Use and Measurement of Fully Softened Shear Strength in Engineering Practice

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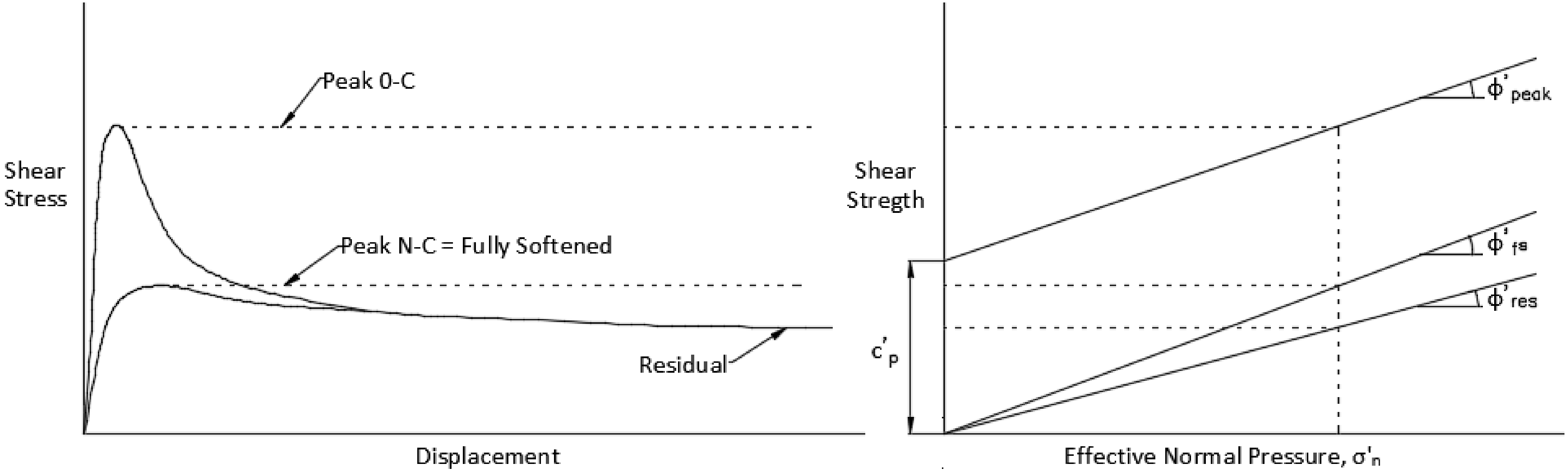
Outline

- Introduction
- Lessons learned from previous researchers
- Use of fully softened shear strength in slope stability analysis
- Measurement of fully softened shear strength
- Closing remarks

Introduction

- The fully softened shear strength (FSSS) was defined by Skempton (1970) as the drained peak strength of a normally consolidated specimen.



After Skempton, A. W. (1970). "First-time slides in over-consolidated clays." *Géotechnique*, 20(3), 320–324.

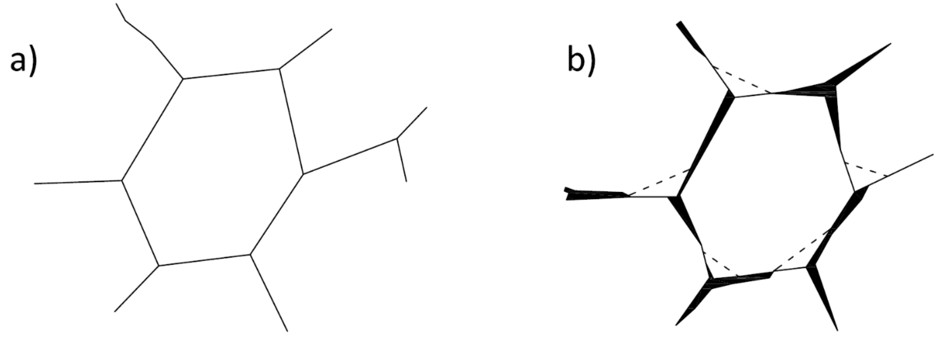
Introduction

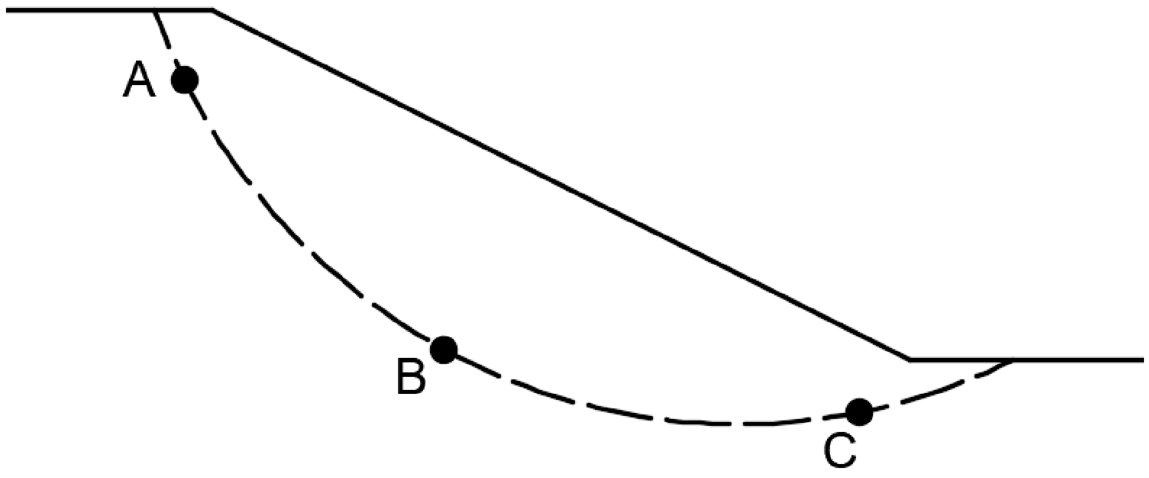
- Based on back-analyses, the FSSS has been found to be the applicable shear strength for:
  - Cuts in heavily overconsolidated clays (Prof. Skempton and his colleagues).
  - Compacted embankments constructed of high plasticity clays subjected to seasonal variation in water content. (Prof. Wright and his colleagues)

