1st C.W.Lovell Lecture, Purdue University

Science and Empiricism in Pile Foundation Design

Mark Randolph

Director, Centre for Offshore Foundation Systems[1]

The University of Western Australia

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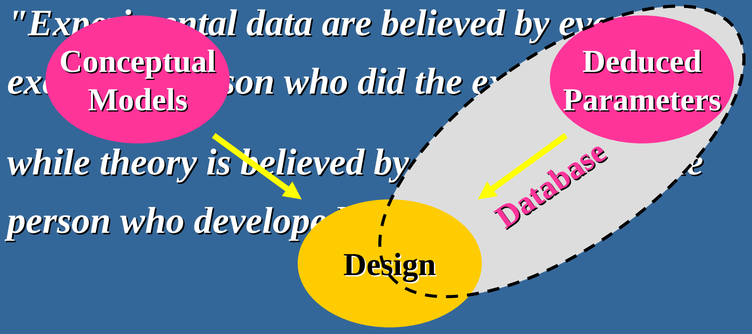
Theme

Science **Empiricism**



"Exp ntal data are believed by ev
ex son who did the ex
while theory is believed by e
person who develope

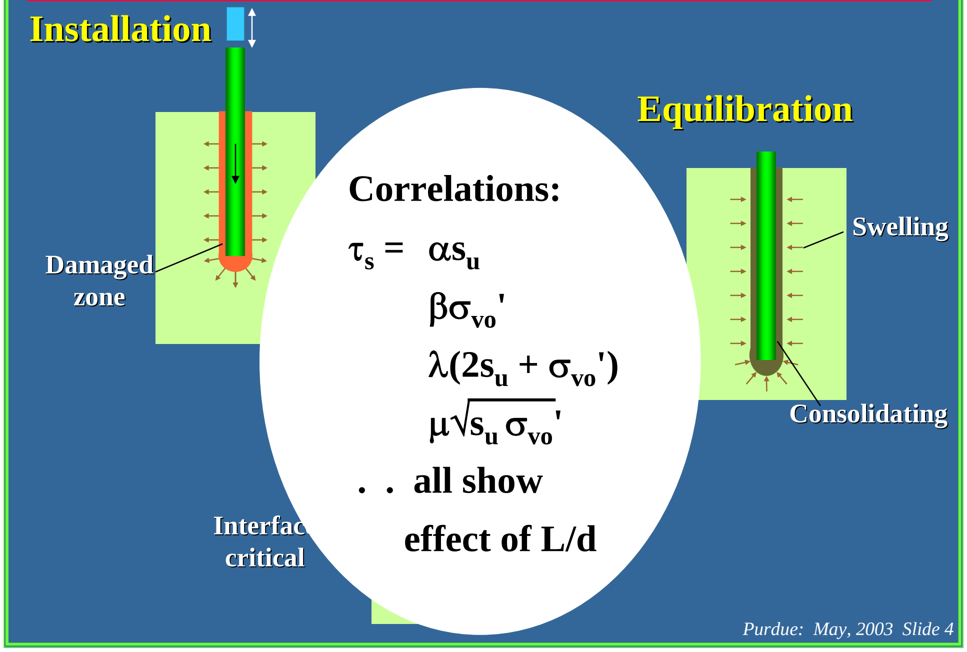
Einstein . . . .

- **Are our conceptual models sound ?**
- **Can they be extrapolated outside the database ?**

Scope of Lecture

- Axial capacity of driven piles (focus: offshore)
  - Effect of pile size (length, diameter)
  - Effect of tip geometry: open or closed-ended
- Dynamic pile testing
  - Dynamic pile-soil interaction models
  - Question of uniqueness
- Response of pile groups (focus: onshore)
  - Settlement: single piles, pile groups, piled rafts
  - General loading: significance of non-linear response

Driven Piles in Clay – Main Phases



Correlations:

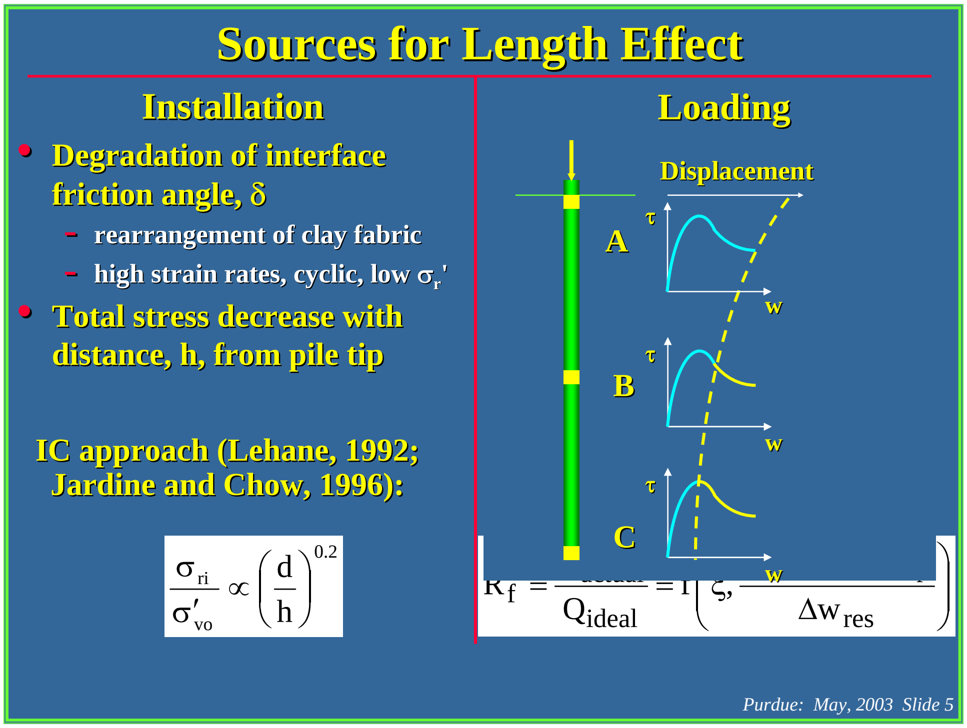
$\tau_s = \alpha s_u$

$\beta \sigma_{vo}'$

$\lambda(2s_u + \sigma_{vo}')$

$\mu\sqrt{s_u \sigma_{vo}'}$

. . all show effect of L/d



Sources for Length Effect

Installation

- **Degradation of interface friction angle, δ**
  - rearrangement of clay fabric
  - high strain rates, cyclic, low σ_r'
- **Total stress decrease with distance, h, from pile tip**

IC approach (Lehane, 1992; Jardine and Chow, 1996):

$$\frac{\sigma_{ri}}{\sigma'_{vo}} \propto \left(\frac{d}{h}\right)^{0.2}$$

Loading

$$R_f = \frac{}{Q_{ideal}} = f\left(\varsigma, \frac{}{\Delta w_{res}}\right)$$

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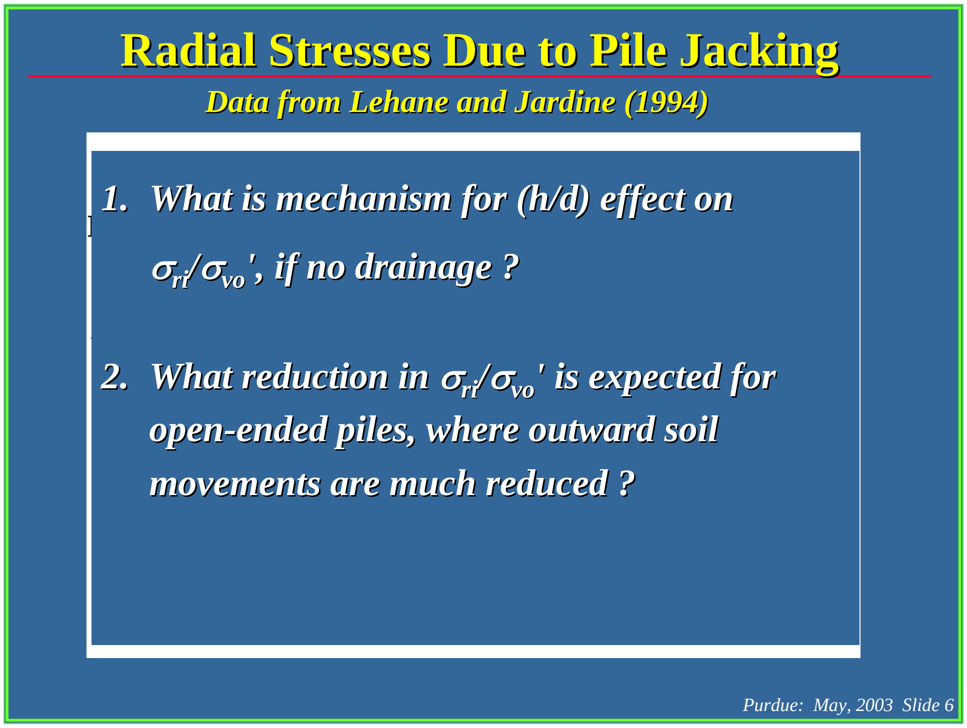

Radial Stresses Due to Pile Jacking

Data from Lehane and Jardine (1994)

1. *What is mechanism for (h/d) effect on σ_{ri}/σ_{vo}', if no drainage ?*
2. *What reduction in σ_{ri}/σ_{vo}' is expected for open-ended piles, where outward soil movements are much reduced ?*

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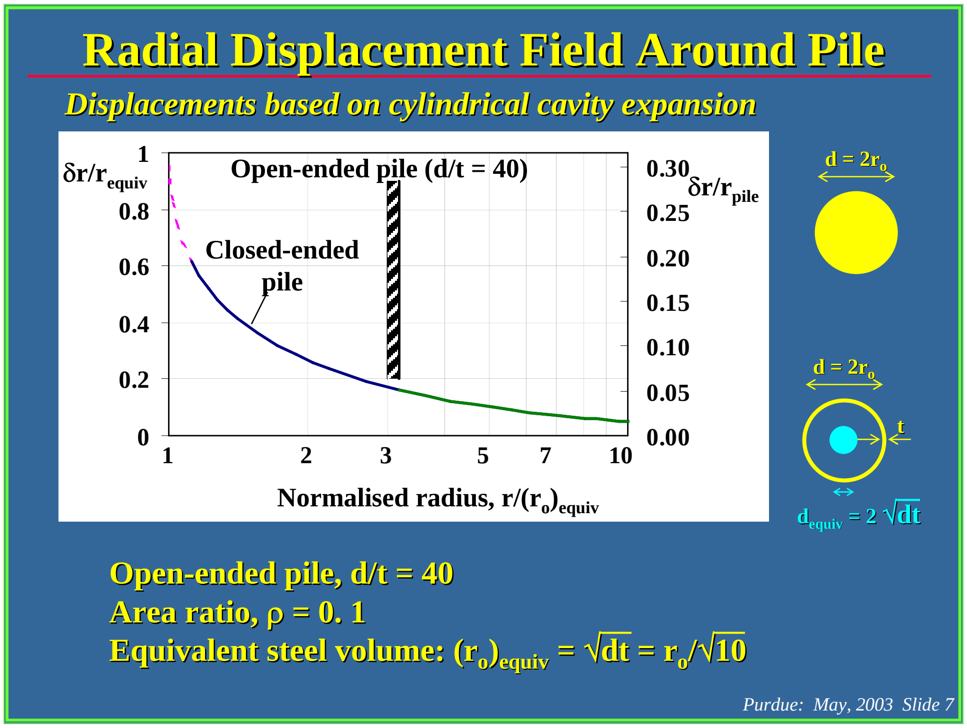

Radial Displacement Field Around Pile

Displacements based on cylindrical cavity expansion

Open-ended pile, d/t = 40
Area ratio, $\rho = 0.1$
Equivalent steel volume: $(r_o)_{equiv} = \sqrt{dt} = r_o/\sqrt{10}$

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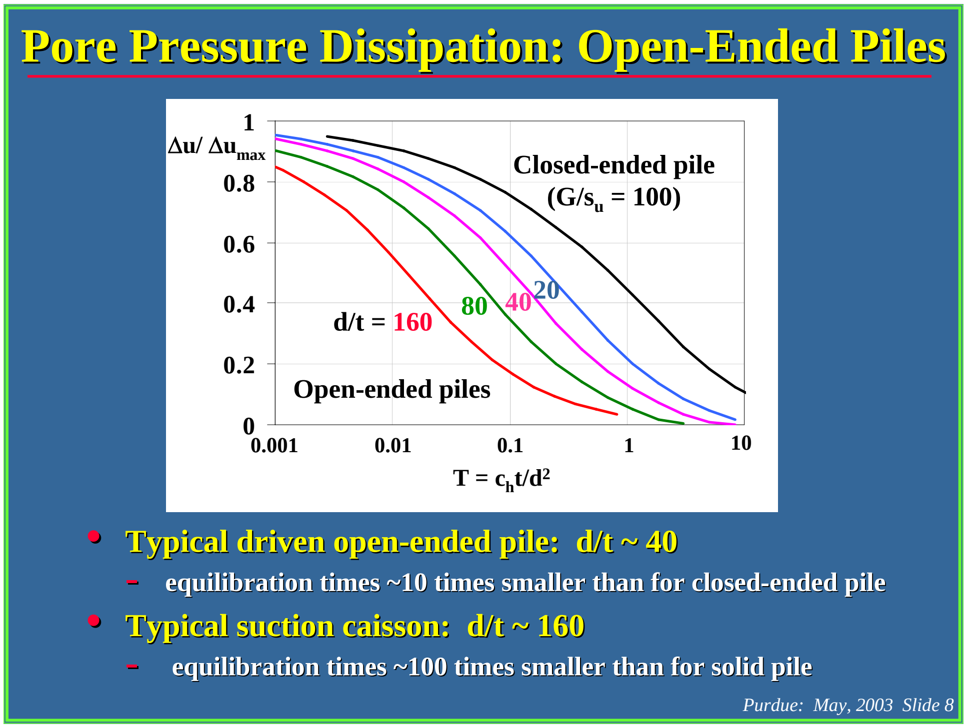

Pore Pressure Dissipation: Open-Ended Piles

- **Typical driven open-ended pile: d/t ~ 40**
  - **equilibration times ~10 times smaller than for closed-ended pile**
- **Typical suction caisson: d/t ~ 160**
  - **equilibration times ~100 times smaller than for solid pile**

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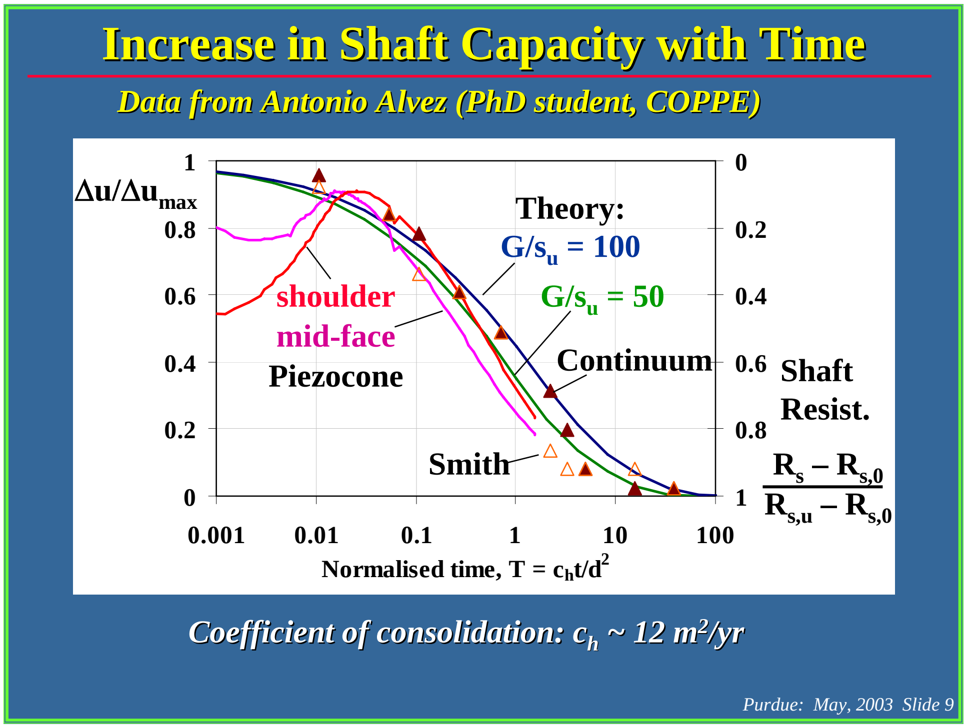

