Using Rammed Aggregate Pier Methods to Reduce Liquefaction Potential

Kord Wissmann, PhD, PE, D.GE

- Chief Engineer (and President) Geopier Foundation Co., Inc.
  - Vice Chair, ASCE Geo-Institute Soil Improvements Committee

New Zealand’s U.S. Ambassador

(Summer 2013)

Outline

- Start with the obvious (why are we here today?)
- One solution – RAP ground improvement
  - What is it? How does it work?
    - What happens to the ground?
      - How do you design it?
        - Any past experience?
- Densipact

The Obvious

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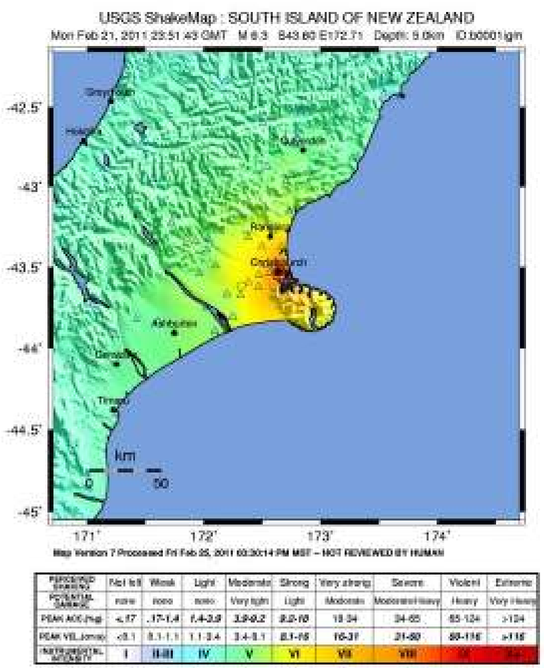
Christchurch hit with 2 large seismic events in Sep 2010 and Feb 2011

(Mw = 7.1; Mw = 6.3 with Amax up to 2.2g)

These EQs reinforced New Zealand's position along the ***Ring of Fire!***

Much liquefaction



(courtesy Google & Wikipedia)

The Obvious

Many choices for reconstruction:

- **Remove bad stuff** - excavate ($$$)
  - Groundwater?
  - Environmental?
- **Bypass bad stuff** – deep foundations.
  - Works good. $$$
    - Design piles for bending
- **Ground improvement**

The Obvious

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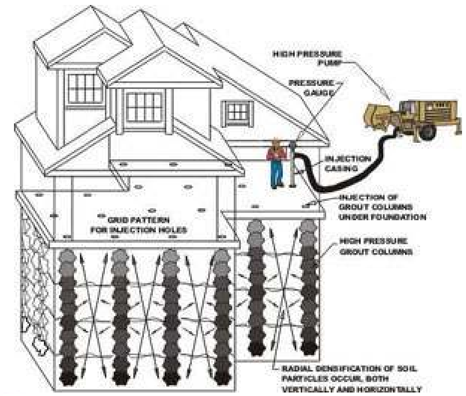
Ground Improvement Options:

- **Low mobility grouting**…limited effectiveness.
- **Vibroflotation / stone columns**…water jets.
- **Mixing…** $$$.
- **DDC**…< $. Large vibrations.
- **RIC**…< $. Moderate vibrations.
- **RAP…this presentation**



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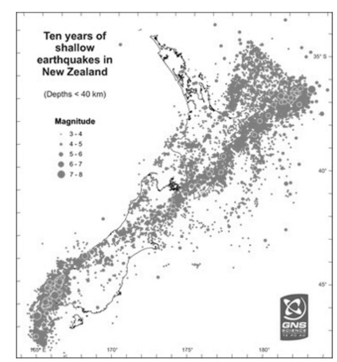

Rammed Aggregate Pier – What is It?

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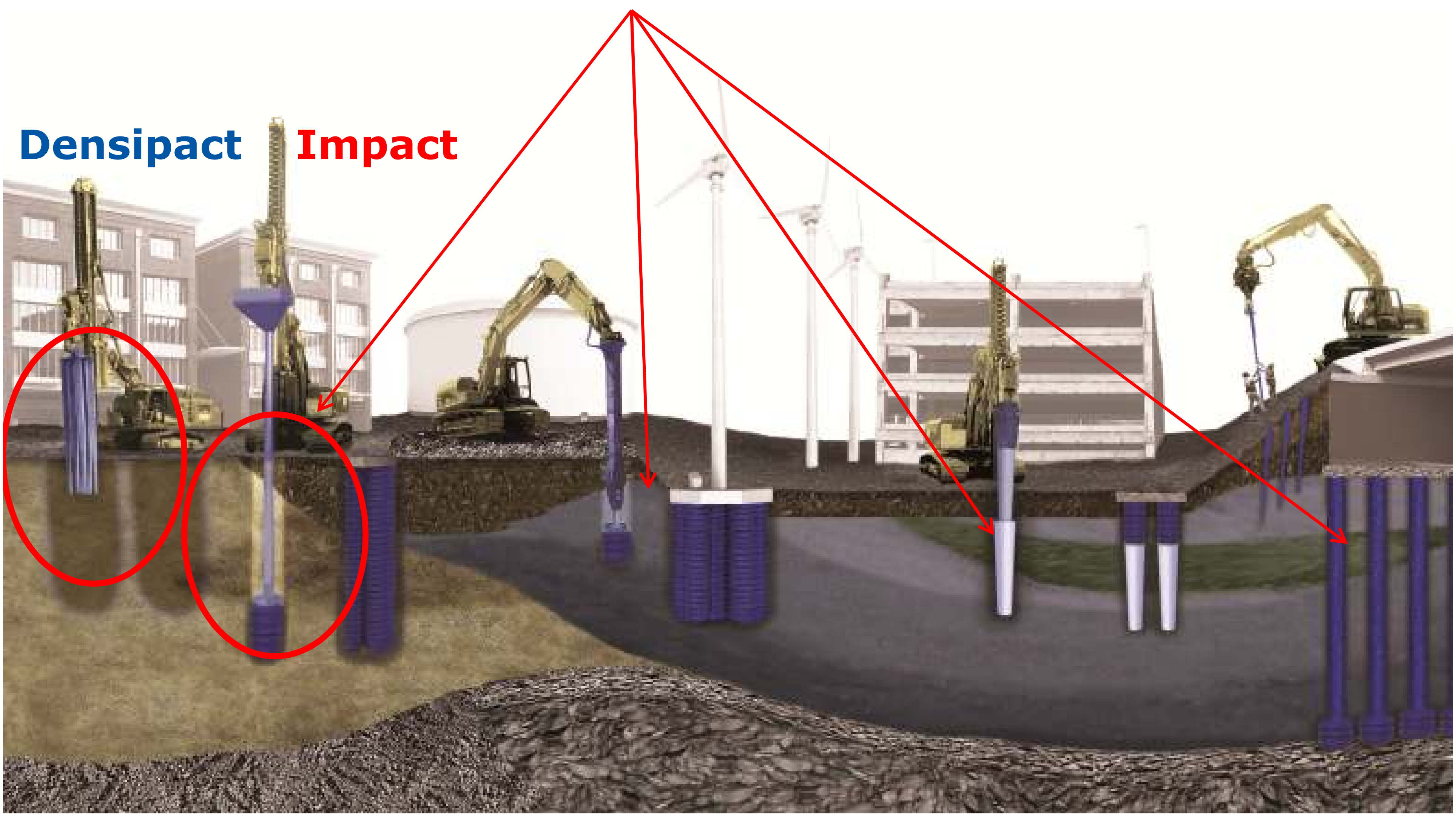
Drilled and displacement methods used to construct RAPs



Impact® Construction

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Displacement Method

Impact Construction

- Displacement approach, no spoils
- Depths to 20m
- Dry process (no water jetting)
- Rapid installations (40 – 100 /day)
- Proprietary mandrel and method

    (NZ Patent Application No. 615252)

Impact Construction

Construction Method

1. Drive mandrel to depth
2. Fill hopper
3. Lift up 1m
4. Drive back down 0.7m (densifies aggregate)
5. Repeat

Controlled process creates:

- Uniform diameter
- 300mm lift thickness.

End of pier construction

Impact Construction - vibrations

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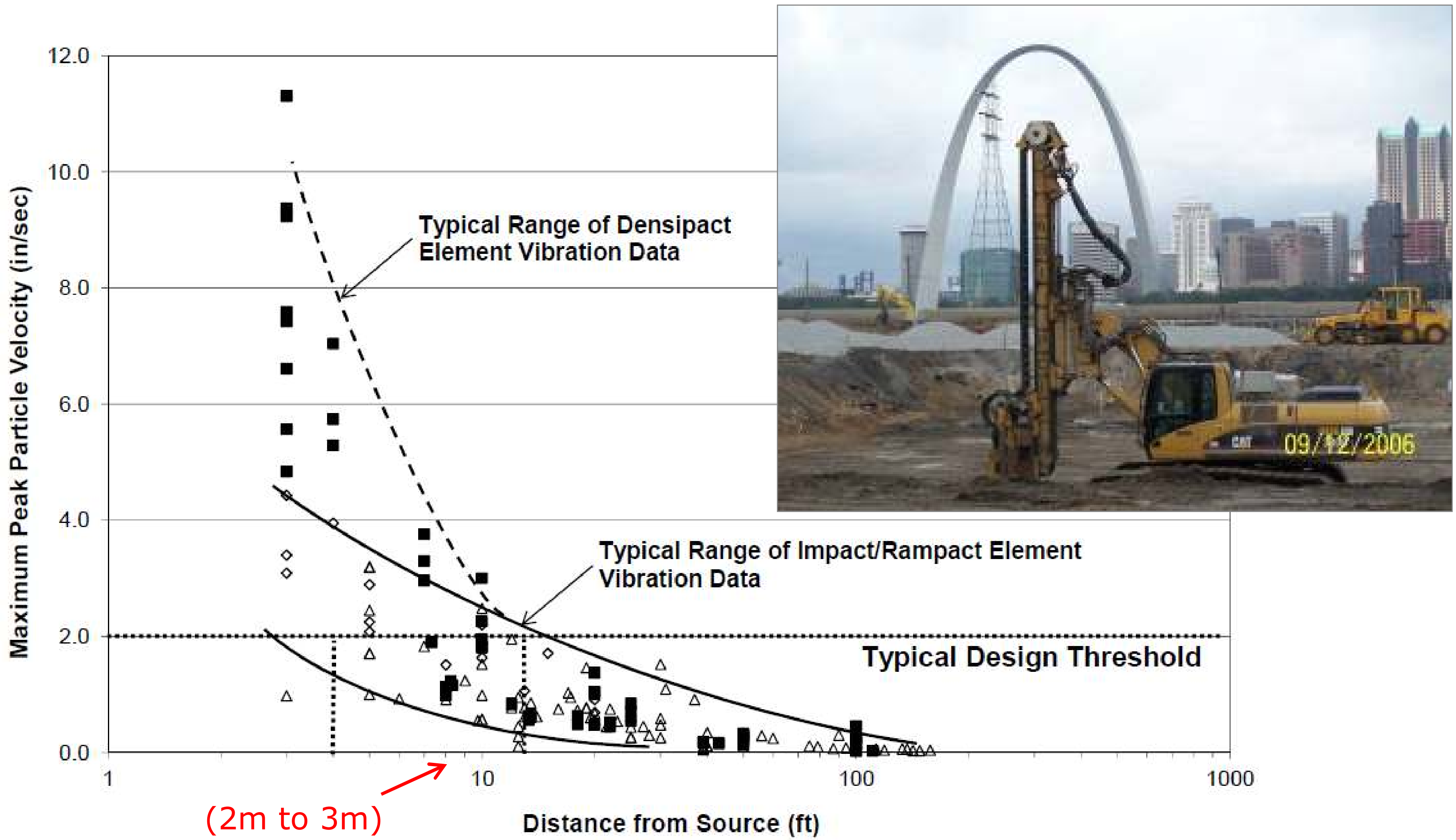
Vibrations ? ……… Reasonable



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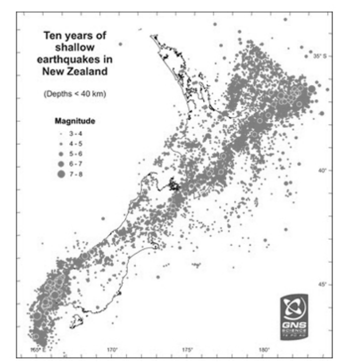

What happens to the ground?

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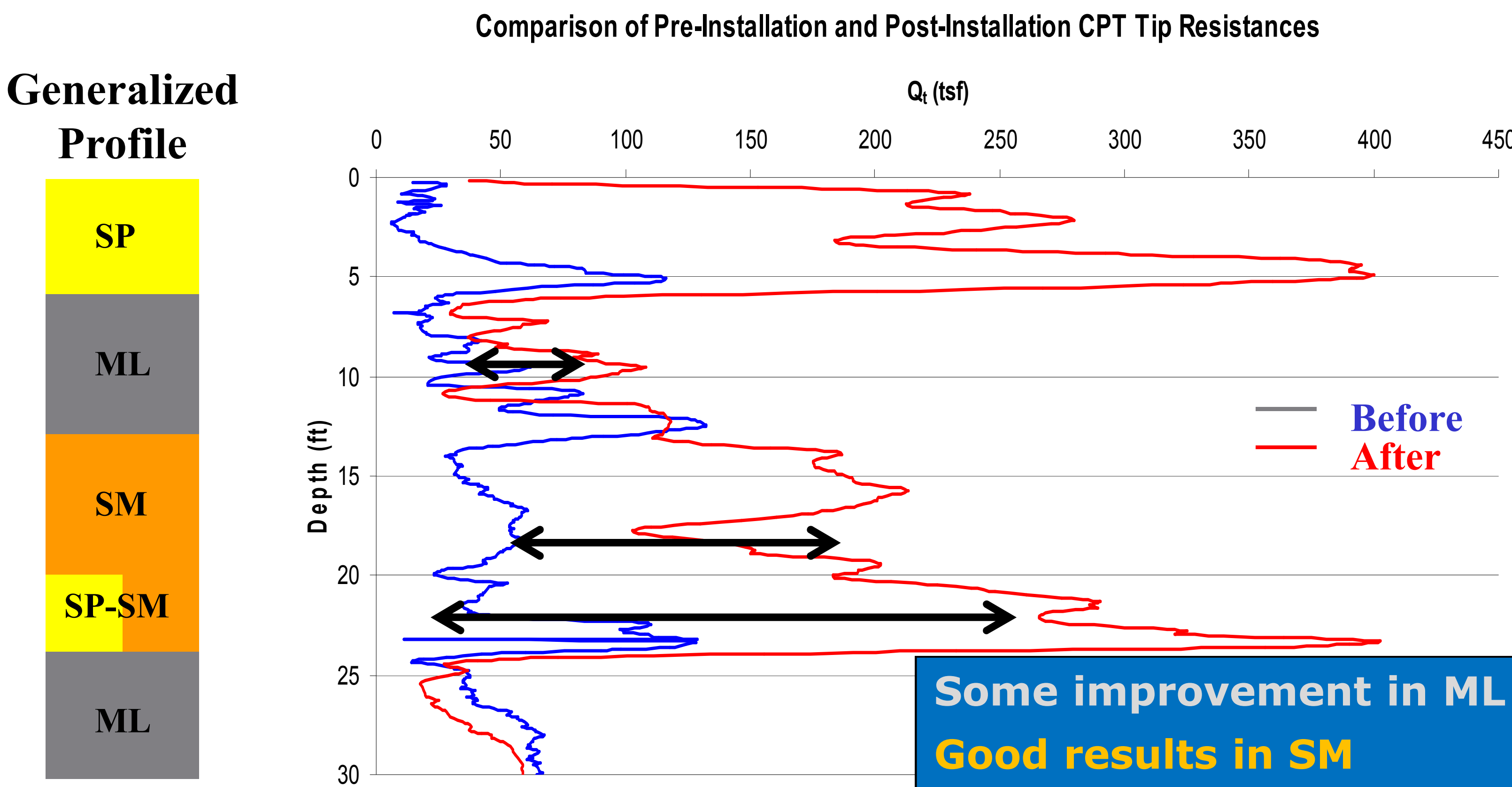
Ramming & cavity expansion of the aggregate = densification

