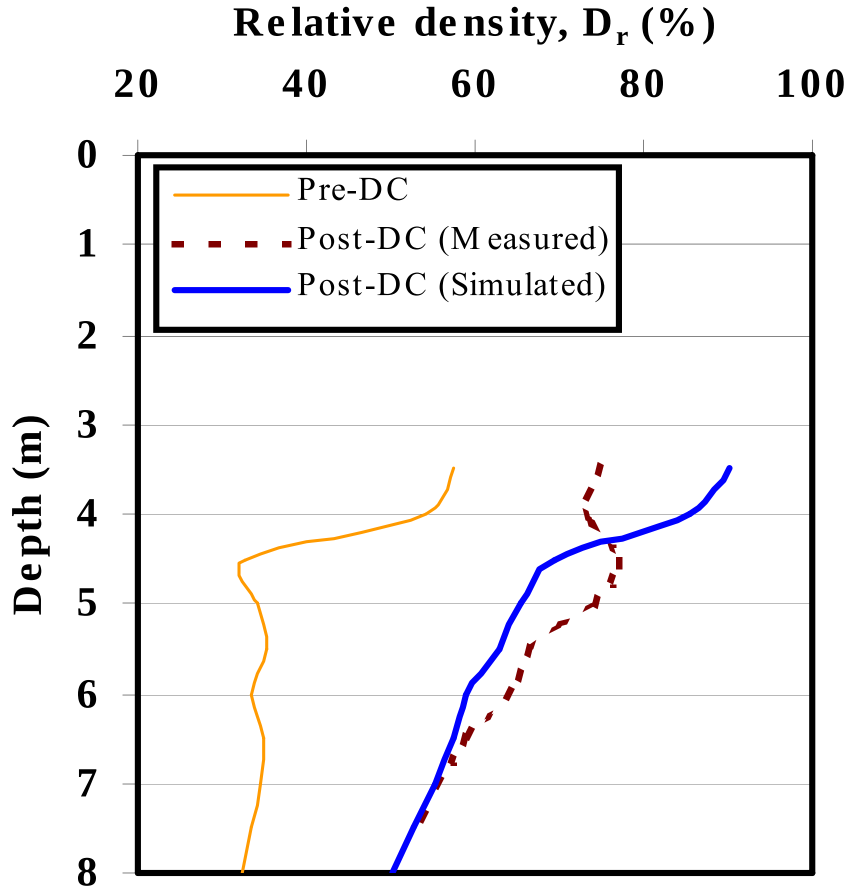
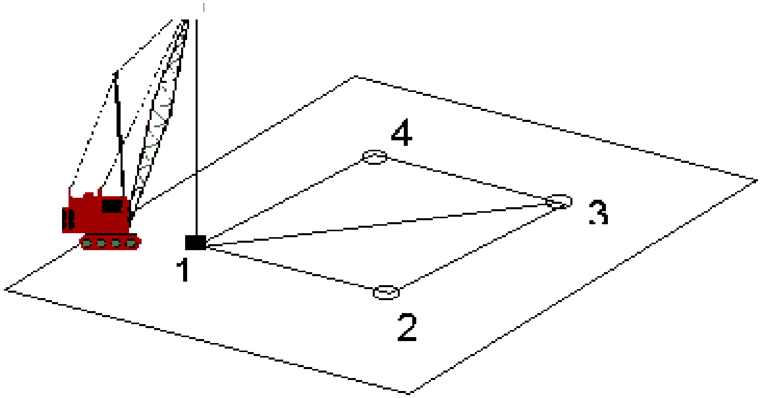
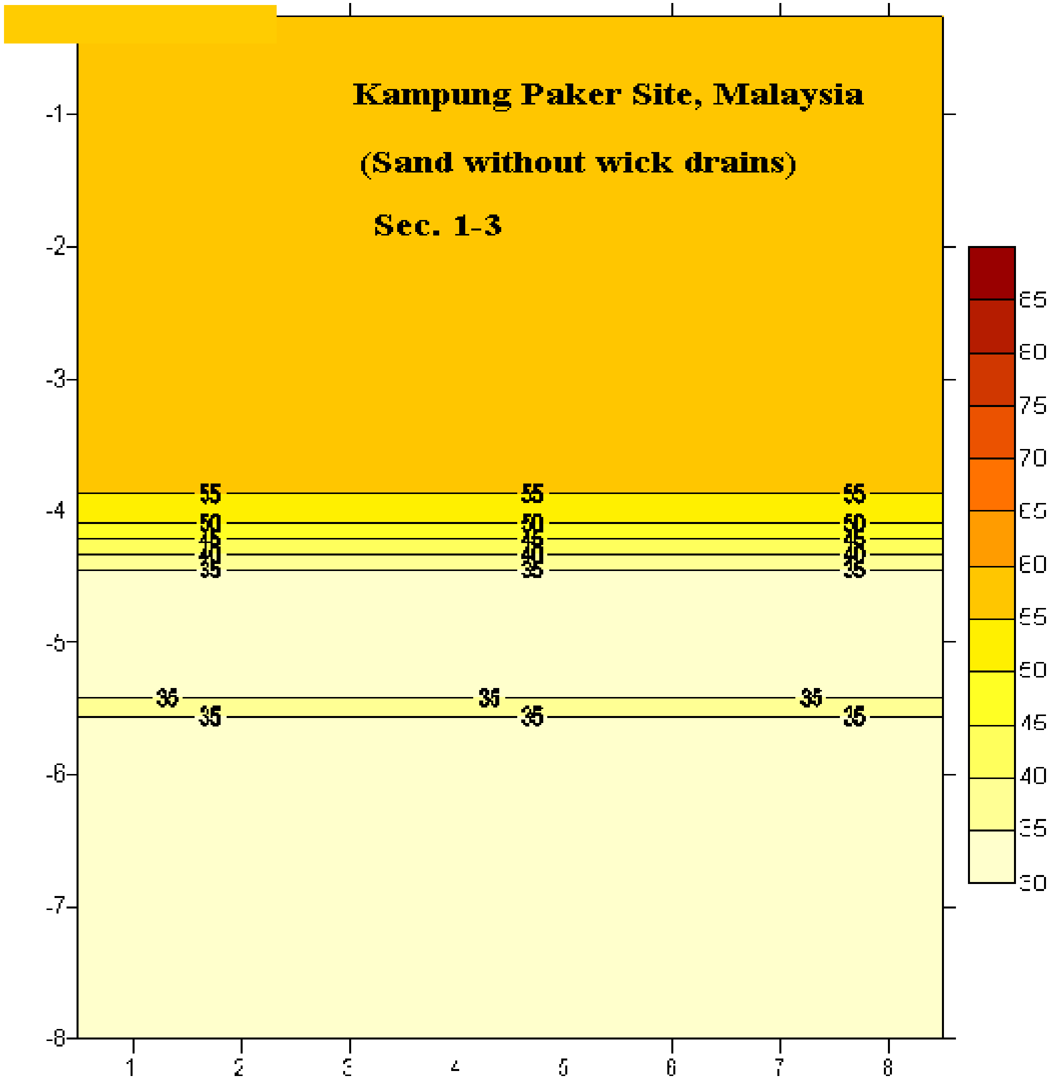
Field Comparisons – Sand

Kampung Pakar Site, Malaysia (Sand w/o wick drains)




