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Funding:

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Lateral Load Analysis of Pile Groups Based on Full-Scale Tests

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Brigham Young University

With Research Assistants

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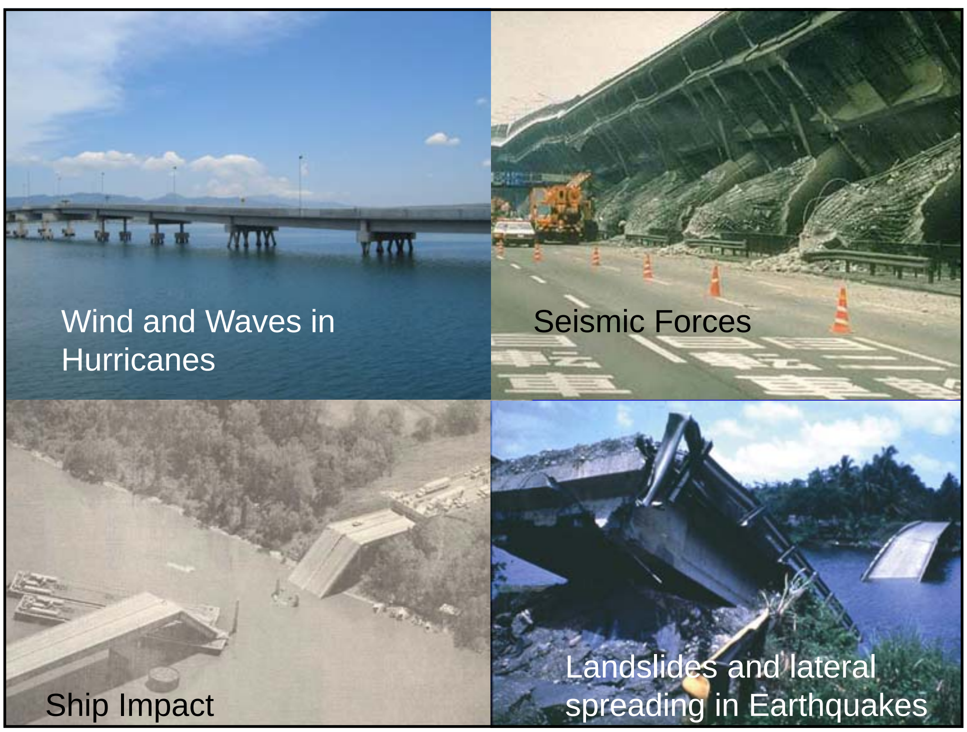
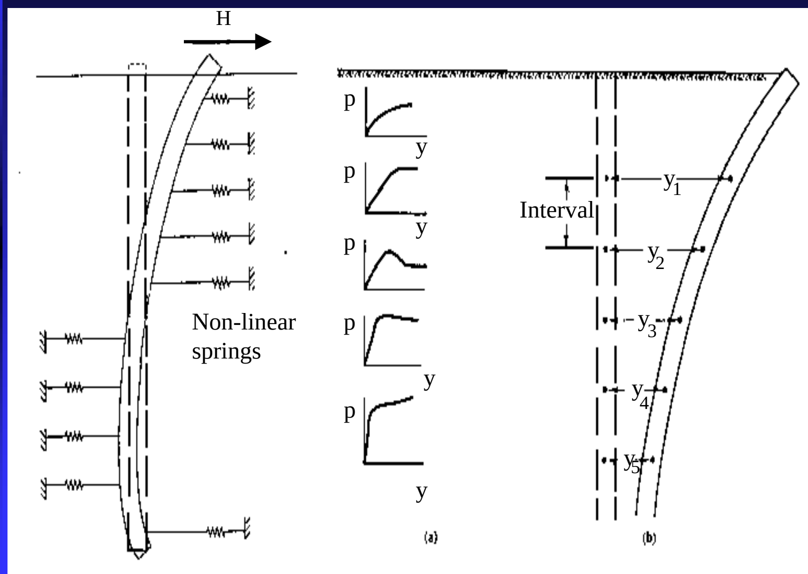


Lateral Pile Load Analysis



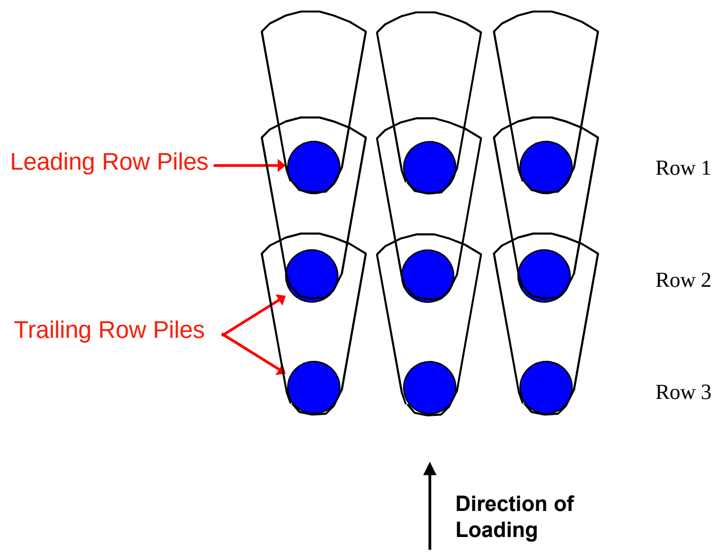
Pile Groups for Bridges on I-15

Good Group Behavior

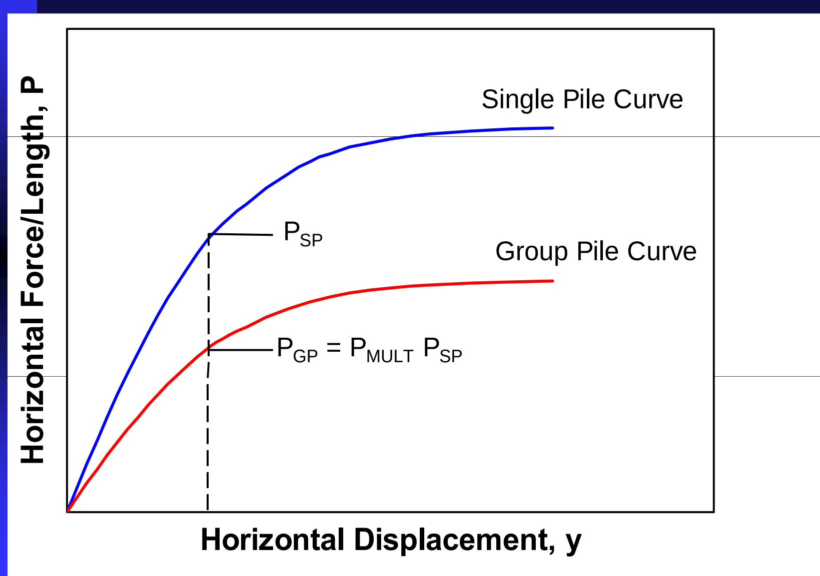
Poor Group Behavior

Group IQ = Lowest IQ of anyone in the group

Pile Group Interaction



P-Multiplier Concept (Brown et al, 1988)

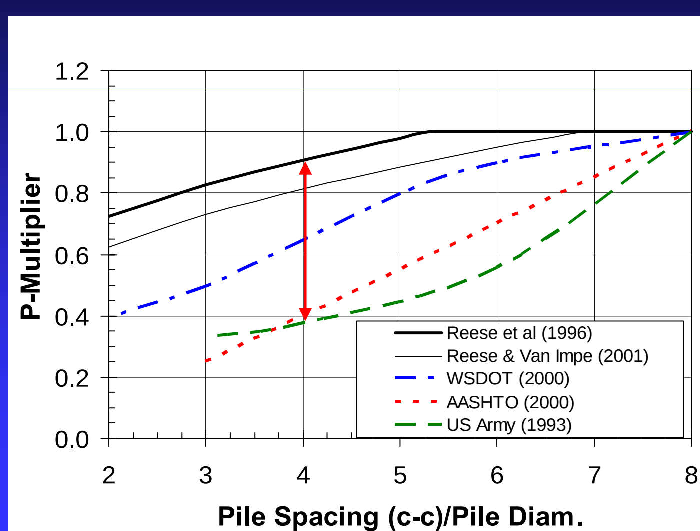


P-multipliers from Full-Scale Tests
(Situation in 1998)

Soil Type (Reference)	Front Row	2nd Row	3rd Row
Clean Sand (Brown et al. 1988)	0.8	0.4	0.3
Stiff Clay (Brown et al. 1987)	0.7	0.5	0.4
Soft Silty Clay (Meimon et al. 1986)	0.9	0.5	-

BYU has conducted 11 Full-scale tests over the past 10 years

P-multiplier vs. Spacing Curves



Limitations of Test Database

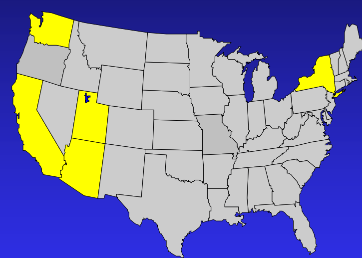
- Relatively few full-scale pile group load tests with necessary measurements.
- All full-scale tests performed at about 3 pile diameter spacing.
- Nearly all full-scale tests involved 3 rows or less.

Pile Group Project Objectives

- Determine p-multiplier as a function of spacing.
- Evaluate p-multipliers for groups with more than three rows.
- Evaluate effect of pile diameter on lateral resistance and p-multipliers.
- Examine effect of cyclic loading on lateral resistance.
- Evaluate available computer models for analyzing lateral response.

Sponsors

- Utah DOT - FHWA
- Caltrans
- Washington DOT
- Arizona DOT
- New York DOT
- Syro Steel
- PDCA-Build Inc.
- National Science Foundation



“One good test is worth a thousand expert opinions.”

Werner Von Braun

Designer of Saturn V Moon Rocket

Space Shuttle Columbia Disaster

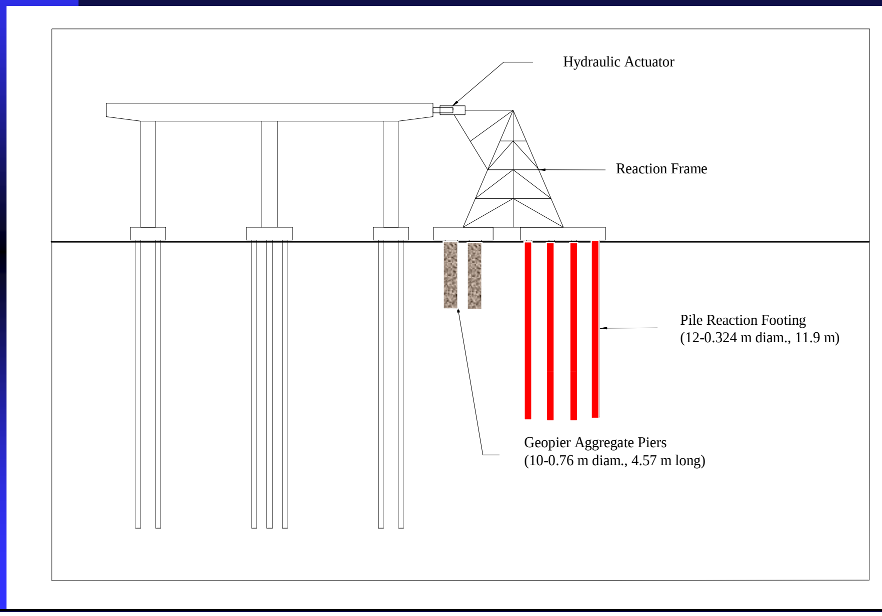
Analyses based on impact of small ice particles imply styrofoam impact won't be a problem.