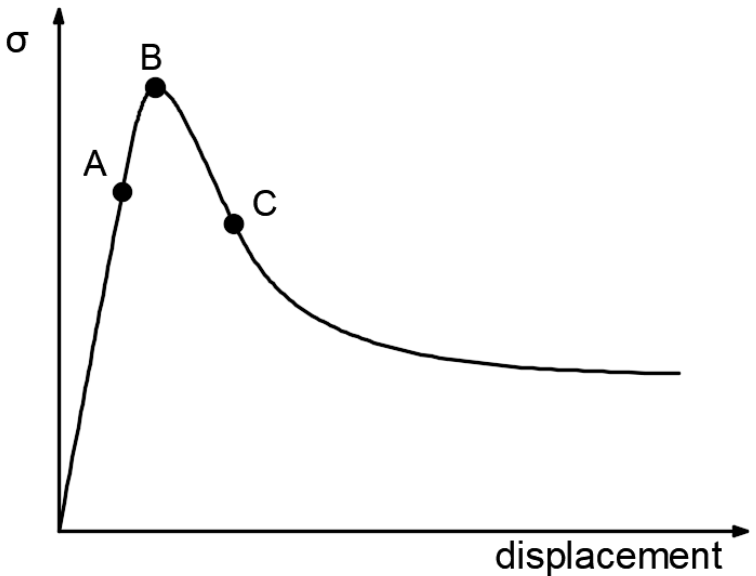
- Characteristics of the failures:
  - Mobilized shear strength below the peak strength measured in the lab using undisturbed or freshly compacted specimens.
  - Failure occurred several years after construction.

Introduction

- Mechanisms proposed to explain the characteristics of the failures
  - Fissures in the clay mass
  - Progressive failure
  - Seasonal variation in water content
  - Creep







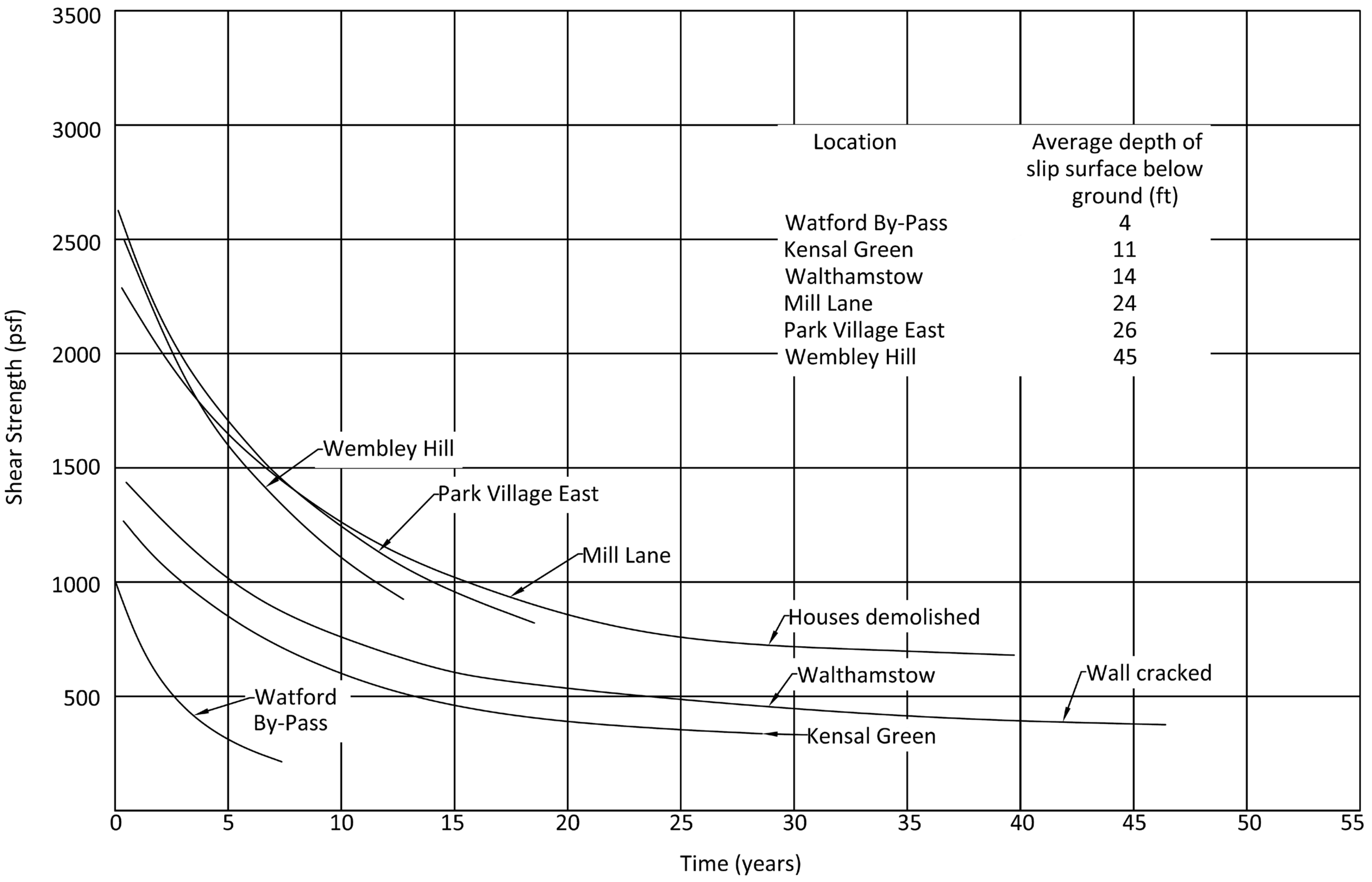
Lessons Learned from Previous Researchers

Lessons Learned from Previous Researchers

- Gregory (1844)
  - First paper describing a long-term failure in a cut in stiff clay.
  - Water percolating into the fissures was the believed reason of the failure.

- Skempton (1948)
  - First time the term fully softened shear strength was used. It appears that it was used related to undrained shear strength.
  - Shear strength decreases with time.