Increase in Shaft Capacity with Time

Data from Antonio Alvez (PhD student, COPPE)

Coefficient of consolidation: $c_h \sim 12$ m²/yr

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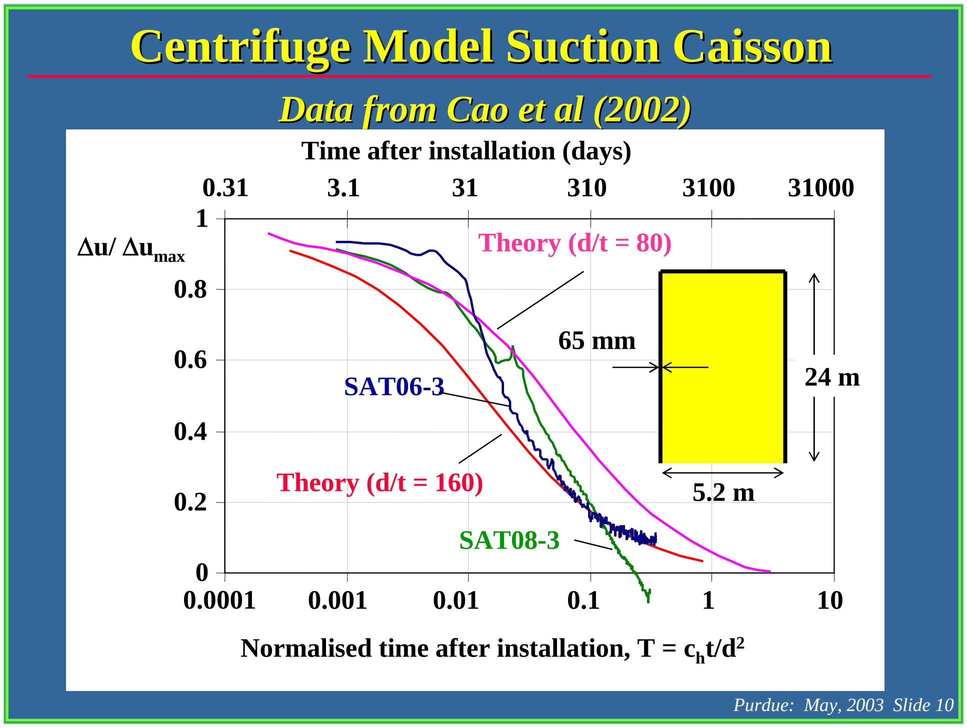

Centrifuge Model Suction Caisson

Data from Cao et al (2002)

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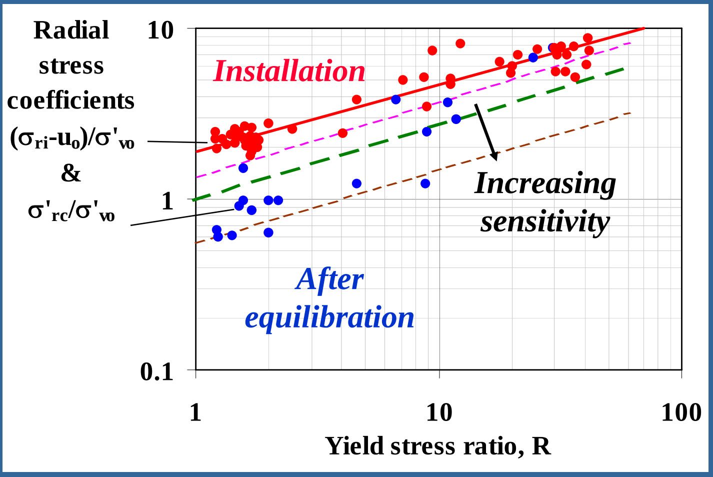
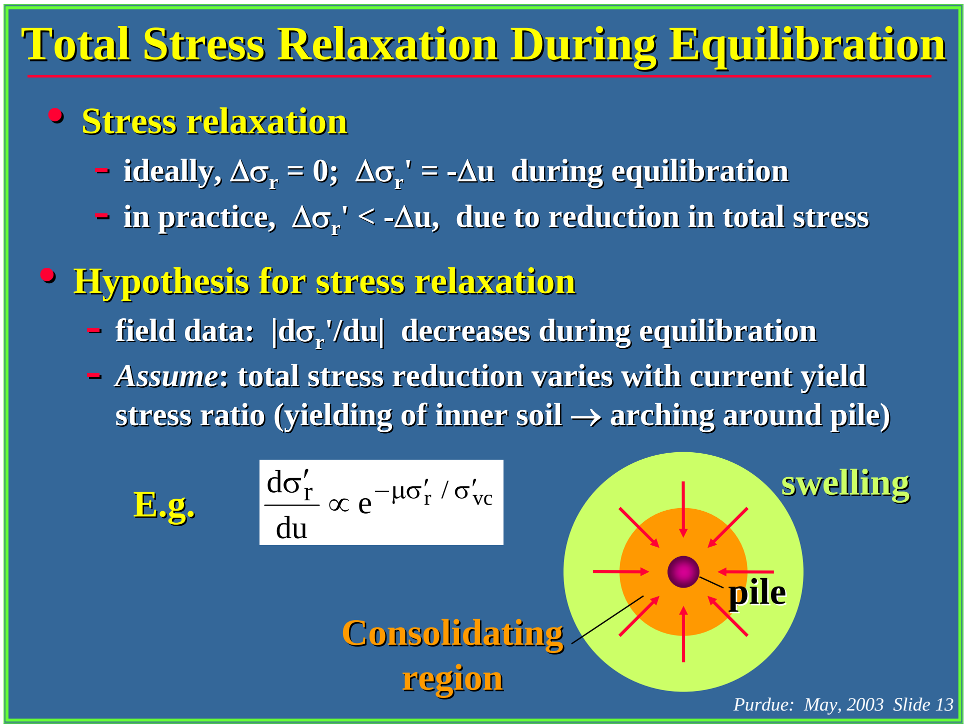
Consolidation Effects During Installation

- **Significant (20 %) consolidation occurs for T ~ 0.1**
  - offshore (open-ended: d_o ~ 2 m), t_{20} ~ 0.5 to 5 days
  - onshore (d ~ 0.5 m), t_{20} ~ 0.3 to 3 days
  - small field (d ~ 0.1 m), t_{20} ~ 0.3 to 3 hours
- **Partial drainage during installation will increase degree of damage**
  - reduction in radial stress (apparent h/d effect)
  - greater damage to soil fabric adjacent to pile
- **Anomalous low shaft friction (τ_s/σ_{vo}' values) in low plasticity clays**
  - partial consolidation during installation a key factor

Total Stress Relaxation During Equilibration

Data from Chow (1997)





Total Stress Relaxation During Equilibration

- **Stress relaxation**
  - ideally, $\Delta\sigma_r = 0$; $\Delta\sigma_r' = -\Delta u$ during equilibration
  - in practice, $\Delta\sigma_r' < -\Delta u$, due to reduction in total stress
- **Hypothesis for stress relaxation**
  - field data: $|d\sigma_r'/du|$ decreases during equilibration
  - *Assume*: total stress reduction varies with current yield stress ratio (yielding of inner soil → arching around pile)

E.g.

$$\frac{d\sigma'_r}{du} \propto e^{-\mu\sigma'_r / \sigma'_{vc}}$$

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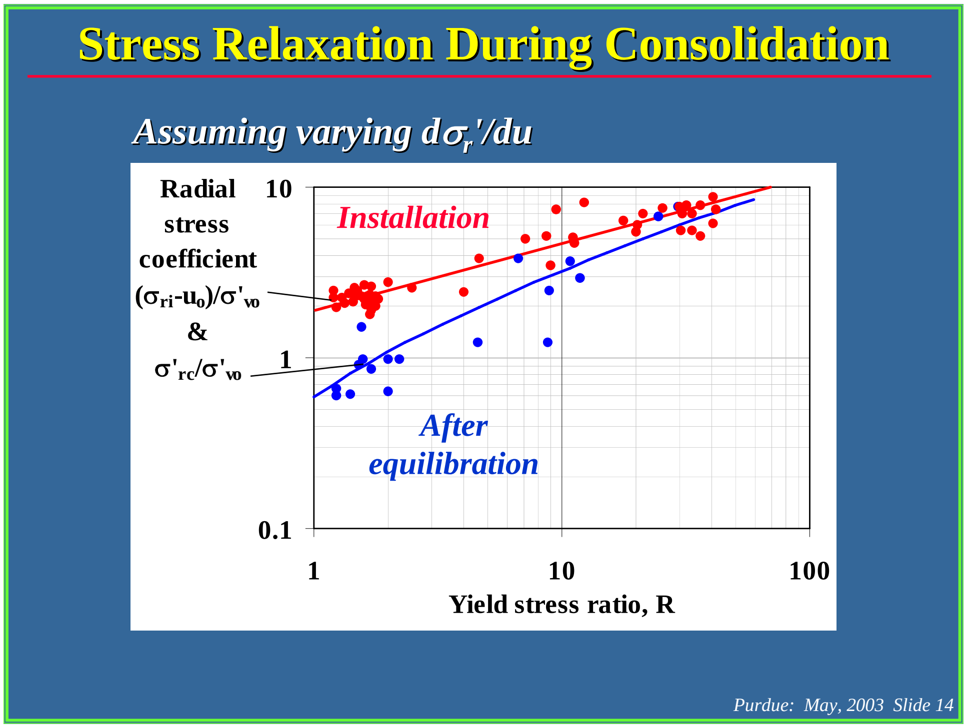

Stress Relaxation During Consolidation

Assuming varying $d\sigma_r'/du$

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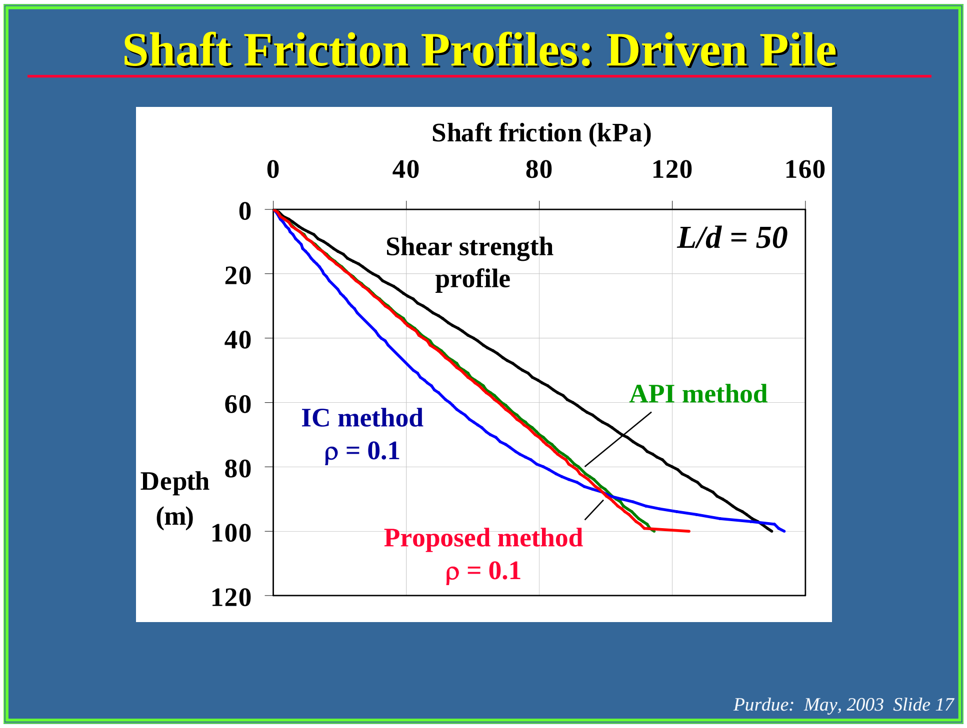
Example Application: New Horizons

- **Offshore West Africa: active development area**
  - **soft, high plasticity, clays with high water contents**
  - **uncharacteristically high friction angles (undisturbed)**
- **Generic soil properties**
  - **shear strength:** $s_u \sim 1.5z$ kPa
  - **effective unit weight:** $\gamma' \sim 3.5$ kN/m^3
  - **yield stress ratio:** R ~ 2
  - **sensitivity:** $S_t \sim 4$
  - **plasticity index:** PI ~ 100 %
  - **friction angle:** $\phi' \sim 35°$
  - **interface friction angle:** $\delta \sim 20°$ (residual ~12°)

Typical Pile Dimensions



Shaft Friction Profiles: Driven Pile

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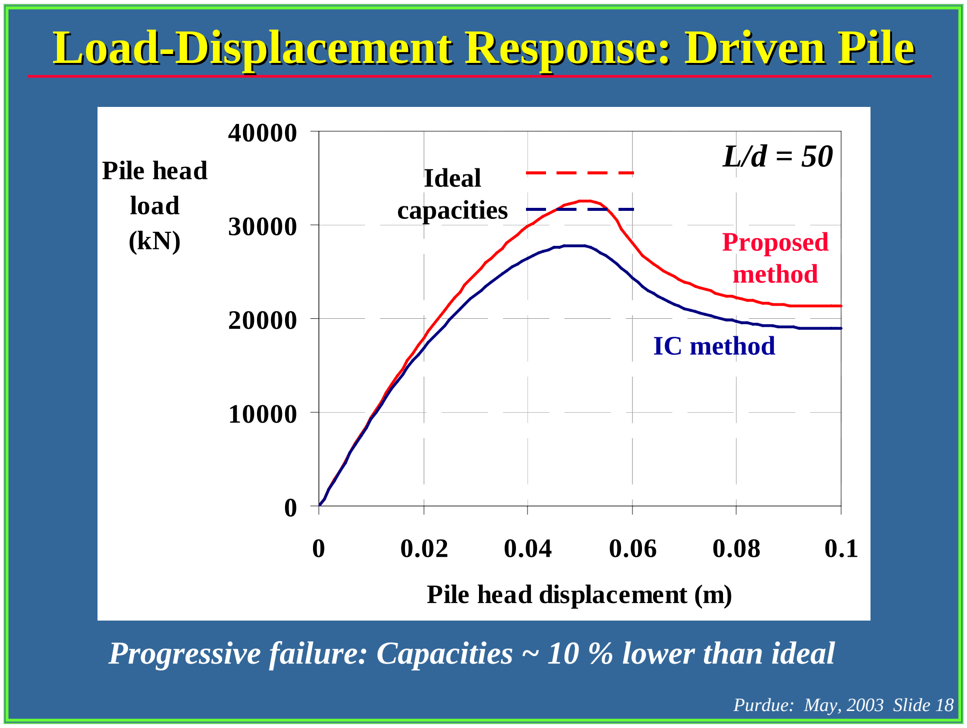

Load-Displacement Response: Driven Pile

Progressive failure: Capacities ~ 10 % lower than ideal

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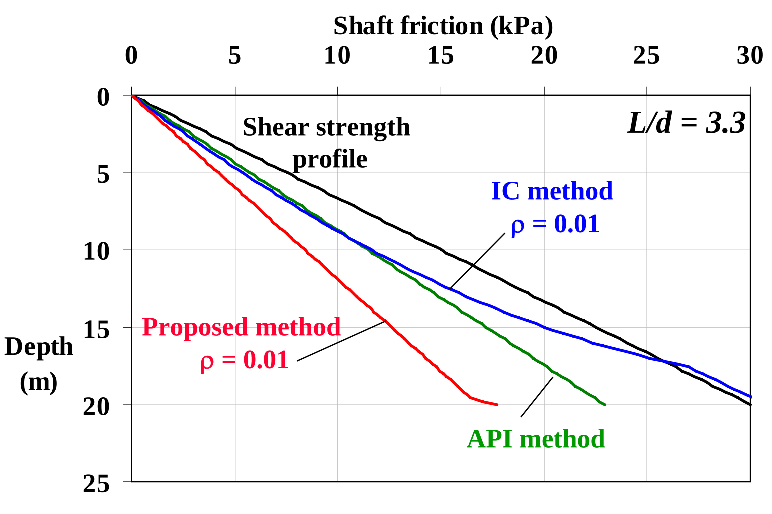
Shaft Friction Profiles: Suction Caisson