[Typical before / after CPT sounding]:



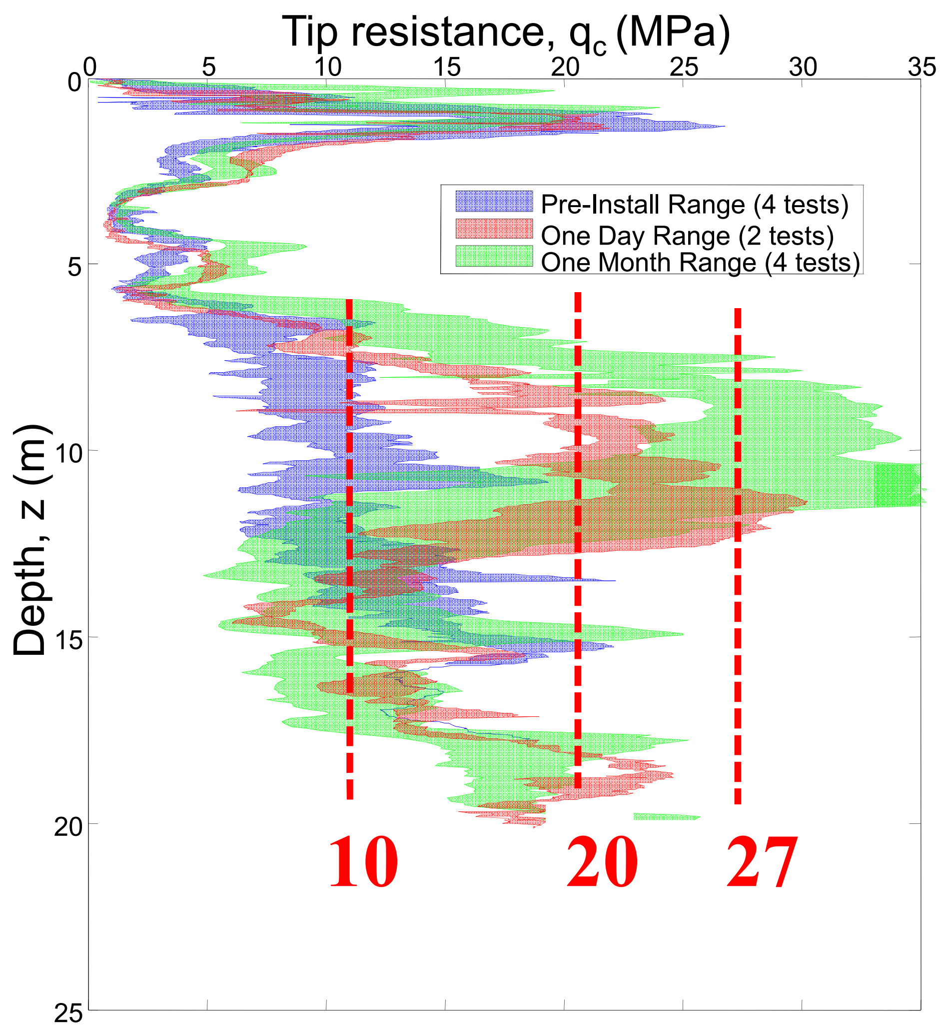
Some improvement in ML

Good results in SM

Best results in SP

What happens to the ground?

Aging results in increased penetration resistance with time



New Madrid MO site (s = 2.3m)

Improvement Factor:
1 Day, I_F = 2.0
1 Day to 30 Days, I_F = 1.35

(Courtesy: David Saftner, PhD (UM-Duluth) & Russell Green, PhD (Virginia Tech))

What happens to the ground?

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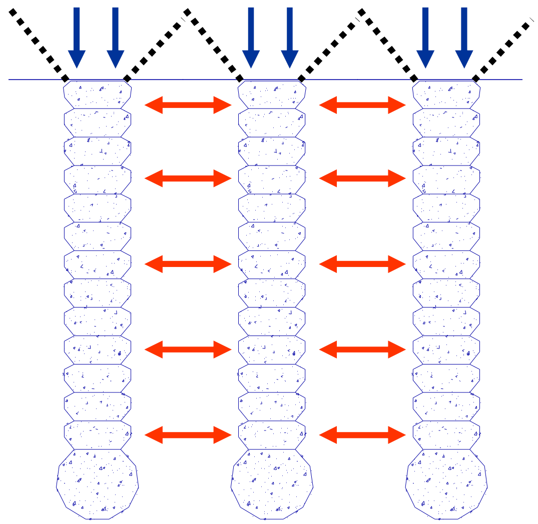
Pier installation increases lateral stress to ~ K_p (Handy 2001)



(Refs: Handy 2001, Thompson & Suileman, 2010, many others)

What happens to the ground?

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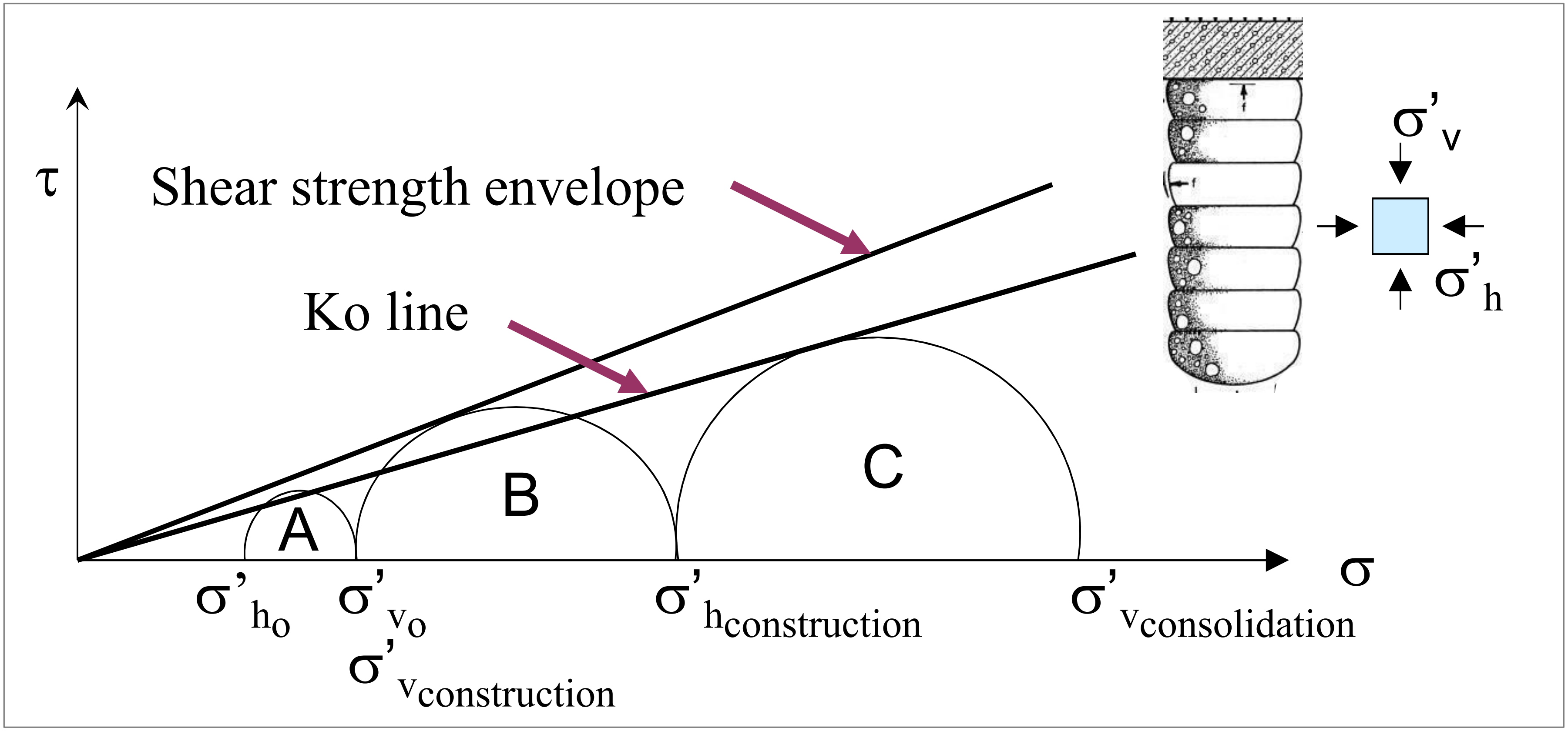
Theoretical construct showing influence of lateral stress increase (Handy 2001)



Increasing lateral stress **decreases** matrix soil **compressibility**.

Ref: Handy 2001

What happens to the ground?

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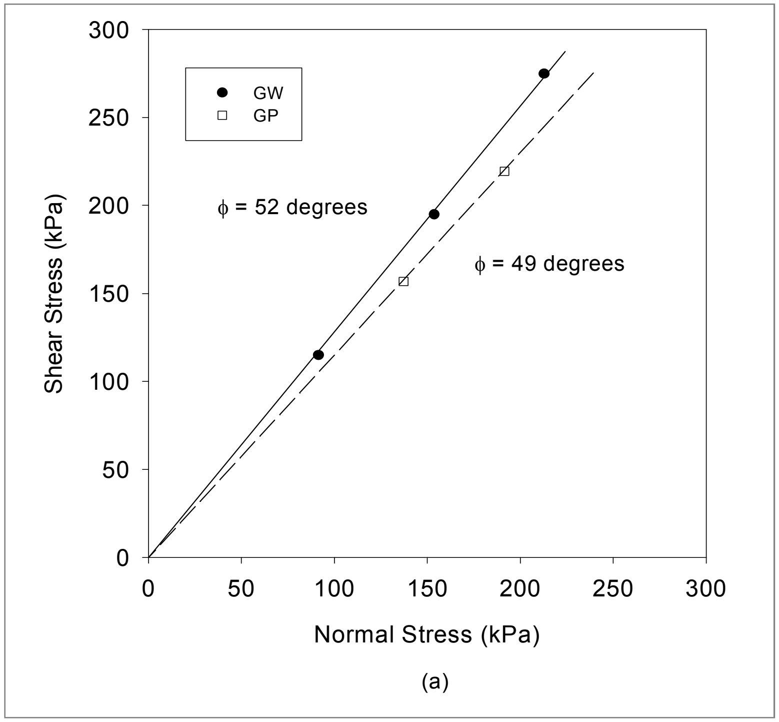
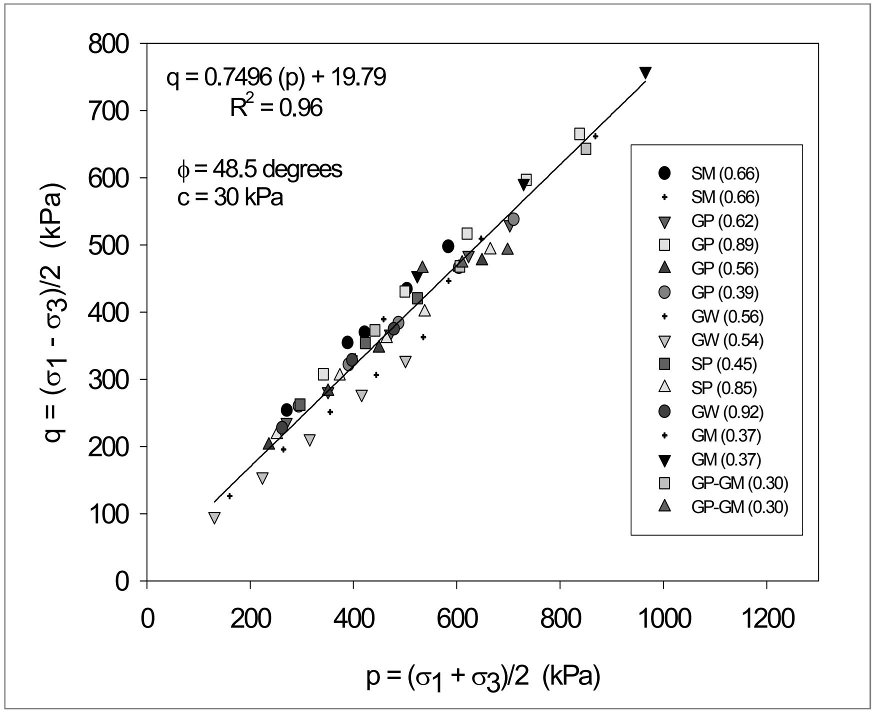
High pier aggregate friction angle from tamping: results in high stiffness





Full-scale top-of-pier direct shear test results
(Fox and Cowell 1998)

Laboratory triaxial shear tests
(White et al 2002)

Pier Friction angle: = **48** degrees (o/g stone)
= **52** degrees (w/g stone)

How do you design it?

