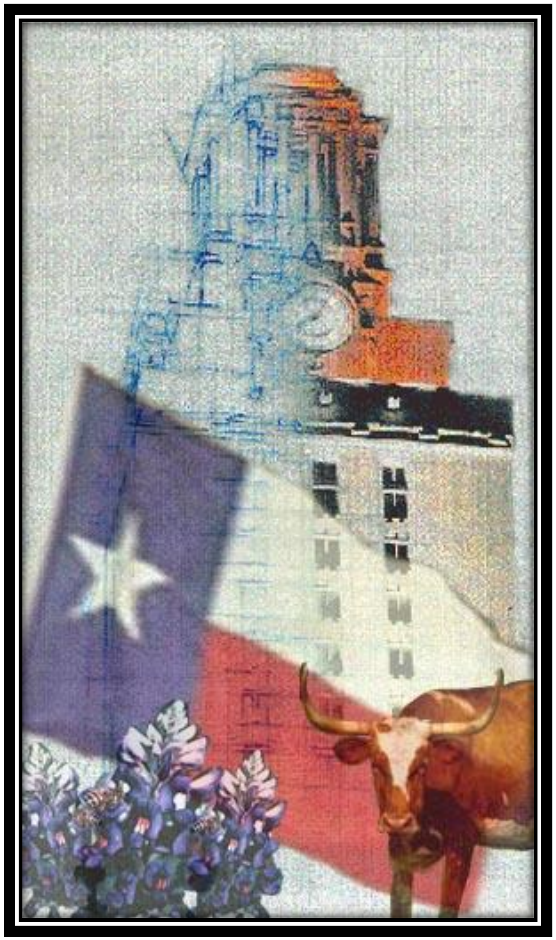
Building a Framework for Predicting Foundation Settlements on Granular Soil with Dynamically Measured Properties



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Stiffness-Based Ground Deformation Prediction Workshop
Seattle, WA
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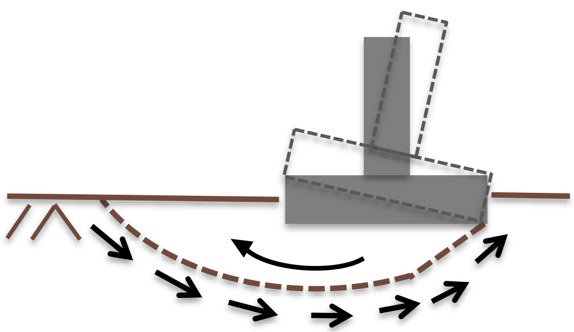
1. Outline

1. Present a brief background on field and laboratory seismic measurements.
2. Discuss a new framework for predicting settlements using dynamic soil properties.
3. Present a new approach to characterizing liquefiable soils in the field.
4. Show advances in dynamic torsional resonant column and cyclic torsional shear testing in the laboratory to evaluate parameters that effect V_S and G.
5. “Mention” two additional important areas of research.
6. Conclusions

1. Background - Shallow Foundations on Granular Soil

Main Design Criteria

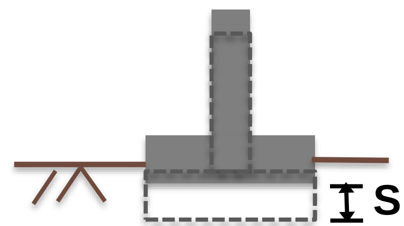
1. Bearing Capacity: $Q_{design} = Q_{ult}/F.S.$

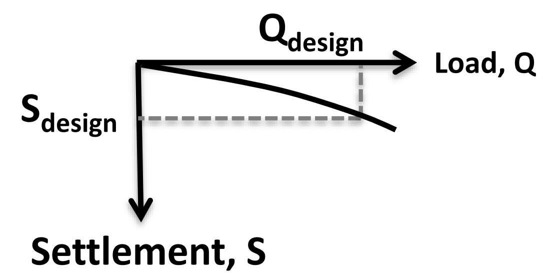


Approach

- Limit equilibrium analysis
- Requires strength parameters (ϕ' and c')

2. Permissible Settlement: $S \leq S_{design}$ (Typically Controls)





Traditional Approach

- Based on SPT and CPT correlations
- Soil sampling is hard and/or expensive in granular soil so rarely performed
- Stresses and strains are undefined

New Framework

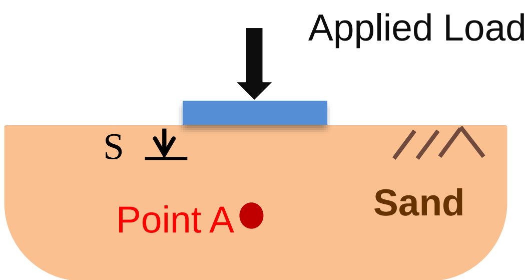
- Deformation-based analysis
- Stresses and strains are calculated
- Key factor is field V_S measurements

2. New Framework for Settlement Predictions under Working Loads Using Dynamic Soil Properties

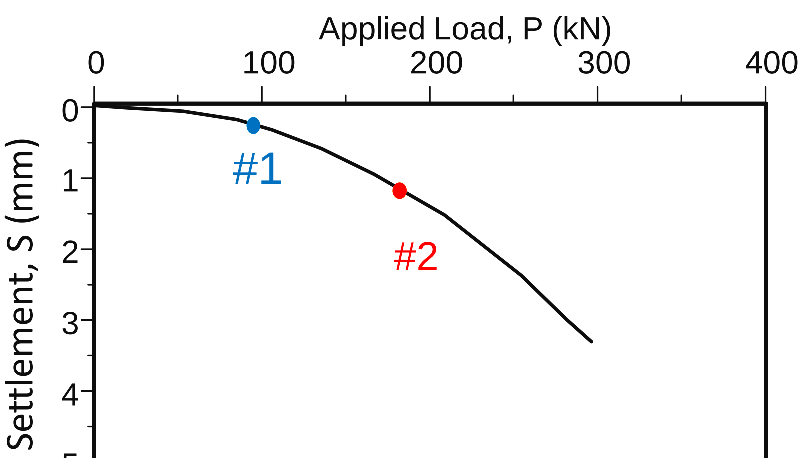
Framework:

- Requires Stiffness Parameters
- G Changing with γ and σ
- ν Changing with γ (but presently assumed ν = constant)

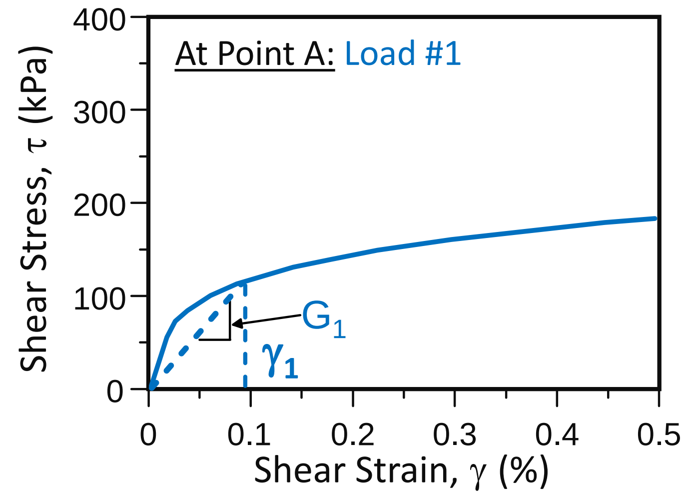
1. Loading Applied



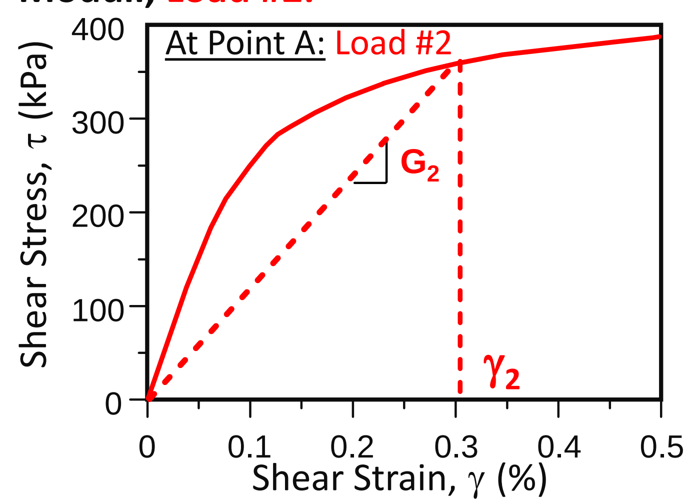
2. Load - Settlement Curve



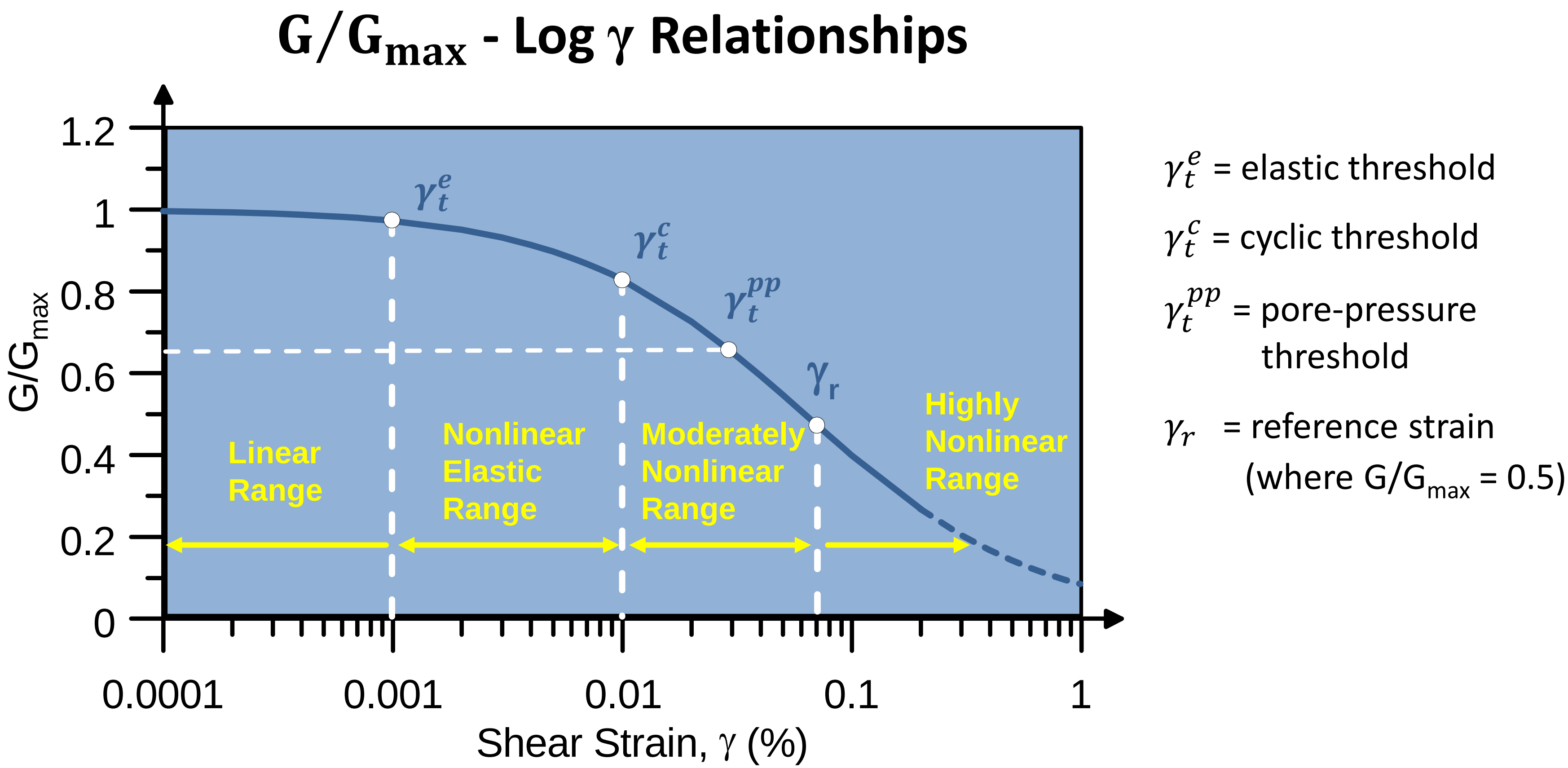
3. Stress - and Strain - Dependent Moduli, Load #1:



4. Stress - and Strain - Dependent Moduli, Load #2:



Background Information on Dynamic Soil Properties



Laboratory tests methods (torsional resonant column) made it possible to measure strains over a wide strain range beginning in the linear range and extending somewhat into the highly nonlinear range (γ ~ 0.2 to 0.3%).

Background Information on Dynamic Properties of Granular Soils

Linear (Small-Strain) Range

$$G_{max} = f(C_U, D_{50}, e, \sigma_0')$$

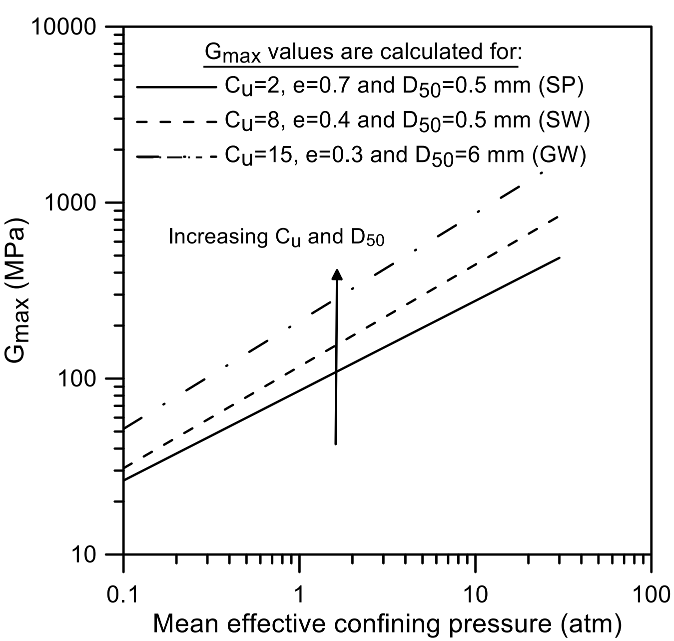
$$G_{max} = G_{max\_1atm} \cdot \left(\frac{\sigma_0'}{P_a}\right)^{n_G}$$

where:

G_{max_1atm} = small-strain shear modulus at σ_0' = 1 atm

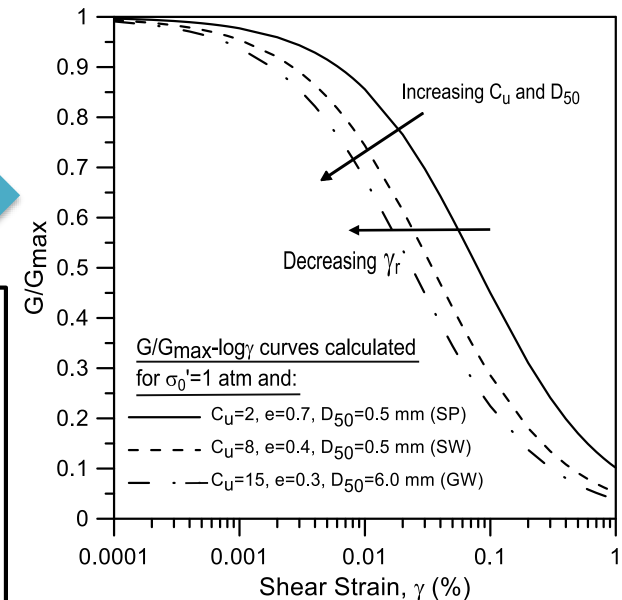
n_G = exponent of normalized confining pressure, and

P_a = atmospheric pressure.



Linear, Nonlinear-Elastic, and Moderately Nonlinear Ranges

G/G_{max} - log γ



Modified Hyperbolic Model

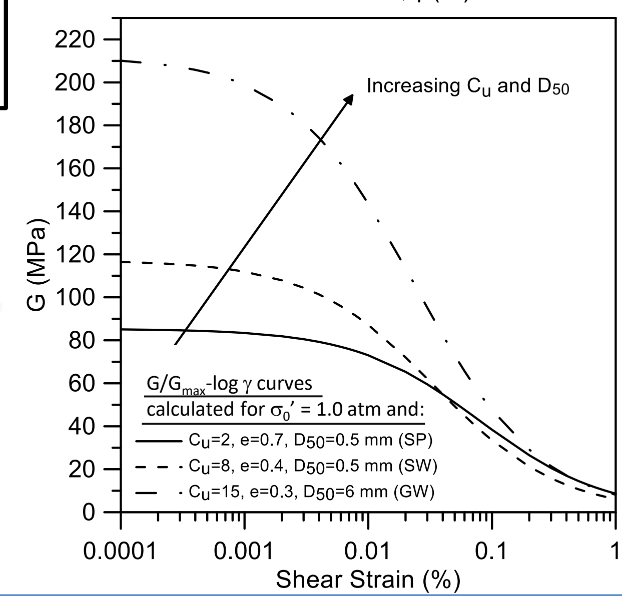
$$G/G_{max} = \frac{1}{1 + \left(\frac{\gamma}{\gamma_r}\right)^{a}}$$

where:

$\gamma_r = \gamma$ at $G/G_{max} = 0.5$, and

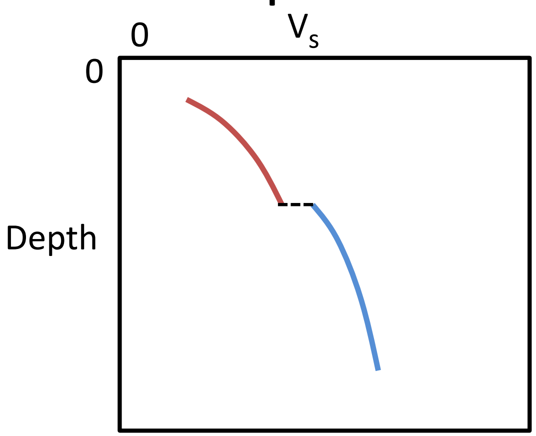
a is curvature coefficient.

G - log γ



3. Modeling with Dynamically Measured Soil Properties (MoDaMP)

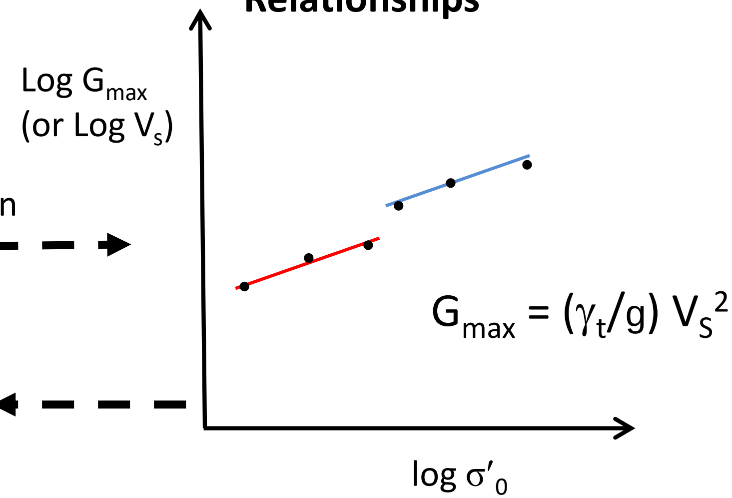
Step # 1 - Field Seismic Testing for V_s-Depth Profile