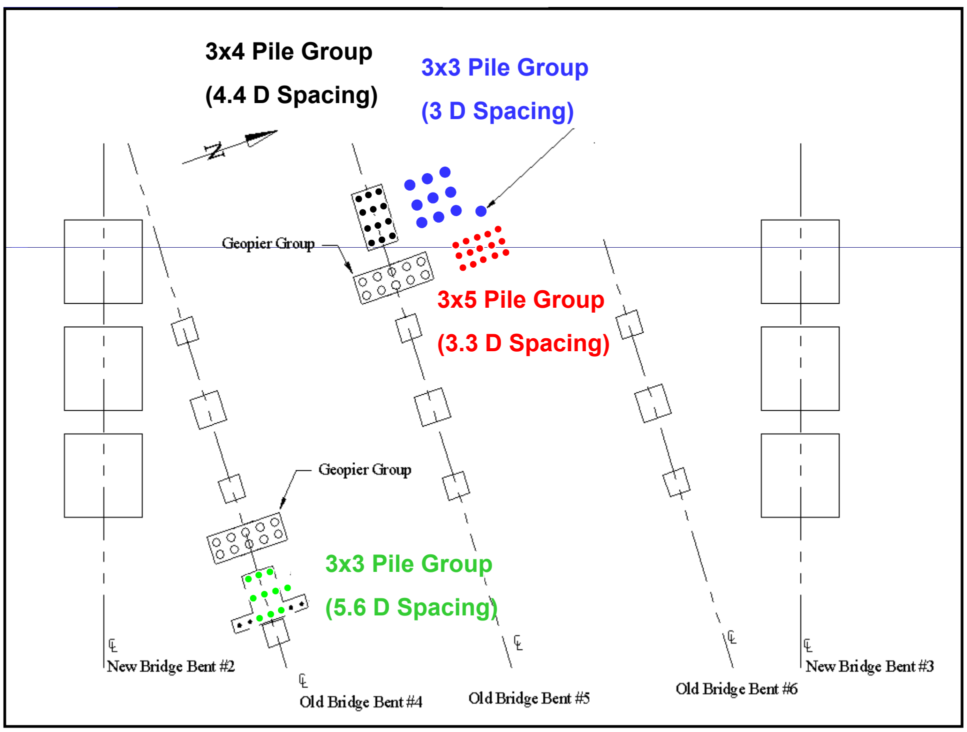
Full-scale test shows a problem!

Bent Test with Carbon Fiber Joint Wrapping

BYU - Univ. of Utah Collaboration

Bent Test Layout on I-15 (Salt Lake City, Utah)

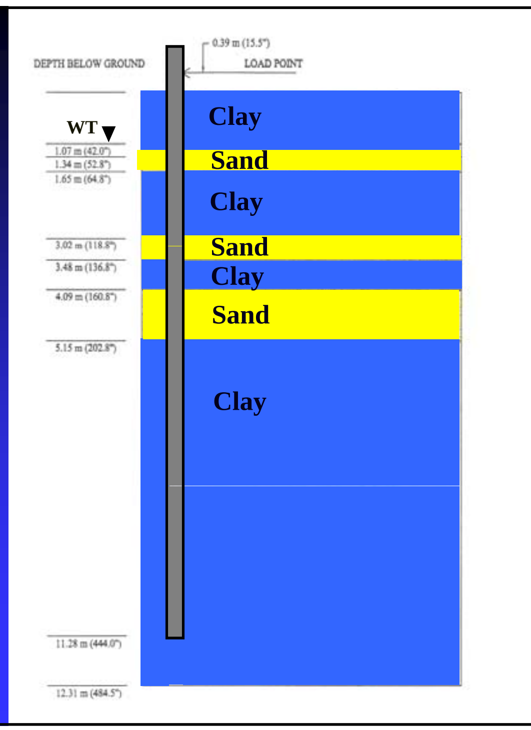




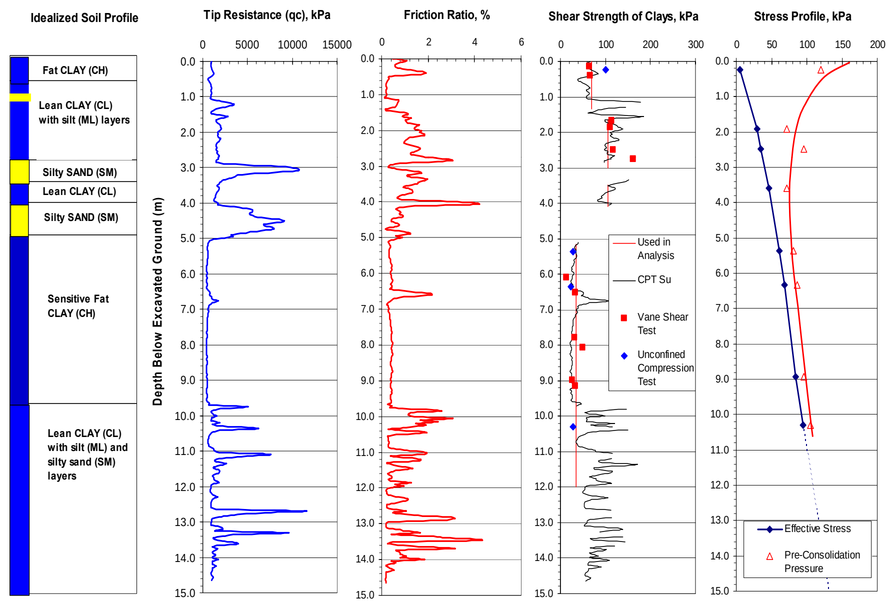
Site Characterization

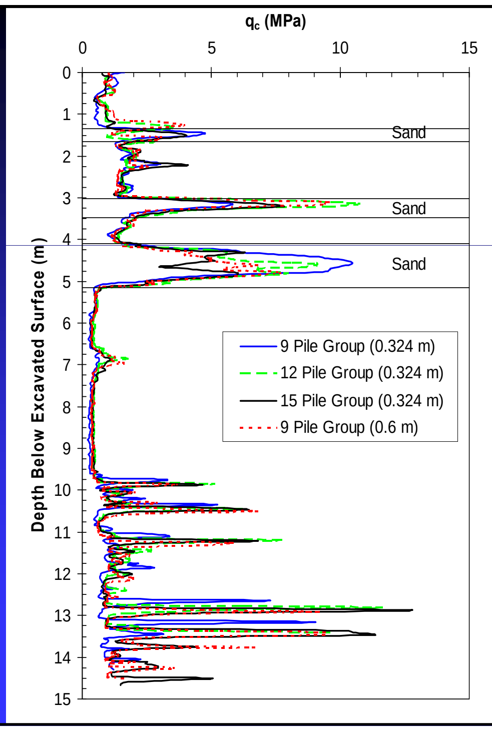
- Field Testing
  - Cone Penetration Testing (CPT)
  - Standard Penetration Testing (SPT)
  - Dilatometer Testing (DMT)
  - Pressuremeter Testing (PMT)
  - Shear Wave Velocity Testing
- Lab Testing
  - Atterberg Limits
  - Grain Size Distribution
  - Undrained Strength Testing

Generalized Soil Profile



Field & Lab Test Results





Comparison of CPT Soundings

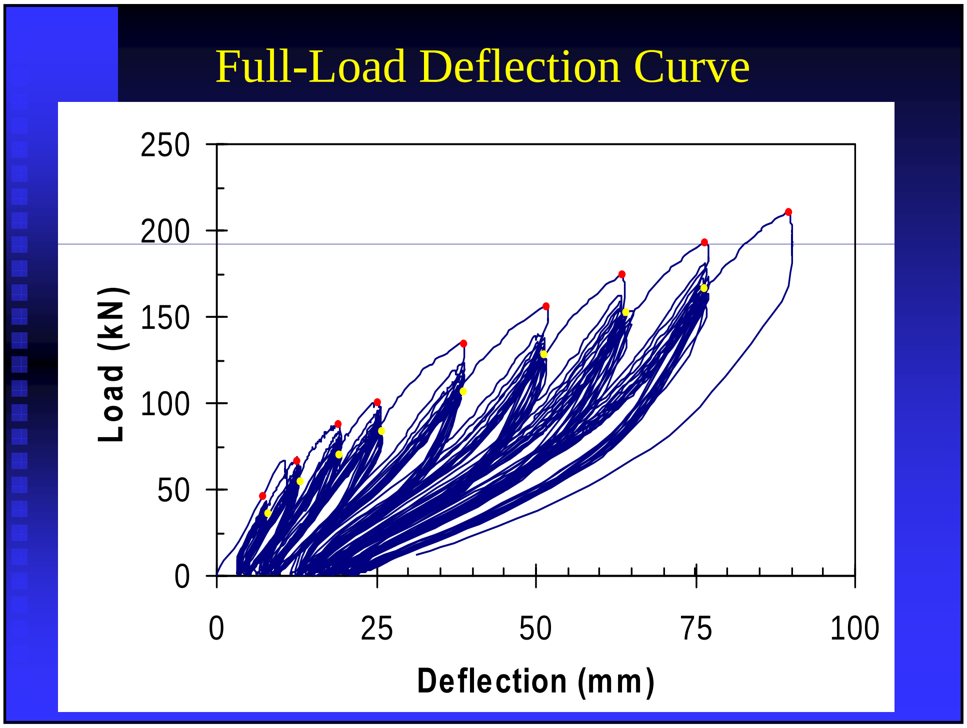
Single Pile Load Tests

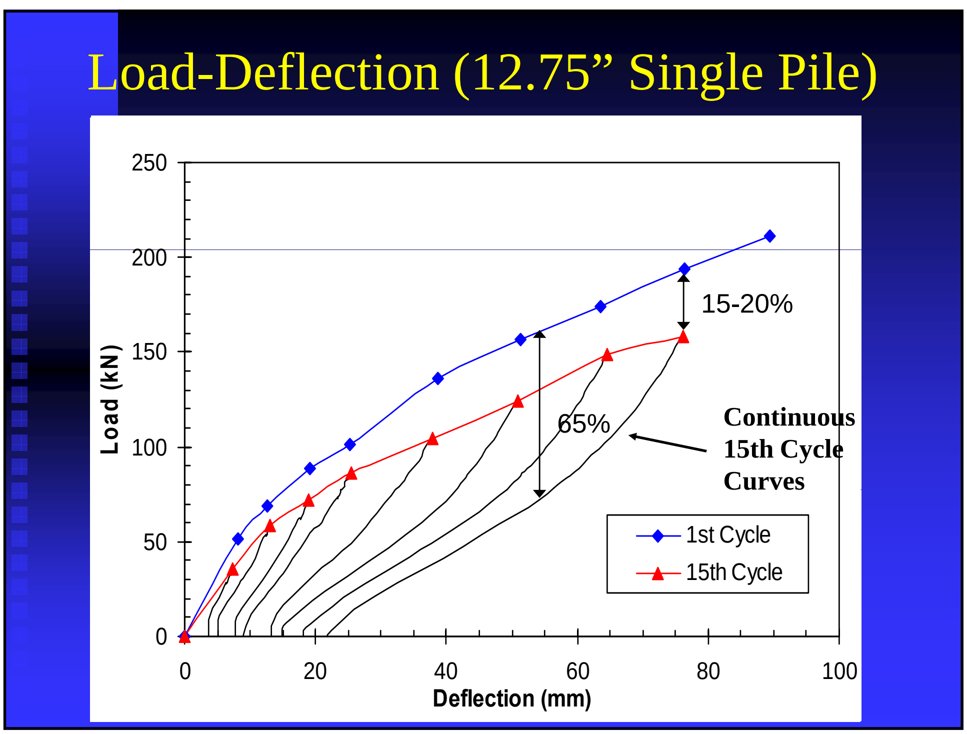
12.75" OD Steel Pipe Pile

24" OD Steel Pipe Pile

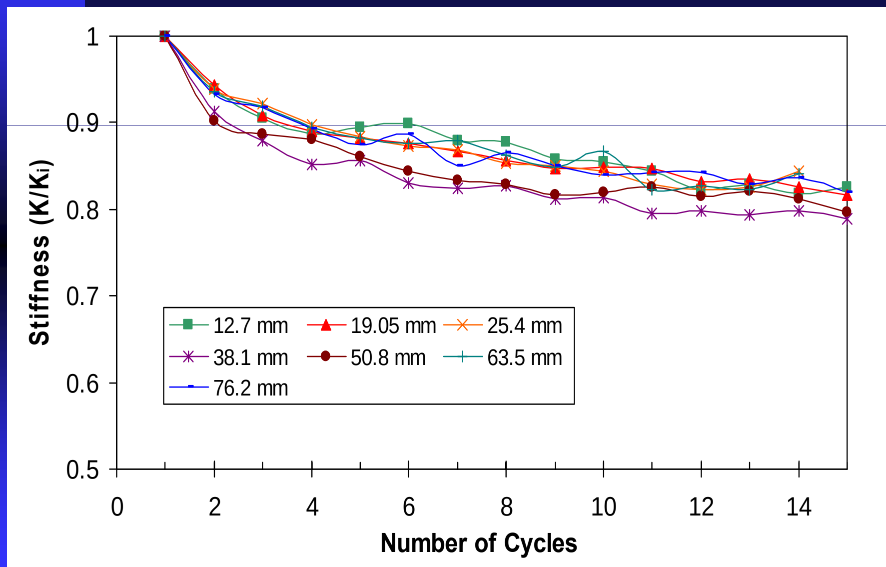
Single Pile Test Procedure

- Test performed in incremental fashion with initial 5 min hold.
- 15 cycles at each increment to the same deflection.
- Load applied in one direction only.


