Emerging Trends in Site Response and SSI Modeling

Juan M. Pestana
University of California, Berkeley

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Brief Overview of State-of-the-Art

- Nonlinear Site Response Analyses
  - 1-D fairly well validated. Several models available. Material characterization at different deformation levels well understood.
  - Regular incorporation of behavior near liquefaction and that of dilatant material for 1-D conditions.
  - For relatively simple models, the inverse problem (i.e., System Identification) provides a robust algorithm to obtain model parameters. Often, it results in non-stationary (i.e., time dependent) parameters.
  - Use of vertical arrays (of accelerometers) to validate methodology/ prediction power over varying range of observed response.

Brief Overview of State-of-the-Art

- Soil Structure Interaction.
  - Shallow foundation: Improvements in energy radiation and response by incorporating separation during shaking.
  - Deep Foundation: Use of relatively simple methods (elastic) for small deformations and FEM and or hybrid formulations (i.e., nonlinear Winkler Foundation and FEM) for large deformations including gapping or liquefaction response.
    - Fairly well established for 1-D Conditions (small groups)
  - For all of them, standard use of numerical procedures such as FEM, FDM (among others) to predict/estimate performance.
  - Reinforced Earth Walls and similar structures not included in this discussion- significant advancement in the last 5 years.

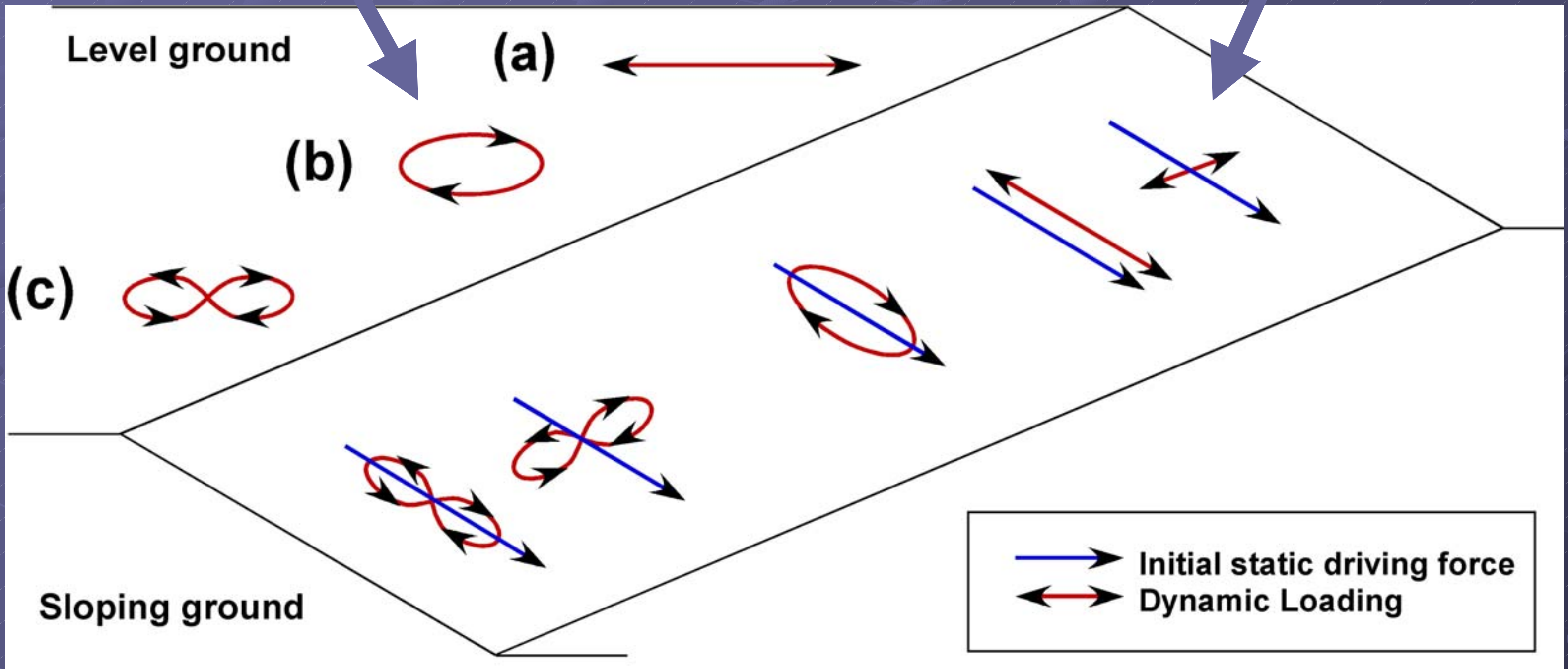
Emerging Trends

- Nonlinear Site Response Analyses
  - Recognition of the importance of stress history and multidimensional shaking on the predicted response over all levels of stress and strain. This is particularly true for liquefaction analyses and soft clayey deposits for which anisotropy plays an important role.
  - Recognition of stress level dependence, cementation in the characterization of material response. The use of more sophisticated soil models that simulate more accurately soil behavior.
  - The inverse problem (i.e., System Identification) for advanced models to obtain material parameters is much more involved. Need to develop robust and efficient methodology. Potential benefit, it may result in stationary models.

Illustration: Multidirectional Response

Ishihara & Nagase (88)

Boulanger et al. (91)

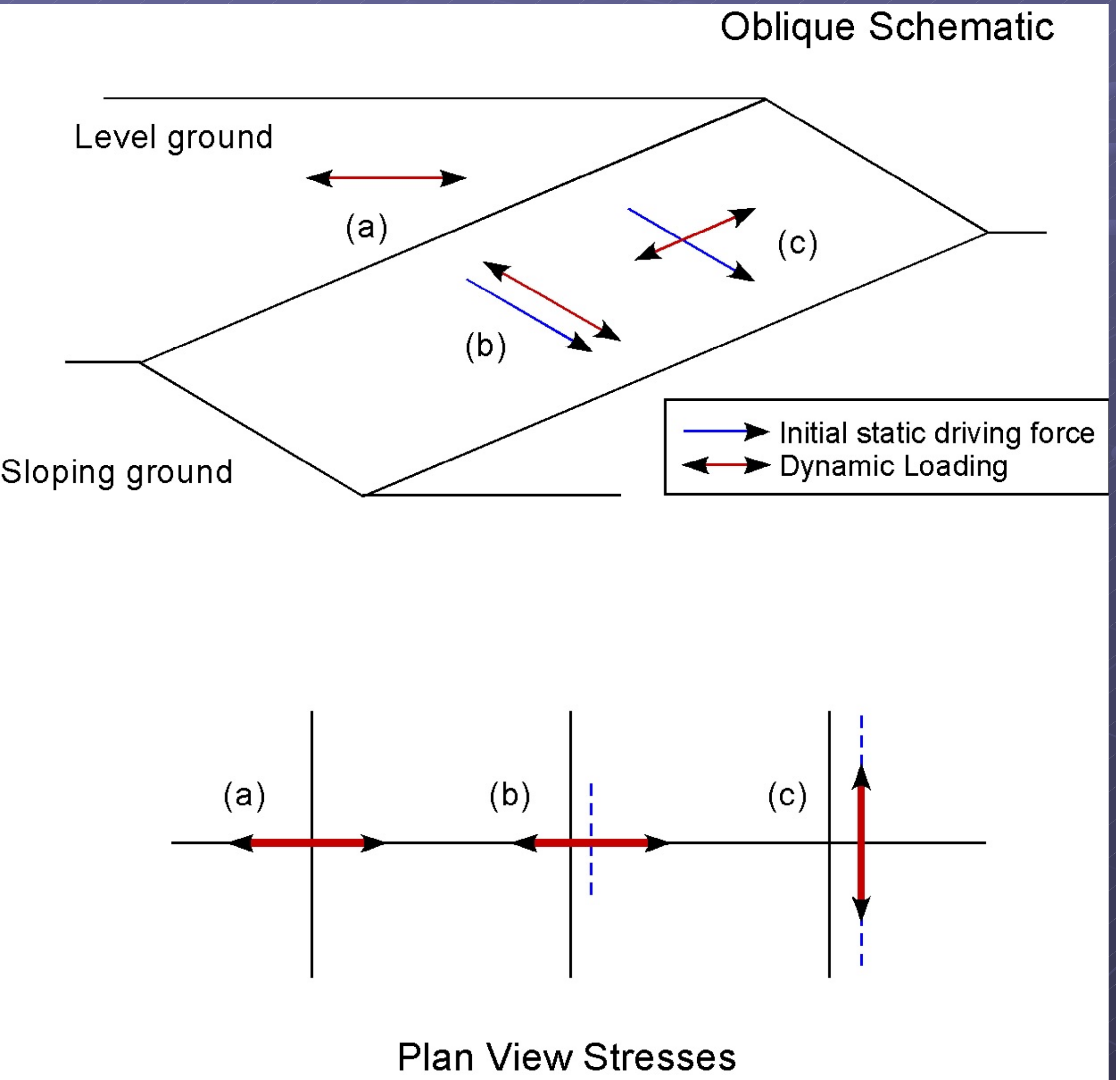


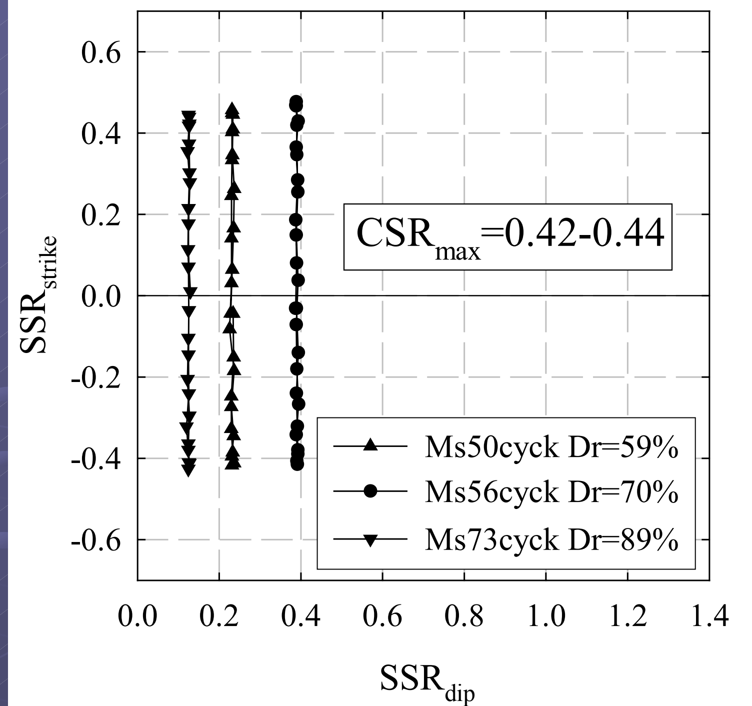
Schematic of 2-Directional Loading Conditions