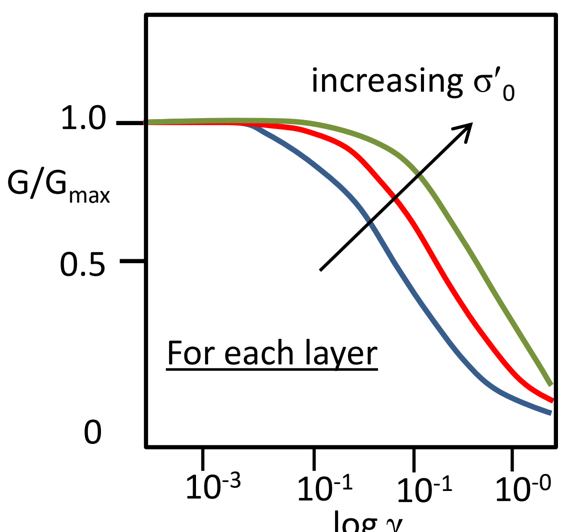
Develop Small-Strain

Field Relationships

Step # 2 - Field log G_{max} – log γ Relationships

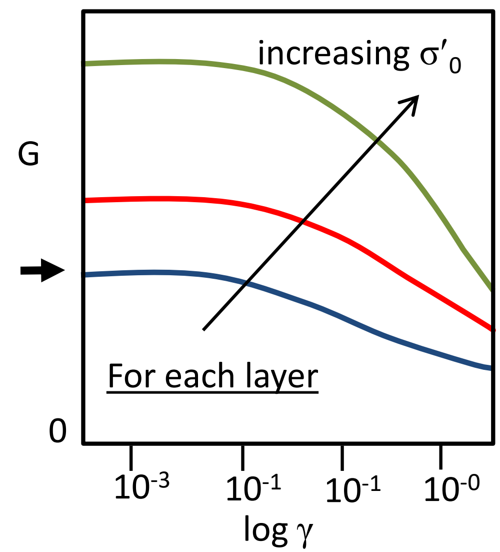


Step # 3 - Dynamic Laboratory Tests for G/G_{max} – log γ Relationships

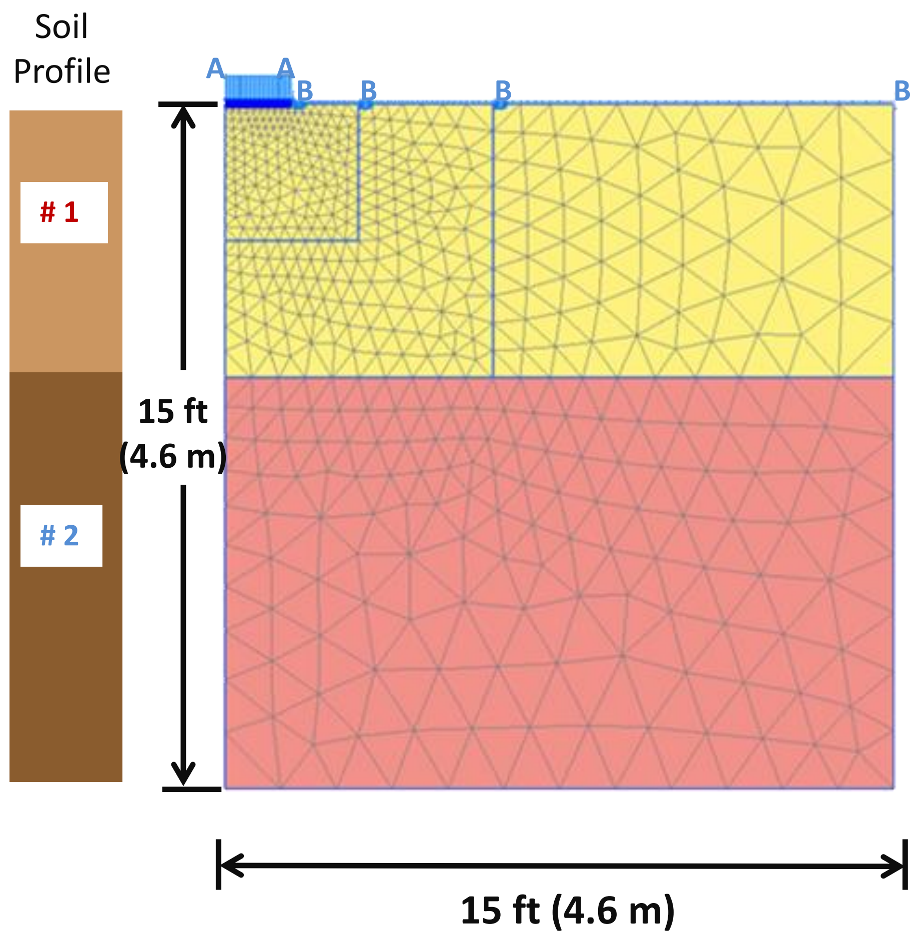


Combine

Step # 4 - Combine Field Seismic and Dynamic Laboratory Tests for G – log γ Relationships



PLAXIS Finite Element Model with MoDaMP

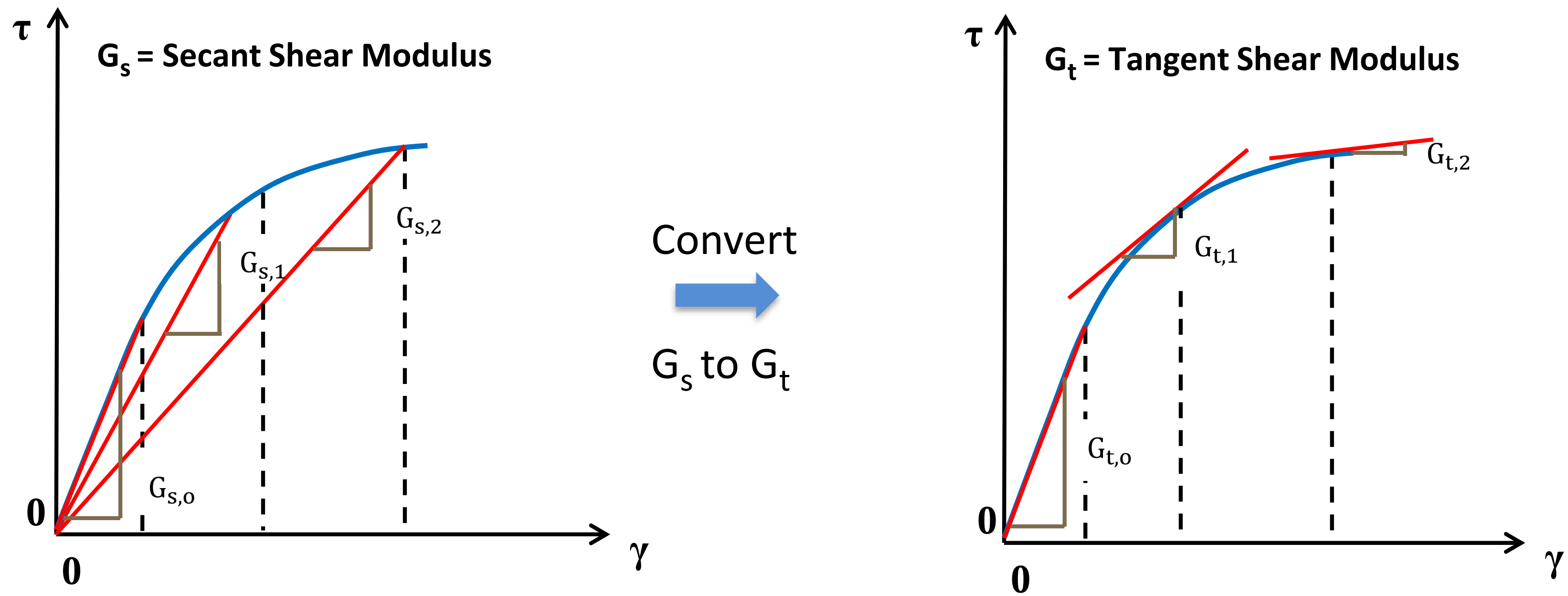


	Layer 1	Layer 2
G_{max_1atm}	1827 ksf	1980 ksf
ν_0	0.3	0.3
a	1.00	1.00
γ_r (%)	* Equation 6.3	* Equation 6.3

* Equation 6.3: $\gamma_r = 0.0200 \, log\left(\frac{\sigma_0}{P_a}\right) + 0.0277$

- 946, 15-node triangular elements.
- 15 x 15 ft (4.6 x 4.6 m) dimensions.
- Footings are modeled as flexible.
- Axisymmetric model.
- The lower boundary is fixed in both directions.
- The vertical boundaries are fixed only in the horizontal direction.

Modeling with Dynamically Measured Soil Properties (MoDaMP)



Using G values and Poisson's ratio, the elastic stiffness matrix is created

$$\begin{bmatrix} d\sigma_{xx} \\ d\sigma_{yy} \\ d\sigma_{zz} \\ d\sigma_{yz} \\ d\sigma_{zx} \\ d\sigma_{xy} \end{bmatrix} = \frac{2G_t}{(1-2\nu)} \begin{bmatrix} 1-\nu & \nu & \nu & 0 & 0 & 0 \\ \nu & 1-\nu & \nu & 0 & 0 & 0 \\ \nu & \nu & 1-\nu & 0 & 0 & 0 \\ 0 & 0 & 0 & (1-2\nu)/2 & 0 & 0 \\ 0 & 0 & 0 & 0 & (1-2\nu)/2 & 0 \\ 0 & 0 & 0 & 0 & 0 & (1-2\nu)/2 \end{bmatrix} \begin{bmatrix} d\varepsilon_{xx} \\ d\varepsilon_{yy} \\ d\varepsilon_{zz} \\ 2d\varepsilon_{yz} \\ 2d\varepsilon_{zx} \\ 2d\varepsilon_{xy} \end{bmatrix}$$

Verification of MoDaMP in the Elastic Range

MoDaMP was verified by predicting settlements of a rigid, circular footing on an elastic half-space.