4
3
1
2


Kampung Paker Site, Malaysia
(Sand without wick drains)
Sec. 1-3
-1
-2
-3
-4
-5
-6
-7
-8
1
2
4
5
6
7
8
55
50
45
40
35
75
70

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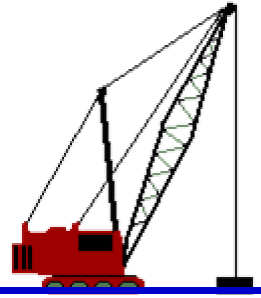

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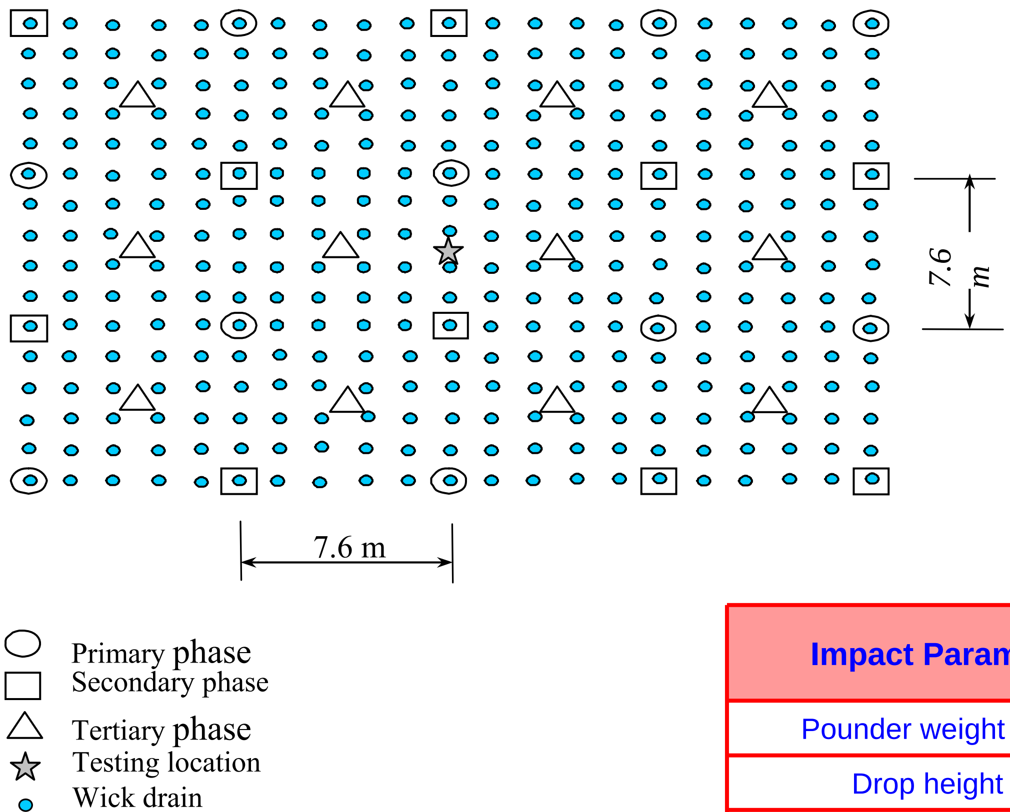
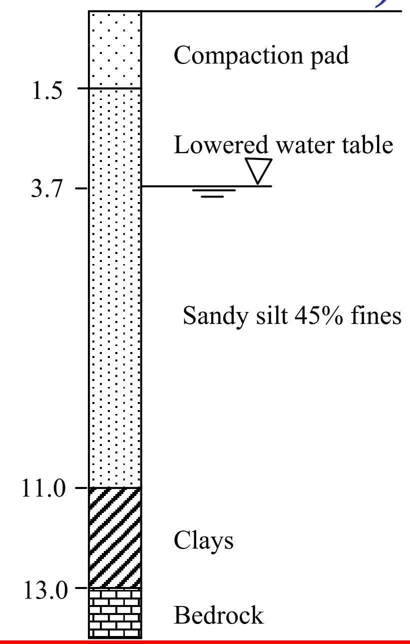
Field Comparisons – Sandy Silt

Steinaker Dam Project, Utah (Sandy silt w/ wick drains)





Impact Parameters	Initial ironing	1st pass	2nd pass	3rd pass
Pounder weight (tonne)	30.0	30.0	30.0	30.0
Drop height (m)	18.0	30.0	30.0	30.0
No. of impacts at each grid point	2	30	30	20