Full-Load Deflection Curve
250
200
150
100
50
0
Load (kN)
0
25
50
75
100
Deflection (mm)

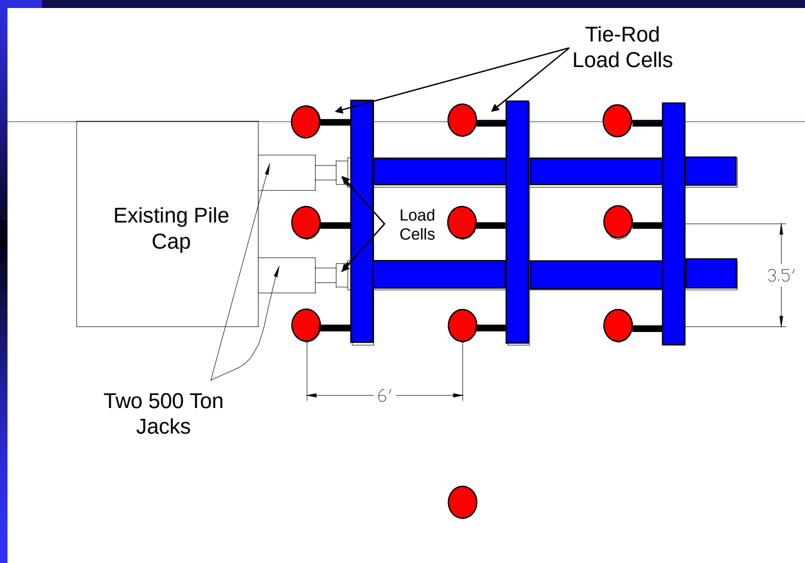

Load-Deflection (12.75” Single Pile)
250
200
150
100
50
0
Load (kN)
0
20
40
60
80
100
Deflection (mm)
15-20%
65%
Continuous
15th Cycle
Curves
1st Cycle
15th Cycle