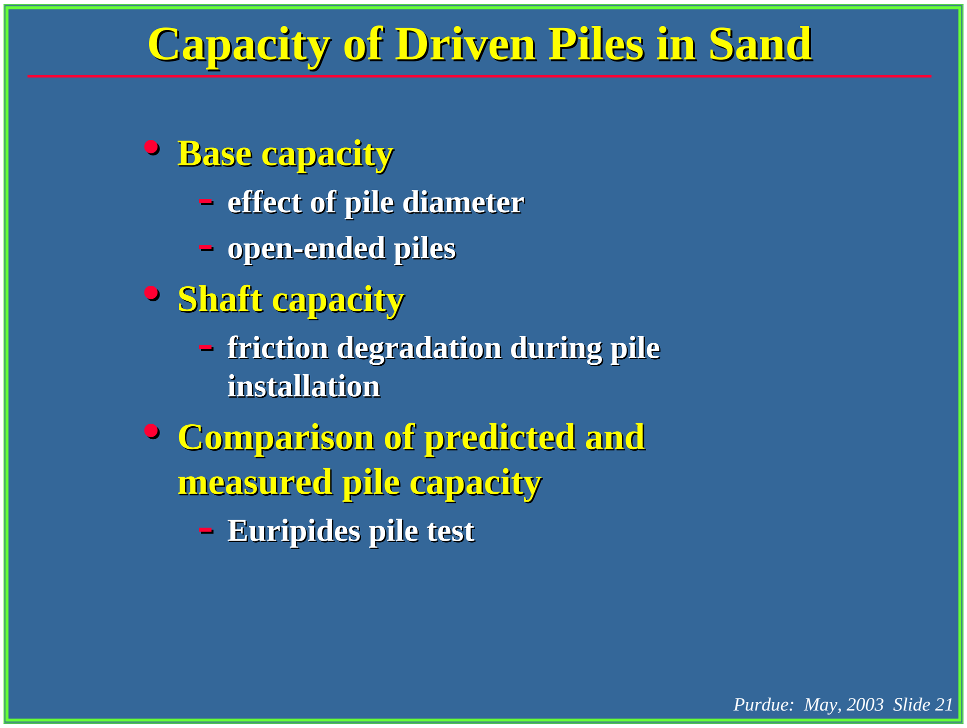
Summary: Pile Shaft Capacity in Clay

Science

- Analytical models
  - installation (SP, CE)
  - equilibration (radial cons)
  - loading (load transfer)
- Adjustment for open-ended piles
  - reduction in installation stresses by $s_u \ln(\rho)$

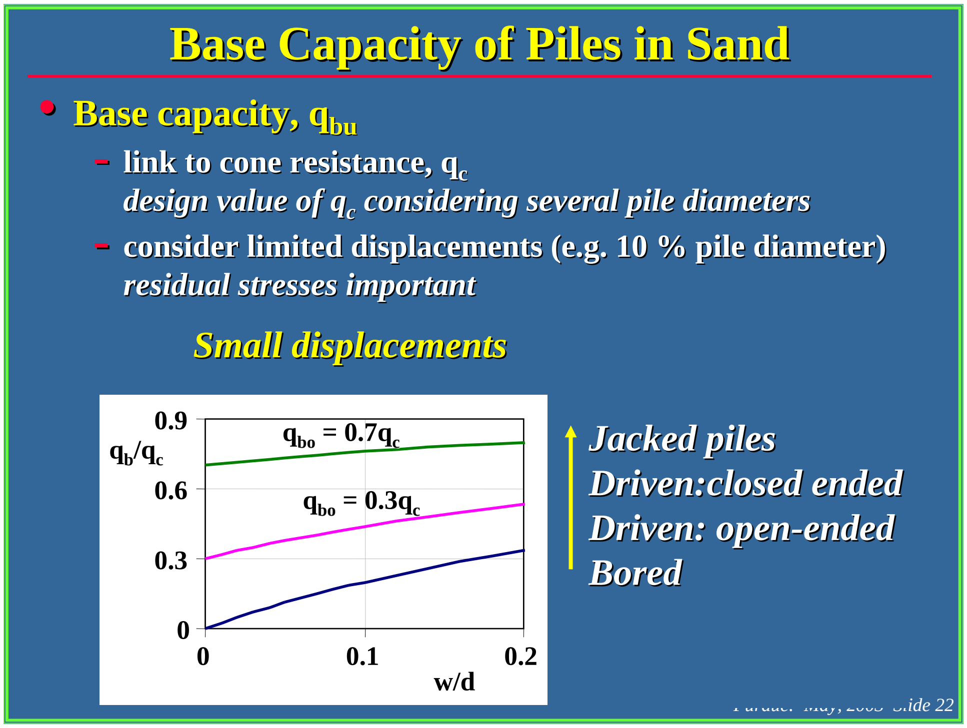
Empiricism

- Database correlations
  - radial stress changes for each phase
  - *h/d effect (distorted by partial consolidation)*
  - *hypothetical dependence of* $d\sigma_r'/du$ *on* σ_r'
- Consolidation parameter
  - scale c_h from piezocone measurements



Capacity of Driven Piles in Sand

- Base capacity
  - effect of pile diameter
  - open-ended piles
- Shaft capacity
  - friction degradation during pile installation
- Comparison of predicted and measured pile capacity
  - Euripides pile test

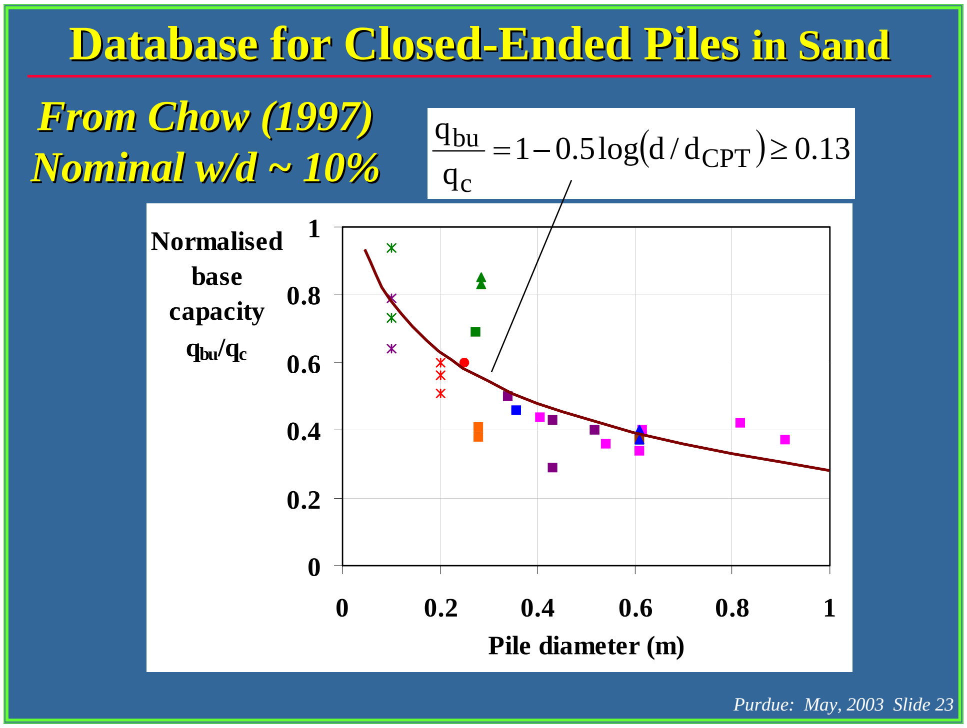


Base Capacity of Piles in Sand

- Base capacity, q_{bu}
  - link to cone resistance, q_c
    design value of q_c considering several pile diameters
  - consider limited displacements (e.g. 10 % pile diameter)
    residual stresses important

Small displacements

Jacked piles
Driven:closed ended
Driven: open-ended
Bored



Database for Closed-Ended Piles in Sand

From Chow (1997)
Nominal w/d ~ 10%

$$\frac{q_{bu}}{q_c} = 1 - 0.5\log\left(d/d_{CPT}\right) \geq 0.13$$

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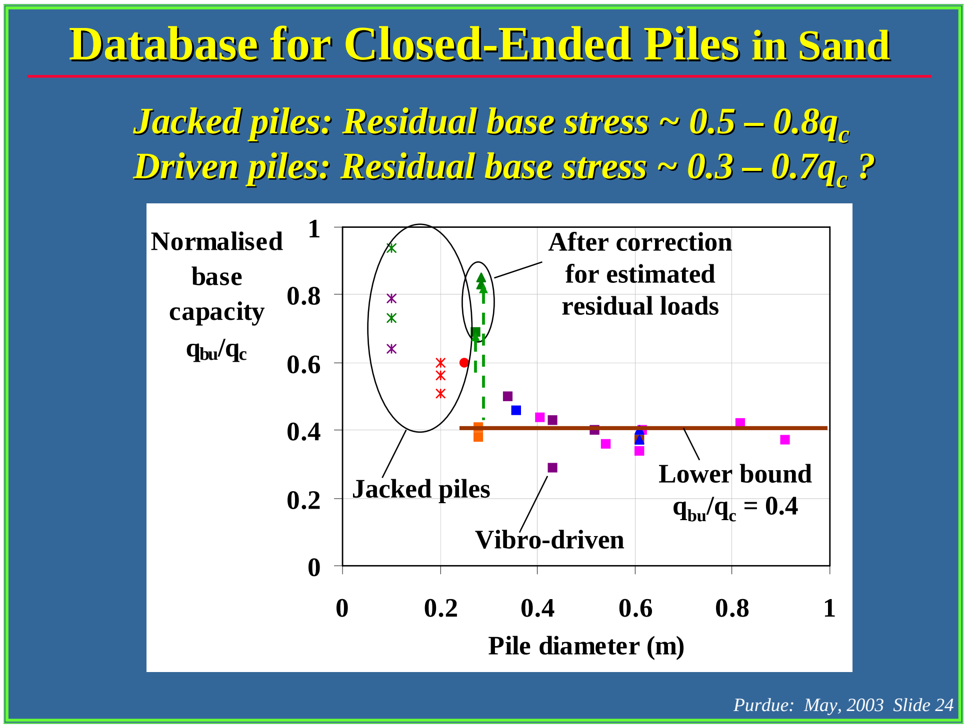

Database for Closed-Ended Piles in Sand

Jacked piles: Residual base stress ~ 0.5 – 0.8q_c
Driven piles: Residual base stress ~ 0.3 – 0.7q_c ?

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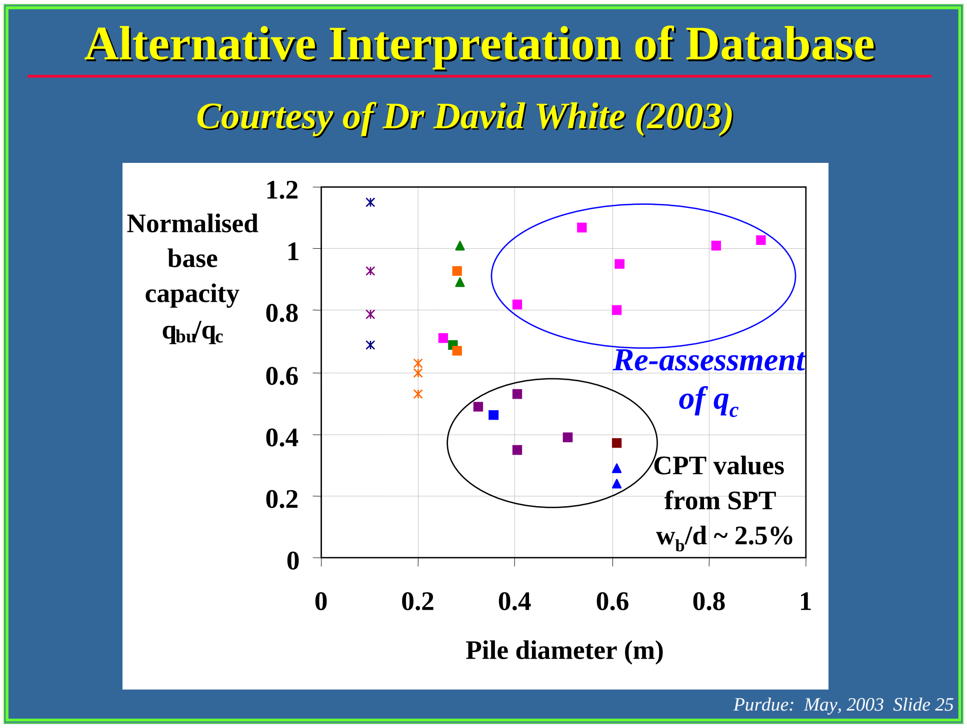

Alternative Interpretation of Database

Courtesy of Dr David White (2003)

Re-assessment of q_c

CPT values from SPT
w_b/d ~ 2.5%

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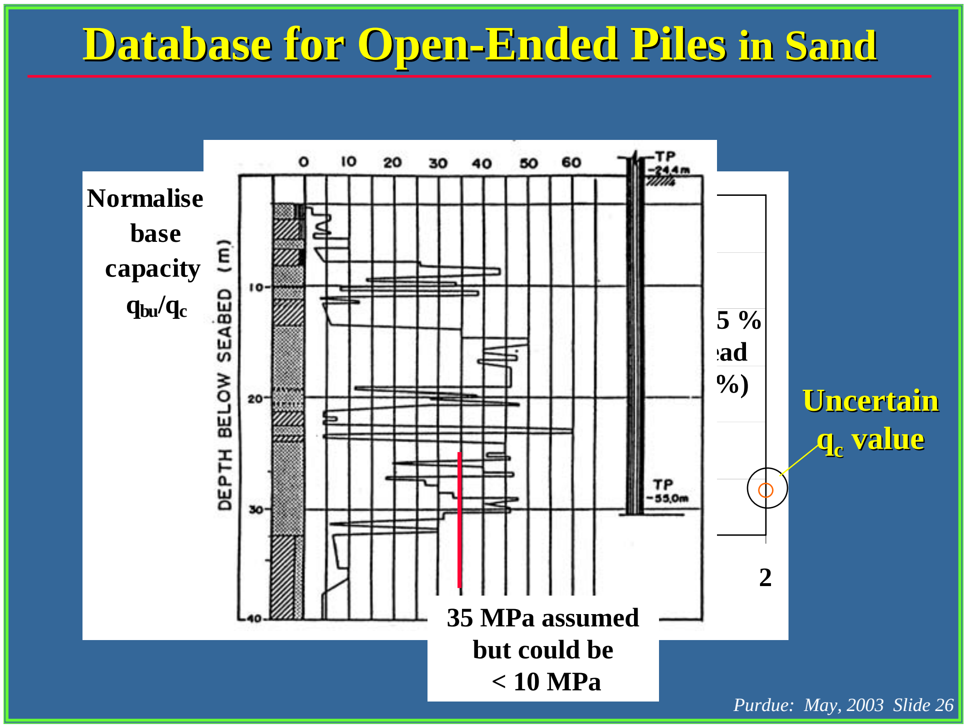