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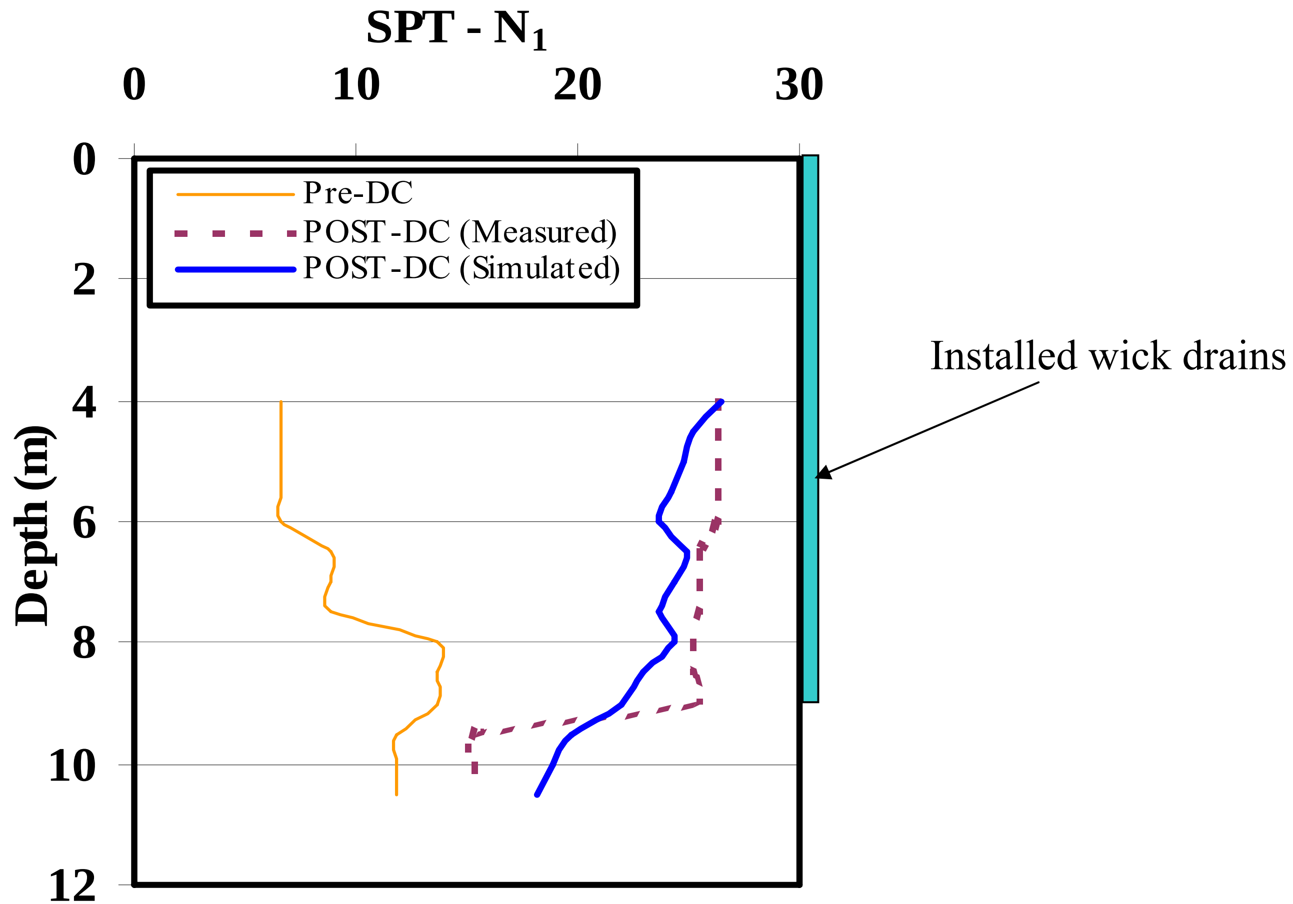
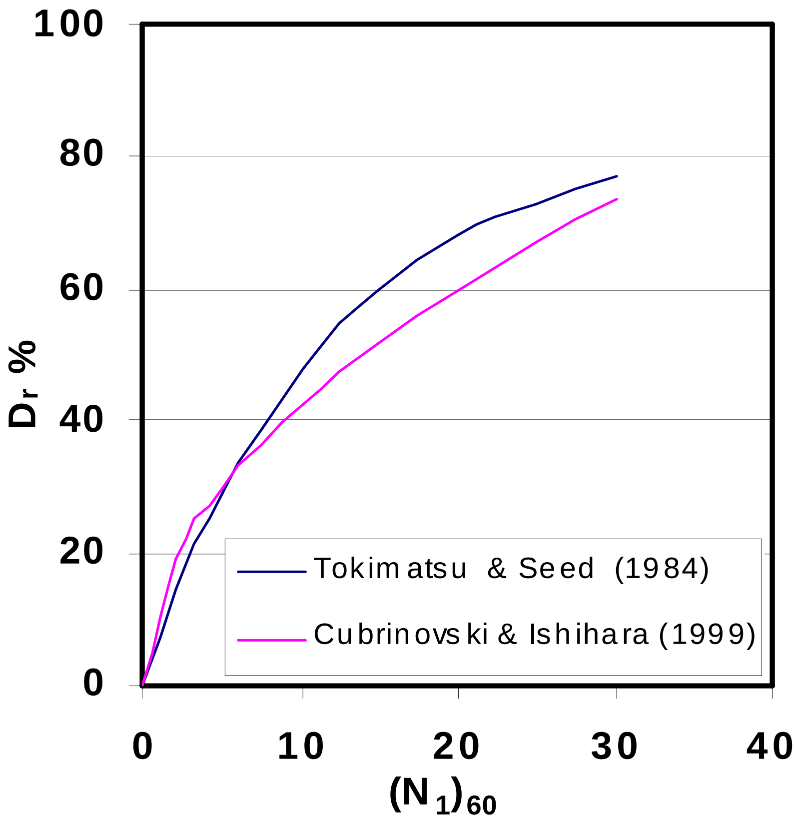
Field Comparisons – Sandy Silt

Steinaker Dam Project, Utah (Sandy silt w/ wick drains)



Relative Density Verses $(N_1)_{60}$

For Clean Sands



For Silty Sands

Equivalent clean sand blow count is used (NCEER 1997)

$$(N_1)_{60cs} = A + B(N_1)_{60}$$

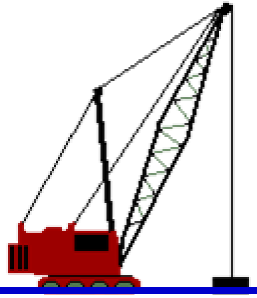
$A = 0.0,\ B = 1.0$ for $FC \leq 5$ %

$A = 5.0,\ B = 1.2$ for $FC \geq 35$ %

$$A = e^{\left[1.76 - \left(\frac{190}{FC^2}\right)\right]}$$

$$B = \left[0.99 + \left(\frac{FC^{1.5}}{1000}\right)\right]$$

for 5 % < FC < 35 %



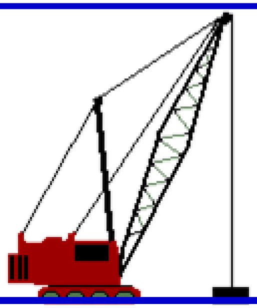
The parameters controlling post-improvement density have been identified:

I. Site-Specific Conditions:

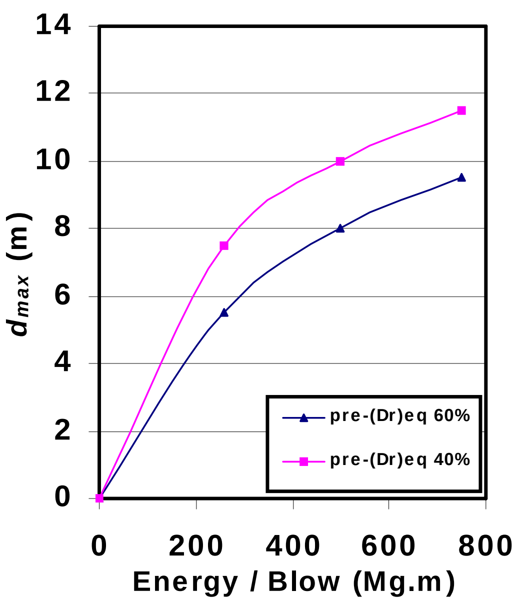
- Pre-improvement relative density or $(N_1)_{60cs}$.
- Hydraulic conductivity *k* and silt content *FC*.

II. DC Operational Parameters:

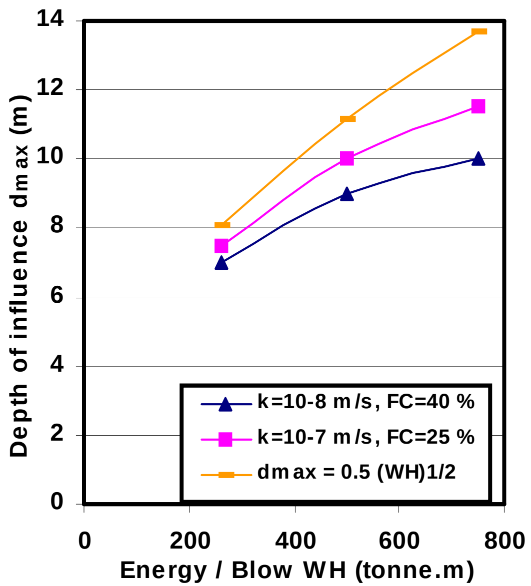
- Energy per impact *WH.*
- Total number of impacts per grid point N_I.
- Wick drain spacing S_w.
- Impact grid spacing *S.*
- Time cycle between impacts *T*.