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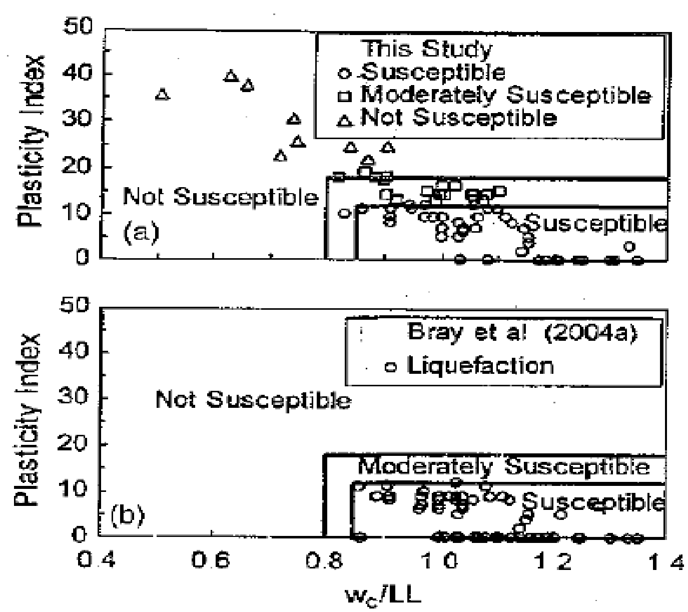
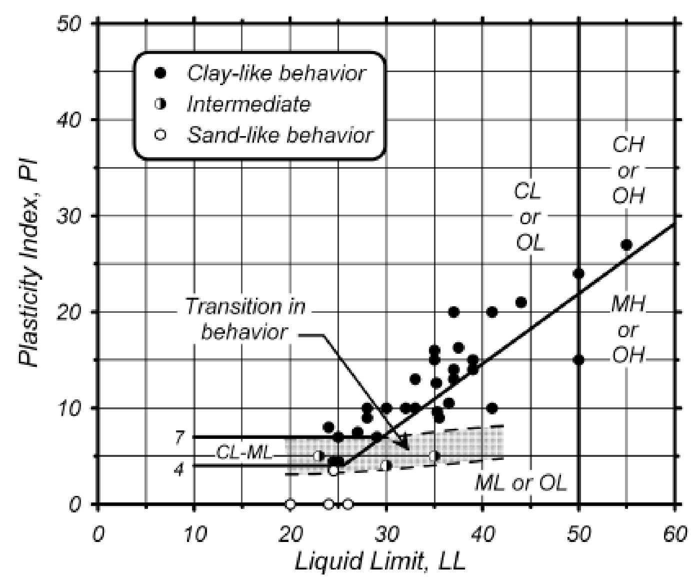
Densification: Include non-plastic silt

1. Bray and Sancio (2006): Liquefaction for PI<12 and WC/LL > 0.85.
2. Idriss and Boulanger et al. (2008): Liquefaction for PI< 7.

(Rule of thumb: Consider liquefaction for PI<10 and not if PI>10)



Bray and Sancio



I&B

What happens to the ground?

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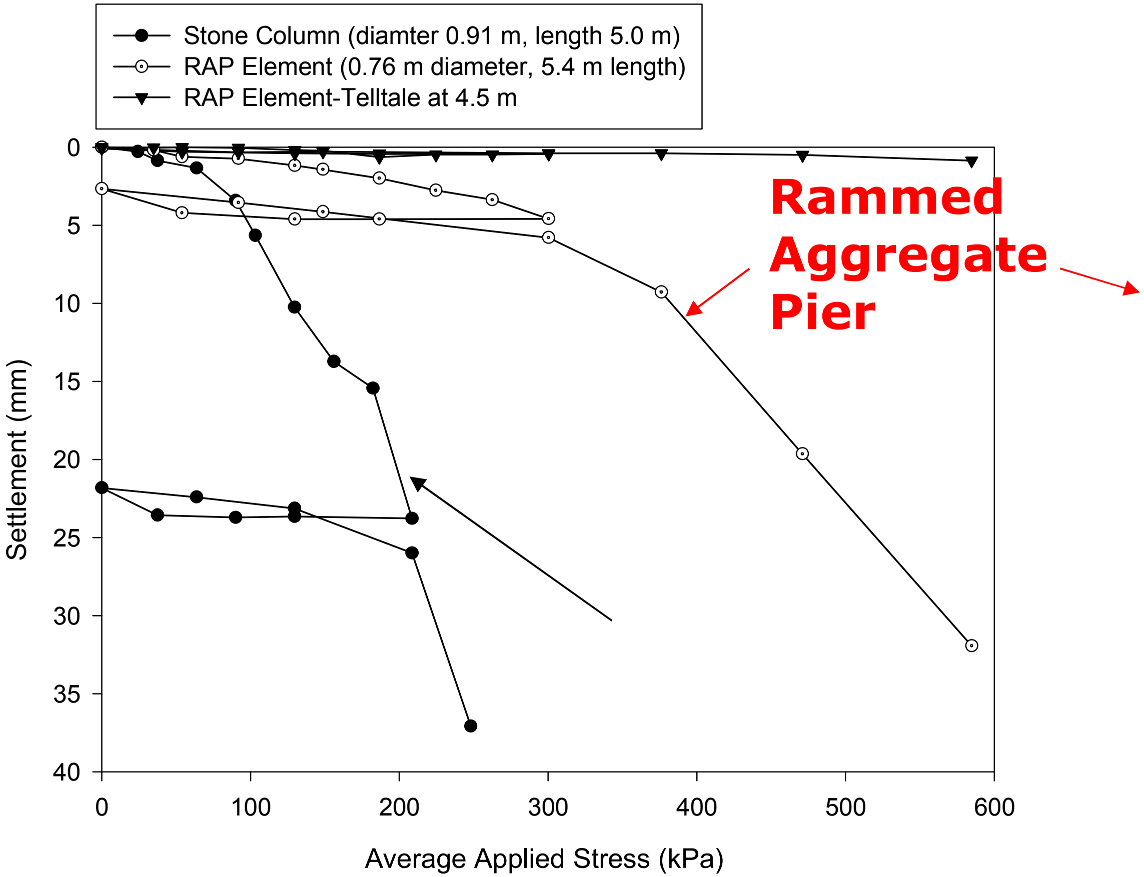
High pier stiffness from direct ramming measured by modulus load tests



RAP process

RAP is not the same as a stone column

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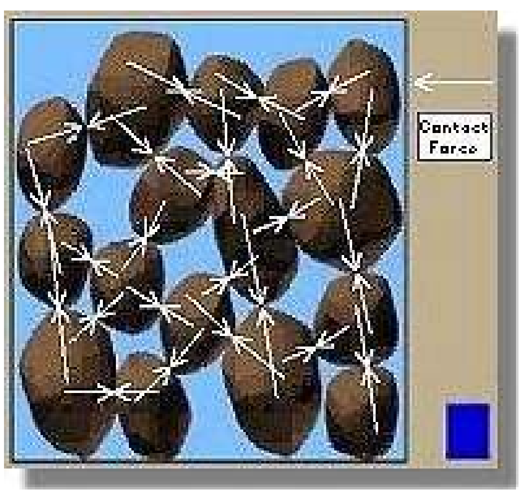
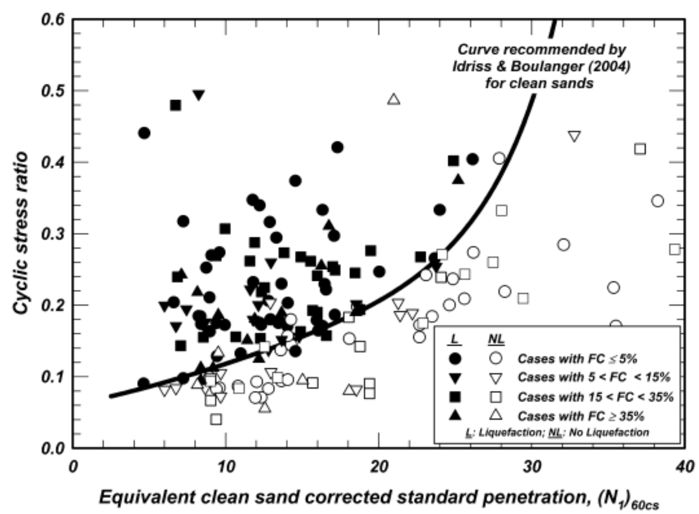
- Other uses you may be interested in

Liquefaction - What is it?

If the level of EQ shaking is of sufficient intensity and duration:

- Loose sands contract,
- Pore water pressures increase, effective stress decreases
- Causing reduction in soil shear strength.
- Results in both a loss of soil shear strength and settlement as the excess pore water pressures dissipate.
- Seed's Simplified method for design (Youd et al. 1997)





How do you design it?

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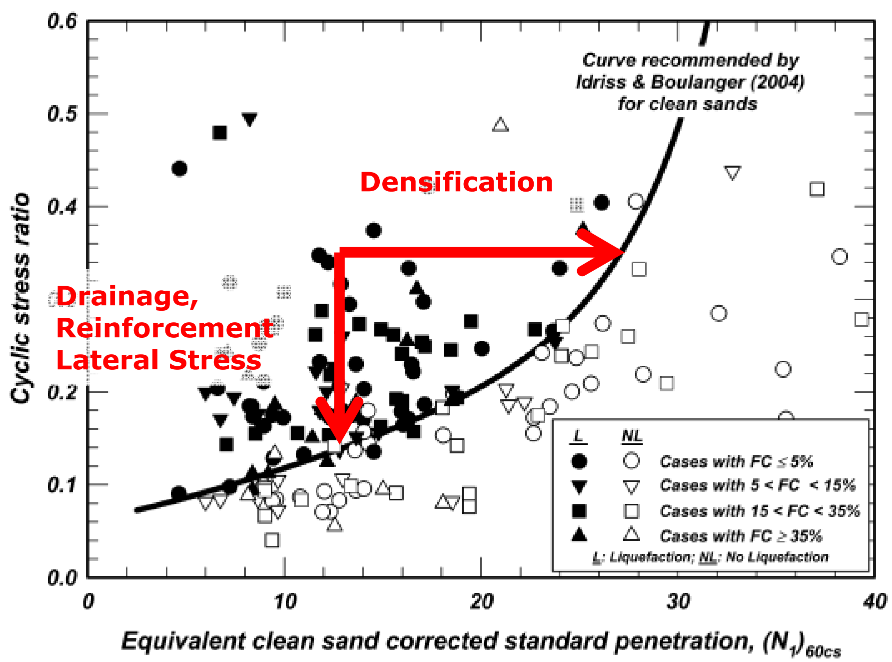
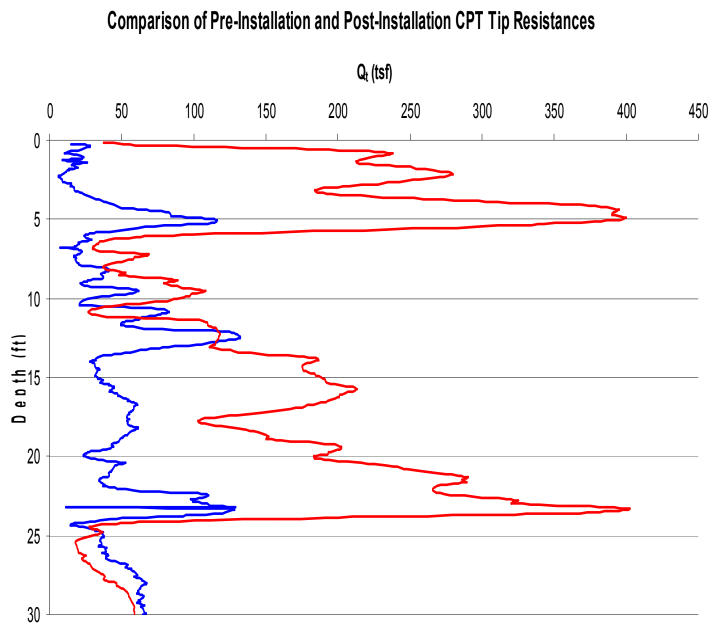
Liquefaction **abatement** using ground improvement:

- **Densification**
  - **+ Drainage, Reinforcement, Lateral Stress Increase**
    - **Building a surface crust**



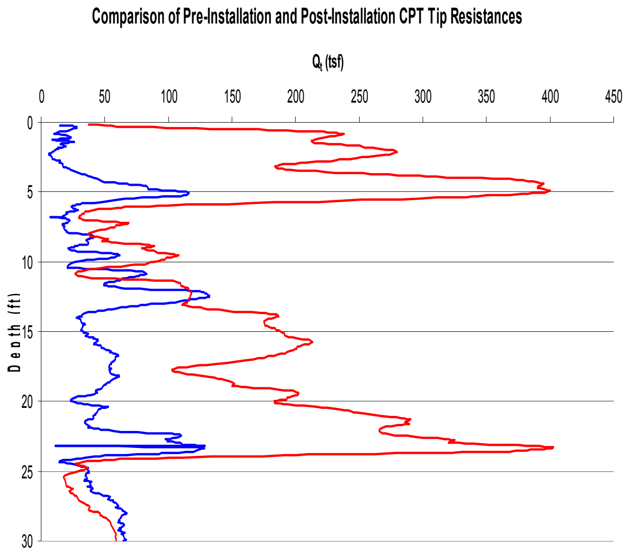


(from R. Green, 2007)

How do you design it?

Densification

- Use Impact Pier or Densipact to densify / reinforce
  - Measure increase in penetration resistance



Best results in SP - liquefiable
Good results in SM - liquefiable
Some improvement in ML- liquefiable?

How do you design it?

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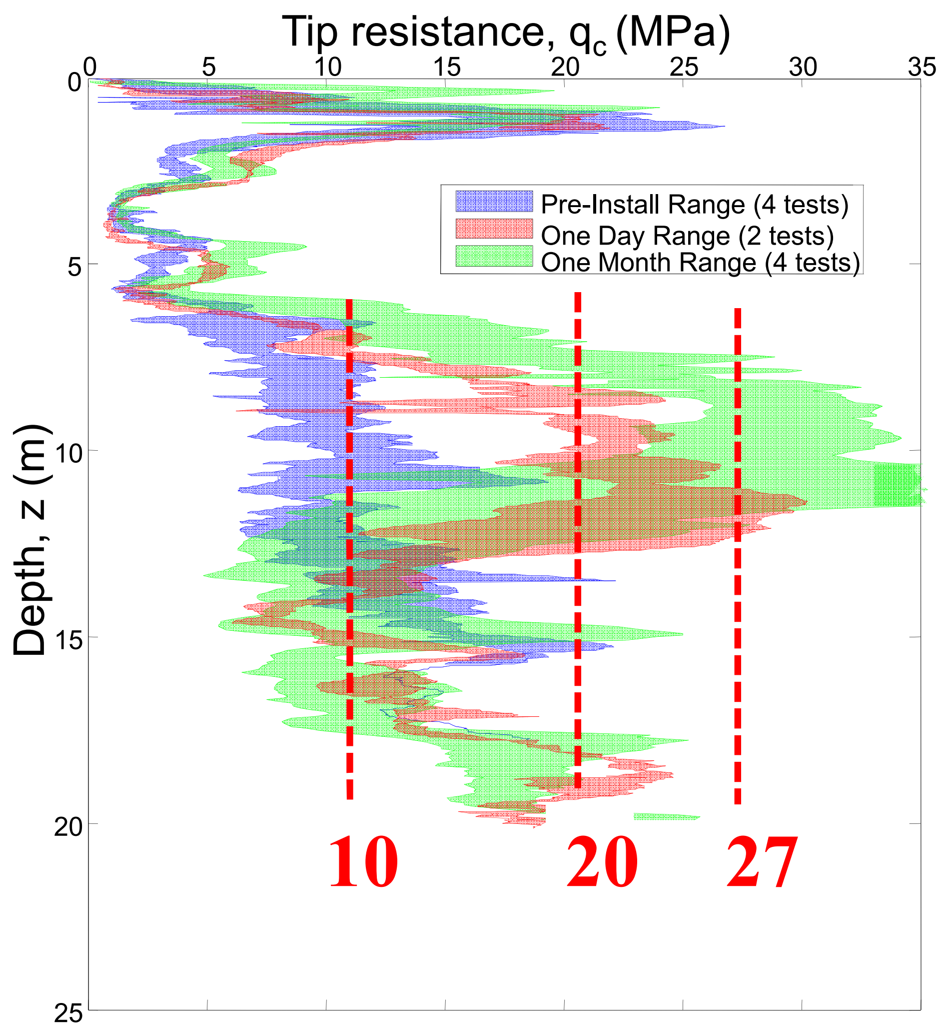
Densification: Correct for aging



