Brief Introduction:
Site Characterization and Fundamentals of Soil Behavior

1. Purpose of site characterization programs

2. Fundamental aspects of soil behavior

3. Laboratory and In Situ testing

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Objectives of Site Characterization Programs

A. Stratigraphy (Soil Profiling)

1. Soil Type
   - Need sufficient information to classify soil (e.g. USCS)
   - At minimum need to distinguish between cohesive and granular layers

2. Relative State
   - Cohesive – consistency
   - Granular – relative density

3. Ground water table conditions

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Objectives of Site Characterization Programs

B. Engineering Properties

1. Initial State Variables
   - Initial state of stress (σ'_{vo}, K_0)
   - Stress history (σ'_p and OCR)

2. Engineering Properties
   - Hydraulic Conductivity (k_v)
   - Consolidation (c_c, c_α, σ'_p, c_v)
   - Stress-strain-strength (c', ϕ', s_u)

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Basic Soil Behavior

Clay Behavior

Clays have very low hydraulic conductivity due to their very small interparticle pore sizes and hence have an ***undrained*** response during rapid loading or shearing, e.g., during in situ penetration testing. The small pore size also means that clays can develop significant capillary pressure, which enables one to obtain **undisturbed tube samples** for determining engineering properties from laboratory tests.

Sand Behavior

Sands have very high hydraulic conductivity due to much larger pore sizes and hence have a ***drained*** response during in situ testing. In addition, the combination of high hydraulic conductivity and very low capillary pressure essentially **precludes undisturbed tube sampling using conventional methods**. Hence engineering properties are generally inferred from in situ testing.

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Historical Simplification of Soil Behavior

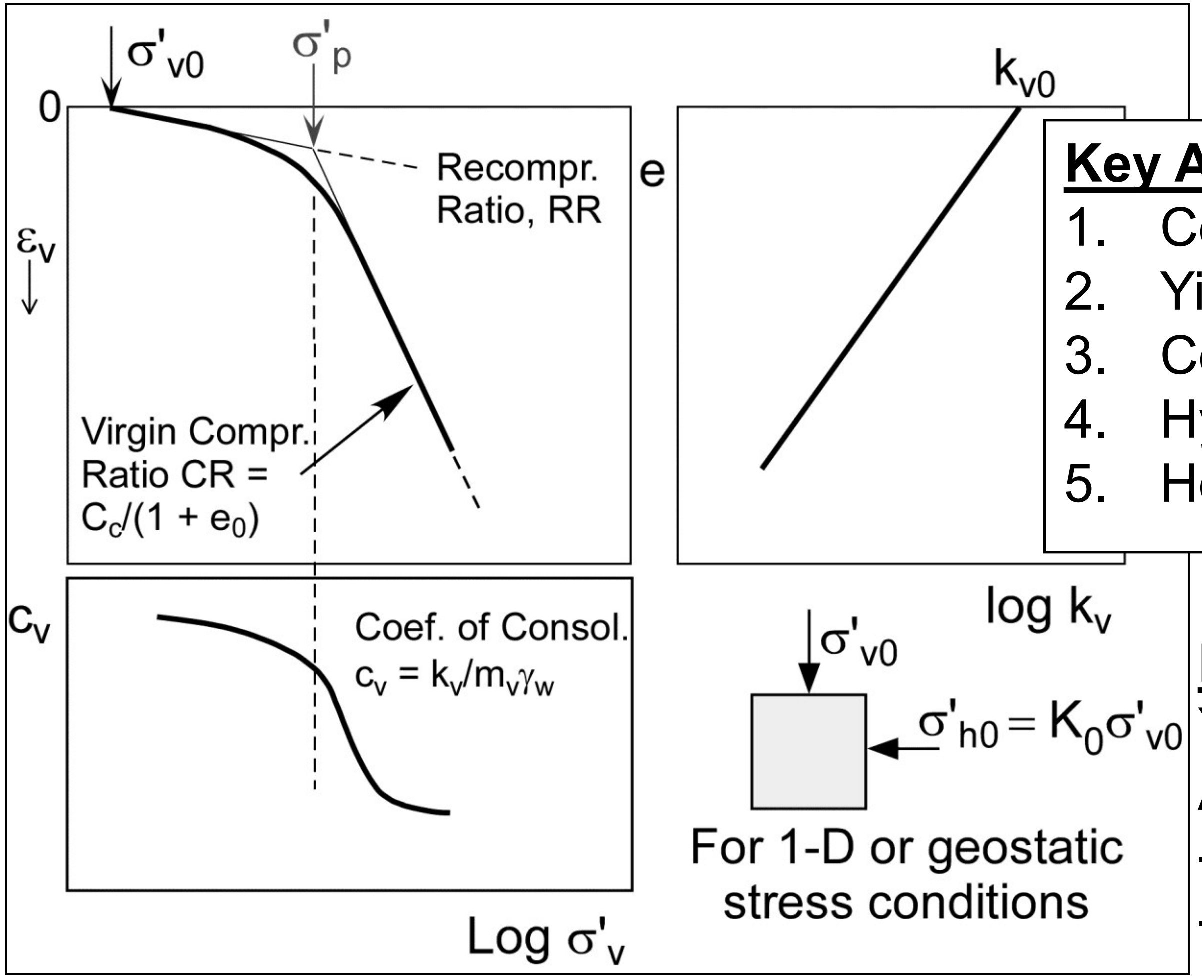
Clay Behavior

The in situ undrained shear strength of clays is a unique function of its water content and that it can be measured by any in situ or laboratory shear test that does not allow changes in water content.

Sand Behavior

Strength and compressibility characteristics of sands can be determined from laboratory tests run on reconstituted samples prepared at the estimated in situ relative density.

Basic Soil Behavior - CLAY



1-D Consolidation

Key Aspects:

1. Compressibility (RR and CR)
2. Yield stress (σ'_p)
3. Coefficient of consolidation (c_v)
4. Hydraulic conductivity (k_v)
5. Horizontal stress (σ'_{h0} or K_0)

Most Important Parameter:

Yield stress = $\sigma'_{vy} \equiv \sigma'_p \equiv p'_c$

Also known as:

- Preconsolidation stress
- Maximum past pressure

Deformation Parameters - Clay

1. 1-D compressibility parameters (CR and RR from ε-logσ'_v) or Constrained Modulus M (Janbu from ε-σ'_v)

2. Undrained Young's Modulus, E_u

3. Small strain shear modulus, $G_{max} = V_s^2 \rho_t$ where V_s = shear wave velocity and ρ_t = bulk density

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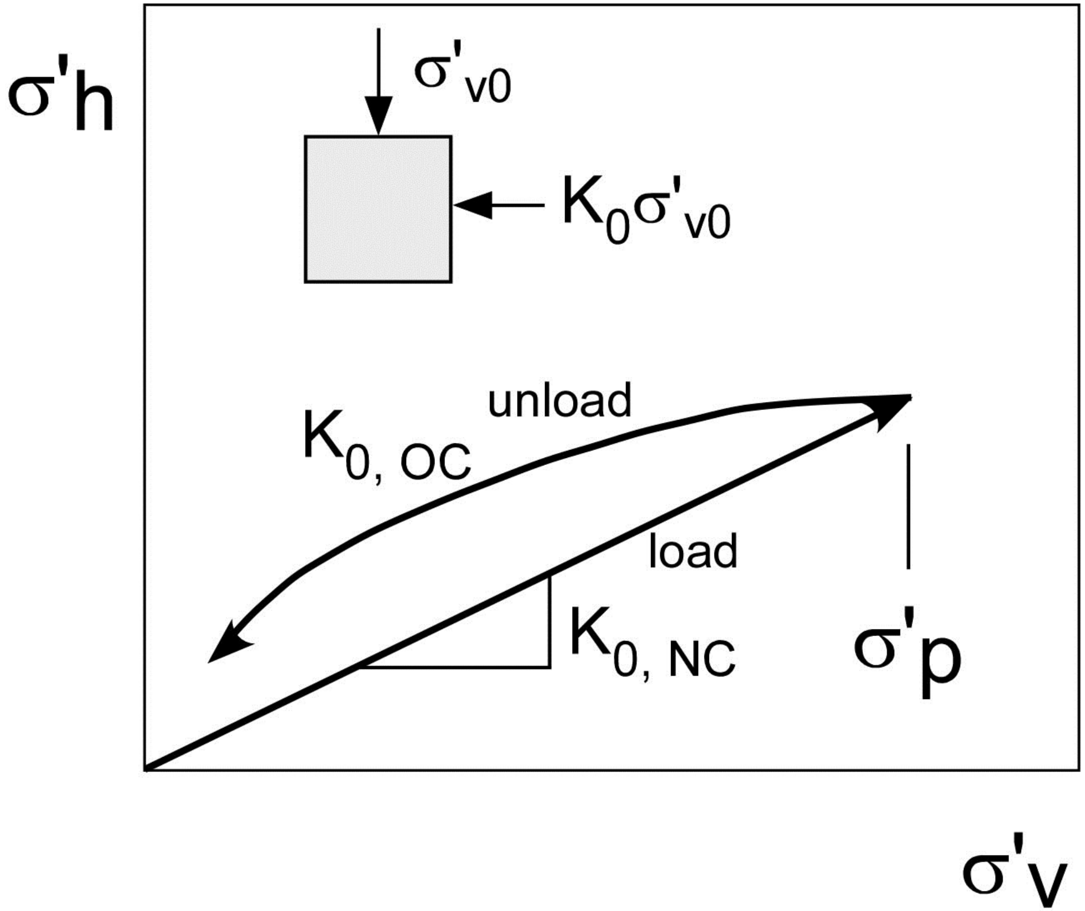
K_0 – OCR Relationship for Clays