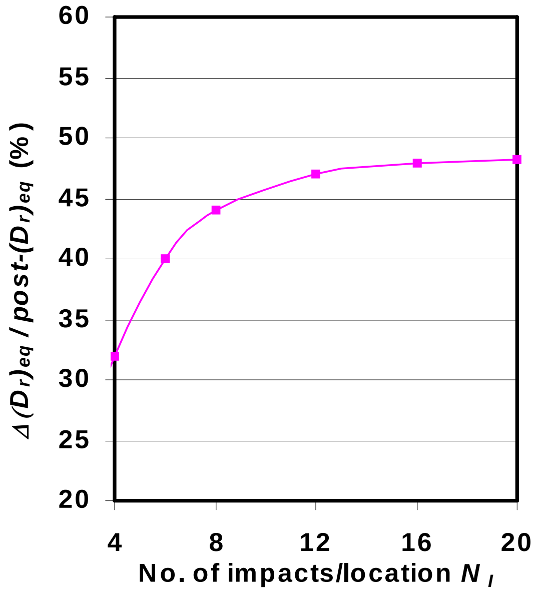
Numerical Simulations and Parametric Study



Effect of pre-$(D_r)_{eq}$

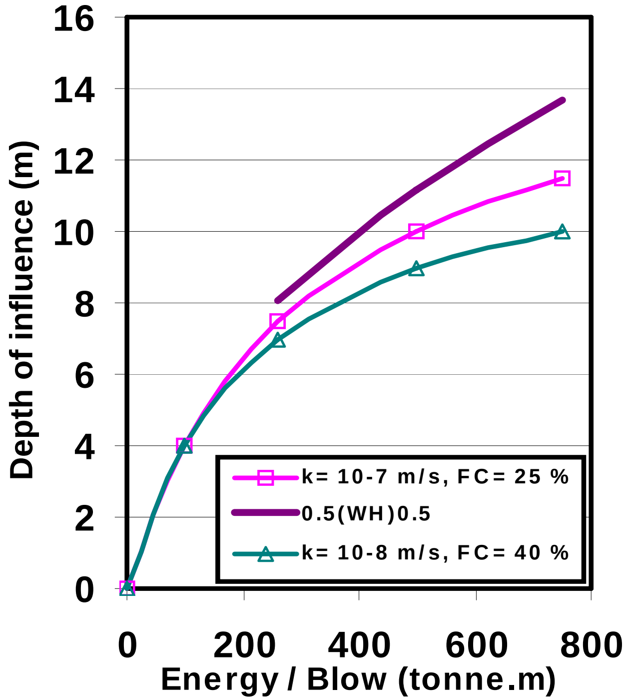


Effect of Hydraulic Conductivity (*k*) and Fines Content (*FC*)

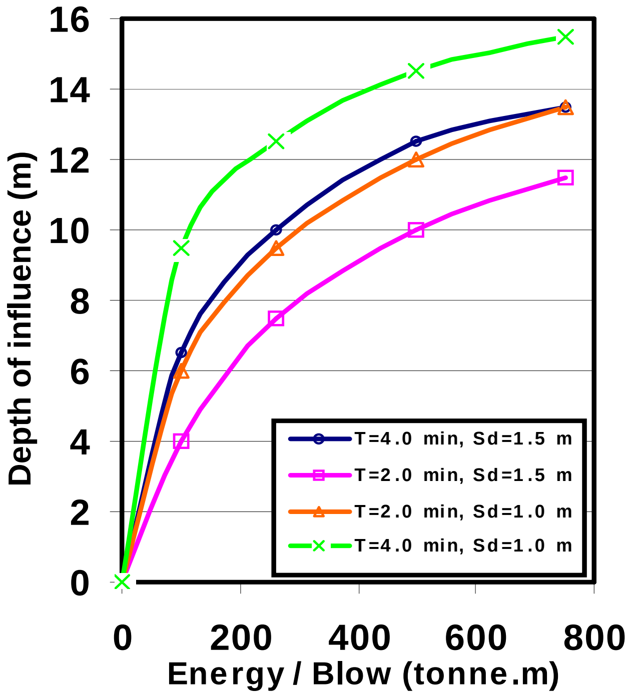


Effect of Number of Impacts N_I

Effects of Fines & Drain Spacing

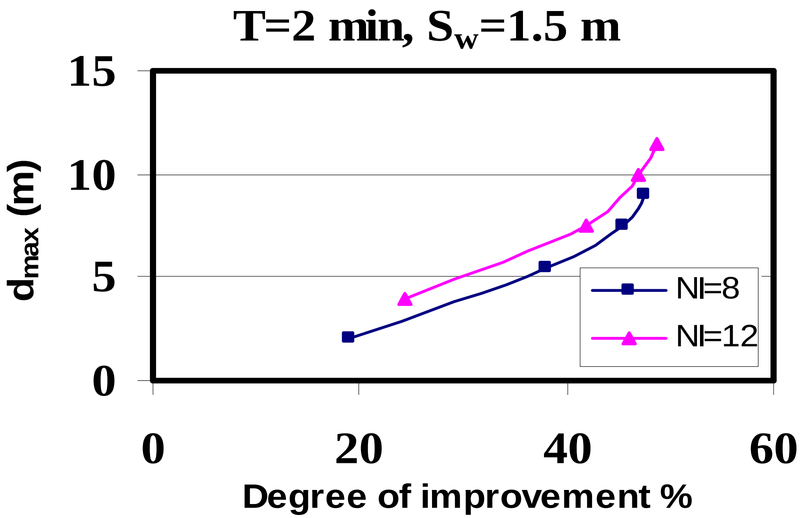


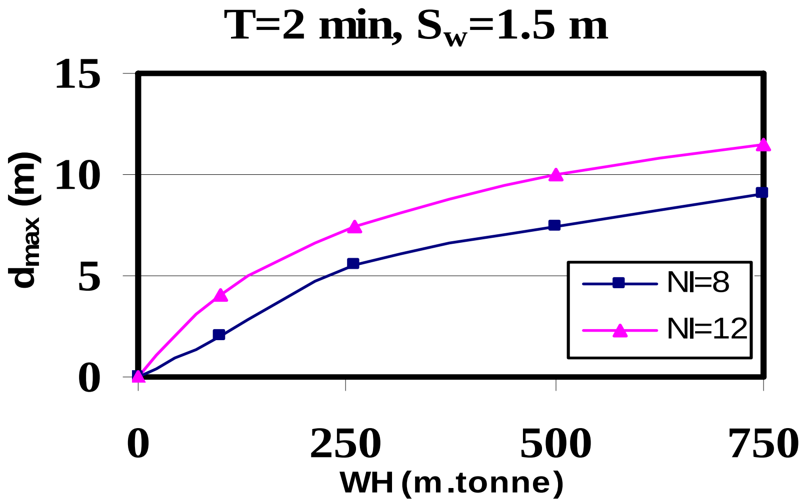
Effect of Fines
(drain S=1.5m)



Effect of Drain spacing S
& Impact Time Lag T; (k=10^{-7} m/s)

Design Charts and Design Guidelines





Example Design Chart

For silty sand deposit with k= 10^{-7} m/sec,

FC =25 %, and equivalent $pre\text{-}D_r$ of 40 %.