New Madrid MO site (s = 2.3m)
Improvement Factor:
1 Day, I_F = 2.0
1 Day to 30 Days, I_F = 1.35

From many sites using compaction methods:

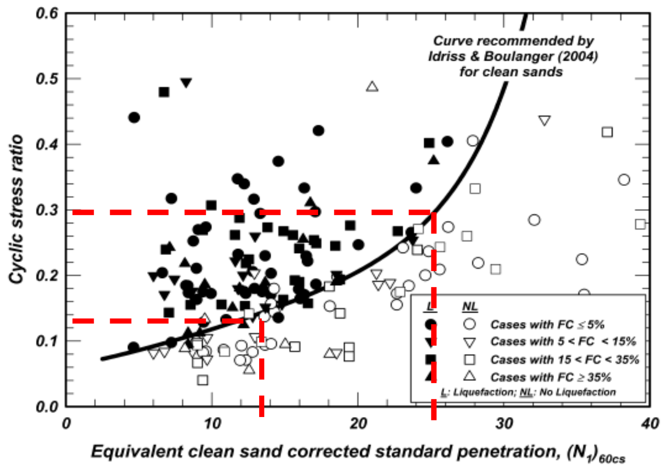
$$\frac{q_c(t)}{q_{c,fresh}} = 1 + 0.16\log(t)$$

(Courtesy: David Saftner (UM-Duluth) & Russell Green (Virginia Tech))

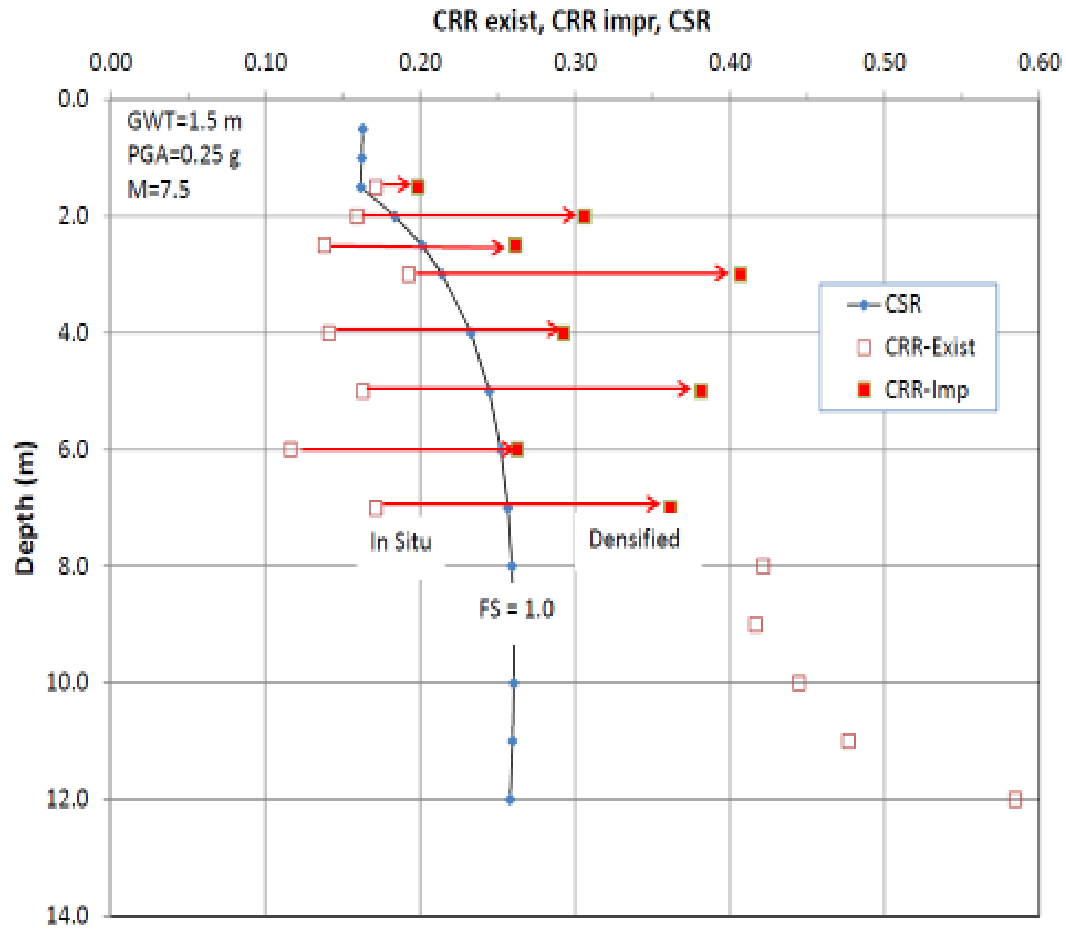
Impact Pier design: assume x1.25 for design where CPT testing < 5 days

How do you design it?

Densification: Example summary of FoS vs Liquefaction

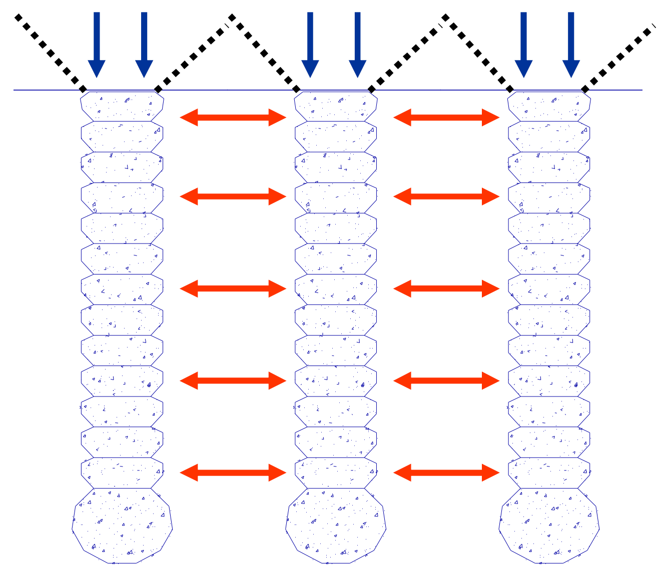


Densification provides increase in CRR



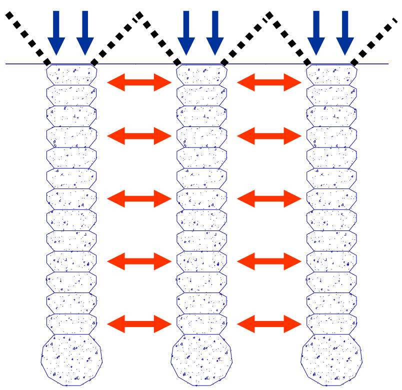
Liquefaction **abatement** using ground improvement:

- **Densification**
  - **+ Drainage, Reinforcement, Lateral Stress Increase**
    - **Building a surface crust**



Drainage:

- Depends on ability of piers to (freely) drain pore water
  - Sand drain construction: $k_{drain} / k_{soil} = 200$
  - RAP Impact pier: $k_{drain} / k_{soil} = 10$ (measured)
  - **Dynamic FEA (Green): small increase in CRR**

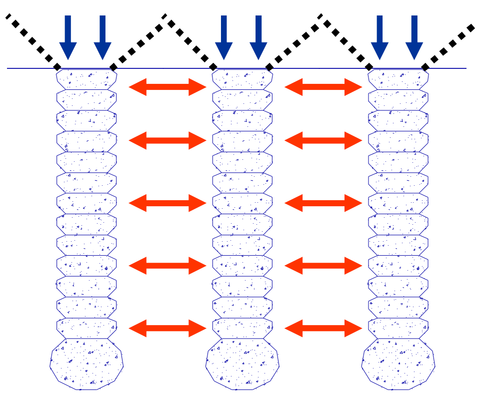


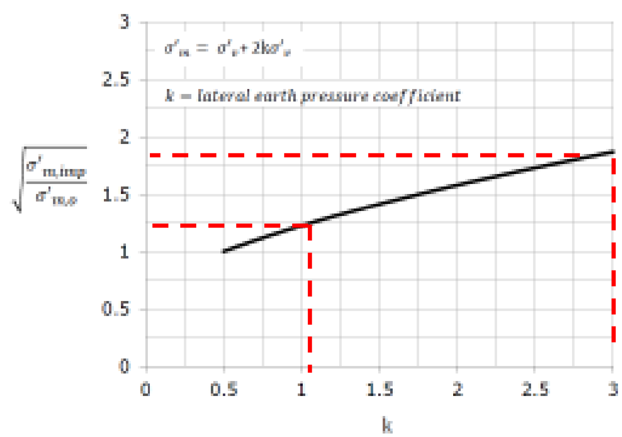
Impact pier constructed in ground.
Casing driven around pier.
Casing + soil removed.
System de-aired.
Full scale constant head k test.

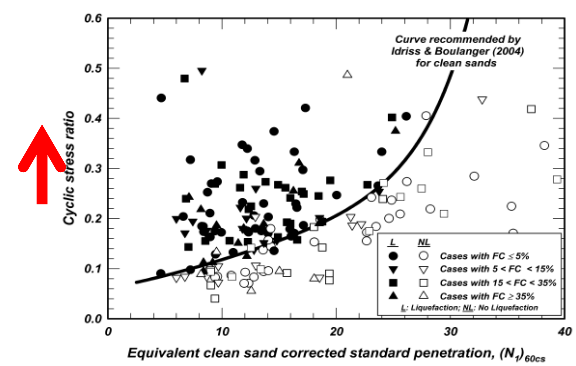
(from R. Green, 2010)

Lateral Stress Increase

- Increasing lateral stress increases the resistance to shearing
  - CRR = τ_r / σ_v' $\quad\quad$ τ_r = CRR x σ_v'
  - Lateral pre-stress increases mean stress (σ_m') by factor of 1.5 to 3
  - Proposed method: $(\tau_r)_{imp} = (\tau_r)_0 \times CRR \times [\mathrm{sqrt}(\sigma_{m,imp}' / \sigma_{m,0}')]$
  - *Lateral stress improvement factor of increases CRR by **1.2** to 1.7*







Lateral stress increases CRR by ~ 20%

How do you design it?

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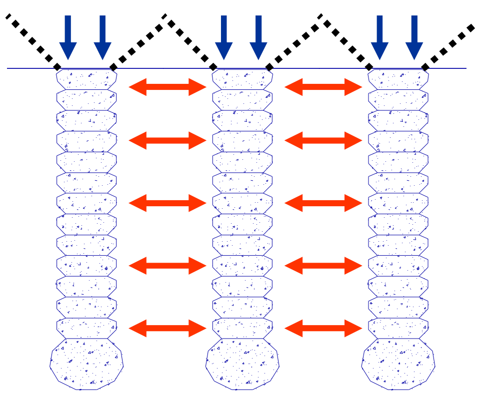
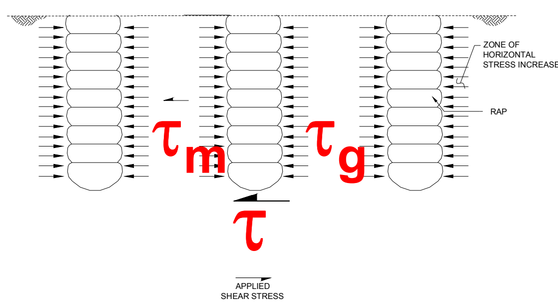
Shear Reinforcement

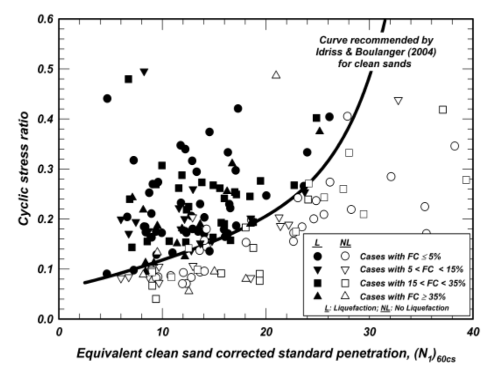
- Dynamic FEA by Green et al. (2008) and independently by Boulanger et al. (2012) confirm importance of flexural rigidity reduction. **Shear reinforcement method provides small (5% to 10%) decrease in CSR**

Lateral Stress Increase

- Increasing lateral stress increases the resistance to shearing
  - CRR = τ_r / σ_v'; Lateral stress increases mean stress (σ_m') by 1.5 to 3
  - Proposed method: **lateral stress increases CRR by ~ 1.1**







Shear reinforcement and lateral increase FS ~ 20%

How do you design it?

Now that we have reducing triggering, how much settlement?

Many methods!:

Design Method	SPT	CPT	Comments
Tokimatsu & Seed (1987)	X		Outdated
Ishihara & Yoshimine (1992)	X	X	Good but complex design figures
Zhang, et al (2002)		X	Based on P.K Robertson , I&S work
Cetin, et al (2004)	X		Proposed new triggering and volumetric strain expressions
Moss, et al (2006)		X	Extension of Cetin, et al (2004)
Idriss and Boulanger (2008)	X	X	Slight updates to NCEER (1996 and 1998) procedures. Updates to I&S.

How do you design it?

