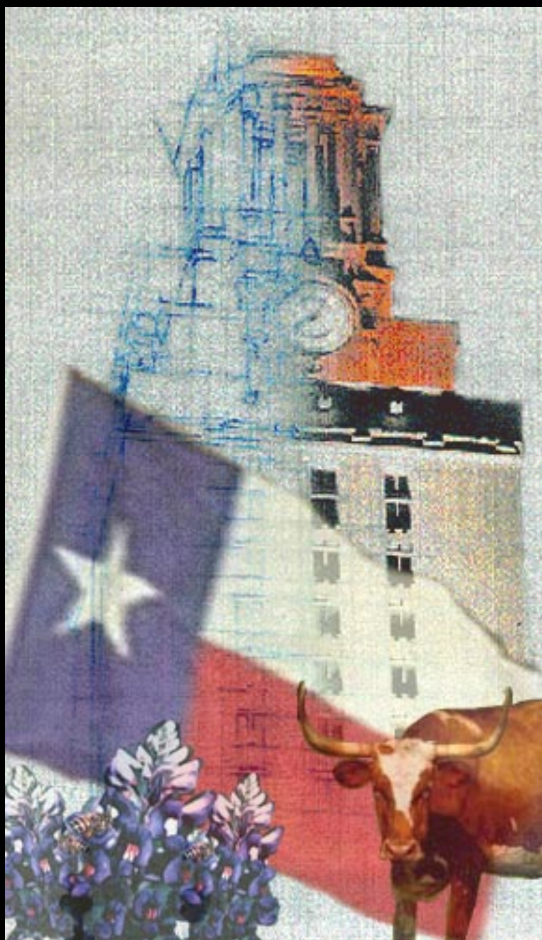
Characterizing Geotechnical Materials with Seismic Waves: Static and Dynamic Applications



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Foundation Performance Association
Houston, TX
8 November 2017

Outline

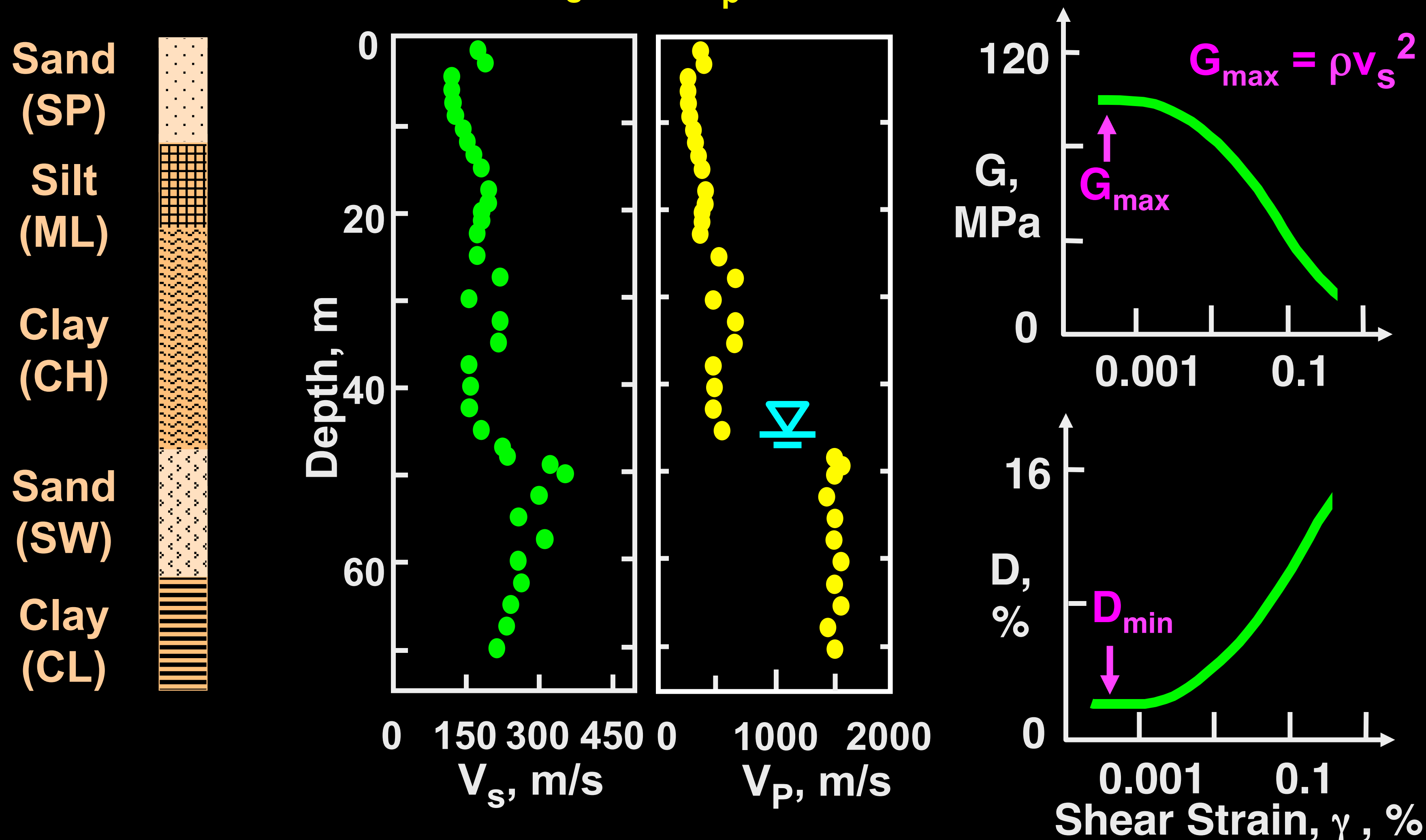
1. Brief Background
    - emphasize small-strain field measurements
    - laboratory tests used for parametric studies
2. Present a Number of Examples
    - static and dynamic problems
3. Show the Link Between Field and Laboratory Seismic Measurements
4. Concluding Remarks

1. Background: Field and Laboratory Seismic (Stress Wave) Measurements

1. Soil Profile

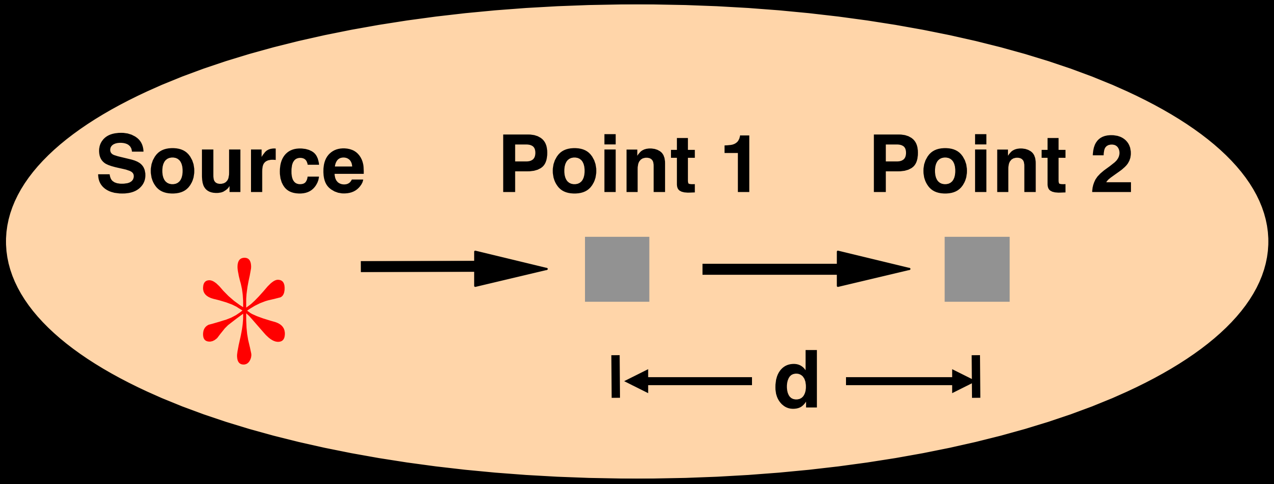
2. Field: Linear V_s and V_p

3. Lab: Linear and Nonlinear G and D



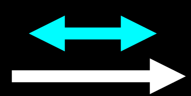
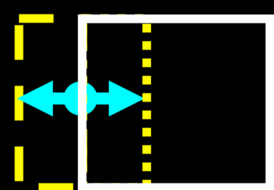
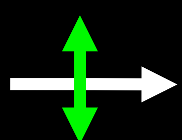
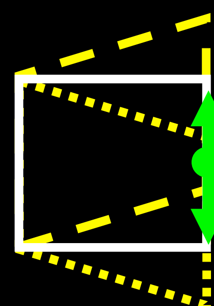
1a. Field: Seismic Measurements

Objective: measure time, t, for a given stress wave to propagate a given distance, d ... then velocity = d/t

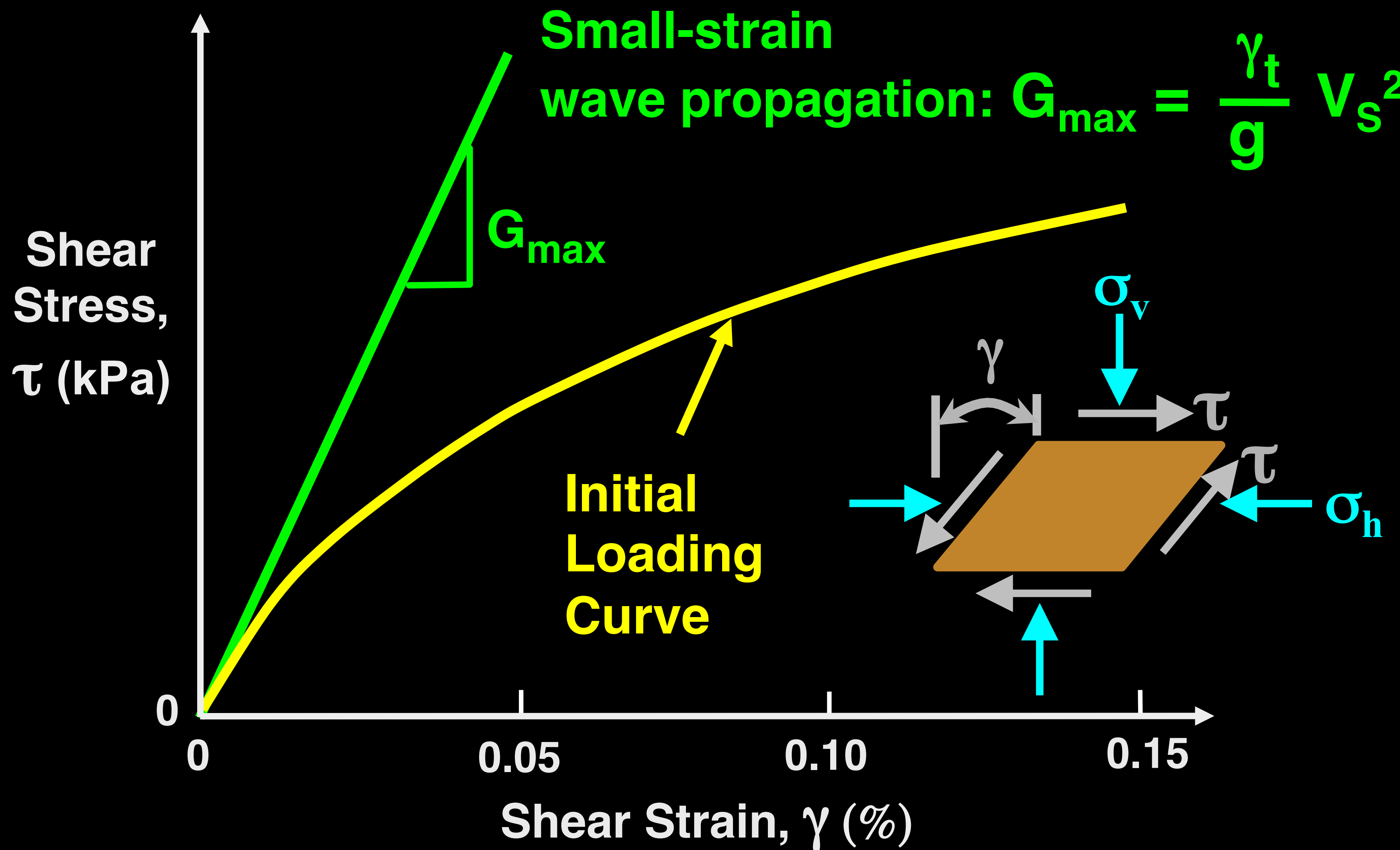


Key characteristics:
1. small-strain (linear) measurements
2. proper sources
3. oriented receivers

Field Measurements with Compression (P) and Shear (S) Waves

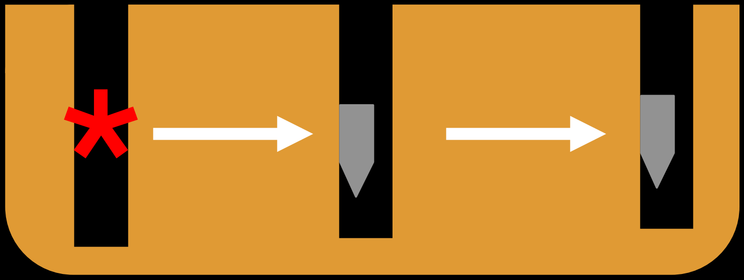
Wave Type	Particle Motion	Distortion	Wave Velocity	Small-Strain Modulus
P			V_p	$M_{max} = \frac{\gamma_t}{g} V_p^2$
S			V_s	$G_{max} = \frac{\gamma_t}{g} V_s^2$

Small-Strain Seismic Measurements

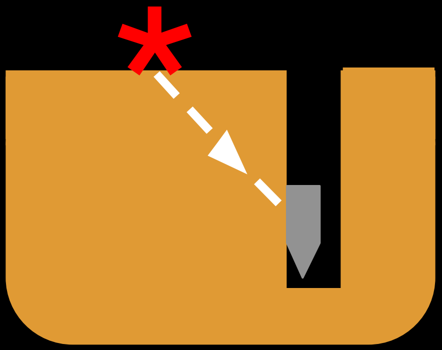


Field Seismic Methods

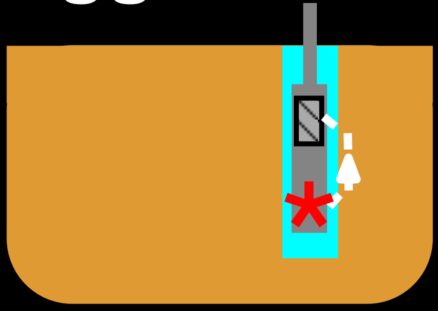
1. Crosshole



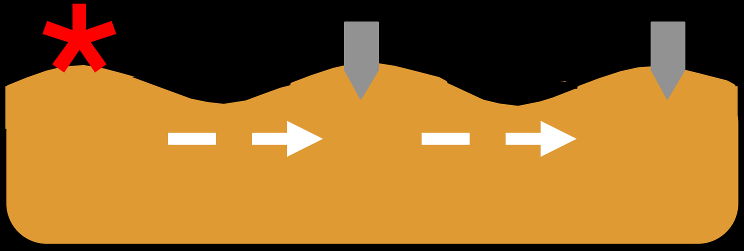
2. Downhole (Seismic CPT)



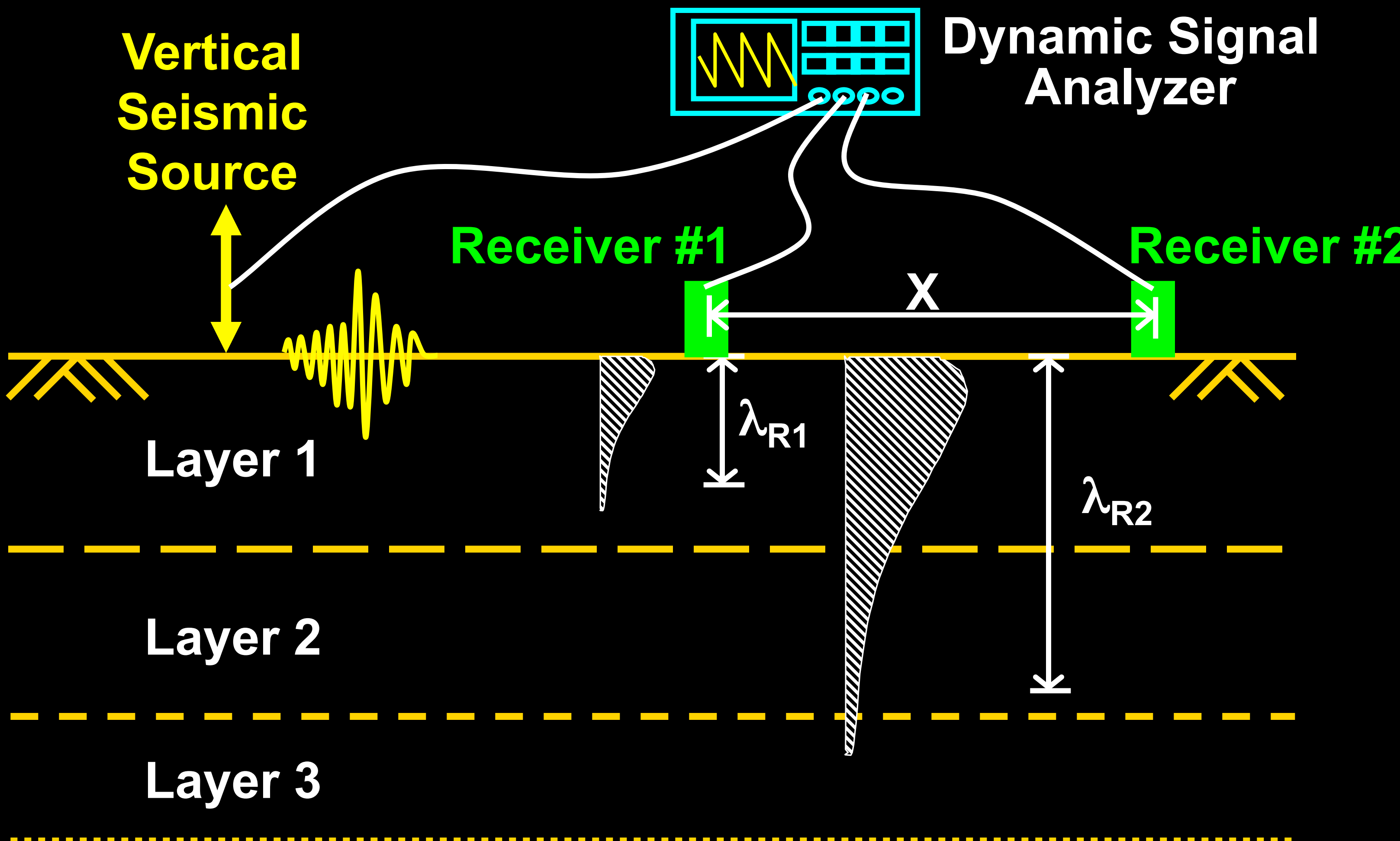
3. P-S Suspension Logger



4. Surface Waves

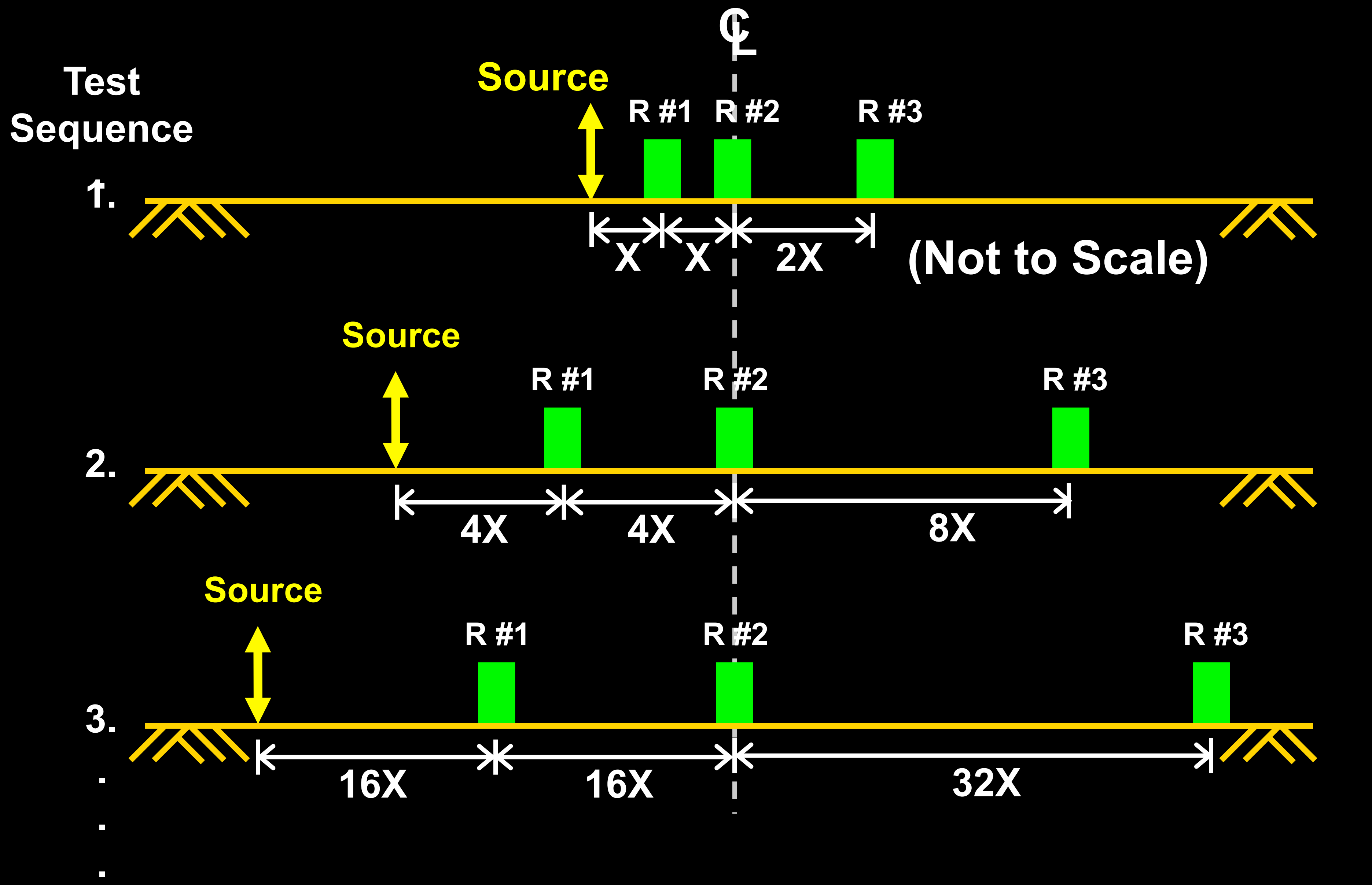


Overview of SASW*: Generalized Field Arrangement and Sampling



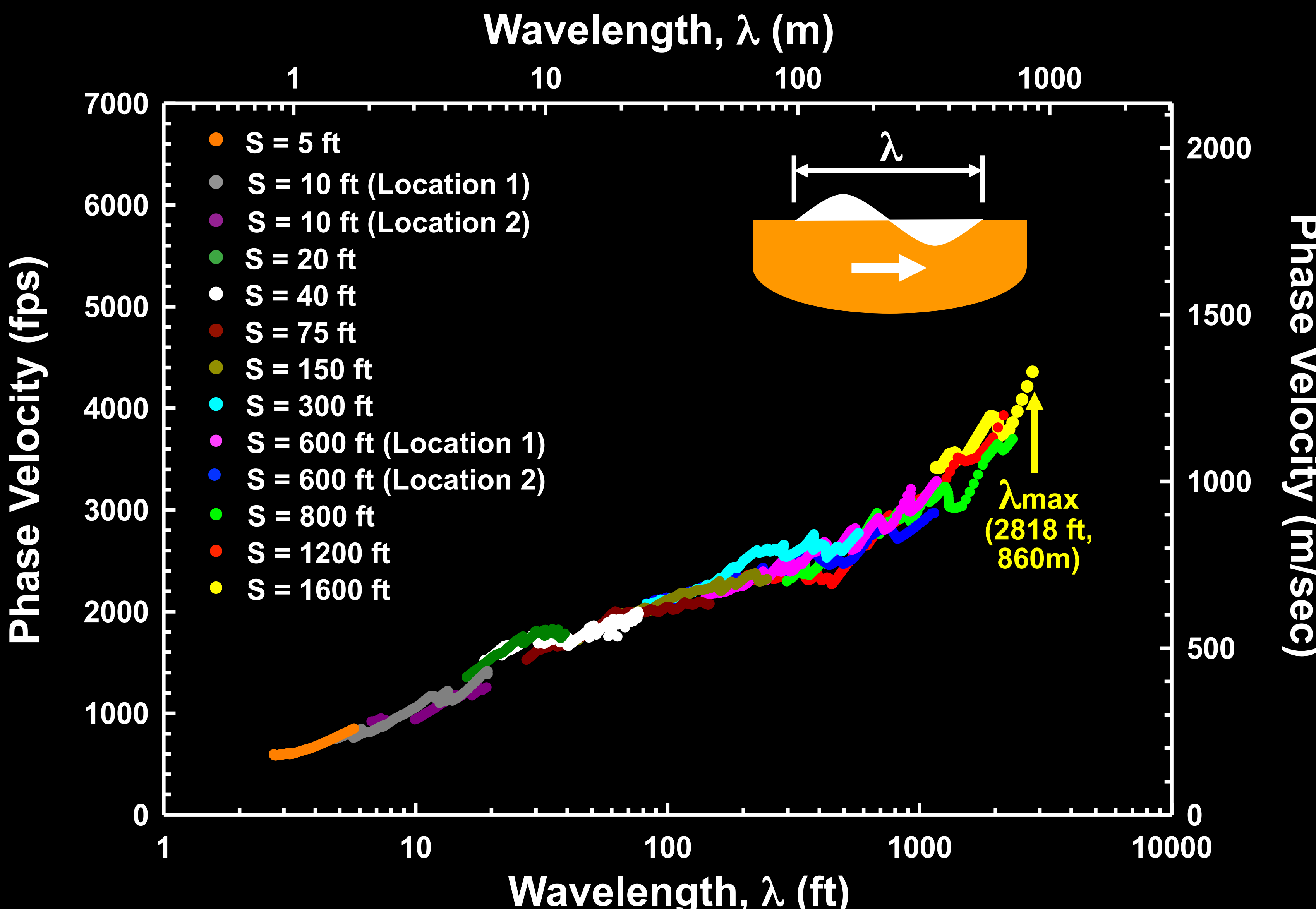
* SASW = Spectral Analysis of Surface Waves