Lessons Learned from Previous Researchers

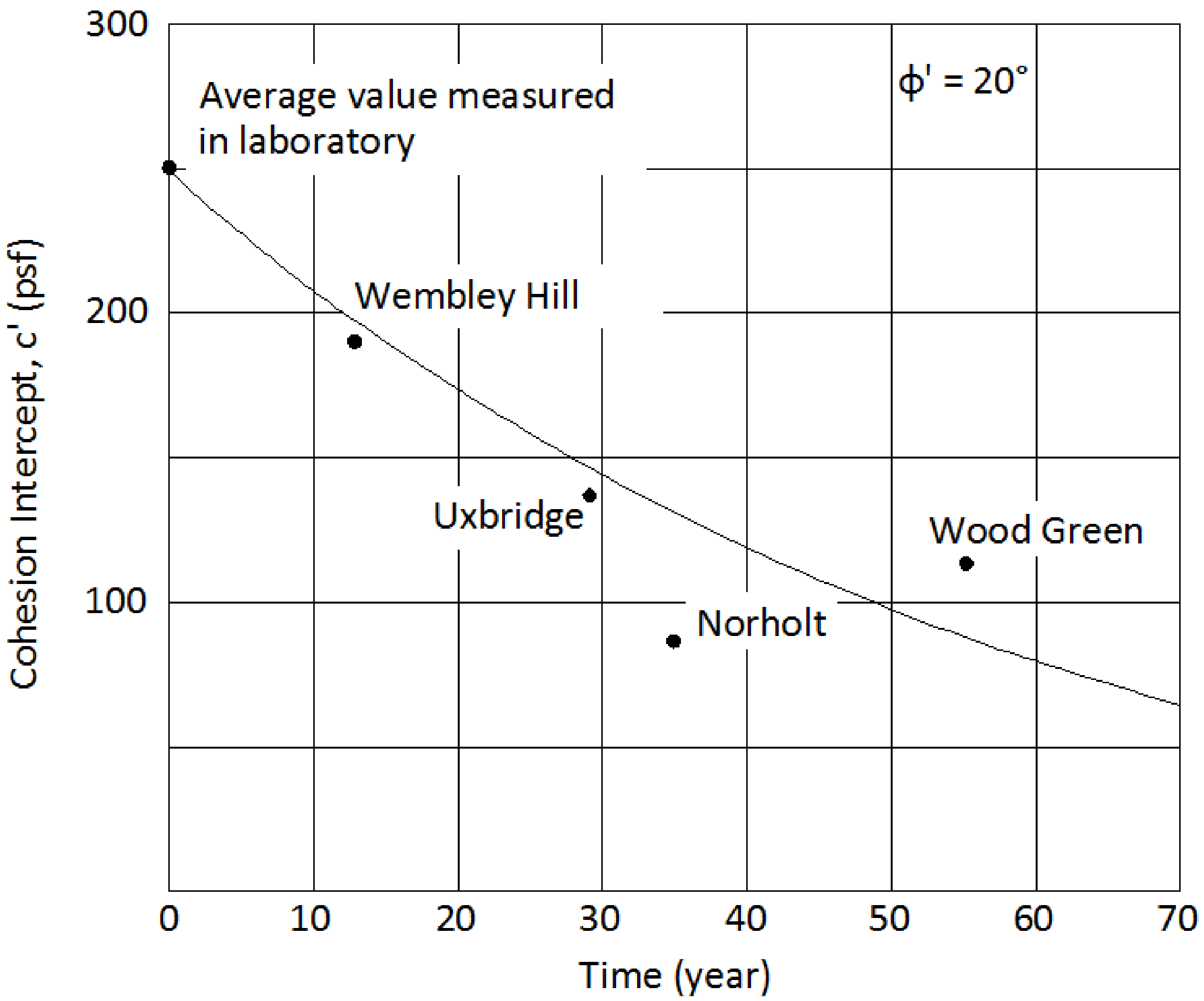


Lessons Learned from Previous Researchers

- Henkel and Skempton (1955)
  - Cuts in stiff clays should be analyzed using drained shear strength.
  - Effective stress cohesion might decrease over time.

- Henkel (1957)
  - Hypothesized that the time component of failure in cuts in stiff clays was due to a decrease in effective stress cohesion with time.
  - Back-analyzed slope failures assuming the effective stress friction angle was constant.

Lessons Learned from Previous Researchers



Lessons Learned from Previous Researchers

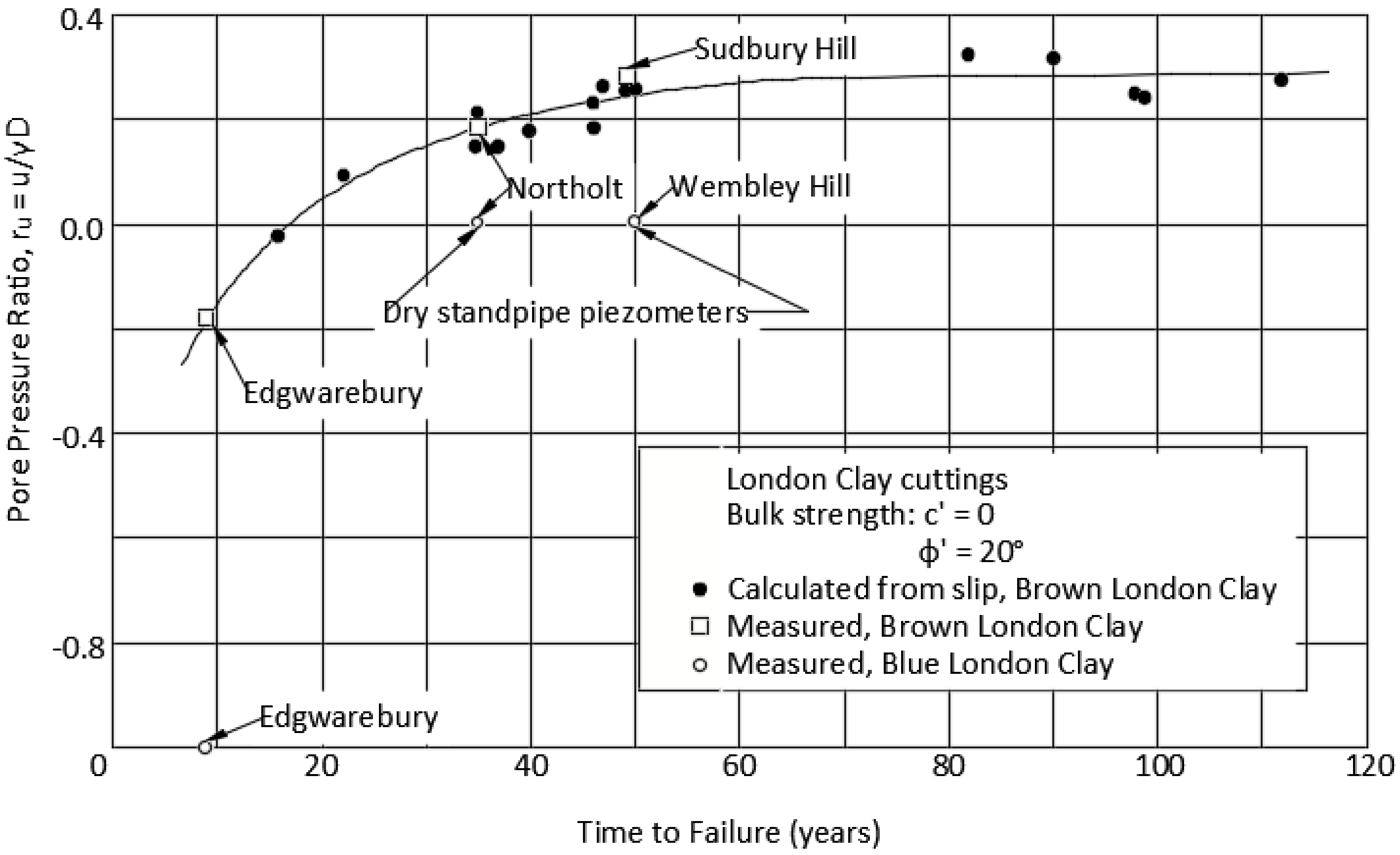
- Skempton (1964)
  - Skempton presented his Rankine Lecture on the long-term stability of clay slopes.
  - Postulated that cuts in stiff clays experience a decrease in shear strength towards residual.