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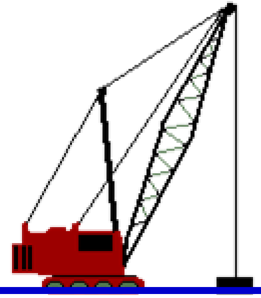

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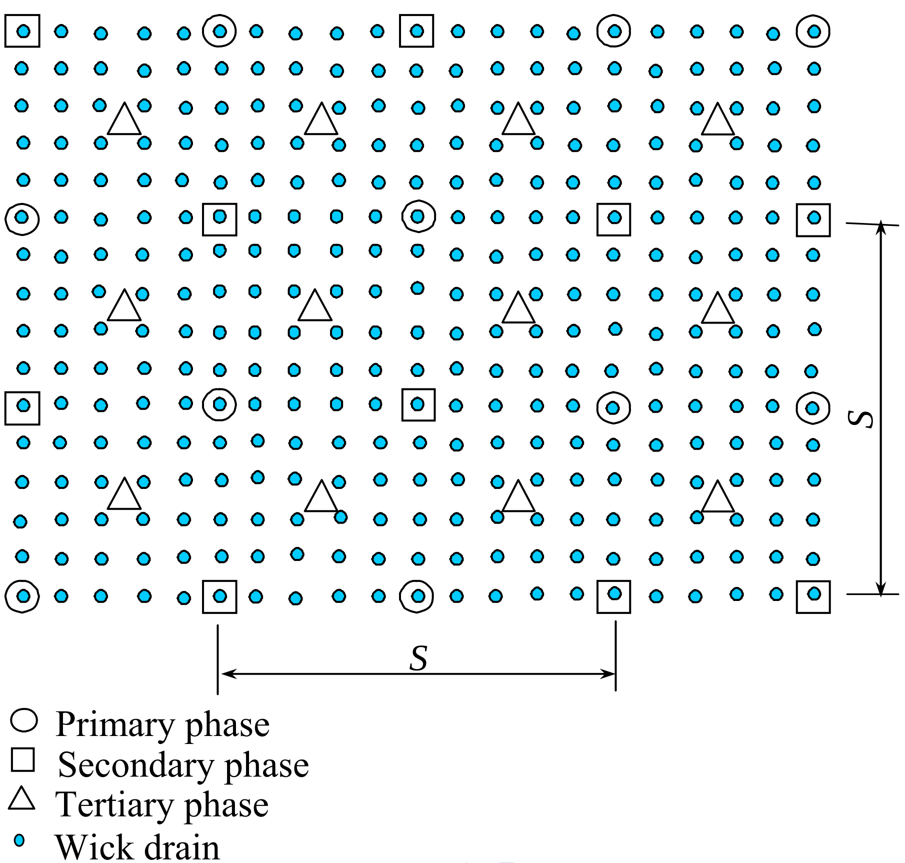
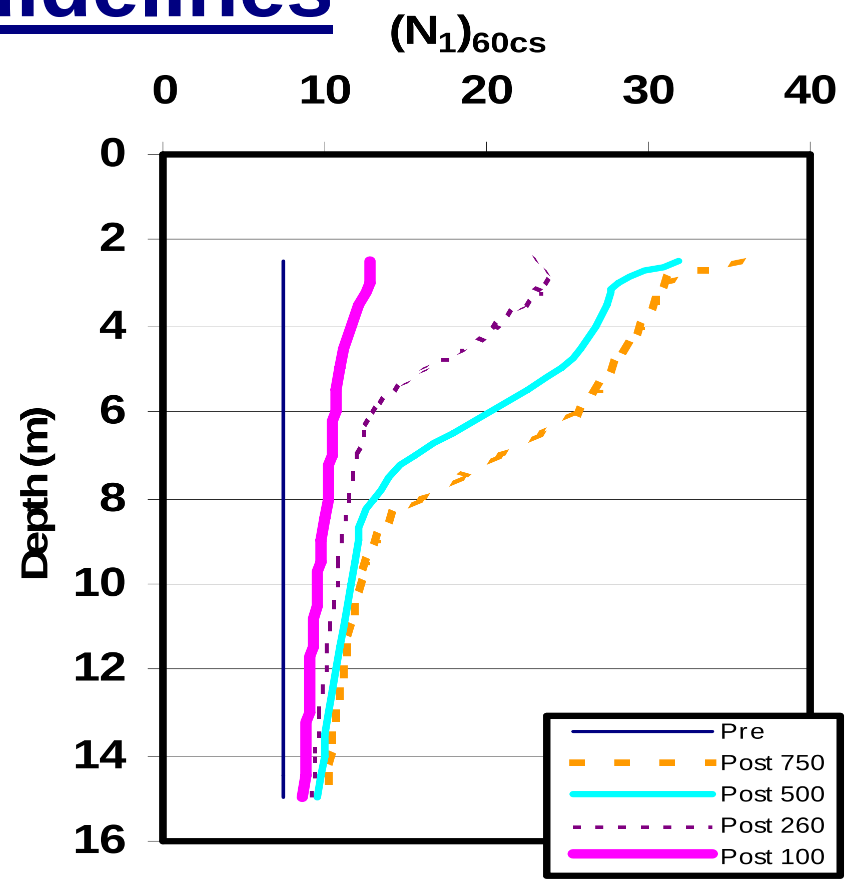
Design Guidelines



Impact Grid Pattern



Example Design Chart

(Post 750: WH = 750 Mg. m)

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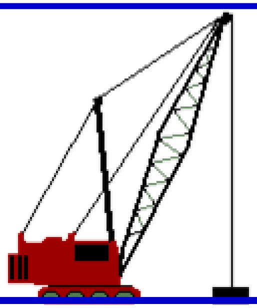

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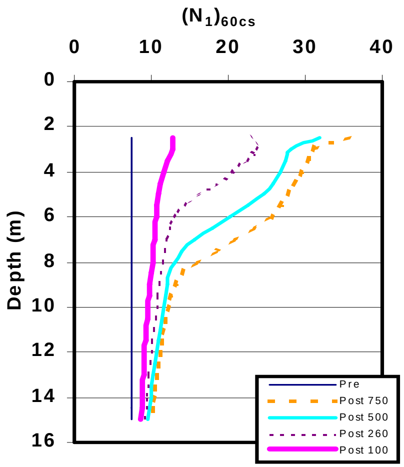
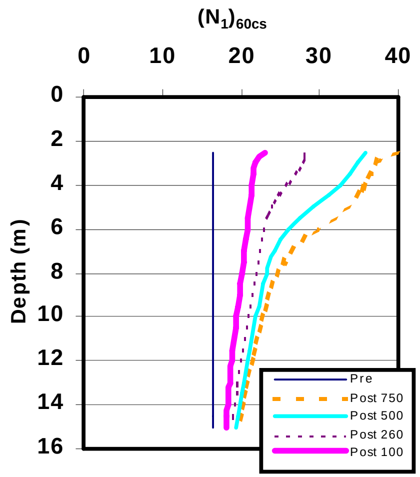
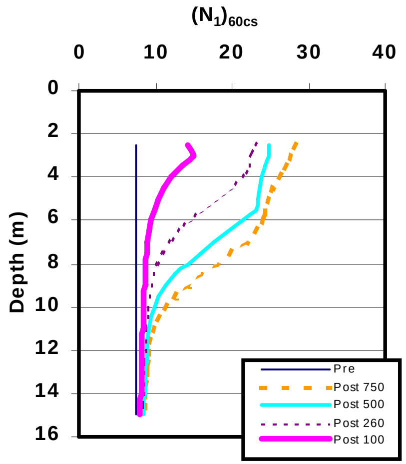