Database for Open-Ended Piles in Sand

Uncertain q_c value

35 MPa assumed but could be < 10 MPa

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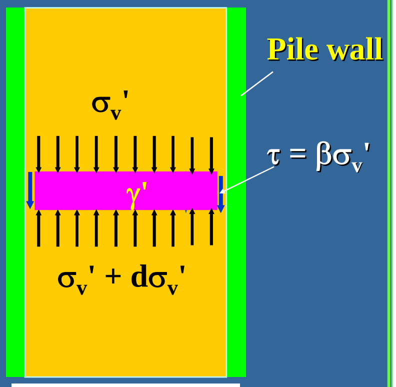
Base Capacity for Open-Ended Piles

- **Plugging of open pile**
  - arching in pile leads to potentially high internal friction
  - moderate soil plug lengths (h_p/d_i) sufficient for high q_{plug}
- **Deformation controlled by:**
  - residual stresses induced in soil plug
  - densification below pile tip



$$\frac{q_{plug}}{\sigma'_{vtip}} \le e^{4\beta h_p / d_i}$$

β_{min} ~ 0.15 – 0.2

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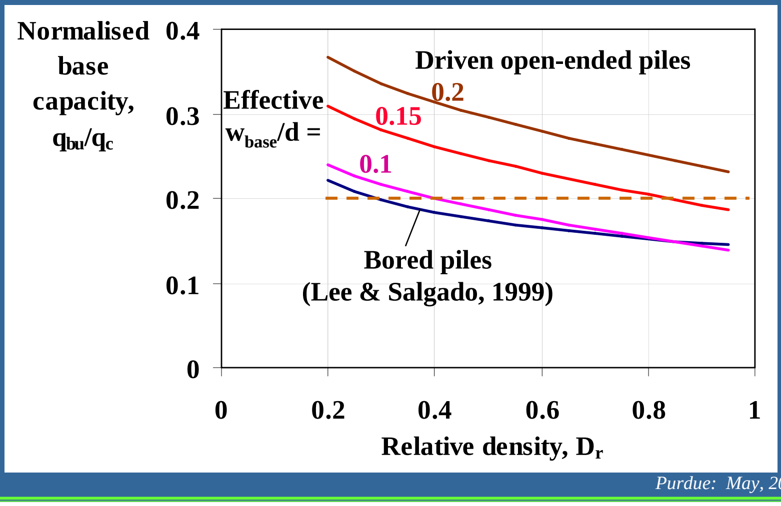
Design Base Capacity for Open-Ended Piles

Lehane & Randolph (2001):

- Combining compression in soil plug and below pile base
- Adding load from soil plug and pile annulus



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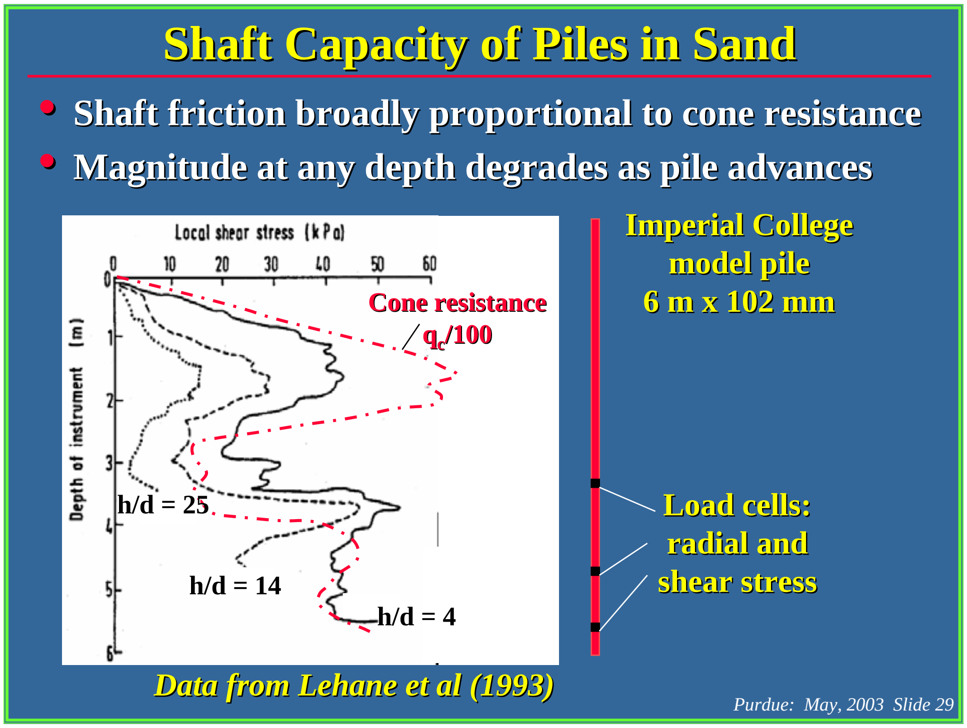


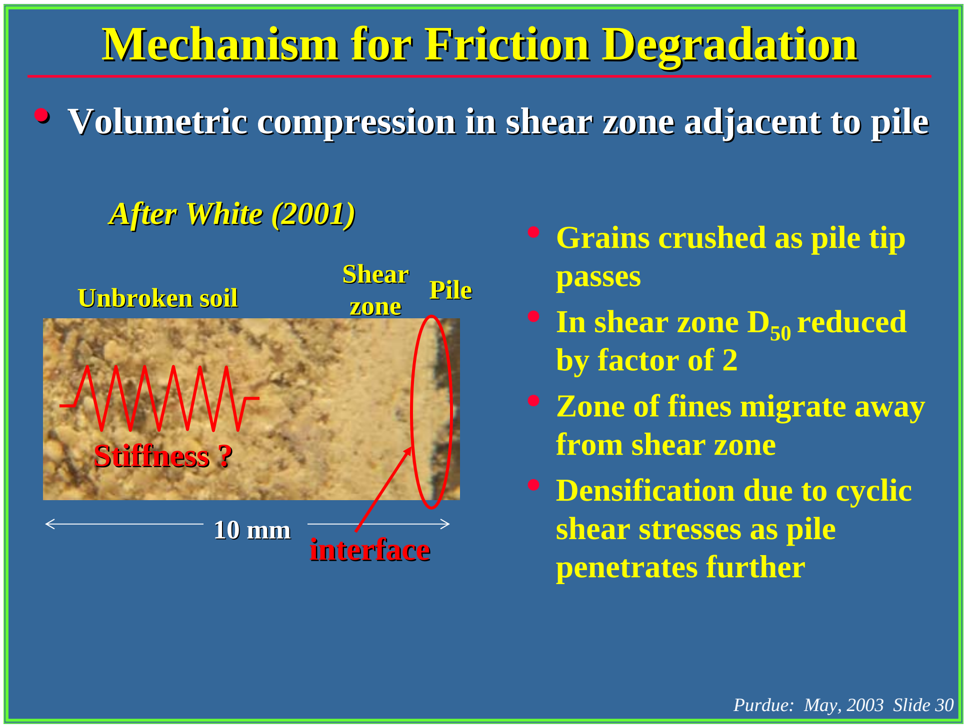
Shaft Capacity of Piles in Sand

- Shaft friction broadly proportional to cone resistance
- Magnitude at any depth degrades as pile advances

Imperial College model pile 6 m x 102 mm

Load cells: radial and shear stress

Data from Lehane et al (1993)



Mechanism for Friction Degradation

- Volumetric compression in shear zone adjacent to pile

After White (2001)

- Grains crushed as pile tip passes
- In shear zone D_{50} reduced by factor of 2
- Zone of fines migrate away from shear zone
- Densification due to cyclic shear stresses as pile penetrates further

Models for Shaft Friction

Loading in Compression

- **Imperial College: MTD** (Jardine & Chow, 1996)

$$\tau_s = \left(\frac{q_c}{45} \left(\frac{\sigma'_{vo}}{p_a} \right)^{0.13} \left(\frac{d}{h} \right)^{0.38} + \Delta\sigma'_{rd} \right) \tan\delta_{cv}$$

Dilation during shearing

  - open-ended piles: replace d by d_{equiv}

- **Exponential decay** (e.g. Randolph et al, 1994)

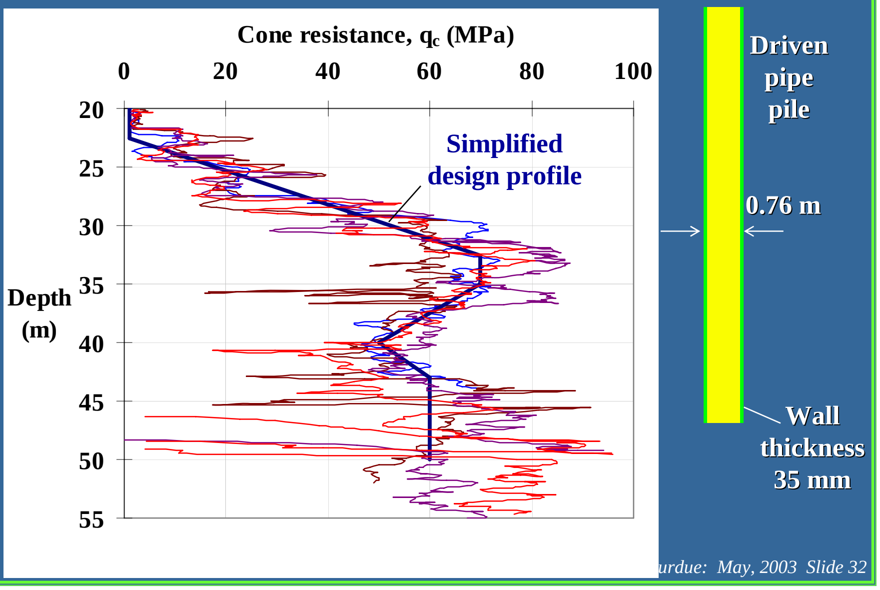
$$\tau_s = \left(K_{min} + \left(K_{max} - K_{min} \right) e^{-\mu h / d} \right) \sigma'_{vo} \tan\delta_{cv}$$

where $K_{min} \sim 0.3$; $K_{max} \sim 1$ to $2\ \%$ of q_c/σ'_{vo} ; $\mu \sim 0.05$ to 0.1

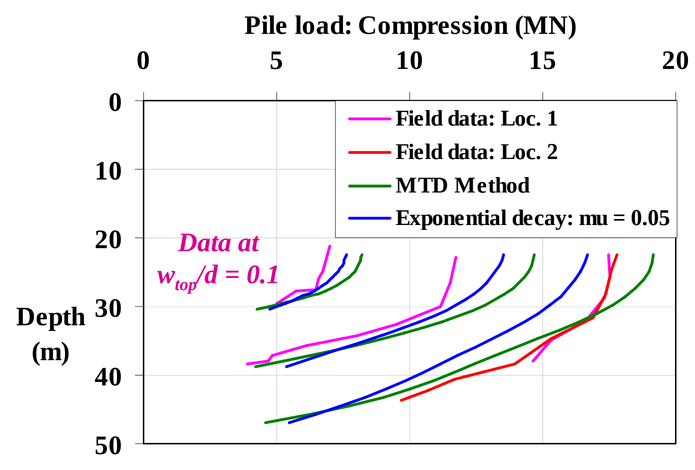
  - open-ended piles: reduce K_{max}

Euripides Pile Test

- Major joint industry-sponsored instrumented pile test



Load Profiles from Euripides Pile Test



- Computed load profiles range above and below data
- Measured tension/compression shaft friction: 0.6 to 0.9

Summary: Pile Capacity in Sand

Science

- Conceptual models
  - *weighting of q_c*
  - *estimation and allowance for residual loads*
  - *diameter independence*
  - friction degradation
- Open-ended piles
  - soil plug mechanics

Empiricism

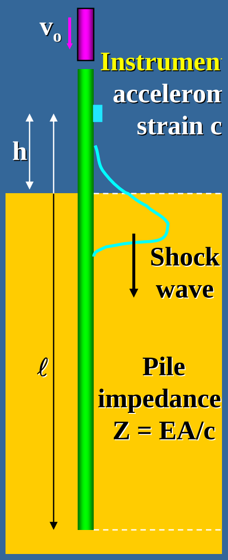
- Correlations
  - base capacity with q_c
  - *diameter dependence*
  - maximum shaft friction with q_c
  - rate of degradation of shaft friction with h/d

- Conservatisms
  - strain-hardening base response: plunging $q_b \sim q_c$
  - increase in shaft capacity with time (50 to 100 % gain)

Dynamic Pile Testing

- Uncertainty in pile capacity necessitates reliance on load testing of piles
  - static load testing (external or internal reaction)
  - dynamic load testing (~1 % of cost of static load testing)
  - Statnamic (fast load test using accelerated reaction mass)
- Interpretation of dynamic pile testing
  - 'continuum' model of dynamic pile-soil interaction to replace empirical model of Smith (1960)
  - explicit modelling of soil plug in open-ended piles

Principles of Dynamic Pile Testing



Computer Simulation

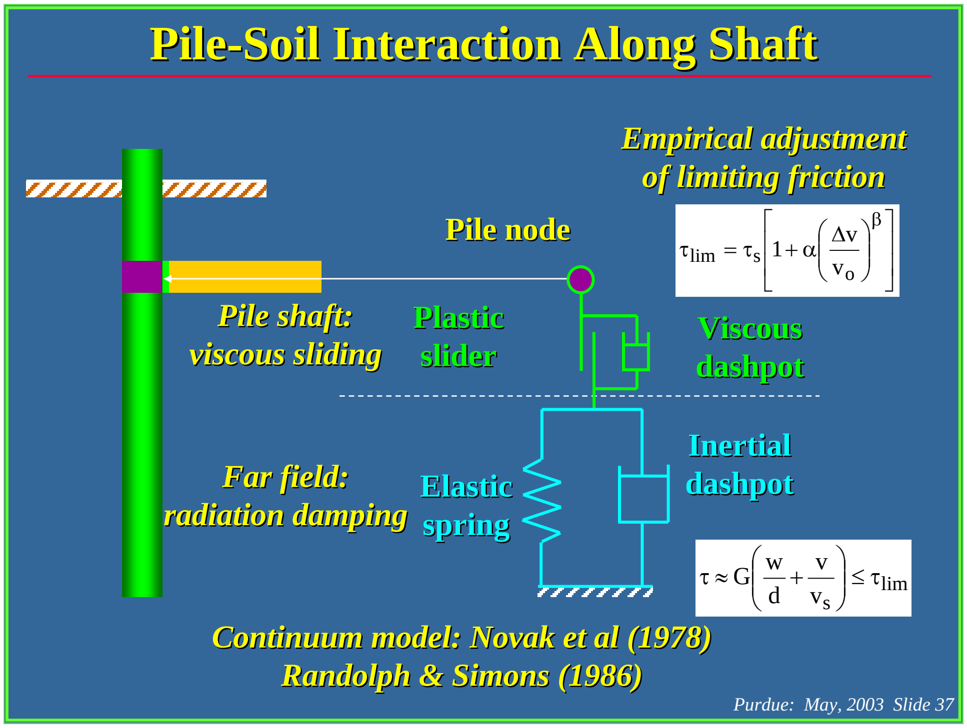
- Measured Force (F) and velocity (v)
  - factor velocity to give "force", Zv
  - downward travelling wave:

$$F_d = 0.5(F + Zv)$$

  - upward (reflected) wave:

$$F_u = 0.5(F - Zv)$$

- Simulation: downward wave as input
  - aim to match computed and measured upward waves
  - adjust soil parameters to optimise match



Pile-Soil Interaction Along Shaft

Empirical adjustment of limiting friction

$$\tau_{lim} = \tau_s\left[1+\alpha\left(\frac{\Delta v}{v_o}\right)^{\beta}\right]$$

Pile node

Pile shaft: viscous sliding

Plastic slider

Viscous dashpot

Far field: radiation damping

Elastic spring

Inertial dashpot

$$\tau \approx G\left(\frac{w}{d}+\frac{v}{v_s}\right) \le \tau_{lim}$$

Continuum model: Novak et al (1978)
Randolph & Simons (1986)