Multiple Source-Receiver Positions

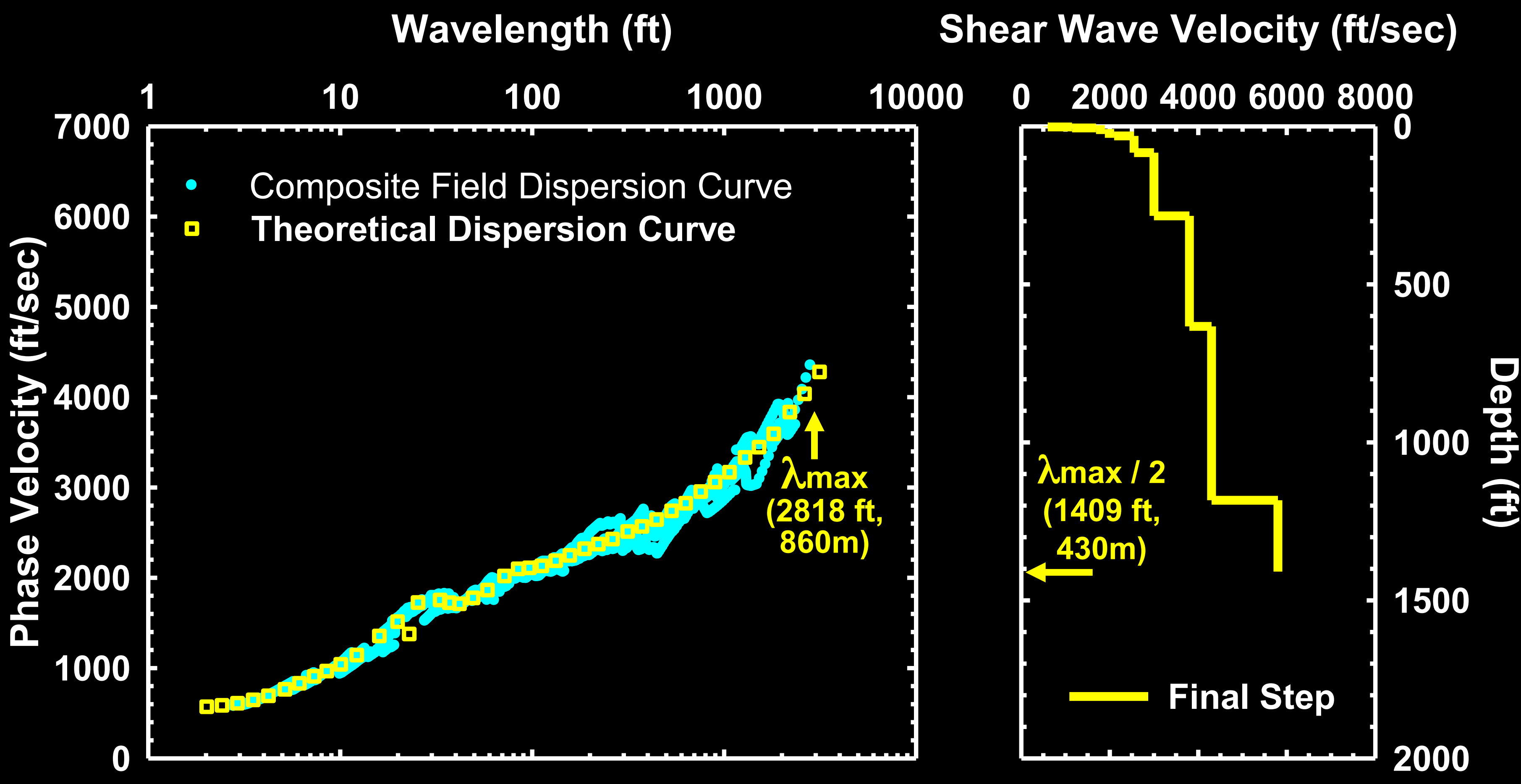


Liquidator Working as a Seismic Source on Top of Yucca Mountain

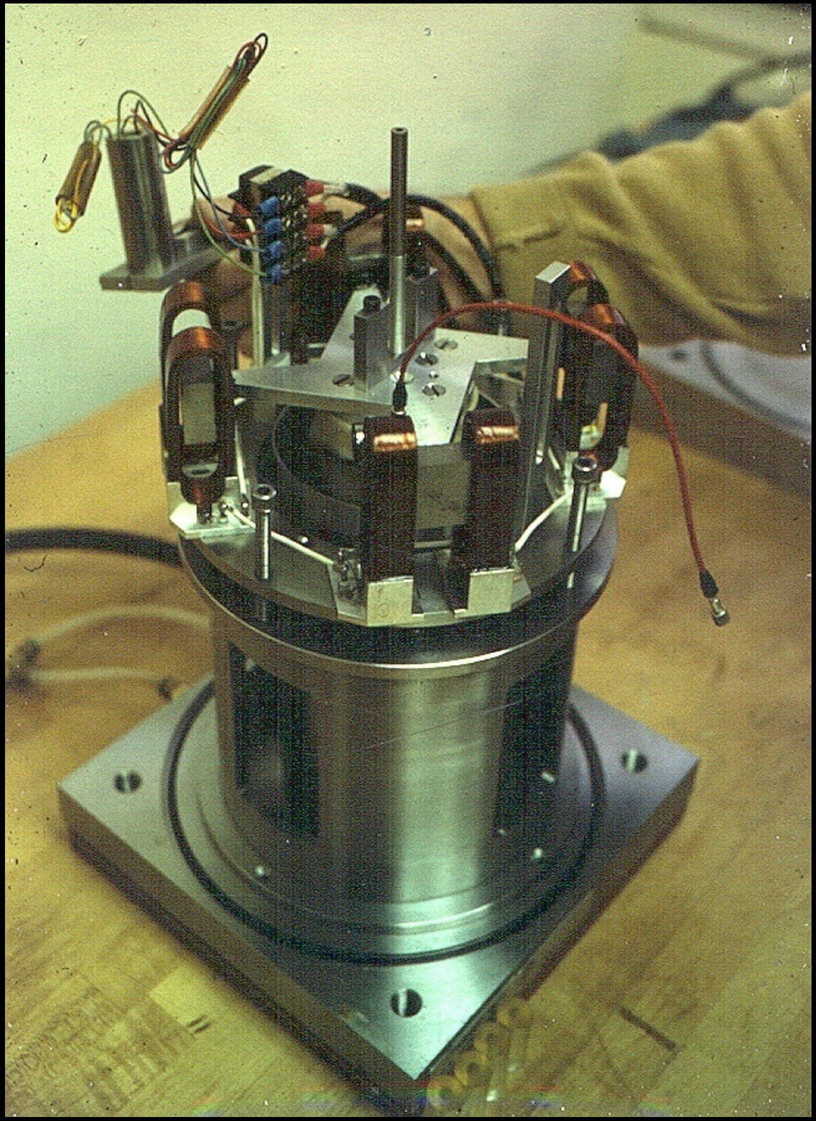
Composite Field Dispersion Curve Generated from All Receiver Spacings

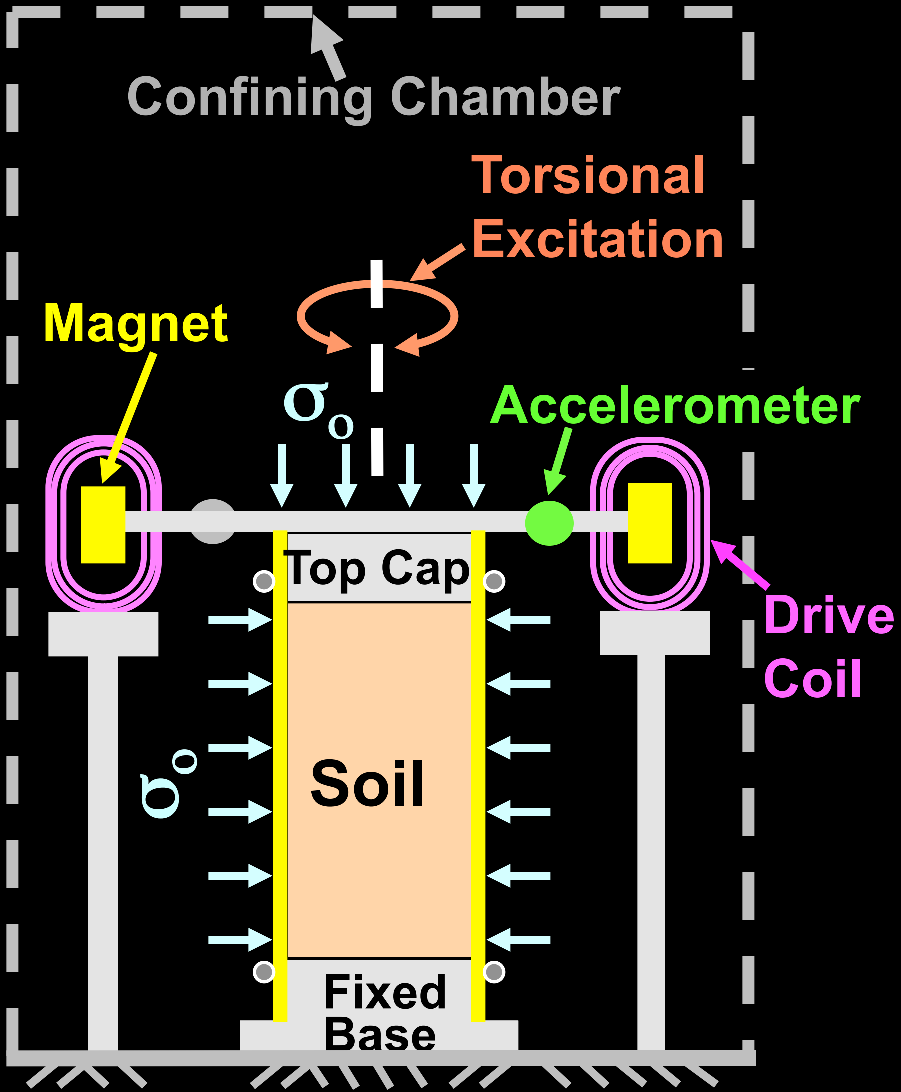


Best-Match Theoretical Dispersion Curve (Final Step in Forward Modeling)



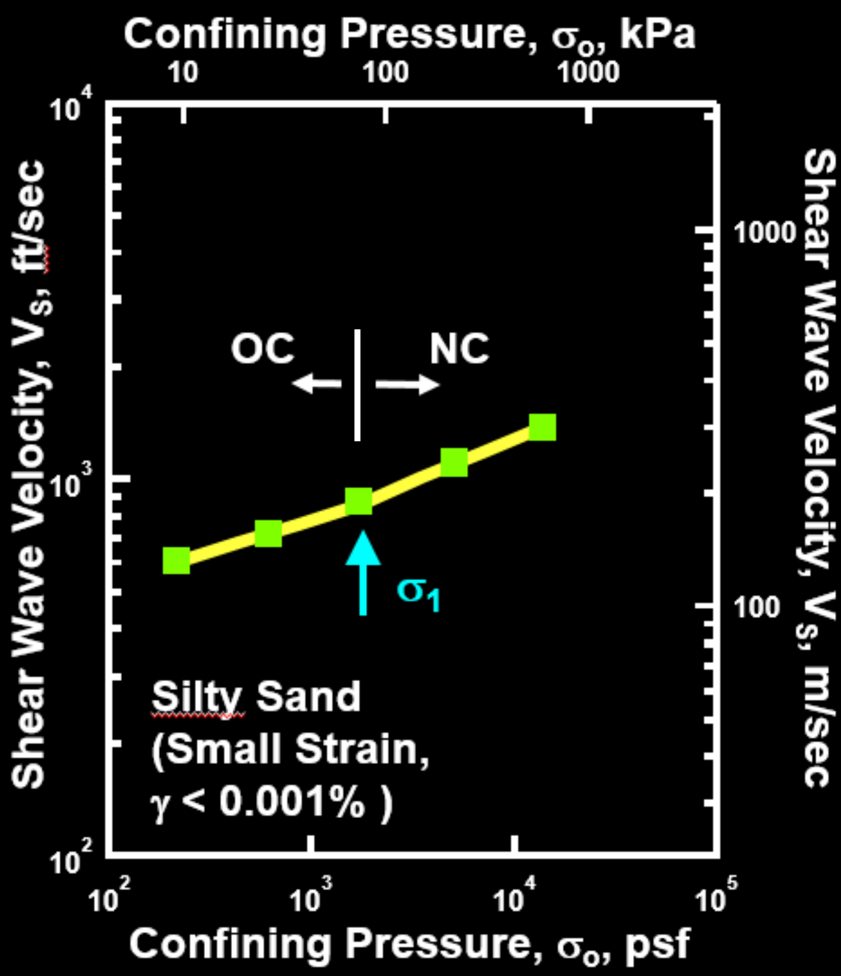
1b. Laboratory: Combined Resonant Column and Torsional Shear (RCTS) Test



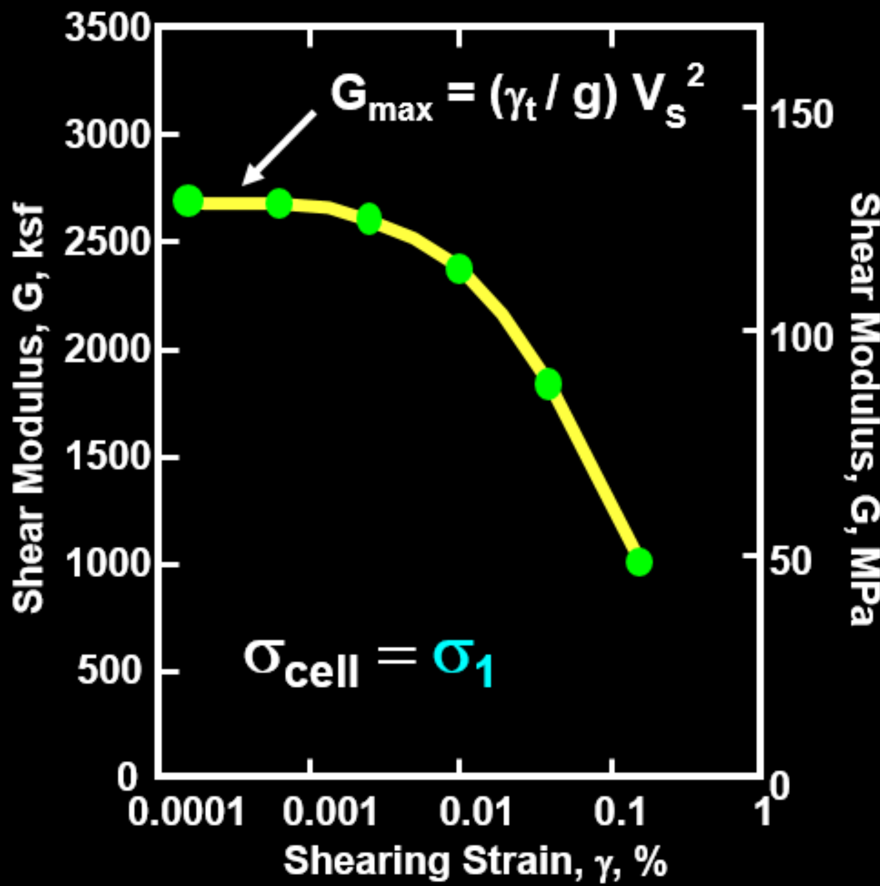


Laboratory Parametric Studies

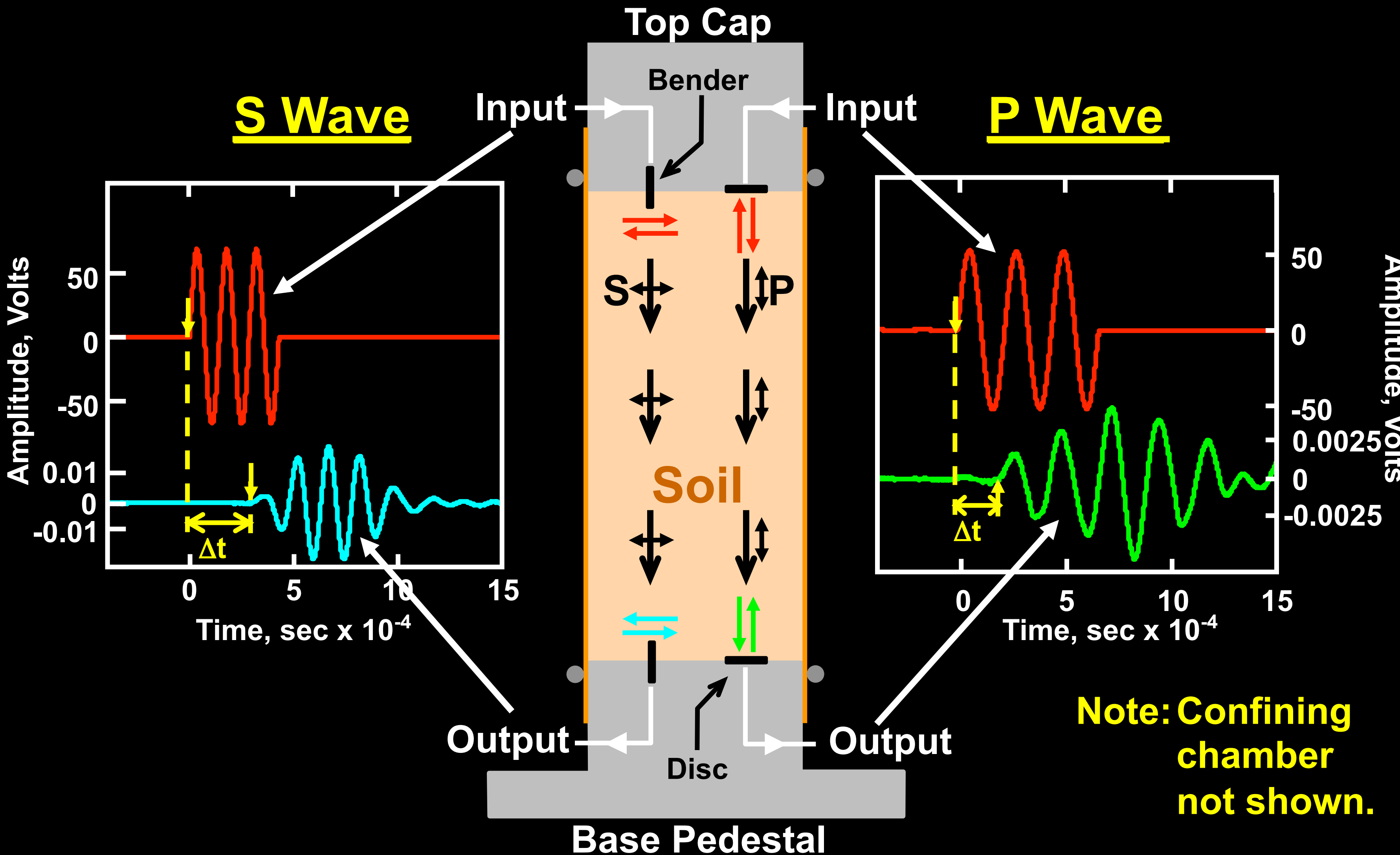
a. Log V_s – log σ_o



b. G – log γ



Small-Strain V_p and V_s Measurements: Piezoelectric Transducers



Note: Confining chamber not shown.

2. Examples: Applications and Case Histories

- static loading conditions
- dynamic loading conditions

Static Loading Conditions

2.1 Site Characterization

- layering, ground water table, etc.
- underground structures
- tunnel investigations *
- dams, levees, etc. *
- SMW landfills

2.2 Process Monitoring

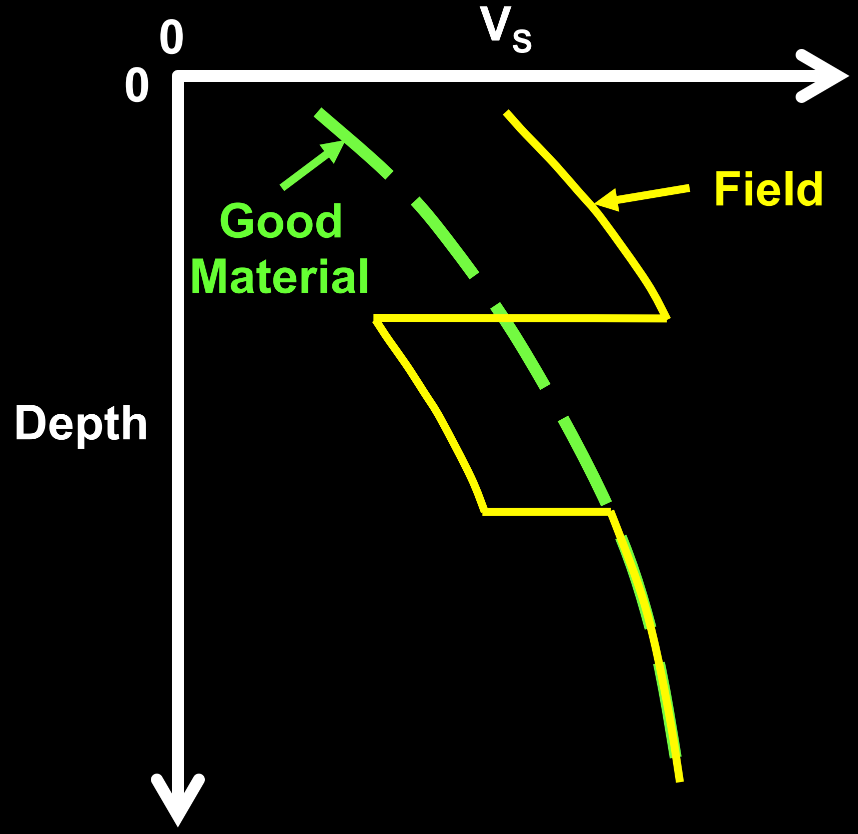
- grouting evaluations
- ground improvement studies *
- areas of deterioration
- sample disturbance

2.3 Movements under Static Loads

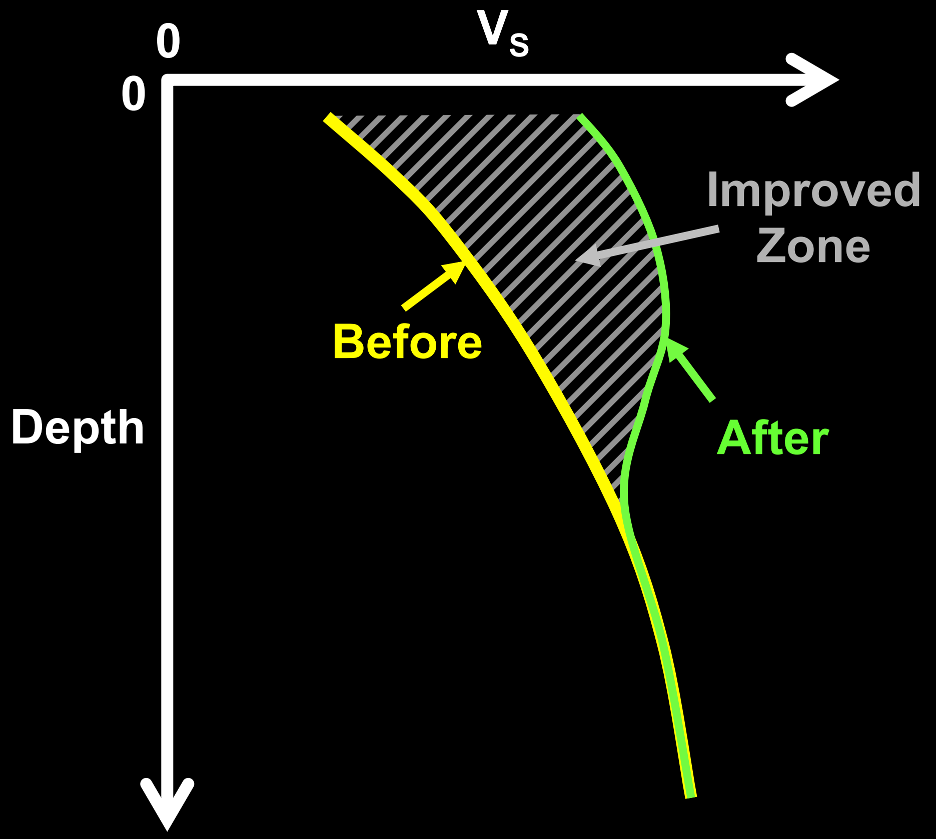
- footing settlements *
- retaining wall movements