Stiffness Degradation vs Load Cycle

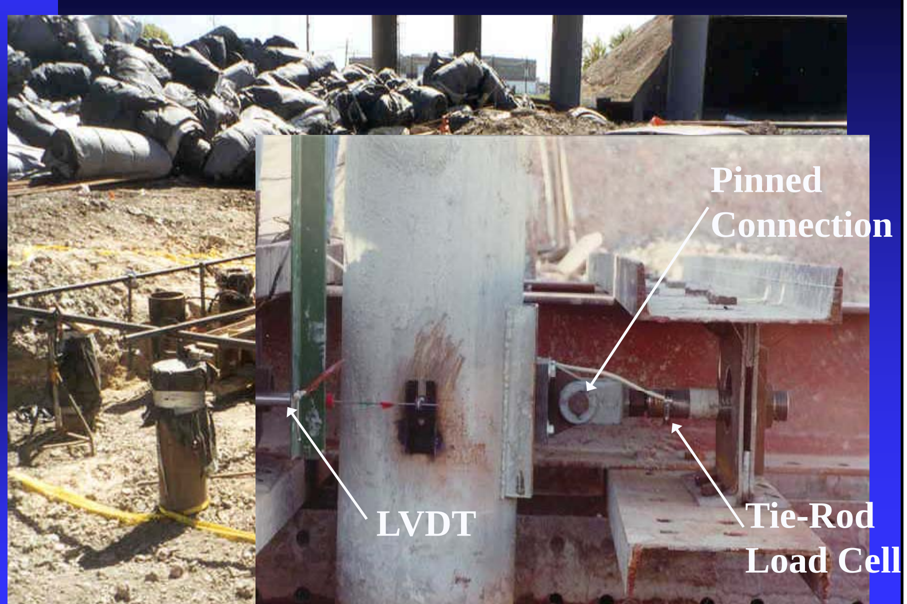


PILE GROUP LOAD TESTS

3x3 Pile Group at 5.6 Diameter Spacing

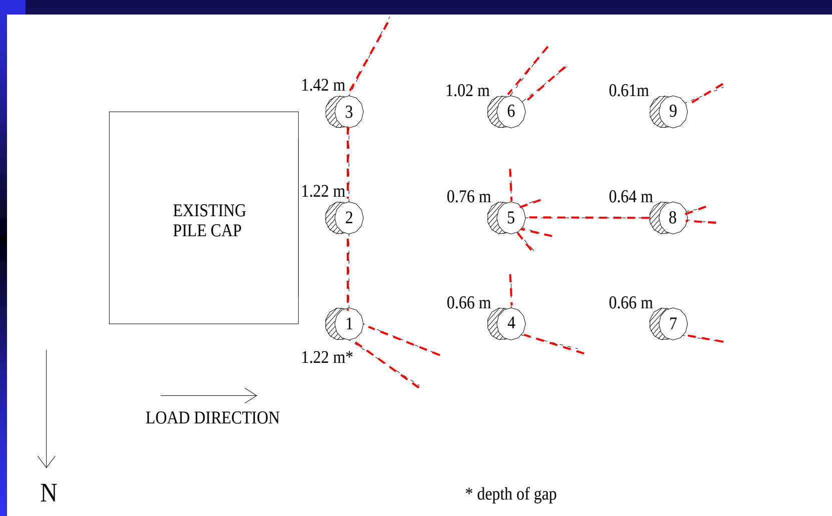


9 Pile Group at 5.6 D Spacing

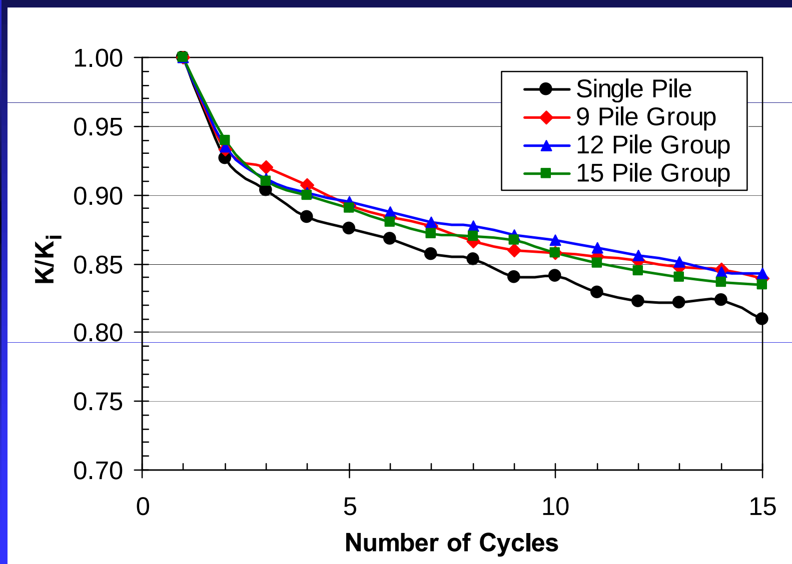


3x5 Pile Group at 3.3 D Spacing

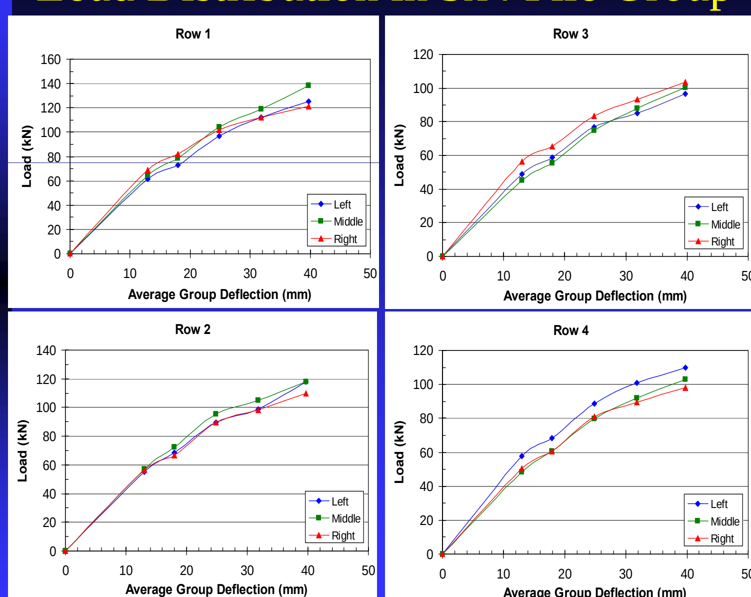
Crack Patterns During Lateral Load



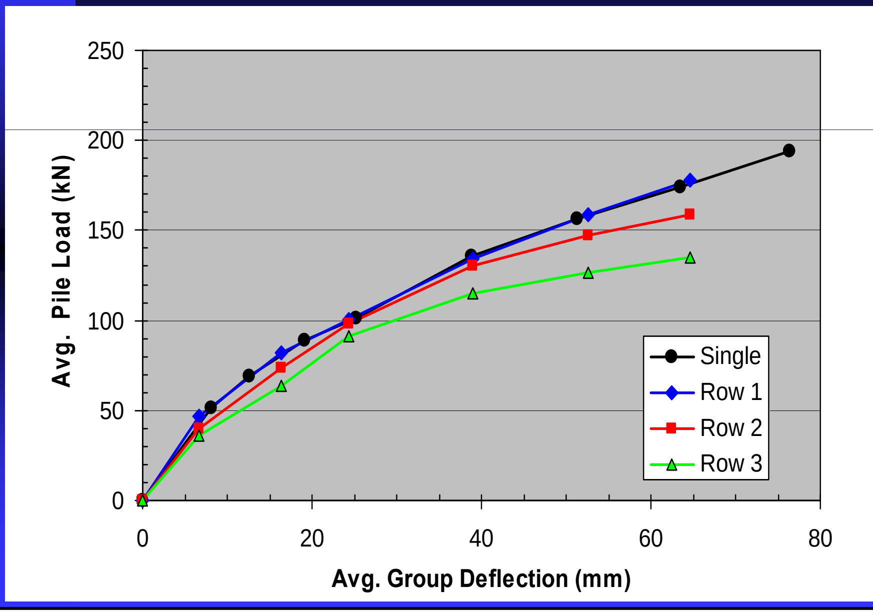
Stiffness Reduction with Cycling



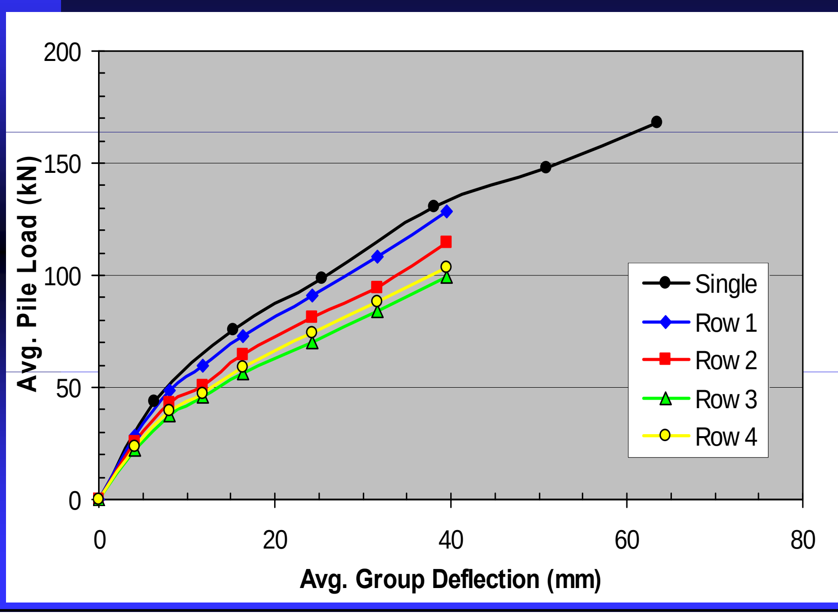
Load Distribution in 3x4 Pile Group

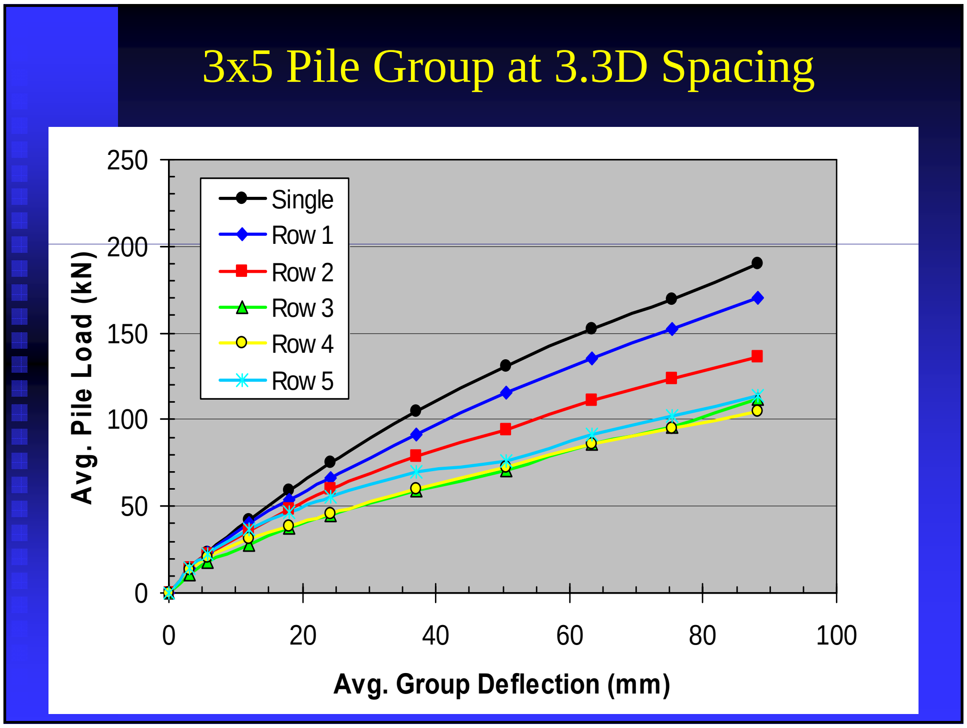


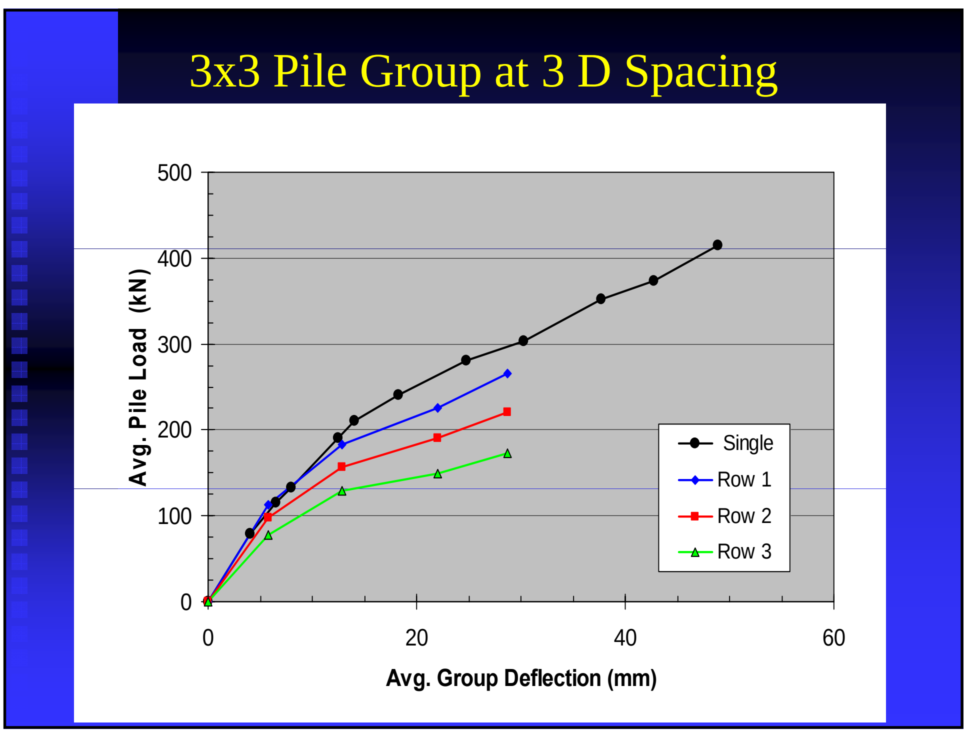
3x3 Pile Group at 5.6 Dia. Spacing



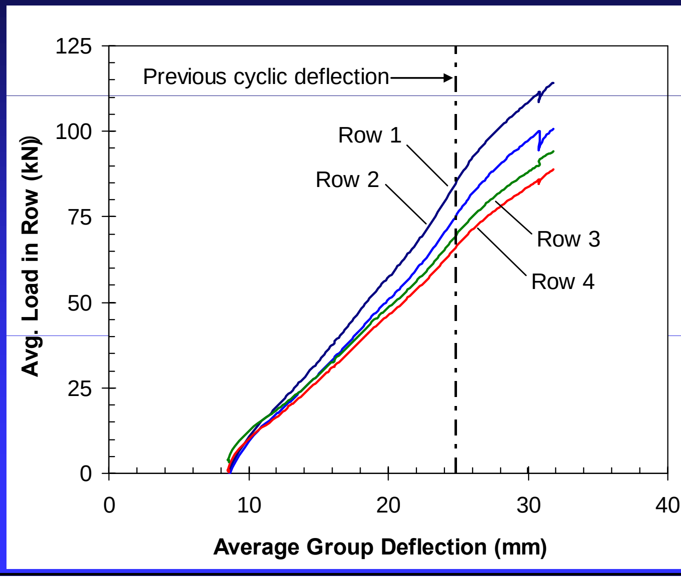
3x4 Pile Group at 4.4 D Spacing



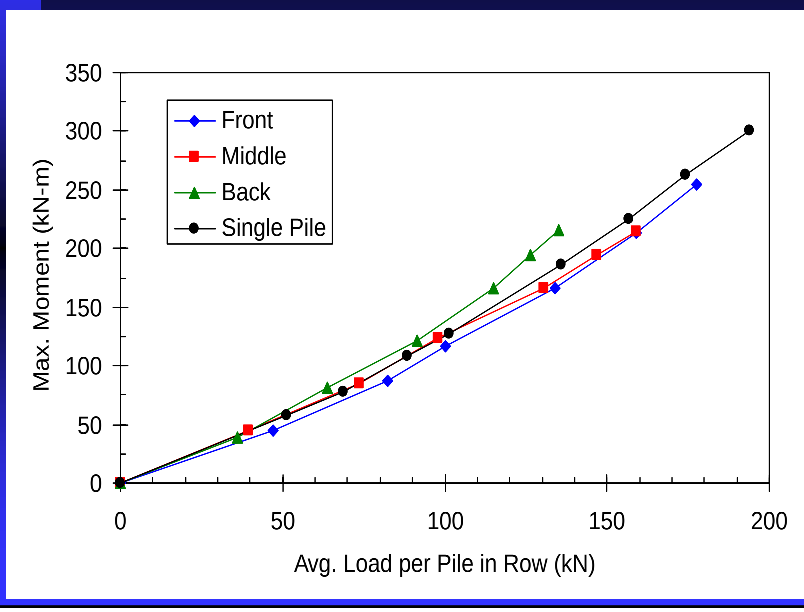

3x5 Pile Group at 3.3D Spacing
Avg. Pile Load (kN)
Avg. Group Deflection (mm)
Single
Row 1
Row 2
Row 3
Row 4
Row 5
0
50
100
150
200
250
0
20
40
60
80
100


3x3 Pile Group at 3 D Spacing
Avg. Pile Load (kN)
Avg. Group Deflection (mm)
Single
Row 1
Row 2
Row 3
0
100
200
300
400
500
0
20
40
60