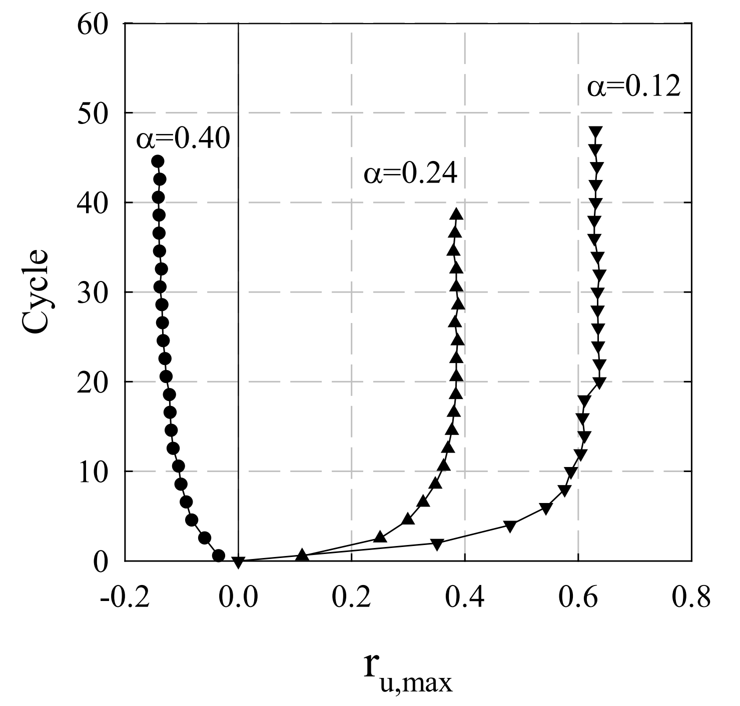
EXAMPLES OF PREVIOUS WORK IN THIS AREA

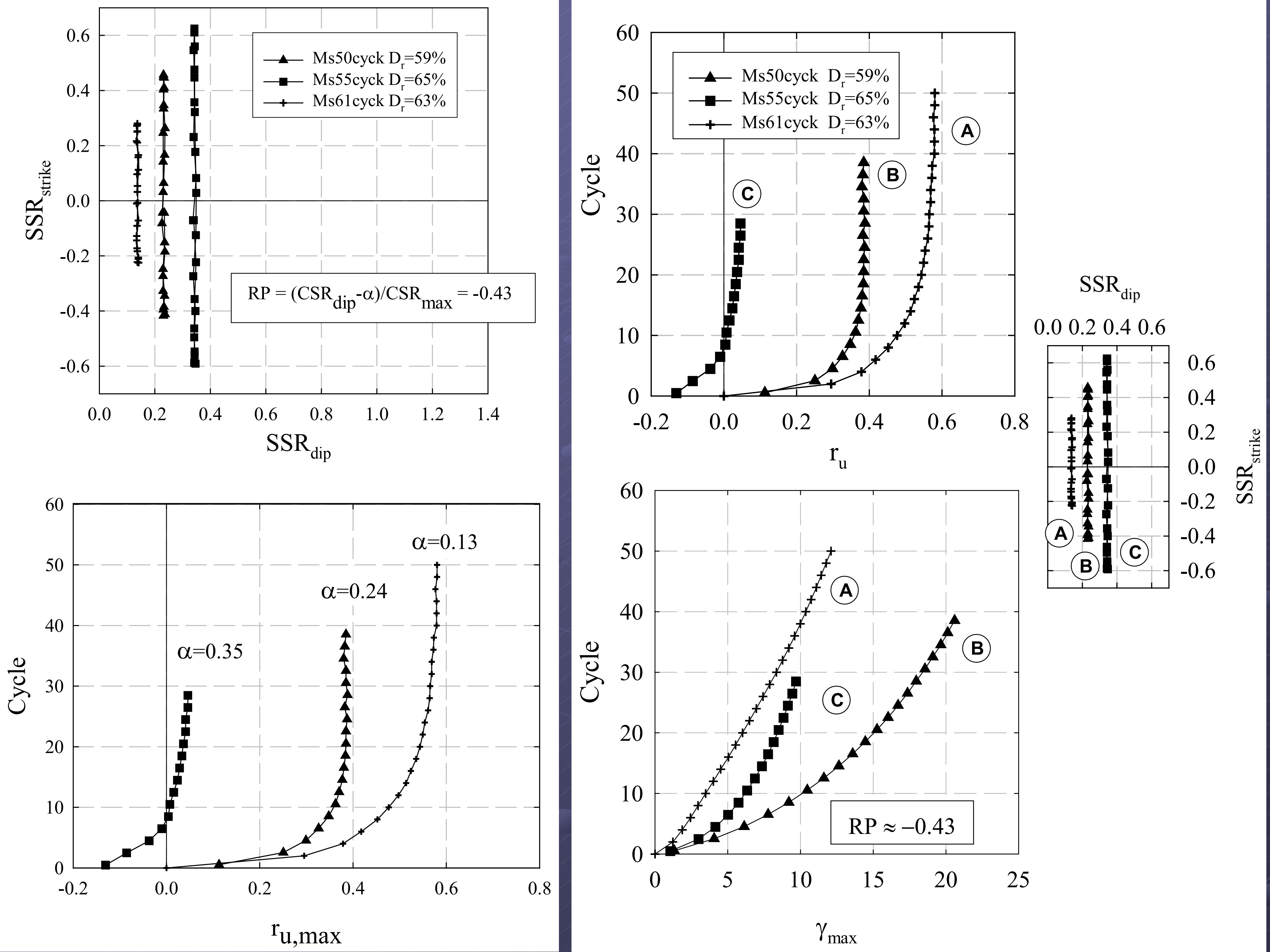
MULTIDIRECTIONAL SIMPLE SHEAR DEVICE

Effect of Cyclic Loading in the Direction Perpendicular to the Slope (Strike Direction)

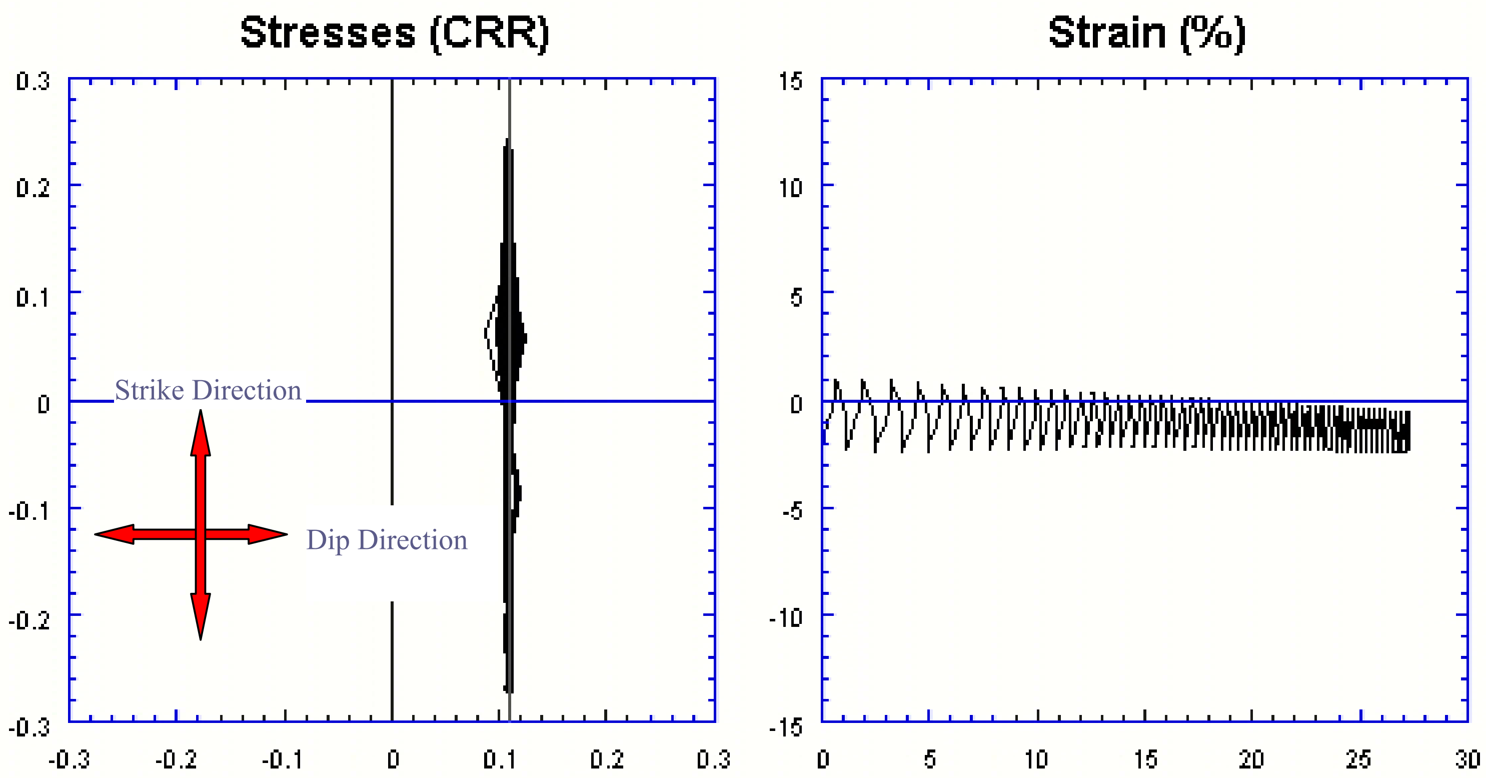







Ms50cyck D_r=59%
Ms55cyck D_r=65%
Ms61cyck D_r=63%
RP = $(CSR_{dip}-\alpha)/CSR_{max}$ = -0.43
SSR_{strike}
SSR_{dip}
Cycle
r_u
$r_{u,max}$
α=0.35
α=0.24
α=0.13
A
B
C
γ_{max}
RP ≈ −0.43

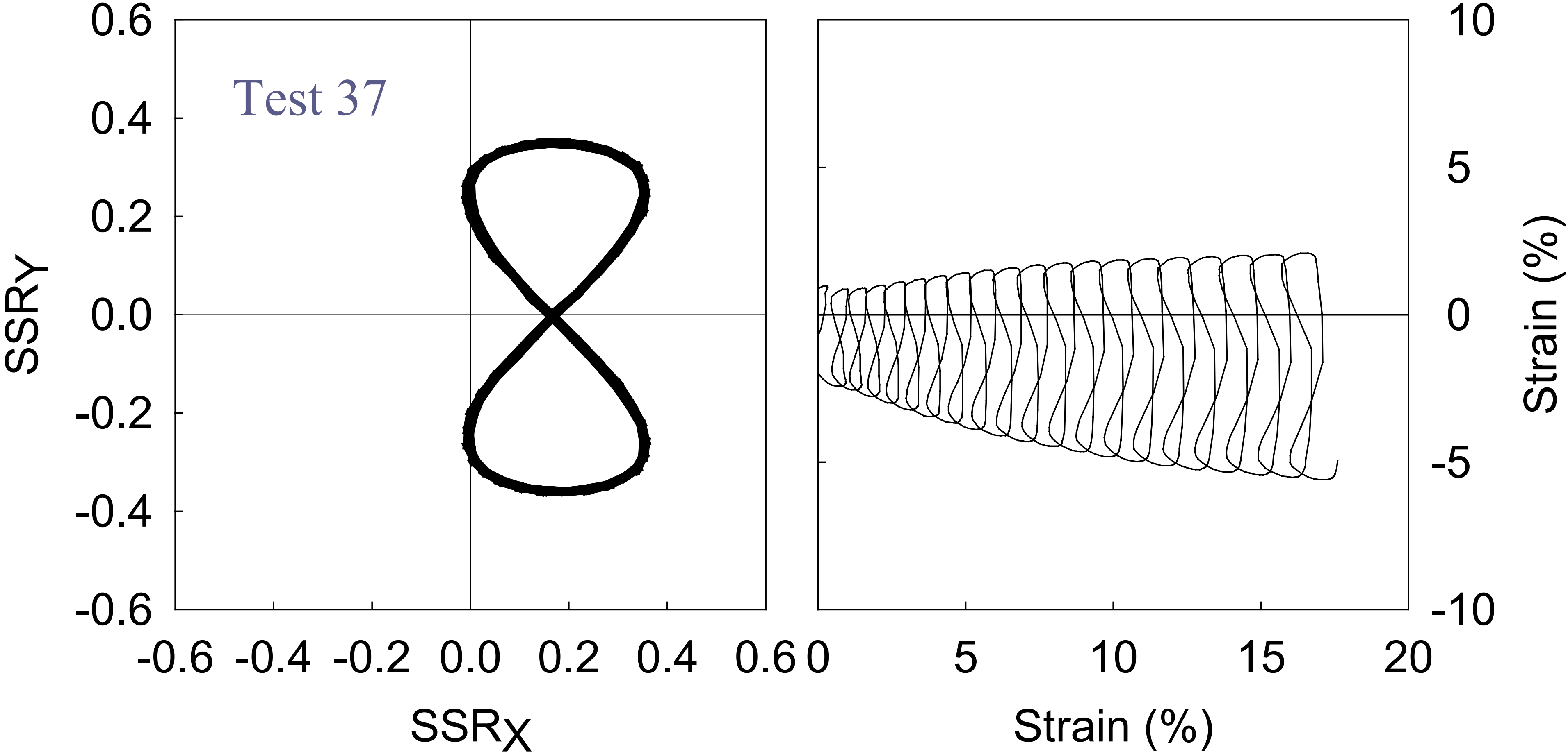
STRAIN POTENTIAL
Difference between Cyclic and Permanent Strains



Downhill

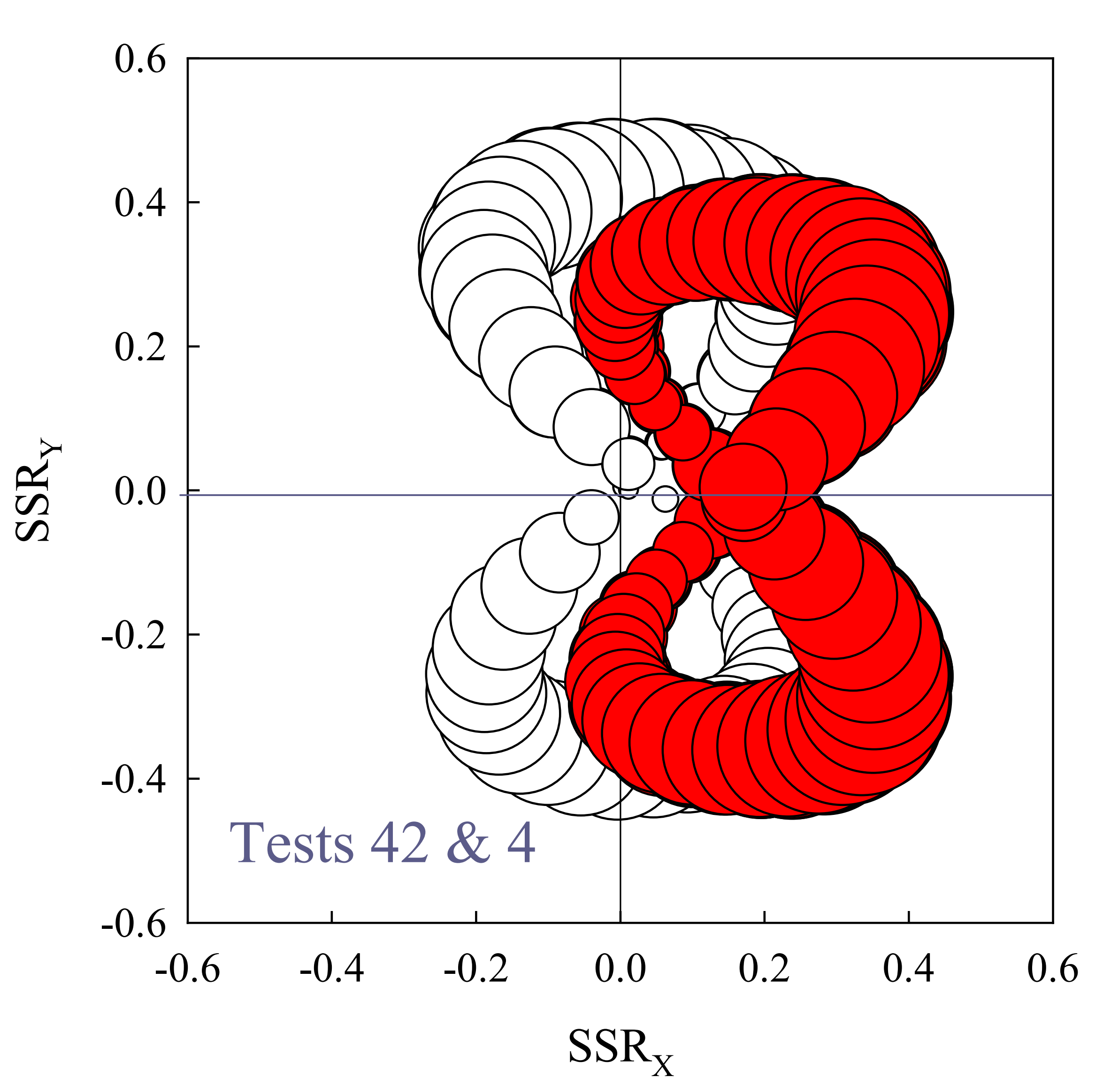
D_r=65% σ_v=85 kPa CRR= 0.25 α= 0.11

STRAIN POTENTIAL- Multidirectional Shaking Difference between Cyclic and Permanent Strains