1. From elastic theory (Richart et al., 1970):

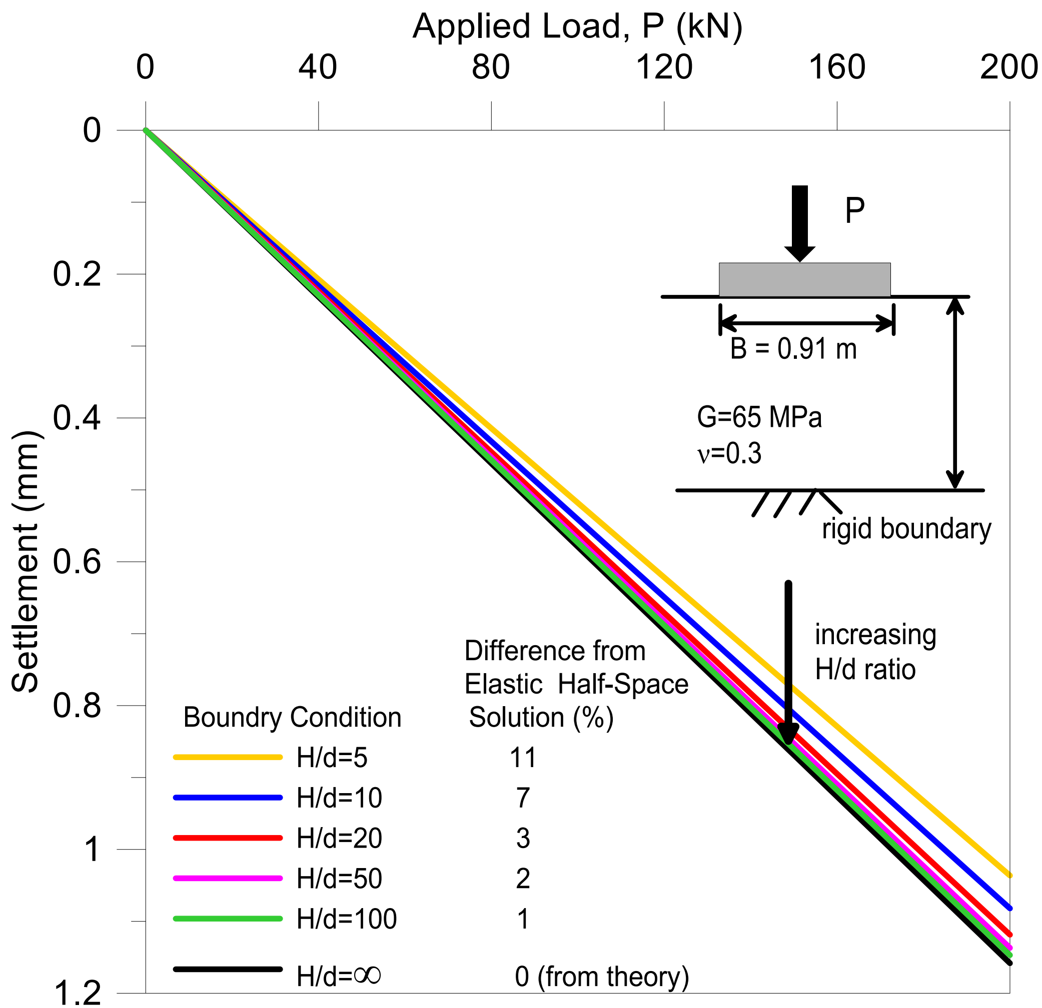
$$S = P\frac{1-\nu}{2GB}$$

   S = the settlement,
   P = the applied load and
   B = is the footing diameter

2. New framework implemented in PLAXIS:

   Using MoDaMP with

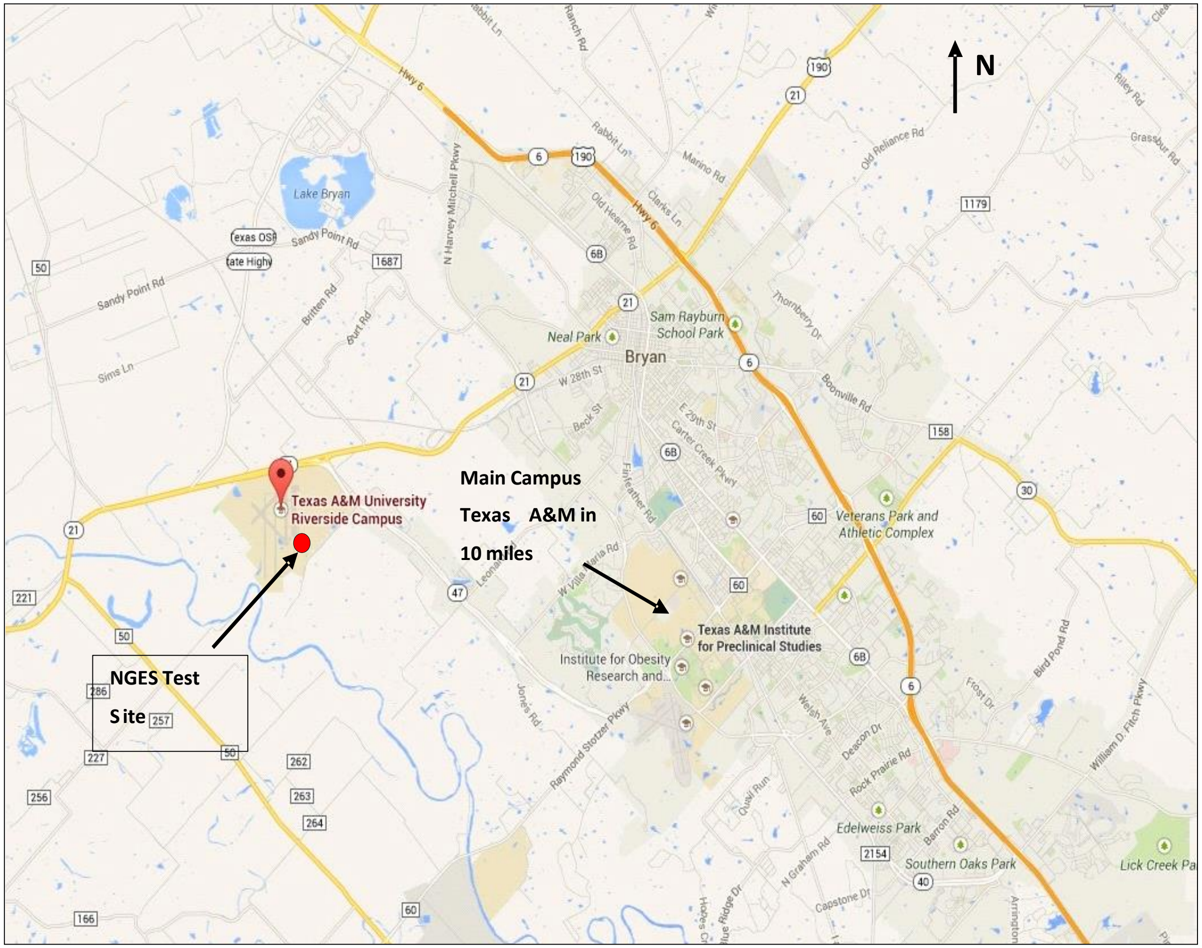
   γ_r =1000%,
   a =1.0 and
   n_G =0.0



4. Prediction Study:

Load-Settlement Tests at the NGES* Test Site

Developed at Texas A&M University

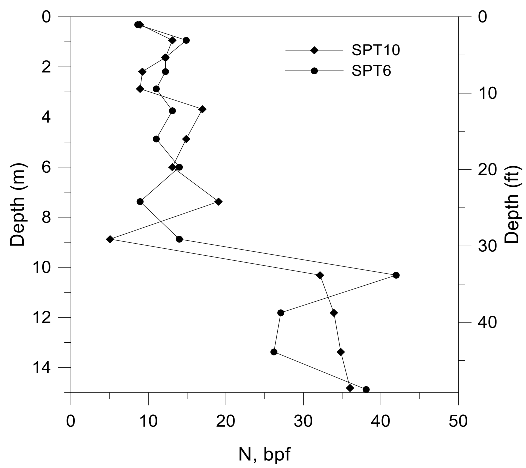


*NGES = National Geotechnical Experimentation Site

Characterization of the NGES Test Site

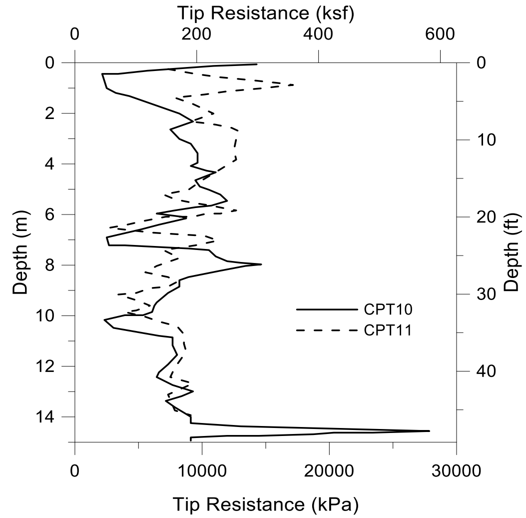
Field Penetration Testing and Field Seismic Testing

Traditional Field Testing



SPT

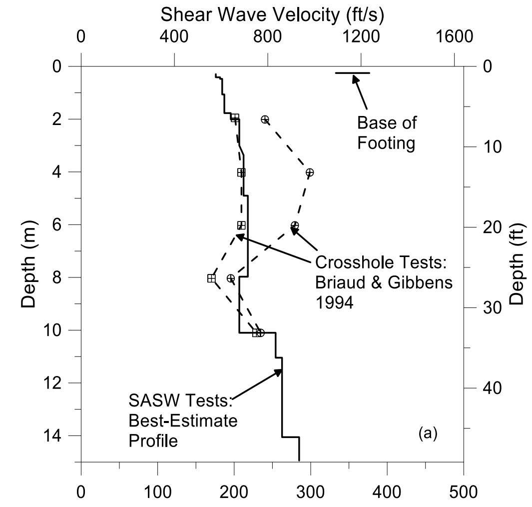
- Energy efficiency on average 53% (Briaud and Gibbens, 1994).
- N_{avg} ~12 between 3.5 ft and 30 ft.

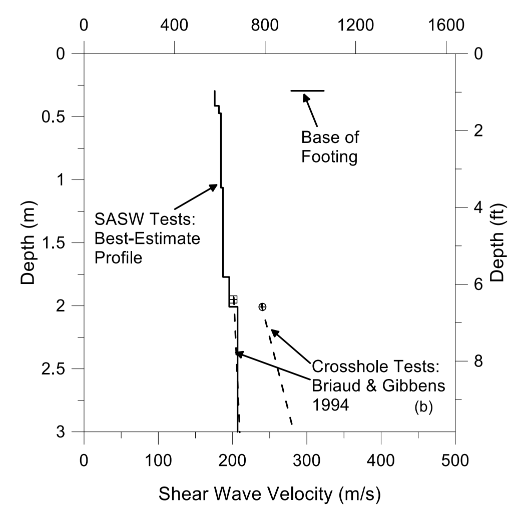


CPT

- Five soundings were performed.
- Two representative q_{tip} shown.

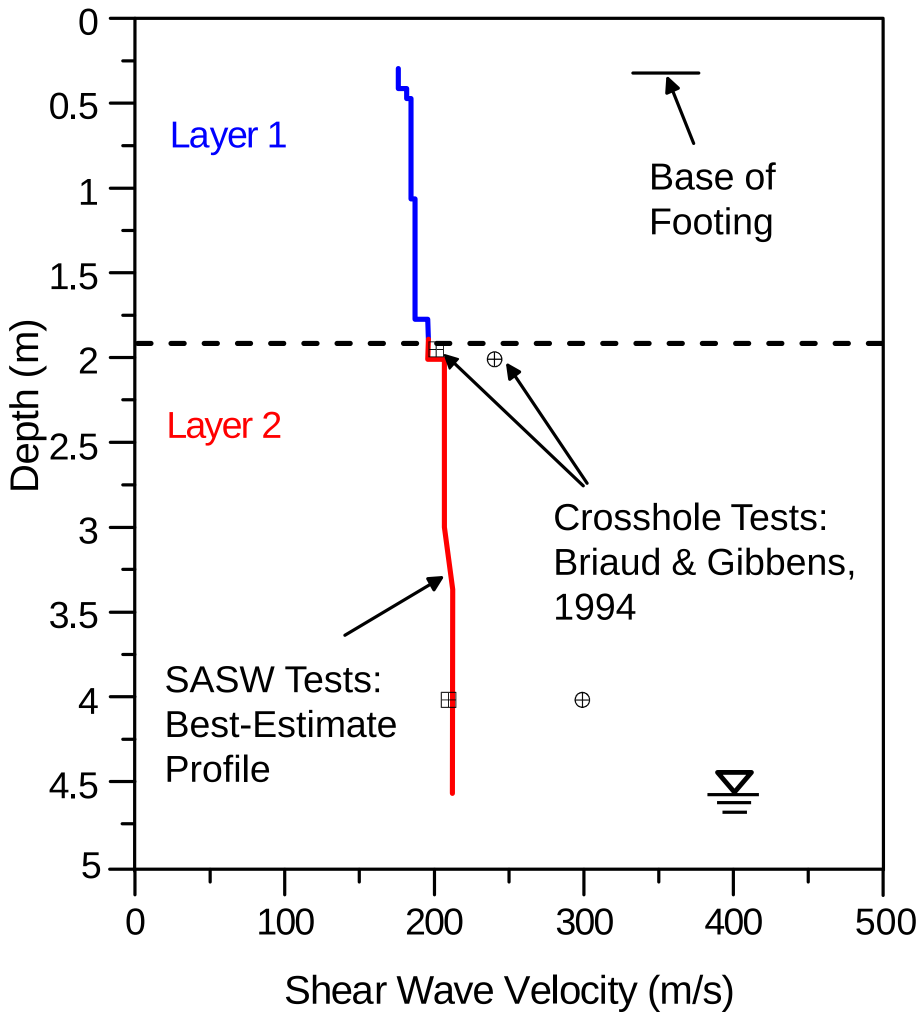
SASW (Park et al., 2009)