- Skempton (1970)
  - Reassessed his opinion on the strength mobilized in first-time failures in cuts in stiff-clays.
  - Defined the FSSS as the drained strength of a clay in its normally consolidated state.
  - Proposed the FSSS as the applicable strength for first-time failures in cuts in stiff clays.

Lessons Learned from Previous Researchers

- Vaughan and Walbancke (1973)
  - Measured pore pressures below steady state values in a cut 9 years after it was made.
  - Observations showed a very slow rate of pore pressure equilibration to steady state conditions.
  - The slow rate of pore pressure equilibration was used to explain the delay in failures in cuts in stiff clays.

Lessons Learned from Previous Researchers



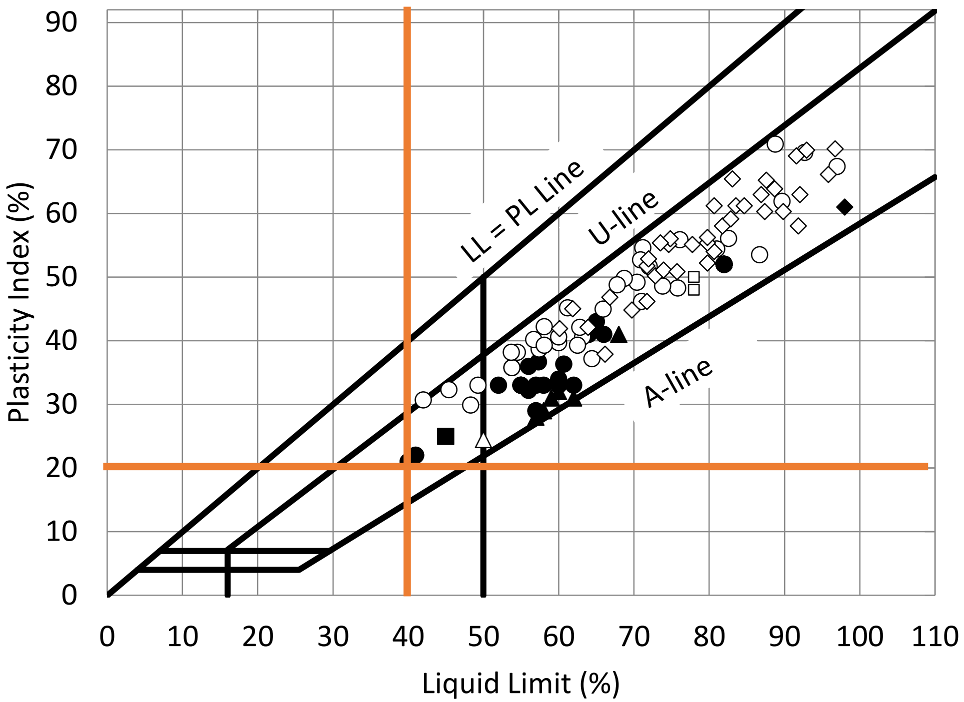
Lessons Learned from Previous Researchers

- Lessons learned
  - The critical scenario for cuts in stiff clay is the long-term or drained case.
  - Cuts in stiff clays and compacted high plasticity clay embankments experience a decrease in shear strength with time towards the fully softened shear strength.
  - One single mechanism cannot be isolated to explain this phenomenon.
  - The delay in failures in cuts in stiff clays is attributed to a slow dissipation of pore pressures.

Use of Fully Softened Shear Strength Slope Stability Analysis

Use of FSSS in Slope Stability Analysis

- What soils does the FSSS concept apply to?
  - 68 case histories of failures in cuts in stiff clays and 74 in compacted clay embankments.



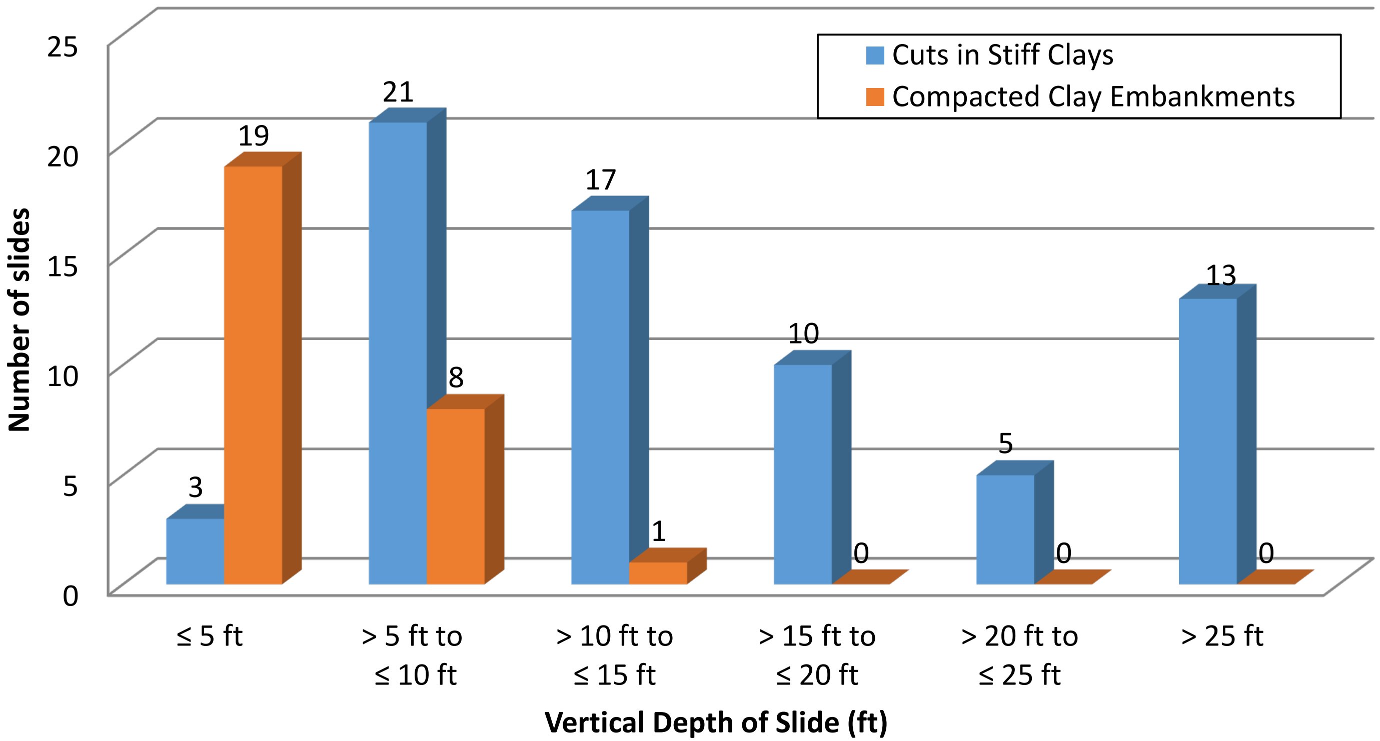
  - The FSSS concept applies when the clays involved have liquid limits above 40 and plasticity indices above 20.