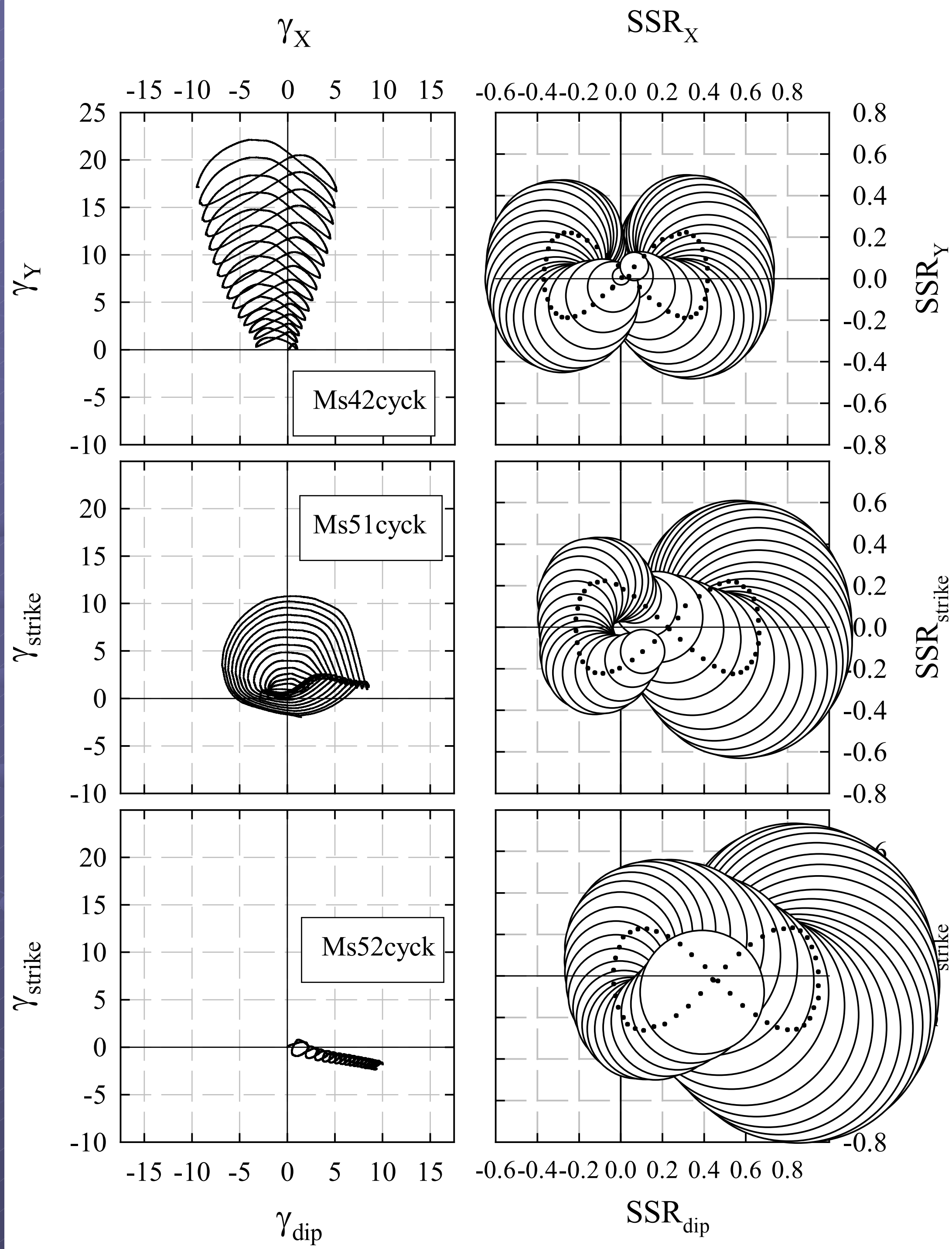
Plan View Stresses & Strains

Pore Pressure Development



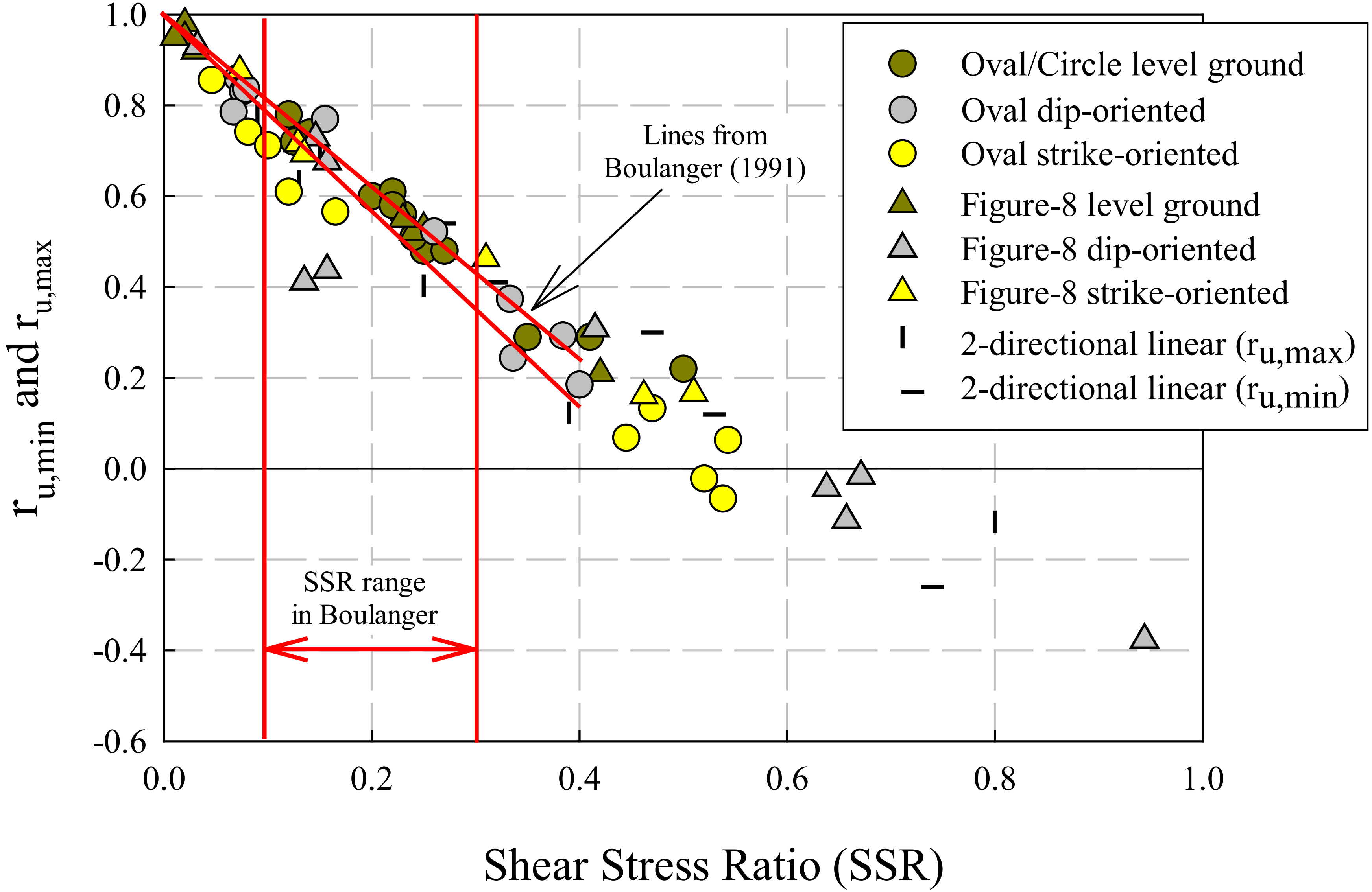
Bubble Size ↓

Pore Pressure ↑

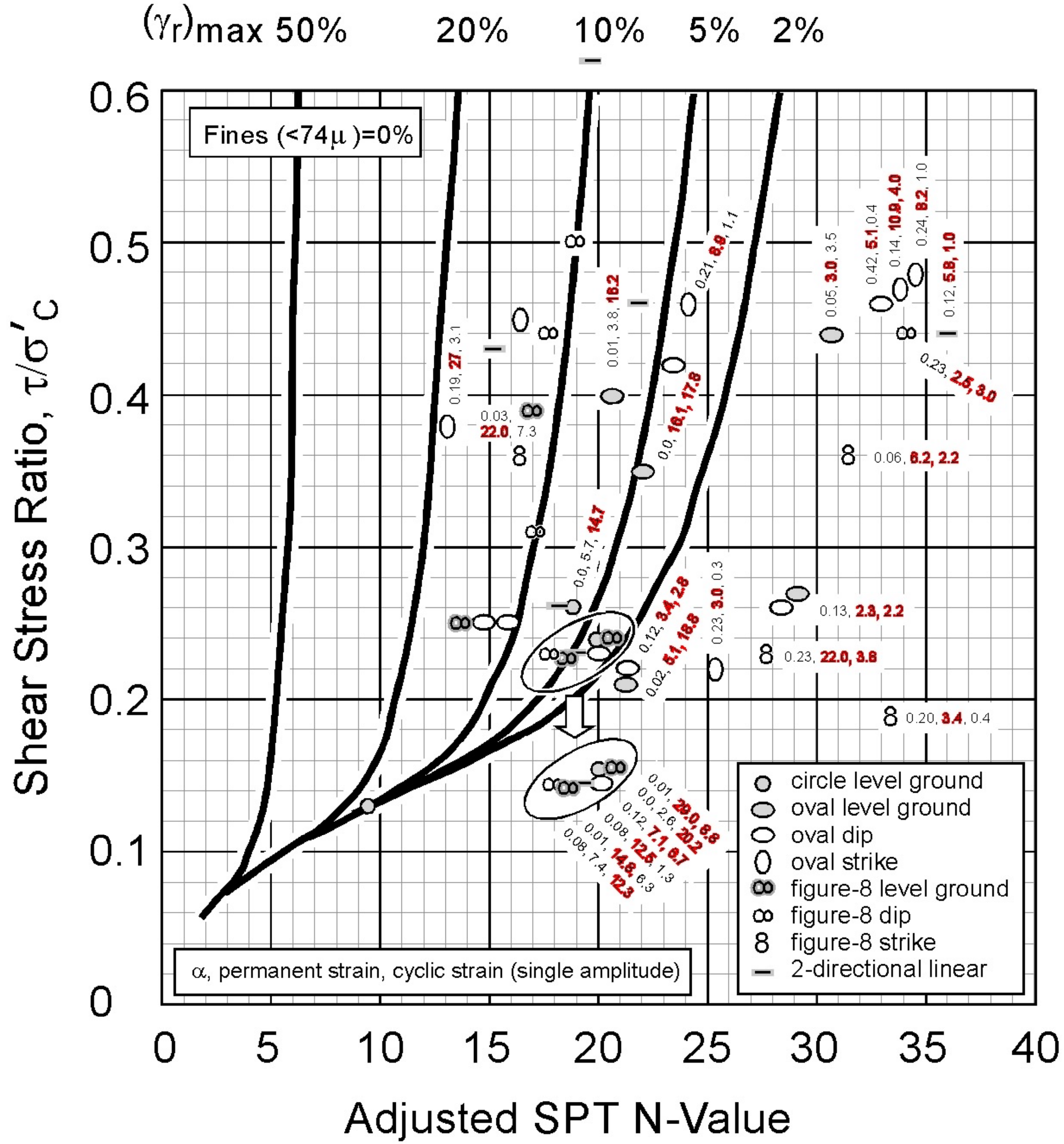


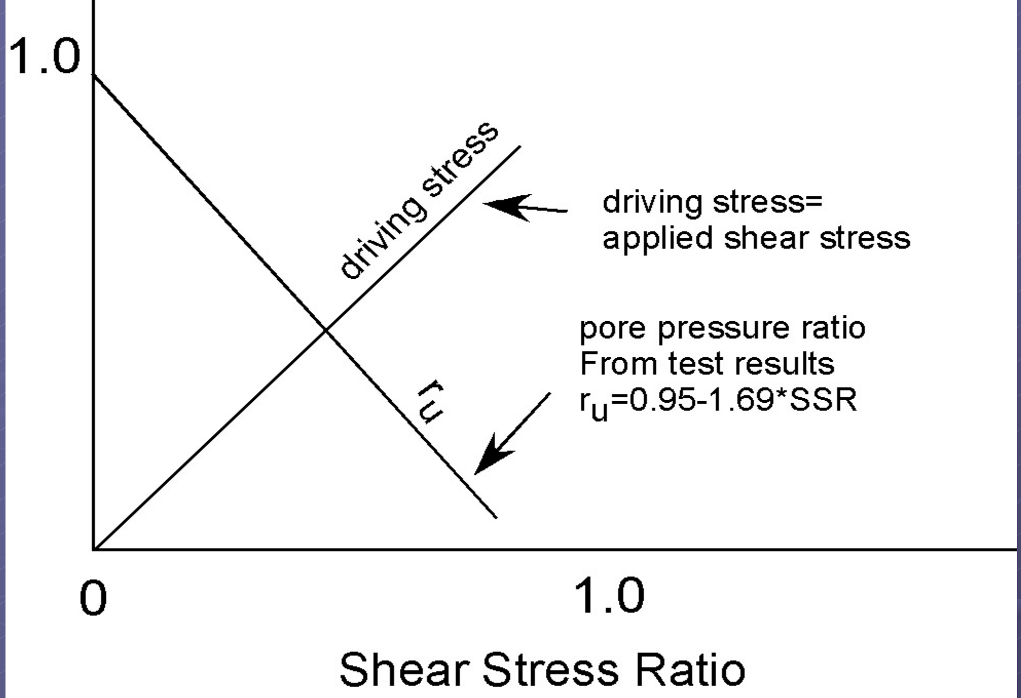
γX
SSRX
γY
SSRY
Ms42cyck
Ms51cyck
γstrike
SSRstrike
Ms52cyck
γdip
SSRdip