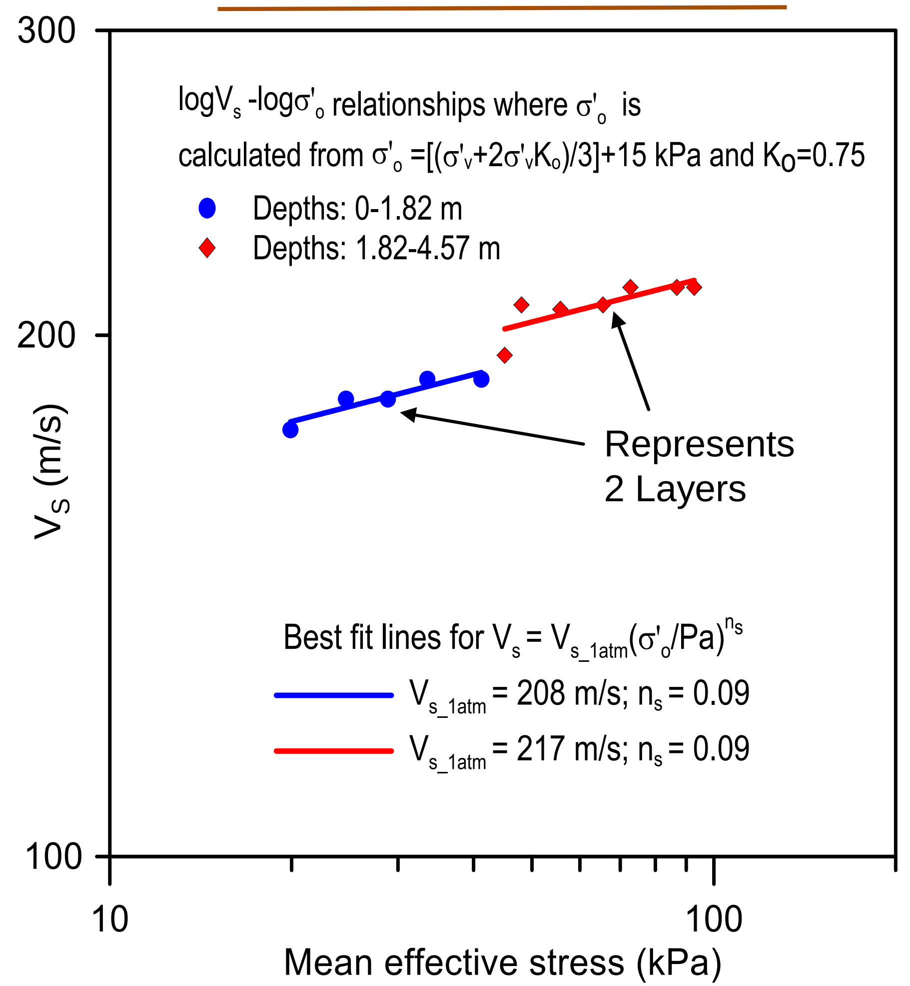


Characterization of the NGES Test Site

V_S – Depth Profile from Field Seismic Testing



Evaluated as if RC Test Results

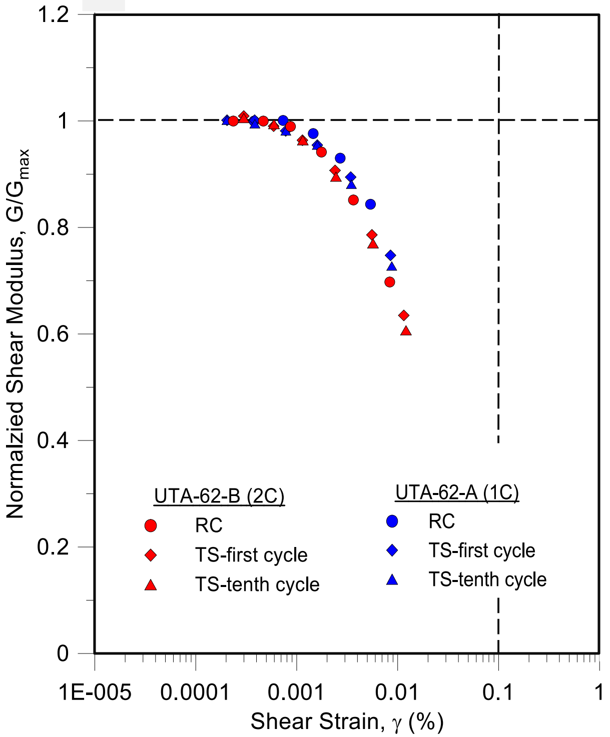


Characterization of the NGES Test Site

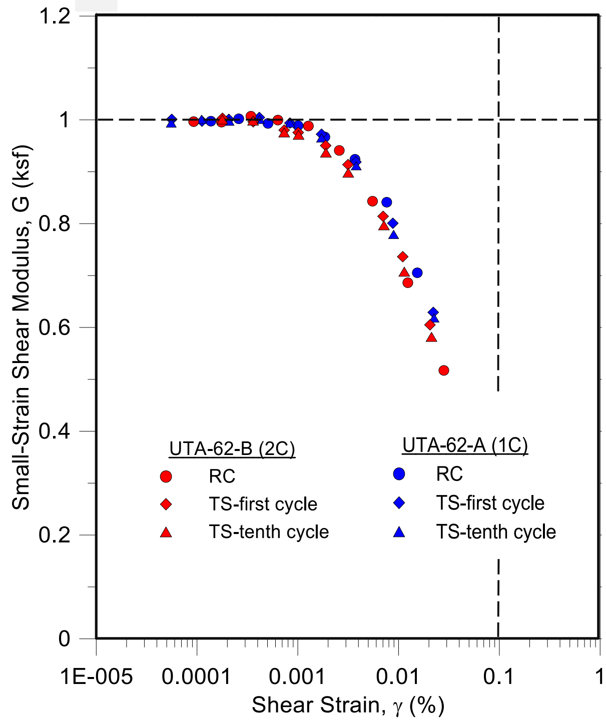
G/G_{max} - log γ Relationships from Laboratory RCTS Testing

Two, hand-carved, intact specimens

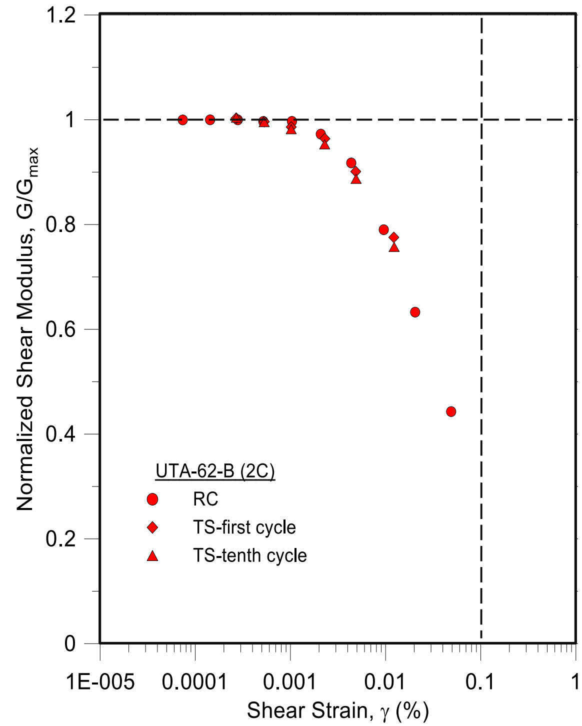
$\sigma_0' = 0.41$ atm (6 psi)



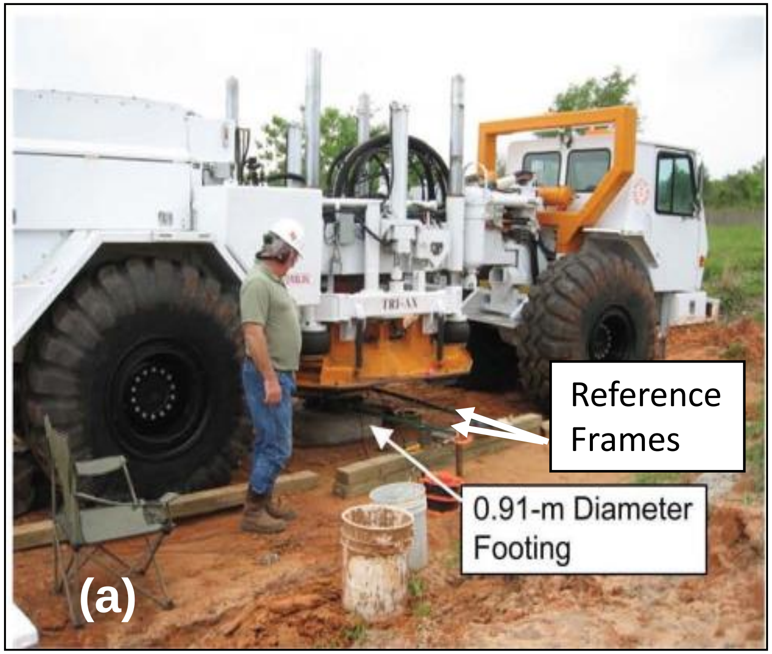
$\sigma_0' = 1.63$ atm (24 psi)