Use of FSSS in Slope Stability Analysis

- What pore pressures should I use?
  - For cuts in stiff clays:
    - Use a pore pressure ratio of 0.3, for **preliminary designs**.
    - Use pore pressures from steady-state seepage conditions from the worst possible scenario for **final designs**.
  - For compacted clay embankments use steady state seepage conditions from a water table coinciding with the slope surface for preliminary and final designs.

Use of FSSS in Slope Stability Analysis

- How deep does the FSSS concept apply?



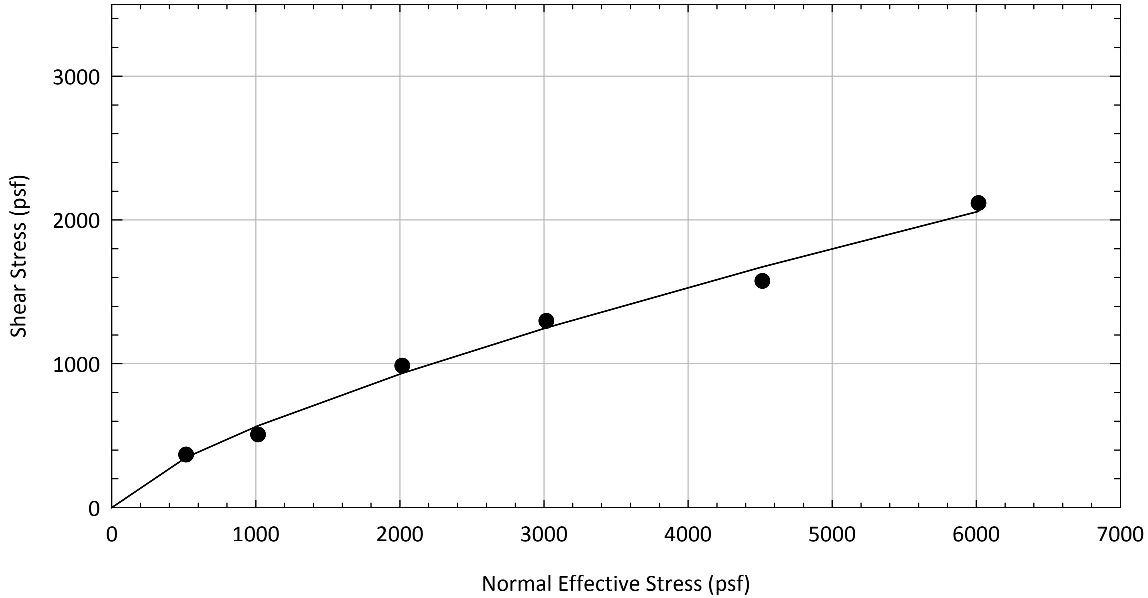
- Slides in stiff clays occur over a wide range of depths.
- Slides in compacted clay embankments these tend to be shallow (≤ 10 ft deep).

Use of FSSS in Slope Stability Analysis

- What shape should be assumed for the failure envelope?
  - The calculated factor of safety is highly influenced by the assumed shape of the failure envelope.
  - Several researchers have shown that the fully softened failure envelope is curved.
  - The power function below is an easy way to characterize this curvature.

$$s = a\,P_a\left(\frac{\sigma'}{P_a}\right)^b$$

s = Shear strength
a, b = Fitting parameters
P_a = Atmospheric pressure
σ‘ = Effective normal stress on the failure plane



Use of FSSS in Slope Stability Analysis

VIRGINIA TECH

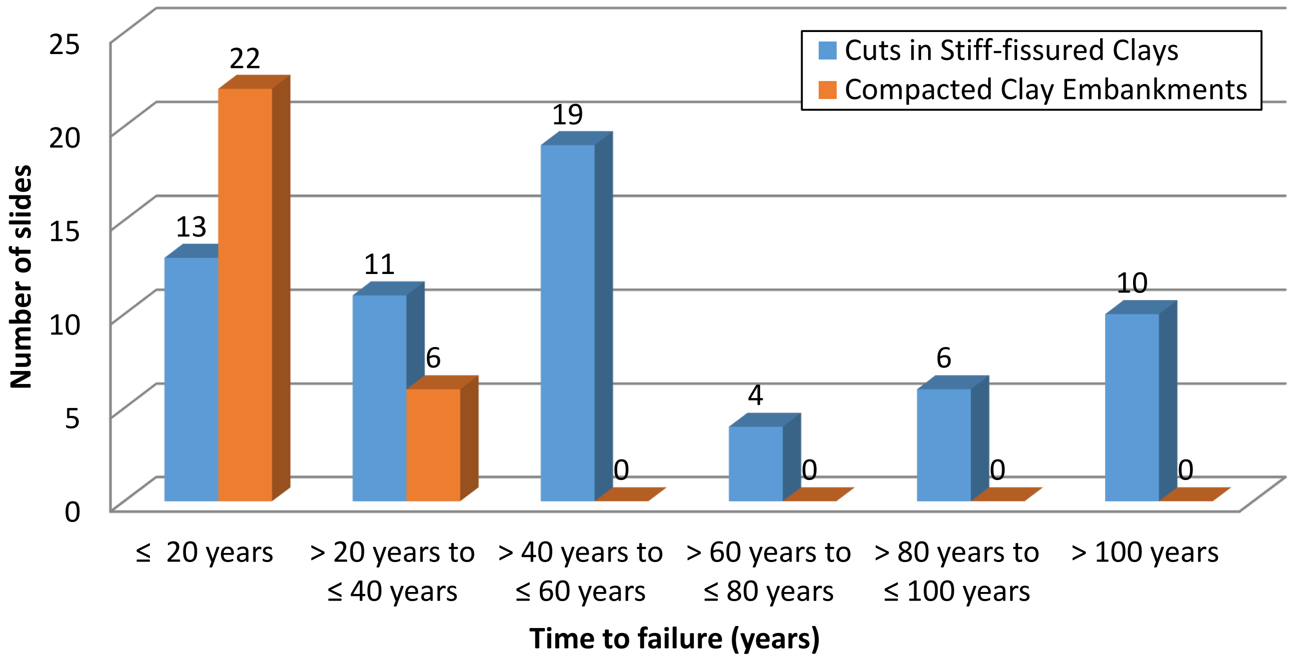
- What factor of safety should be used with the FSSS concept?
  - Most codes and standards have required factors of safety associated with using peak shear strength for design.
  - Required factors of safety should be based on uncertainties in the parameters that control the design and the consequences of failure.