k_0 = coefficient of lateral earth pressure at rest



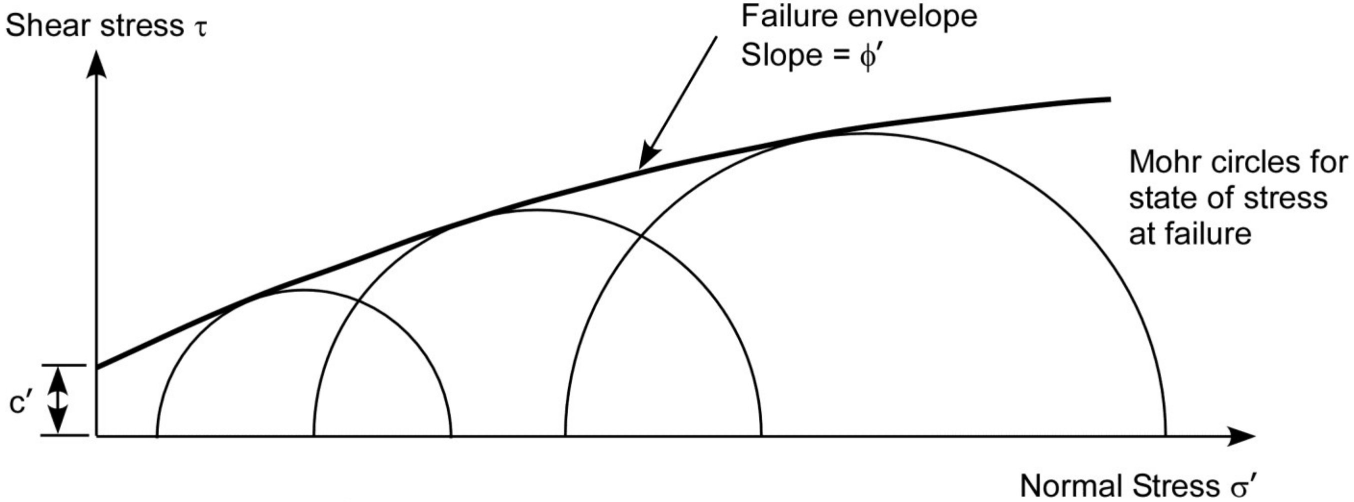
For simple case of loading followed by unloading, K_0 increases with increasing OCR such that:

$$K_{0,OC} = K_{0,NC}(OCR)^n$$

Basic Soil Behavior - CLAY

Drained Shear Strength

Dilatant vs contractive behavior is function OCR (void ratio)



For straight line failure envelope:
$\tau = c' + \sigma'\tan\phi'$

<u>Most Important Parameters:</u>
Effective stress parameters c' and ϕ'

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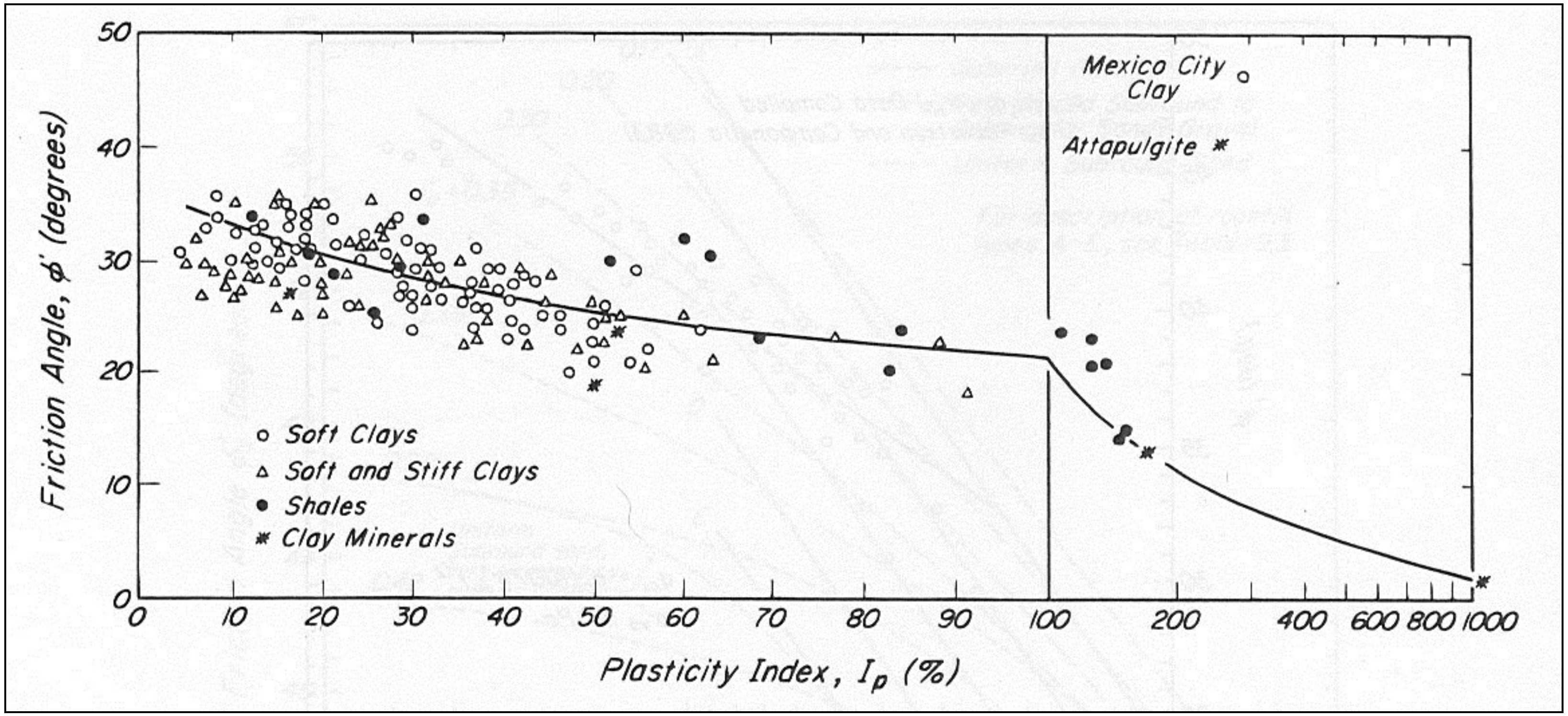
Effective stress parameters - CLAY