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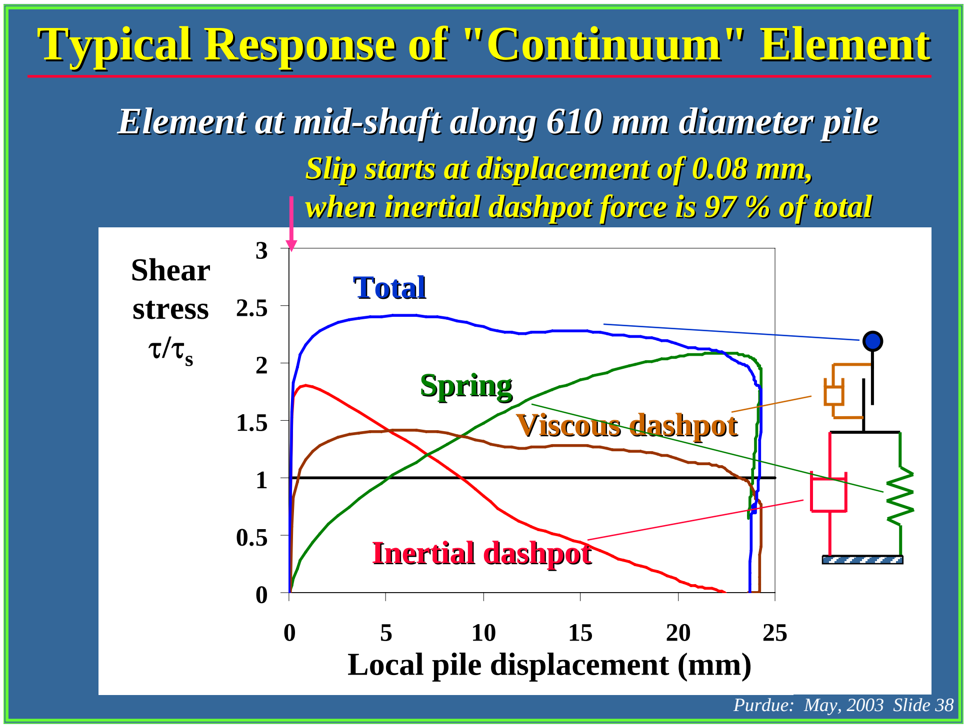

Typical Response of "Continuum" Element

Element at mid-shaft along 610 mm diameter pile

Slip starts at displacement of 0.08 mm,
when inertial dashpot force is 97 % of total

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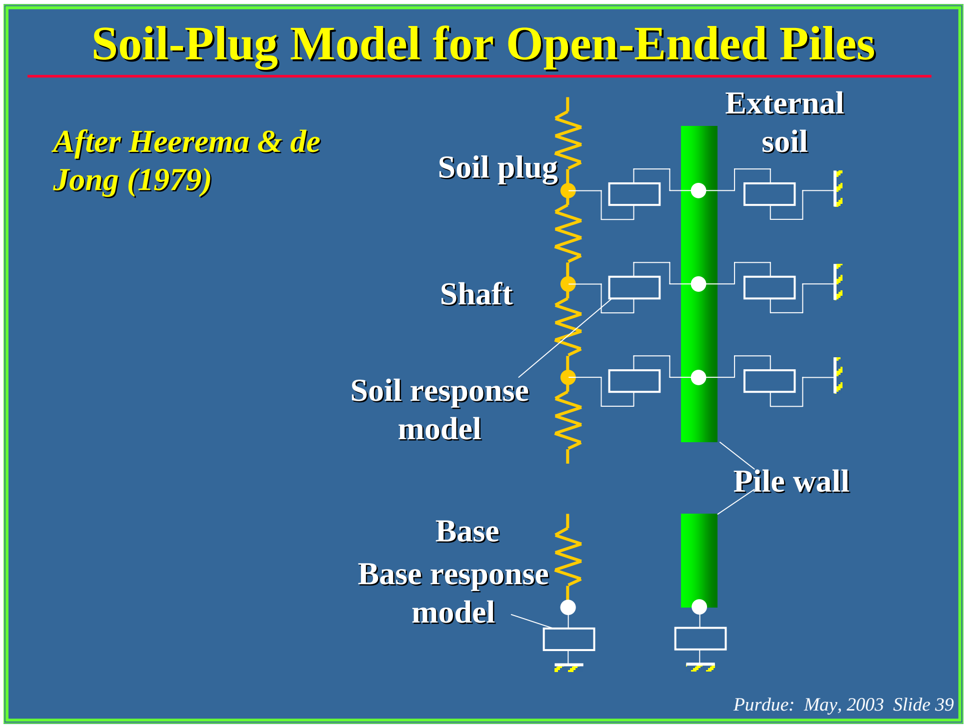


Soil-Plug Model for Open-Ended Piles

After Heerema & de Jong (1979)

External soil

Soil plug

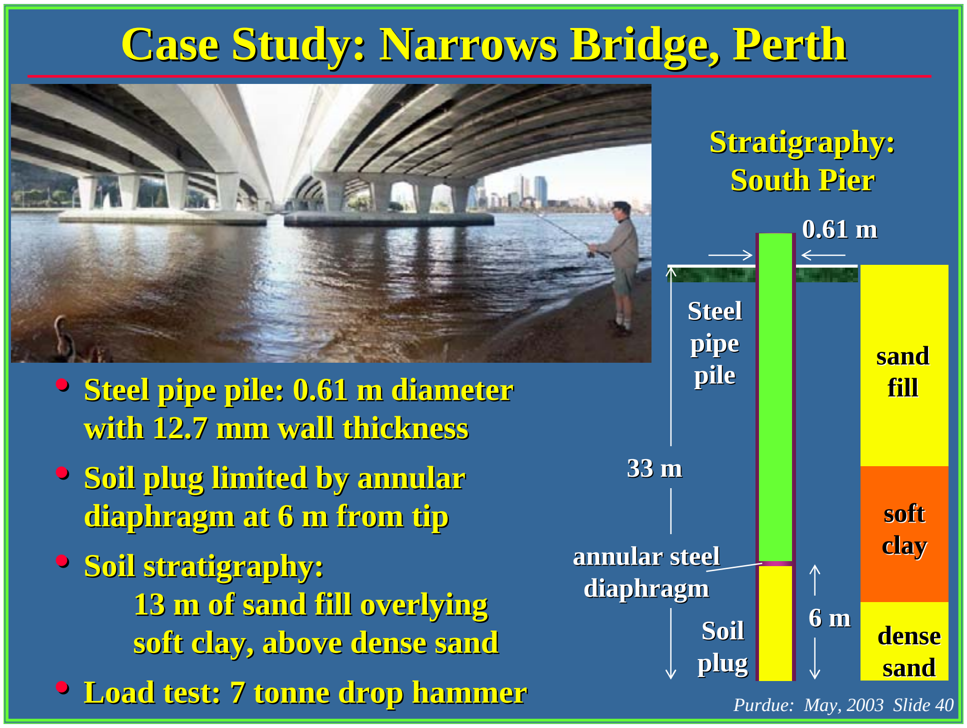
Shaft

Soil response model

Pile wall

Base

Base response model



Case Study: Narrows Bridge, Perth

- Steel pipe pile: 0.61 m diameter with 12.7 mm wall thickness
- Soil plug limited by annular diaphragm at 6 m from tip
- Soil stratigraphy:
  13 m of sand fill overlying soft clay, above dense sand
- Load test: 7 tonne drop hammer

Stratigraphy: South Pier

0.61 m

Steel pipe pile

33 m

annular steel diaphragm

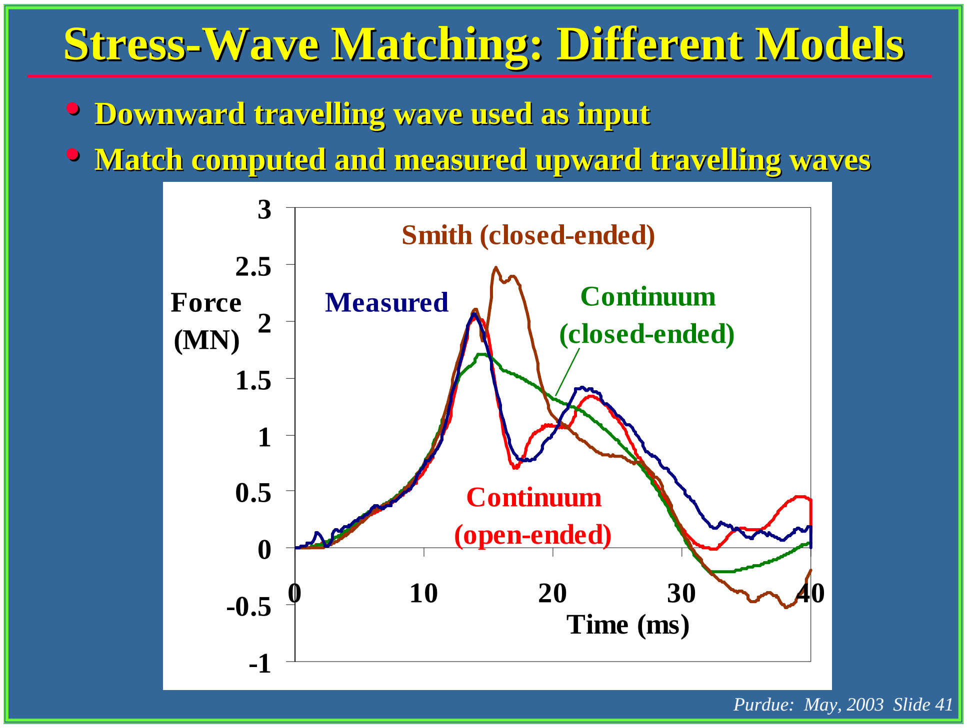
Soil plug

6 m

sand fill

soft clay

dense sand



Stress-Wave Matching: Different Models

- Downward travelling wave used as input
- Match computed and measured upward travelling waves

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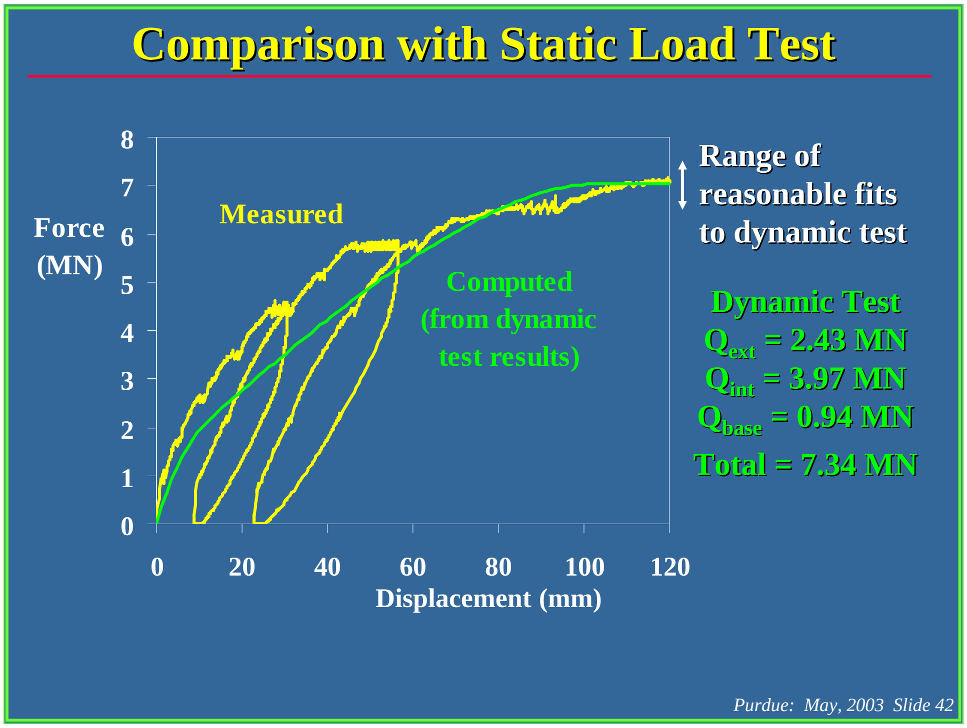

Comparison with Static Load Test

Range of reasonable fits to dynamic test

Dynamic Test

Q_{ext} = 2.43 MN

Q_{int} = 3.97 MN

Q_{base} = 0.94 MN

Total = 7.34 MN

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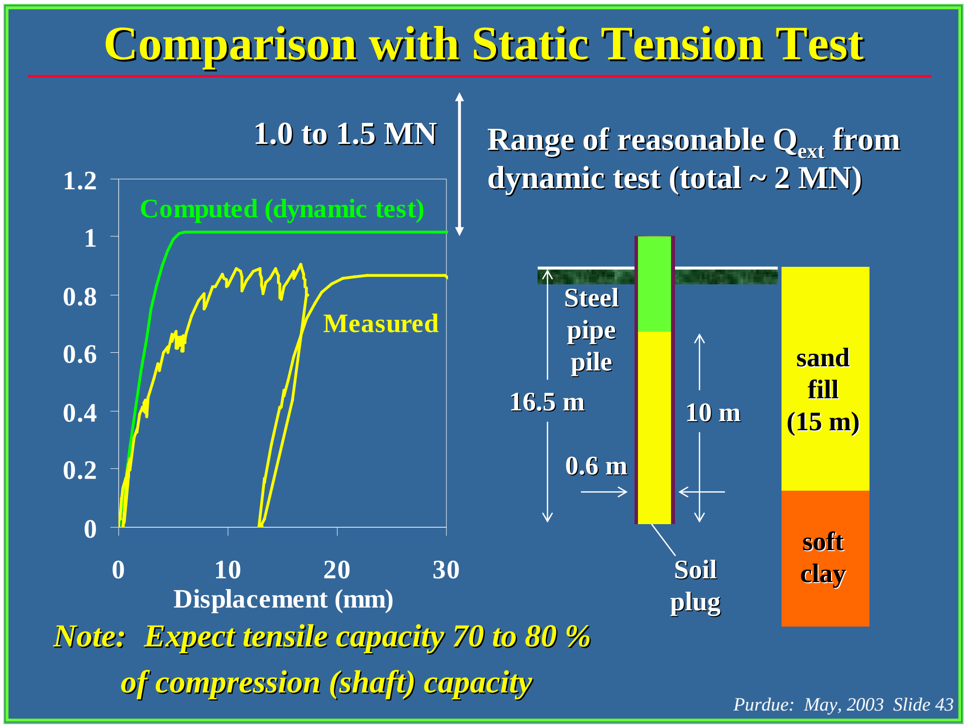
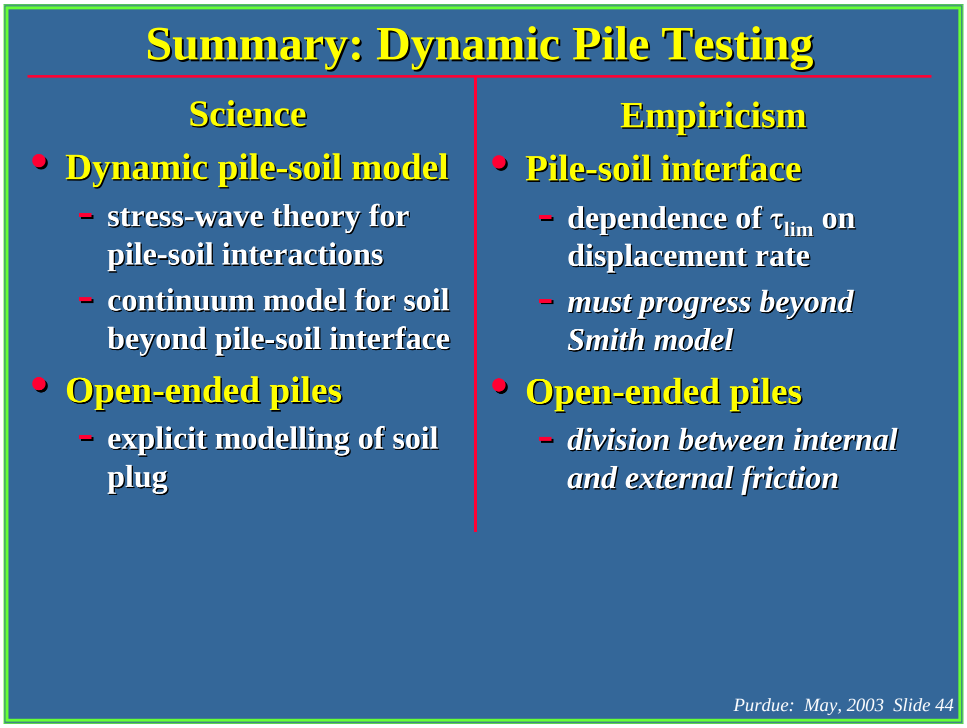