General Approach

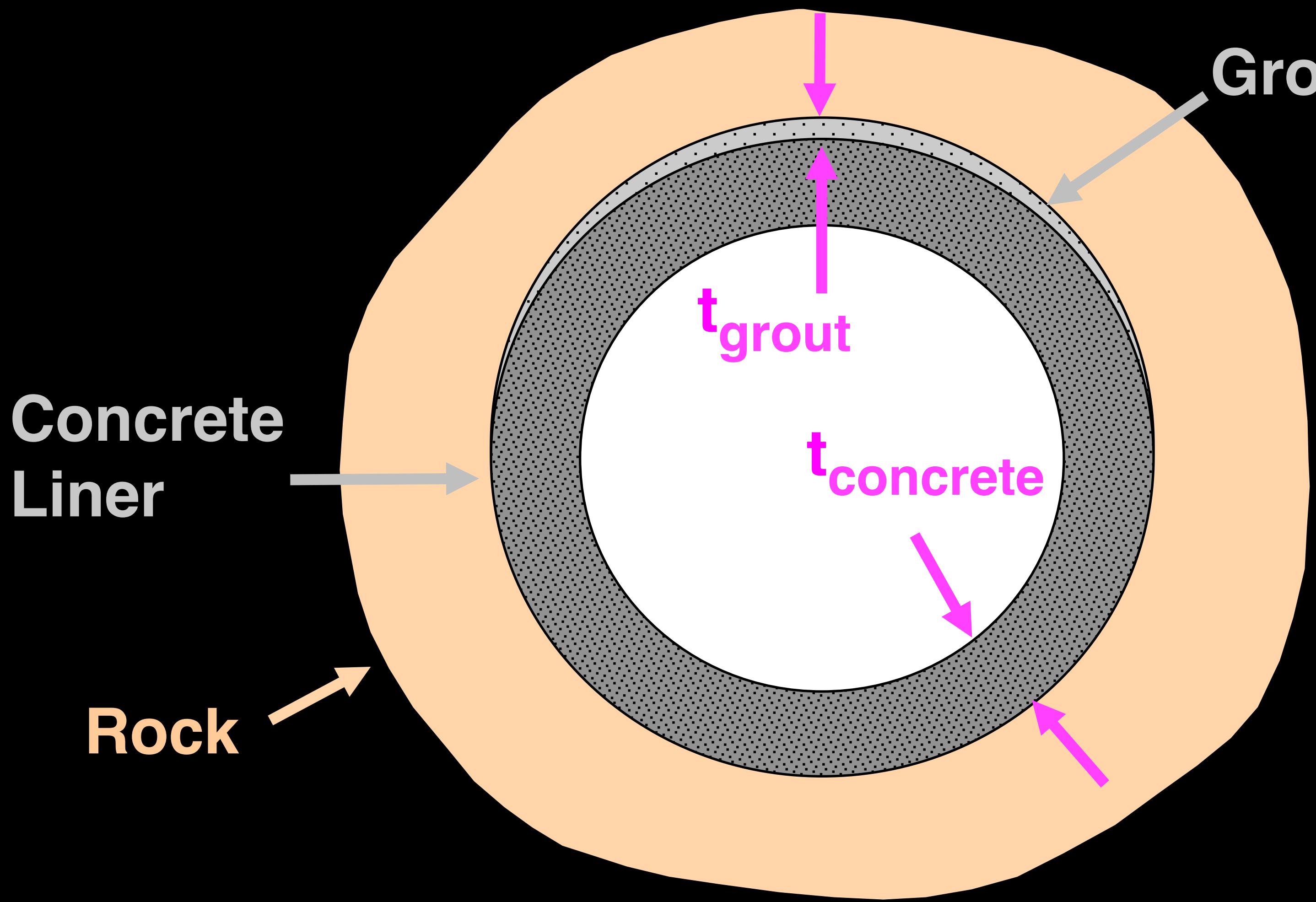
Estimate Material Quality



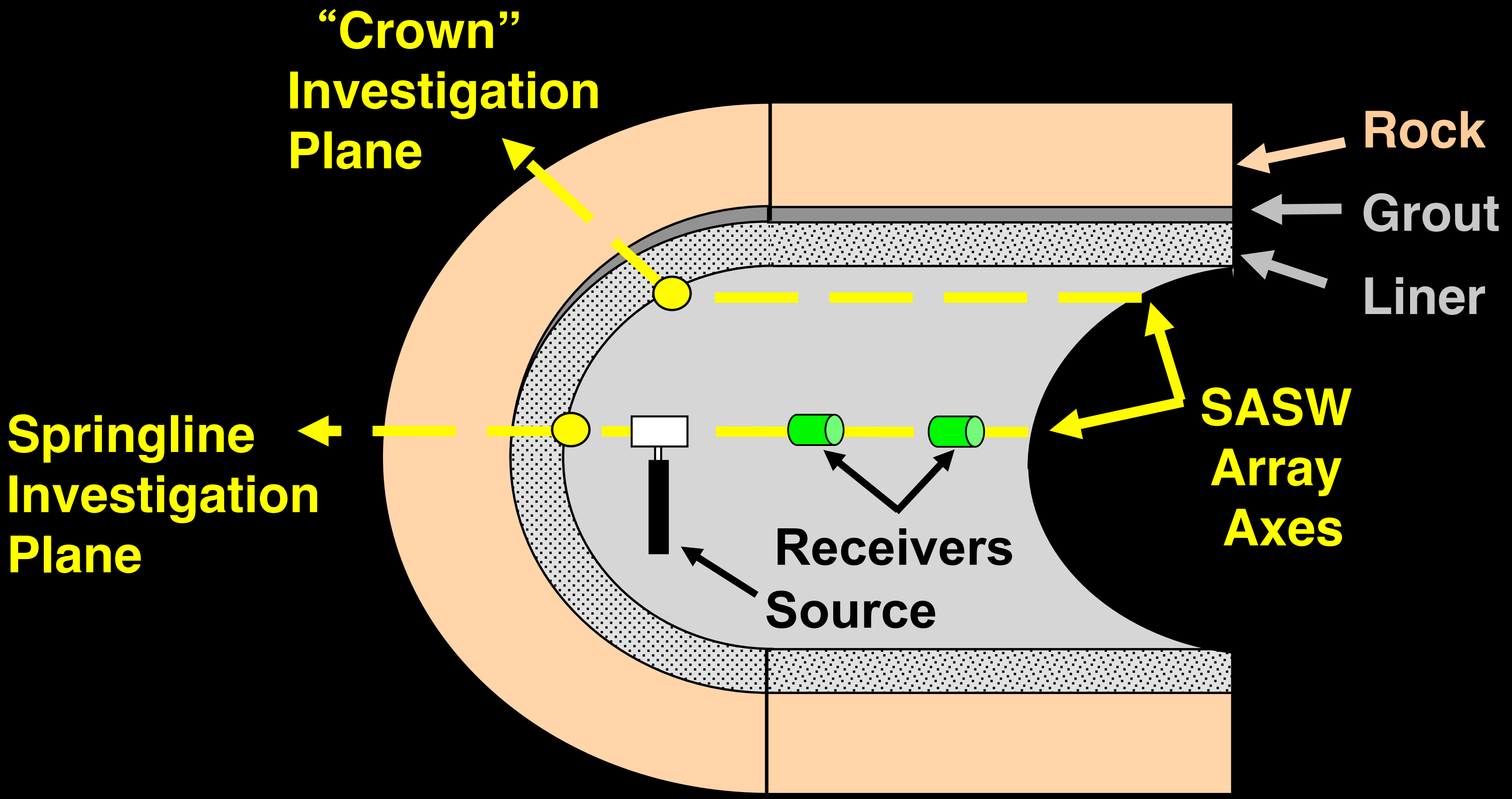
Evaluate Changed Condition



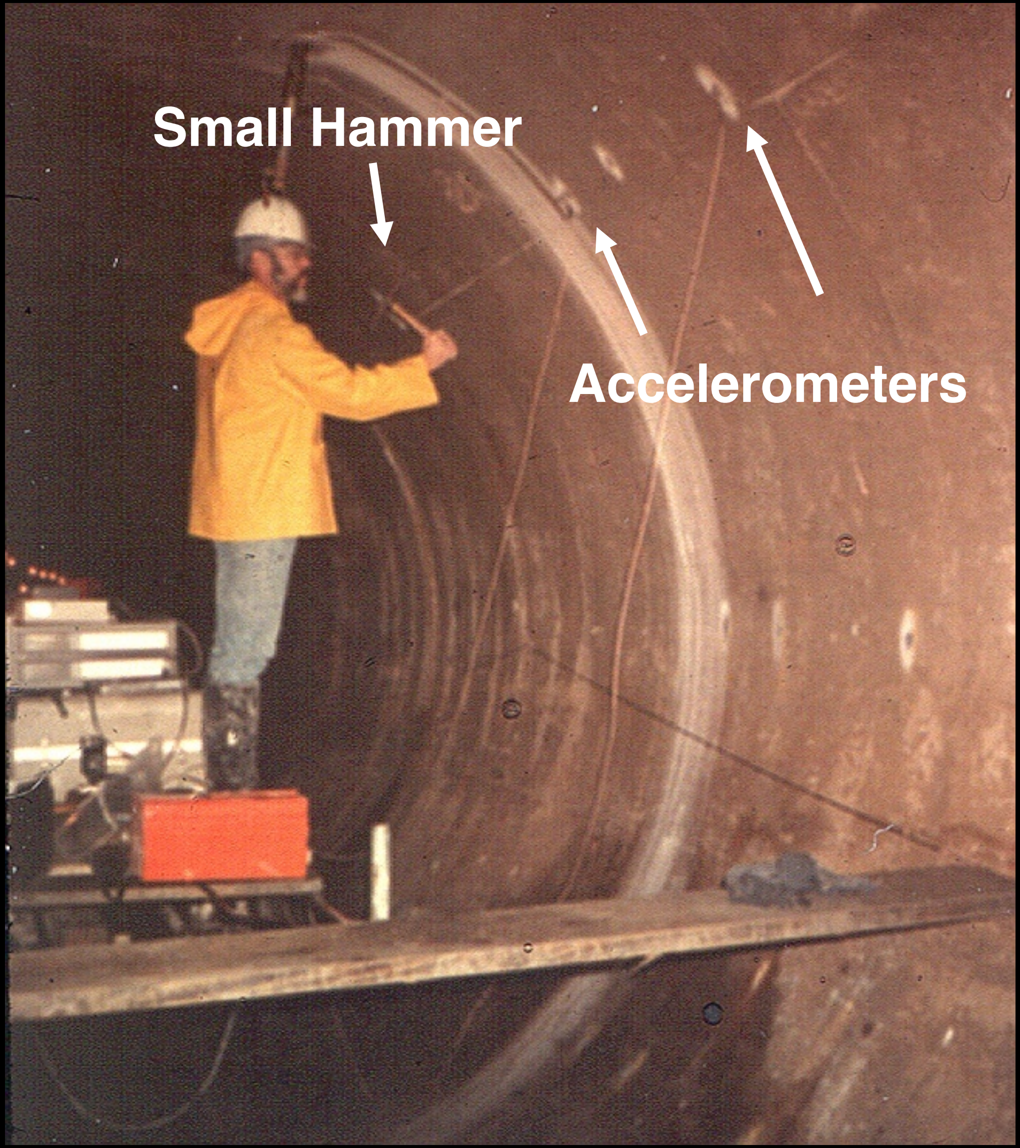
2.1a Site Characterization:
Tunnel Investigation



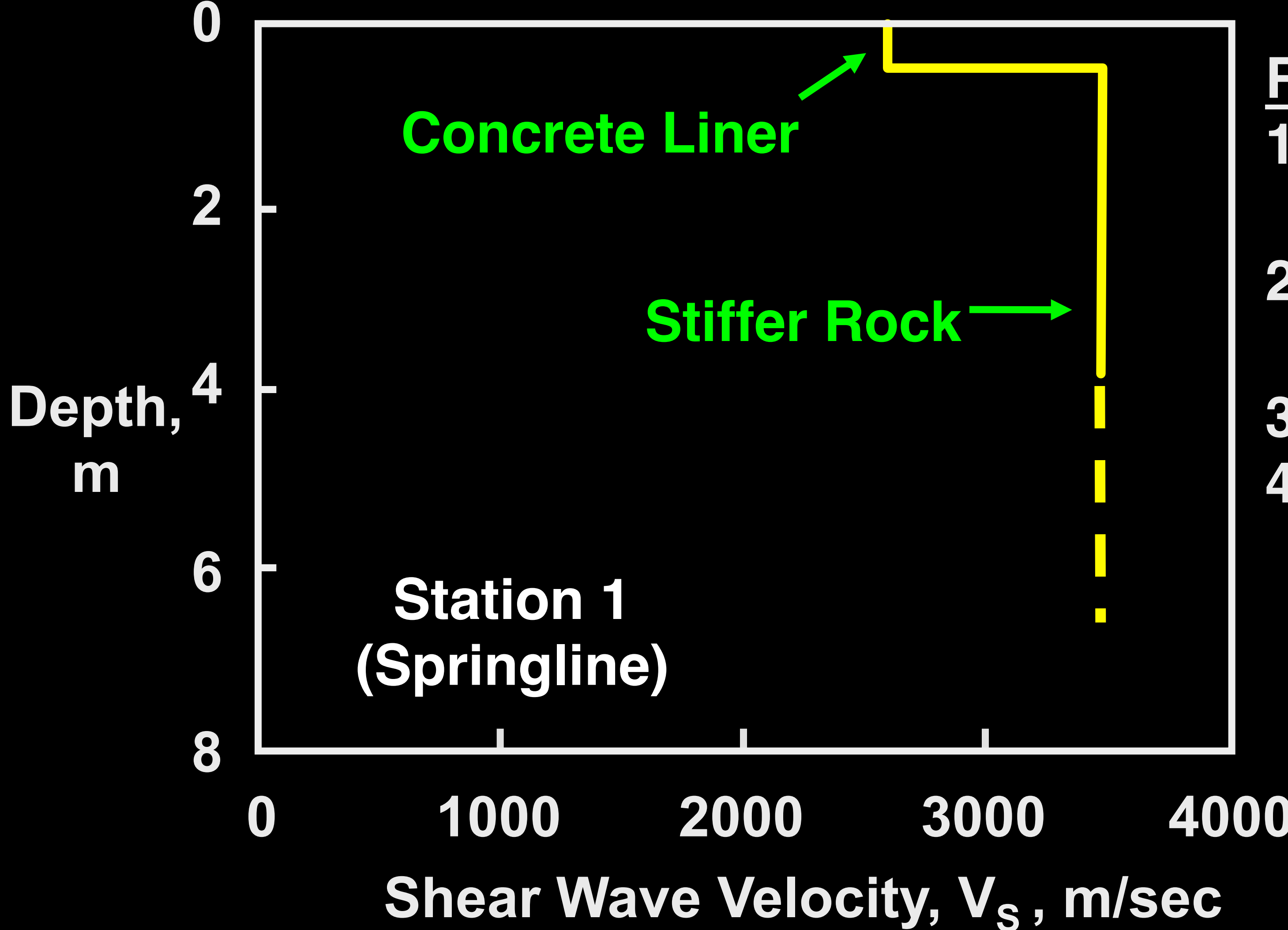
SASW Testing Arrangement and Planes of Investigation



Conducting SASW Tests



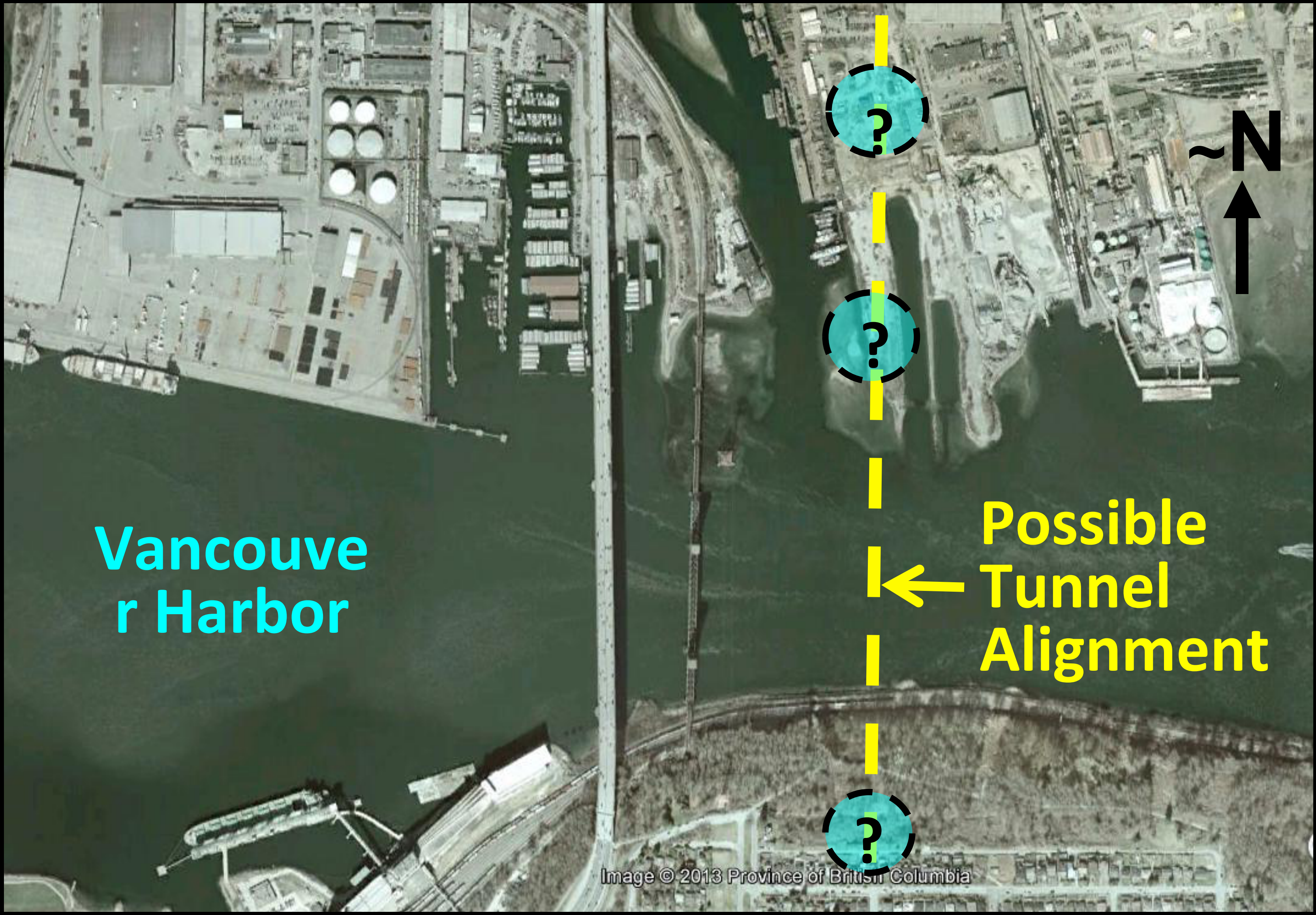
Interpreted V_S Profile Behind Tunnel Wall at Springline



Results:

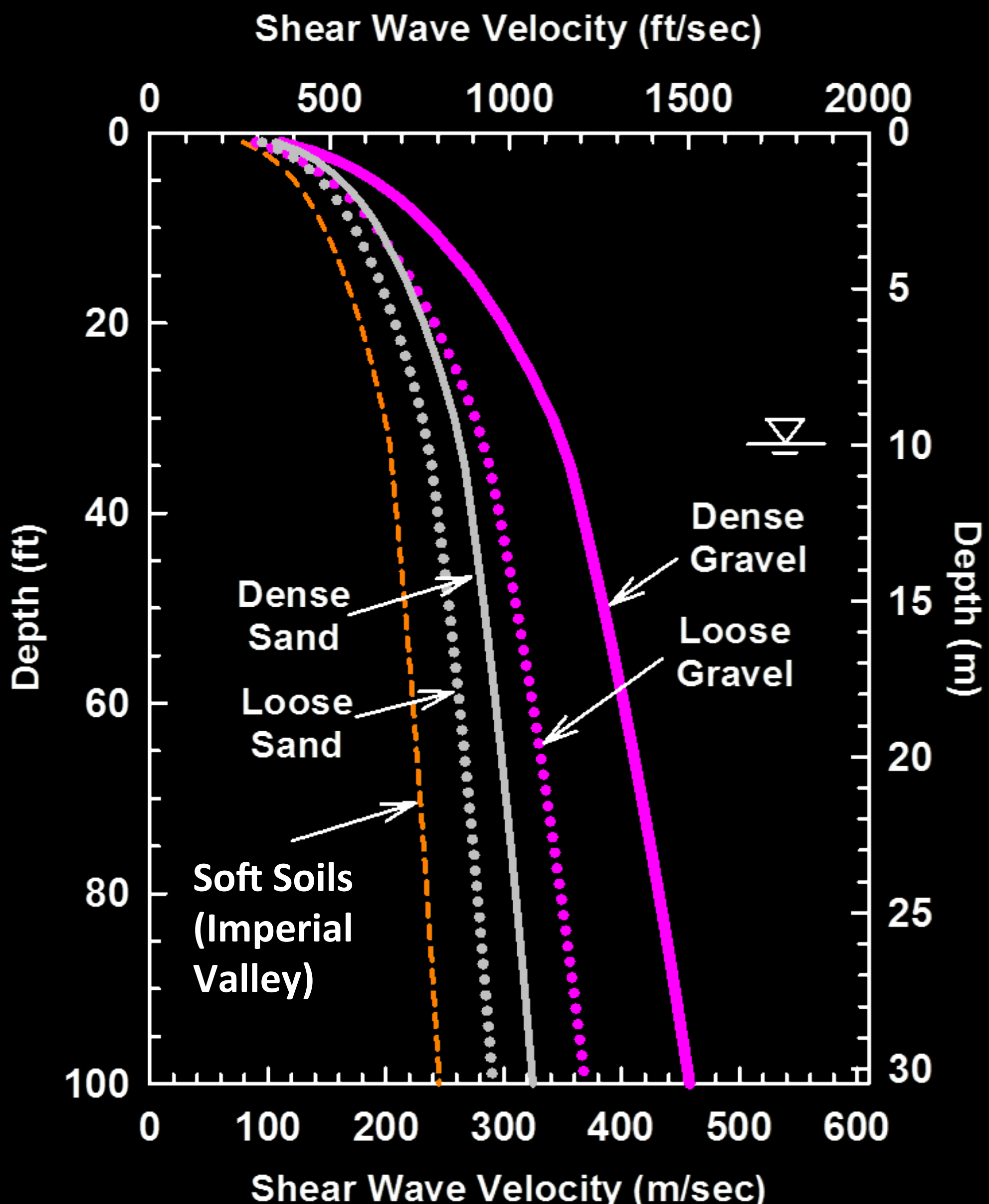
1. high-quality concrete
2. thickness: ~ 0.3 m
3. no voids
4. rock stiffer than liner

2.1b Site Characterization: Proposed Locations of Water Tunnel Shafts



SASW Testing Locations

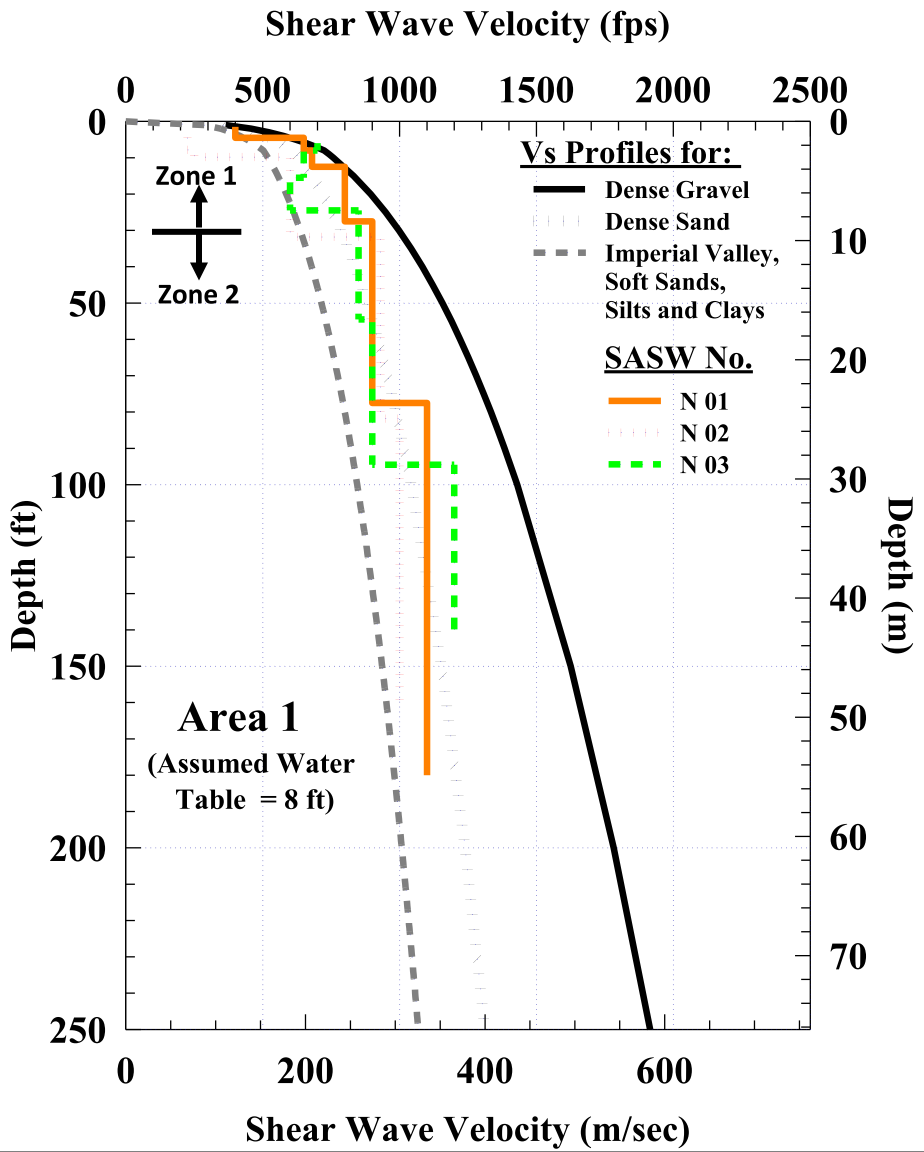
V_s Template

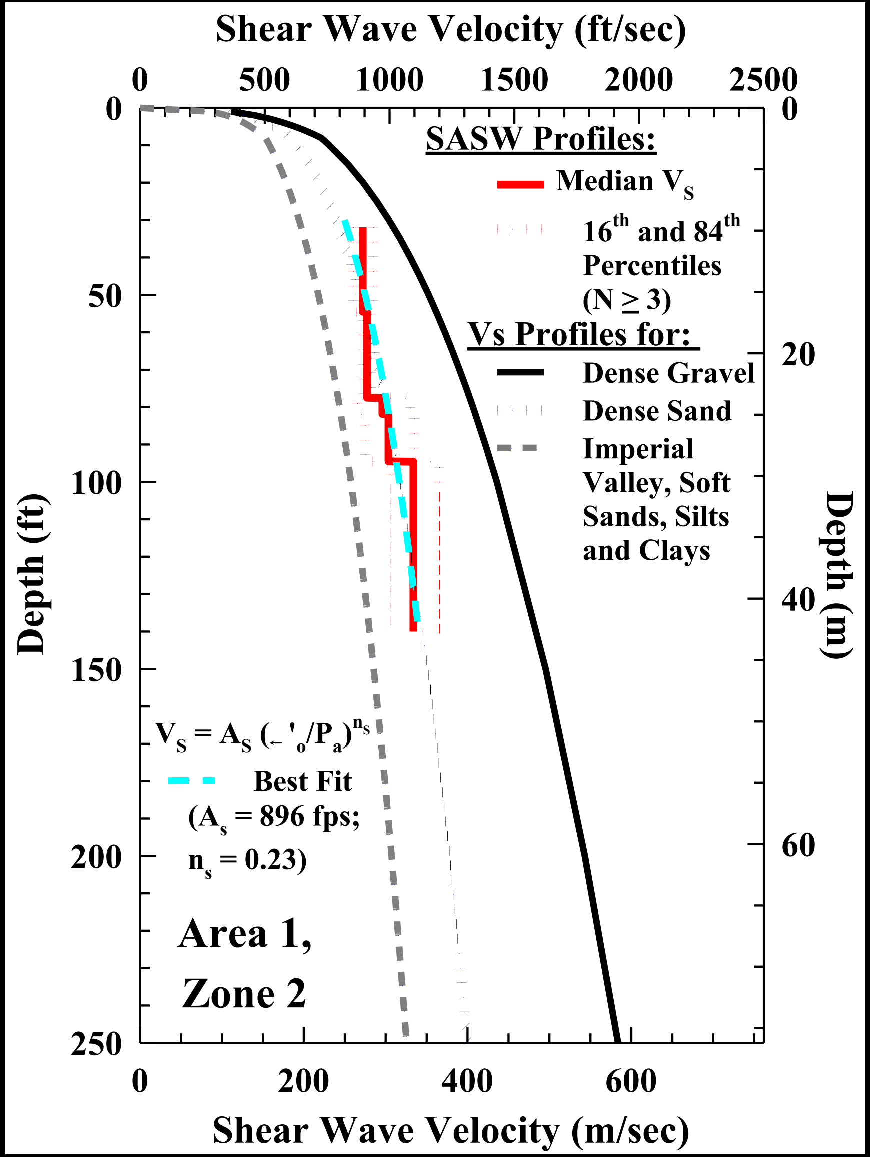


$V_S = A_S\,(\sigma_o'/P_a)^{n_s}$

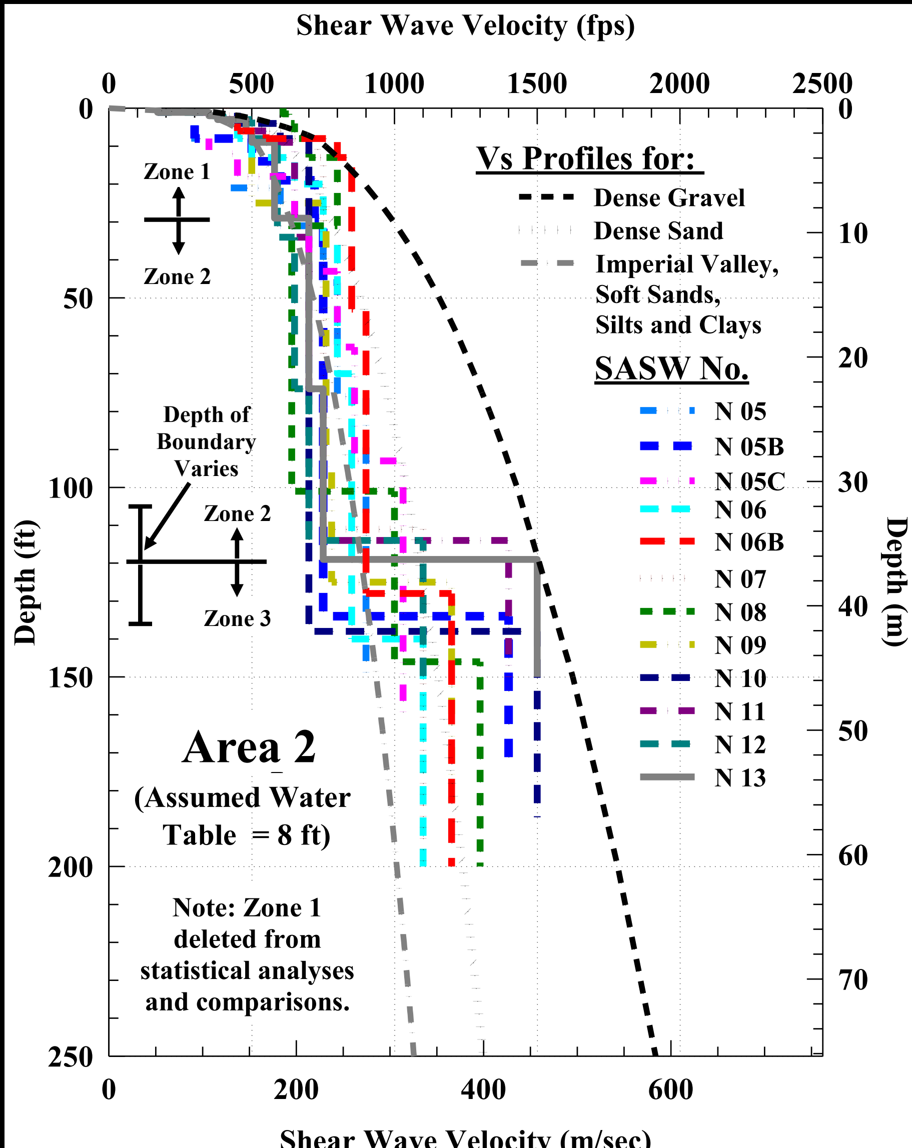
- $A_S = V_S$ at $\sigma_o' = 1$ atm
- K_o assumed equal to 0.5