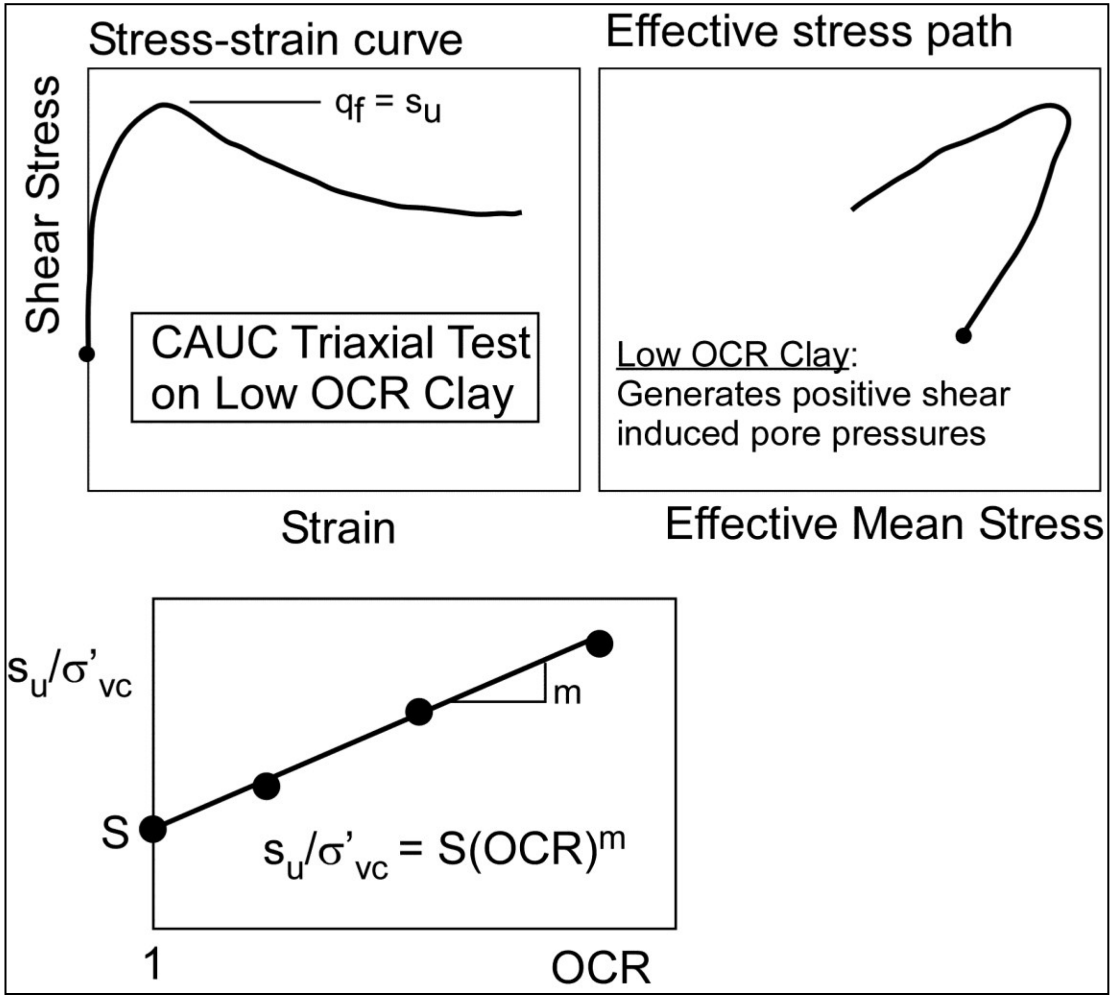
1. For low to normally consolidation clays c' = 0

2. c' > 0 for OC clays although this is in part function of use of linear failure envelopes



[from Terzaghi et al. 1996]

Basic Soil Behavior - CLAY



Undrained Shear Strength

Key Aspects:

1. Shear induced pore pressures
2. Effect of OCR
3. Anisotropy
4. Rate effects

Most Important Parameter:

Undrained shear strength = s_u

Also at times need:
Remolded undrained shear strength (s_{ur}) or Sensitivity, $S_t = s_u/s_{ur}$

Critical Soil Behavior Issues - s_u

Three key factors affecting laboratory measured s_u:

1) Sample disturbance ⇒ most critical,
2) Mode of shearing (anisotropy), and
3) Rate of shearing (rate effects)

Factor 1: Sample Disturbance ⇨ Laboratory Reconsolidation

1. Significant reduction in σ'_s for soft clays reduces measured s_u – big problem for strength index tests
2. Use anisotropic or K_0 reconsolidation via either the Recompression or SHANSEP techniques to remediate effects of sample disturbance

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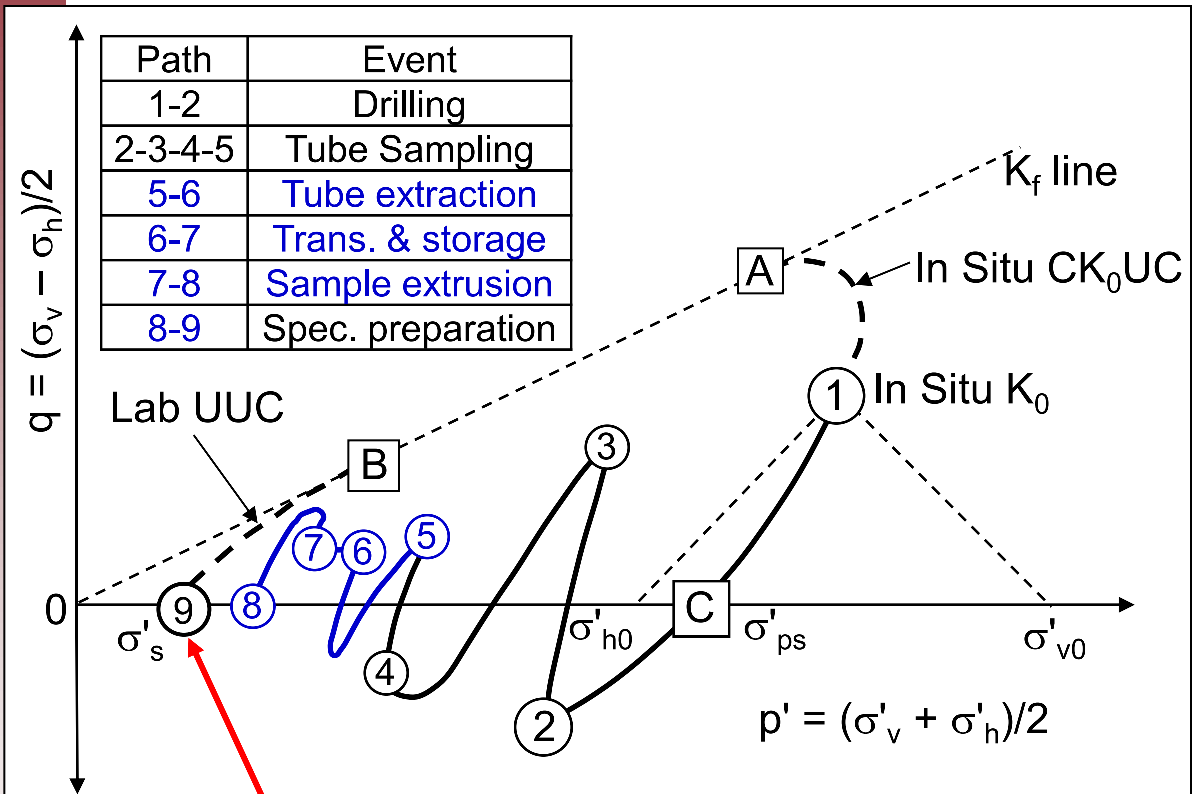
"Undisturbed" Tube Sampling for Laboratory Testing



Path	Event
1-2	Drilling
2-3-4-5	Tube Sampling
5-6	Tube extraction
6-7	Trans. & storage
7-8	Sample extrusion
8-9	Spec. preparation

Sampling effective stress [residual stress] = σ'_s
= effective stress for all Express/Index Strength Tests

- **①–② Drill Borehole**
- **②–⑤ Tube Sampling**
- **⑤–⑥ Tube Extraction**
- **⑥–⑦ Transportation & Storage**
- **⑦–⑧ Sample Extrusion**
- **⑧–⑨ Specimen Setup**

How to quantify this disturbance?