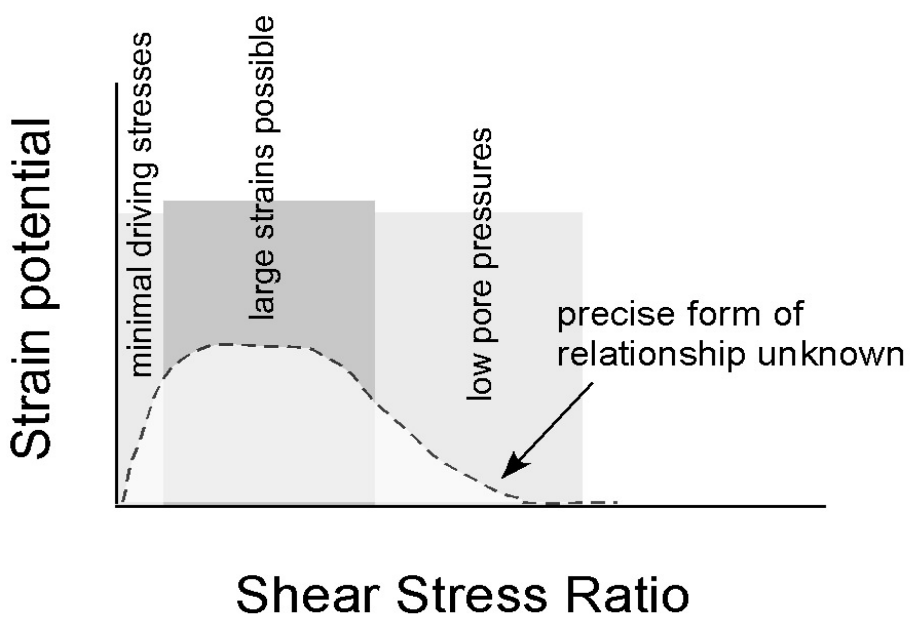
All "liquefied" Tests



Residual Shear Strain Potential




1.0
driving stress
driving stress=
applied shear stress
pore pressure ratio
From test results
r_u=0.95-1.69*SSR
r_u
0
1.0
Shear Stress Ratio

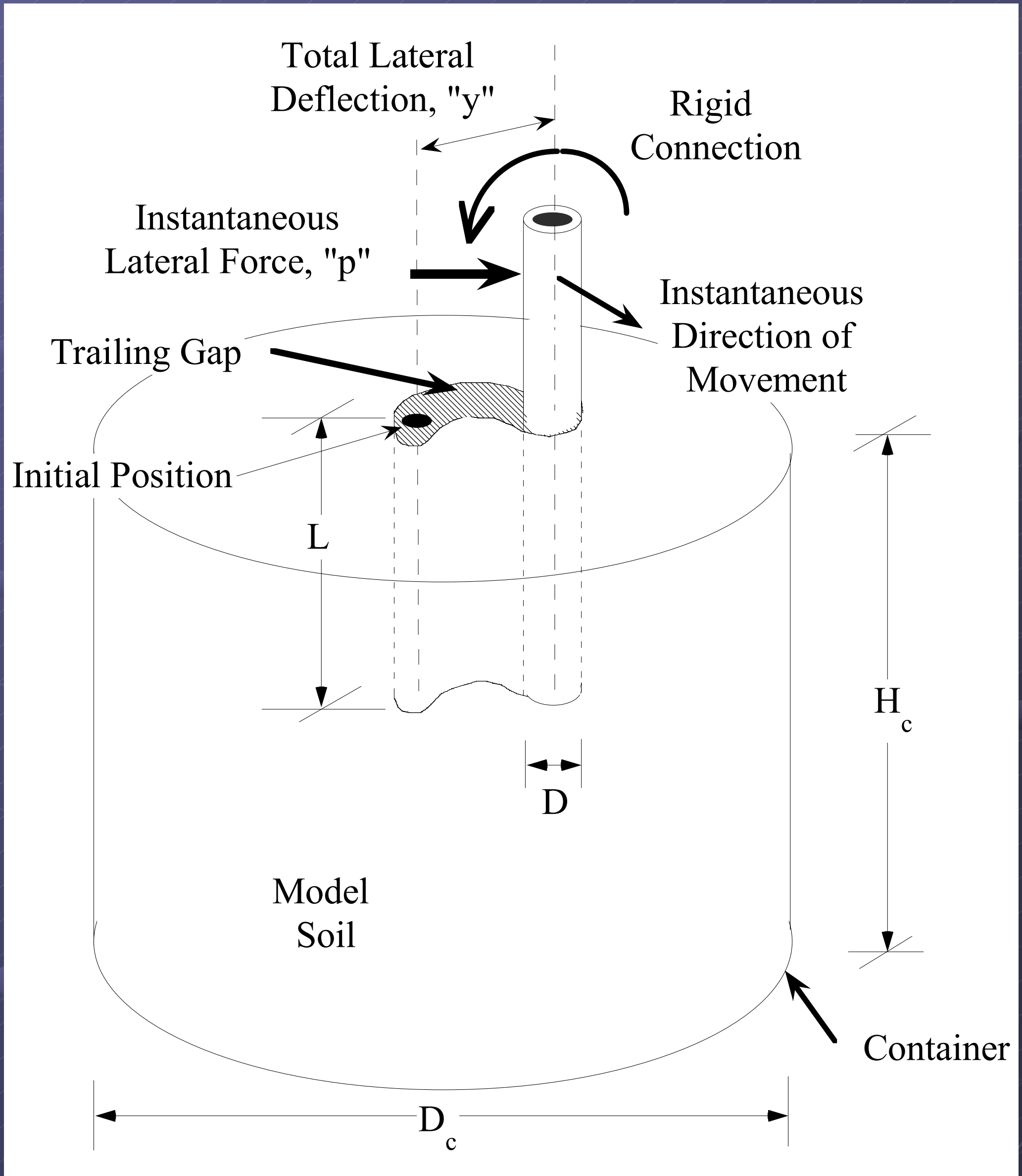

Strain potential
minimal driving stresses
large strains possible
low pore pressures
precise form of
relationship unknown
Shear Stress Ratio

Emerging Trends

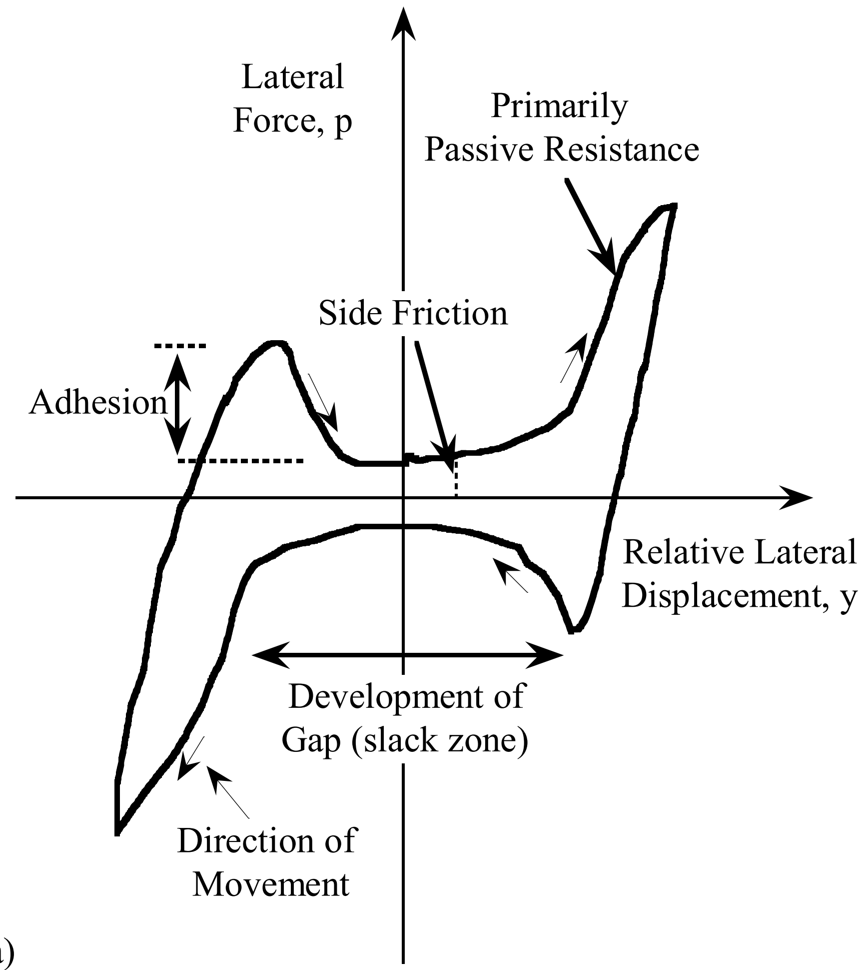
- Soil Structure Interaction- Focusing in Deep Foundations.
  - Use of relatively simple description of soil structure interaction but incorporate all structural elements in the evaluation of global response.
  - Use of more detailed description of SSI for areas significantly stressed during earthquake loading. (Example of incorporation of gapping with degradation in p-y elements)
  - Increased importance of multidirectional shaking and previous history in the response of foundation elements.
  - Need/Development of a robust algorithm/procedure to obtain material parameters based on field response.

Example: Soil-Pile Structure Interaction

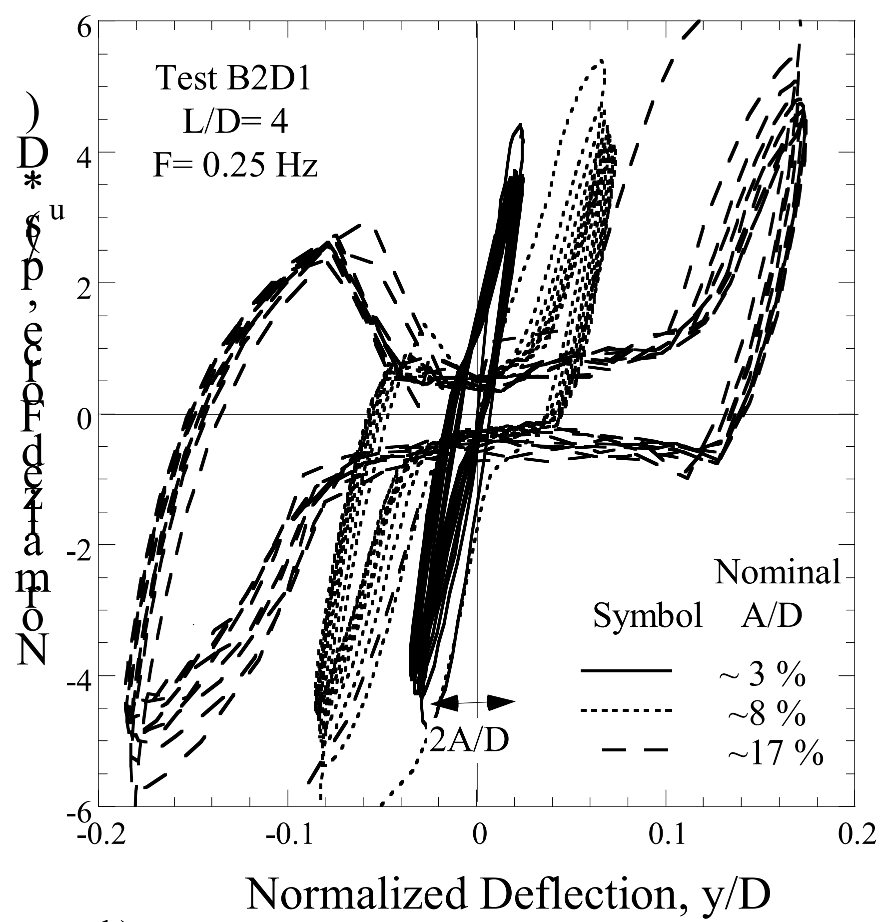
Effect of Multidirectional Loading



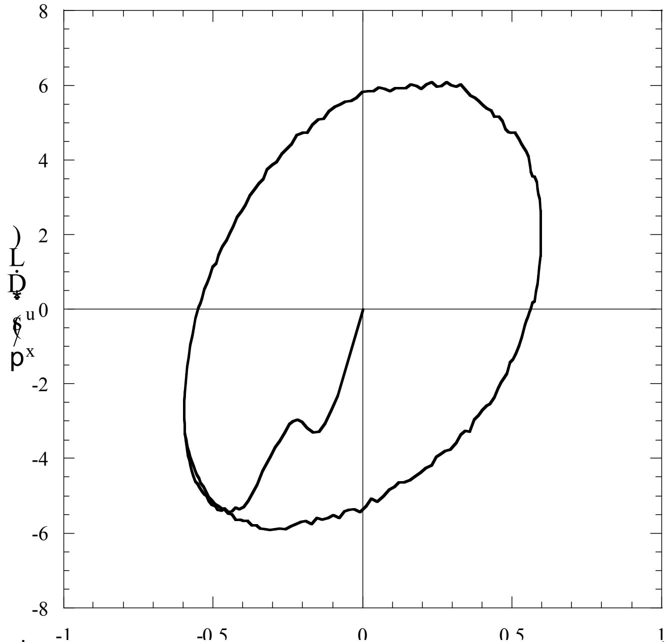
Gapping Behavior in 1-D



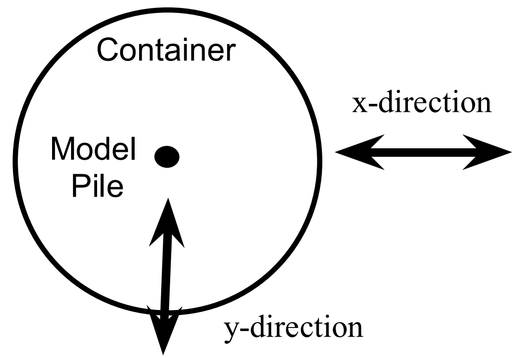
a)