Liquefaction **abatement** using ground improvement:

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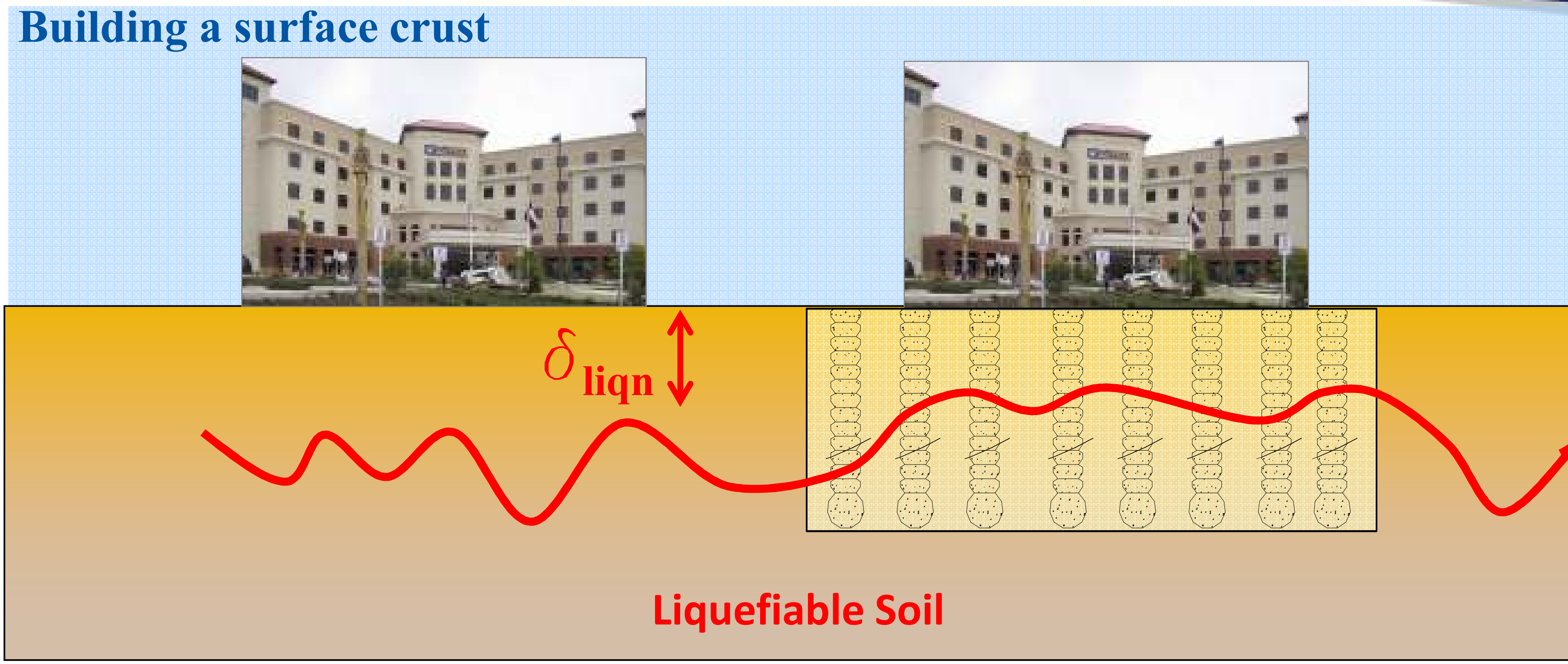
How do you design it?



- Concept by Ishihara (1985) extended by Youd and Garris (1999).
  - Requires absence of lateral spreading.
    - Influence of imposed building shear stresses important (Bray)
      - Estimate settlements using Zhang et al. (2002)

How do you design it?

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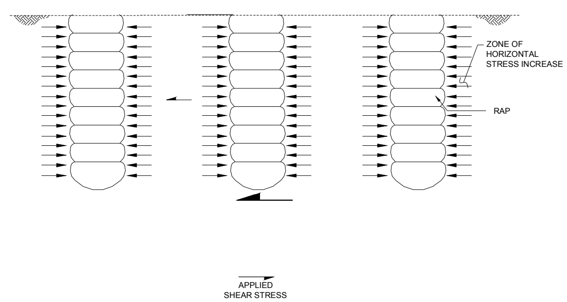
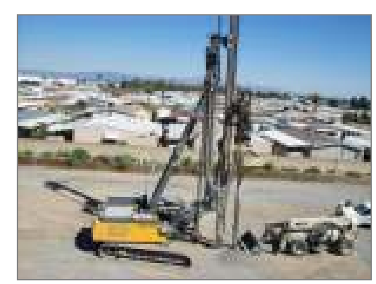
Liquefaction Mitigation - Summary

- Approaches
  1. **<u>Densification</u>** approach when possible to increase CRR.
     - Design for settlement = state-of-the-practice.
  2. Other mechanisms provide incremental betterments:
     - Drainage + shear reinforcement + lateral stress provide increase in FS of about 20%
  3. Consider non-liquefiable engineered crust per local conditions





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Experience?

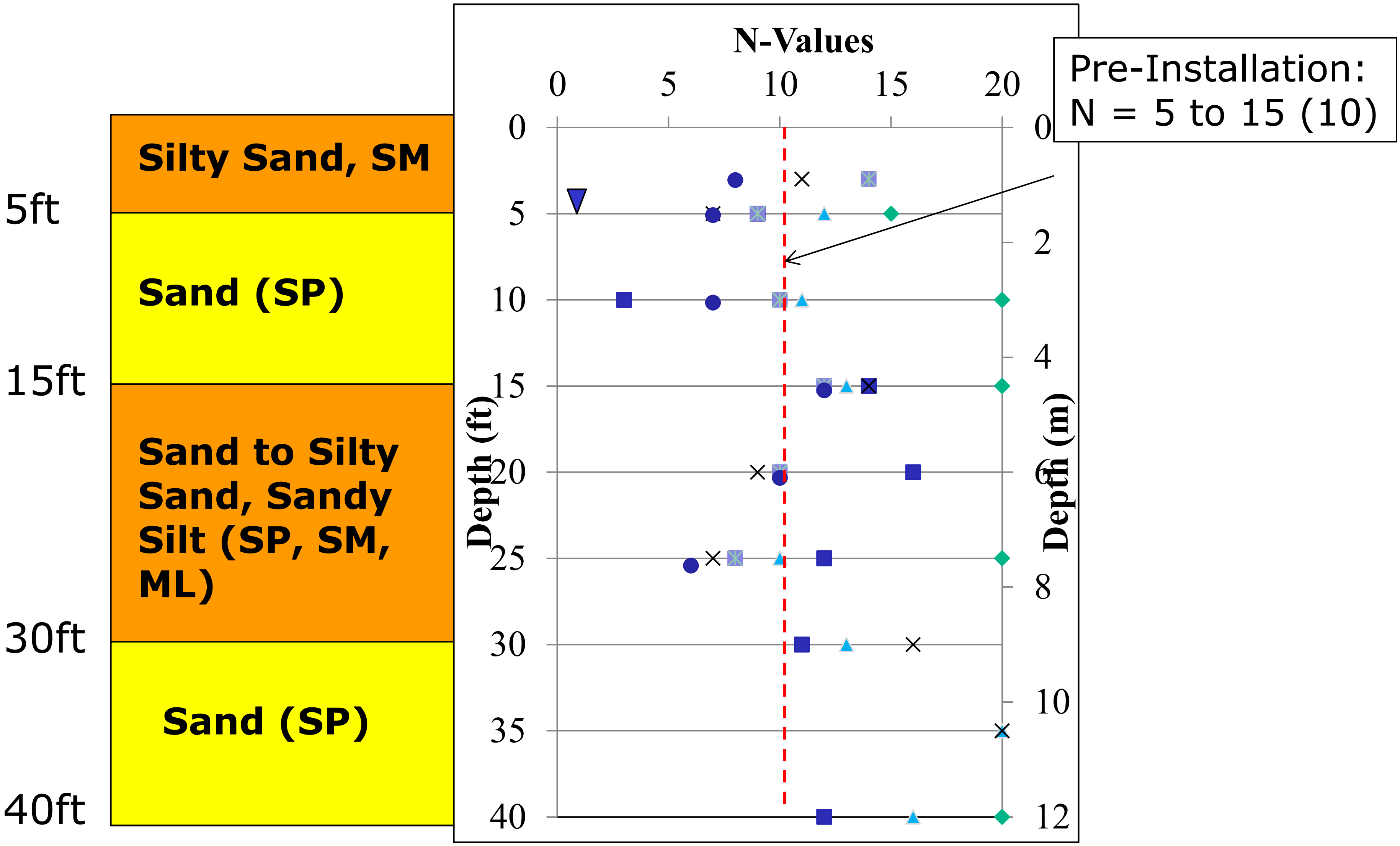
- Global experience:
  - Turkey
  - W. Canada
  - Chile
  - Christchurch…
- U.S. experience:
  - California
  - Washington
  - Utah
  - Missouri (New Madrid)
  - Charleston, SC

Experience - Project Example

MORAN ASIAN GARDEN - Westminster, CA

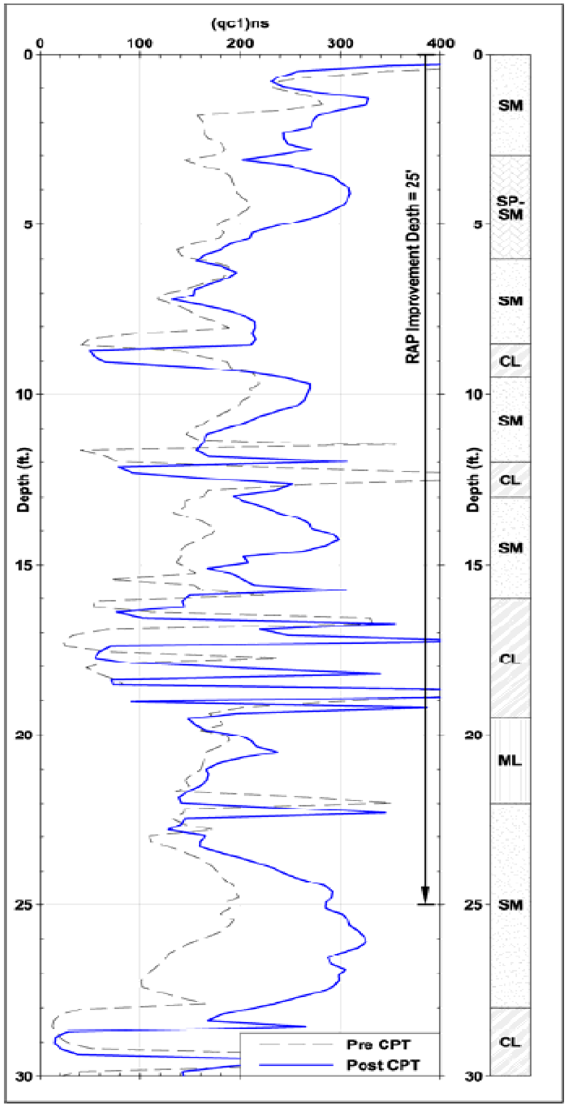
- Senior living residential structure
- 1600 m^2
- 6 stories, loads = 2200 kN
- **M_w = 6.9, a_{max} = 0.45g**
- **S = 2.1 to 2.4m on-center**

Moran Asian Garden –



Experience - Project Example

Moran Asian Garden



Impact Elements = 9.0 m deep

- **Δ_{qc1ns} = 8 to 15 MPa**

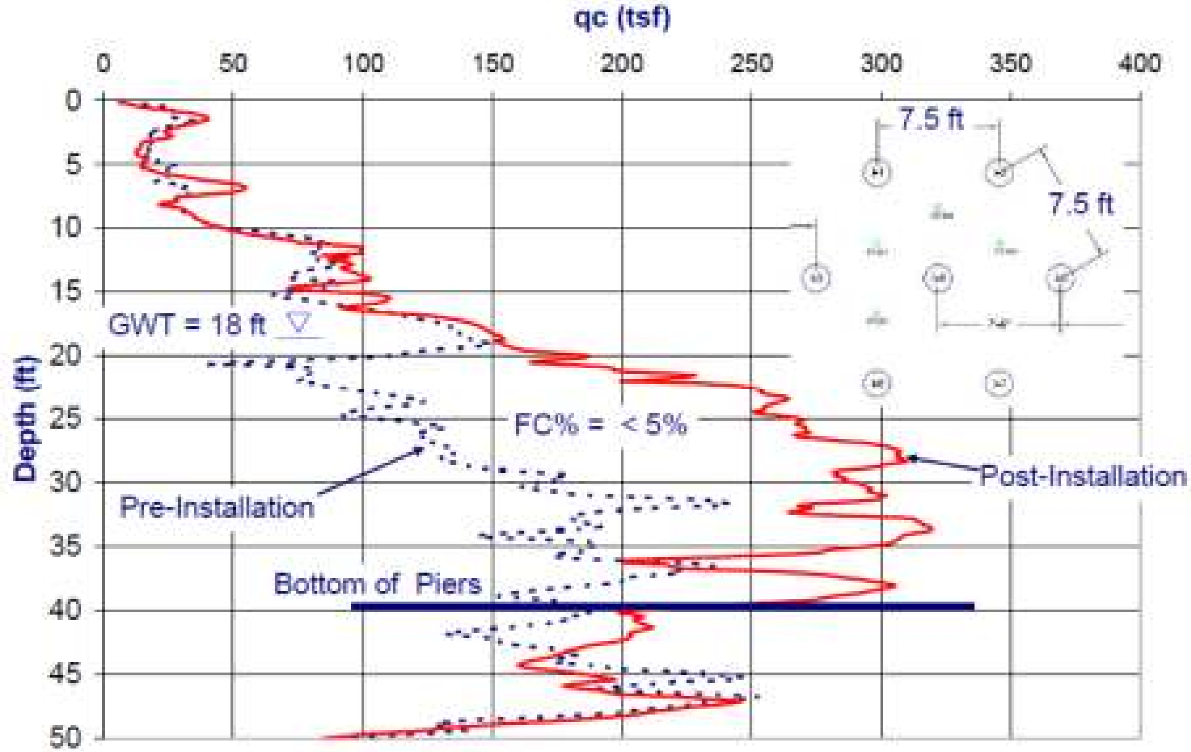
INDUSTRIAL STORAGE FACILITY, New Madrid, MO

- 20,000m^2 storage warehouse
- Static slab pressures =75 kPa
- 7,000 Impact piers for foundation support & liquefaction
- **Silty sand and sand: q_c = 10 to 20 MPa**

INDUSTRIAL STORAGE FACILITY, Southeast, MO

Clay

Sand (SP)



- 2.3m on-center for liquefaction reduction
- **Δq_c = 10 to 25 MPa to achieve q_{ci} = 30 MPa**

Experience – Project Example

Wastewater Treatment Facility – Oakley, CA

- High seismic region
- Delta alluvial deposits
- PGA = 0.37g (10% PE in 50 yrs)
- Unmitigated Liqn = 25 to 75 mm
- Required q_{c1ns} > 13.5 MPa