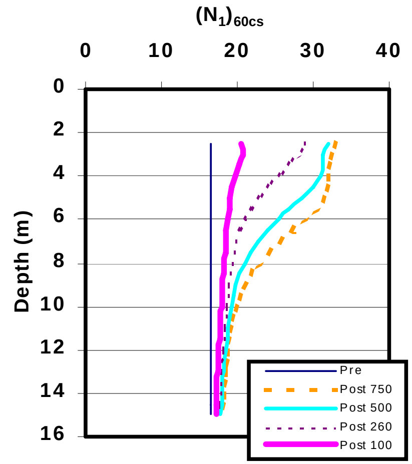
(a) $k=10^{-7}$m/s, $pre\text{-}(N_1)_{60cs}$ = 7.5



(b) $k=10^{-7}$m/s, $pre\text{-}(N_1)_{60cs}$ = 16

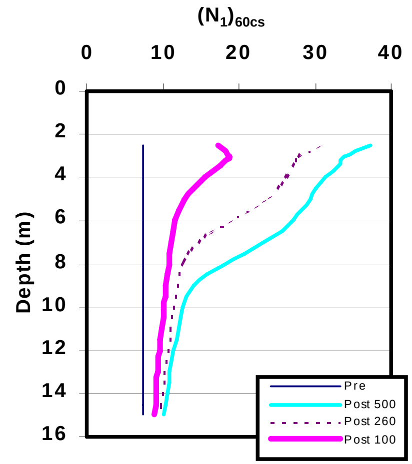


(c) $k=10^{-8}$m/s, $pre\text{-}(N_1)_{60cs}$ = 7.5

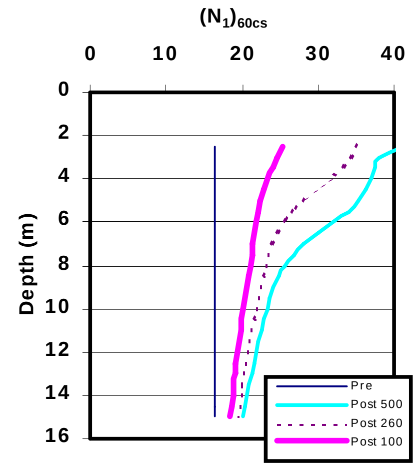


(d) $k=10^{-8}$m/s, $pre\text{-}(N_1)_{60cs}$ = 16

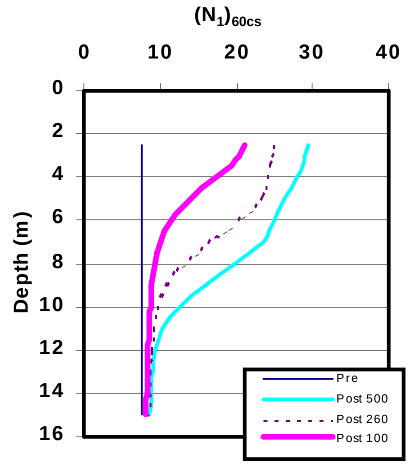
Pre- and post-improvement $(N_1)_{60cs}$ for S = 15.0 m



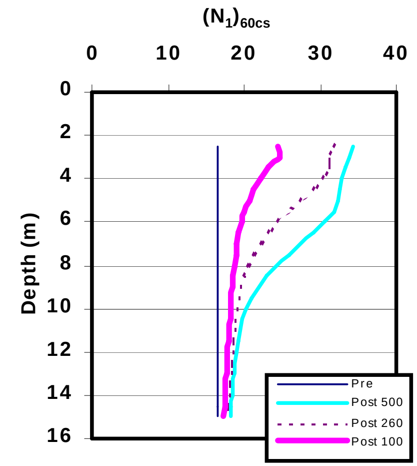
(a) $k=10^{-7}$m/s, $pre\text{-}(N_1)_{60cs}$ = 7.5



(b) $k=10^{-7}$m/s, $pre\text{-}(N_1)_{60cs}$ = 16



(c) $k=10^{-8}$m/s, $pre\text{-}(N_1)_{60cs}$ = 7.5



(d) $k=10^{-8}$m/s, $pre\text{-}(N_1)_{60cs}$ = 16

Pre- and post-improvement $(N_1)_{60cs}$ for S = 12.0 m

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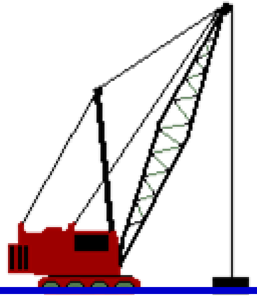

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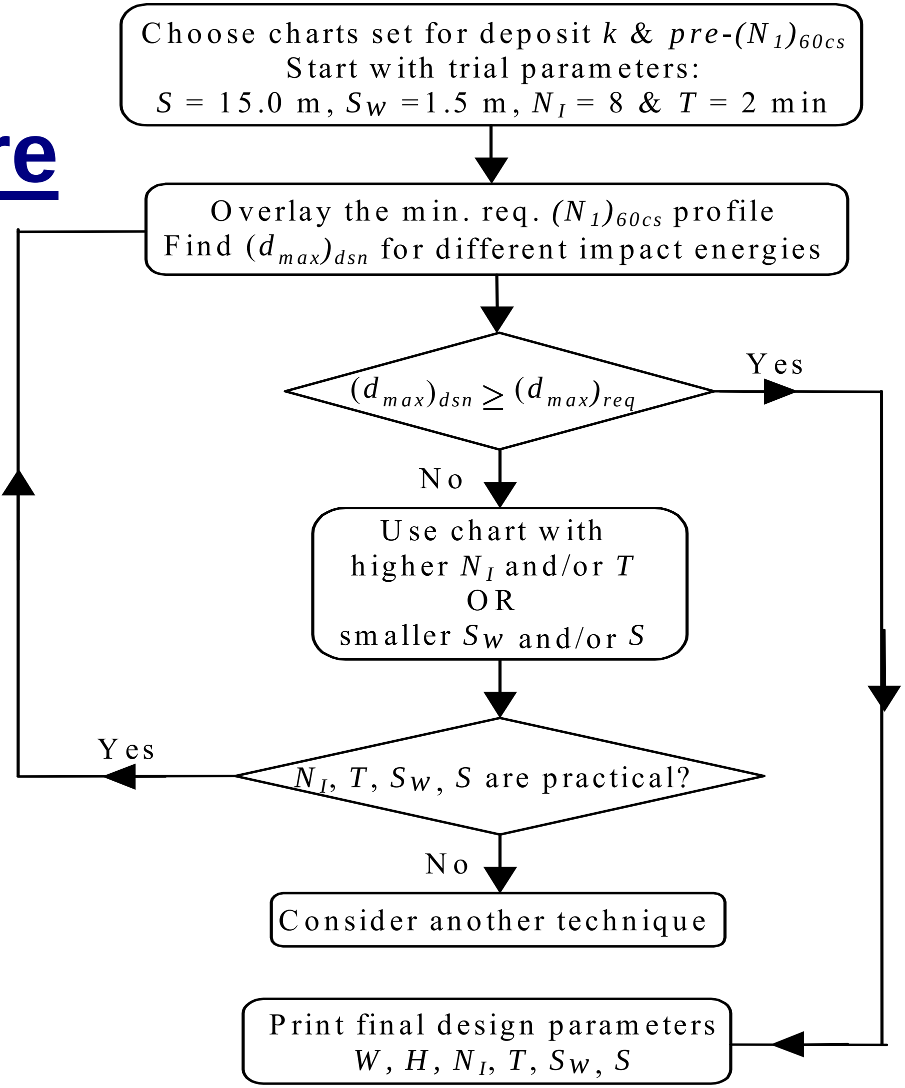
Design Procedure