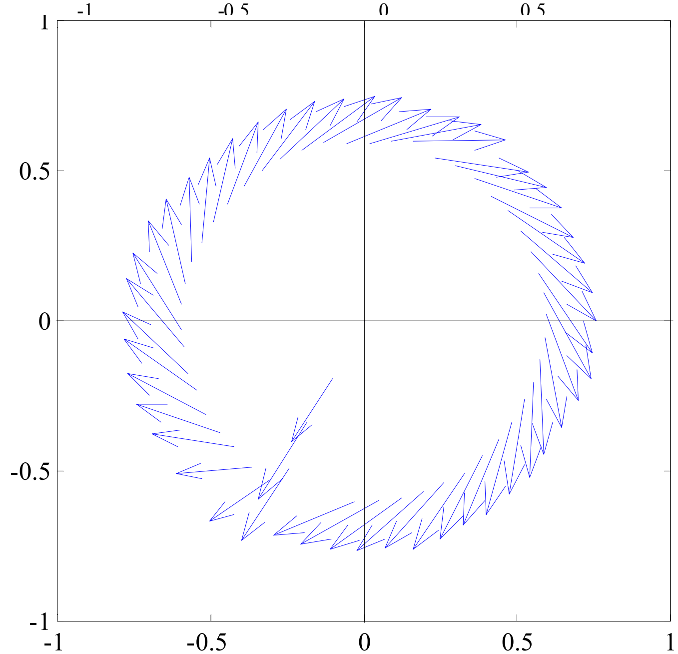


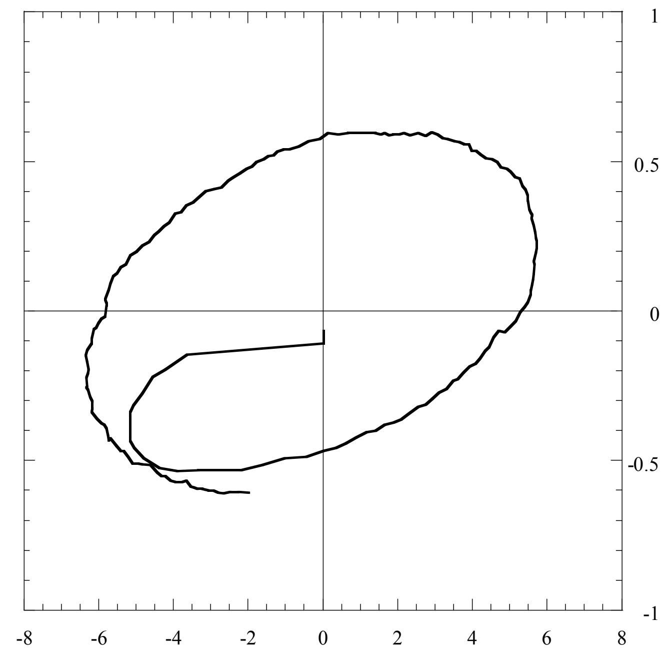
b)

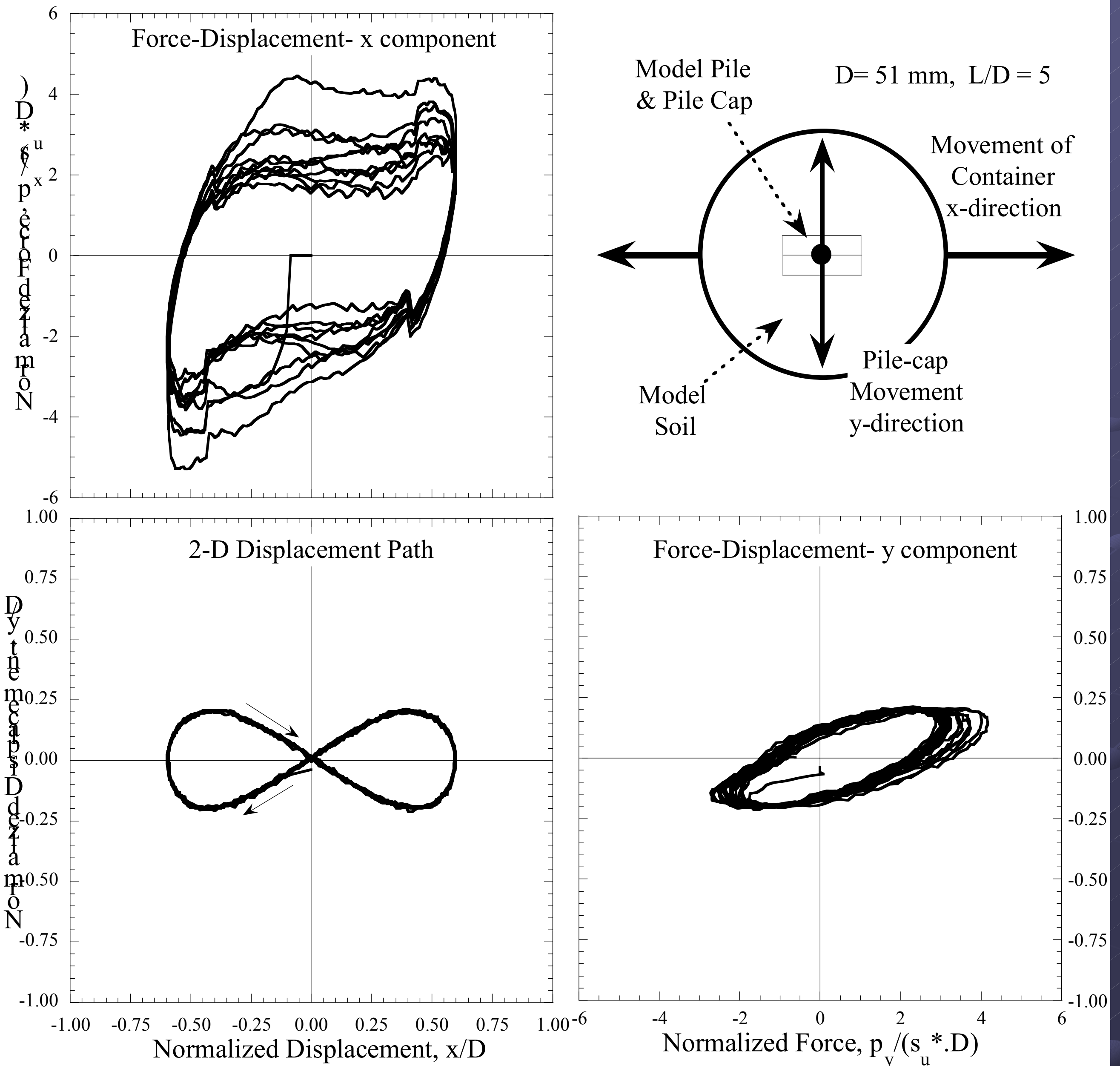


Loading path- Circular. D = 51 mm, L/D = 4 w_{clay} = 116 %, s_u^* = 3.64 kPa				
Test No	Displacement		Frequency (Hz)	
	A_x/D	A_x/A_y	F_x	F_y
fc9012	0.60	1:1	0.05	0.05

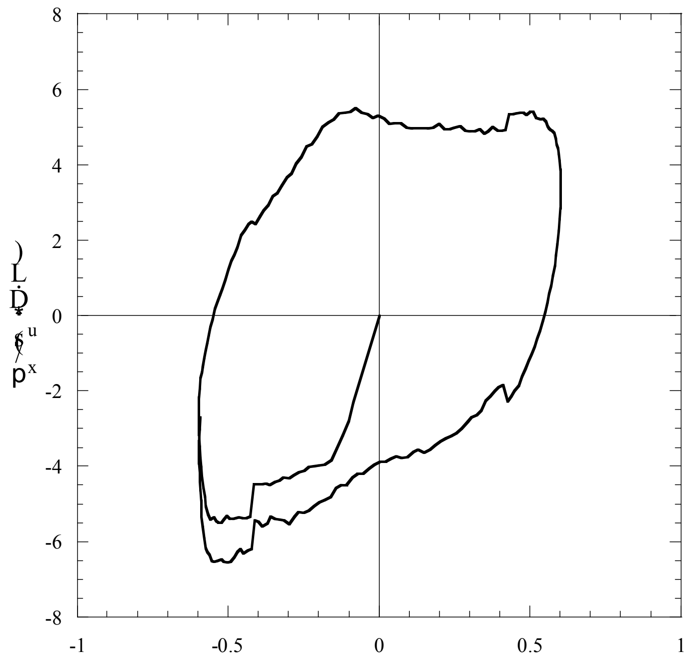




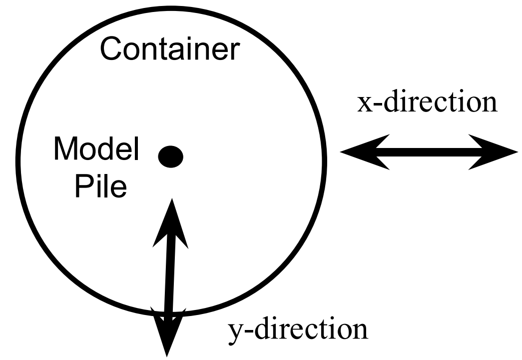


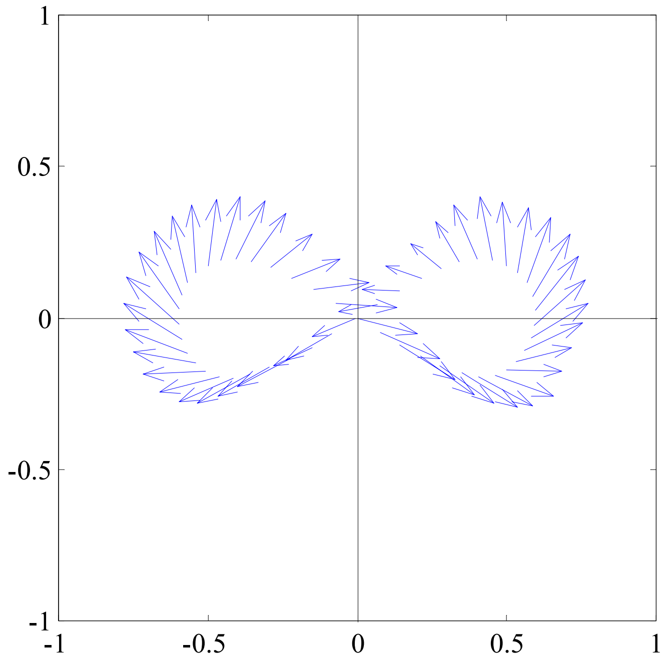


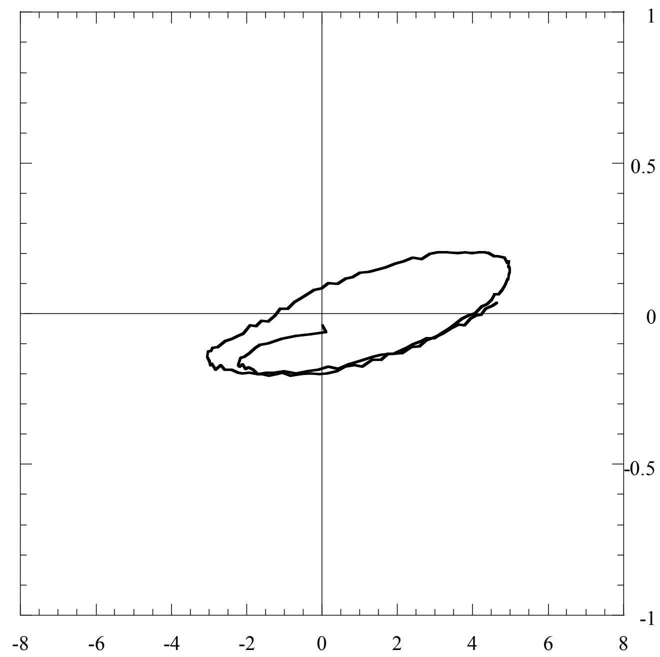
TEST INFORMATION						SOIL PROPERTIES	
Test #	Path	A_x/D	A_x/A_y	F_x (Hz)	F_y (Hz)	ω (%)	s_u* (kPa)
f81312	Figure 8	0.60	3:1	0.05	0.10	108	3.88



Loading path- Figure 8. D = 51 mm, L/D = 4 w_{clay} = 108 %, s_u* = 3.88 kPa				
Test No	Displacement		Frequency (Hz)	
	A_x/D	A_x/A_y	F_x	F_y
f81312	0.60	3:1	0.05	0.10