Design Condition	Factor of Safety
Cost of failure < cost of more conservative design, AND Small uncertainty in soil and groundwater conditions	1.25
Cost of failure > cost of more conservative design, AND Small uncertainty in soil and groundwater conditions	1.50
Cost of failure < cost of more conservative design, AND Large uncertainty in soil and groundwater conditions	1.50
Cost of failure > cost of more conservative design, AND Large uncertainty in soil and groundwater conditions	2.00 or more

Duncan et al. (2014)

Use of FSSS in Slope Stability Analysis

- Are temporary structures affected?
  - Probably not.
  - Main things to consider are the duration of the structure, possible delays in the project and chances of it becoming permanent at some point.



Use of FSSS in Slope Stability Analysis

- How to properly apply the concept in slope stability analysis?
  - Assign the FSSS to the whole slope.
  - Calculate your factor of safety.
  - It is good practice in stiff-fissured clays to perform an stability analysis using the residual shear strength to make sure that the calculated factor of safety is greater than 1.

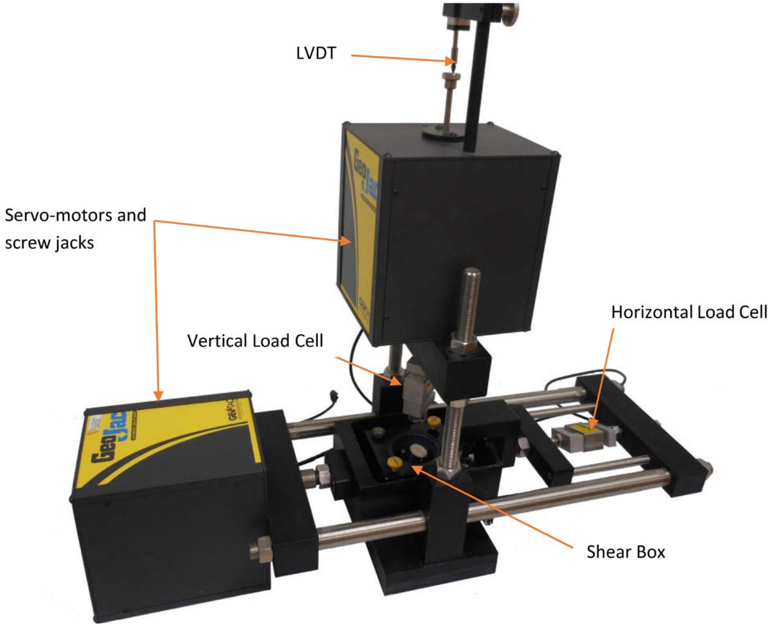
Use of FSSS in Slope Stability Analysis

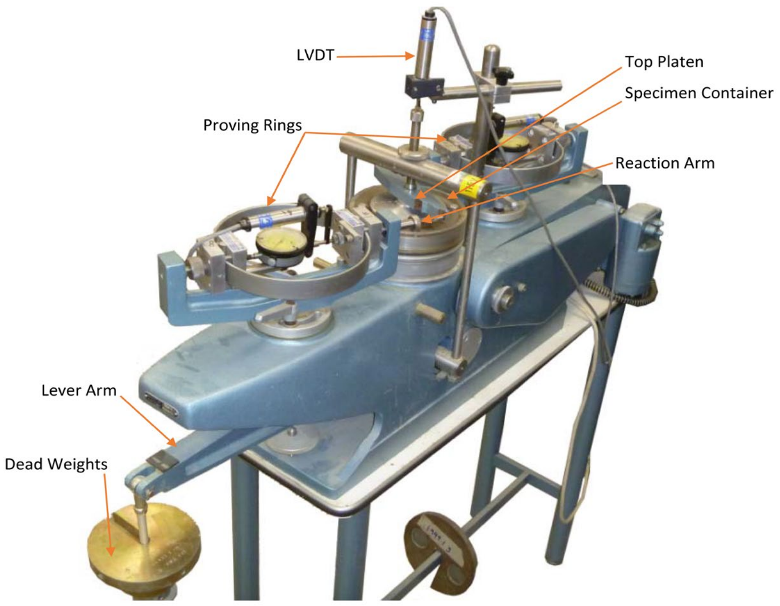
- Lessons learned
  - The FSSS concept applies to cuts in stiff clays and compacted embankments constructed of high plasticity clays.
  - The concept appears to apply only to soils with LL > 40 and PI >20.
  - It is a time dependent process so short term structures might not be affected.
  - Factors of safety required by most codes might be too conservative to be used with the FSSS concept.
  - For compacted clay embankments, failures tend to be shallow and for cut slopes in stiff clays failures can be much deeper.
  - Steady stage seepage conditions should be used for final designs of cuts in stiff clays.
  - A water table coincident with the slope face should be used for compacted clay embankments.