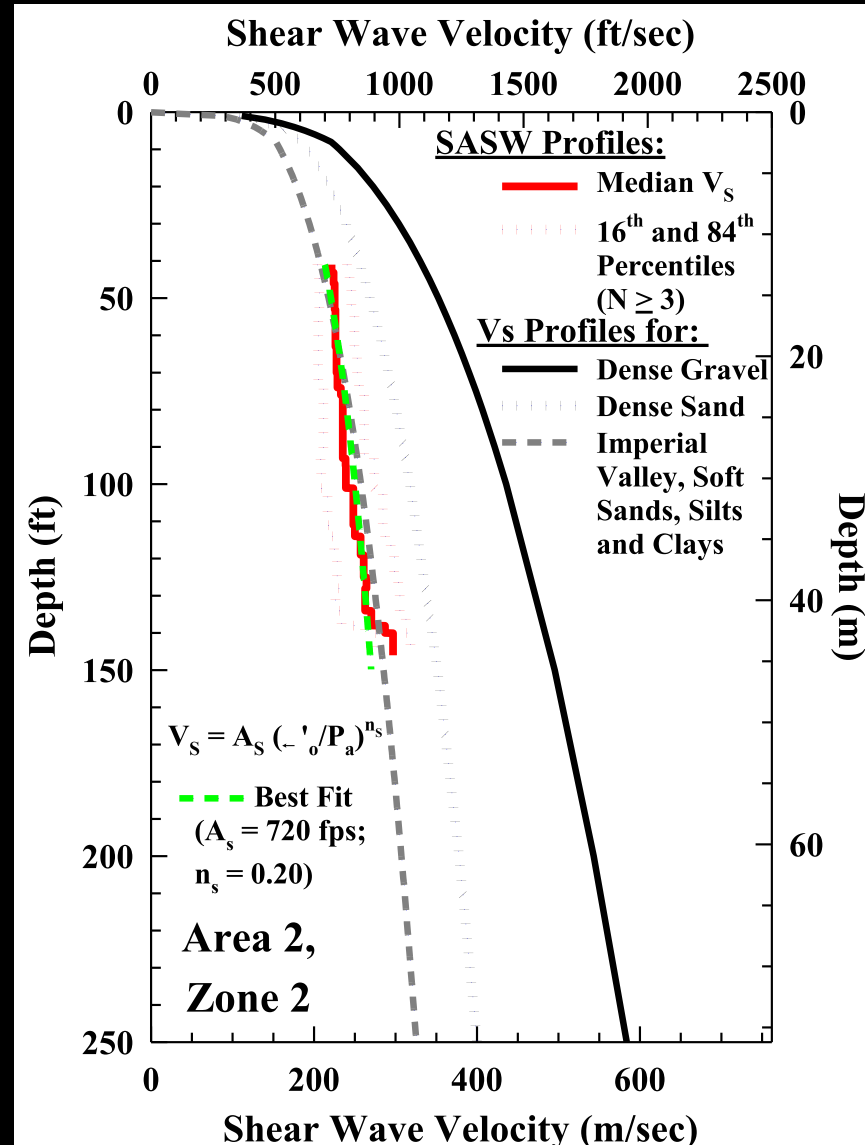
V_s Profiles in Area 1: Relative Character and Variability of Granular Materials?



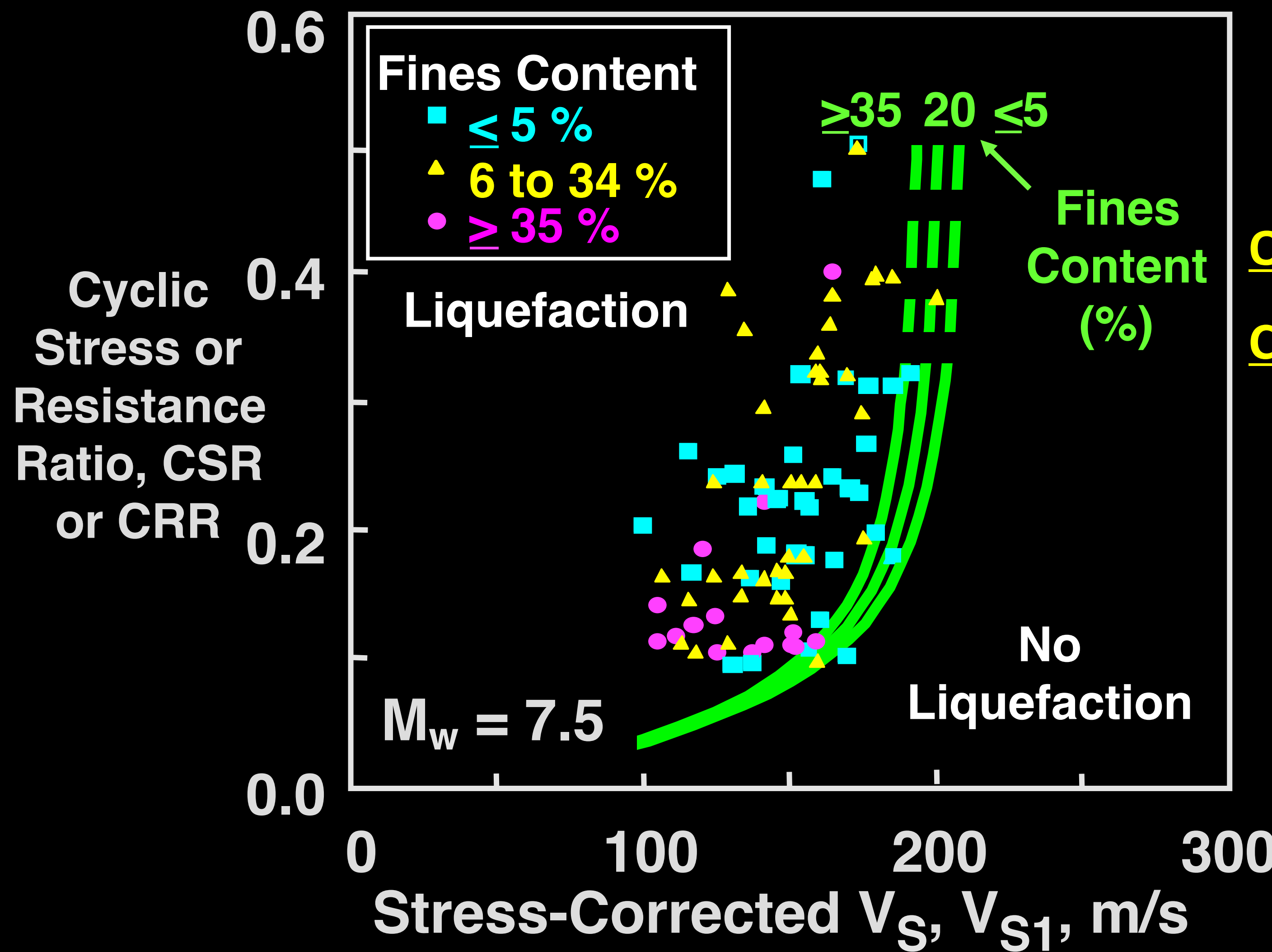


V_s Profiles in Area 2: Relative Character and Variability of Granular Materials?





Liquefaction Resistance from V_S
(Andrus and Stokoe, 2000)



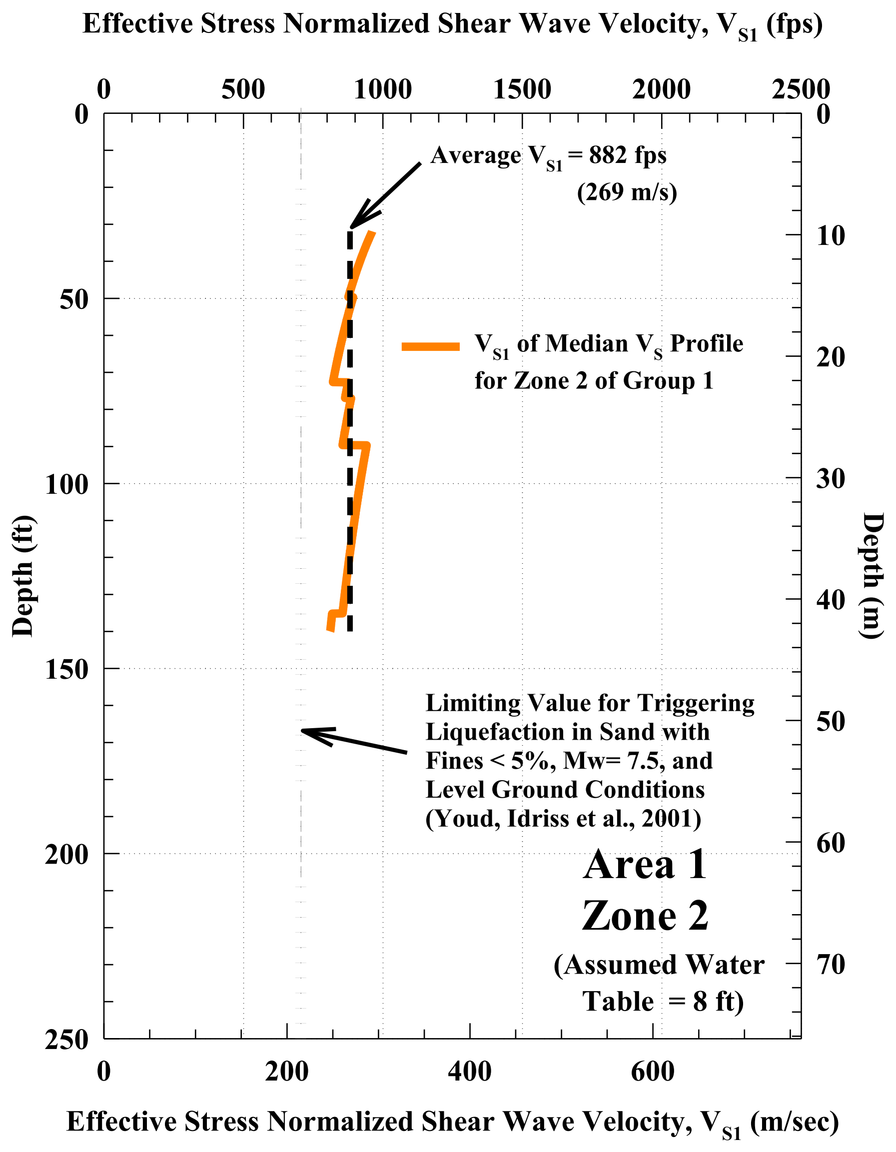
Overburden-Stress Correction for V_s:

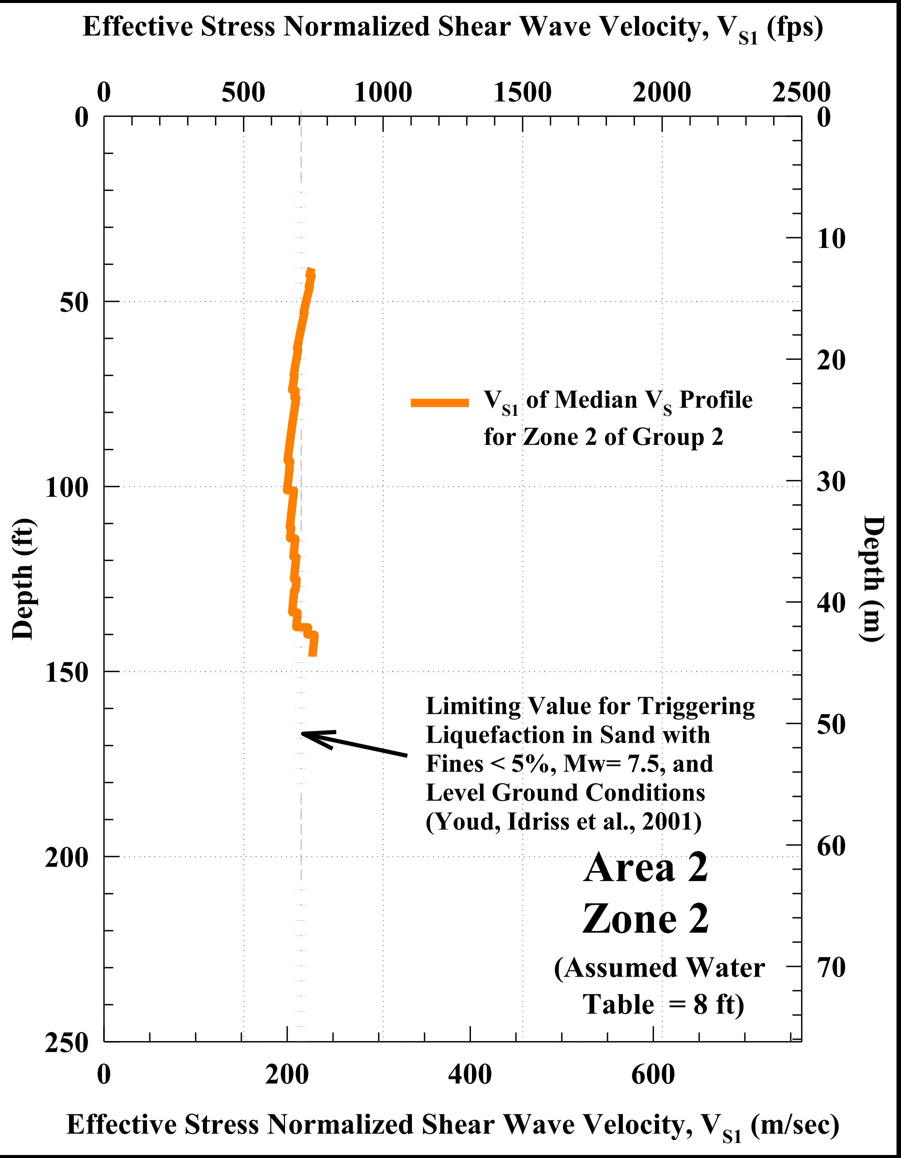
$V_{s1} = V_s(P_a/\sigma'_{vo})^{0.25}$

P_a = 100 kPa

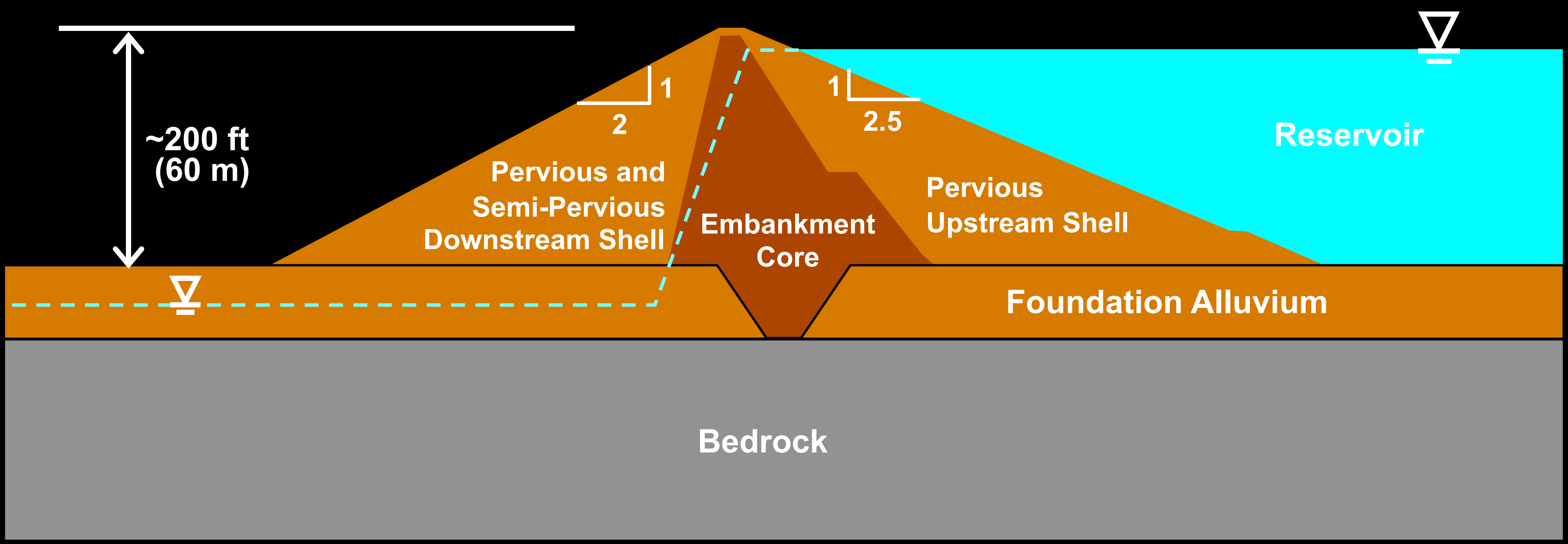
σ'_{vo} = depth * γ_t

Likelihood of Liquefaction Triggering



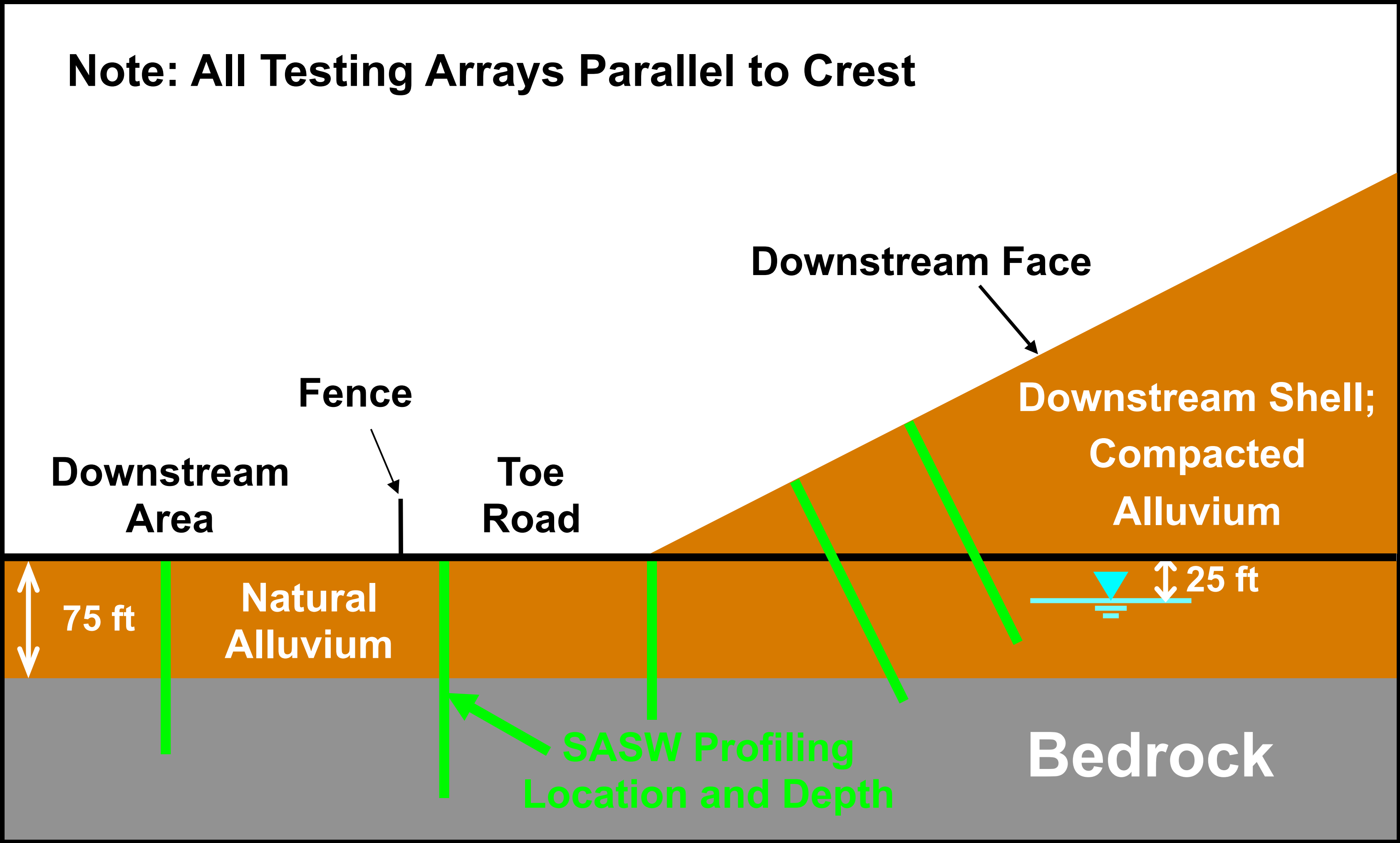


2.1c Dam Investigation: "Quality" of Alluvium Within and Beneath an Embankment Dam