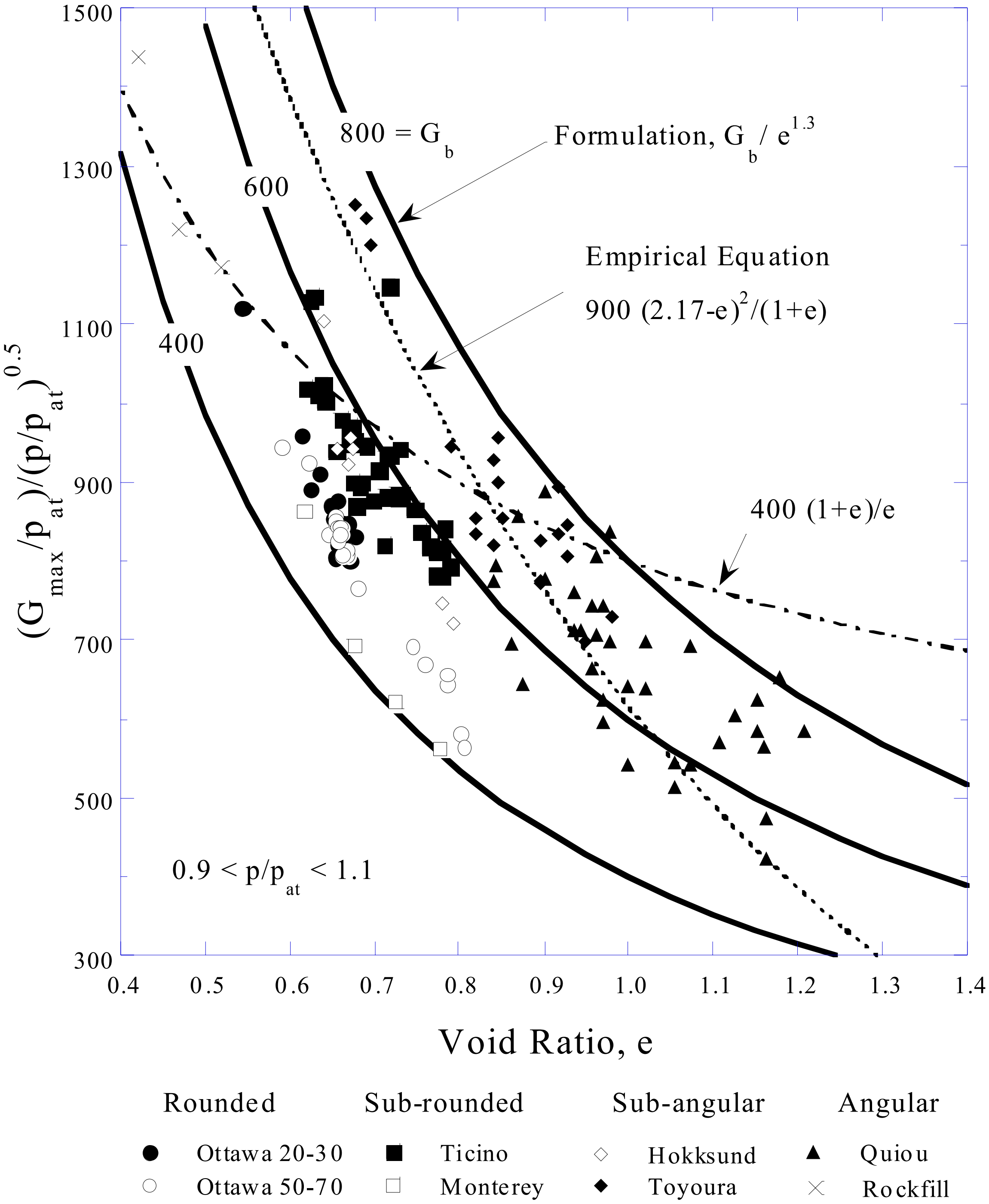
Emerging Trends

- In both applications: The incorporation of uncertainty in the simulation of response.
- Elements of uncertainty
  - Topology of the problem (geometry, identification of soil strata, type of soil)
  - Uncertainties of state: (i.e., for a given soil profile, values of stresses, void ratio, saturation, etc.)
  - Model uncertainty: For each analysis, there is some uncertainty resulting from the choice of material model-> uncertainty of “memory” parameters.

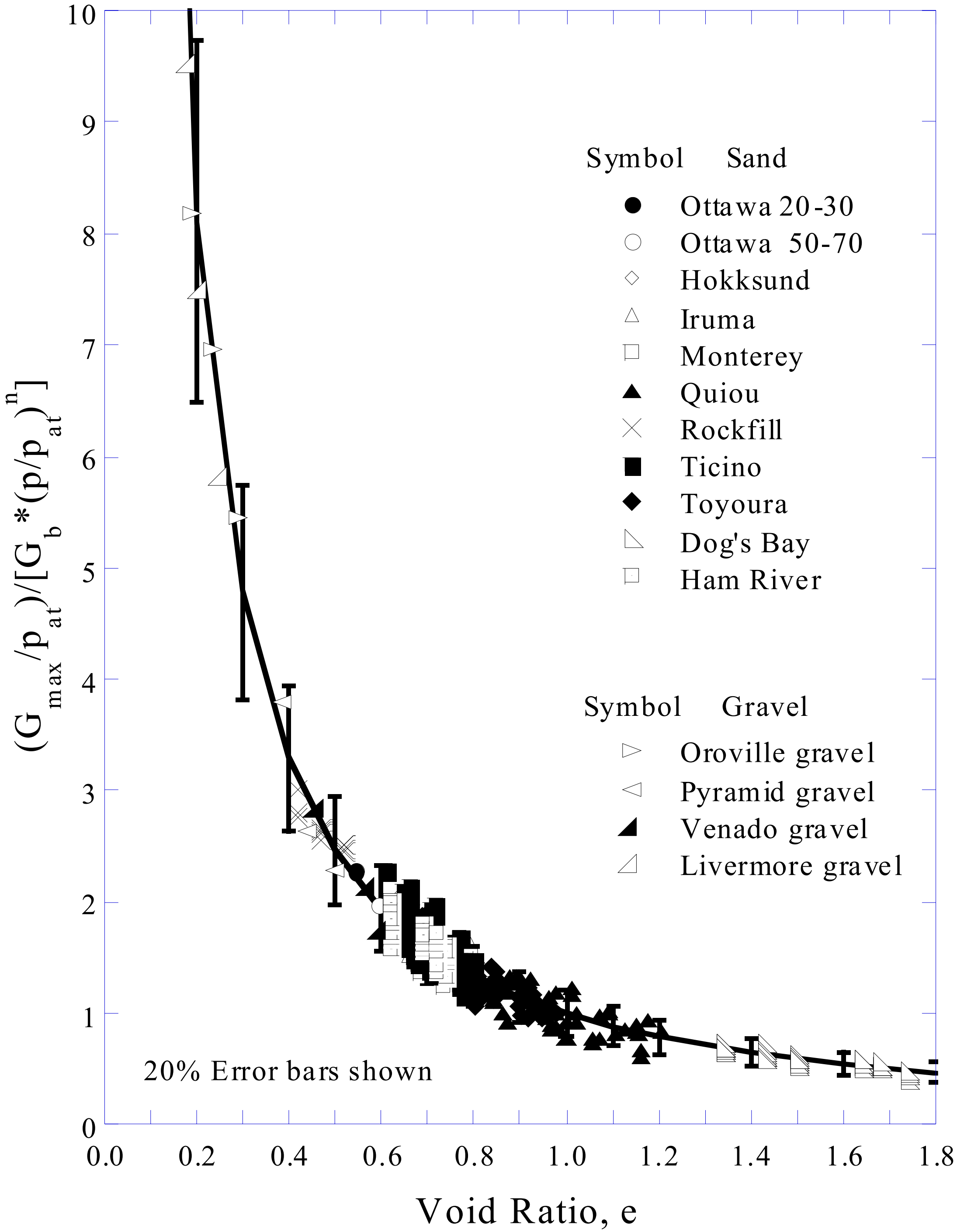
Example: Model Uncertainty

- Use of More sophisticated material models- Tradeoff between complexity and predictive power.
- Determination of Shear Stiffness at small strains, G_{max}
  - Model formulation
  - Application to cemented and uncemented sands
- Shear Modulus Reduction and Damping Factors.
  - New hysteretic formulation
  - Assessment of Performance/Validation
- Application to Site Response Analysis
  - Hierarchical determination of material parameters.

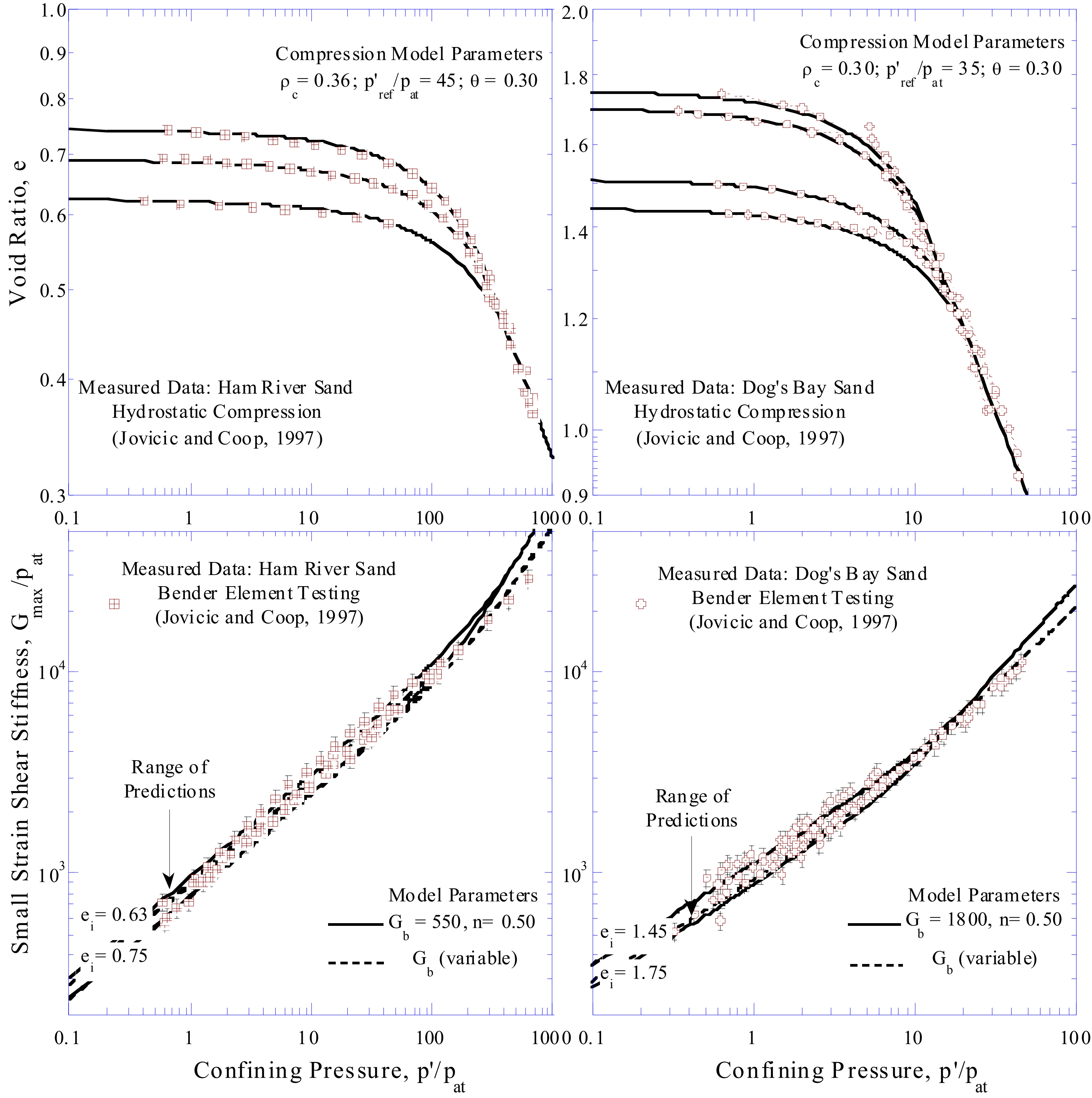
Effect of Volumetric State (i.e., void ratio)