Comparison with Static Tension Test

Range of reasonable Q_{ext} from dynamic test (total ~ 2 MN)

Note: Expect tensile capacity 70 to 80 % of compression (shaft) capacity



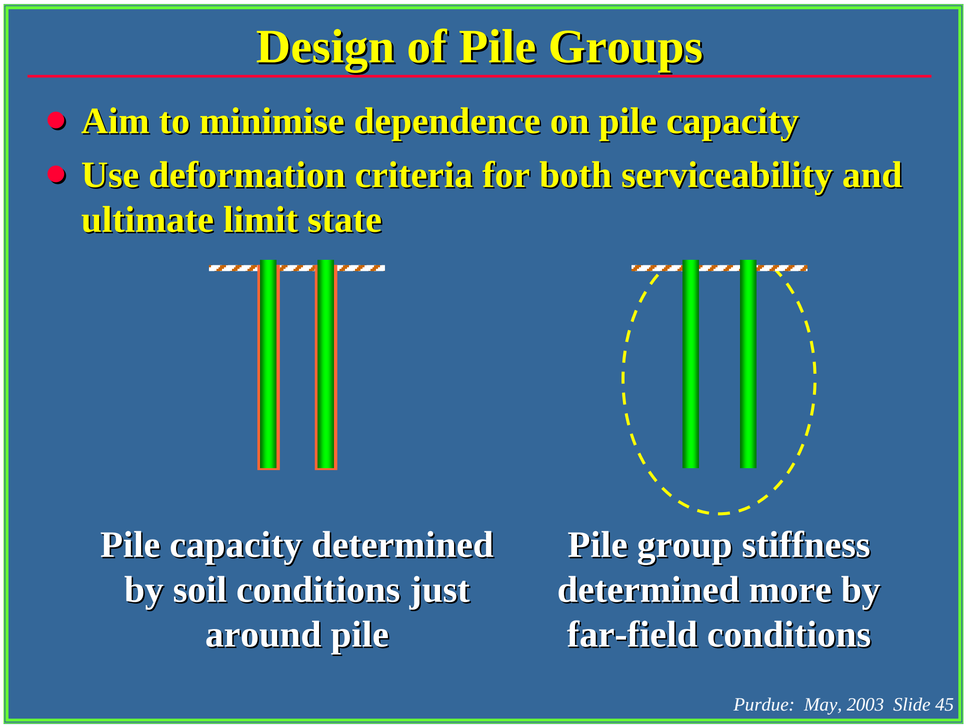
Summary: Dynamic Pile Testing

Science

- Dynamic pile-soil model
  - stress-wave theory for pile-soil interactions
  - continuum model for soil beyond pile-soil interface
- Open-ended piles
  - explicit modelling of soil plug

Empiricism

- Pile-soil interface
  - dependence of τ_{lim} on displacement rate
  - *must progress beyond Smith model*
- Open-ended piles
  - *division between internal and external friction*

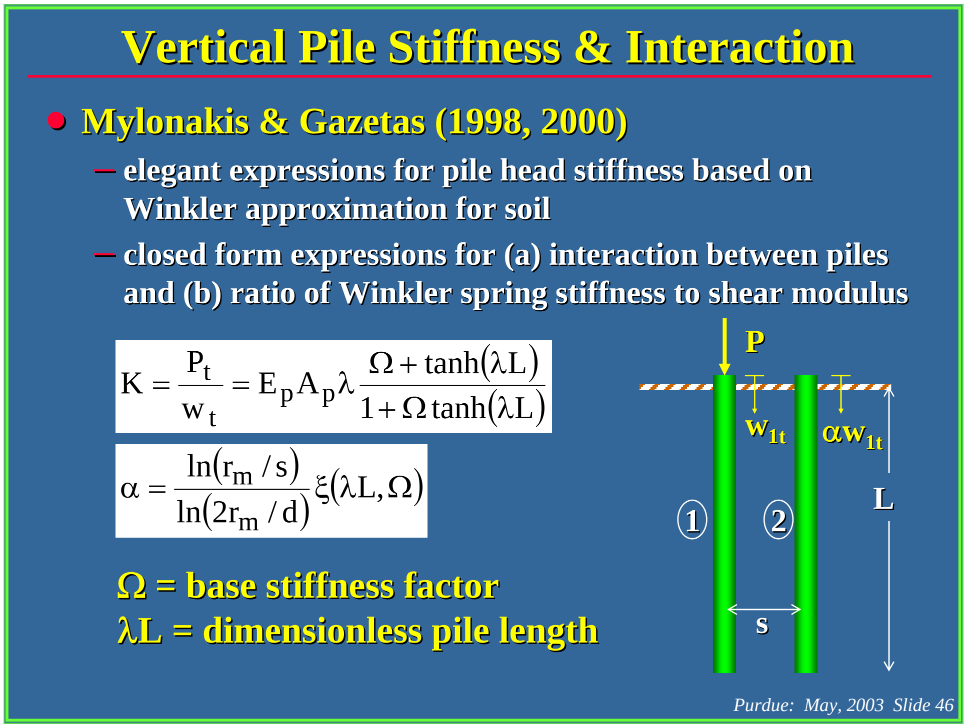


Design of Pile Groups

- Aim to minimise dependence on pile capacity
- Use deformation criteria for both serviceability and ultimate limit state

Pile capacity determined by soil conditions just around pile

Pile group stiffness determined more by far-field conditions



Vertical Pile Stiffness & Interaction

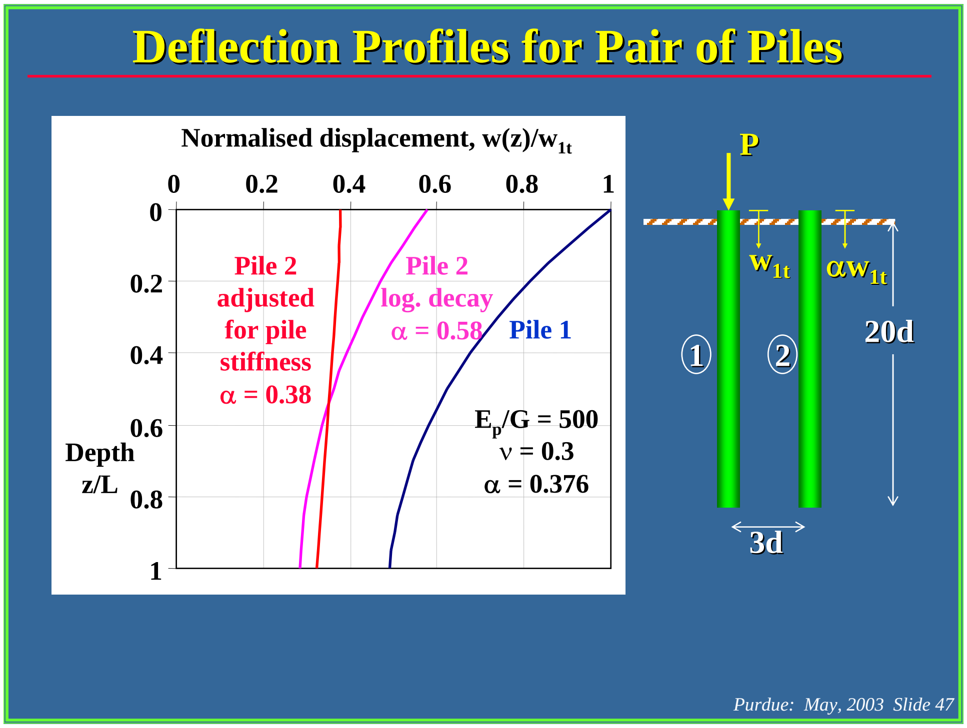
- Mylonakis & Gazetas (1998, 2000)
  - elegant expressions for pile head stiffness based on Winkler approximation for soil
  - closed form expressions for (a) interaction between piles and (b) ratio of Winkler spring stiffness to shear modulus

$$K = \frac{P_t}{w_t} = E_p A_p \lambda \frac{\Omega + \tanh(\lambda L)}{1 + \Omega \tanh(\lambda L)}$$

$$\alpha = \frac{\ln(r_m / s)}{\ln(2 r_m / d)} \xi(\lambda L, \Omega)$$

Ω = base stiffness factor

λL = dimensionless pile length



Deflection Profiles for Pair of Piles

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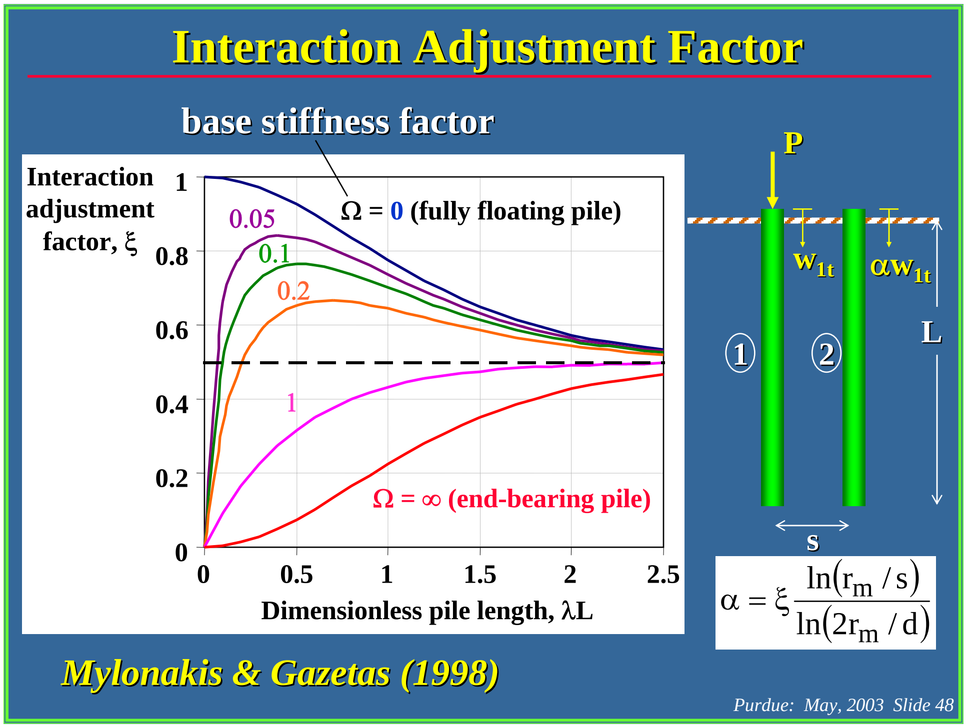

Interaction Adjustment Factor

$$\alpha = \xi \frac{\ln(r_m / s)}{\ln(2r_m / d)}$$

Mylonakis & Gazetas (1998)

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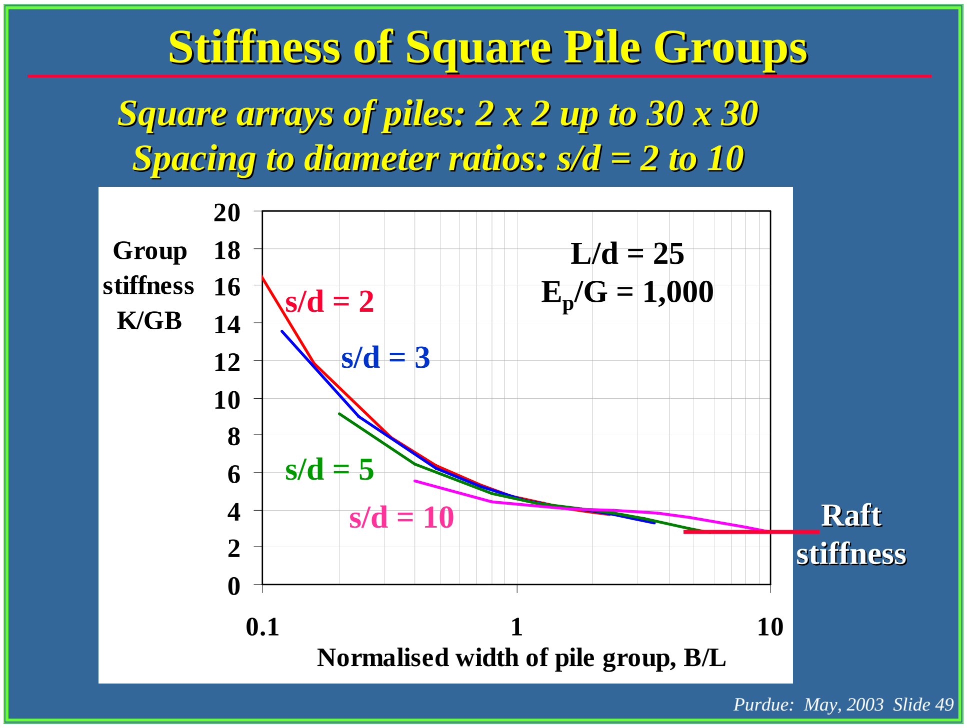

Stiffness of Square Pile Groups

Square arrays of piles: 2 x 2 up to 30 x 30
Spacing to diameter ratios: s/d = 2 to 10

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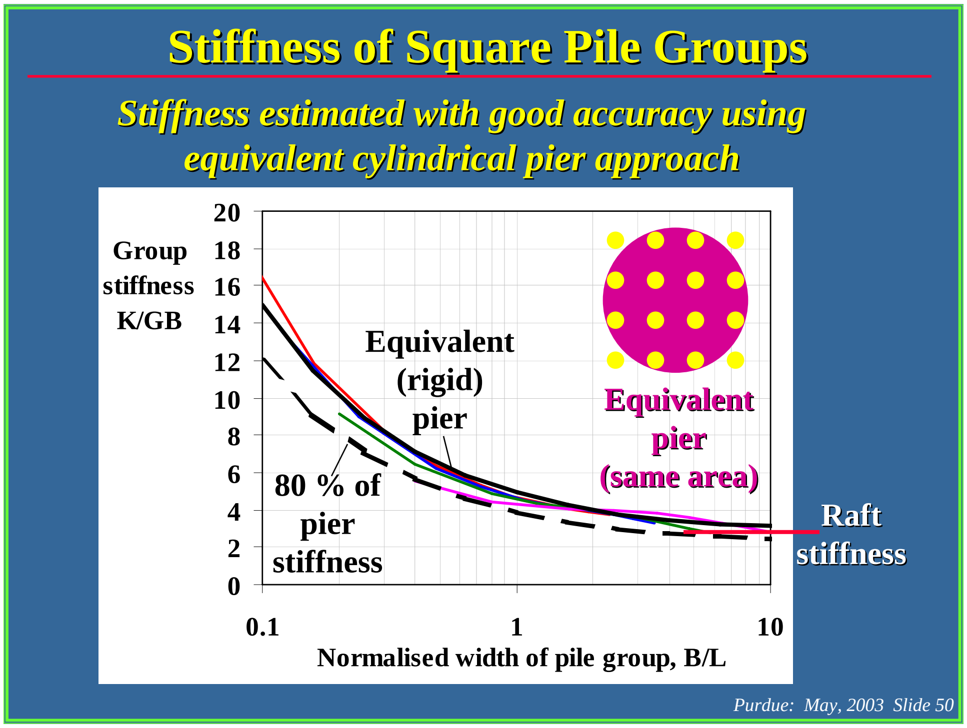

Stiffness of Square Pile Groups

Stiffness estimated with good accuracy using equivalent cylindrical pier approach