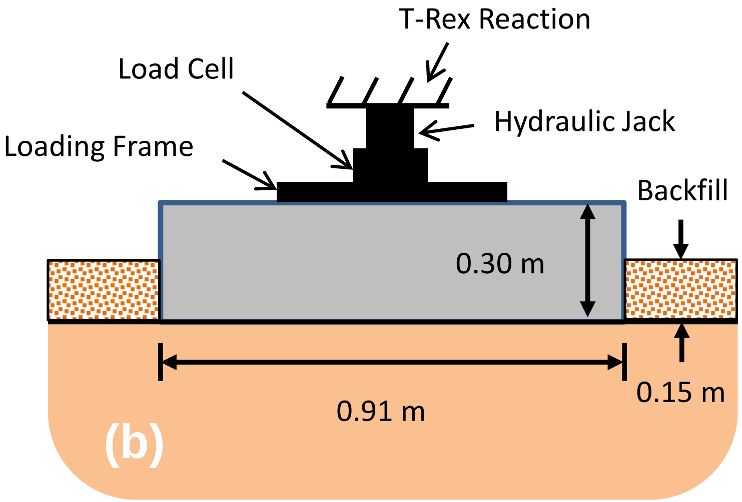


$\sigma_0' = 3.27$ atm (48 psi)

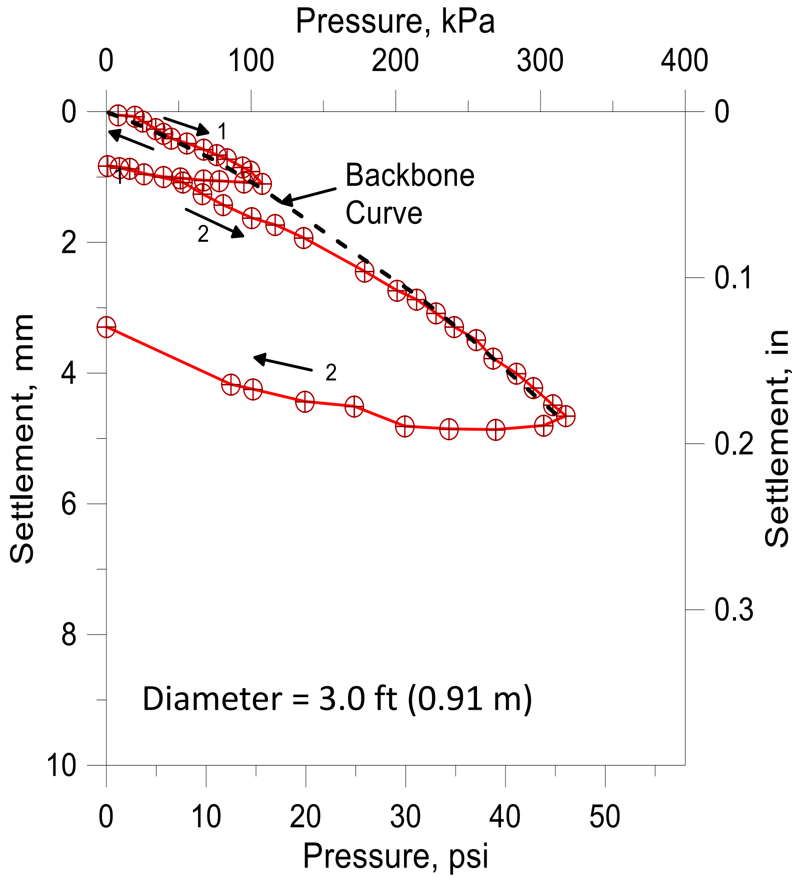


Load-Settlement Tests at the NGES Test Site





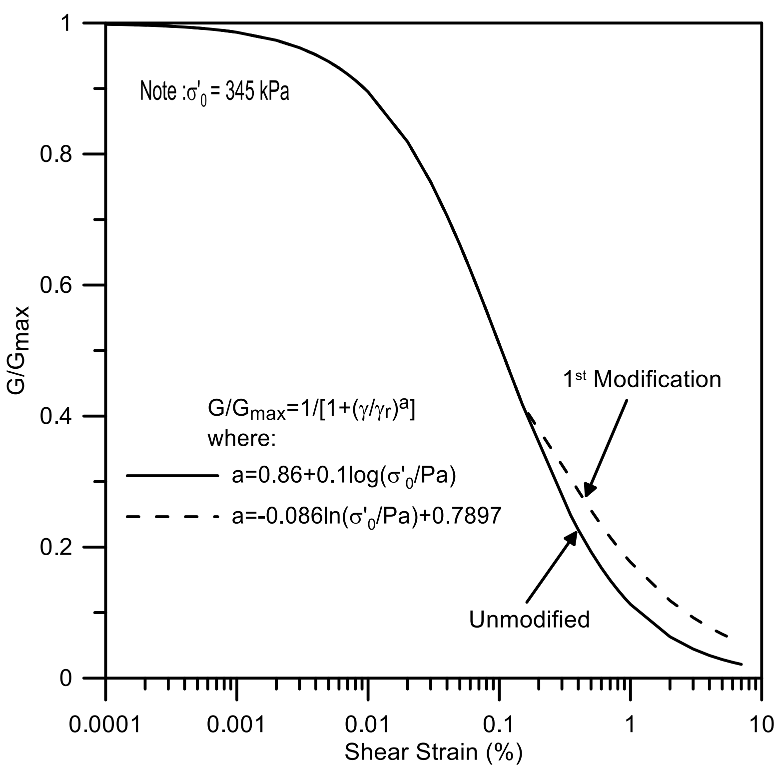
(c) Staged, Load-Settlement Tests (from Park et al., 2009)

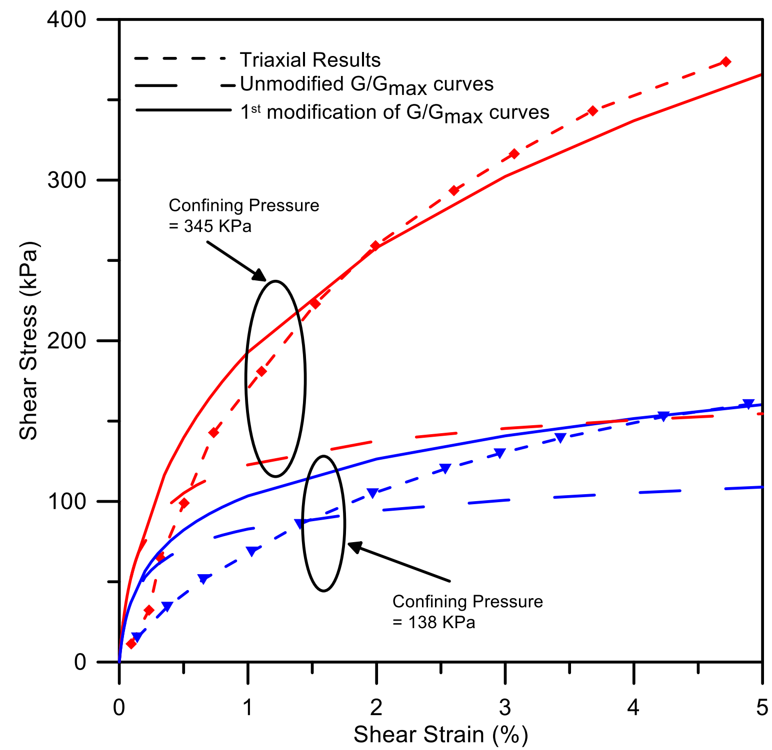


Load-Settlement Predictions with MoDaMP

- The G/G_{max} - log γ curves from RCTS tests are primarily developed over small-to-moderate values of γ, typically less than 0.2 %.
- A two-step procedure is used to modify G/G_{max} - log γ curves at larger strains:

<u>Step 1</u>: Adjusting the "a" coefficient at larger strains based on comparing the τ-γ relationships from the G/G_{max} - log γ curves and triaxial tests.



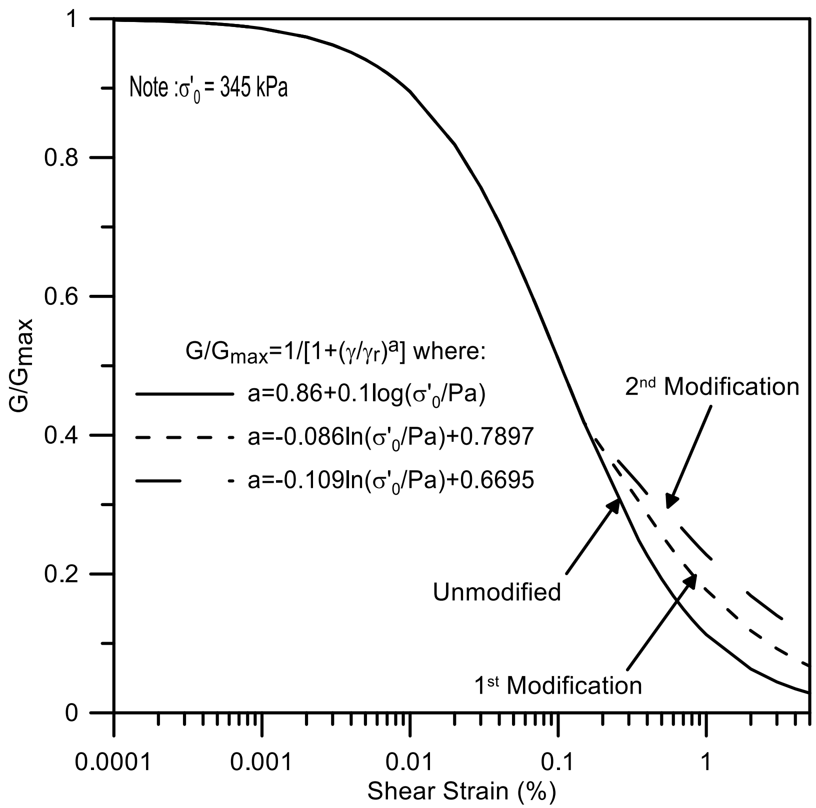


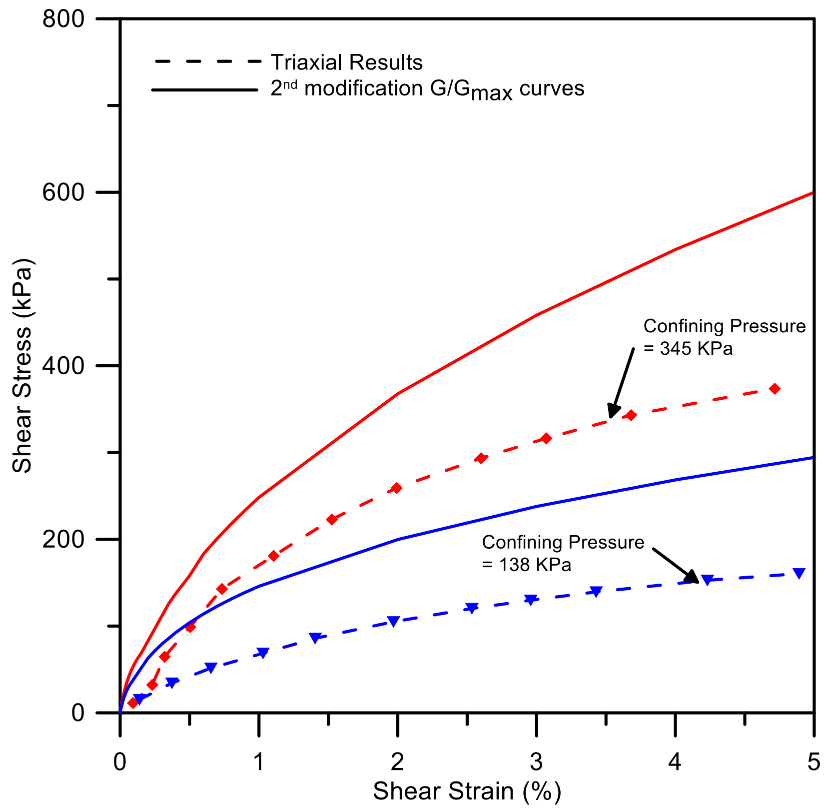
Load-Settlement Predictions with MoDaMP

After Step 1:

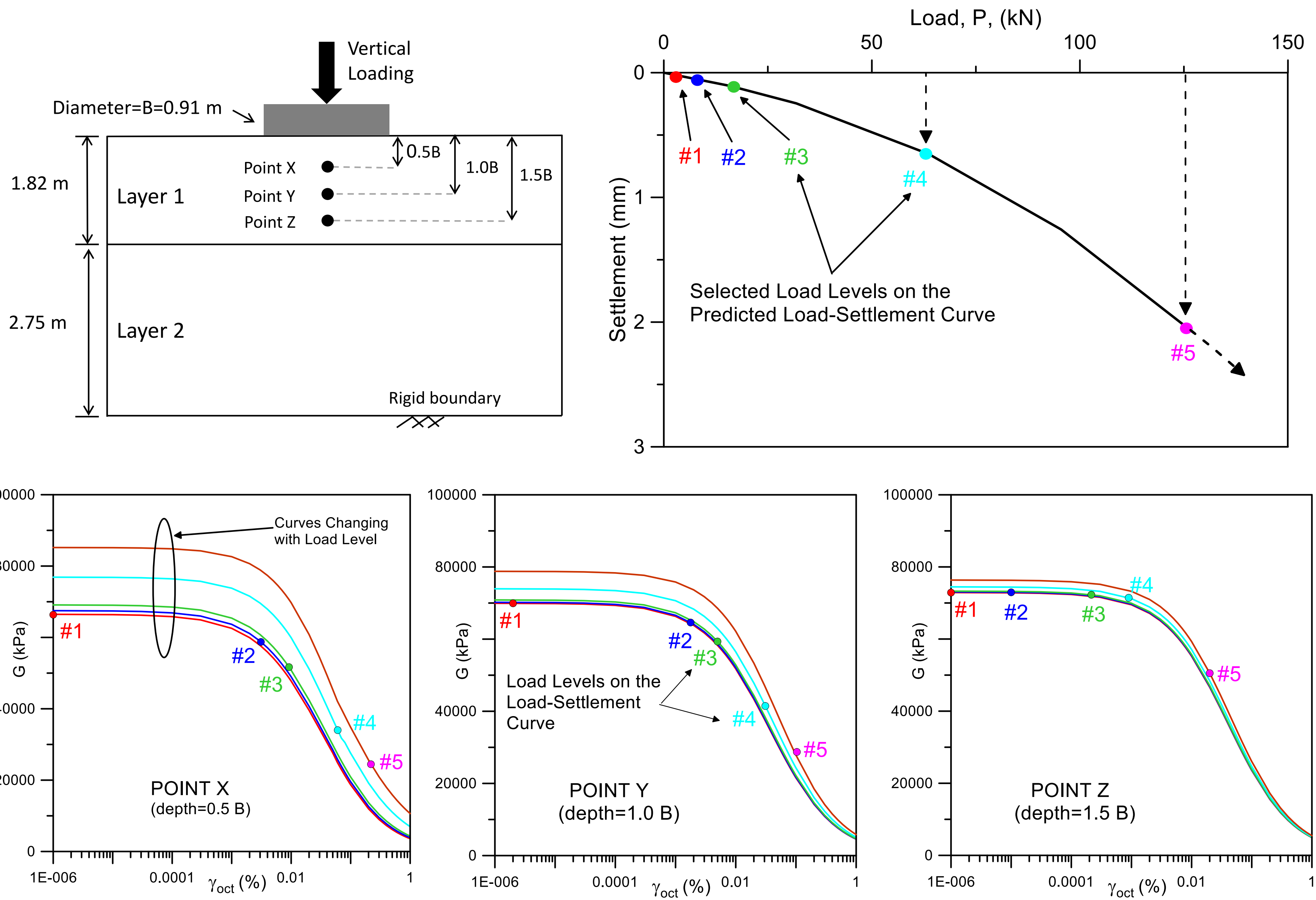
- The predicted settlements were higher than the measured settlements.

Step 2: Adjusting the larger-strain "a" to account for the higher horizontal stresses