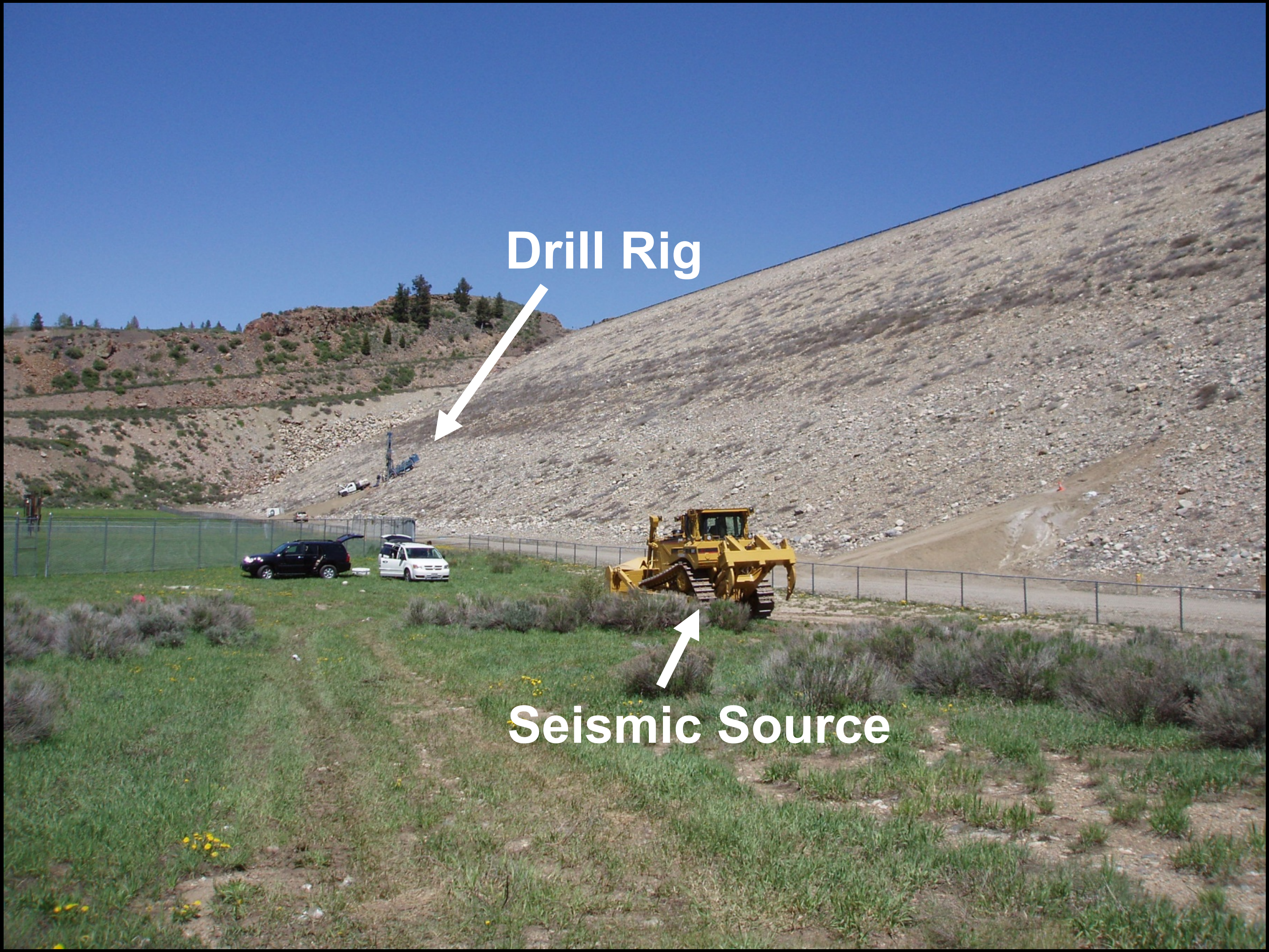


Approximate SASW Testing Locations

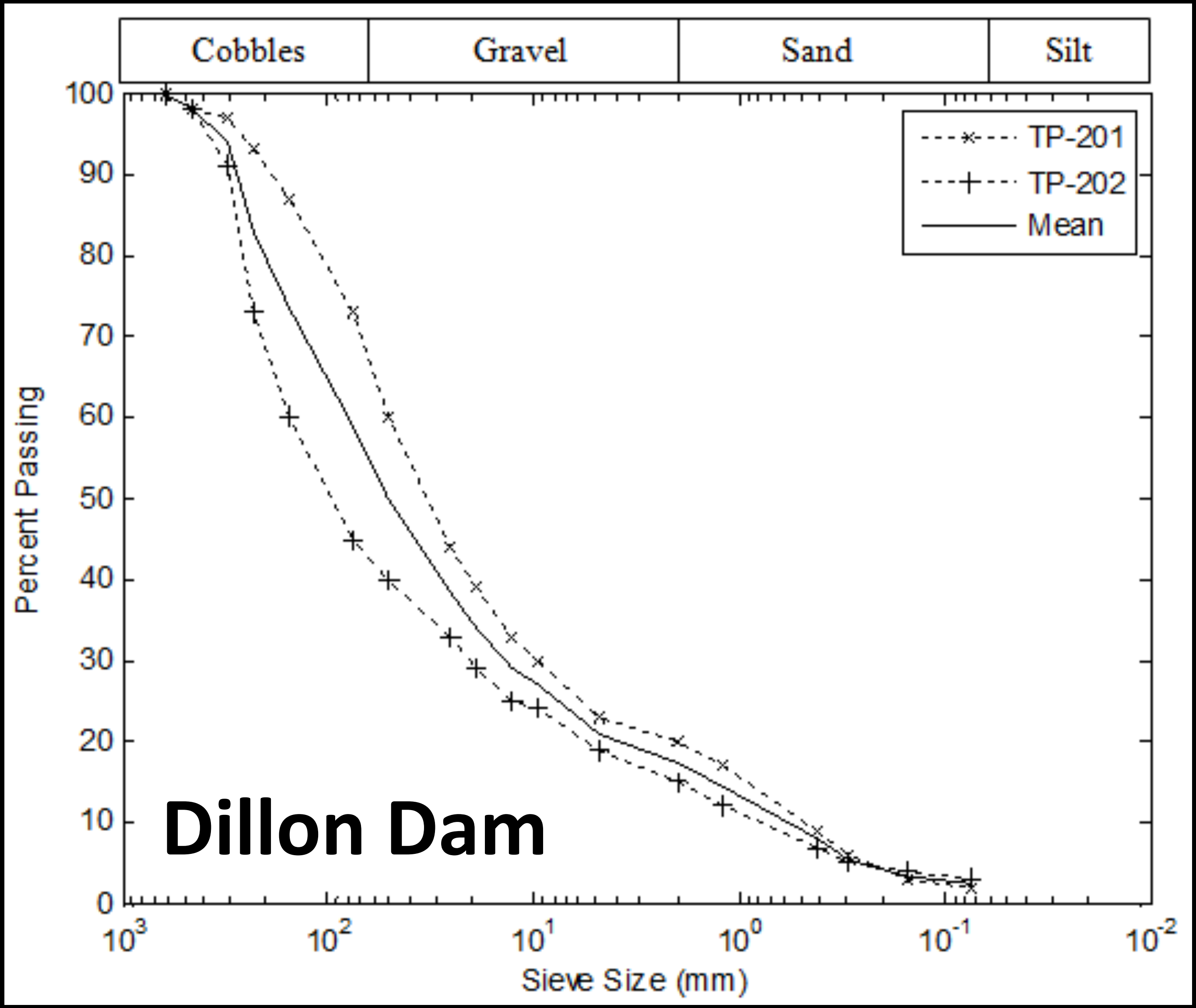
SASW Test Locations - Downstream Face and Downstream Area



Dillon Dam Site



Gradation Curves from Field Samples of Foundation Alluvium

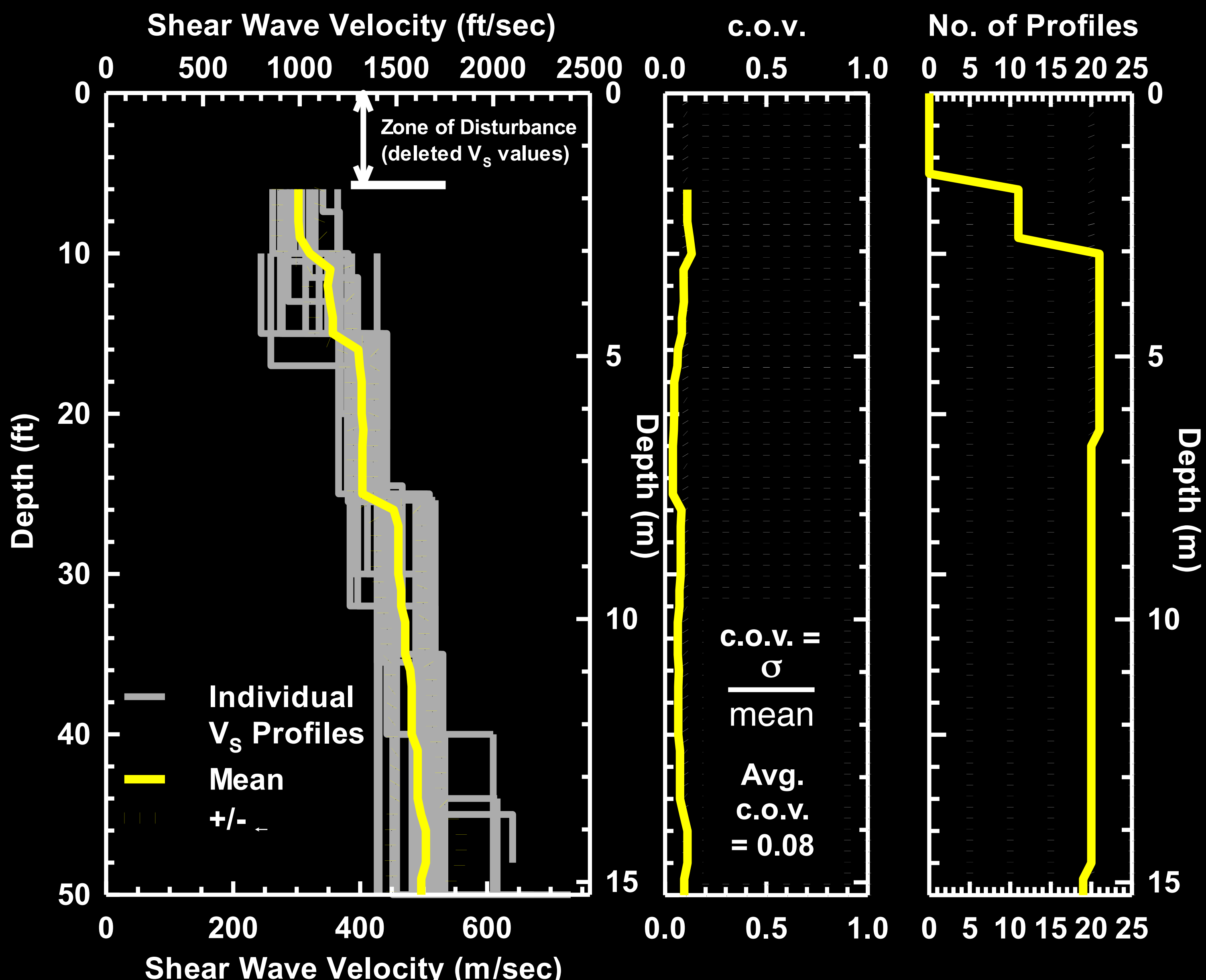


D_{50} ~ 50 mm

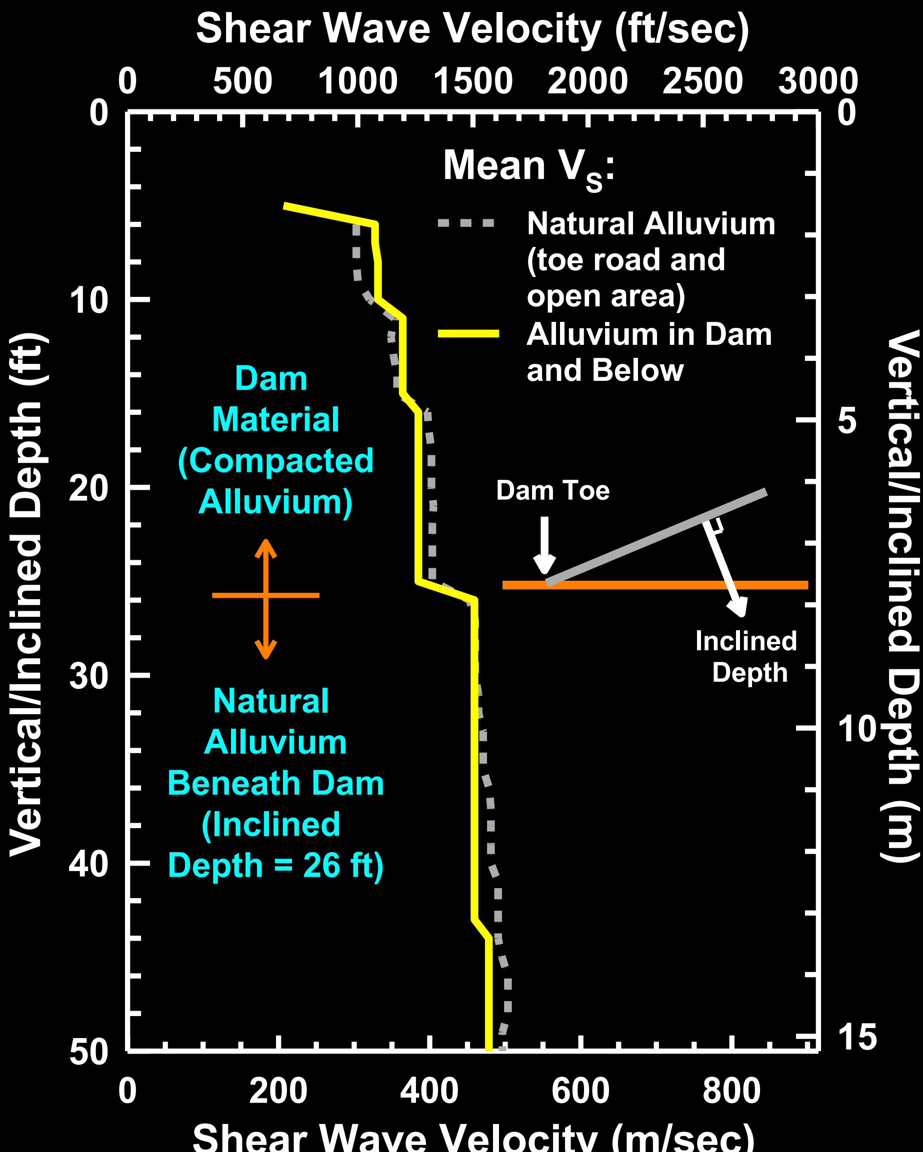
C_u ~ 130

PI = 0

Statistical Analysis of Natural Alluvium



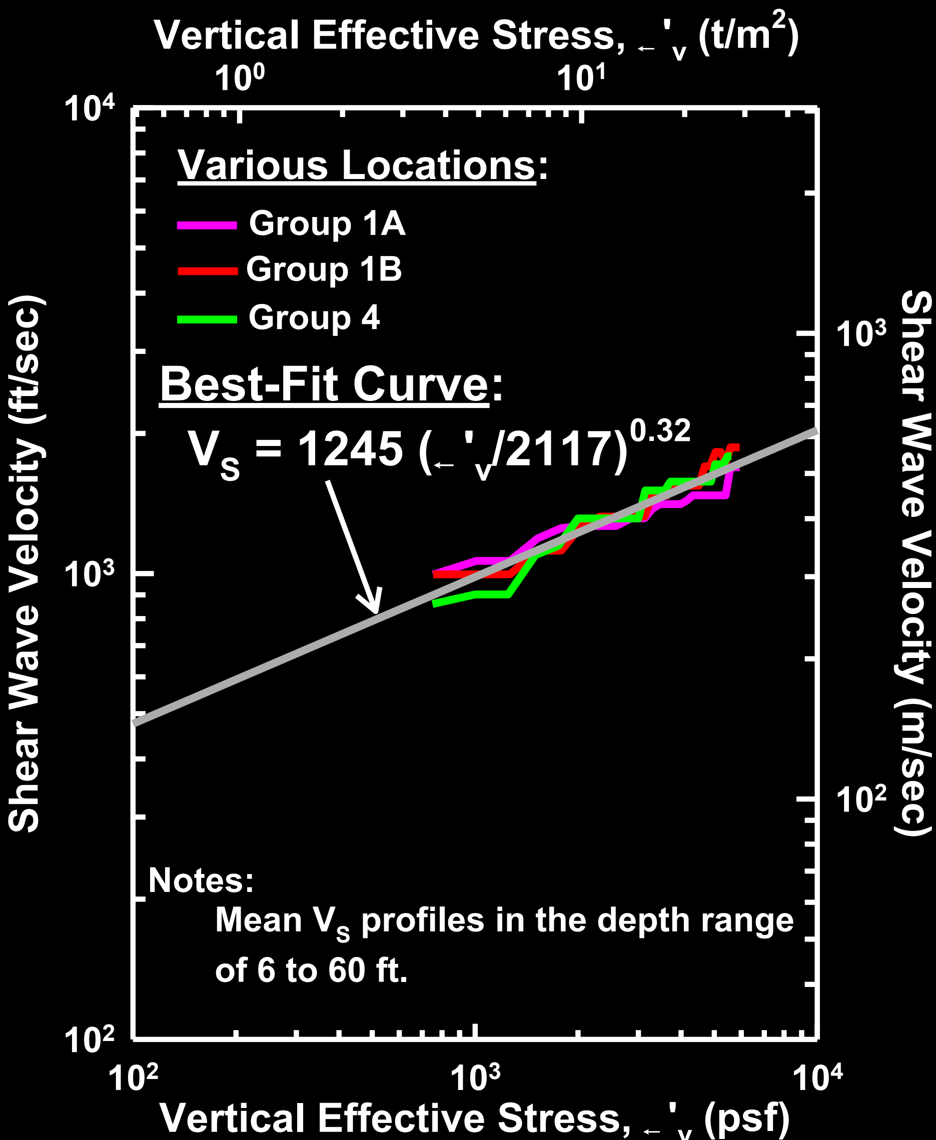
Comparison of Mean V_S Profiles - Natural Alluvium and Compacted Alluvium



Results:

1. Natural alluvium is stiff ($V_S \geq 300$ m/s); hence, dense.
2. Compacted alluvium in dam is similar to natural alluvium so:
   (a) dense and
   (b) not cemented.
3. No loose zone of alluvium under toe of dam.
4. Average c.o.v. < 0.1

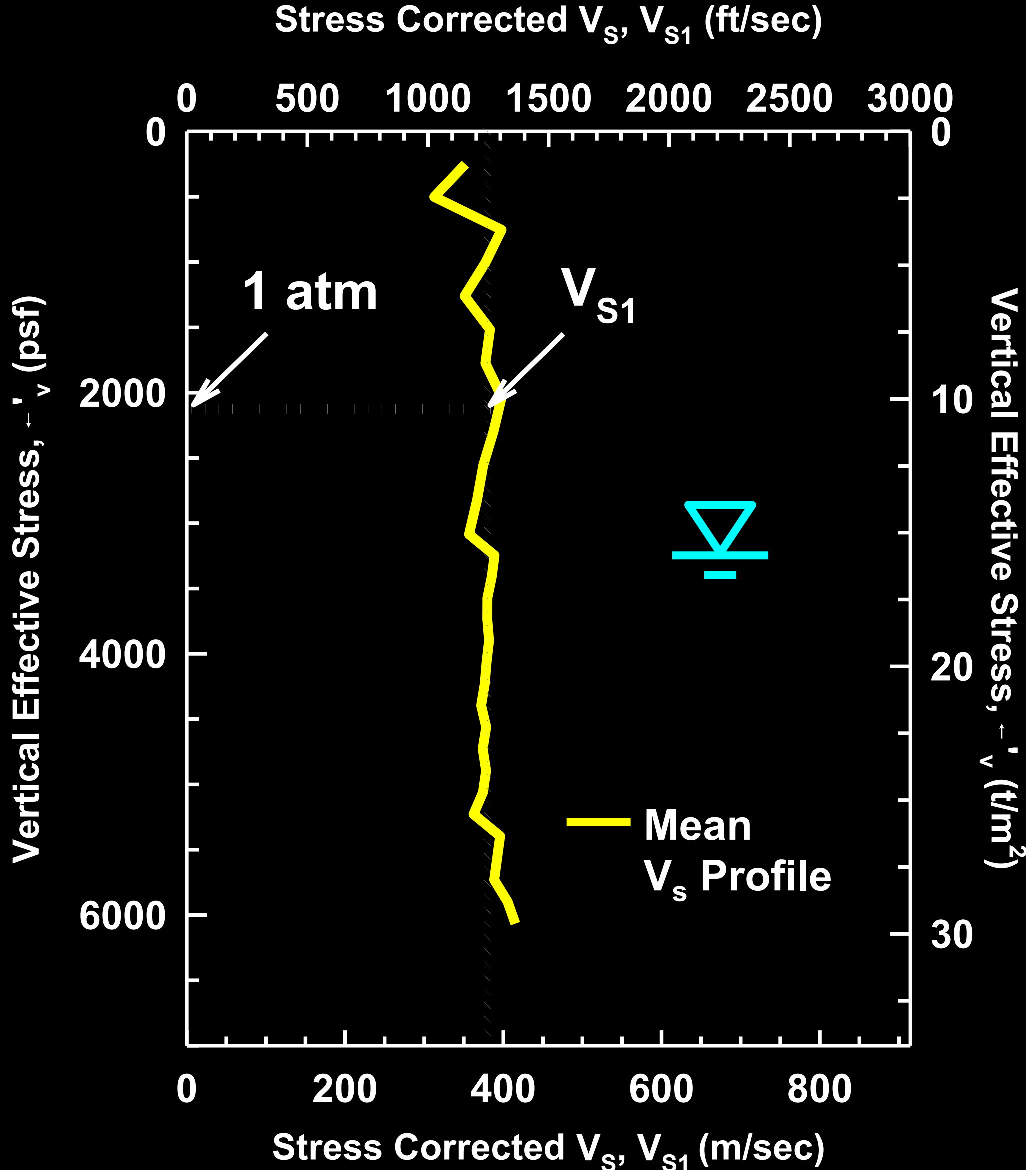
Best-Fit Curve for the Field Log V_S – Log σ_n' Relationship of the Natural Alluvium



Results:

1. n_s = 0.32 is reasonable for uncemented gravelly soils.
2. V_S at depth ~ 1 ft (0.3 m) equals 527 fps (161 m/s) which represents material with:
   (a) large D_{50} (> 25 mm),
   (b) large C_u (> 35) and
   (c) no cementation.
3. Log V_s – Log σ'_v is representive of a normally consolidated soil (… with no plasticity).

Calculated V_{S1} Profile for Natural Alluvium Using n_s = 0.32



Overburden-Stress Correction for V_S:

$V_{s1} = V_s(P_a/\sigma'_v)^{0.32}$

P_a = 100 kPa

σ'_v = depth * γ_t

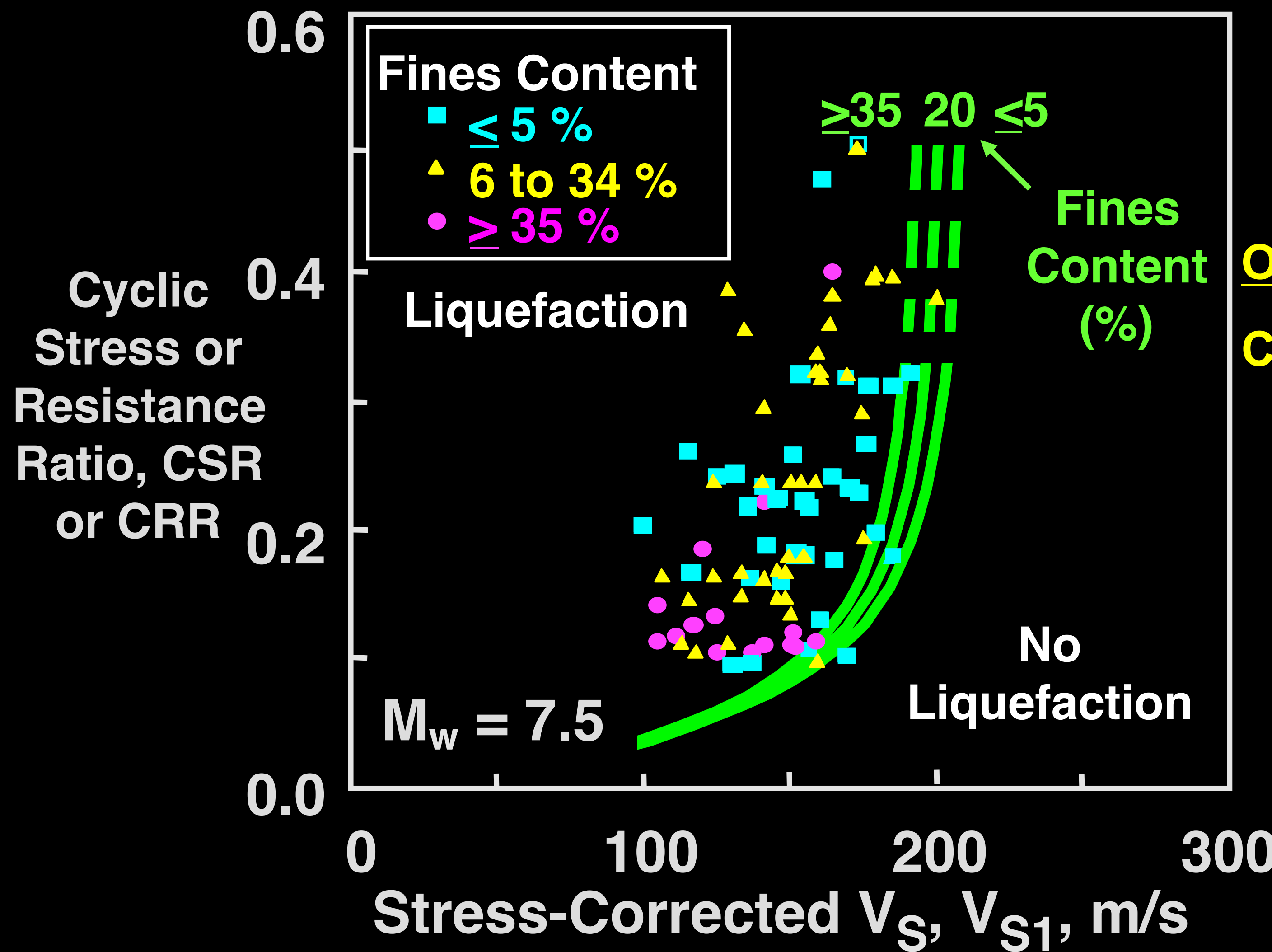
Average V_{S1}

Assumed γ_t ~ 138 pcf

Avg. V_{s1} = 1245 fps

(380 m/s)

Liquefaction Resistance from V_S
(Andrus and Stokoe, 2000)



Overburden-Stress Correction for V_S:

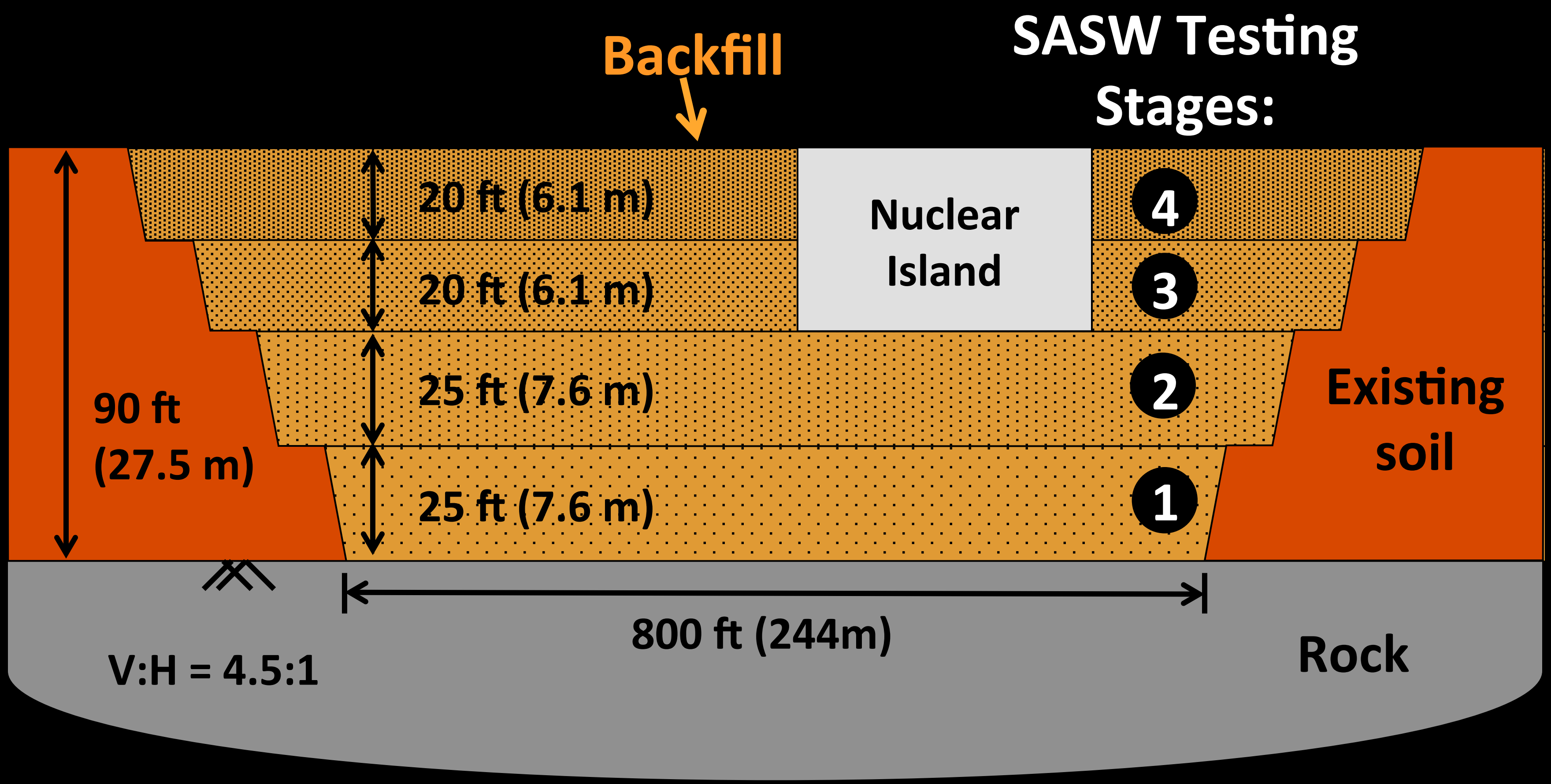
$V_{s1} = V_s(P_a/\sigma'_{vo})^{0.25}$

P_a = 100 kPa

σ'_{vo} = depth * γ_t

2.2a Process Monitoring: Evaluating Compaction of a Thick Granular Fill

Cross-Section of Backfill at Units 3 and 4



Notes: 1. Material in backfill is SP, SP-SM, SM ; nonplastic fines.
2. Loose lifts of 12 in. (30 cm).
3. Minimum compaction of 95% modified Proctor (avg. ~ 98%).