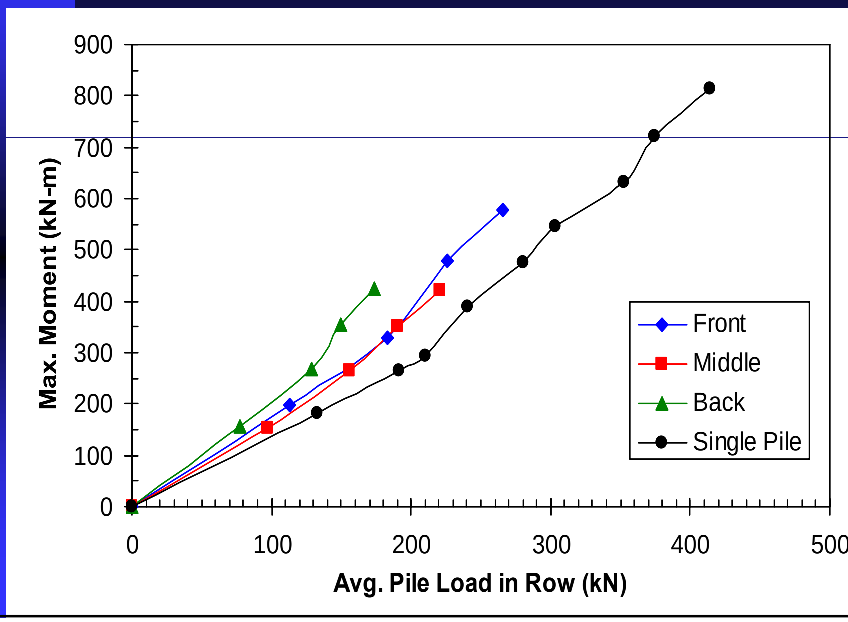
Influence of Cycling on Row Loads



3x3 Pile Group at 5.6 D Spacing

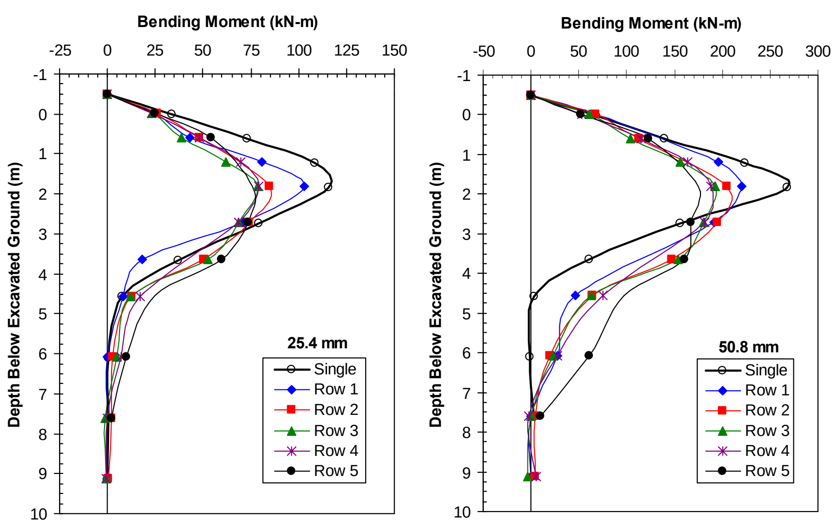


3x3 Pile Group at 3 D Spacing



Bending Moment vs. Depth

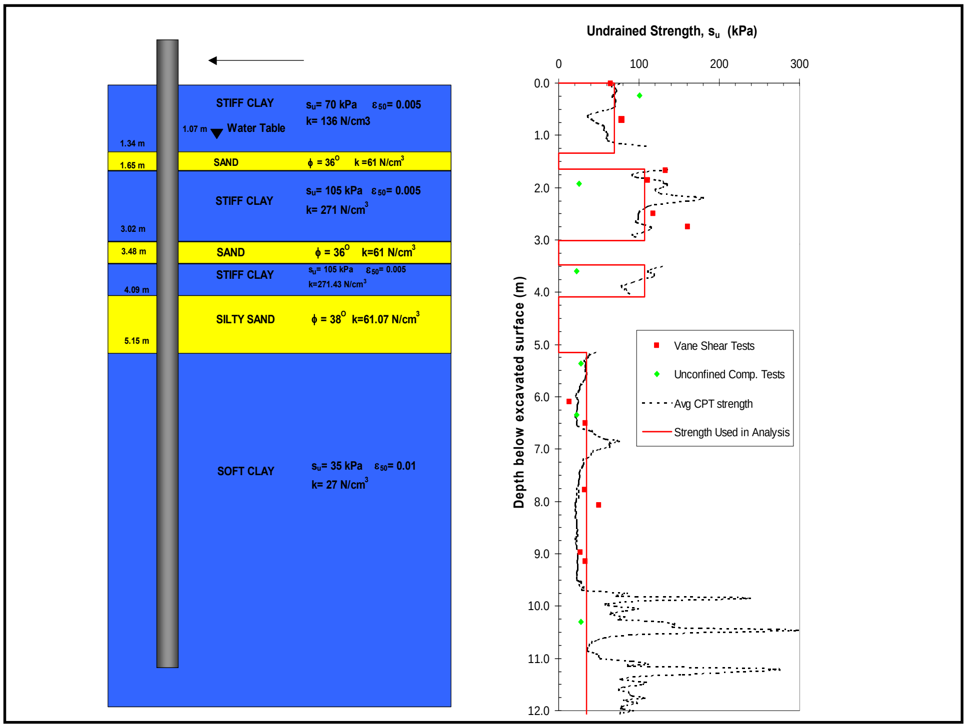
(3x5 Group at 3.3D Spacing)



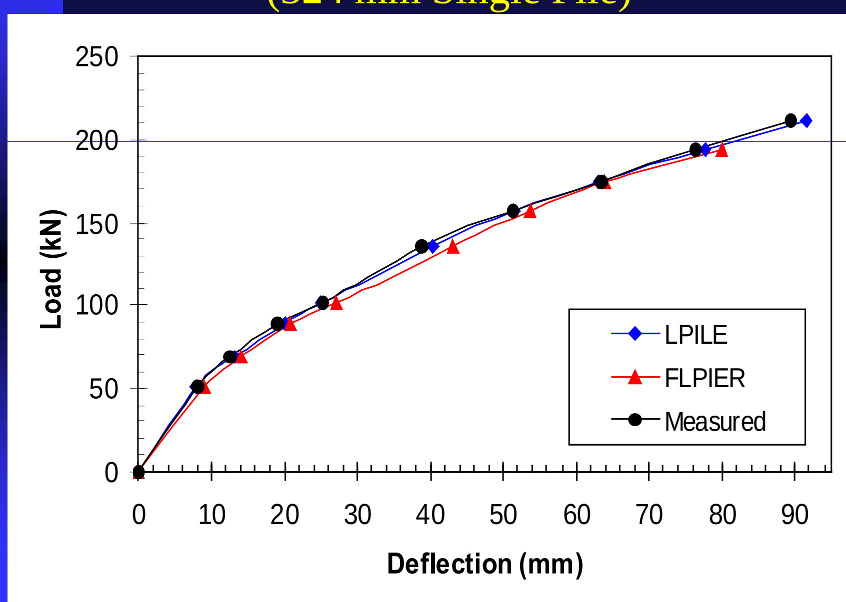
Conclusions from Static Tests

- Load capacity dependent on row position.
- Group effects decrease as pile spacing increases.
- Behavior of 3rd, 4th and 5th row piles very similar
- For a given load, group effects increase maximum bending moment, due to reduced soil resistance.
- Repeated cyclic loading only led to a 15-20% reduction in capacity at the peak load, but much lower resistance at loads less than the peak.

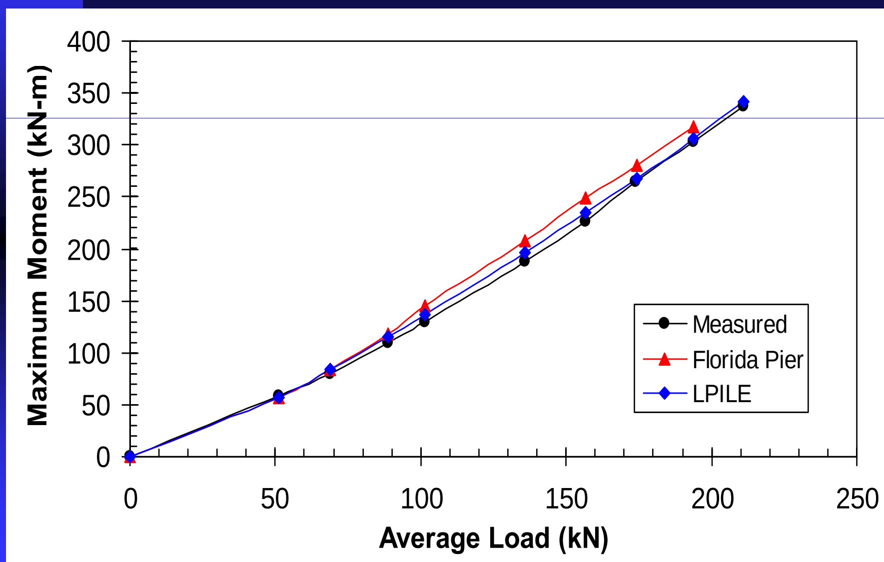
COMPUTER ANALYSIS



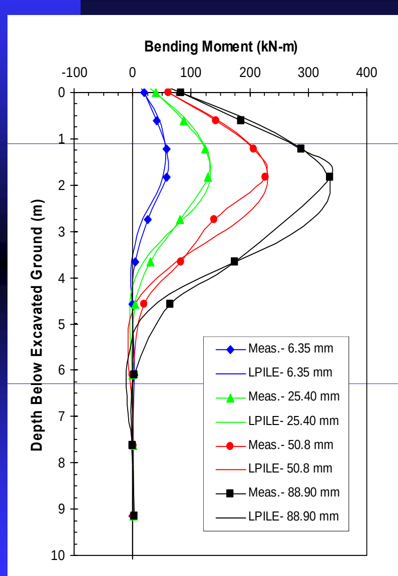
Computed & Measured Load vs Deflection (324 mm Single Pile)

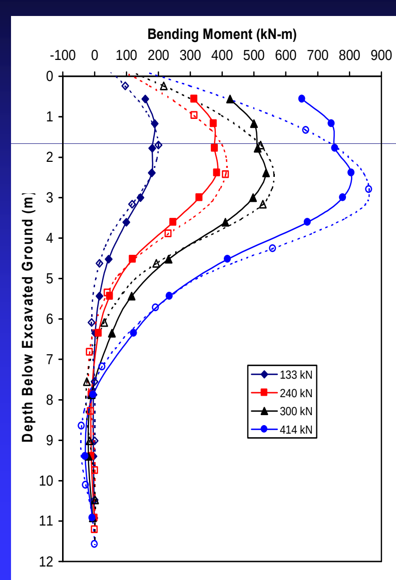


Computed & Measured Moment vs Load (324 mm Single Pile)