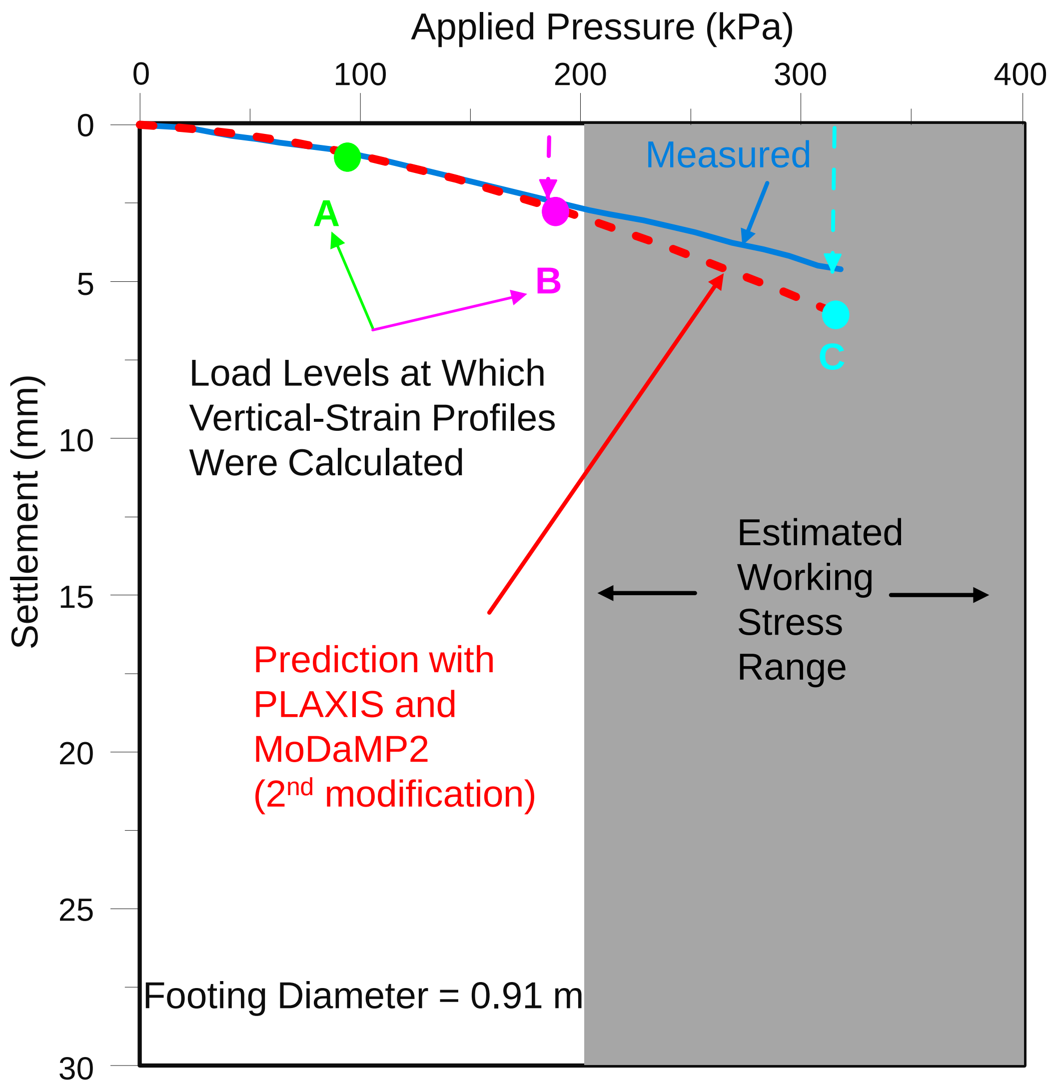


Example of How MoDaMP Works

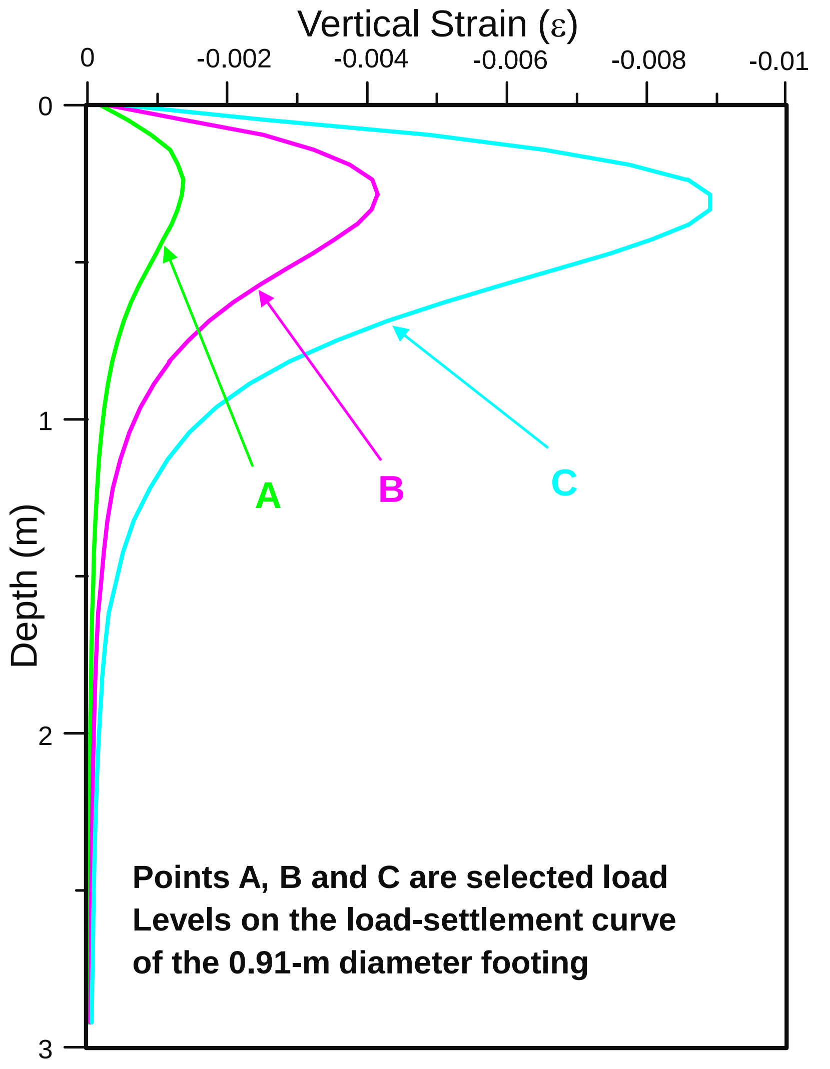


Load-Settlement Predictions with MoDaMP-2

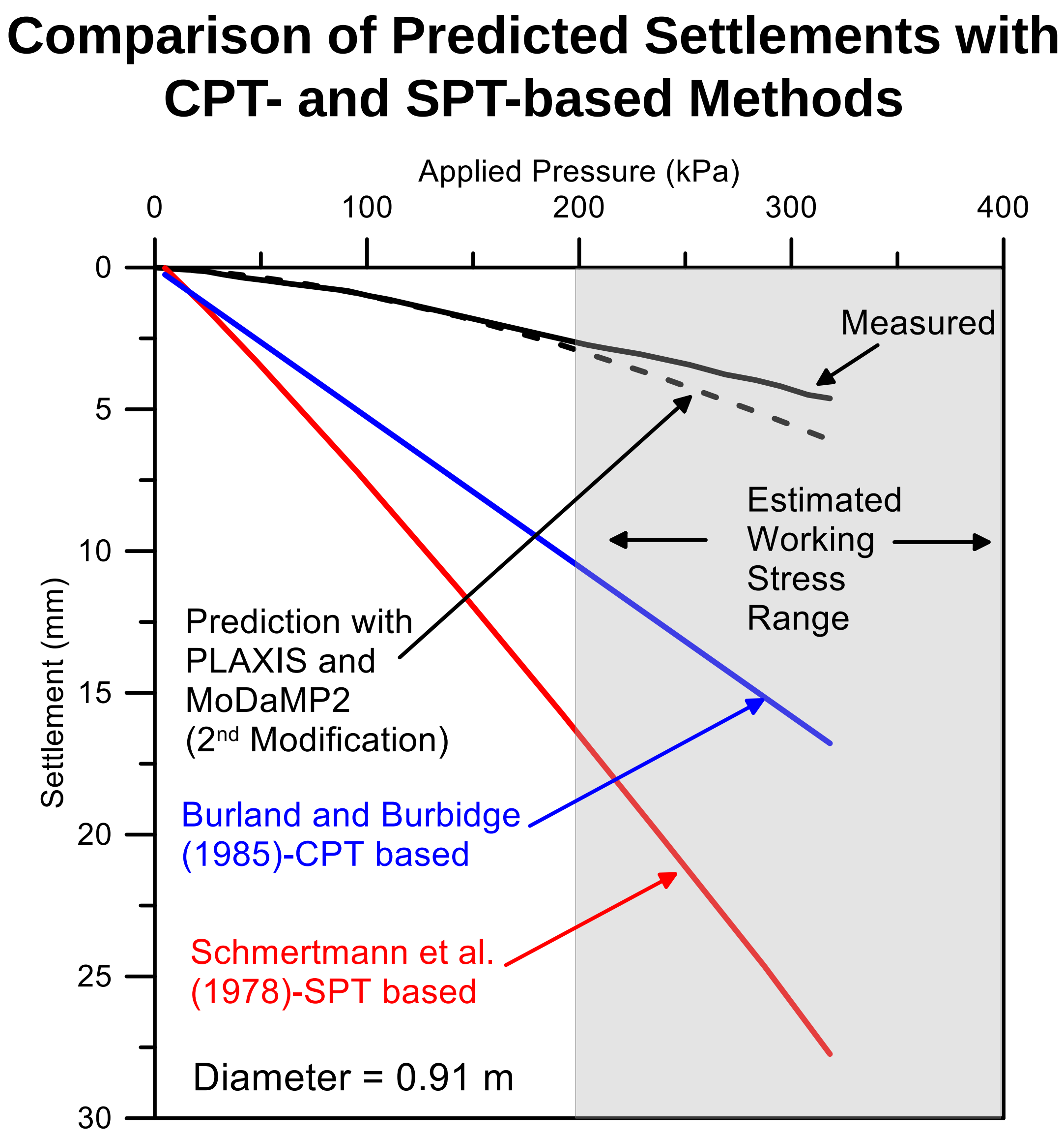
1. Comparison of Predicted and Measured Settlements



2. Predicted Vertical Strains Beneath the Centerline of Footing



Load-Settlement Predictions with MoDaMP



Conclusions: Framework for Predicting Settlements

1. Field seismic measurements are used to characterize the granular soil in terms of the small-strain shear modulus (G_{max}) profile.
2. G_{max} is combined with nonlinear normalized shear modulus-shear strain (G/G_{max}-log γ) relationships that are stress dependent and material dependent.
3. The G/G_{max}-log γ relationships are modified following a two-step process to extend them to strains in the range of several percent.
4. Nonlinearity in the load-settlement curves which was measured in the field tests was captured in the predicted settlements.

Acknowledgements

It is with great pleasure that the writers contribute this paper to the symposium honoring Professor Roy E. Olson. He is an outstanding teacher, researcher, mentor and friend and our interactions with him have enriched our lives.

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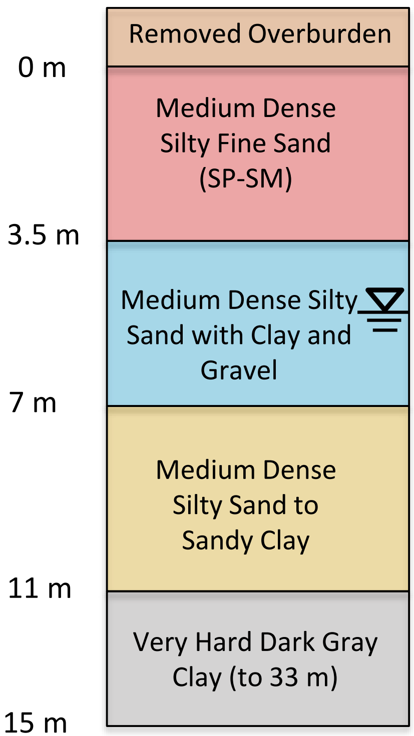
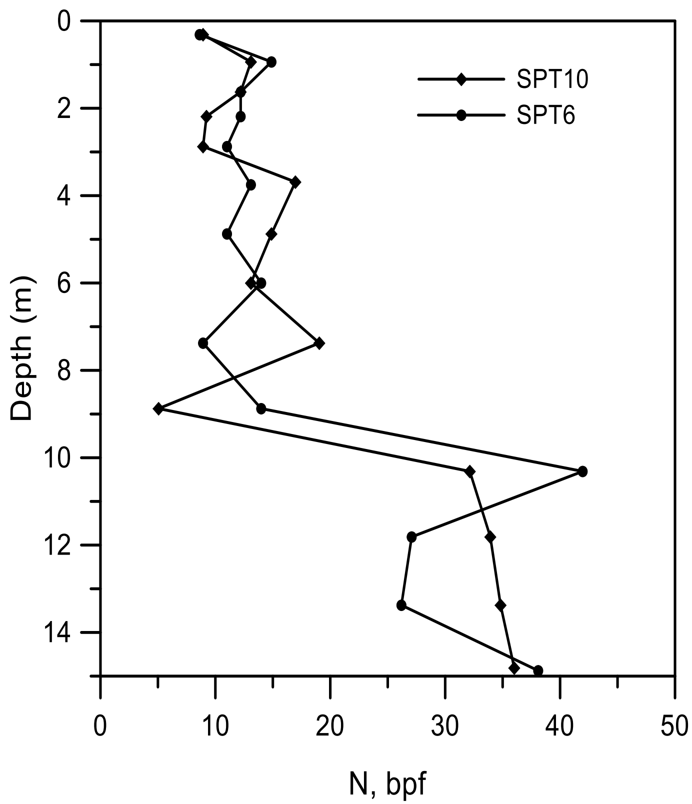
- The writers also appreciate the comments of the reviewers which helped significantly with content and balance of the article.

Soil Conditions at the Texas A&M, NGES* Test Site

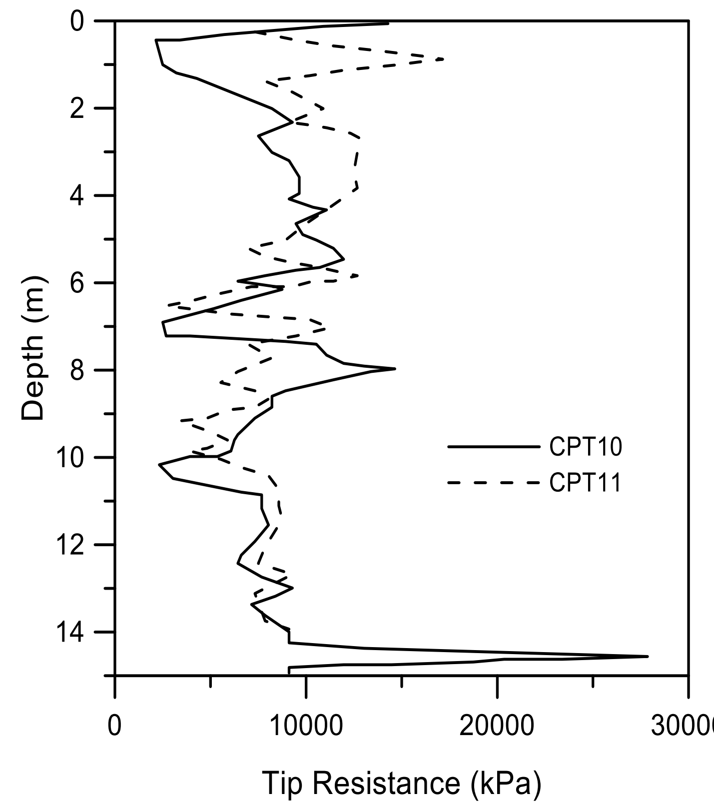
Soil Profile



SPT Blow Count



CPT Tip Resistance



* NGES = National Geotechnical Experimentation Site