Creating 90-ft (27.5-m) Deep Excavation

Plant Vogtle Units 3 and 4 Dec. 10 2009

© 2010 The Southern Company

Relative Locations of Units 3 and 4

Plant Vogtle Units 3 and 4 foundation excavation,
with water vapor rising from cooling towers in background. April, 2010.

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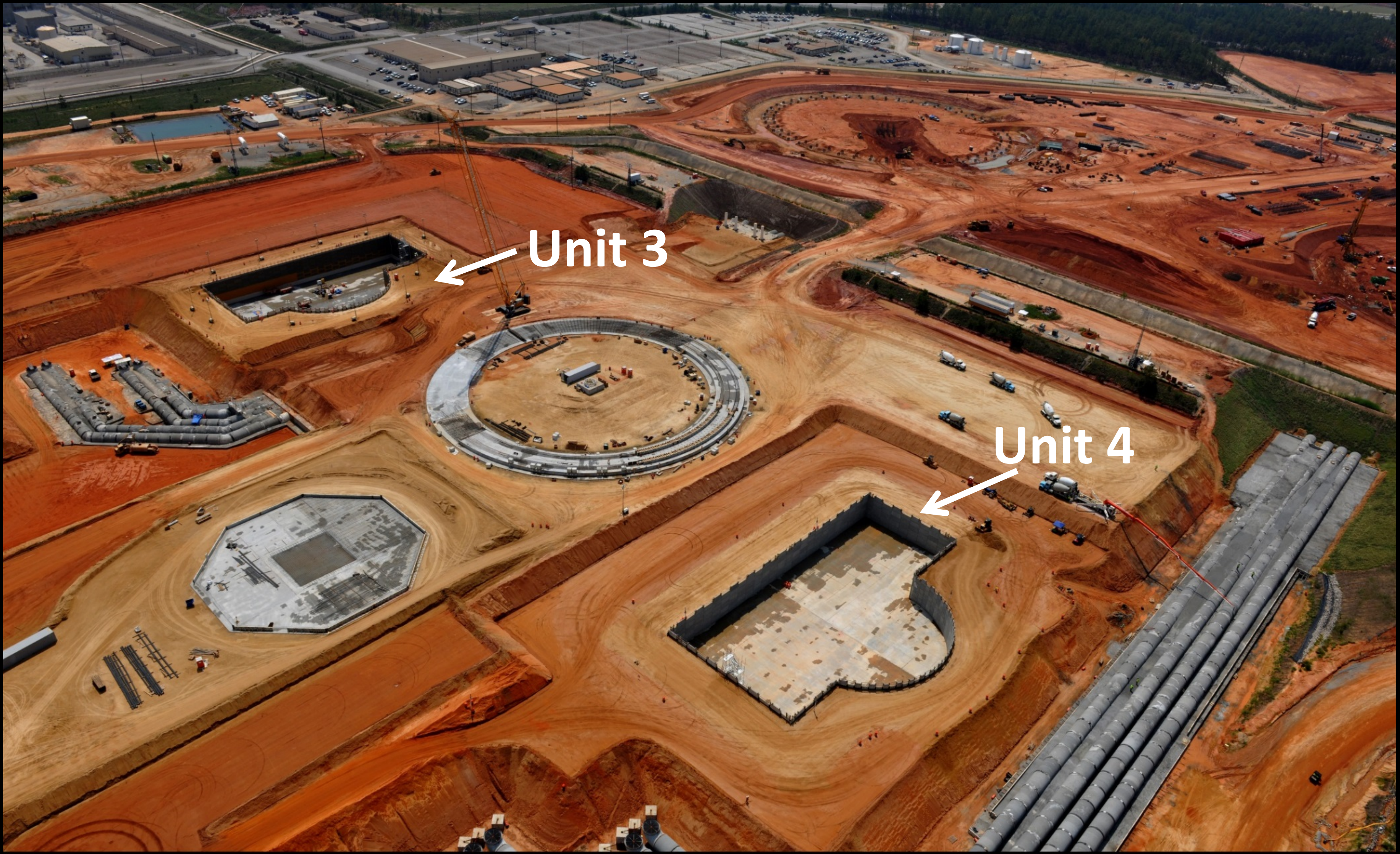
Backfilling Nearly Complete



Aerial photograph of Vogtle 3 and 4 construction site. Unit 3 is located at left and top of photo and Unit 4 to the right and bottom. Heavy lift derrick crane foundation in center. August 11, 2011

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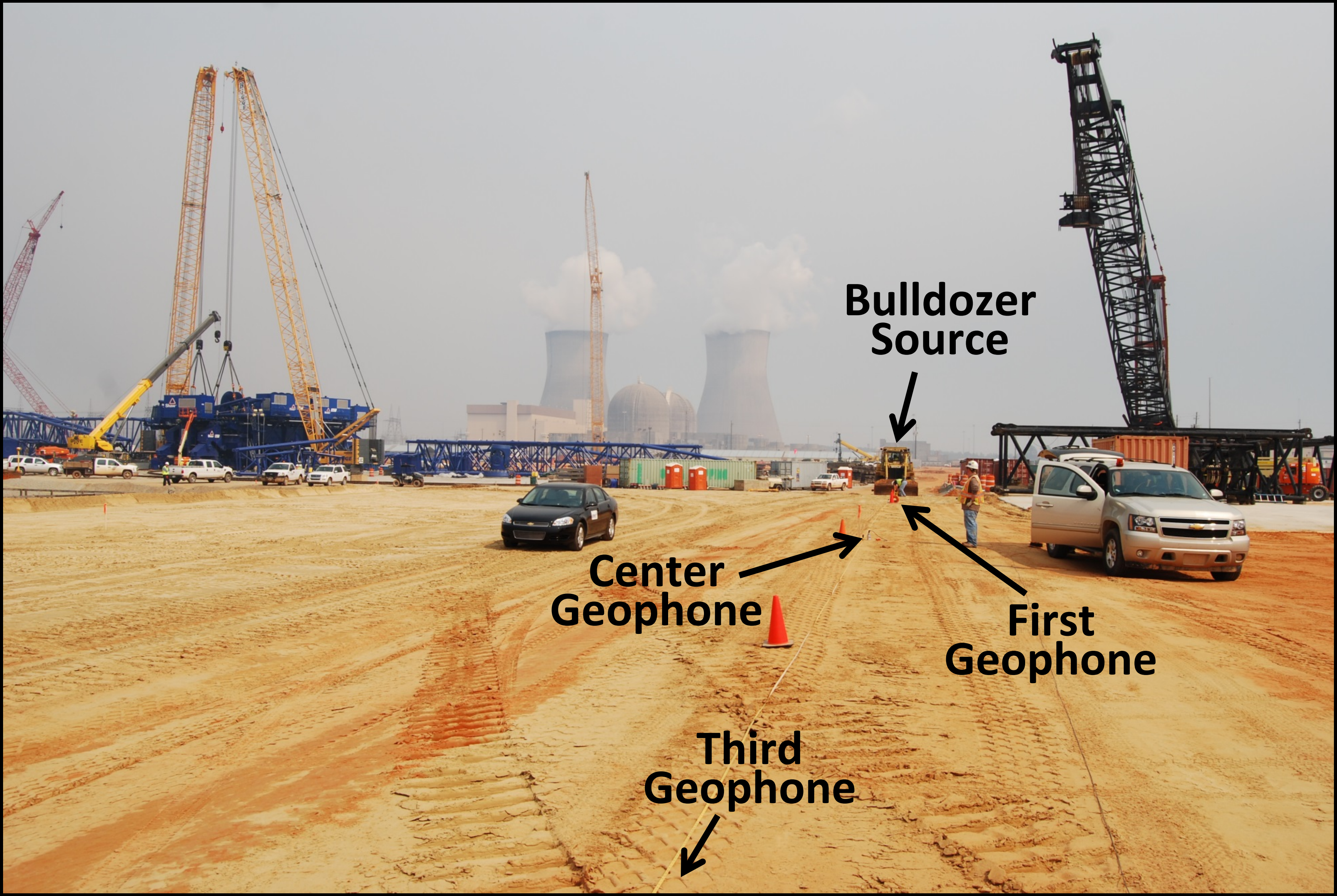
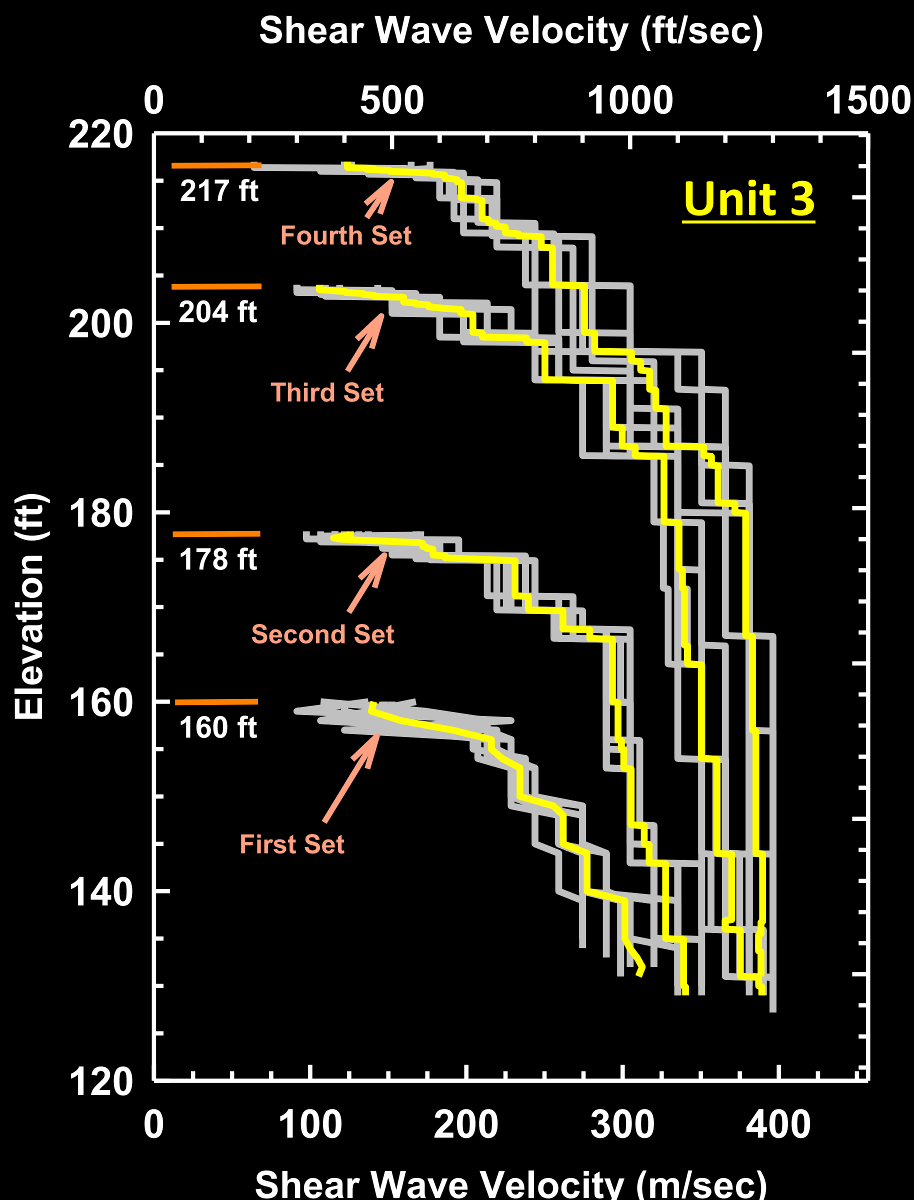
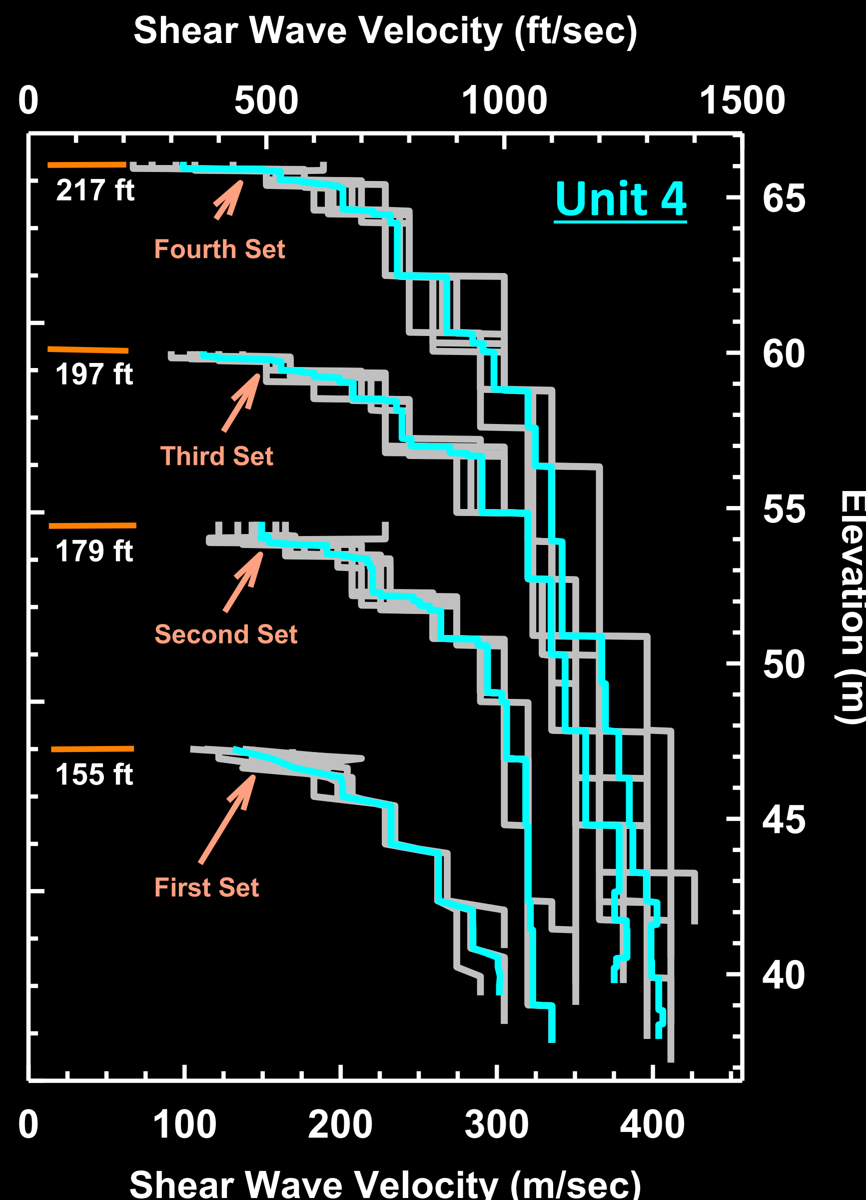
SASW Testing on Completed Backfill

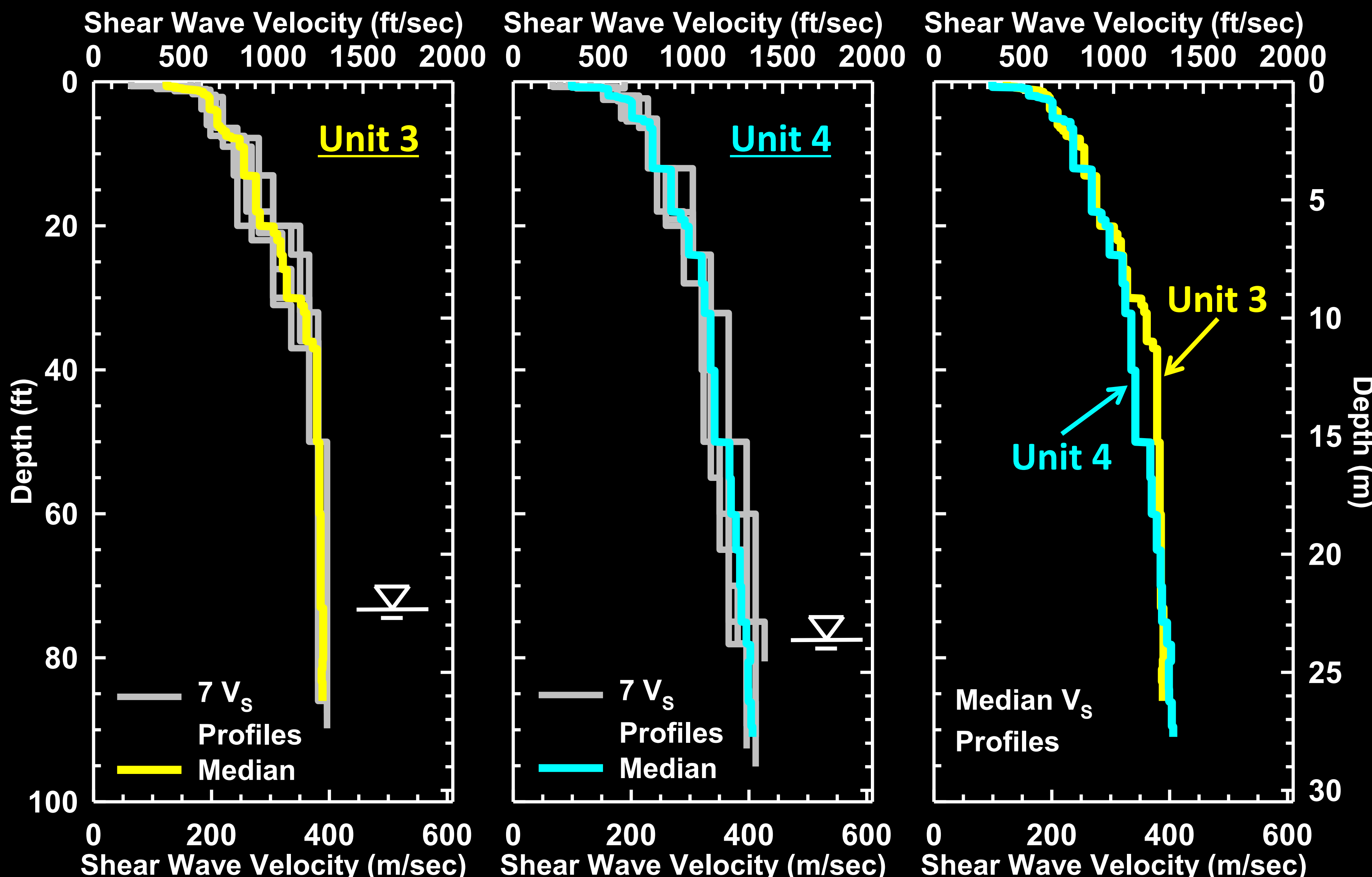


Seismic Testing during Backfilling Process

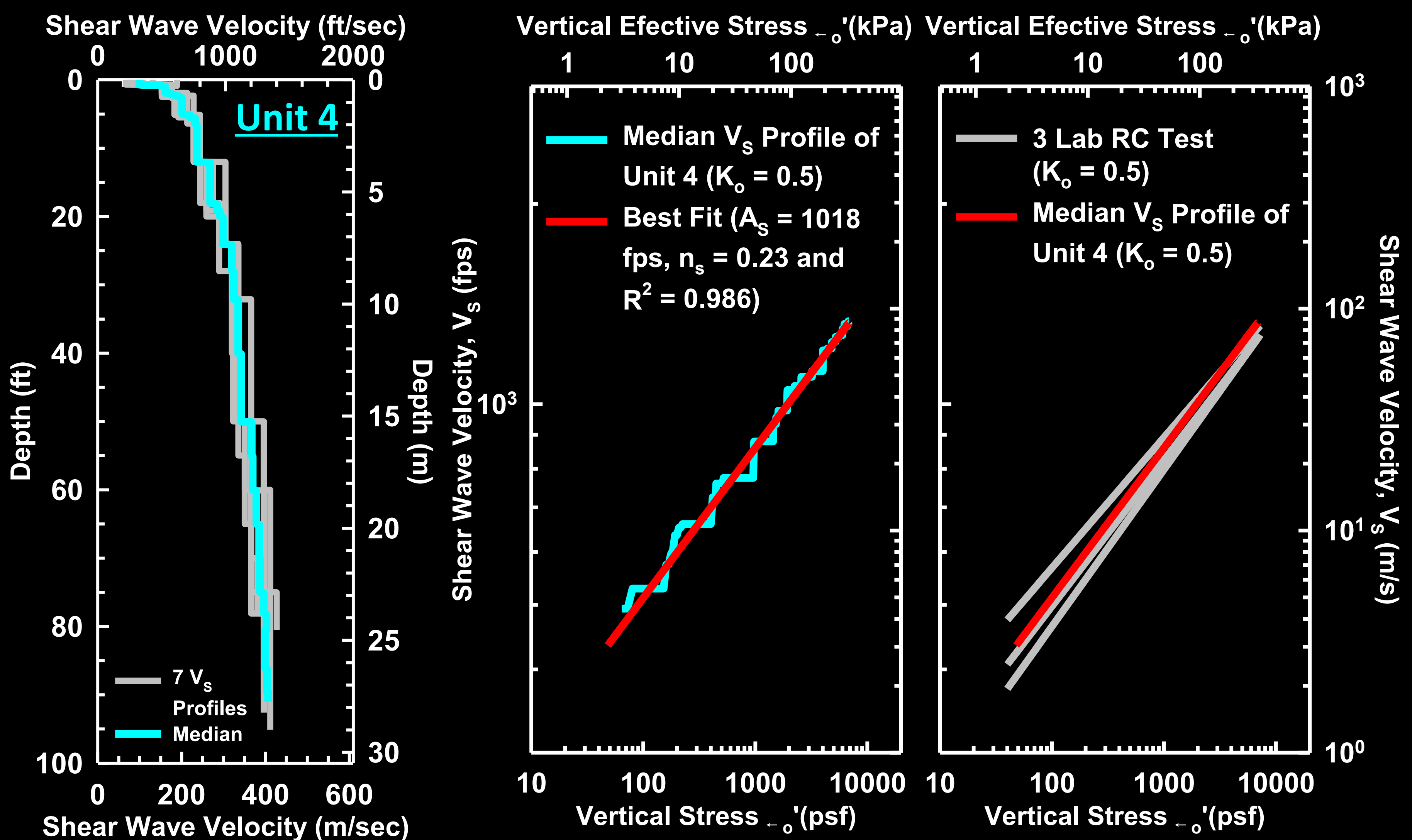




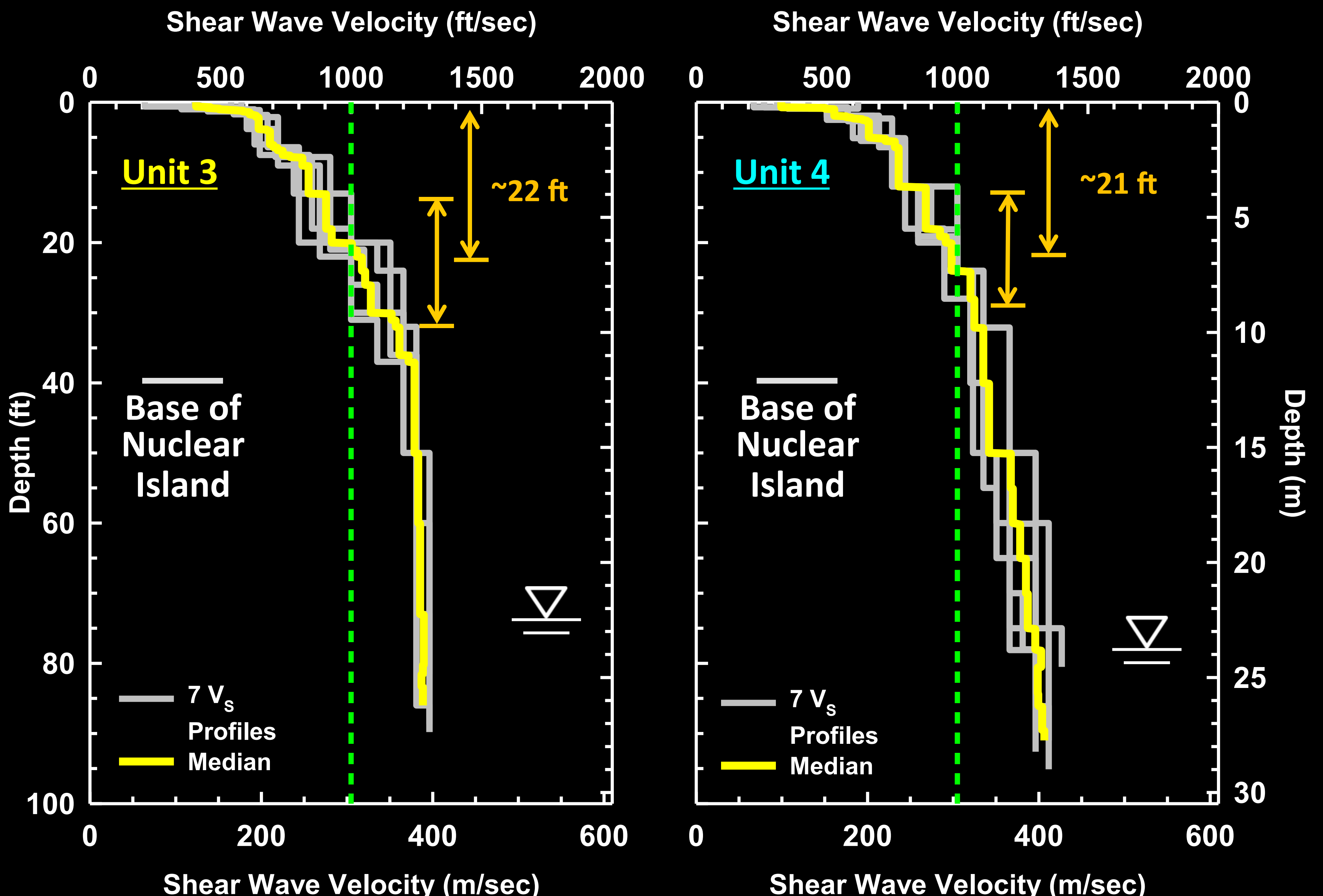
Are the Two Backfills Alike?



Do the Field and Lab V_s Values Agree? (Could V_s Profile be Predicted from Lab?)