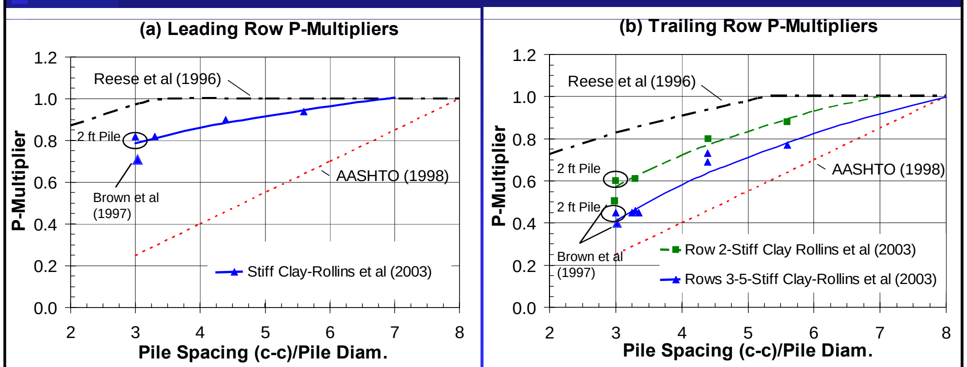


Computed & Measured Moment vs. Depth





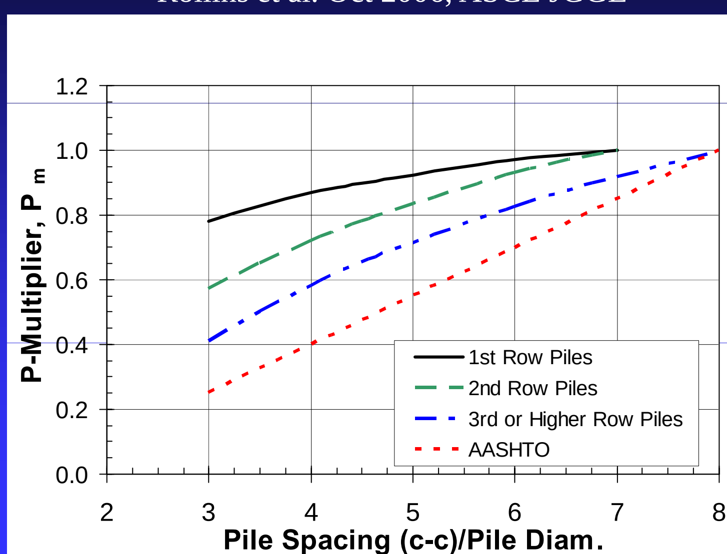
P-multiplier vs Spacing for Stiff Clay

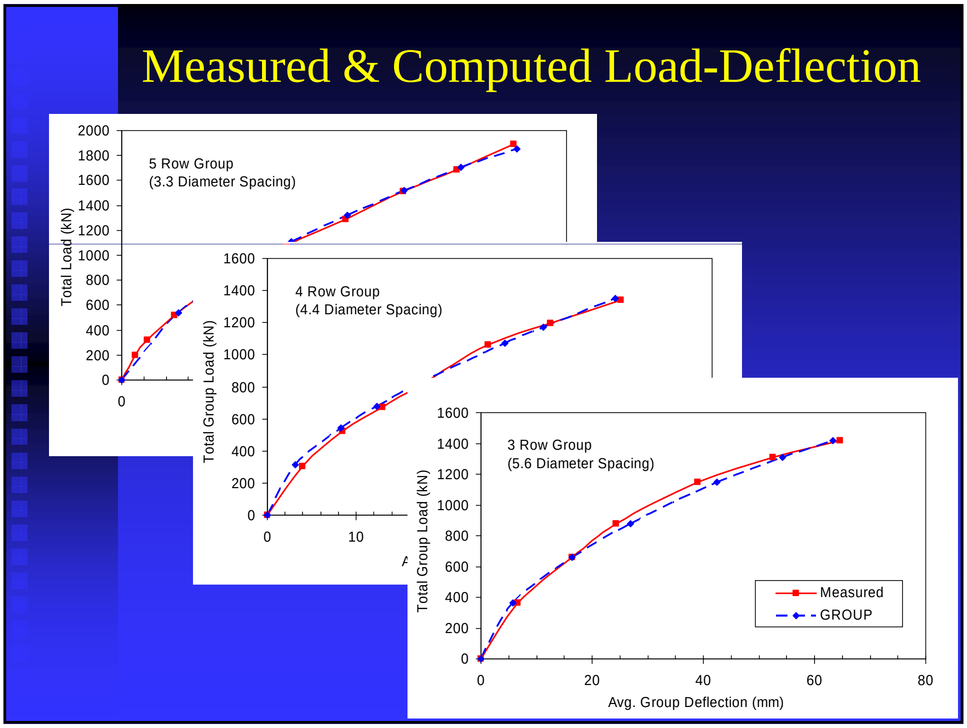


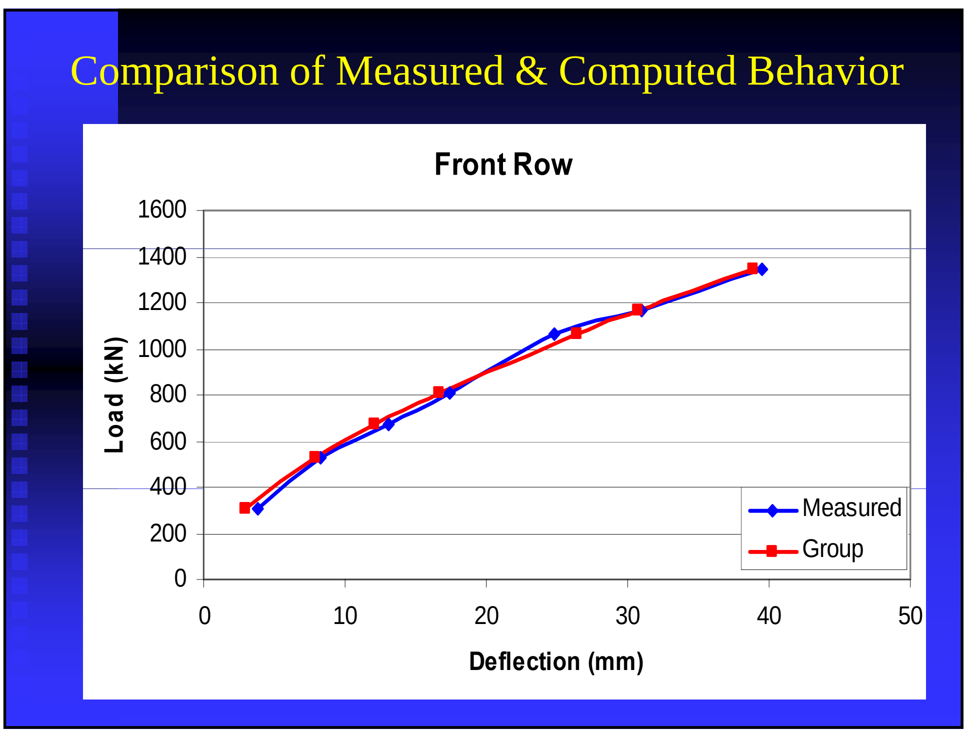
Rollins et al. Oct 2006, ASCE JGGE

P-multiplier Curves vs. Spacing

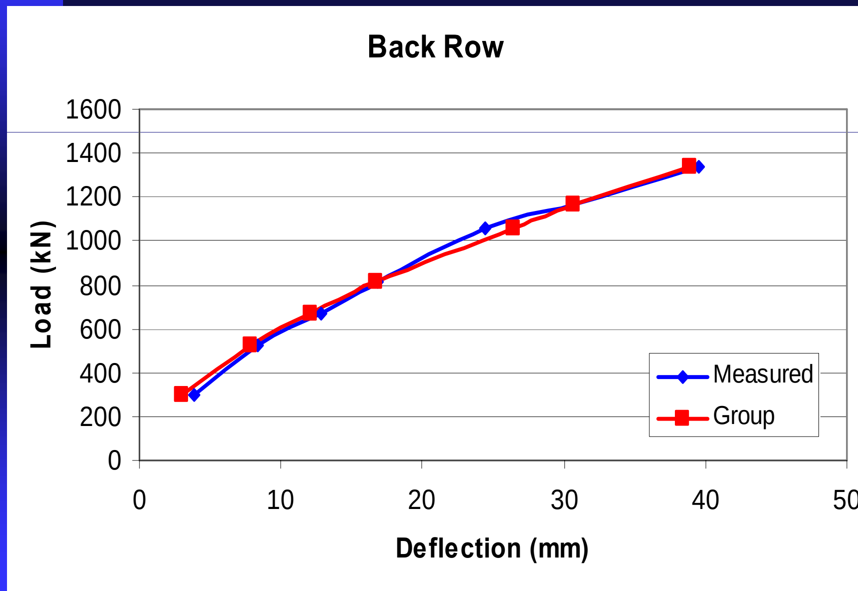
Rollins et al. Oct 2006, ASCE JGGE



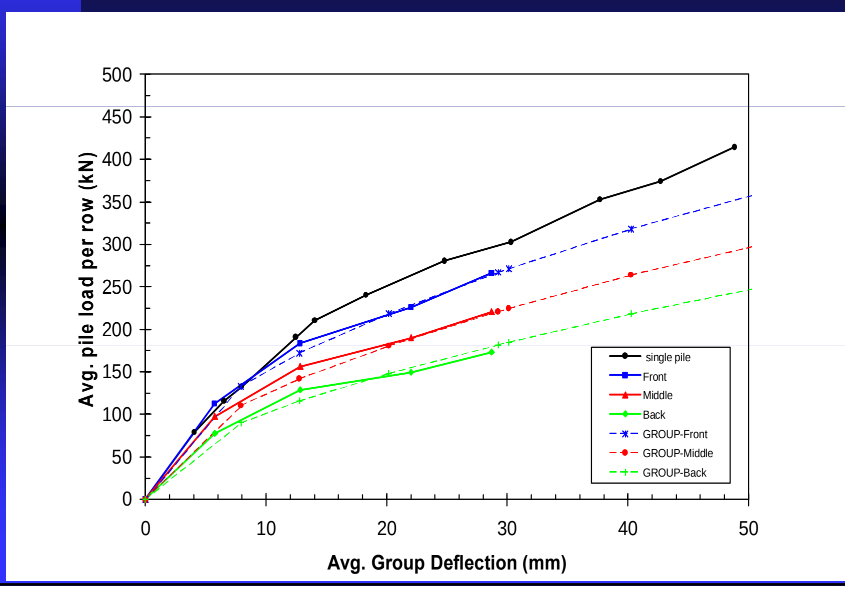

Measured & Computed Load-Deflection
5 Row Group
(3.3 Diameter Spacing)
Total Load (kN)
4 Row Group
(4.4 Diameter Spacing)
Total Group Load (kN)
3 Row Group
(5.6 Diameter Spacing)
Total Group Load (kN)
Measured
GROUP
Avg. Group Deflection (mm)


Comparison of Measured & Computed Behavior
Front Row
Load (kN)
Deflection (mm)
Measured
Group

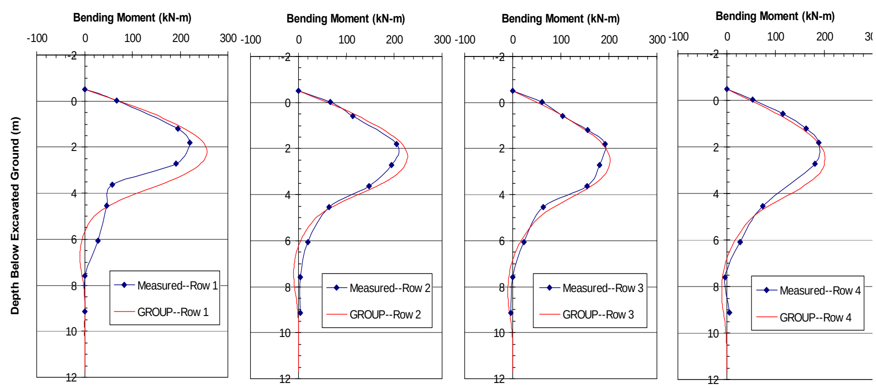
Comparison of Measured & Computed Behavior



Measured & Computed Load-Deflection (9 Pile Group-24" Pile)



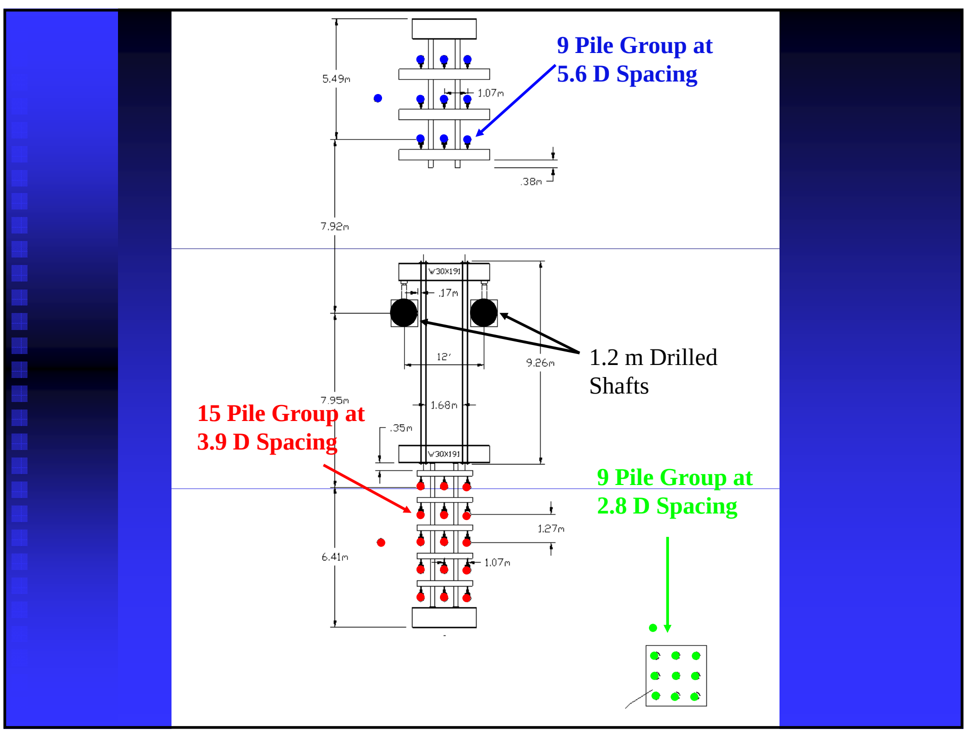
Measured & Computed Moment vs. Depth
(3x5 Pile Group)



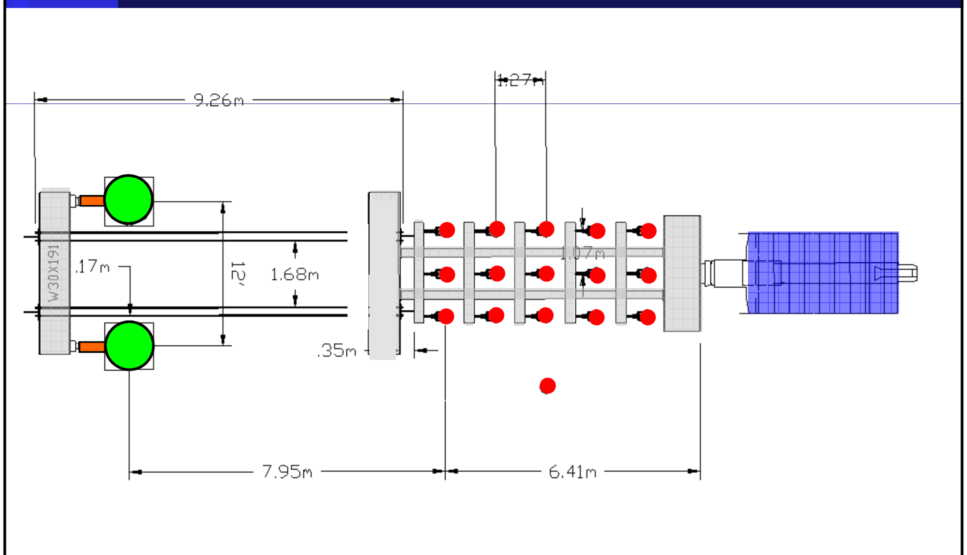
Conclusions from Computer Analysis of Static Tests

- Current computer models for clay provide reasonable estimates of single pile response for virgin loading.
- P-multipliers increase as spacing increases and can be grouped for leading rows and trailing rows.
- P-multipliers from full-scale tests are lower than default values in GROUP program, but higher than AASHTO.
- P-mulitipliers for 0.6 m and 0.32 m piles were about the same at similar spacing.
- With appropriate P-multipliers pile group response can be modeled with reasonable accuracy (10 to 20% error).