Measurement of Fully Softened Shear Strength

Measurement of the FSSS

- Skempton (1977) stated that the fully softened shear strength can be measured on remolded normally consolidated specimens.
- Devices used





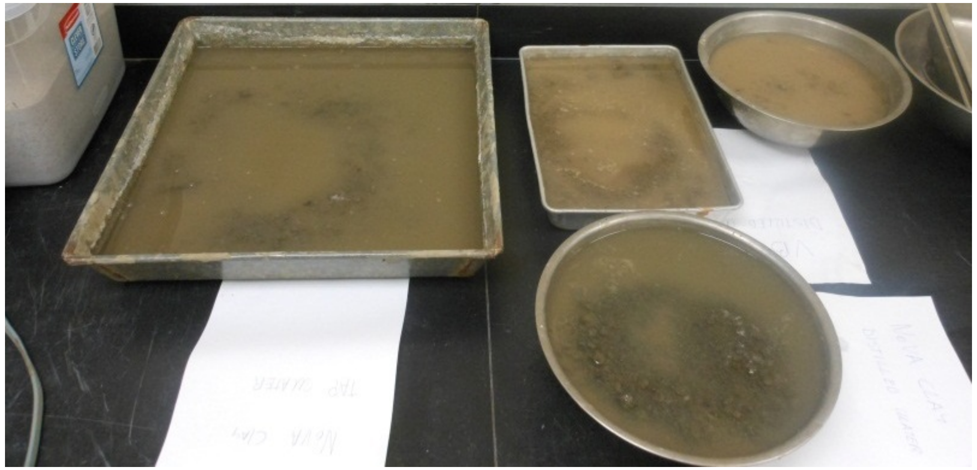
Measurement of the FSSS

- Initial conditions:
  - Liquidity index ranging from 1.0 to 1.5.
  - Samples ball-milled, blenderized, or intact prior to sieving through a No. 40 sieve.

Measurement of the FSSS

Sample preparation

- Soak the soil sample in water.
- Ball-mill or blender the sample, if desired.
- Push it through in a moist condition through a No. 40 sieve.
- Allow the soil sample to air dry to a water content close to the liquid limit.
- Use a Casagrande liquid limit cup to infer the water content.
- The water content is correct if 23 -27 blows are required to close the gap.



Measurement of the FSSS

- Device comparison

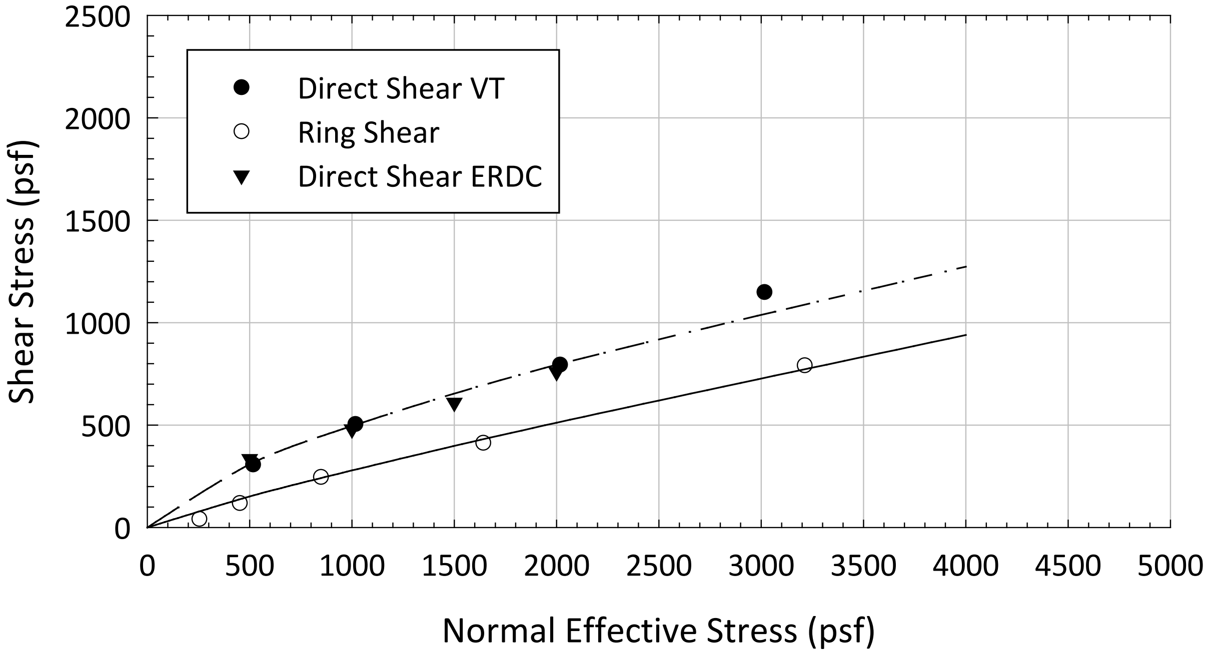
Advantages and disadvantages of apparatuses used to measure FSS.

	Direct Shear	Ring Shear	Triaxial
Advantages	Common Most available Easiest to perform Easiest to interpret data	ASTM standard available Short consolidation time Small amount of soil needed	Common
Disadvantages	Two to three weeks required per point No current standard Soil can extrude from the top Top cap can tilt Stress concentrations	Difficult to run test slow enough Rare Thin sample after consolidation Expensive	Much time required Soft soils difficult to form into test specimens Difficult to conduct tests at low stresses

Duncan, J. M., Brandon, T. L., and VandenBerge, D. R. (2011). *Report of the workshop on shear strength for stability of slopes in highly plastic clays*. Center for Geotechnical Practice and Research, Blacksburg, 79.

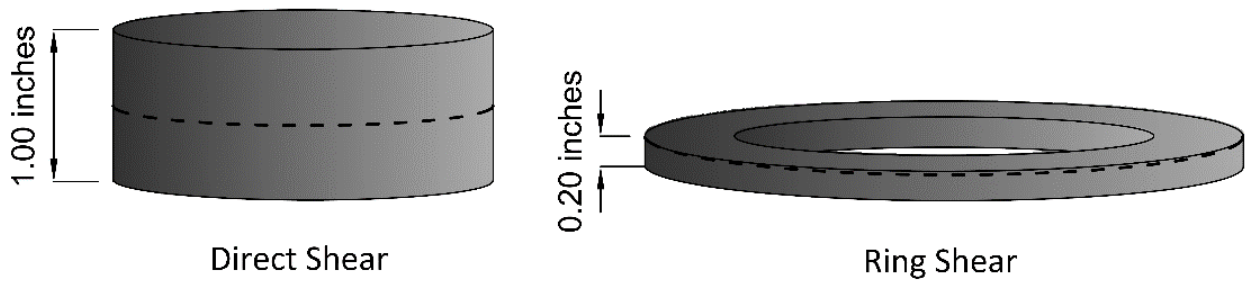
Measurement of the FSSS

- Ring shear vs direct shear
  - Fourteen different soils were tested.
  - Consolidation pressures ranged from 500 psf to 6,000 psf.
  - **In all cases, the ring shear results were considerable lower than direct shear results.**