Wastewater Treatment Facility – Oakley, CA

0 m

M. Dense Silty Sand / Soft Clay
SM / CH

2 m

Loose – M Dense
SM / SP-SM

4.5 m

Dense SP and Stiff Clay

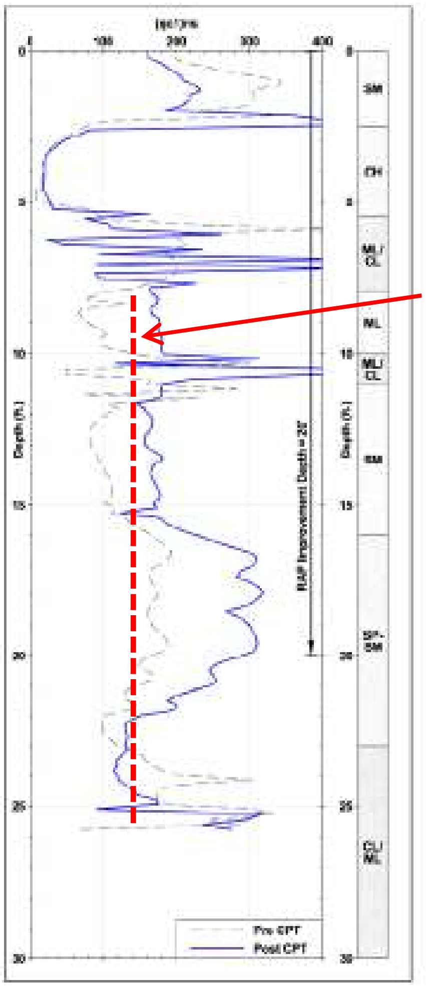
Up to 20m

Experience – Project Example

Wastewater Treatment Facility – Oakley, CA

- Demonstration program at 2.45m spacing

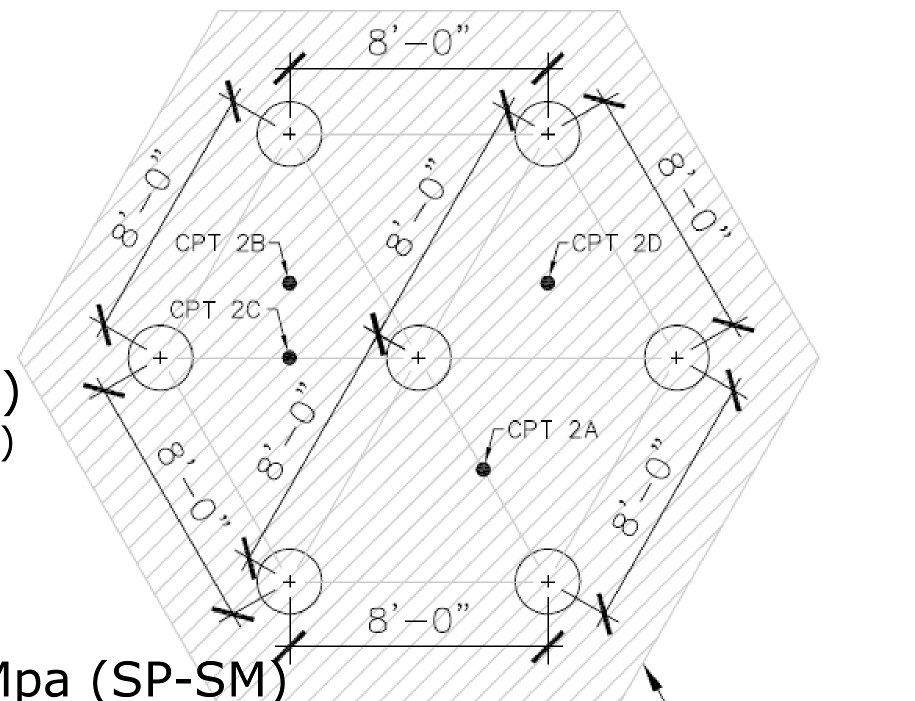
Fig. 10 ISD WWTP 8' OC Modulus Test



Design Criteria

Δq_{c1ns} = 5 Mpa (SM)
(Equivalent delta N = 12)

Δq_{c1ns} = 10 - 15 Mpa (SP-SM)
(Equivalent delta N = 20 – 30)



Experience – Project Example

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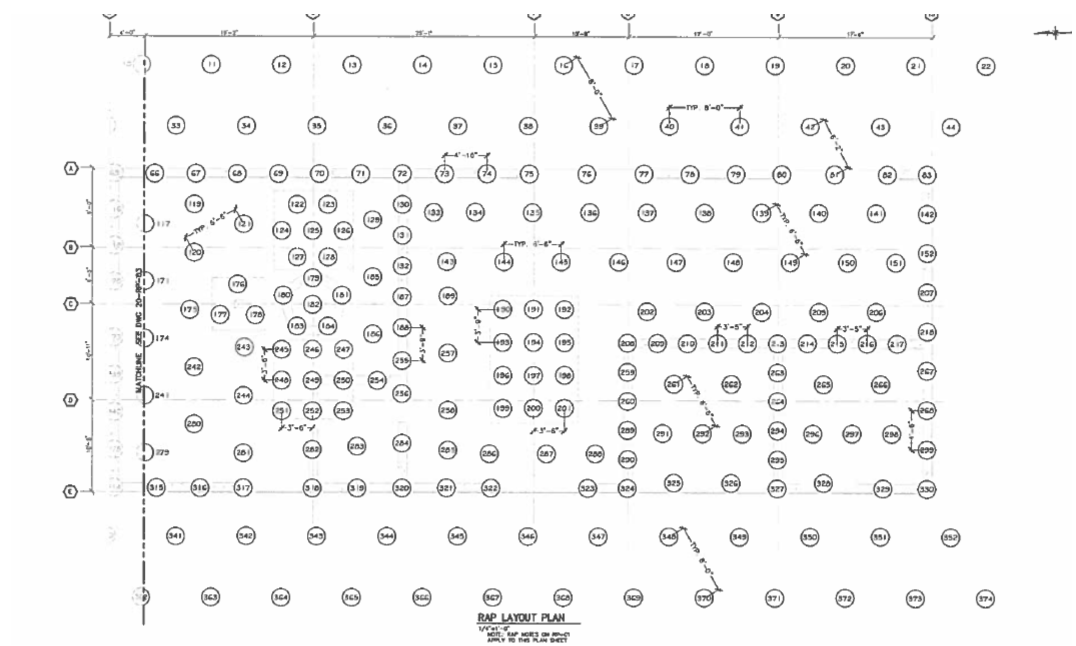
Wastewater Treatment Facility – Oakley, CA

- Total of 2,400 RAP elements installed to 6.7 m in 6 weeks
- Spacing varied from 2 to 2.45 meters depending on loads



Experience Project Example

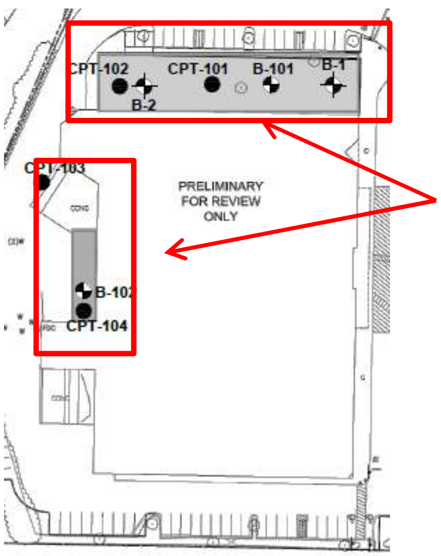
EMERALD QUEEN CASINO - Fife, WA

- New casino + 5-story parking garages

- Layered alluvial deposits:
  - Loose to medium dense SAND
  - Soft to medium stiff SILT
- Impact Pier Solution:
  - 3,500 Piers up to 11m deep
  - Foundation support
  - Liquefaction reduction

Winco Foods Expansion– Vancouver, WA

- Expansion to existing grocery store
- Cascadia Subduction Zone (Northwest U.S.)
- Design governed by liquefaction
- M_w = 6.5, PGA = 0.25g (2% PE 50 yrs)
- Groundwater at 3.0 m
- 150 mm liquefaction induced settlement
- Performance criteria = 25 mm differential settlement

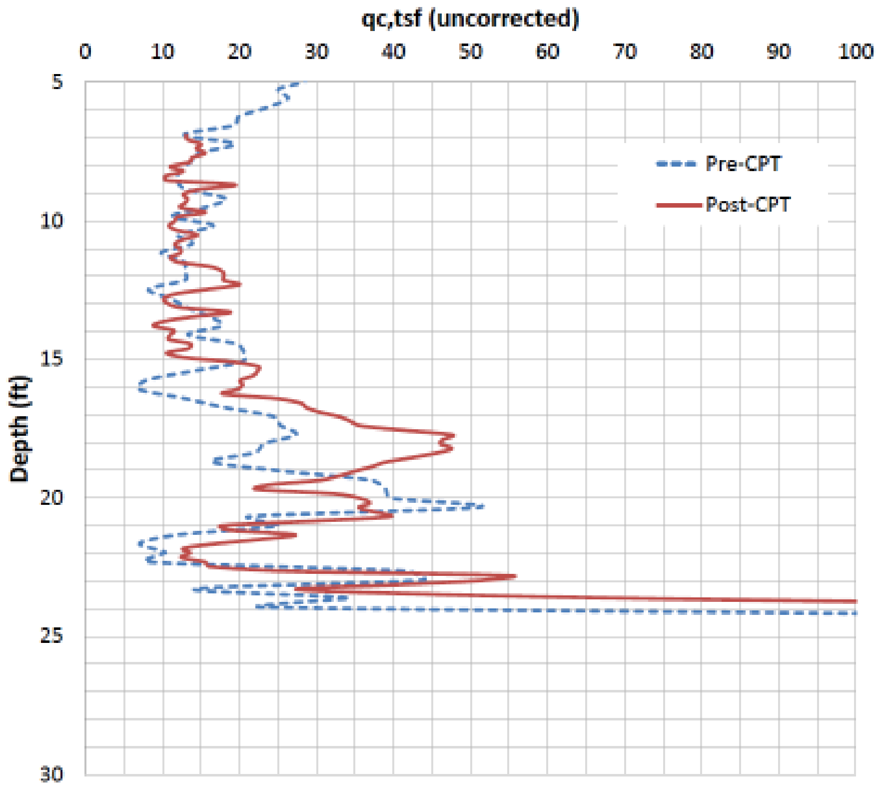


Expansion
Areas

Winco Foods Expansion– Vancouver, WA

- Impact elements = 7.0 m (23 ft) deep
- Spacing = 1.8 m square
- ∆ qc = 10 to 30 tsf in SM and ML

  (Equivalent ∆N = 3 to 9 bpf)
- Settlement < 25 mm

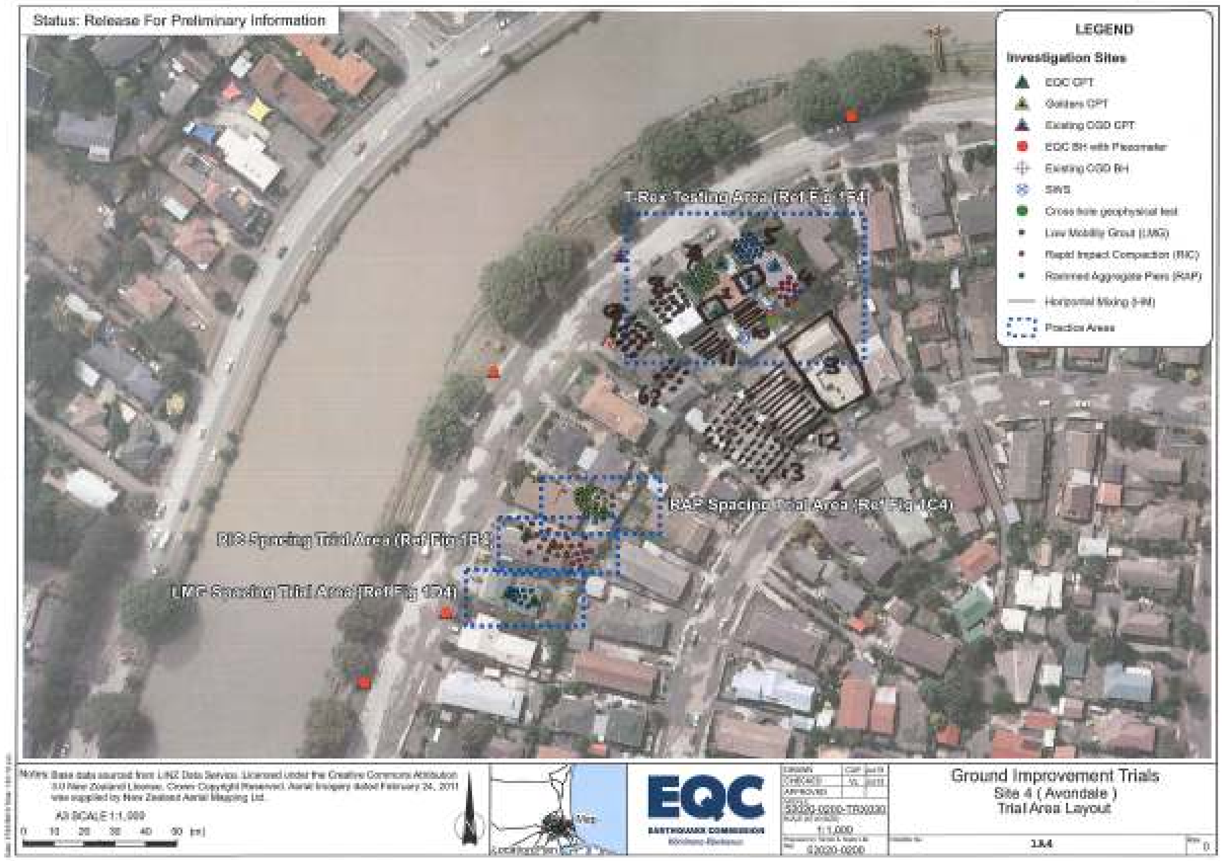


BOGAZICI SHIPYARD - Altinova, Turkey

- 270,000m² shipyard development
- Improvement of soft clay and intermittent SP/SM
- Foundations & liquefaction mitigation for **a_{max} = 0.8g**
- Spacing = 2 m o-c

On-going EQC trials here in Christchurch red zone

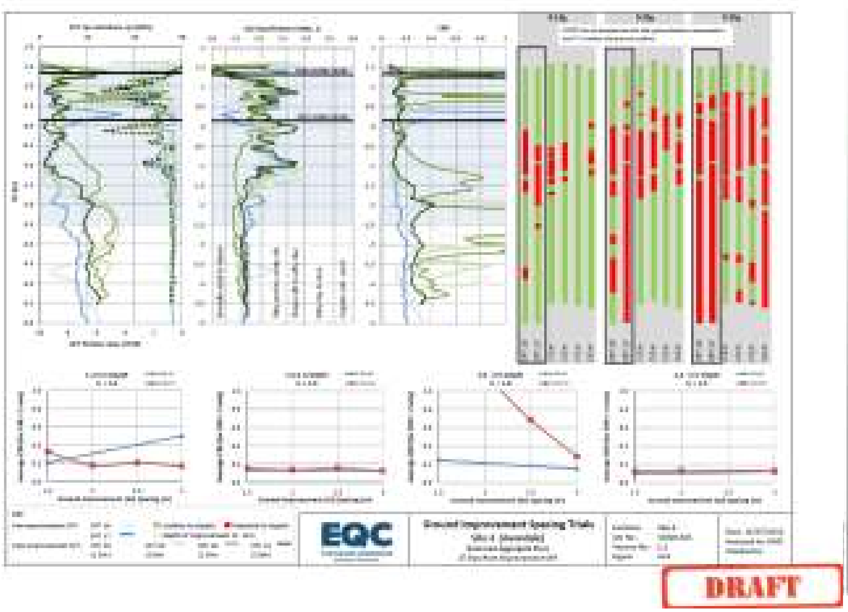
- Compaction grouting, RIC, horizontal mixing, RAP
- RAP: s = 2m o.c.