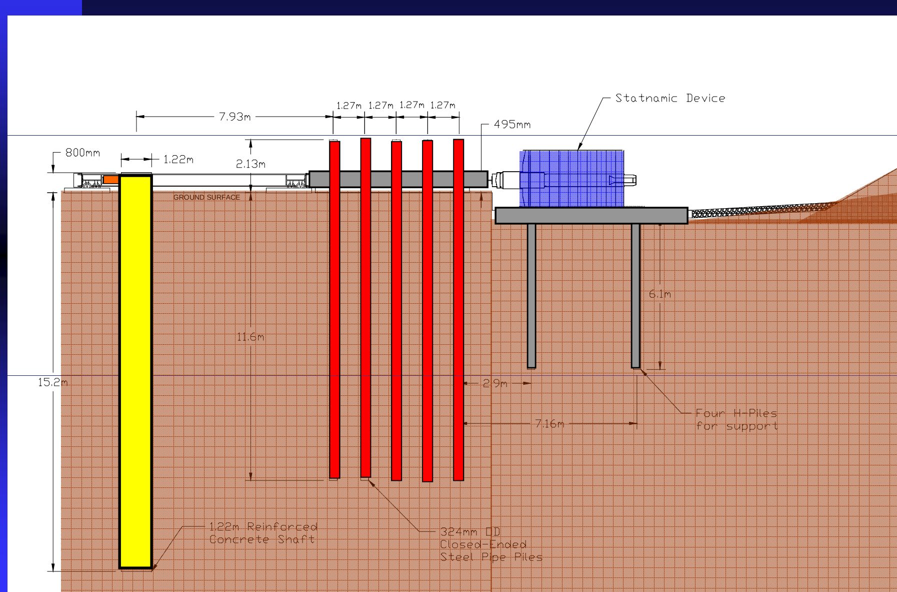

Salt Lake City Intl. Airport
Test Site
North
Funding from NSF

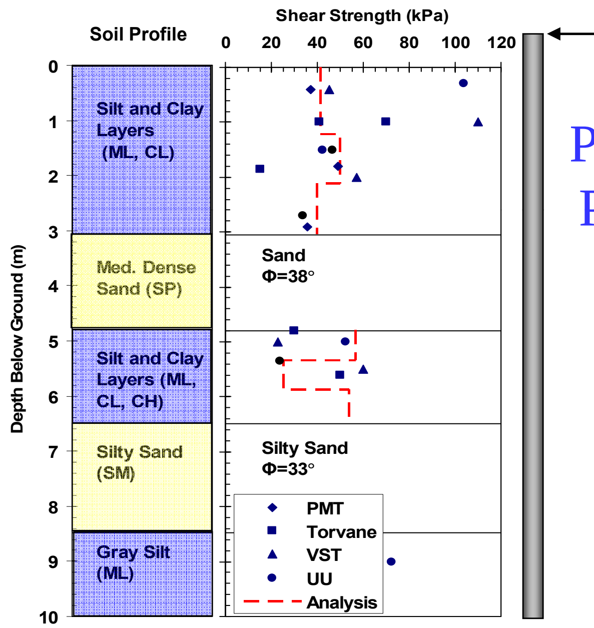

9 Pile Group at
5.6 D Spacing
1.2 m Drilled
Shafts
15 Pile Group at
3.9 D Spacing
9 Pile Group at
2.8 D Spacing
5.49m
1.07m
.38m
7.92m
W30X191
.17m
12'
9.26m
7.95m
1.68m
.35m
1.27m
6.41m

Plan View of 15 Pile Group Test



Profile View of 15 Pile Group Test

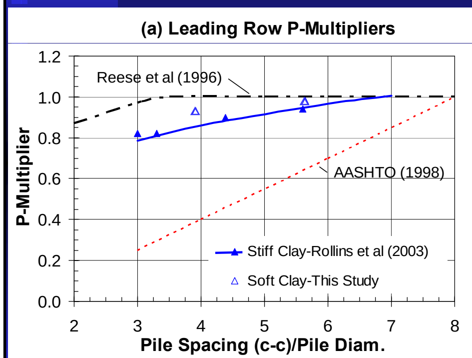


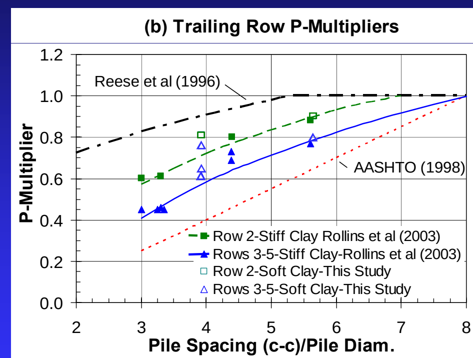


Soil Profile and Properties

How soft is the clay?

Group Interaction Reduction Factors (P-multipliers)