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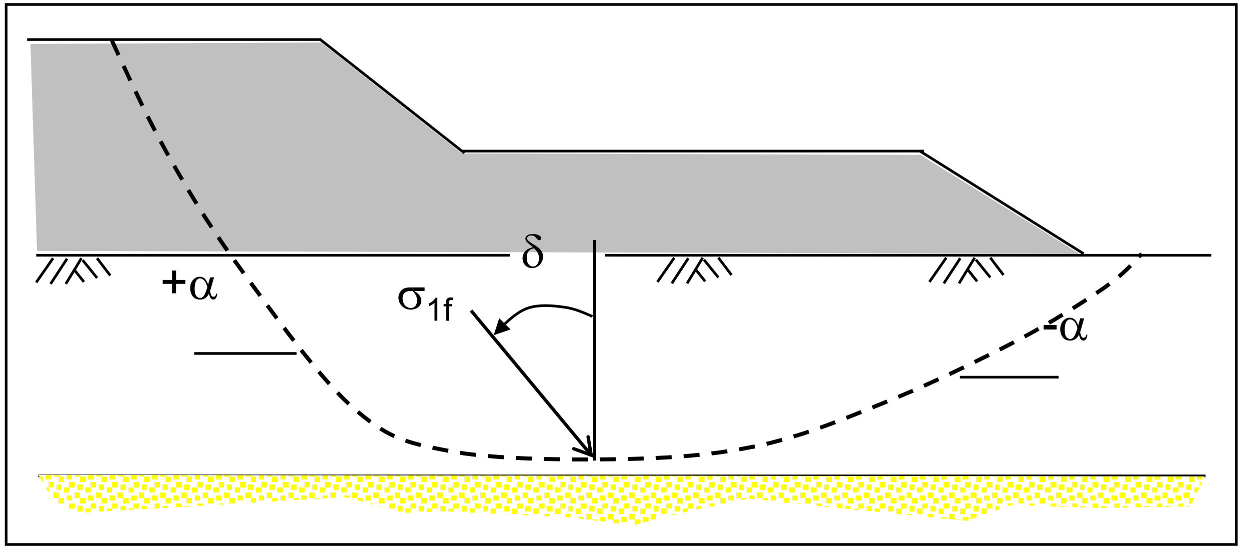
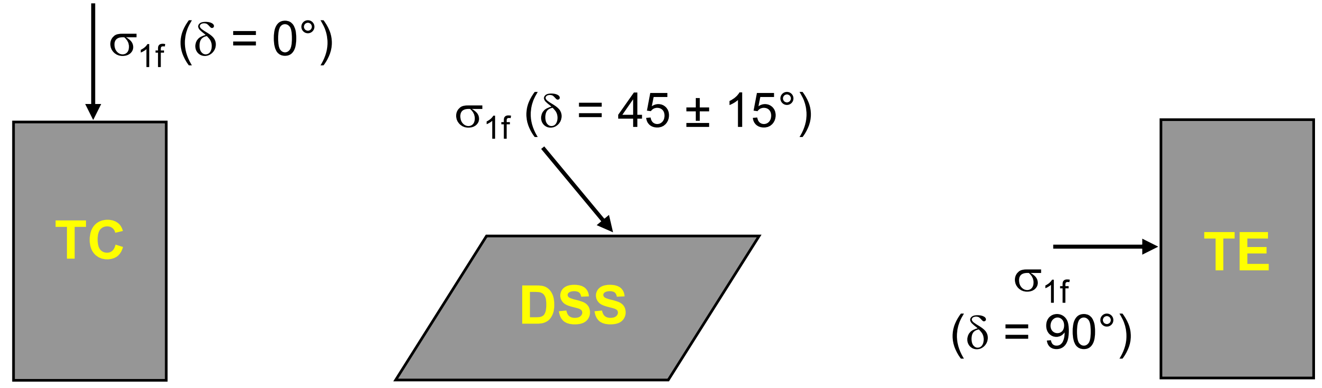
Factor 2: Anisotropy ⇨ Appropriate Mode of Shearing

Stability Problems:
- significant variation in major principal stress at failure (σ_{1f})



Laboratory Simulation



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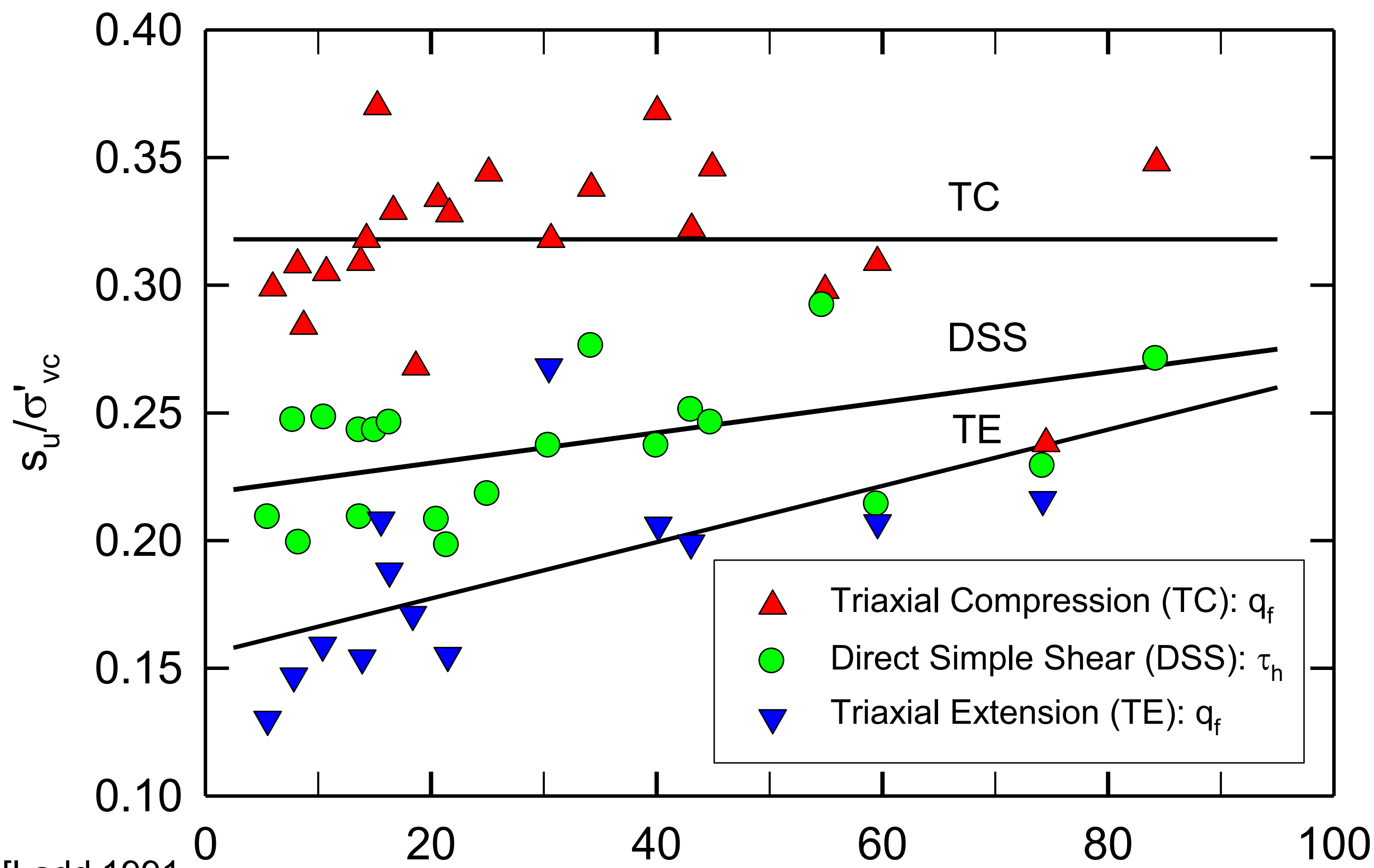
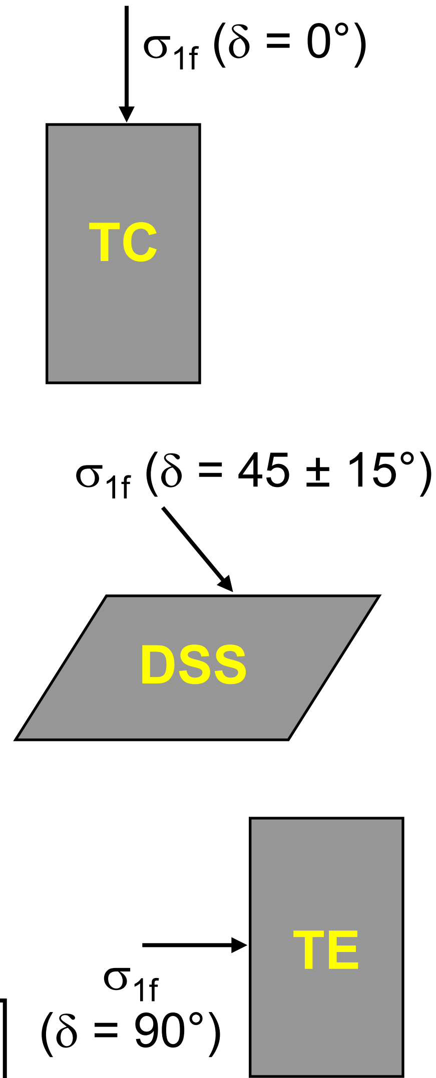
Undrained Shear Strength Anisotropy



[Ladd 1991, Ladd and DeGroot 2003]



- $CK_0UC/E \rightarrow$ max. & min. s_u
- Direct Simple Shear (DSS) $\approx s_u$(ave); [s_u(ave) $\equiv s_u$(mob)]