(courtesy S. Van Ballegooy, Tonkin / EQC)

On-going EQC trials here in Christchurch

- Spacing = 2m o.c.
- Getting good CPT cone response in soils with Ic<1.8; less so for Ic > 1.8
- Improvement of the ground 1 to 2 m below the mandrel insertion depth.
- No significant vibration. Can be applied to within 2 to 3m of structures.



(courtesy S. Van Ballegooy, Tonkin / EQC)

Outline

Tensar | GEOPIER® FOUNDATIONS

- Start with the obvious (why are we here today?)
- One solution – RAP ground improvement
  - ➢ What is it? How does it work?
    - ➢ What happens to the ground?
      - ➢ How do you design it?
        - ➢ Any past experience?
- Densipact
- Other uses you may be interested in

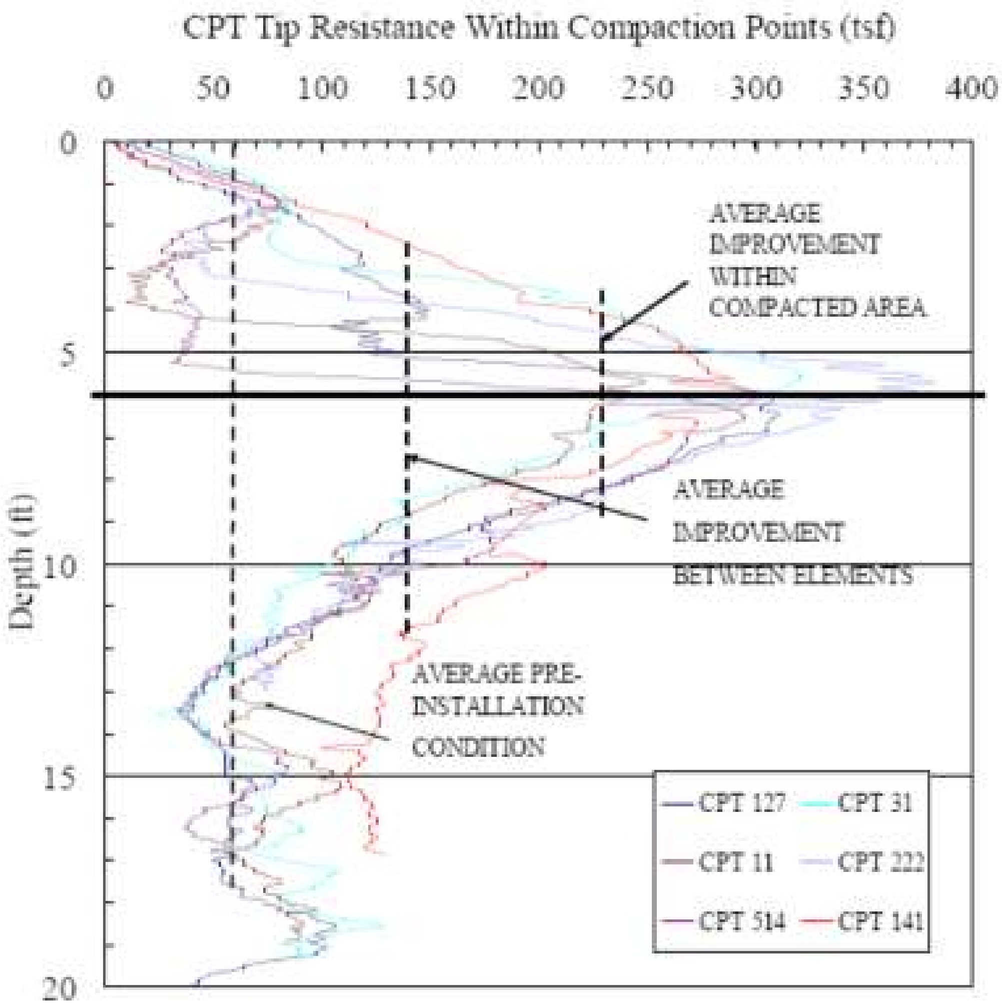
Multi-tined tools for Rammed Compaction® Improvement

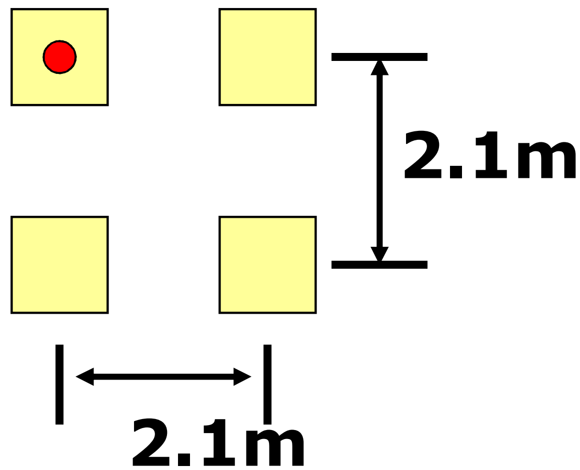
3m long tool

6m long tool

Densipact Experience

Performance – Typical Improvement at RCPs

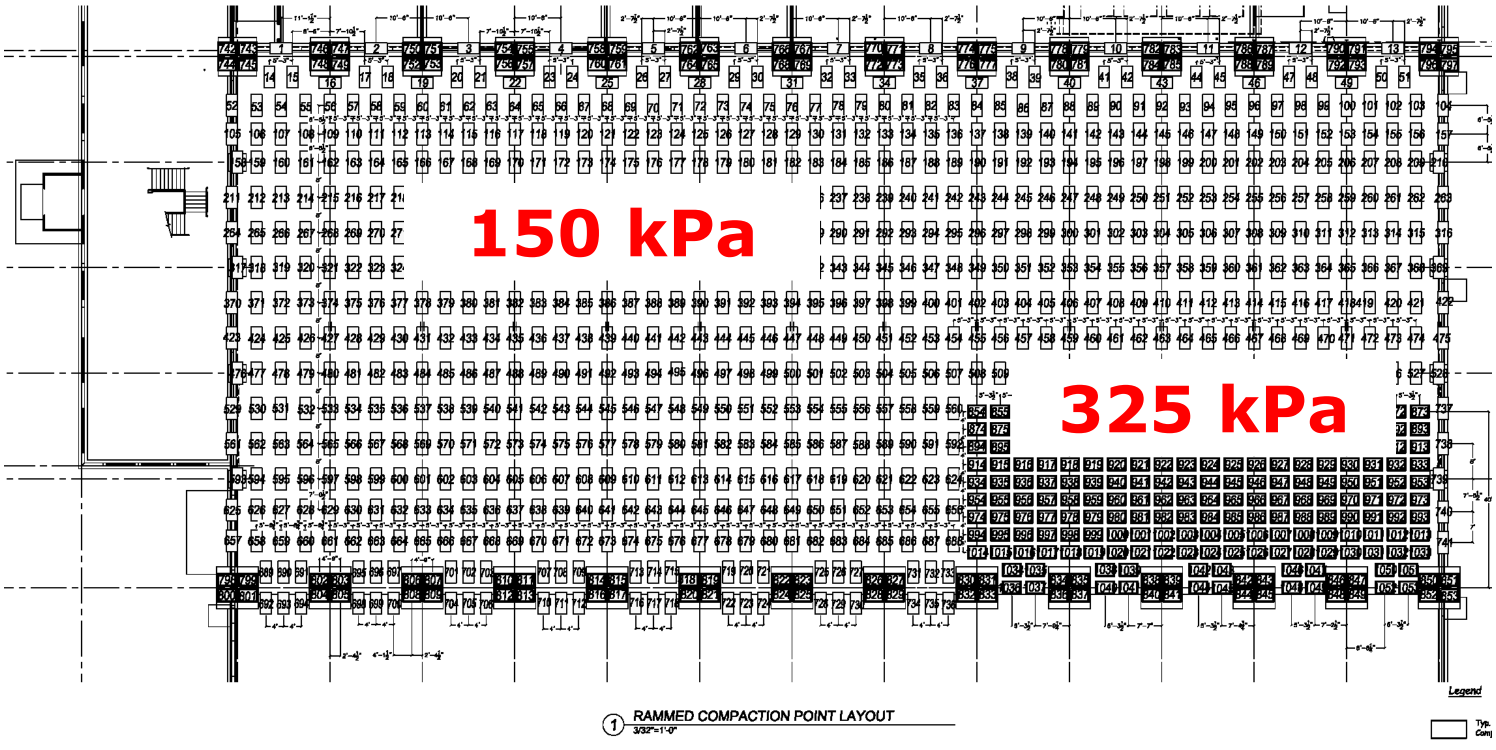




Densipact Experience

Rochling Automotive Facility, Akron, OH

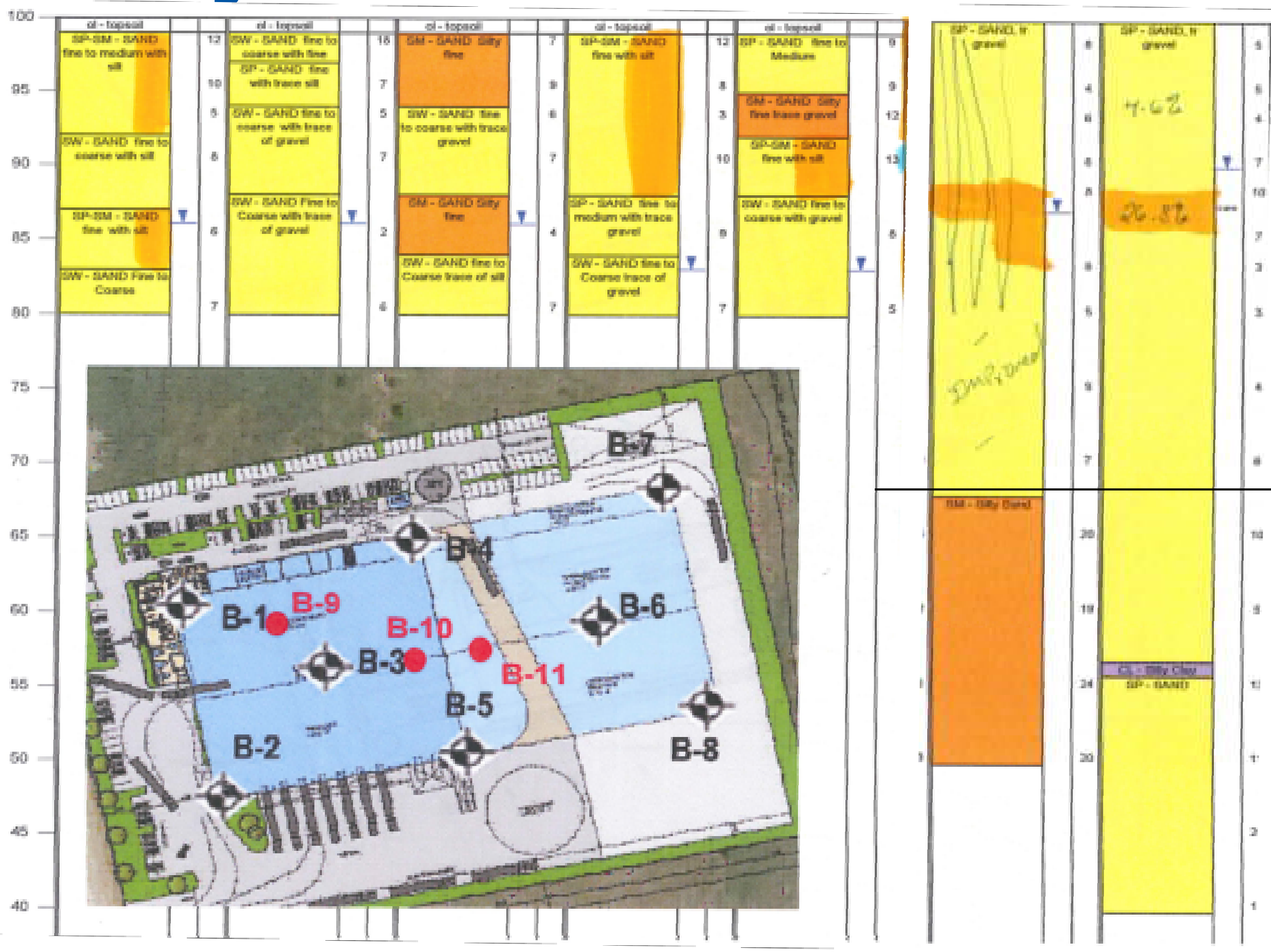
- **8000 m2 automotive manufacturing plant**