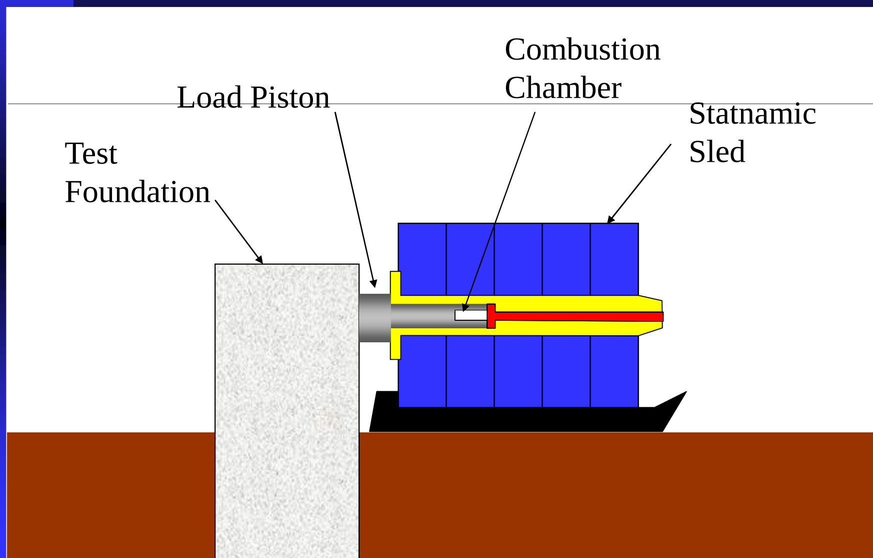


Lateral Statnamic Load Testing

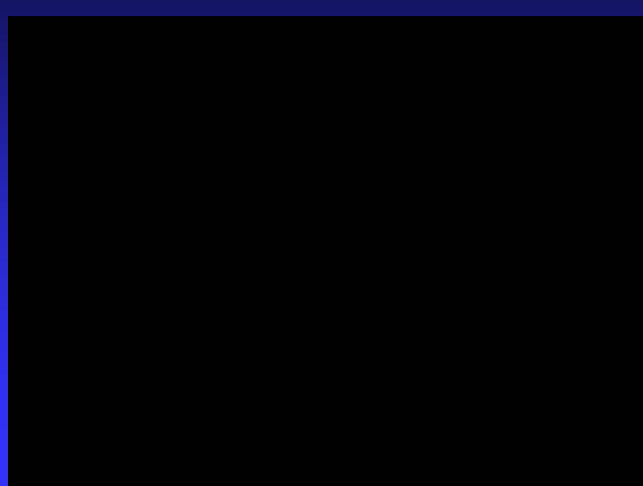
0 to 400 kips in 0.2 seconds

Large Displacement, High Velocity

Schematic of Lateral Statnamic Test



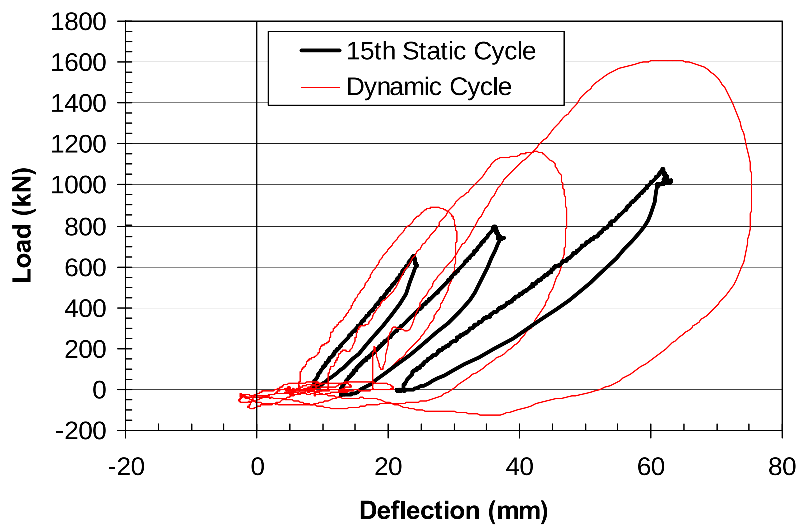
Statnamic Test Firing Videos

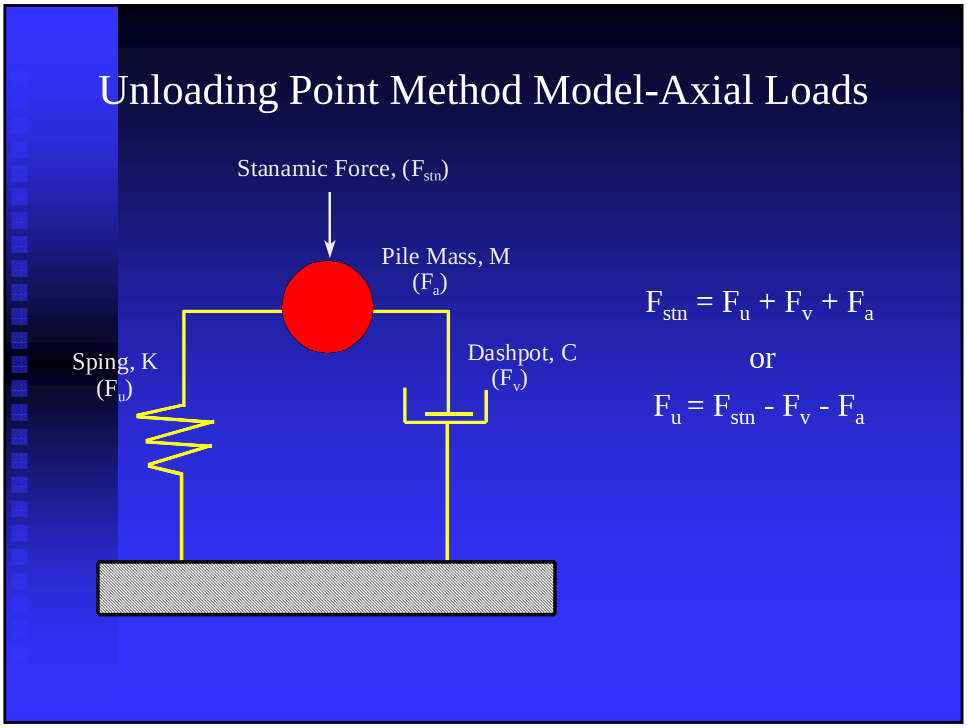


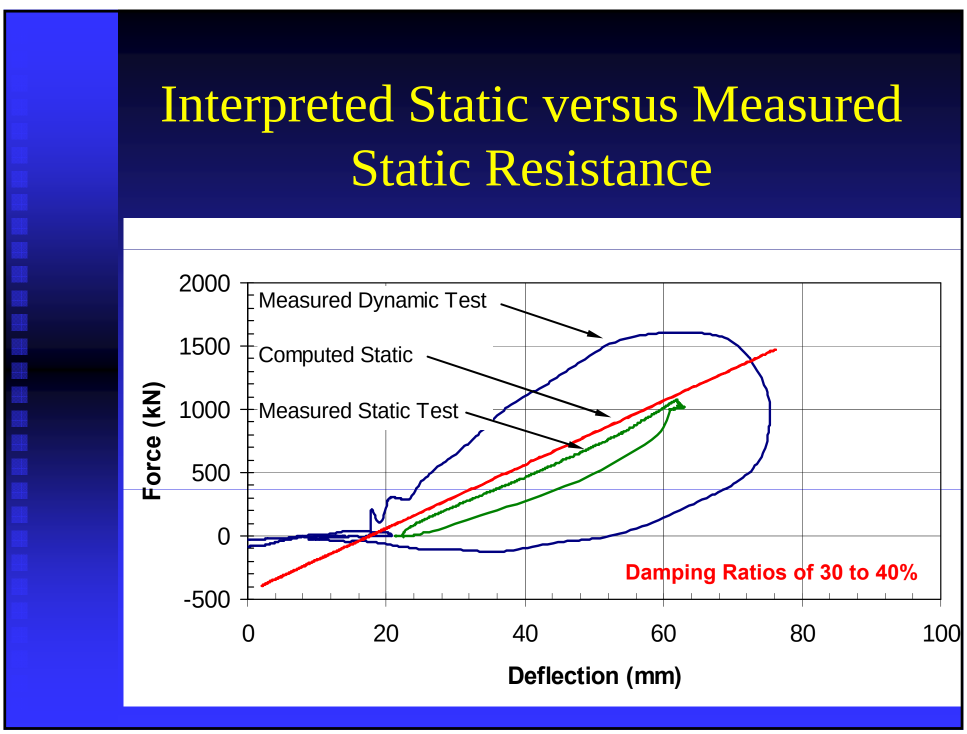
Next time your friends ask…

Yes,
Foundation Design Actually
is Rocket Science

Static vs Dynamic Response



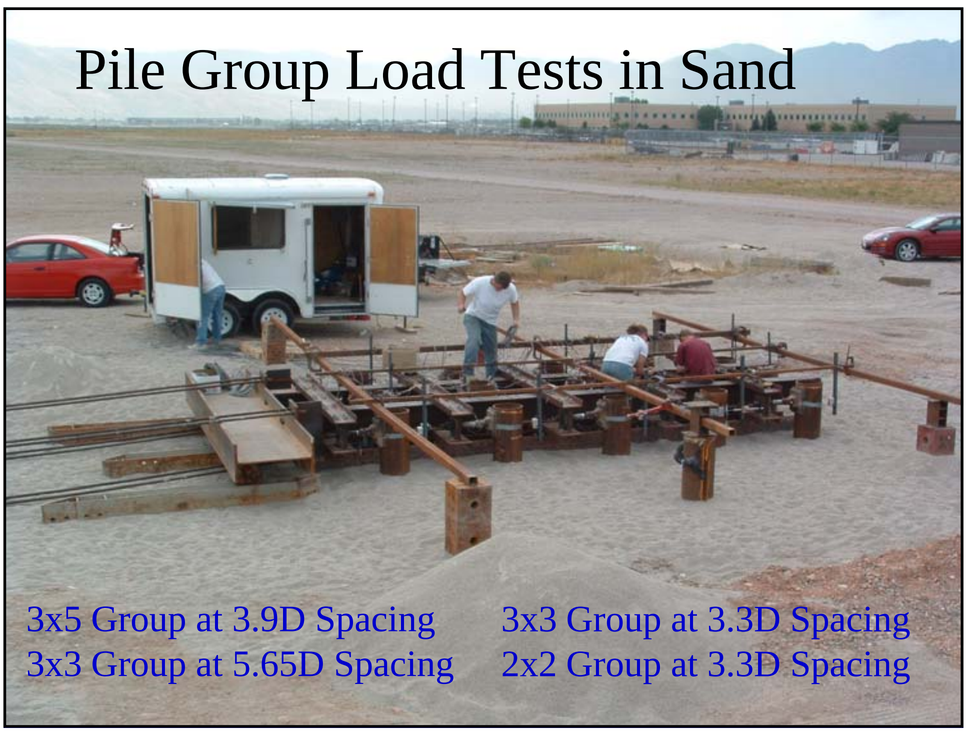

Unloading Point Method Model-Axial Loads
Stanamic Force, (F_{stn})
Pile Mass, M
(F_a)
Sping, K
(F_u)
Dashpot, C
(F_v)
$F_{stn} = F_u + F_v + F_a$
or
$F_u = F_{stn} - F_v - F_a$


Interpreted Static versus Measured Static Resistance
Measured Dynamic Test
Computed Static
Measured Static Test
Damping Ratios of 30 to 40%
Force (kN)
2000
1500
1000
500
0
-500
0
20
40
60
80
100
Deflection (mm)

Conclusions from Statnamic Testing

- Dynamic resistance 50 to 75% higher than static for virgin loading.
- Simple analysis methods can provide reasonable estimates of static resistance.
- Increased resistance largely due to damping with damping ratios typically between 30 and 40%.

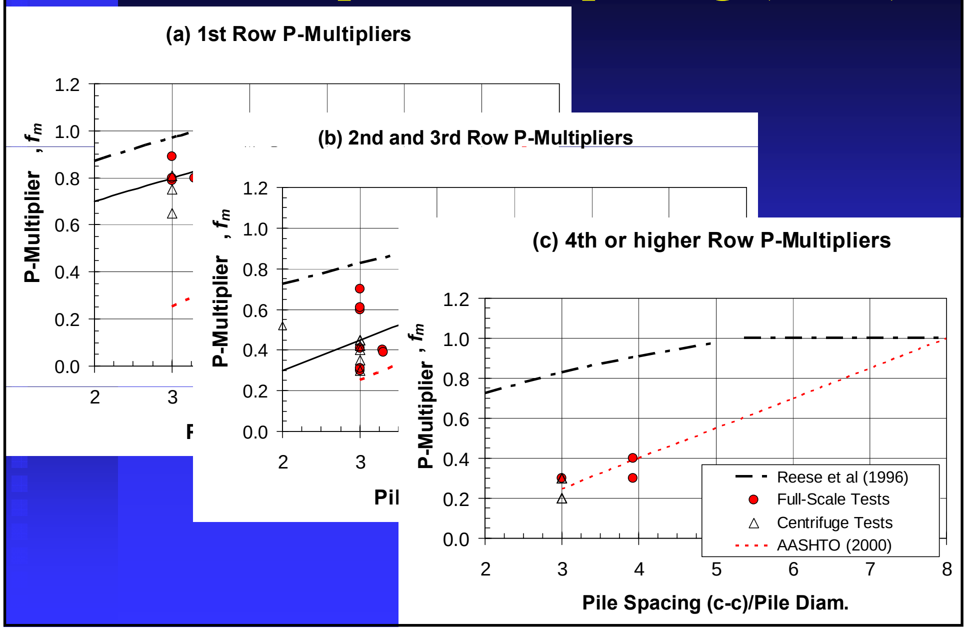
Pile Group Load Tests in Sand



3x5 Group at 3.9D Spacing
3x3 Group at 5.65D Spacing

3x3 Group at 3.3D Spacing
2x2 Group at 3.3D Spacing

P-Multipliers vs Spacing (Sand)

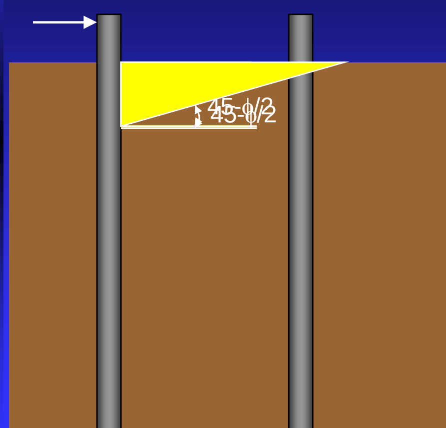


Explanation of Variability in Sand

- Natural variability of sand relative to clay
- Sand more influenced by installation procedure than clays
- Different installation procedures
  - Jetting
  - Driven, Open-ended
  - Sand Compacted around previously driven piles
  - Drilled shafts

Influence of Friction Angle on Group Interaction

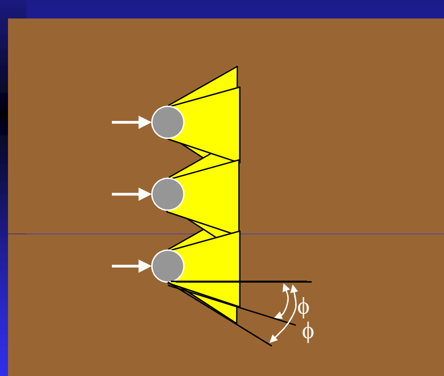
Elevation View



- Passive failure wedge inclined at 45-ϕ/2.
- As ϕ increases the angle gets smaller and wedge gets longer.
- Longer wedge causes more group interaction.

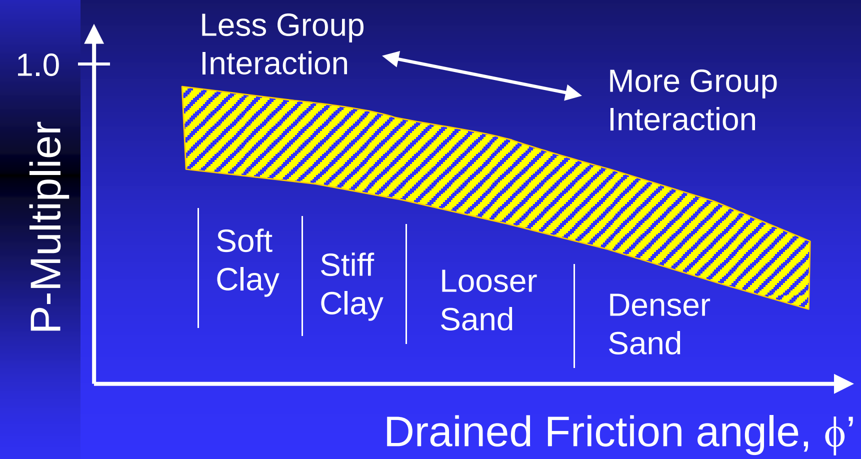
Influence of Friction Angle on Group Interaction

Plan View



- Passive failure wedge fans out at ϕ.
- As ϕ increases the angle gets larger and wedge gets wider.
- Wider wedge causes more group interaction.

Influence of Friction Angle on P-multiplier



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