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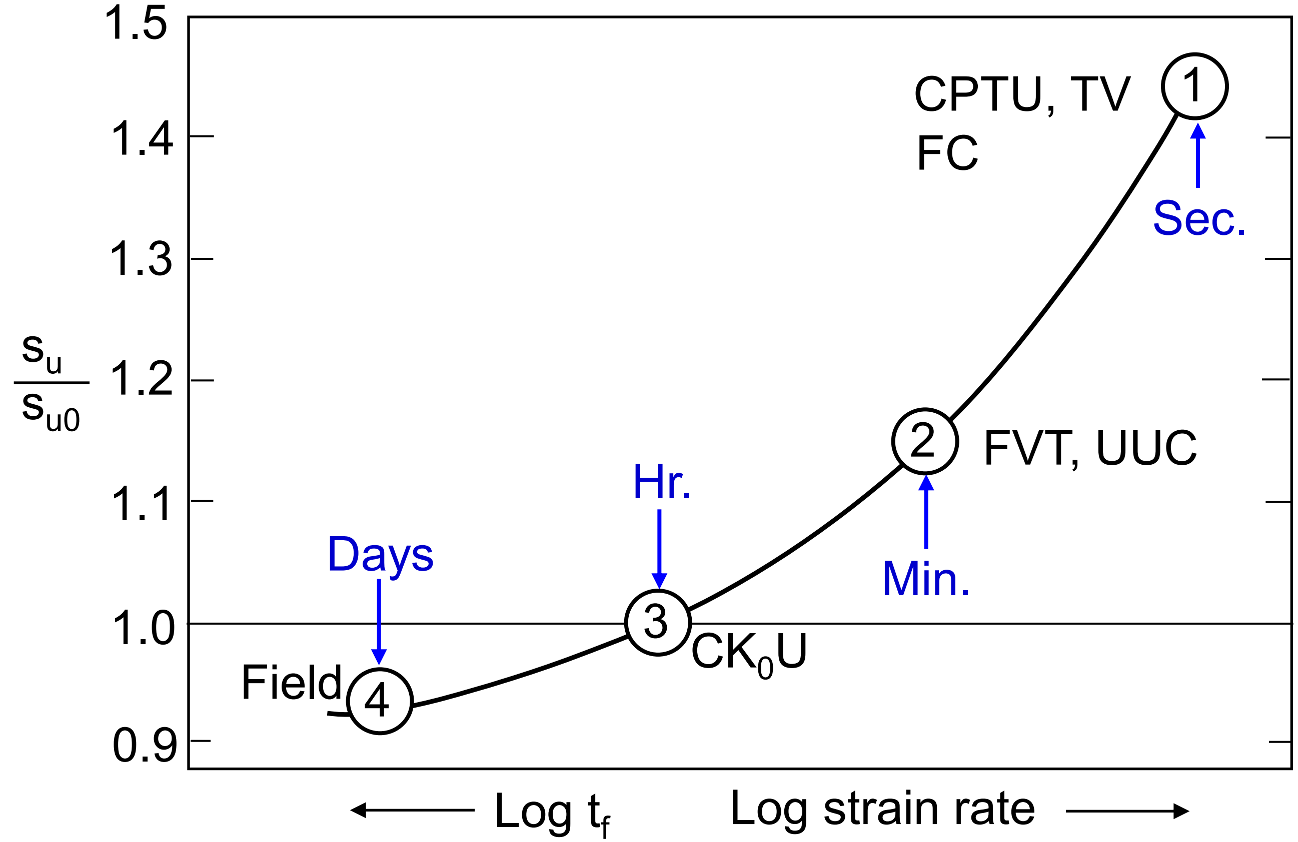
Factor 3: Rate Effects ⇒ Appropriate Rate of Shearing

Conceptual comparison after adjustment to same mode of shearing = s_u(ave)

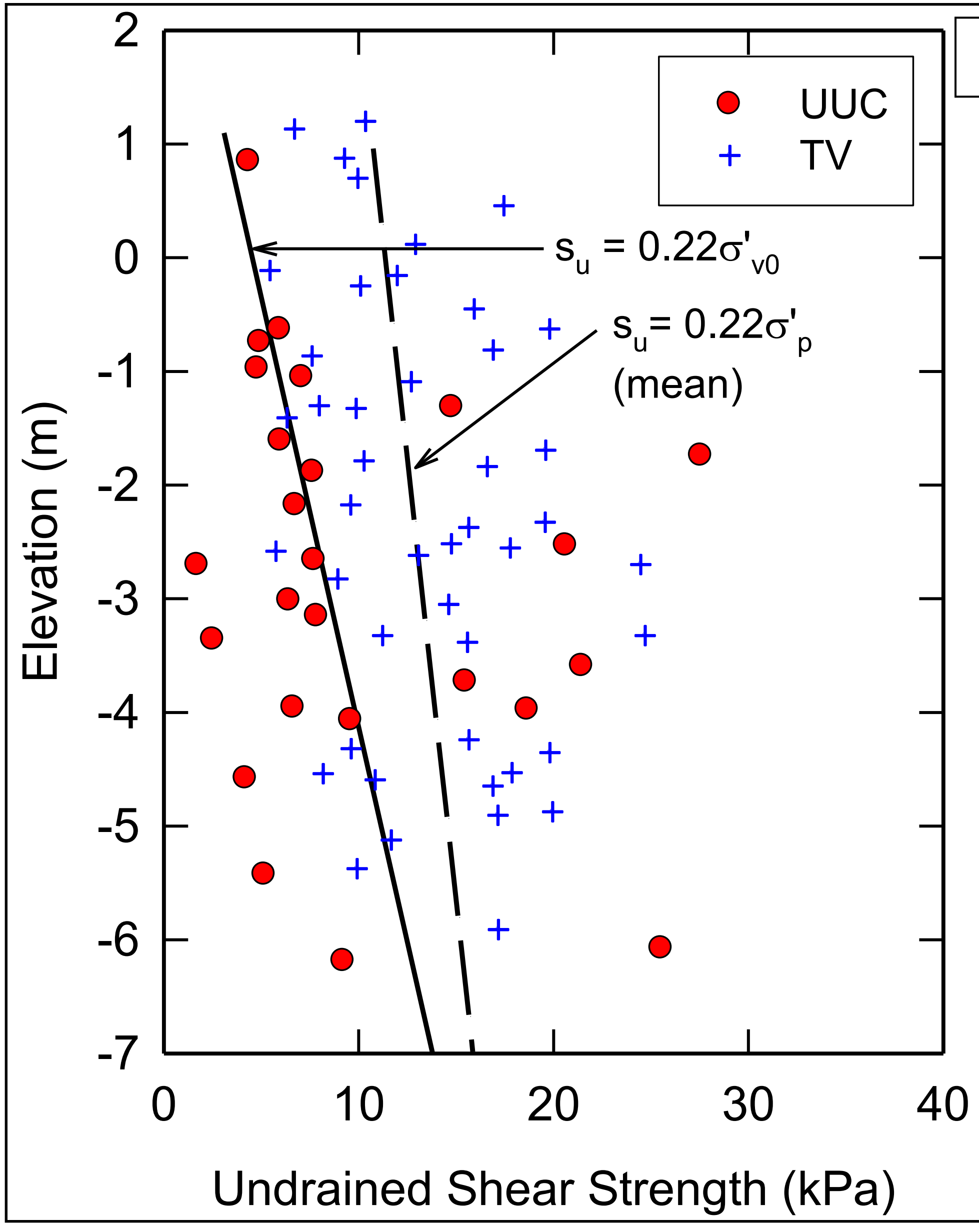


Recommended Lab Shear Rates

Lab CK_0U → TX $\dot{\varepsilon} \approx 0.5 - 1.0$ %/hr

DSS $\dot{\gamma} \leq 5$%/hr

Problems with Index Strength Testing (UUC, TV, PP, etc.)