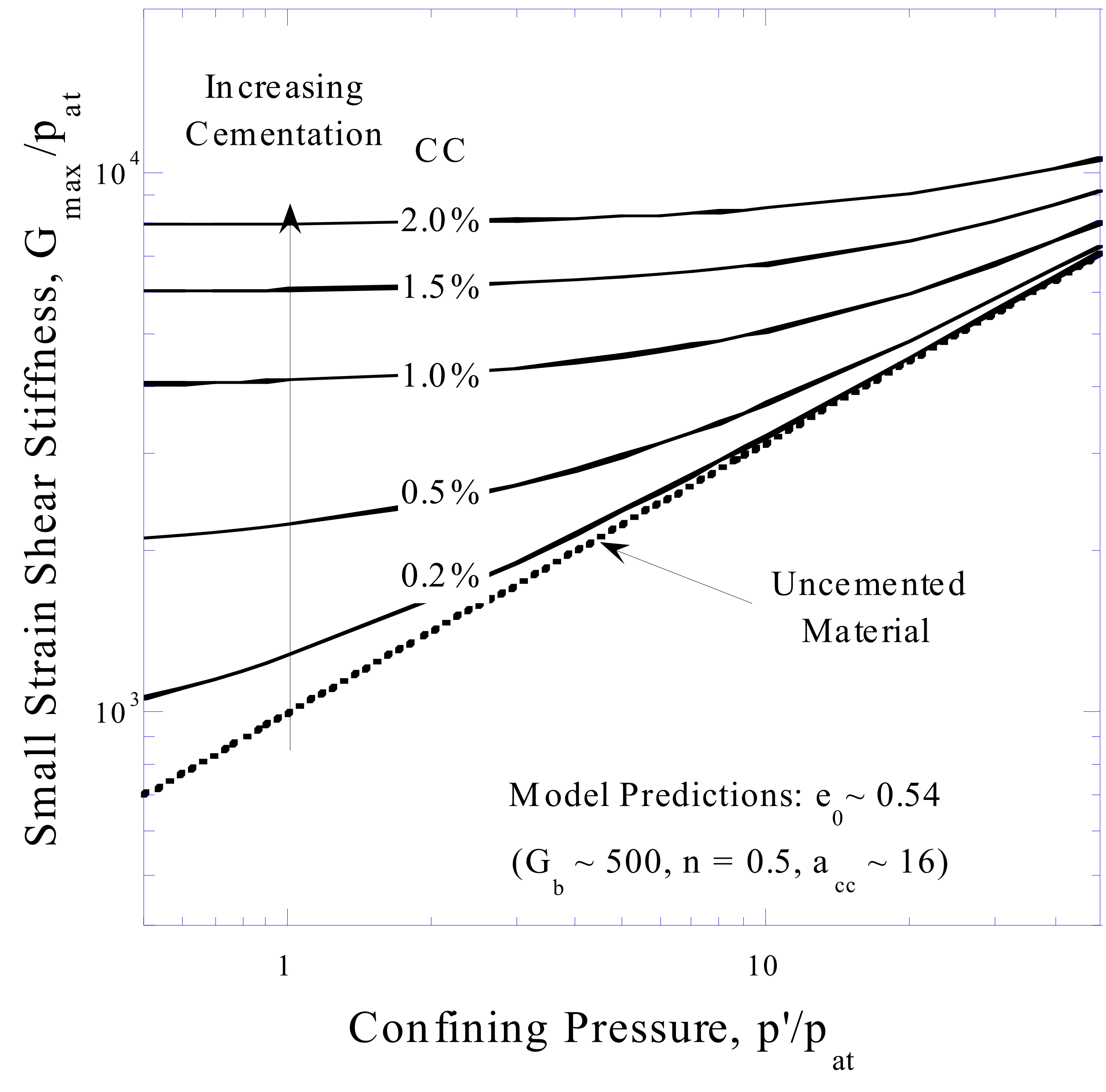


Behavior for Sands & Gravels Effect of Void Ratio



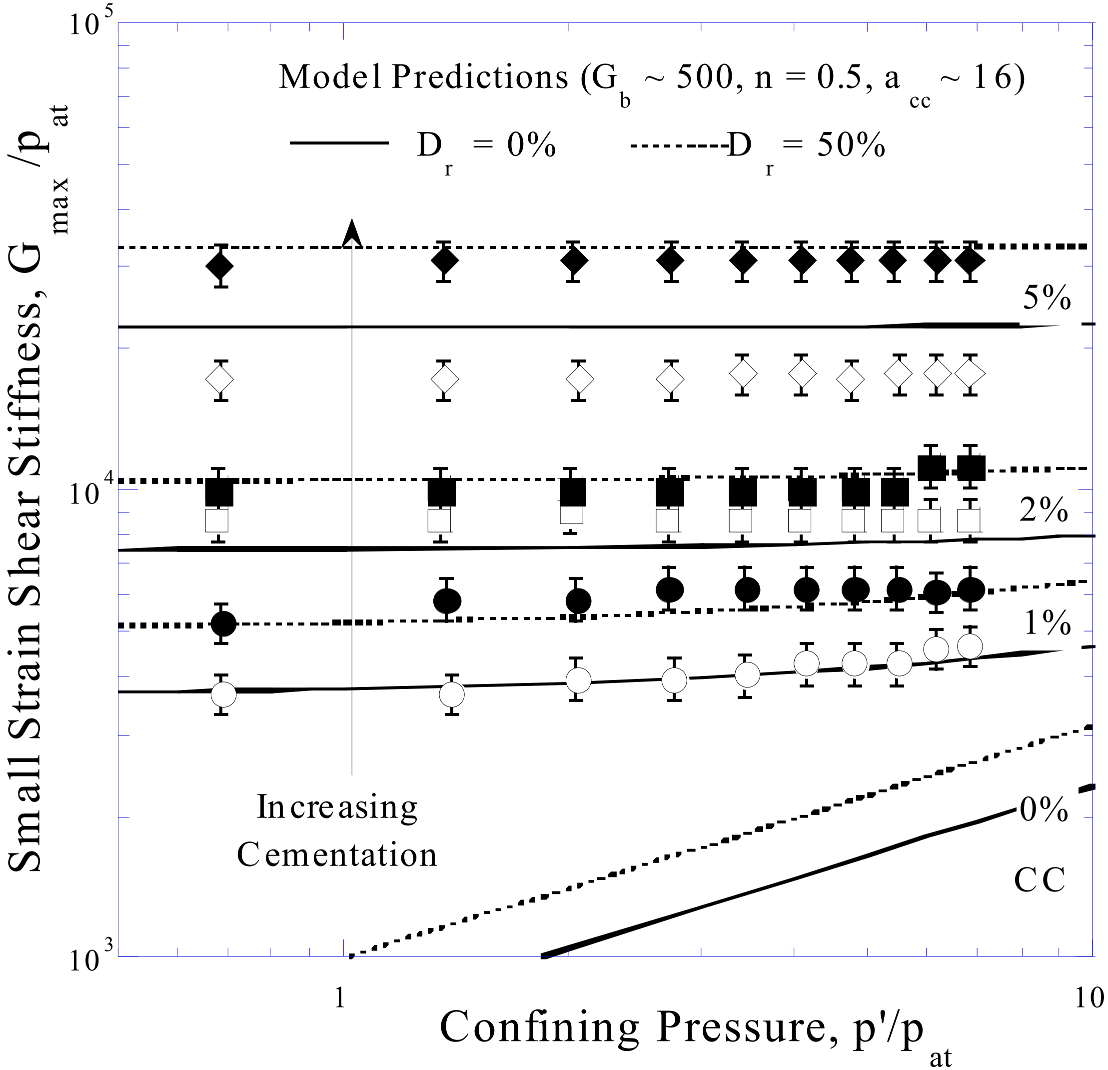
Shear Stiffness at High Confining Pressures





Effect of Confining Stress on the Shear Stiffness of Cemented Sands

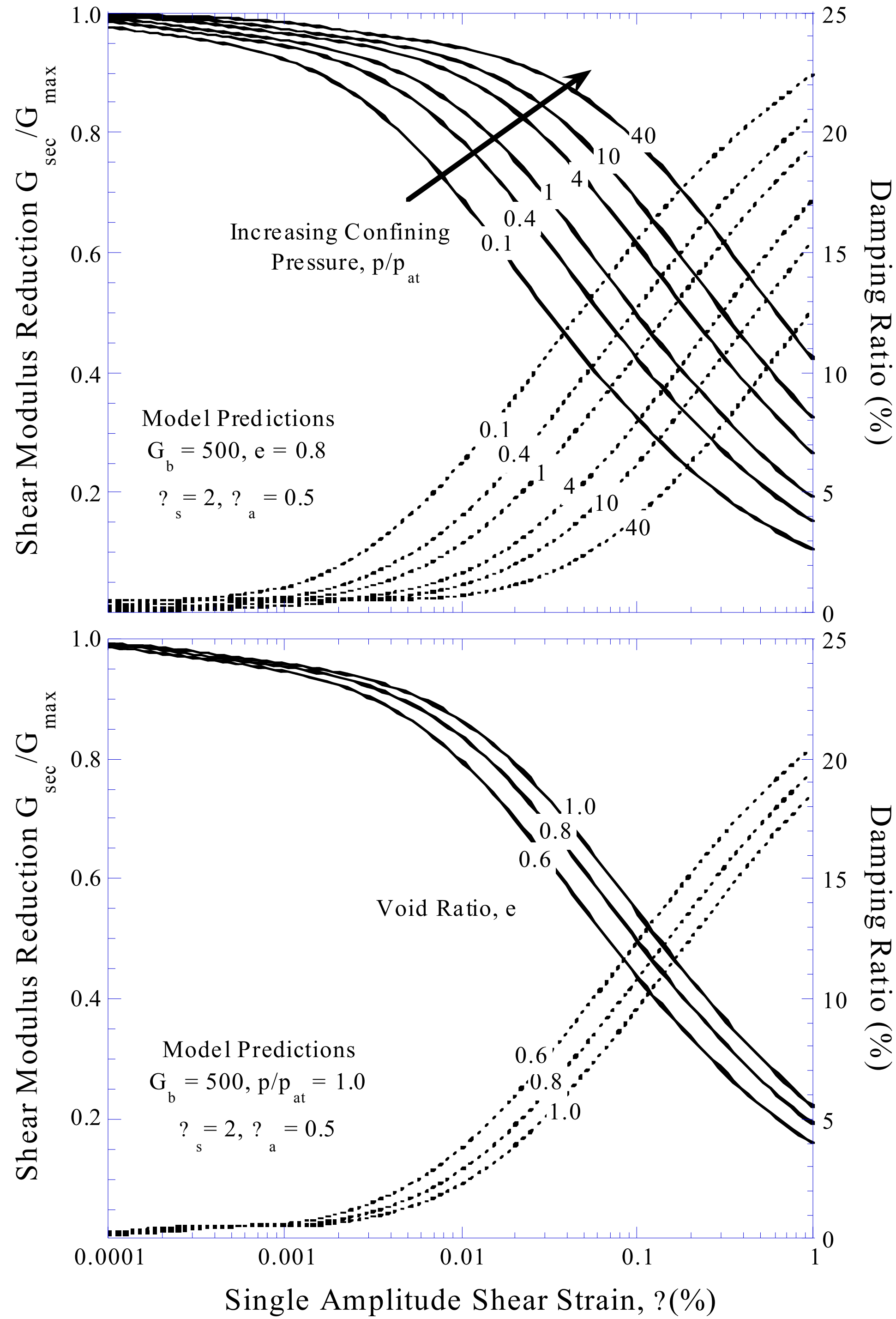
Effect of Confining Stress on the Shear Stiffness of Cemented Sands



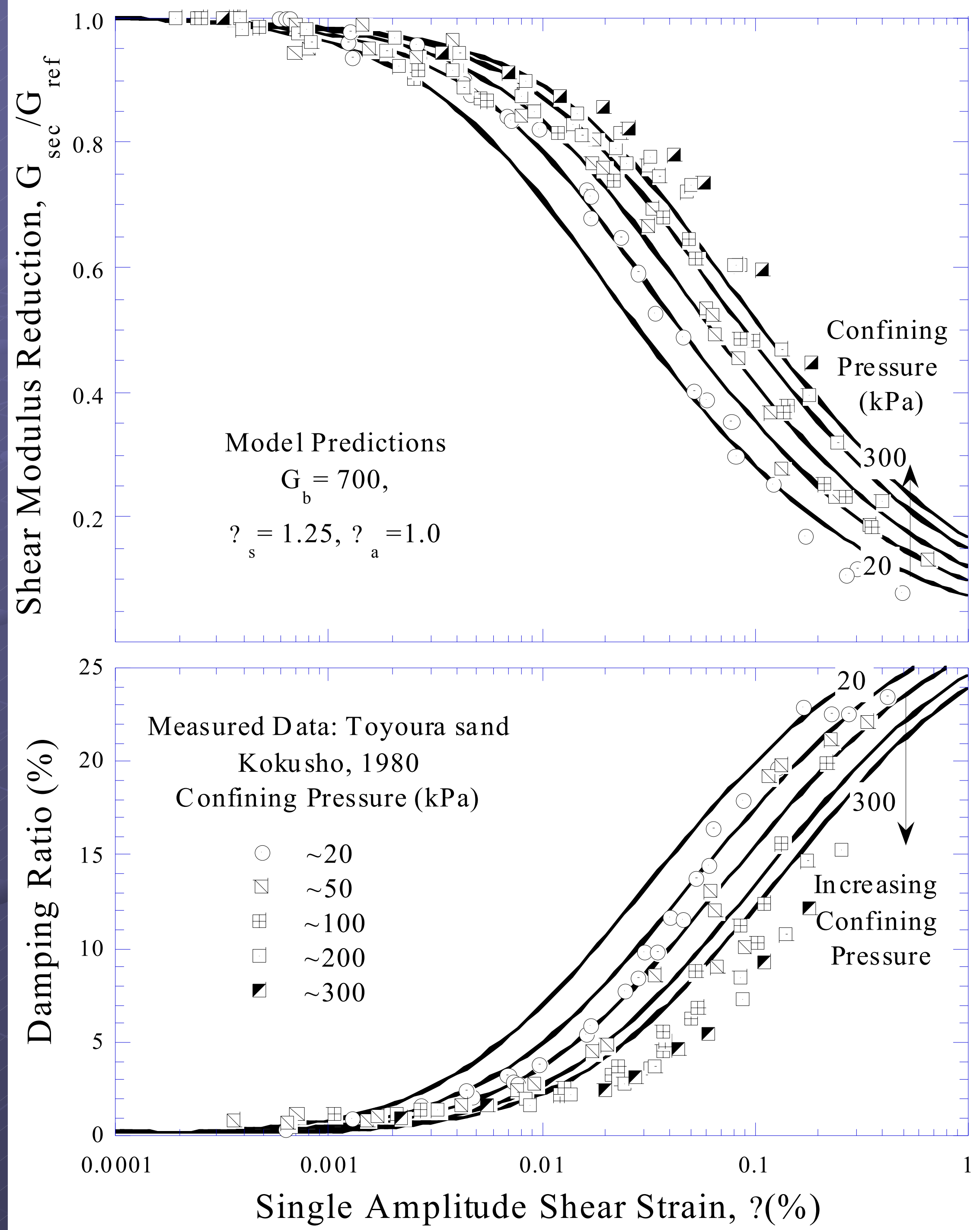
Measured Data: Ottawa 40/100 Sand
Bender Element Tests (Baig et al., 1997)