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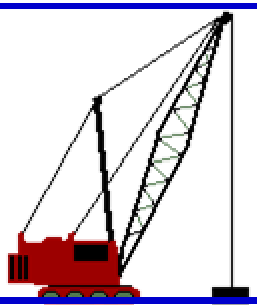

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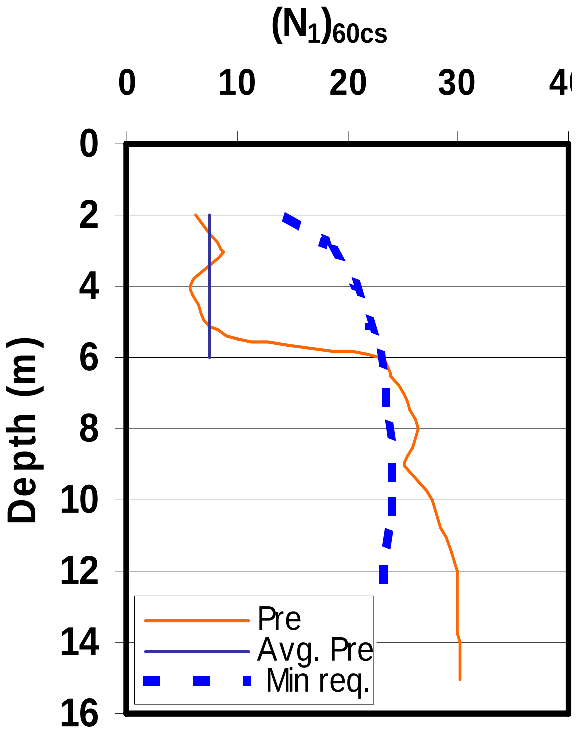
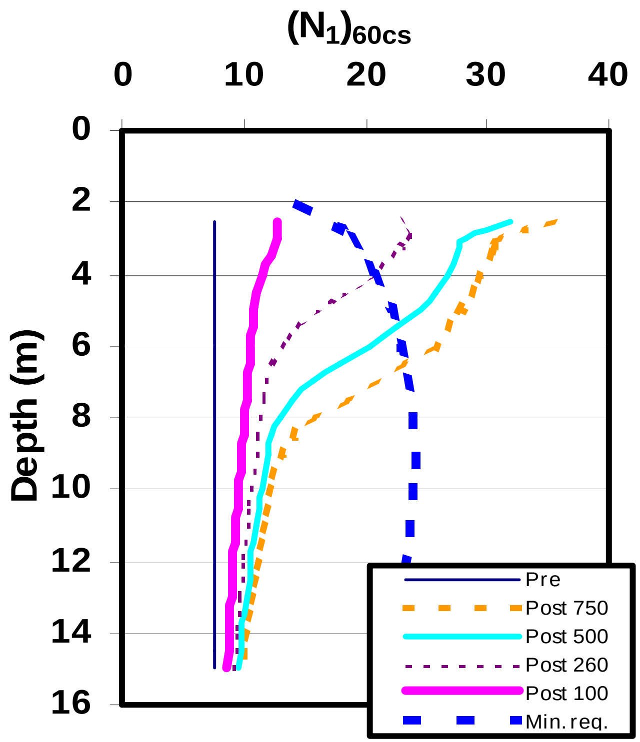
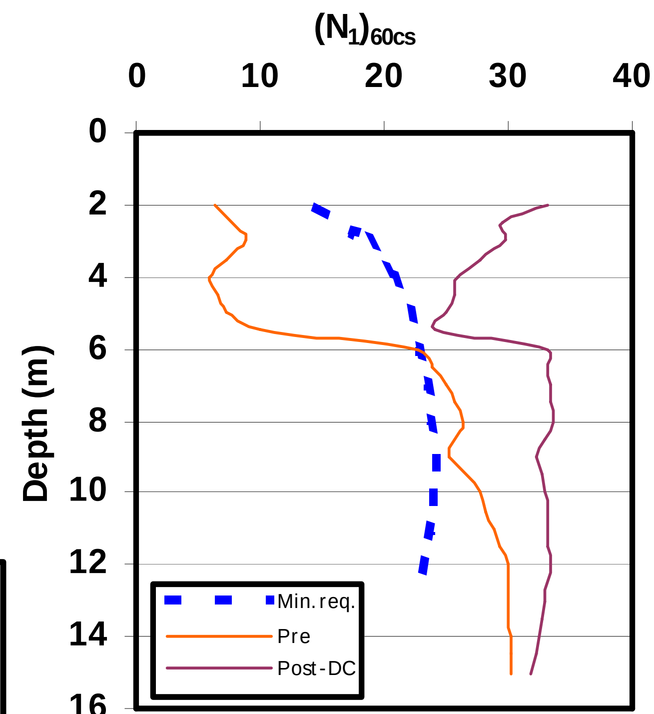
Design Example



Pre- and required $(N_1)_{60cs}$



Design Chart
(k=10^{-7}m/s, *Pre-*$(N_1)_{60cs}$=7.5)



Simulation Results

- ❖ **Design Earthquake of M = 7.5 and a_{max} = 0.25g.**
- ❖ **Recommended Compaction Parameters: WH = 750 Mg.m, N_I = 12, T = 2 min, S_w= 1.5m (rectangular pattern), wick drain equivalent diameter = 5 cm, and S = 15 m.**

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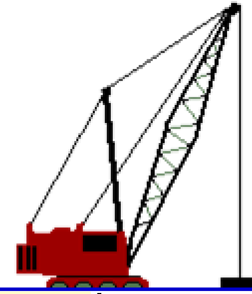