CH Clay Nigerian Swamp

Problems:

- Unknown effective stress state

- Highly variable (and often fast) shear rates

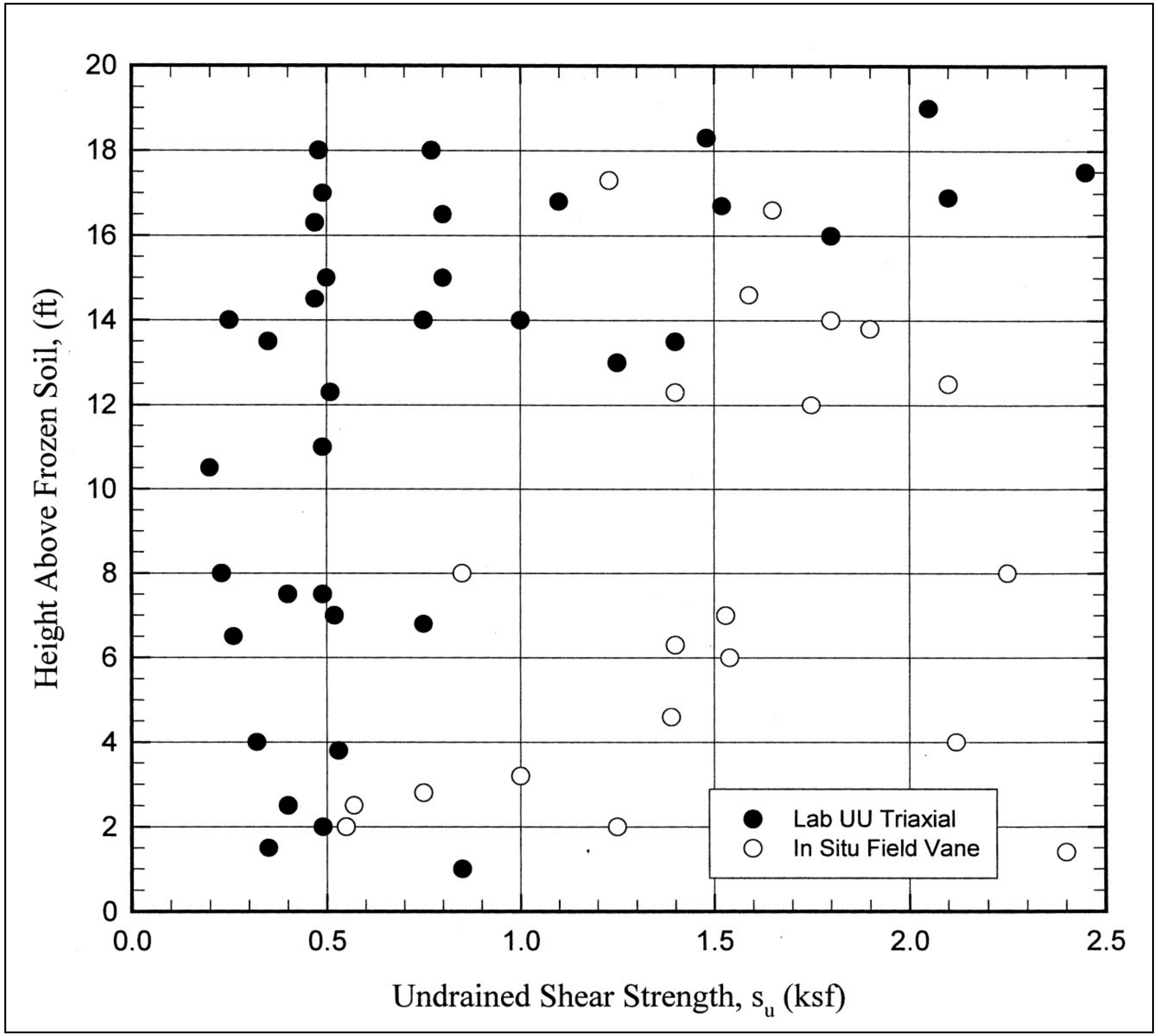
- How account for Anisotropy?

Net Result:

Highly scattered results → very common occurrence

[Ladd and DeGroot 2003]

Undrained shear strength data from Harrison Bay, Alaska (from Sauls et al. 1984)



Basic Soil Behavior - SANDS

For static loading: drained shear behavior governs:

For design need information on: 1) Compressibility and 2) Shear strength (ϕ')

Density (or relative density) is most important parameter. Other factors include: composition, mineralogy, gradation, grain crushing, stress levels, etc.

State Parameter (ψ) – in situ void ratio relative to reference state (= steady state line = critical state line = constant volume shear)

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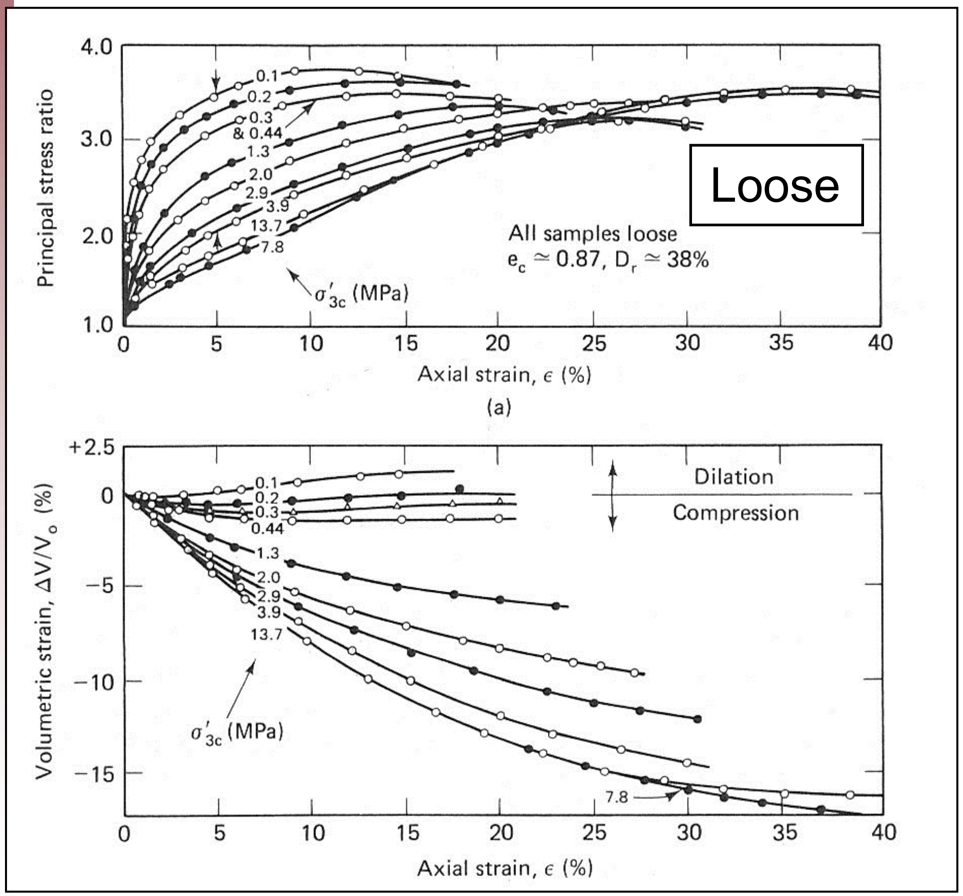
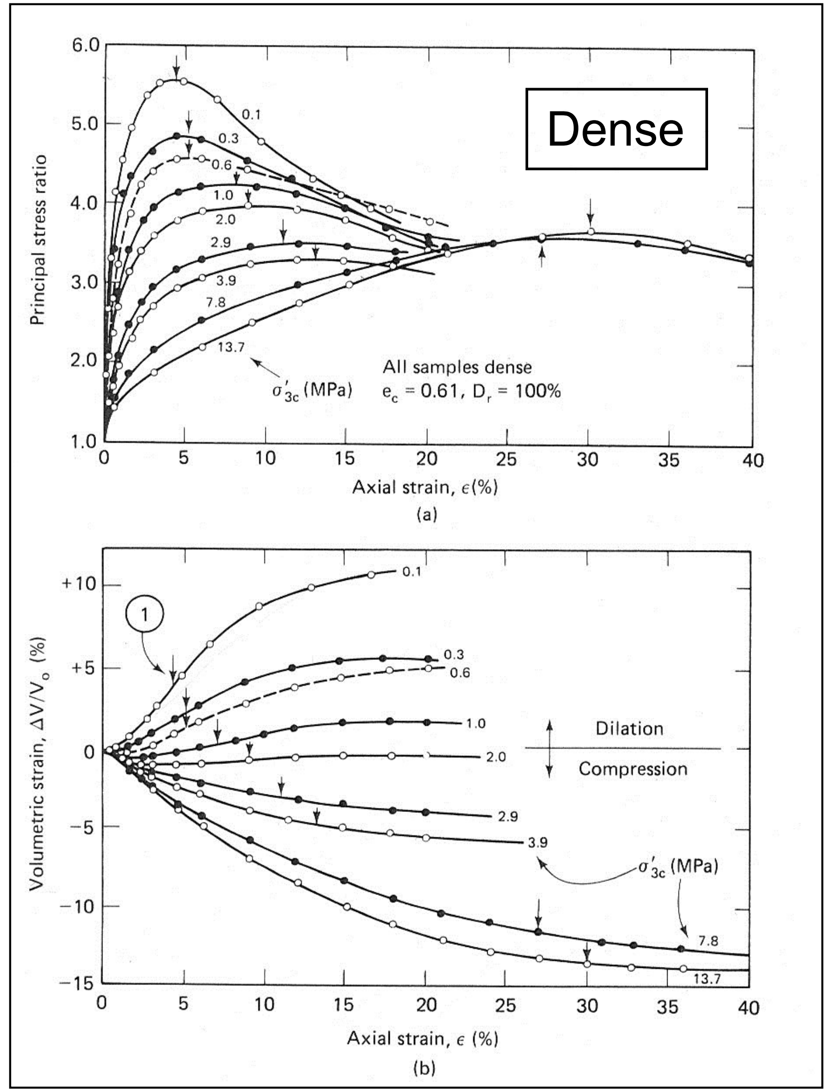
Drained Shear Behavior - SANDS