Relative Density, D_r	Cement Content (%)		
	1	2	5
0 %	○	□	◇
50 %	●	■	◆

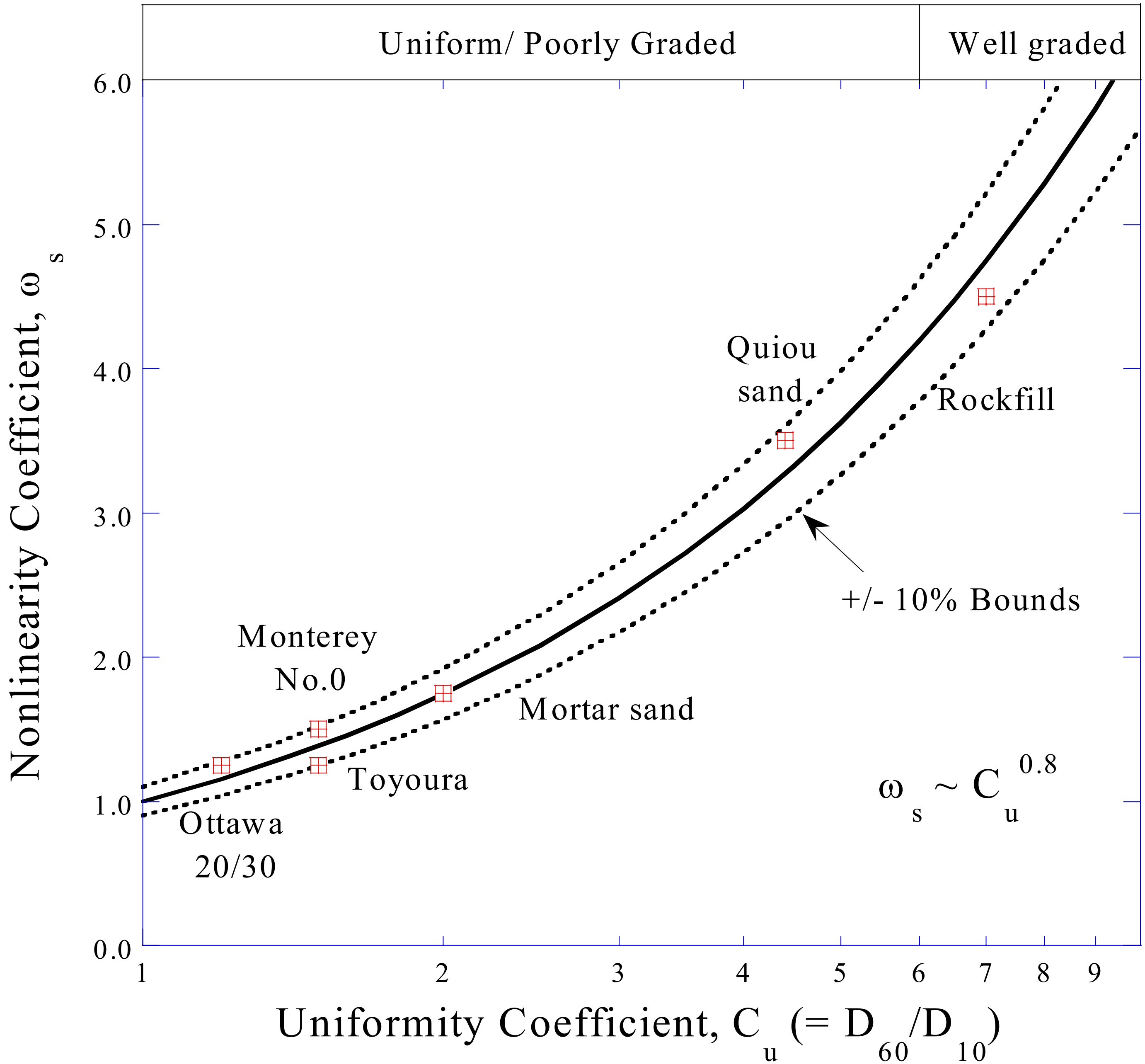
Effect of Confining pressure and void ratio on the Shear Modulus Reduction and Damping Ratio



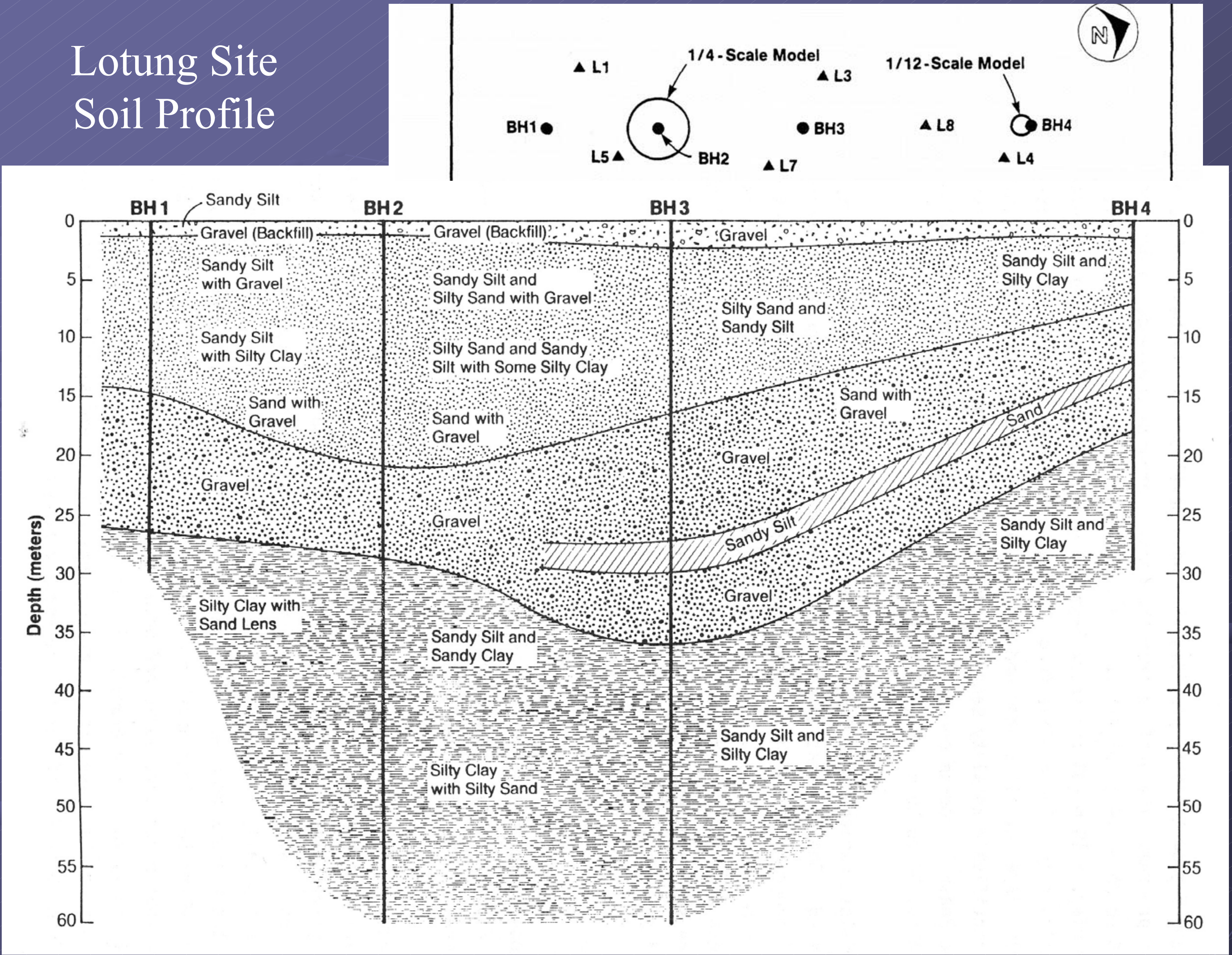
EVALUATION
Effect of Confining pressure and void ratio on the Shear Modulus Reduction and Damping Ratio



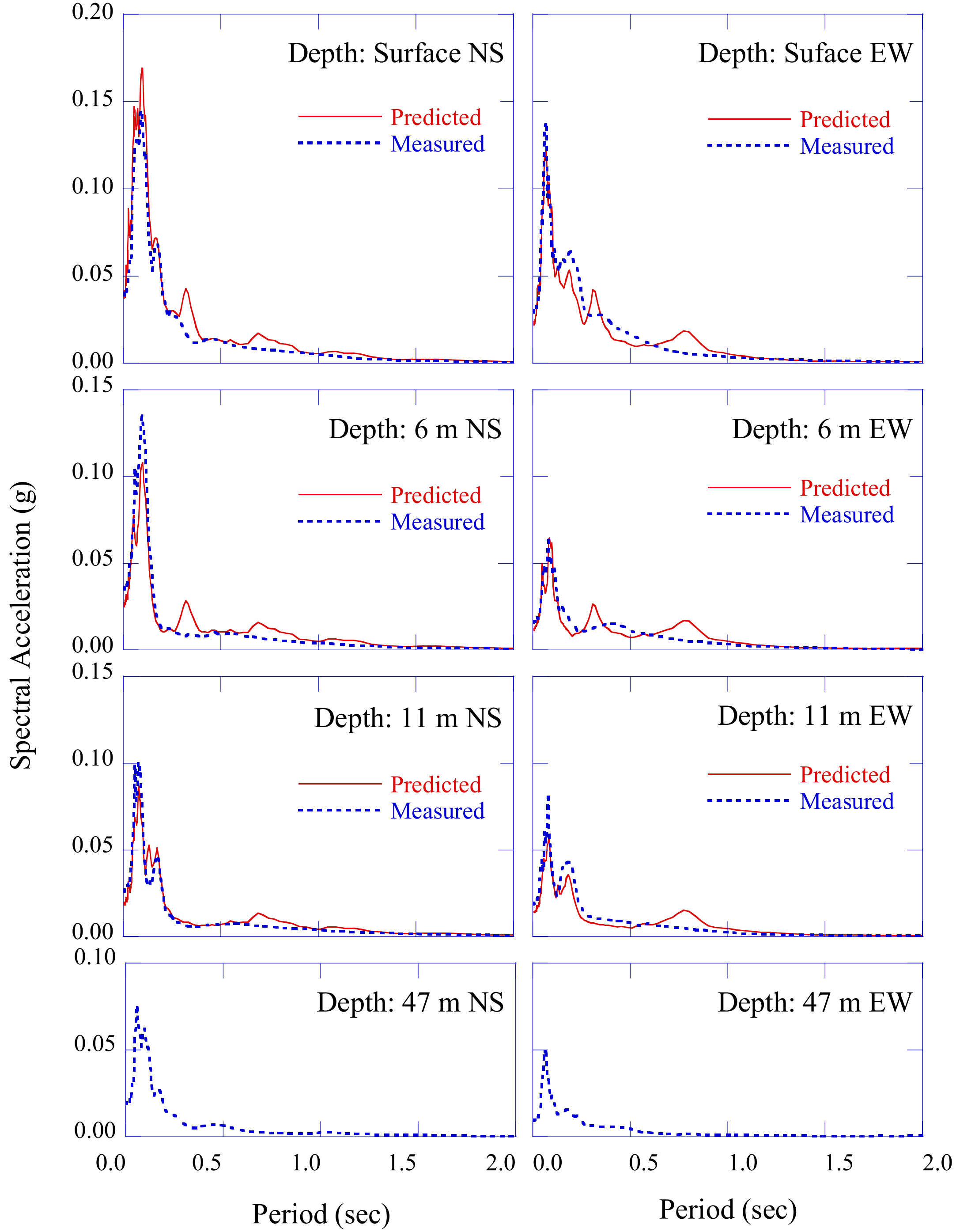
Correlation of Material Parameters with Index Properties



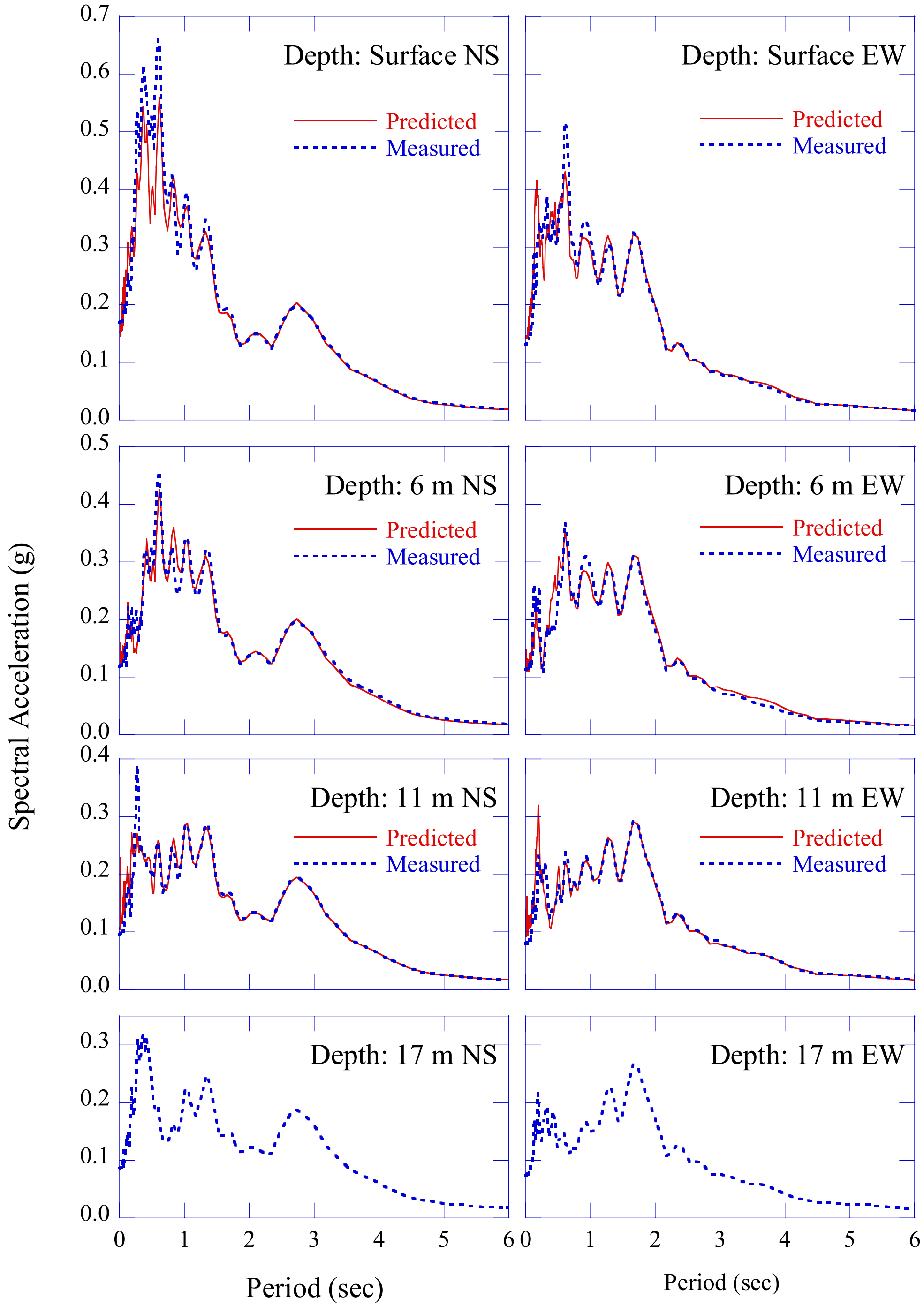
Lotung Site Soil Profile



Lotung Site Predictions Event 10, M_L=3.7



Lotung Site Predictions Event 16, M_L=6.5



Summary

- Significant work to be done- FAR FROM OVER.
- Key elements of Multidirectional response are currently being developed and incorporated in model development/framework.
- Use of more sophisticated material models.
- Development of methodology to perform System Identification for more complex models.
  - Constrained optimization with Bayesian updating. Karman Filter, allow input of seemingly different type of data in the analysis.
  - Neural networks-like approach

Thanks