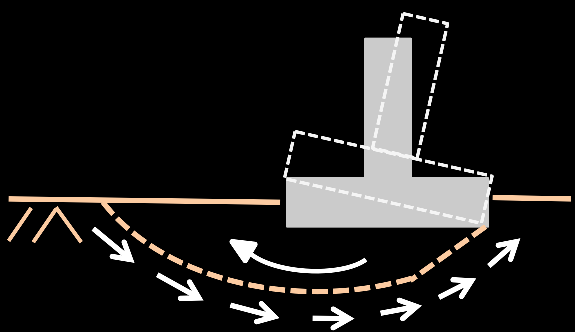
Depth to V_s >1000 fps (300 m/s)



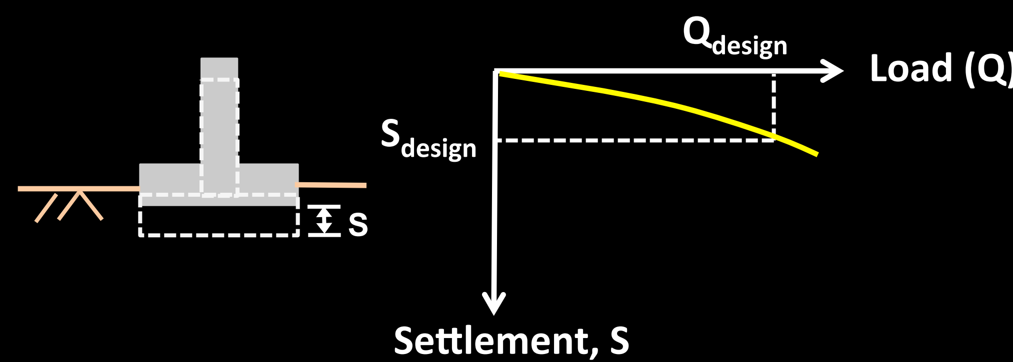
2.3a Predicting Movements Under Static Loads: Shallow Foundations on Granular Soil

Main Design Criteria

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



2. Permissible Settlement: $S \leq S_{design}$



Approach

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

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

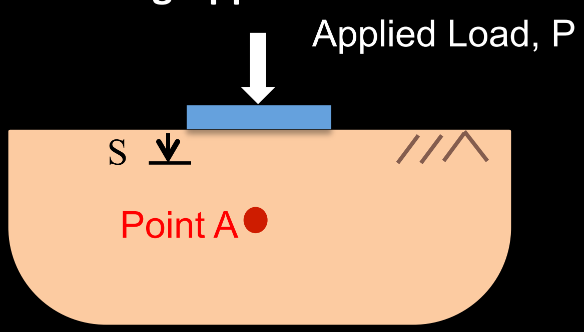
- Deformation-based analysis
- Stresses and strains are calculated

New Framework for Predicting Settlements

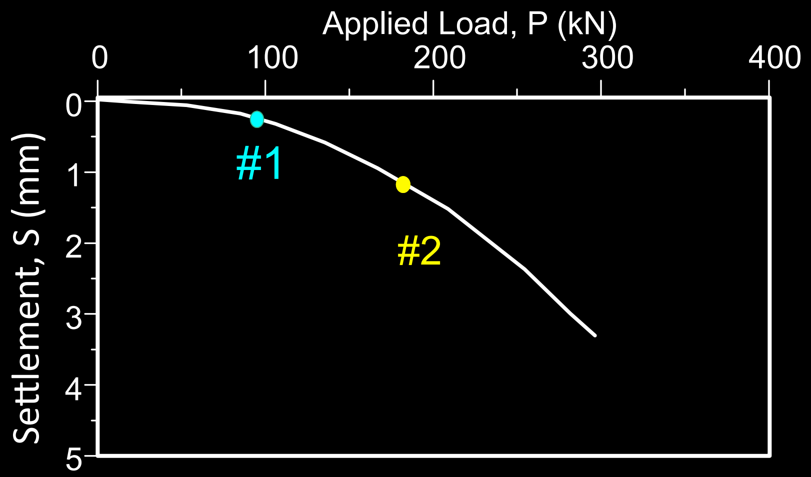
Framework:

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

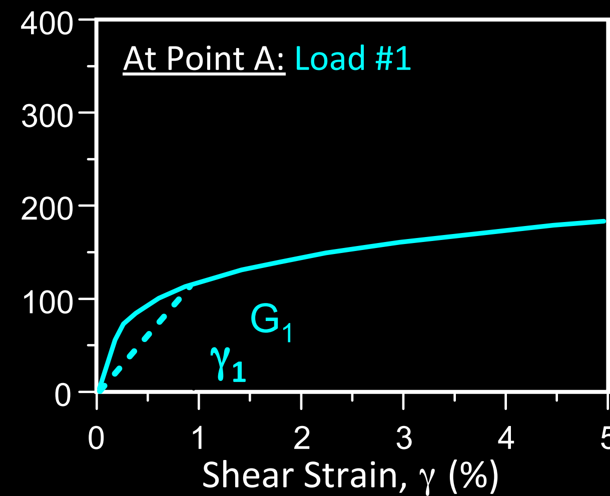
1. Loading Applied



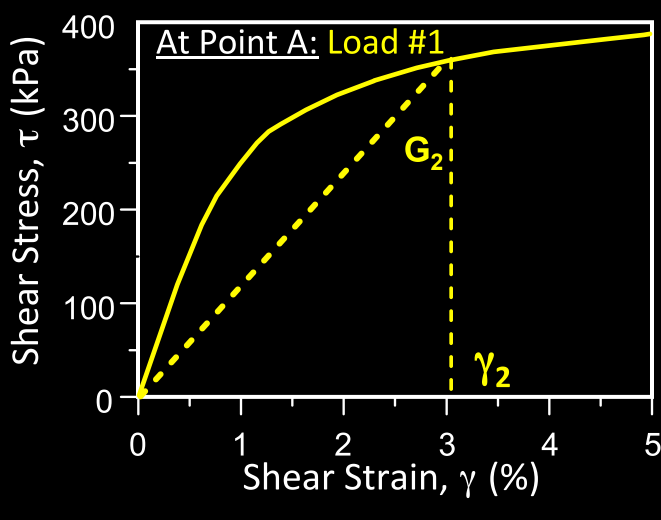
2. Load - Settlement Curve



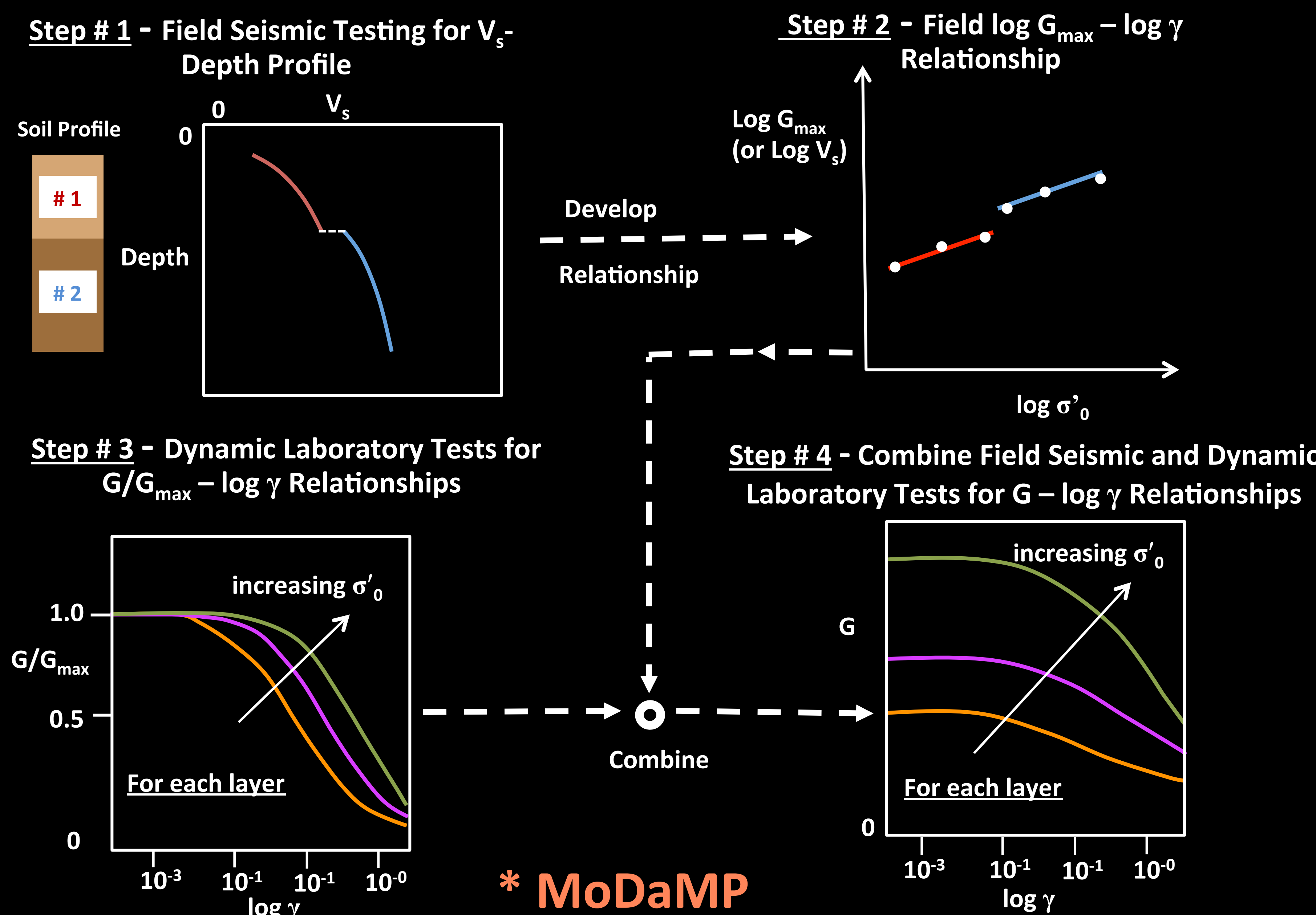
3. Stress - and Strain - Dependent Moduli, Load #1:



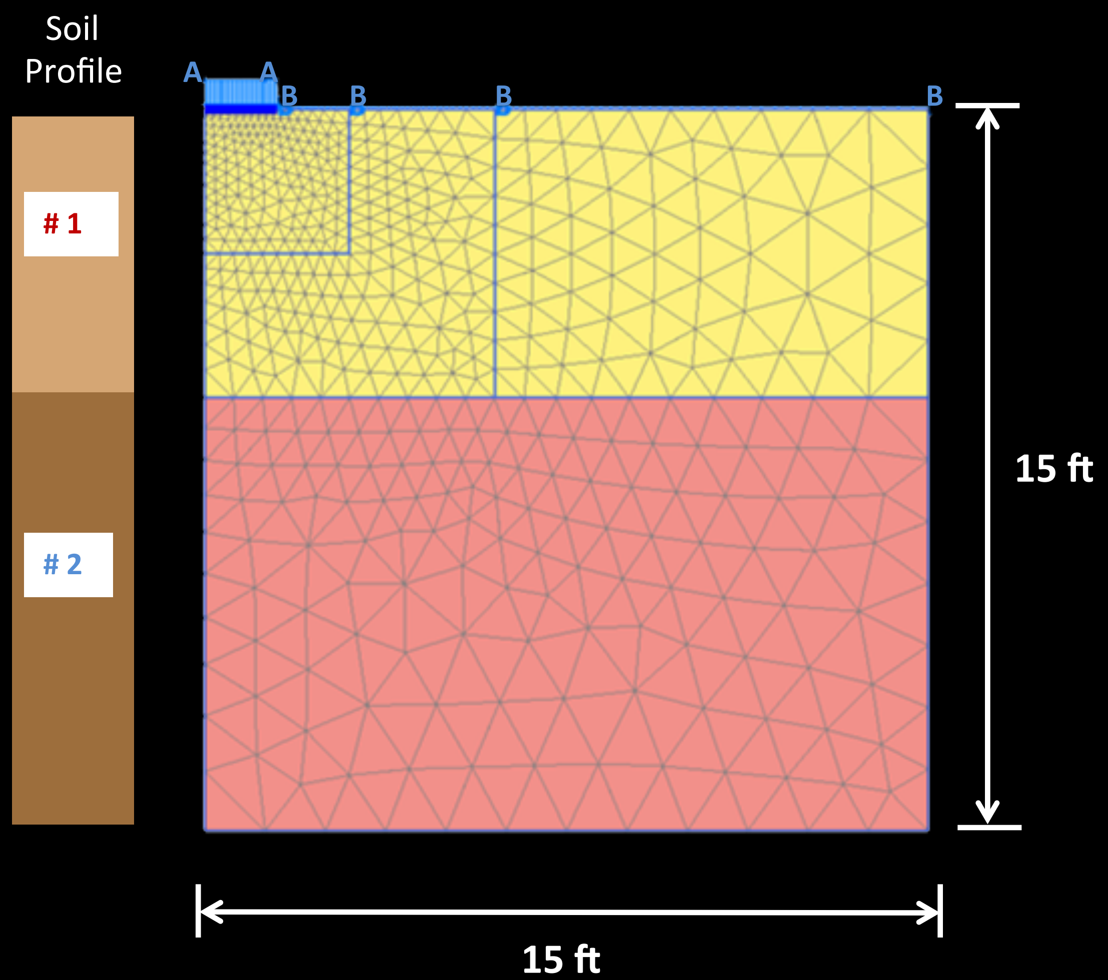
4. Stress - and Strain - Dependent Moduli, Load #2:



Modeling with Dynamically Measured Soil Properties*

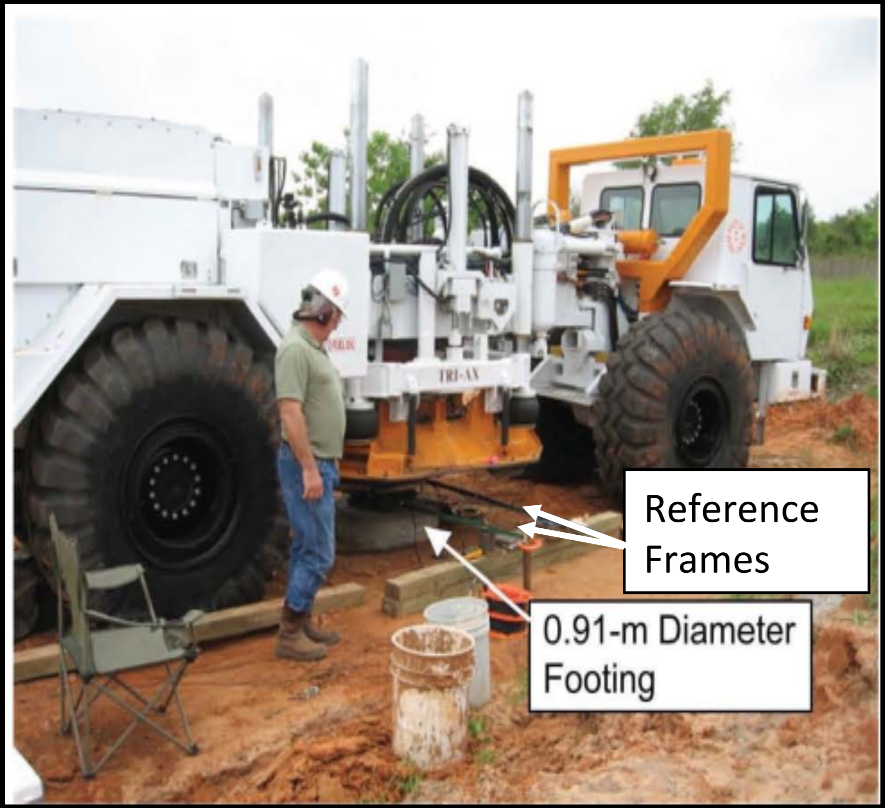


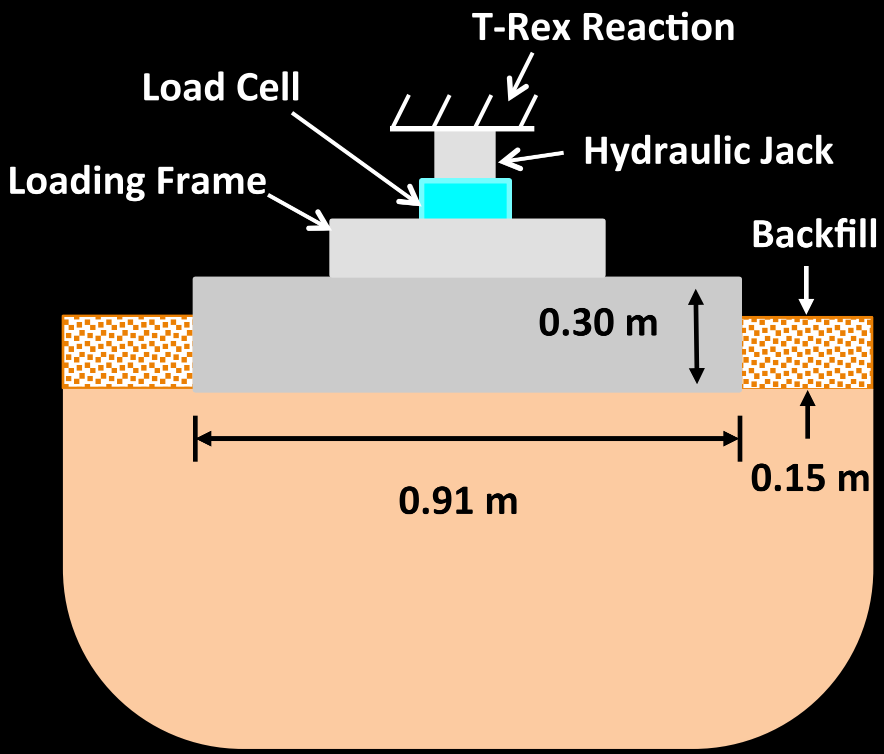
PLAXIS Finite Element Model with MoDaMP



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

Load-Settlement Tests at the NGES Test Site

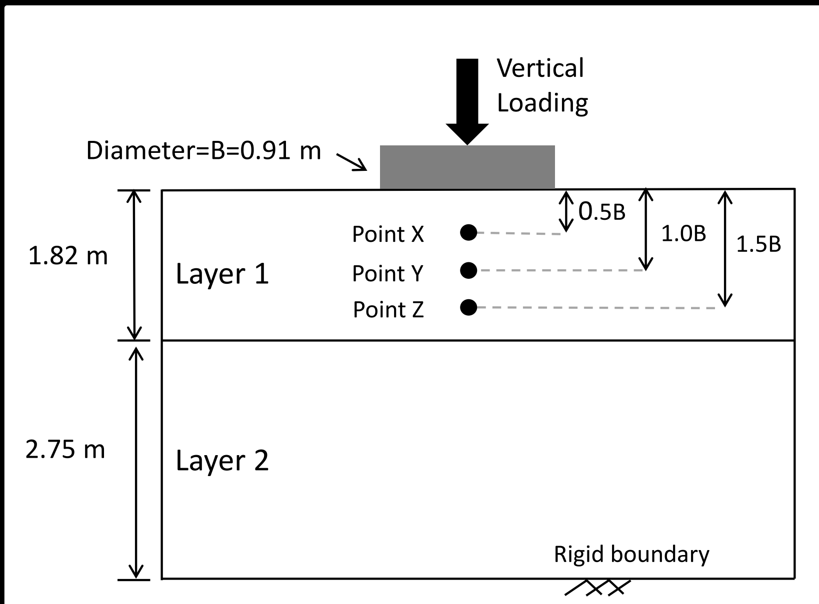


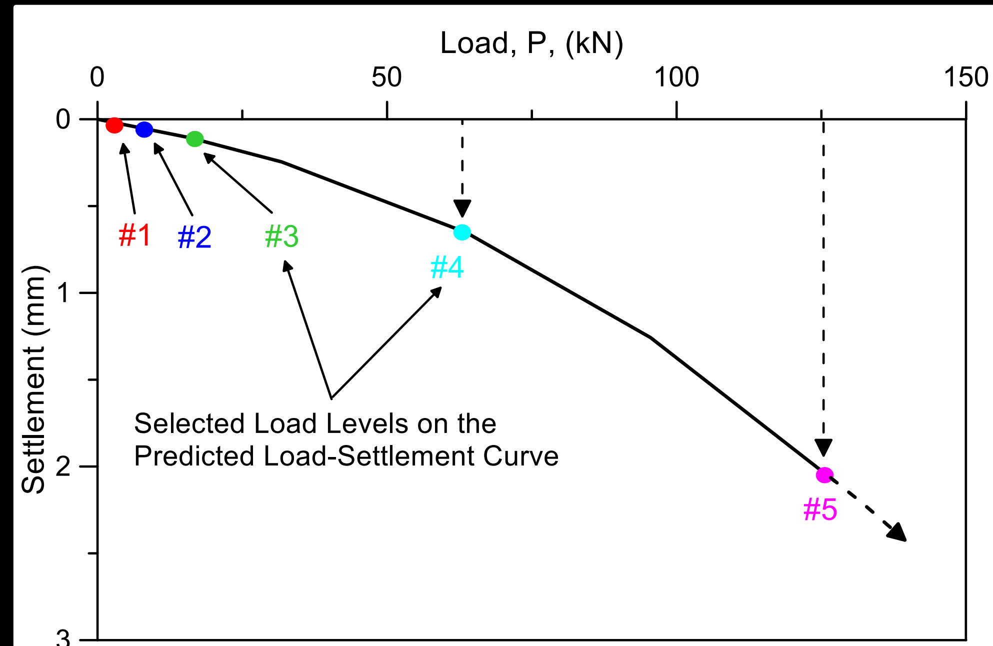


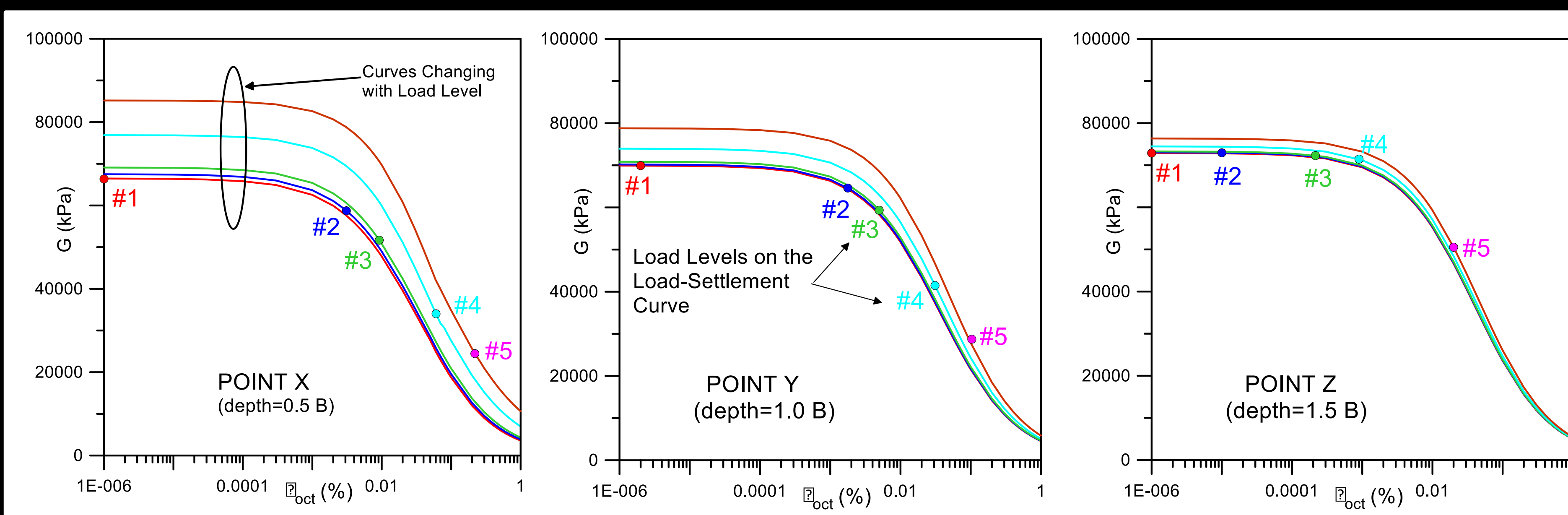
- Two, circular, reinforced concrete footings with diameters of 0.91 m (3.0 ft) and 0.46 m (1.5 ft).
- Loading with T-Rex as a reaction; Settlements measured with linear potentiometers

(Thank you Prof. Briaud!)