Triaxial compression behavior of loose and dense sand at different consolidation stresses

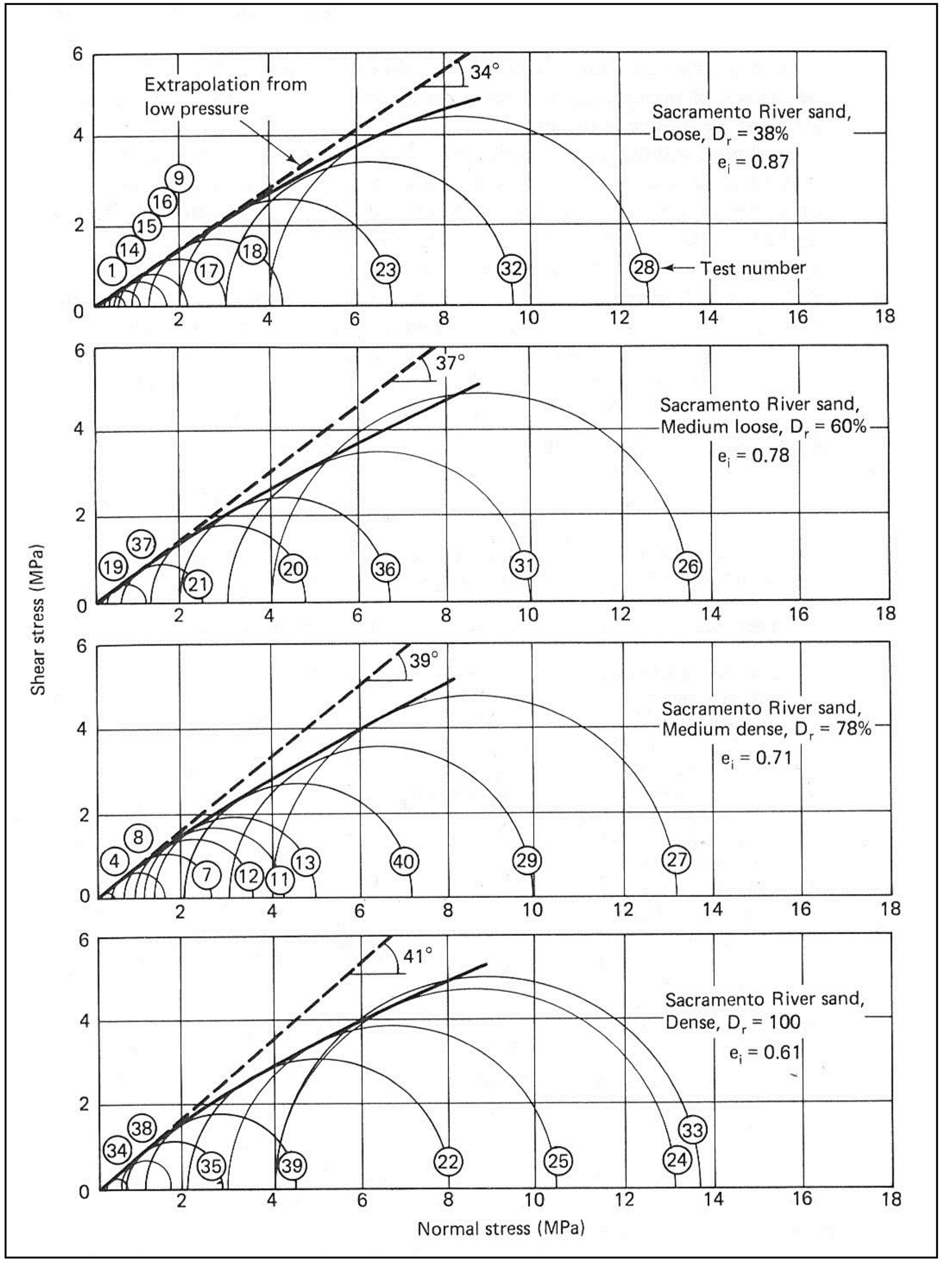




[data by Lee 1965, Figures from Holtz and Kovacs 1981]

Corresponding Mohr Circles for state of stress at failure

Clear evidence of influence of density and stress level on ϕ'



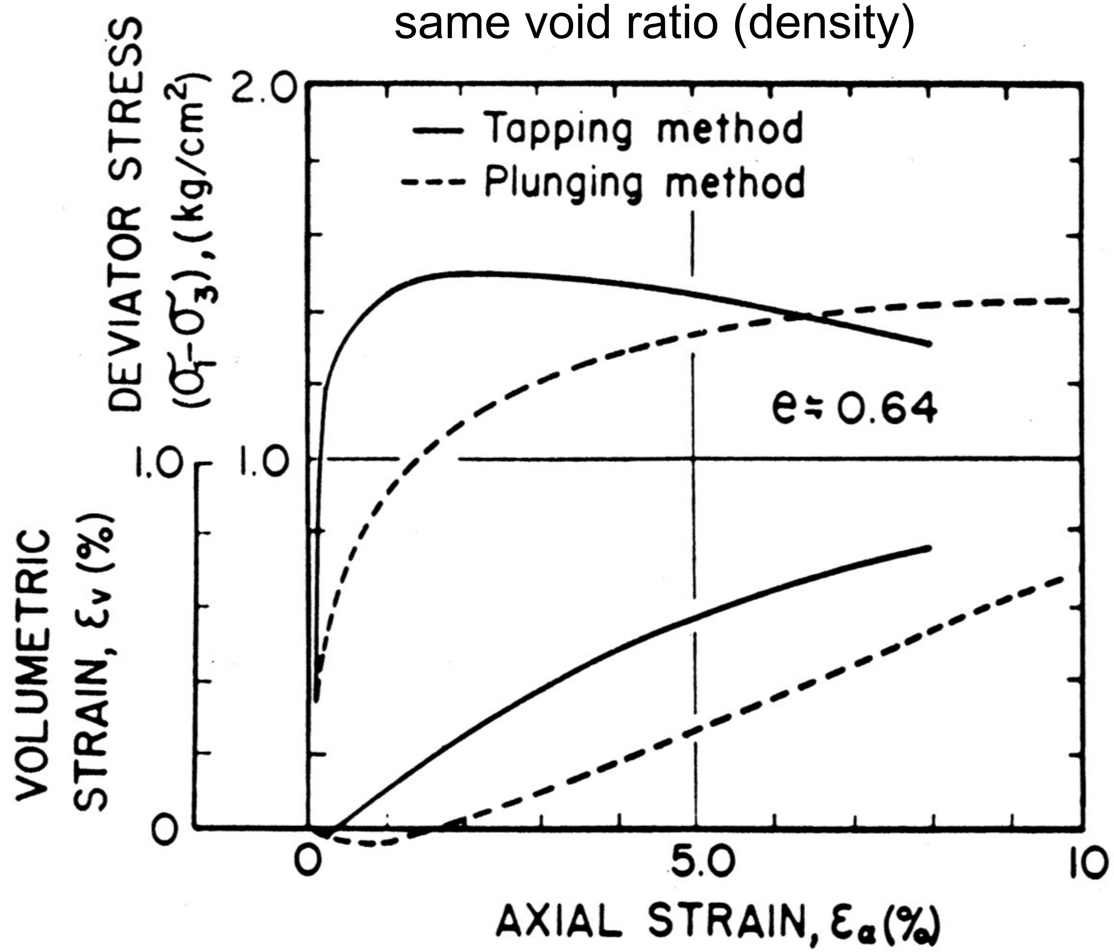
[data by Lee 1965, Figures from Holtz and Kovacs 1981]

Common in practice to reconstitute sand samples in the laboratory to estimated in situ void ratio (density)