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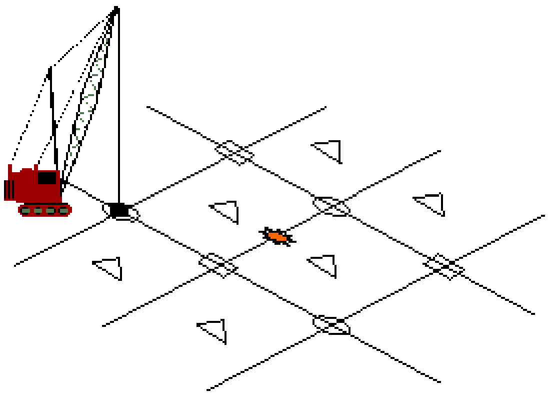
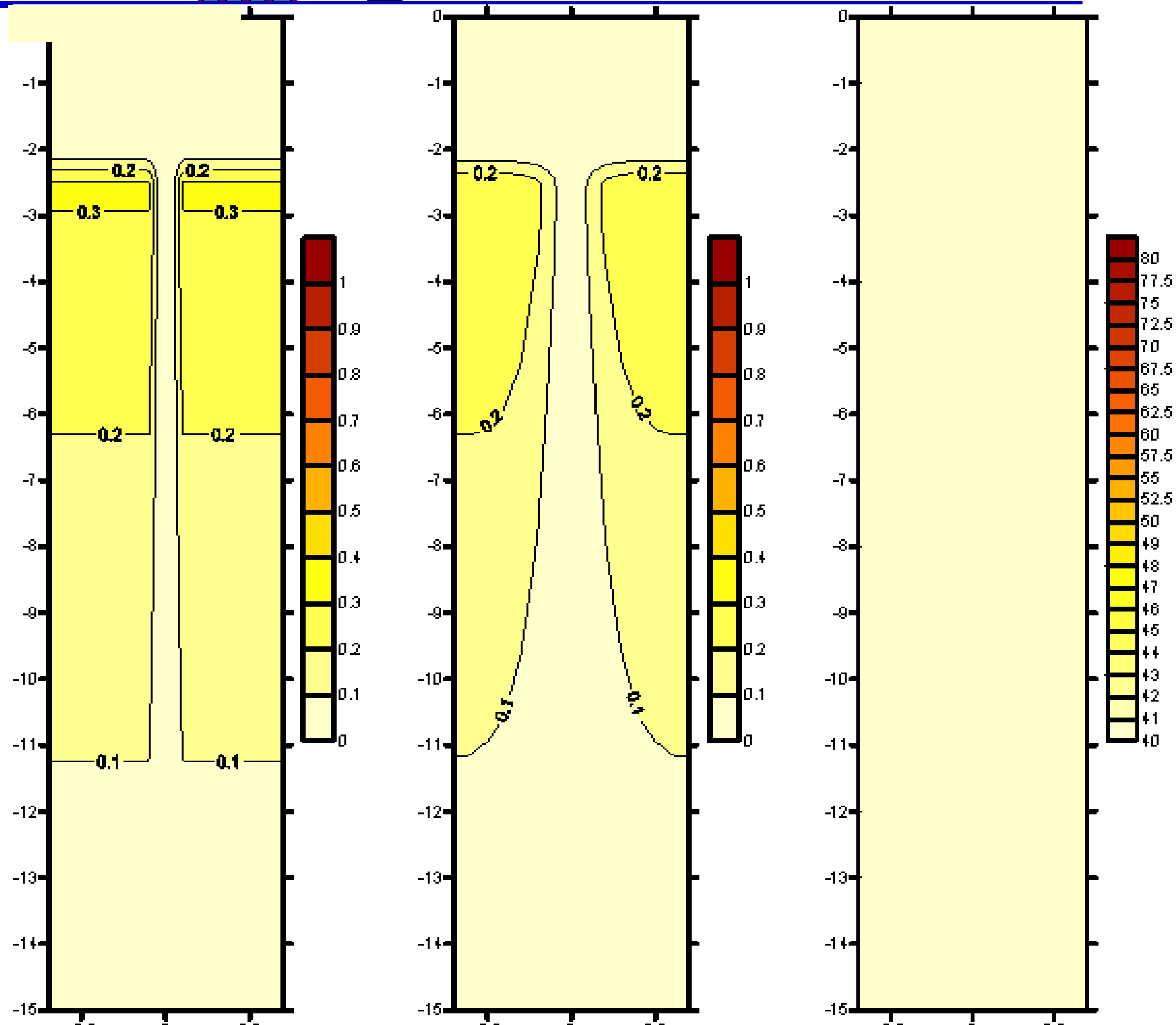


Density & PorePressure Changes around a wick drain During Dynamic Compaction



PWP After Impact   PWP Before Next Impact   Relative Density

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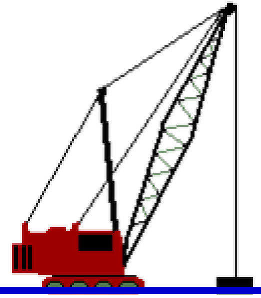

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Conclusions

- Current practice of design DC applications relies mainly on field pilot tests, past experience, and empirical equations based on field observations. No analytical procedure available to analyze the problem.

- A computational simulation model is presented for simulation of DC processes in saturated sand and non-plastic silty deposits.

- The simulation model is based on energy principals governing liquefaction resistance and coupled consolidation equations.

- The model has been verified through comparison with well-documented case histories in both sand and silty soil deposits and found to perform reasonably well.

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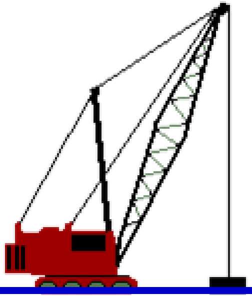

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Conclusions

- **The effects of site-specific conditions and field operational parameters on the achievable densification have been studied.**

- **Design guidelines for liquefaction mitigation of non-plastic silty soils using DC combined with wick drains have been presented.**

- **The recommended guidelines are expected to advance the use of DC to mitigate liquefaction potential in non-plastic silty soils, and reduce the reliance on expensive field trials.**

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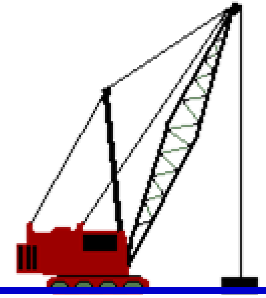

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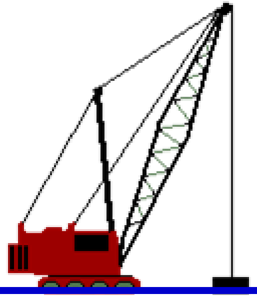
Publications

❖ **Nashed, R., Thevanayagam, S., Martin, G. R., and Shenthan, T. (2004), "Liquefaction mitigation in silty soils using dynamic compaction and wick drains", Proc. 13th World Conference on Earthq. Eng., Vancouver, Canada, Paper No. 1951.**

❖ **Shenthan, T., Nashed, R., Thevanayagam, S., and Martin, G. R. (2004), "Liquefaction mitigation in silty soils using composite stone columns and dynamic compaction", MCEER Research Progress and Accomplishments 2003-2004: *http://mceer.buffalo.edu/publications/resaccom/0304*, pp. 205-220.**

❖ **Shenthan, T., Nashed, R., Thevanayagam, S., and Martin, G. R. (2004), "Liquefaction mitigation in silty soils using composite stone columns and dynamic compaction", Earthquake Engineering and Engineering vibrations Journal, Vol.3, No. 1, *http://mceer.buffalo.edu/eeev/v3issue1/paper04.htm*.**

❖ **Thevanayagam, S., Nashed, R., Shenthan, T., and Martin, G. R. (2005), "Liquefaction and remediation in silty soils", California Depart. of Trans., Caltrans Bridge Research Conference, Sacramento, CA, Paper No. 06-501.**

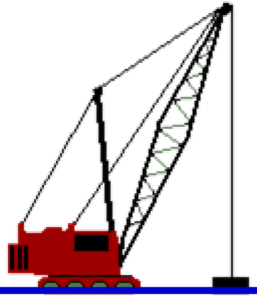


Publications

❖Thevanayagam, S., Nashed, R., Shenthan, T., and Martin, G. R. (2005), "Soil Densification Based on Vibratory and Earthquake Energy Considerations", In "New Applications & Challenging Soils for Ground Improvement Technologies", US-Japan Workshop, September 8-10, 2005, Kyoto, Japan.

❖Nashed, R., Thevanayagam, S., and Martin, G. R. (2006), "A Design Procedure for Liquefaction Mitigation of Silty Soils Using Dynamic Compaction", 8th National Conf. of Earthqu. Eng., Paper No. 1408.

❖Nashed, R., Thevanayagam, S., and Martin, G. R. (2006), "Simulation of dynamic compaction processes in saturated silty soils", Geo Congress 2006, ASCE Paper No. 10926.



THANK YOU

Questions…