Example of How MoDaMP Works

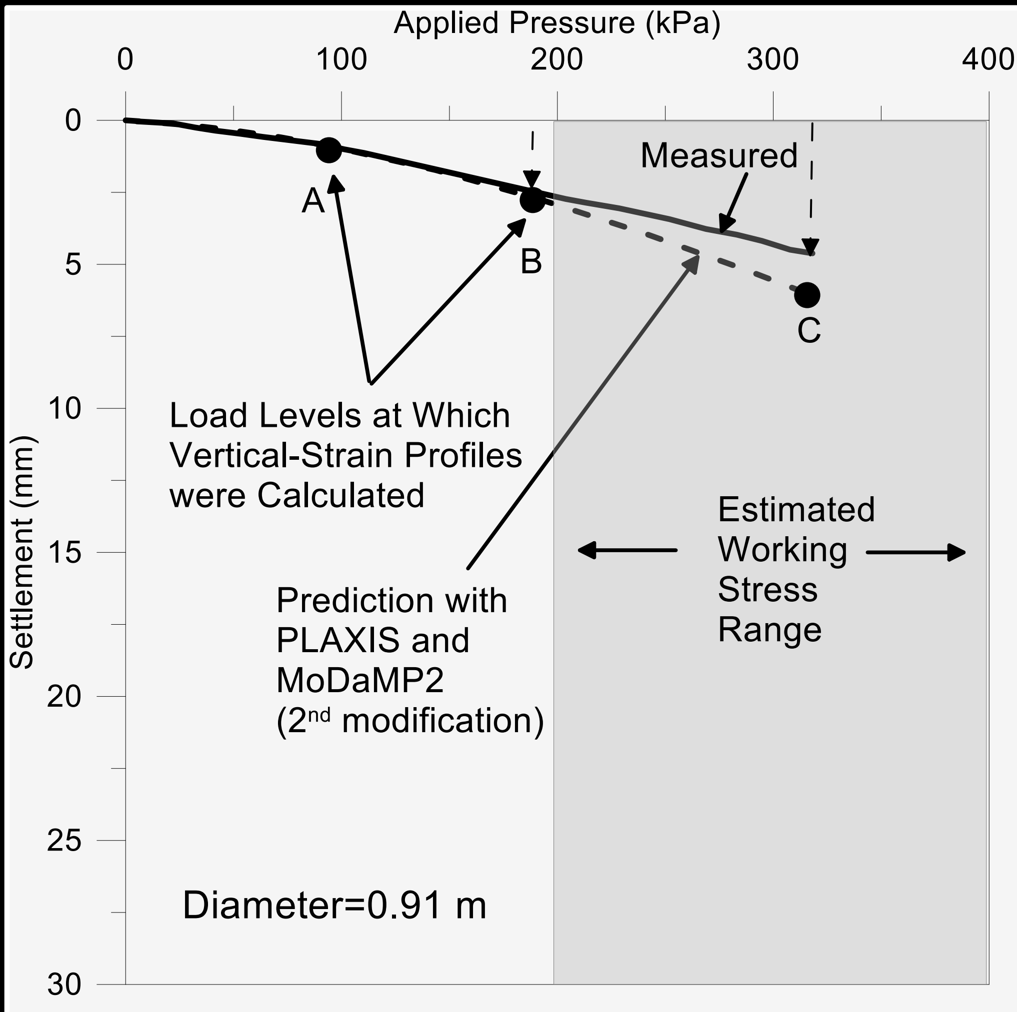






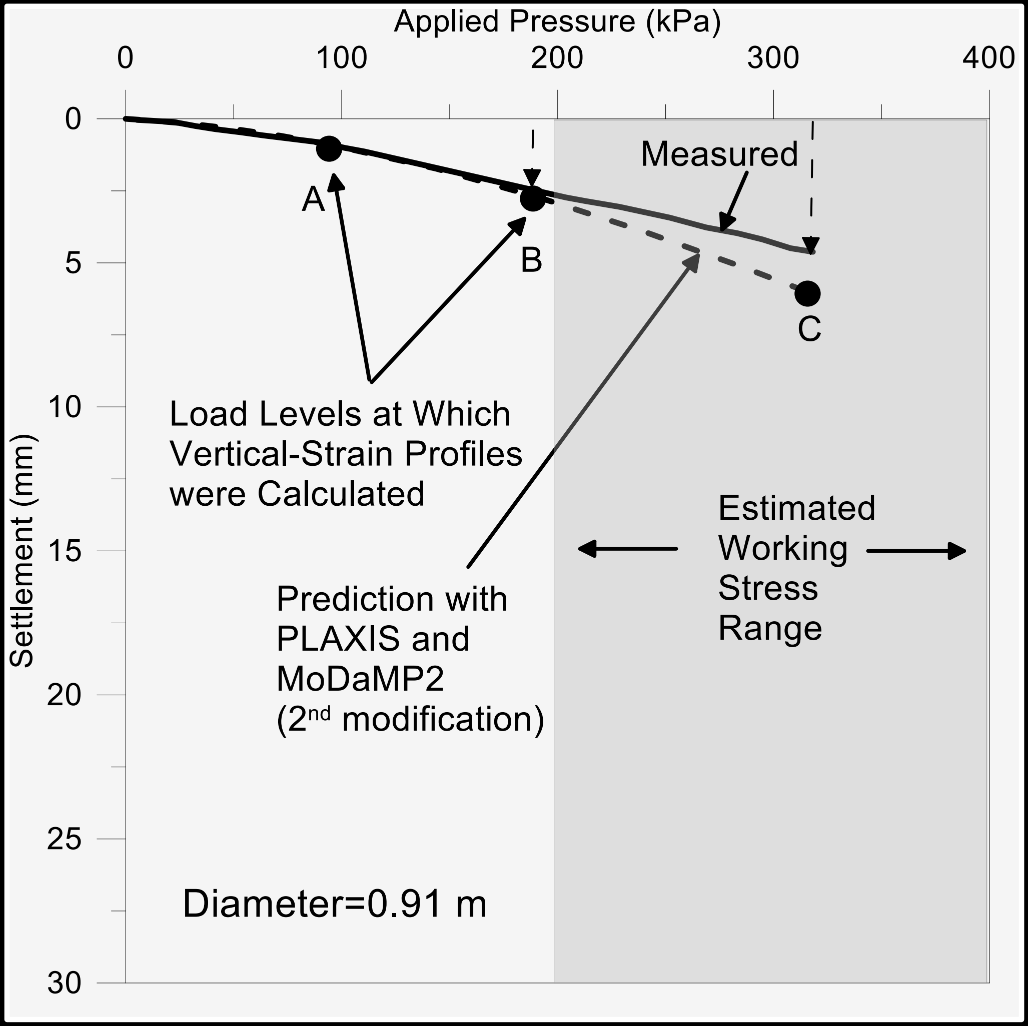
Load-Settlement Predictions with MoDaMP

Comparison of Predicted and Measured Settlements

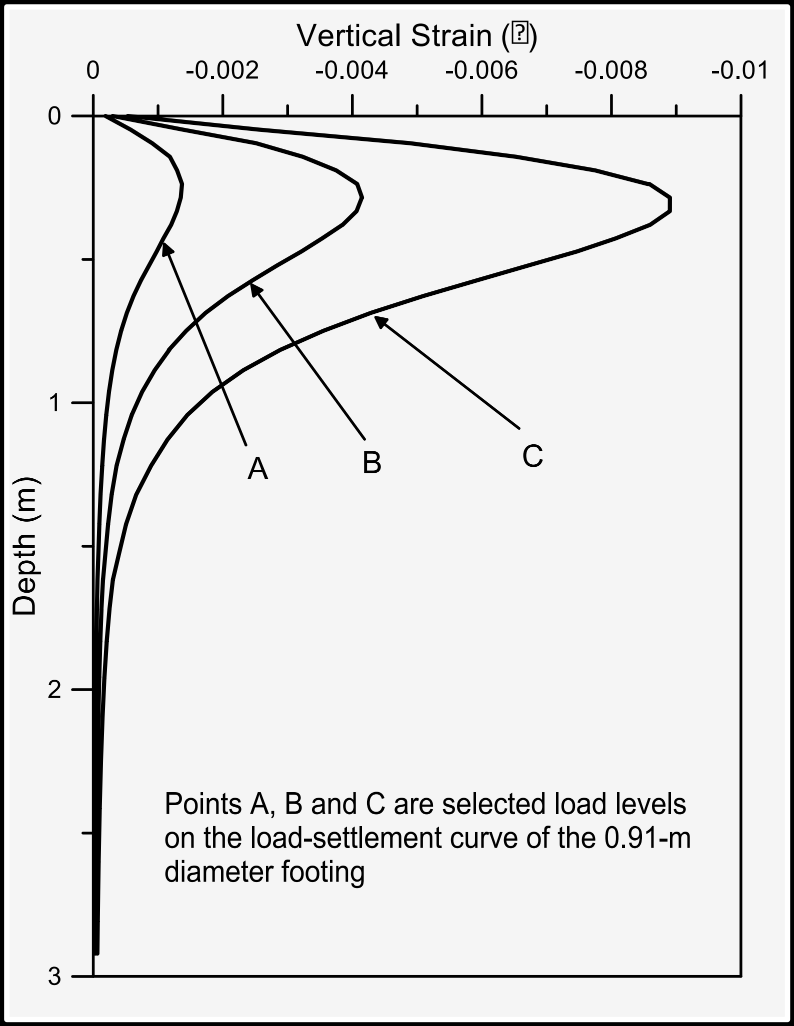


Load-Settlement Predictions with MoDaMP

Comparison of Predicted and Measured Settlements

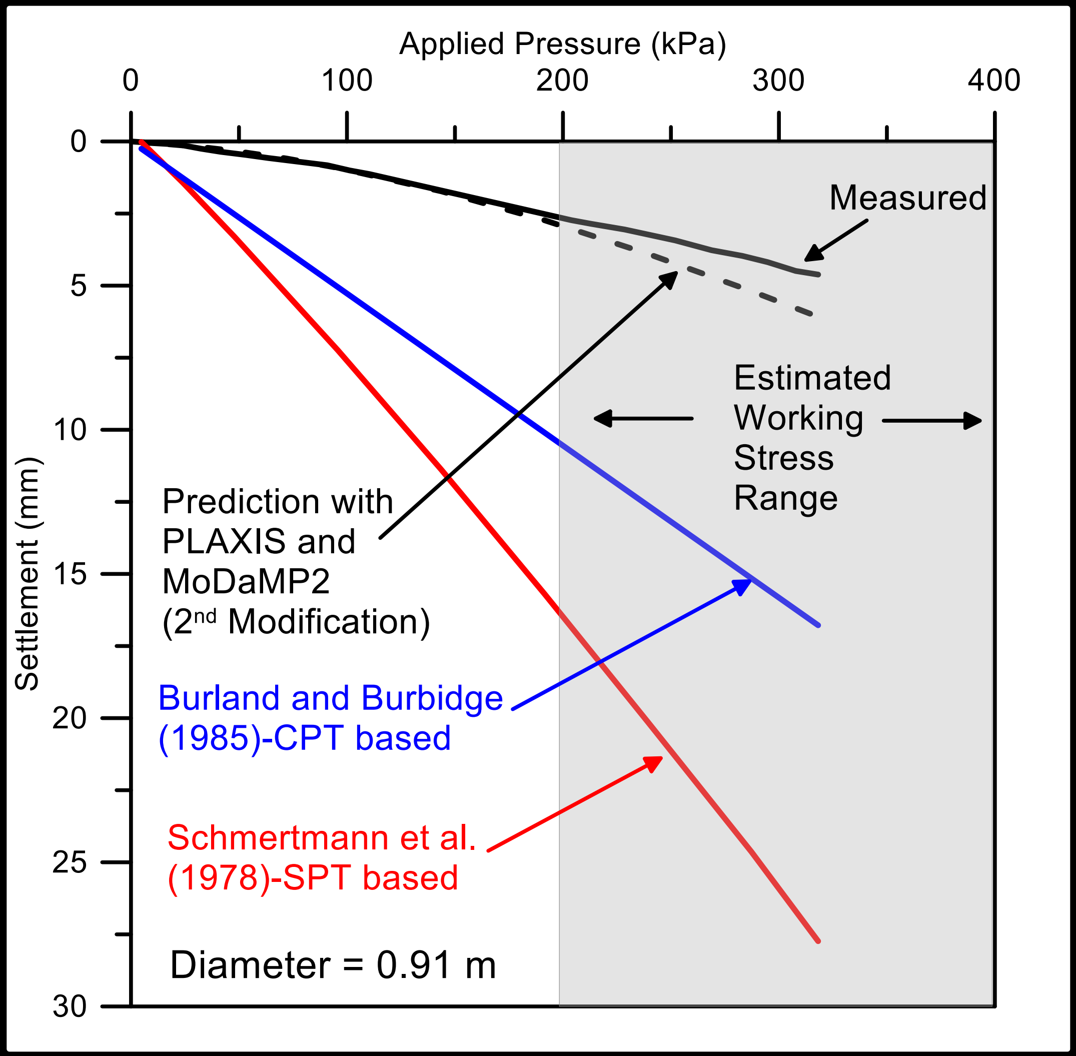


Predicted Vertical Strains Beneath the Centerline of Footing



Load-Settlement Predictions with MoDaMP

Comparison of Predicted Settlements with CPT- and SPT-based Methods



2. Examples: Applications and Case Histories

- static loading conditions
- dynamic loading conditions

2. Examples (Cont'd): Dynamic Loading Conditions

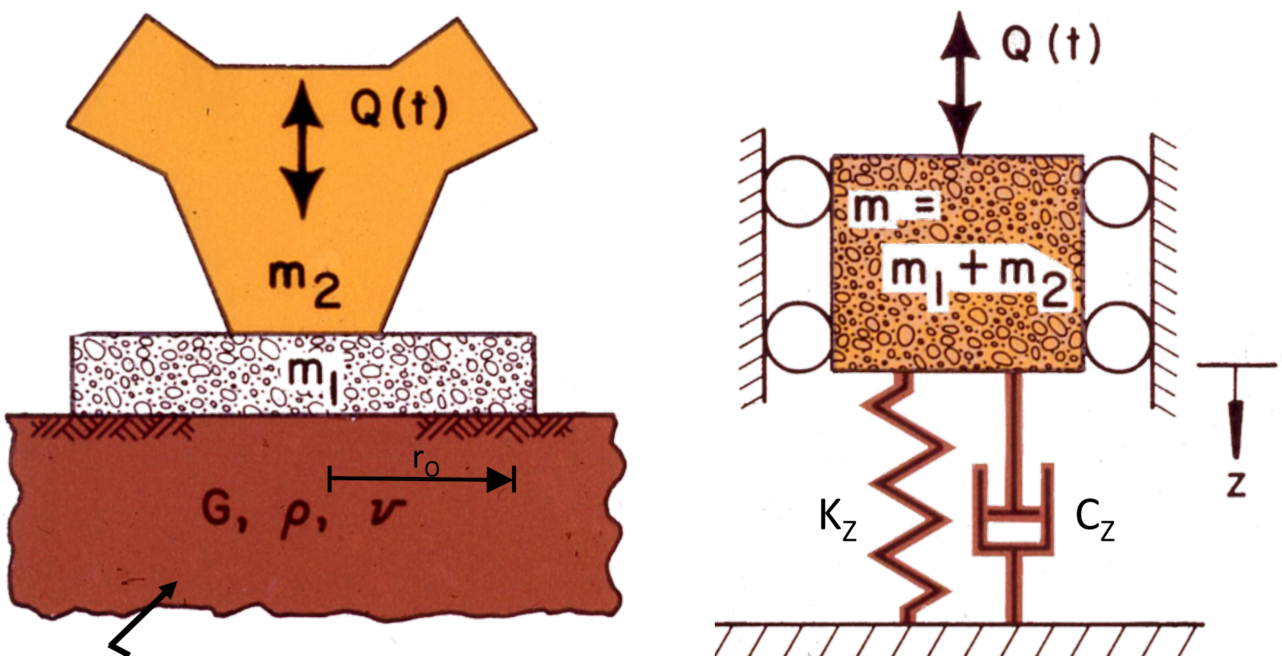
→ 2.4 Machine-Foundation Design

2.5 Vibration-Isolation Barriers

2.6 Earthquake Engineering
site response, soil-structure interaction, liquefaction, etc.

2.4 Dynamically Loaded Machine Foundations

Actual System | Equivalent System



Soil: G = shear modulus

γ_t = total unit weight

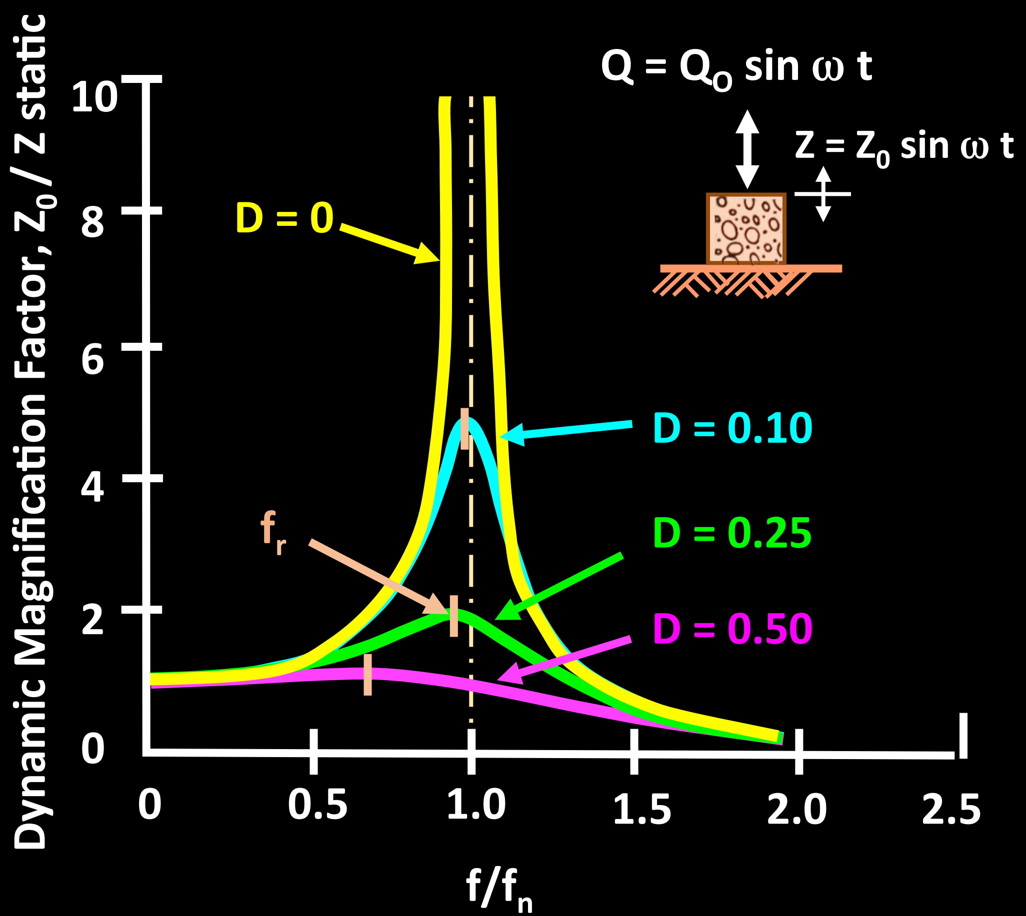
ν = Poisson's ratio

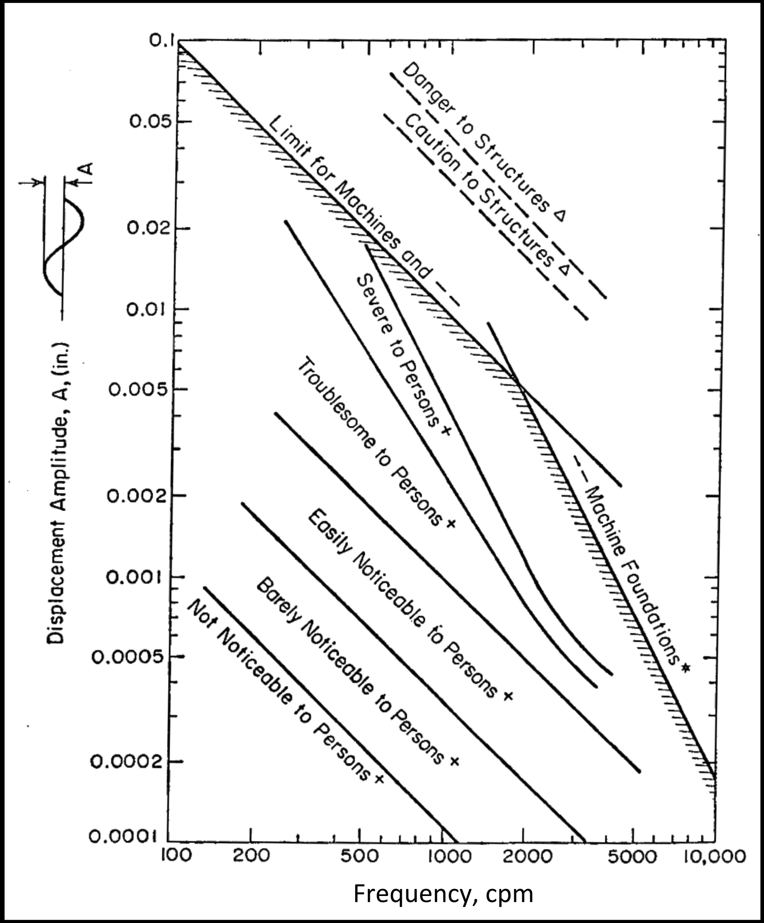
(r_O is based on equal areas)

$K_Z = 4Gr_O/(1 - \nu)$

$C_Z = (3.4\, r_o^2 / 1 - \nu)\sqrt{}$

Evaluating the Dynamic Response of the Machine Foundation System

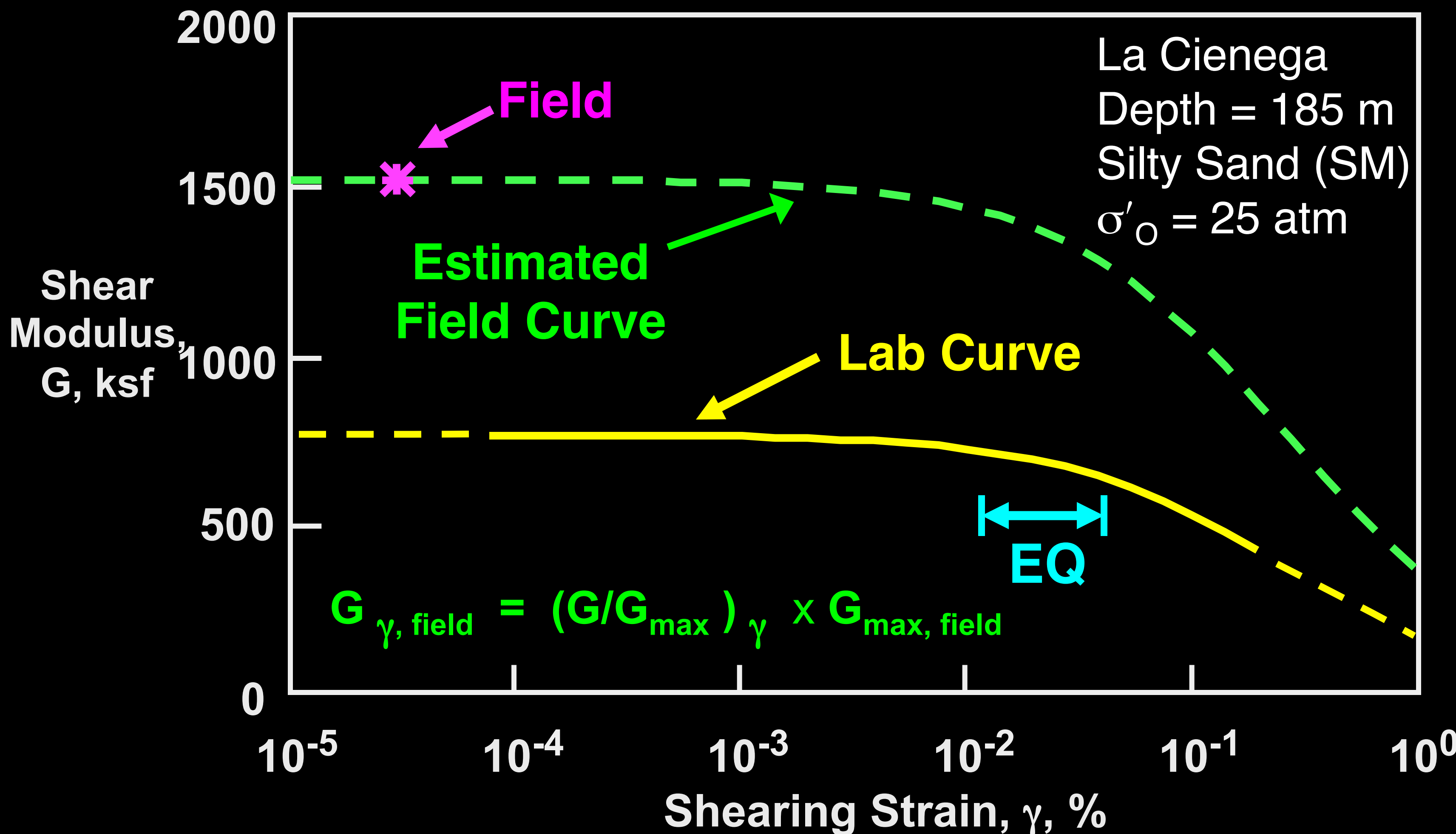




From Richart, Hall and Woods, 1970

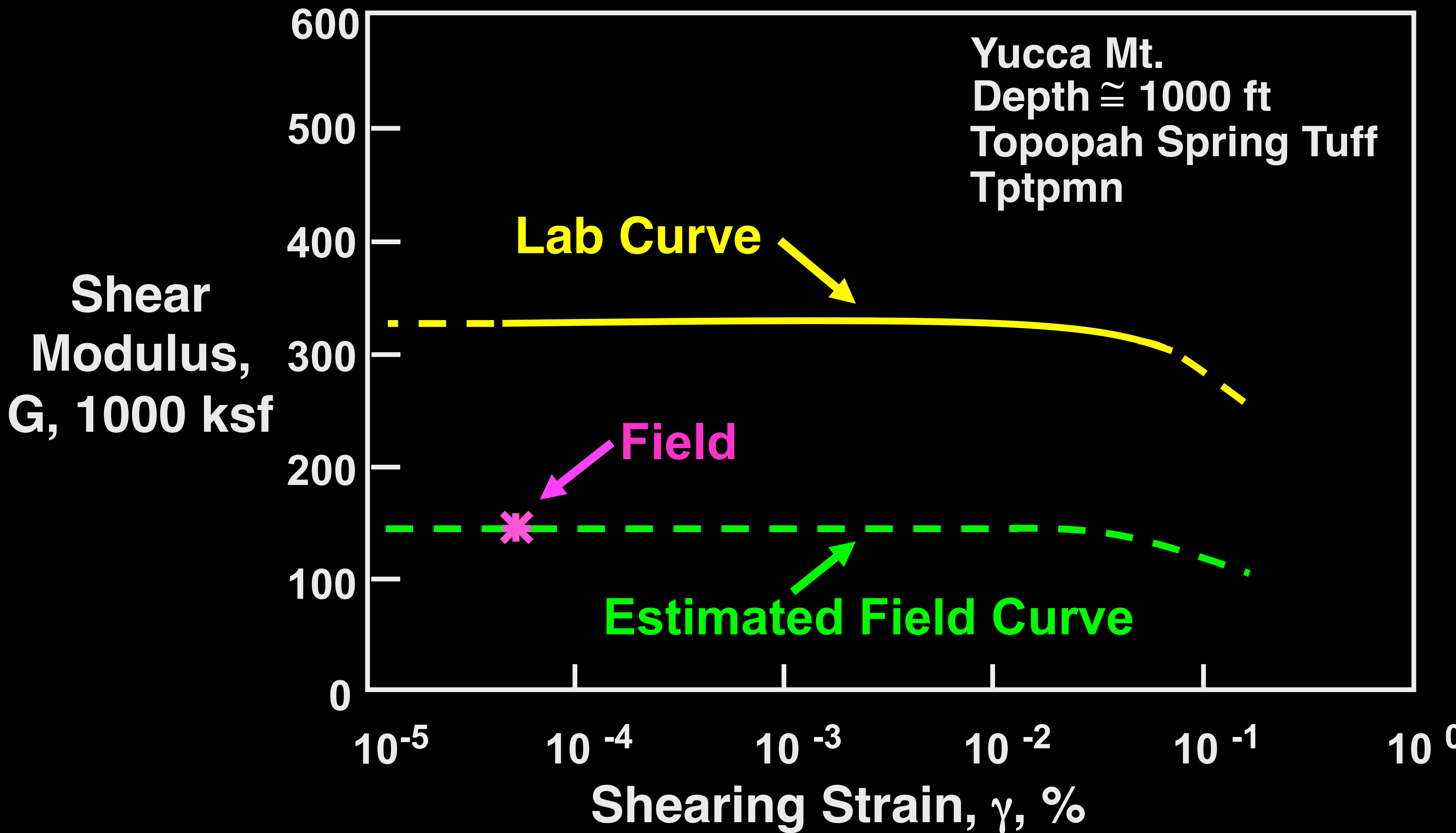
3. Link Between Field and Lab:

Estimating the Field G – log γ Relationship (Soil)



Link Between Field and Lab:

Estimating the Field G – log γ Relationship (Rock)



Concluding Remarks

1. Small-strain mechanical properties, expressed by V_S or G_{max}, play an important role in Geotechnical Engineering.

2. Small-strain mechanical properties are critical in dynamic and static deformational analyses under working loads.

3. Field measurements of V_S form the way to map nonlinear laboratory measurements to field behavior.

4. The importance of V_S or G_{max} (and also V_P and M_{max}) will continue to grow in solving dynamic and static problems.

Thank you