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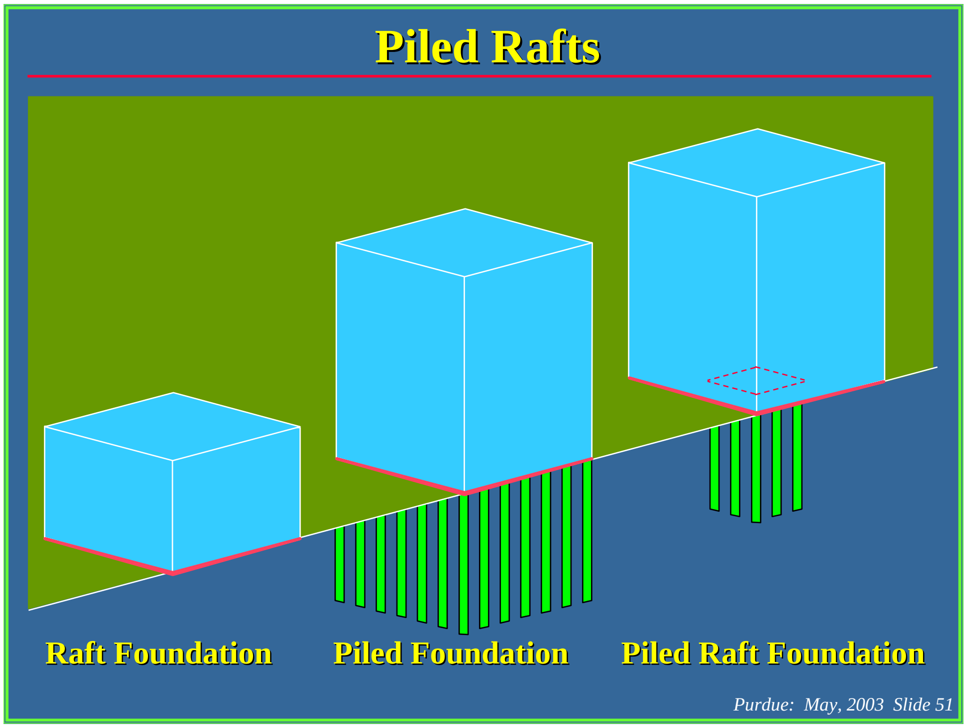
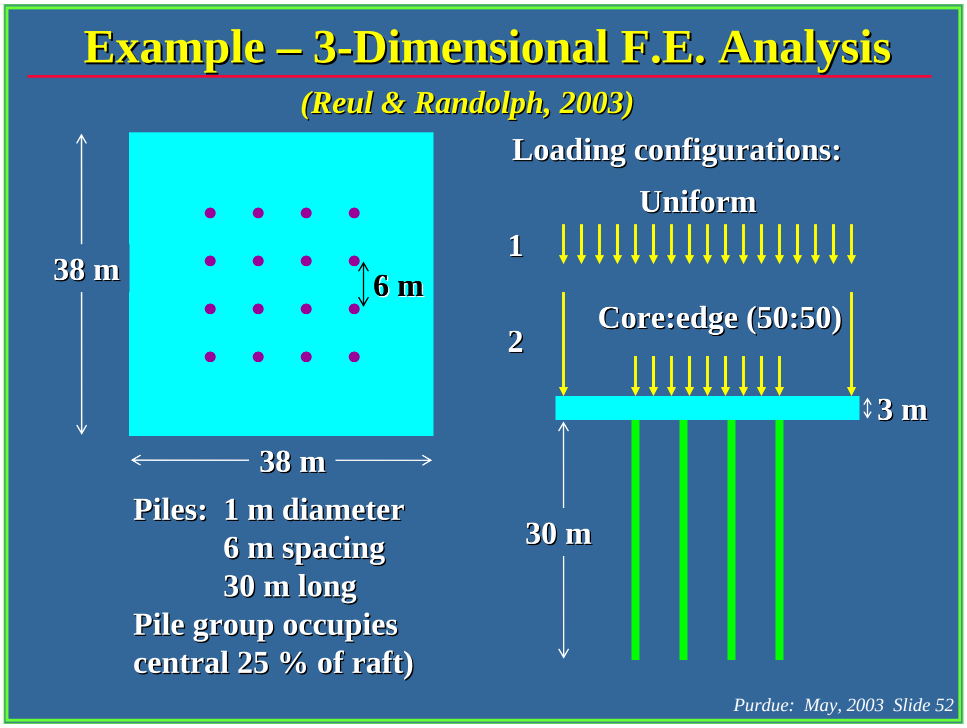


Piled Rafts

Raft Foundation **Piled Foundation** **Piled Raft Foundation**

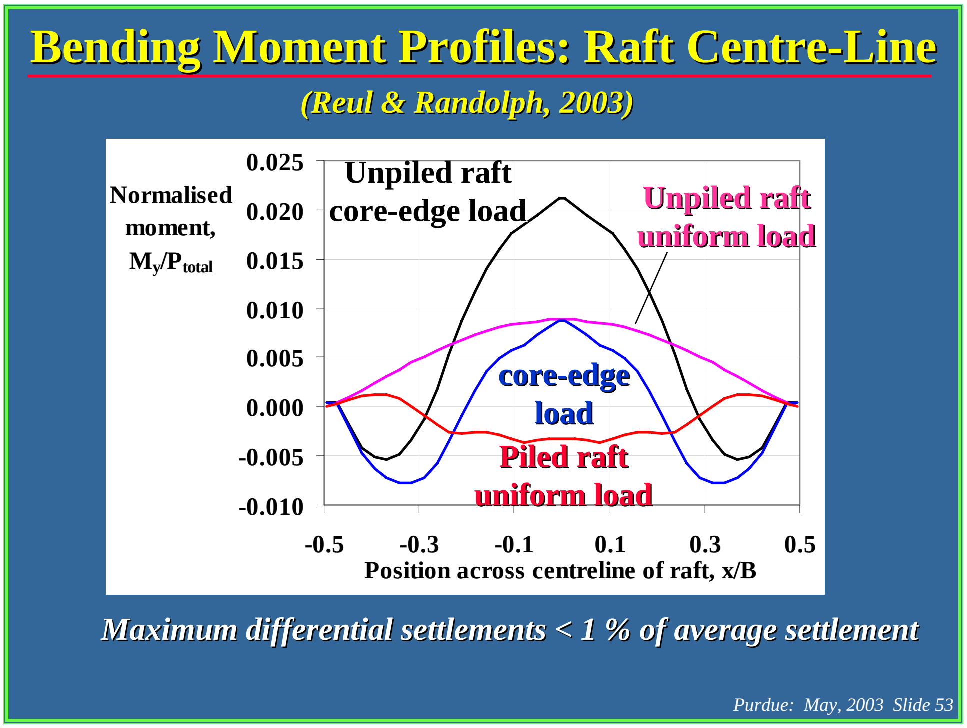


Example – 3-Dimensional F.E. Analysis

(Reul & Randolph, 2003)

Piles: 1 m diameter
6 m spacing
30 m long
Pile group occupies
central 25 % of raft)

Loading configurations:



Bending Moment Profiles: Raft Centre-Line

(Reul & Randolph, 2003)

Maximum differential settlements < 1 % of average settlement

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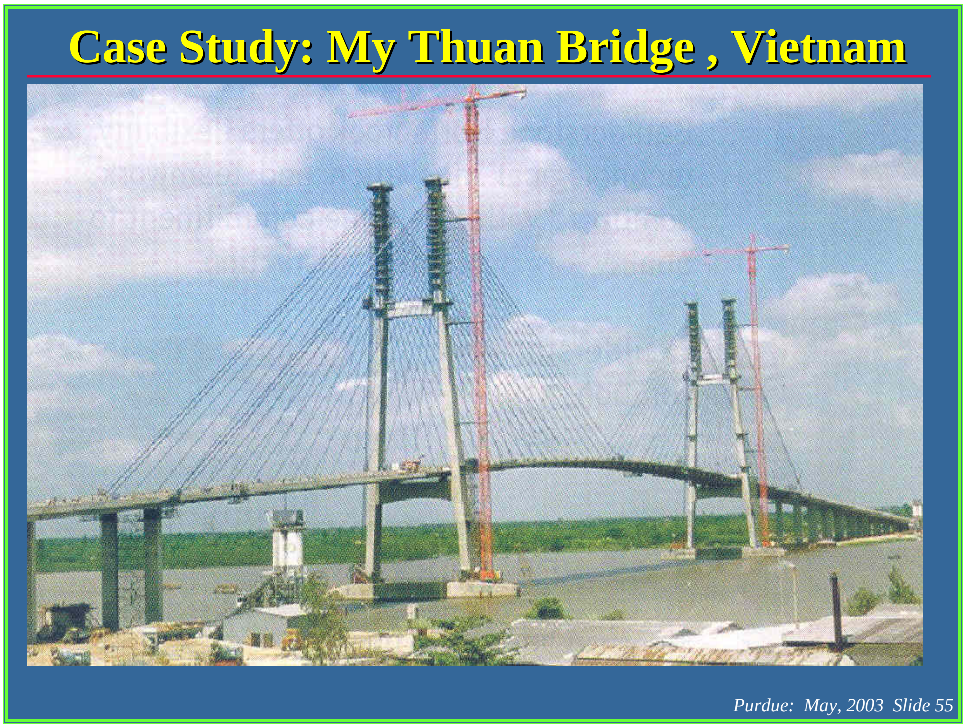

Case Study: My Thuan Bridge , Vietnam

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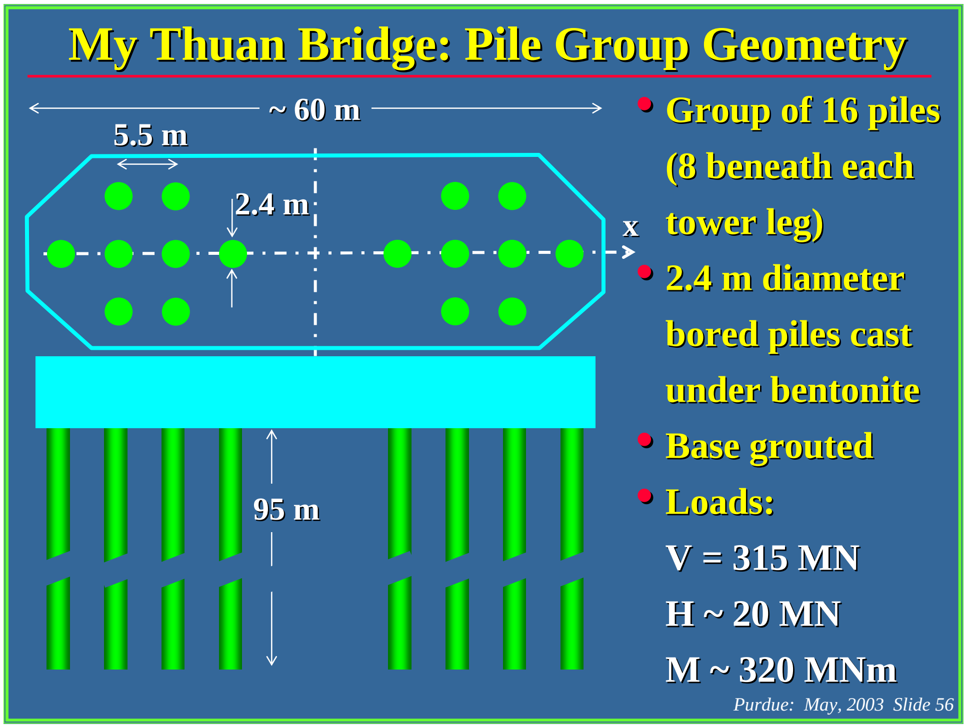

My Thuan Bridge: Pile Group Geometry

- Group of 16 piles (8 beneath each tower leg)
- 2.4 m diameter bored piles cast under bentonite
- Base grouted
- Loads:

  V = 315 MN

  H ~ 20 MN

  M ~ 320 MNm

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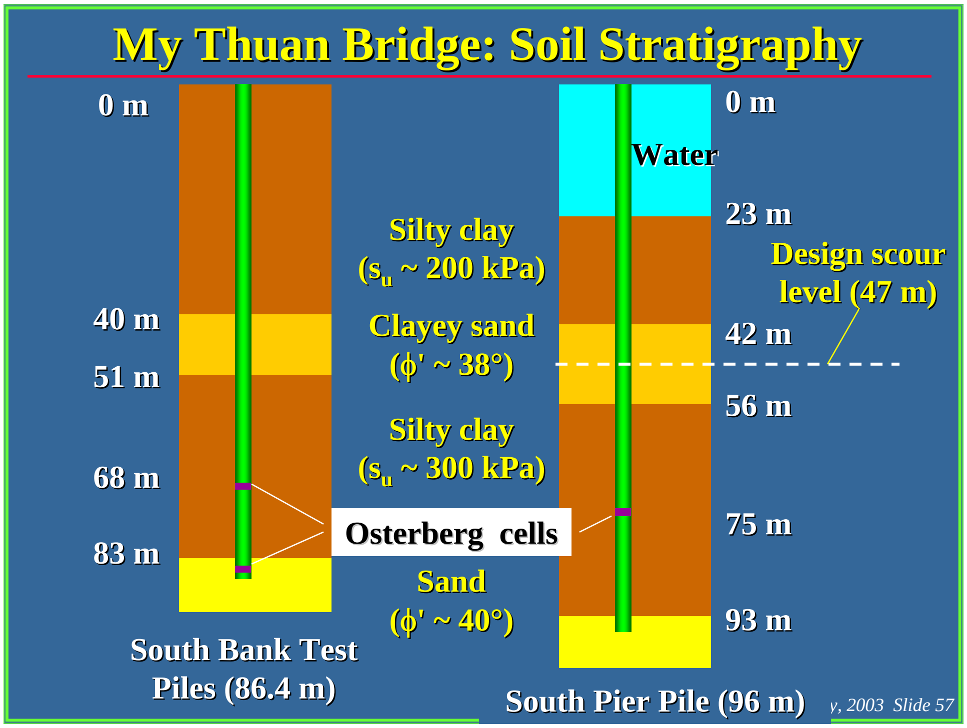

My Thuan Bridge: Soil Stratigraphy

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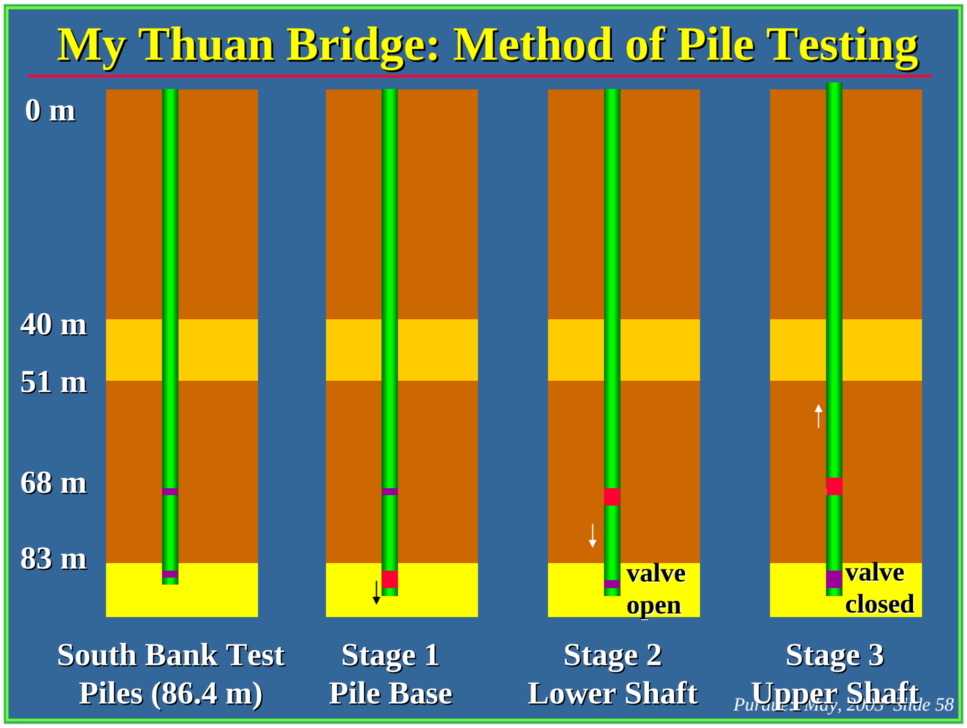