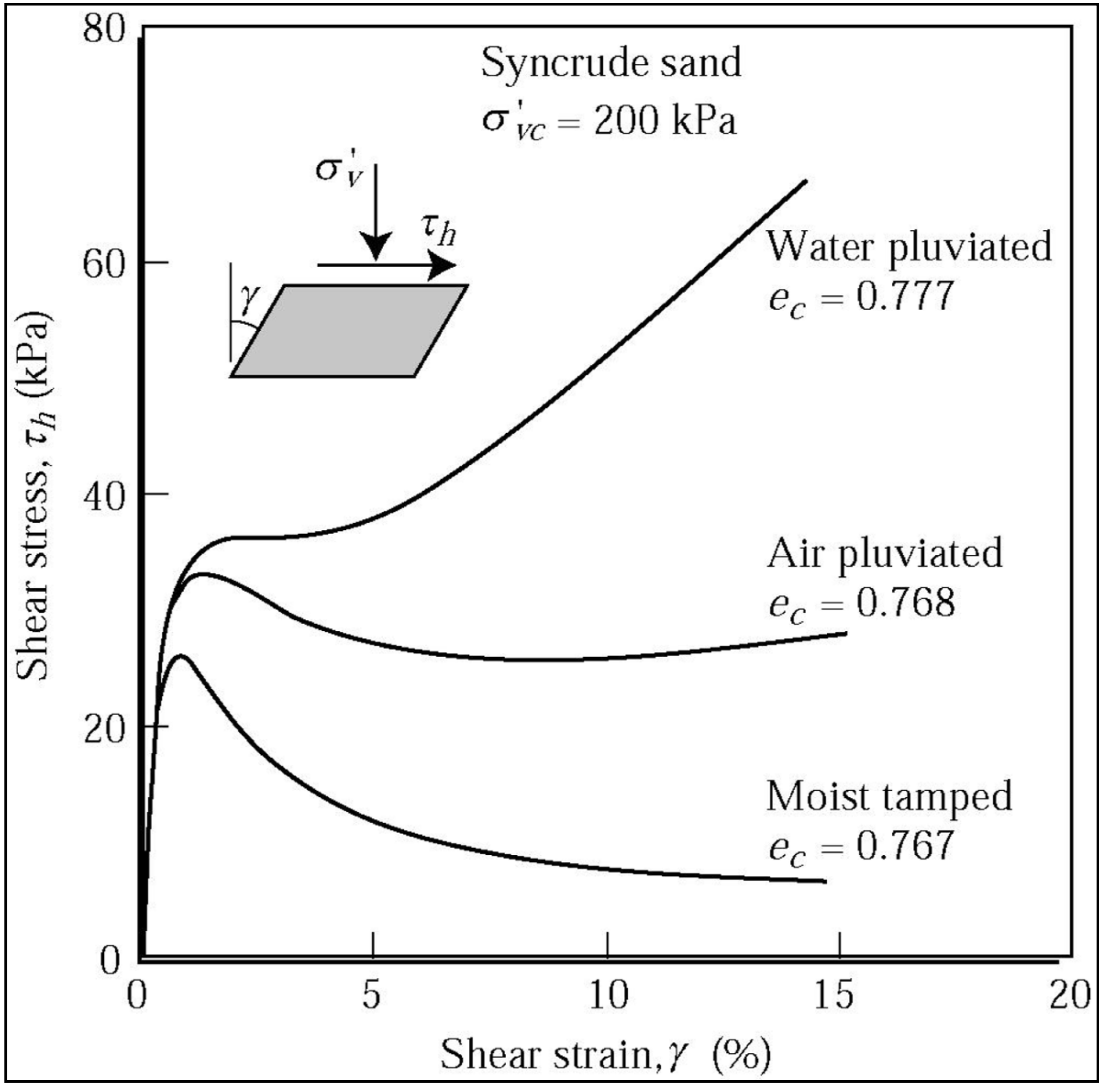
Effect of specimen preparation on drained triaxial compression behavior of sand (from Oda 1972)

- methods include moist tamping, plunging, vibration, air pluviation, wet pluviation, etc.

Specimens prepared to same void ratio (density)



Undrained simple shear response of sand reconstituted using different methods to same void ratio



(Vaid et al., 1995)

In Situ Testing

Best For Soil Profiling

- Less time consuming
- (Semi) continuous data
- Test larger soil mass in natural environment

Empirical Correlations Needed For Engineering Properties

- Poorly defined boundaries
- Cannot control drainage
- Installation disturbance + fast rate of testing

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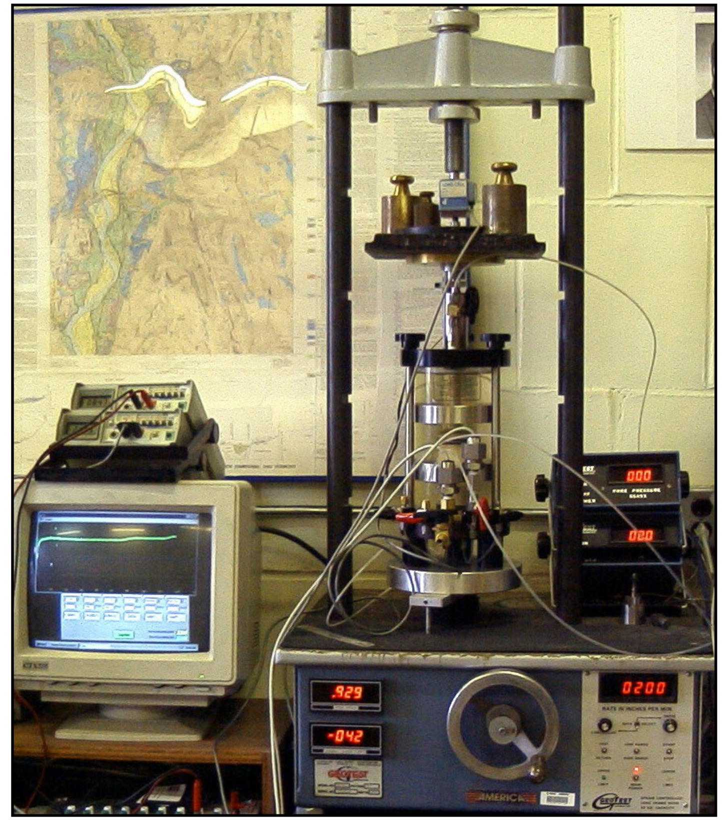
Laboratory Testing

Best For Engineering Properties

- Defined boundary conditions
- Controlled drainage/stress conditions
- Know soil type and macro-fabric

Poor For Soil Profiling

- Expensive/time consuming
- Small, discontinuous specimens
- Stress relief and sample disturbance



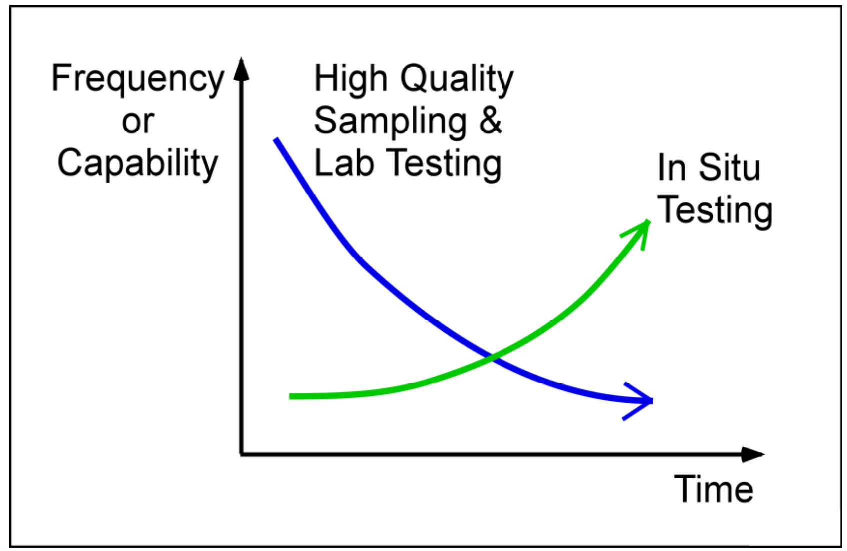
Site Characterization – SOP vs SOA

SOP regressed last 10-20 years in spite of advances in the SOA

- Poor quality and misleading data
- Poor selection of design parameters

Why?

- Low budget for site investigations
- Ignorance: 1) how to obtain better quality information, 2) extent to which poor quality sampling and testing affect soil properties



- Ideally combine in situ testing and follow on laboratory testing on undisturbed samples
- Focus is on projects of **intermediate** to **high importance** (€/$ and safety)

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