Densipact Experience

Tensar. GEOPIER® FOUNDATIONS

Rochling Automotive – Soil Conditions

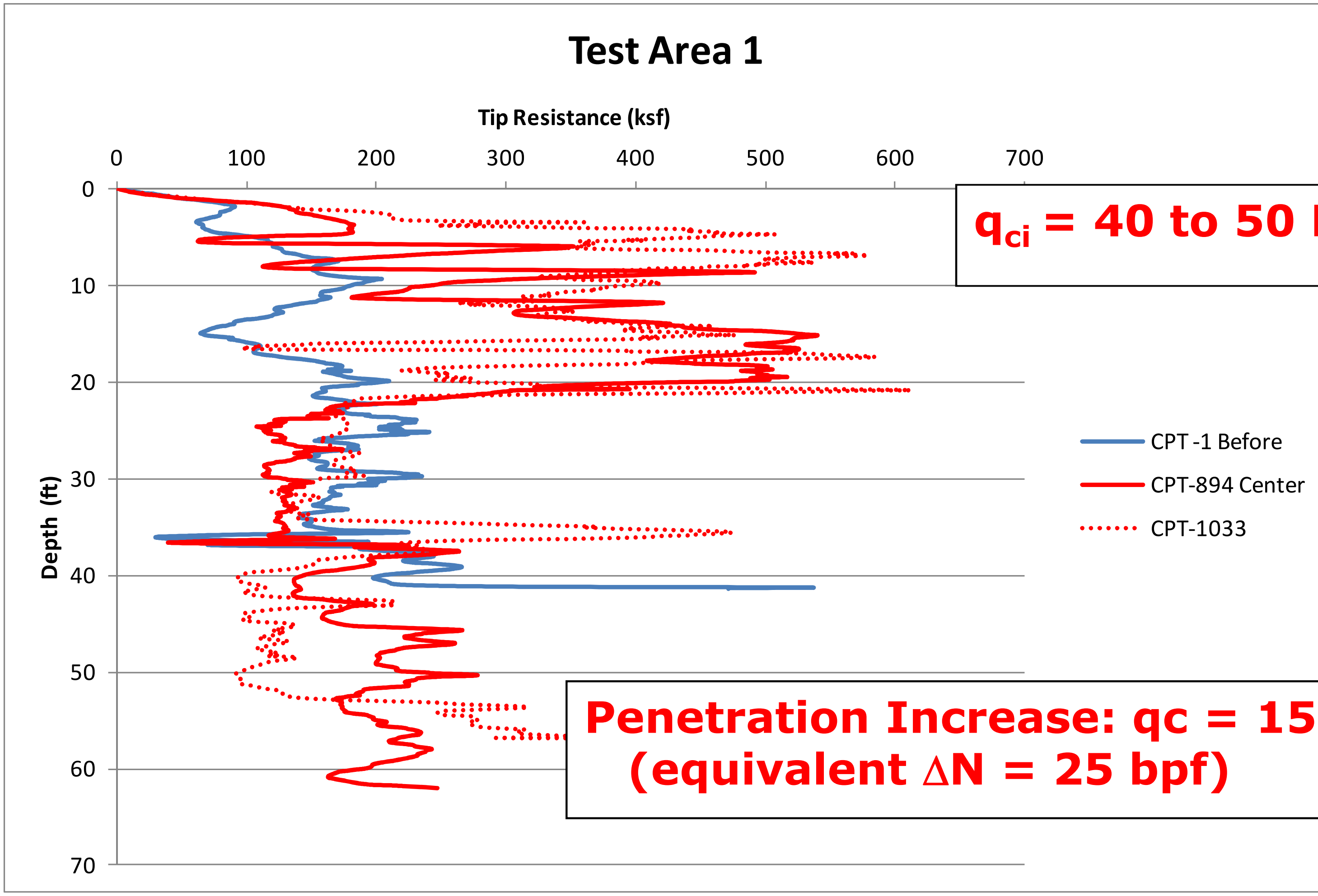


V. loose - loose Sand (SP, SP-SM, SM)

M. dense - dense Sand (SP, SP-SM, SM)

Densipact Experience

Densipact Results: d = 6 m, s = 2.2m



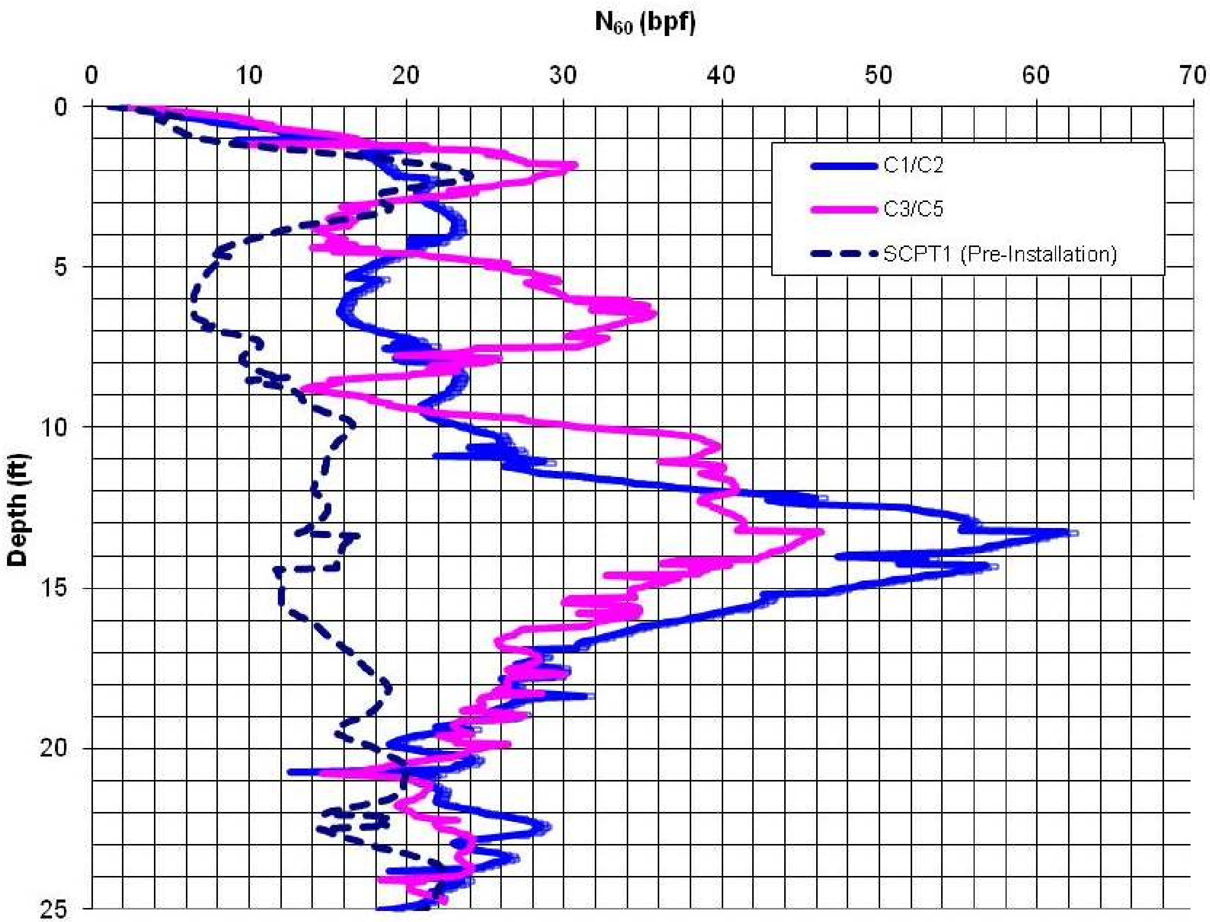
q_{ci} = 40 to 50 MPa

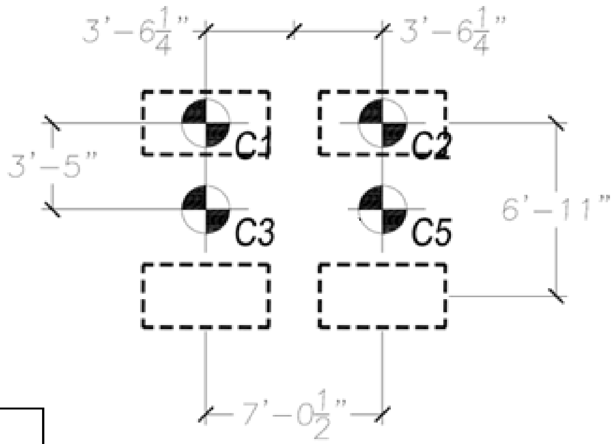
Penetration Increase: qc = 15 Mpa (equivalent ΔN = 25 bpf)

P.F. Chang's Restaurant, Mt. Pleasant, SC

- Liquefaction Mitigation
- Mw = 7.5, pga = 0.35g

Densipact Verification Program

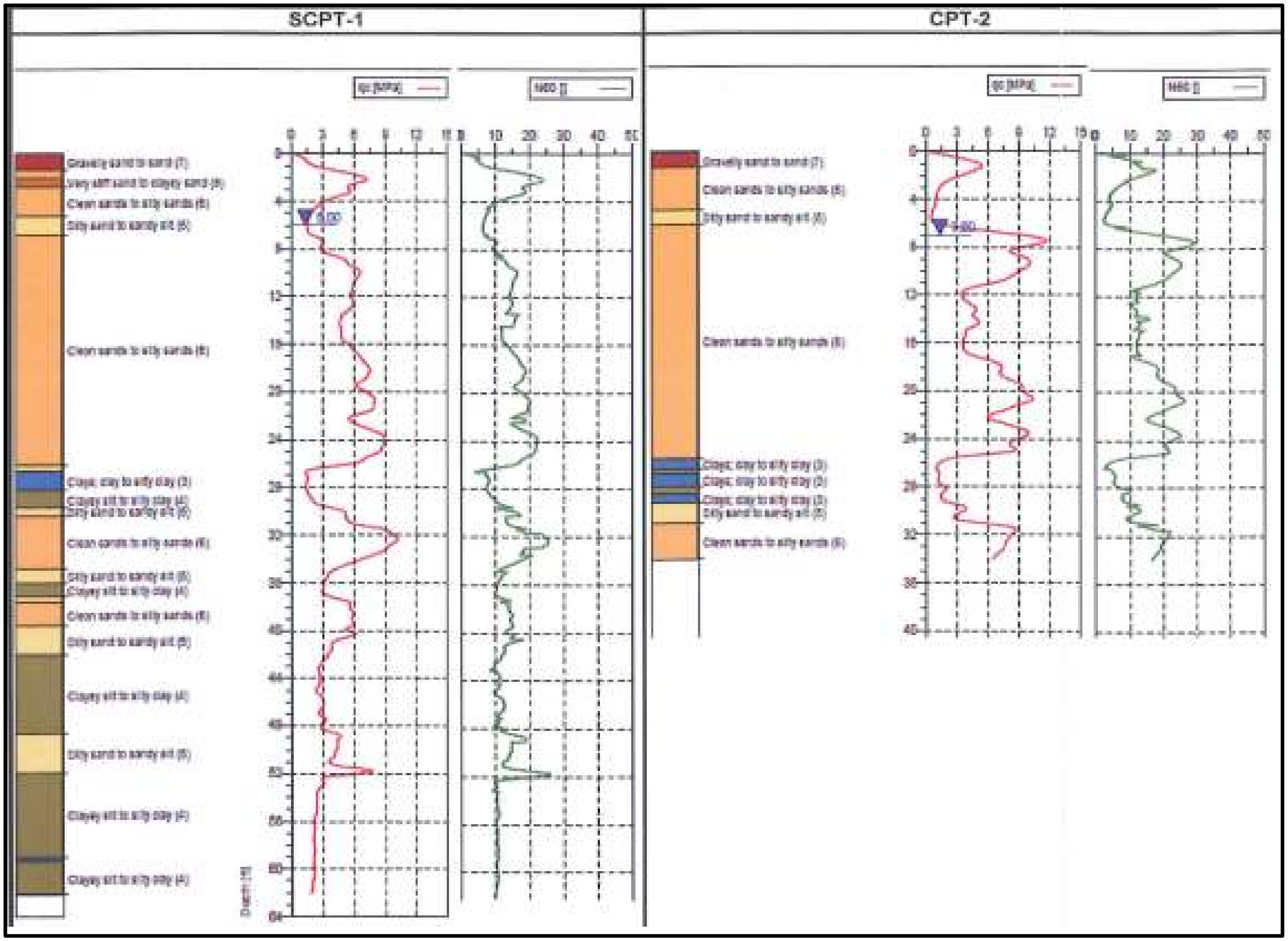




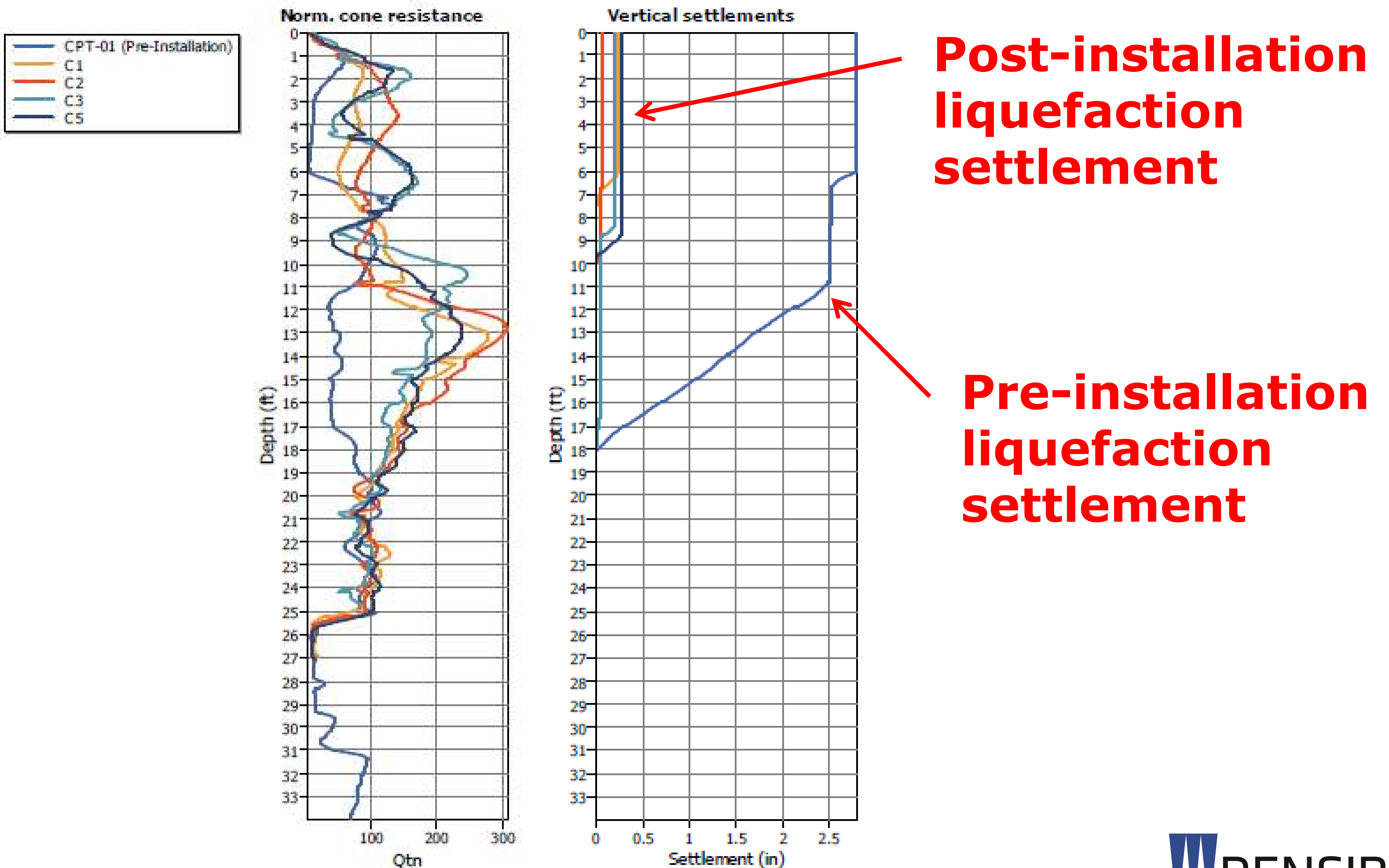
Penetration Increase: ΔN = 20 to 30 bpf)

Densipact Experience

Soil Profile – mostly SM



Densipact Verification Program



Summary

Tensar. GEOPIER® FOUNDATIONS

- Christchurch has many needs and possible solutions
- One solution – RAP ground improvement
  - Effective and *controlled method* to increase density of Sand / Silty Sand
    - The ground is densified - measured by SPT/CPT
      - Design using Seed's simplified method for triggering.
      - Many methods for settlement.
      - Drainage, reinforcement, lateral stress –

        Increase FS by 1.2

- Densipact – "the cat's meow" method in the right spots
- Other uses – building foundations, tanks, and walls.

Thank you for your tremendous hospitality…

Discussion?

(Good luck Kiwis!)