My Thuan Bridge: Method of Pile Testing

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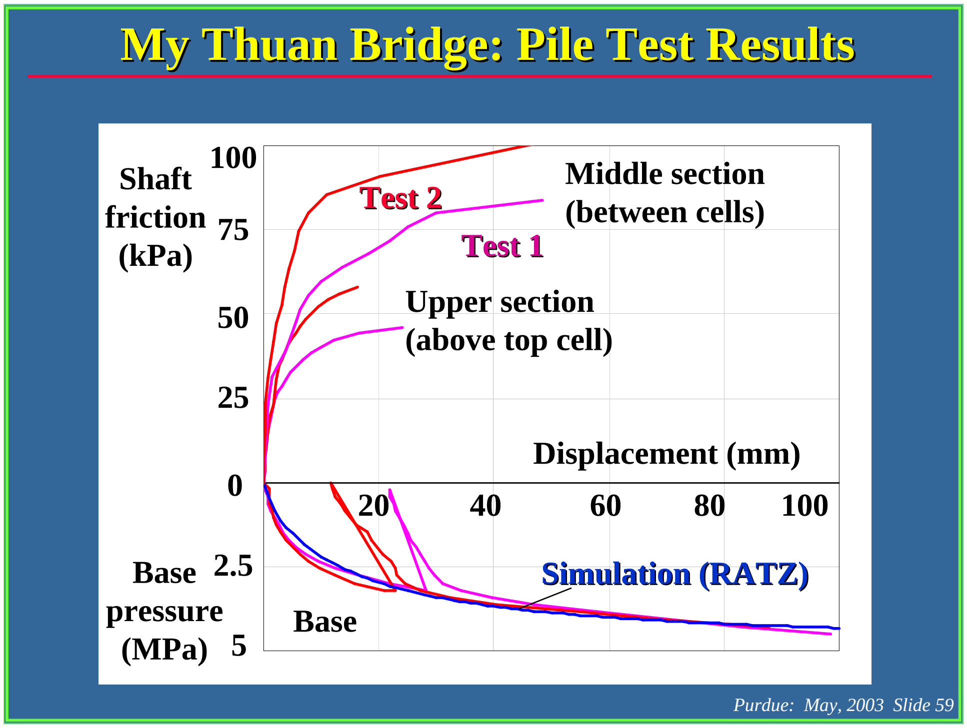

My Thuan Bridge: Pile Test Results

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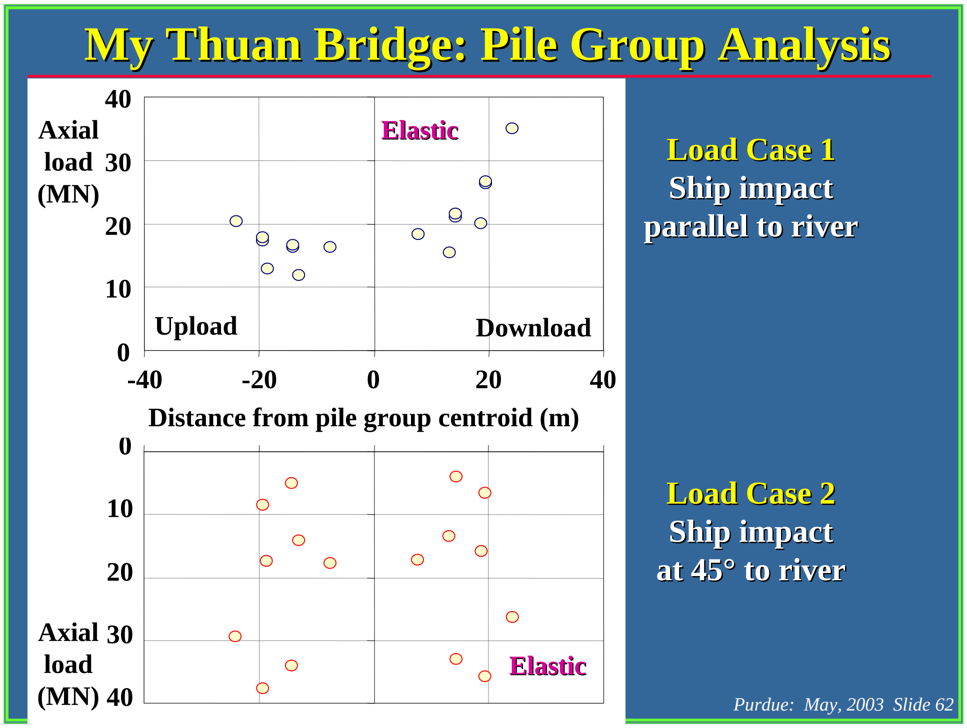
My Thuan Bridge: Construction Issues

- **First test pile showed low friction**
  - significant delay between excavation and concreting
  - questionable bentonite quality (and suspected caking)
- **Improvements:**
  - reduced delay between excavation and concreting
  - improved bentonite quality control and reduce head to 1.5 m above river level
  - wire brush used to scarify shaft edges prior to concreting

My Thuan Bridge: Pile Group Design

- **Test pile load tests (twin Osterberg cells):**
  - shaft friction of 55 kPa (upper) to 90 kPa (lower soils)
  - end-bearing pressure of 4.5 MPa
- **Design conditions assume scour of 47 m**
- **Resulting pile capacity:**
  - ultimate capacity of 34.6 MN
  - factored design capacity of 0.72 x 34.6 = 24.9 MN
- **Load tests on Tower piles (single Osterberg cells):**
  - maximum loads of 26 and 27 MN (failing upper 75 m section of pile)
  - no creep displacements of lower section, confirming actual capacity in excess of 30 MN



My Thuan Bridge: Pile Group Analysis

Load Case 1
Ship impact
parallel to river

Load Case 2
Ship impact
at 45° to river

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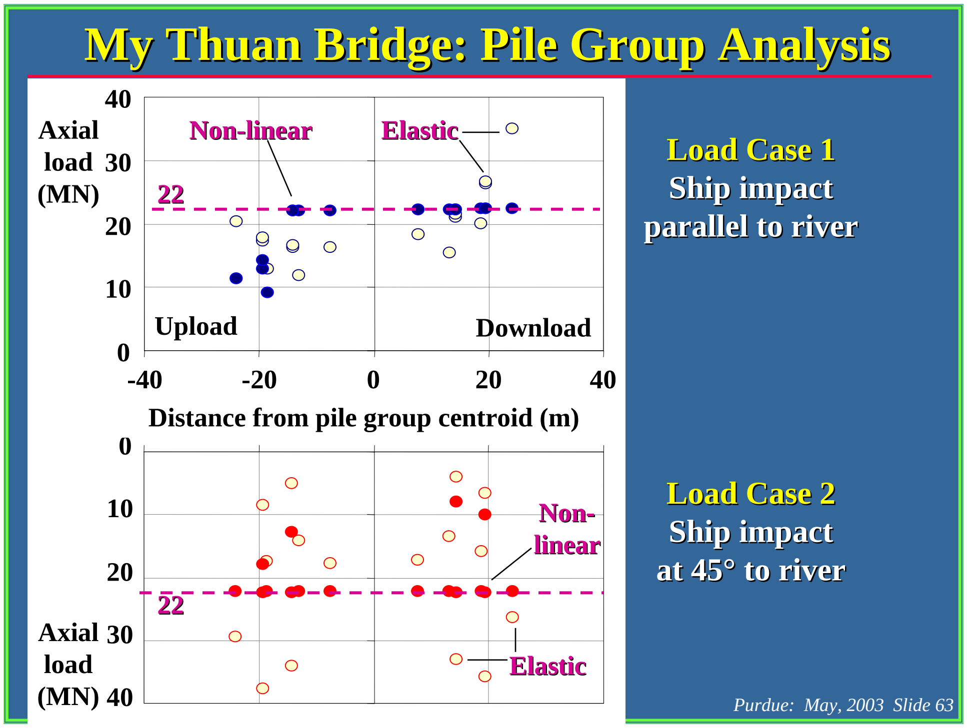

My Thuan Bridge: Pile Group Analysis

Load Case 1
Ship impact
parallel to river

Load Case 2
Ship impact
at 45° to river

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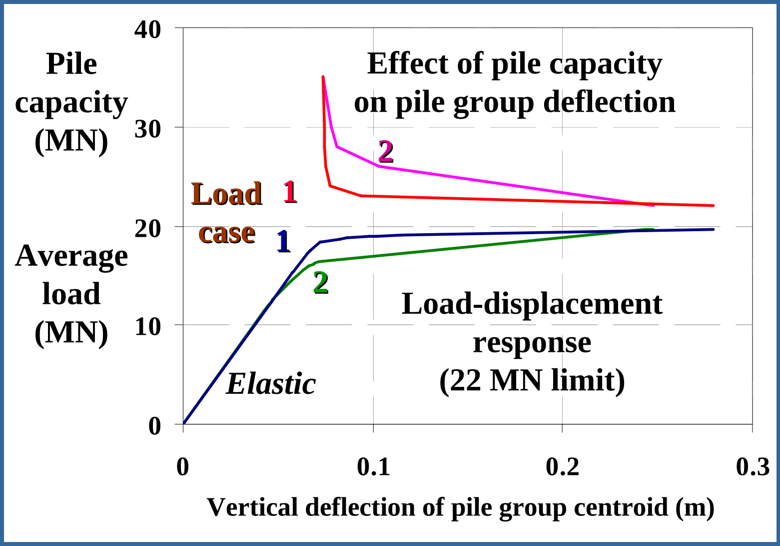
My Thuan Bridge: Non-linear Response



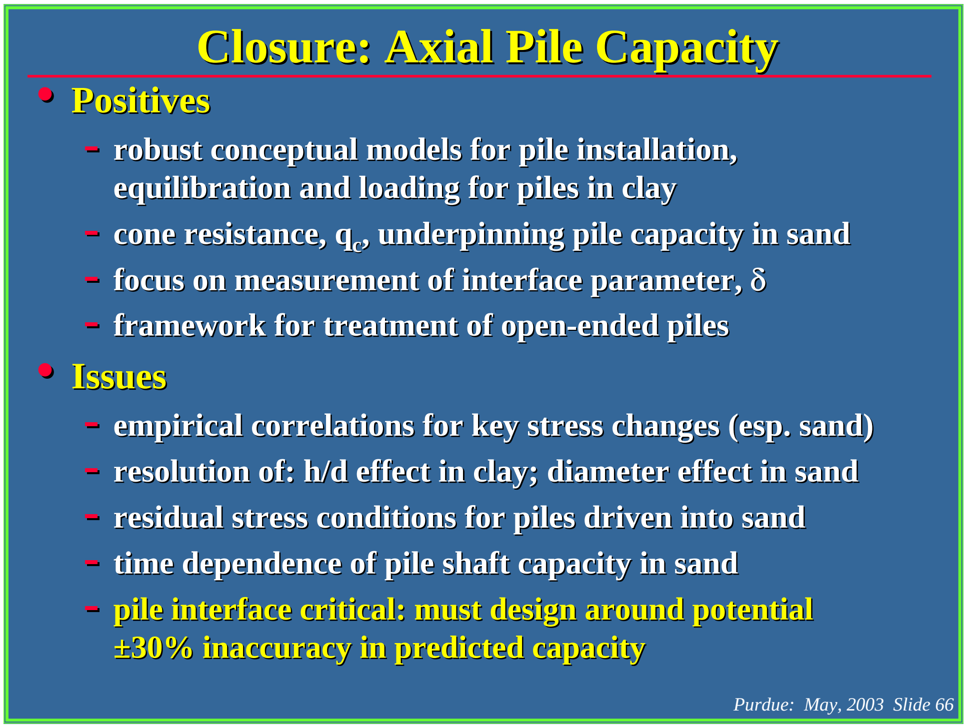
Summary: Pile Group Design

Science

- Settlement of piles
  - simple but effective elastic analytical solutions
  - robust analogue models such as equivalent pier
  - *piled rafts offer a major benefit*
- General loading
  - redistribution of load essential to compensate for elastic extremes

Empiricism

- Soil stiffness
  - geophysical methods to measure shear modulus, G_o
- Rôle of pile testing
  - observational design approach
  - full load-settlement response used in design



Closure: Axial Pile Capacity

- Positives
  - robust conceptual models for pile installation, equilibration and loading for piles in clay
  - cone resistance, q_c, underpinning pile capacity in sand
  - focus on measurement of interface parameter, δ
  - framework for treatment of open-ended piles
- Issues
  - empirical correlations for key stress changes (esp. sand)
  - resolution of: h/d effect in clay; diameter effect in sand
  - residual stress conditions for piles driven into sand
  - time dependence of pile shaft capacity in sand
  - pile interface critical: must design around potential ±30% inaccuracy in predicted capacity

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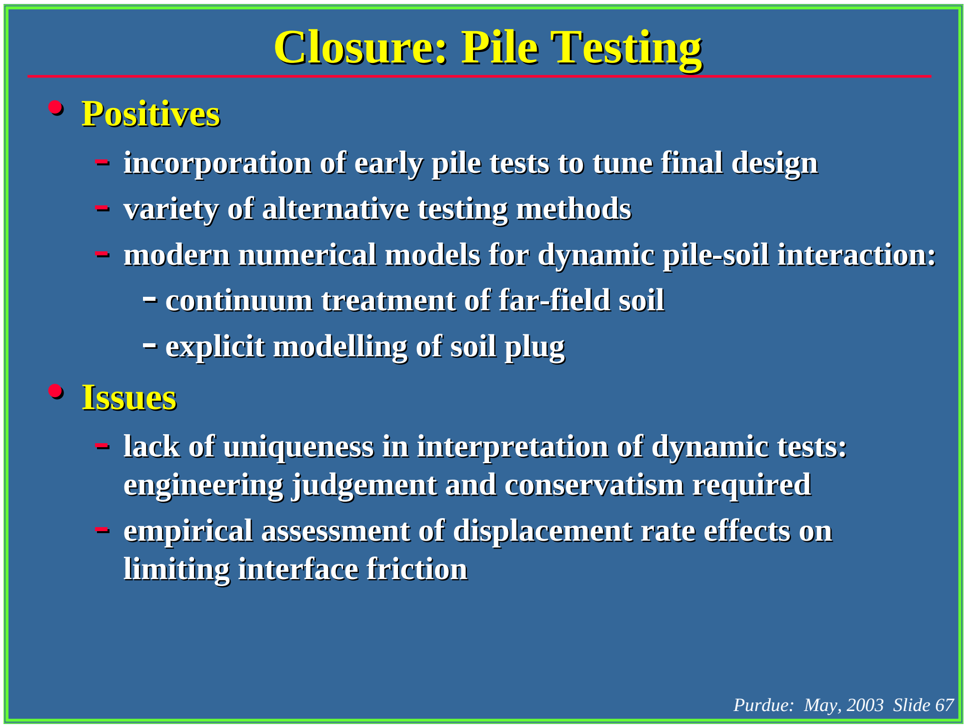

Closure: Pile Testing

- Positives
  - incorporation of early pile tests to tune final design
  - variety of alternative testing methods
  - modern numerical models for dynamic pile-soil interaction:
    - continuum treatment of far-field soil
    - explicit modelling of soil plug
- Issues
  - lack of uniqueness in interpretation of dynamic tests: engineering judgement and conservatism required
  - empirical assessment of displacement rate effects on limiting interface friction

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Closure: Pile Group Design

- **Positives**
  - analytical tools for predicting pile group and piled raft performance
  - ability to allow for non-linear pile response
  - move towards design criteria based on deformation limits
- **Issues**
  - guidelines needed for assessing soil stiffness, in particular factoring of small-strain shear modulus
  - national design codes must adapt to permit highly loaded piles beneath (primarily) raft foundations

Acknowledgements

Sincere and heartfelt thanks to many who have helped form this lecture:

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