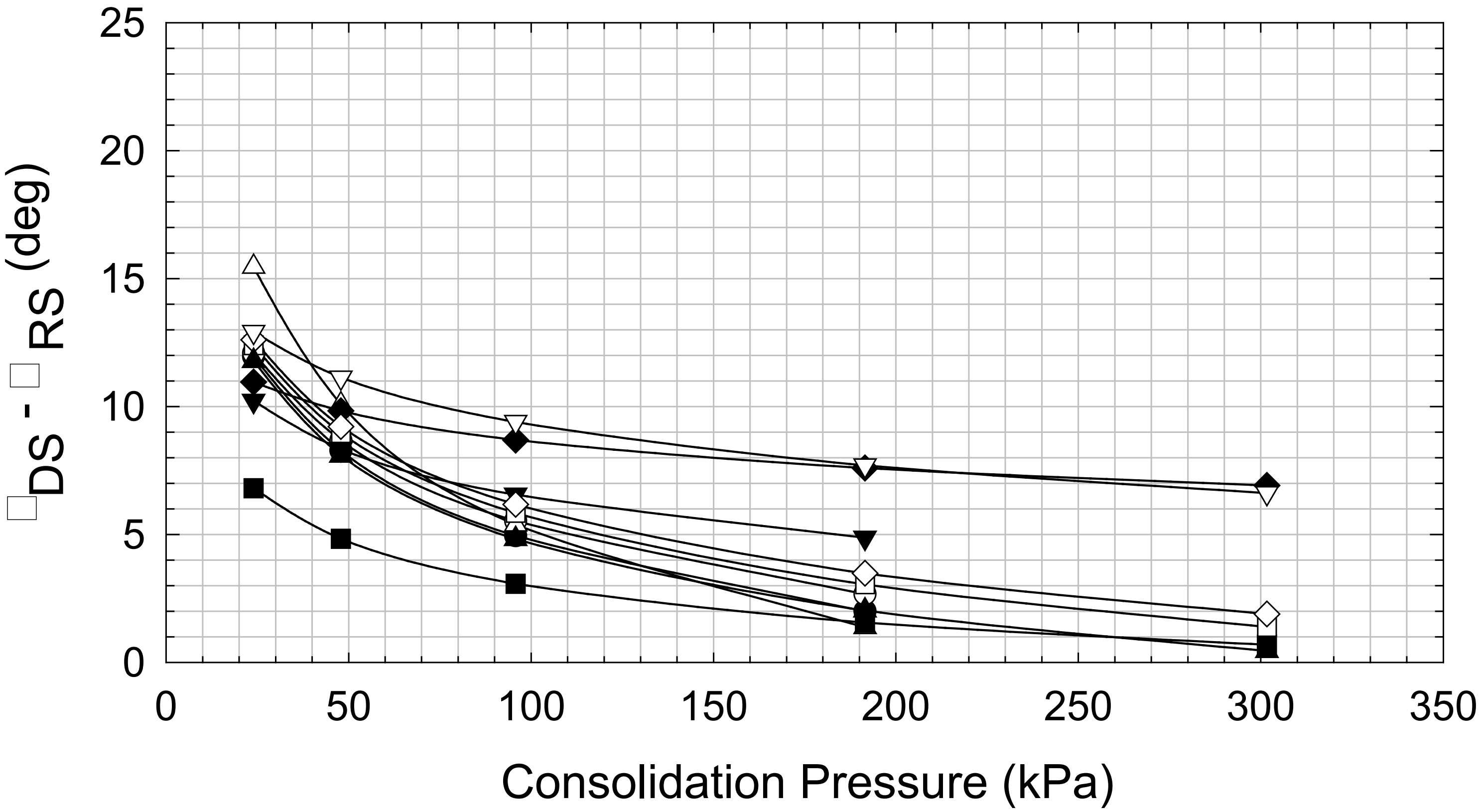
Measurement of the FSSS

- Causes of the difference in shear strength measured
  - Differences in the effect of progressive failure.
  - Location and thickness of the failure plane in the ring shear device.
  - Test specimen is pre-sheared close to the failure surface during specimen preparation.
  - Available speeds in the ring shear device cannot assure drained conditions during shear for all soils.



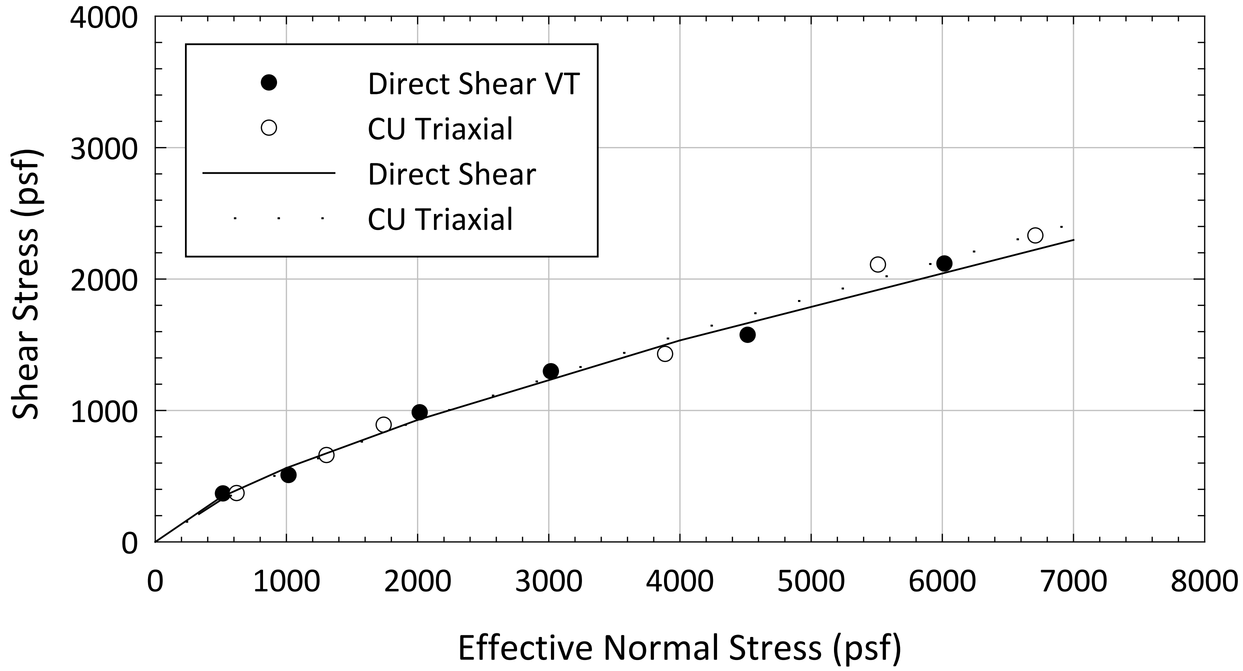
Measurement of the FSSS

- Difference in the shear strength measured decreases with increasing consolidation pressure.



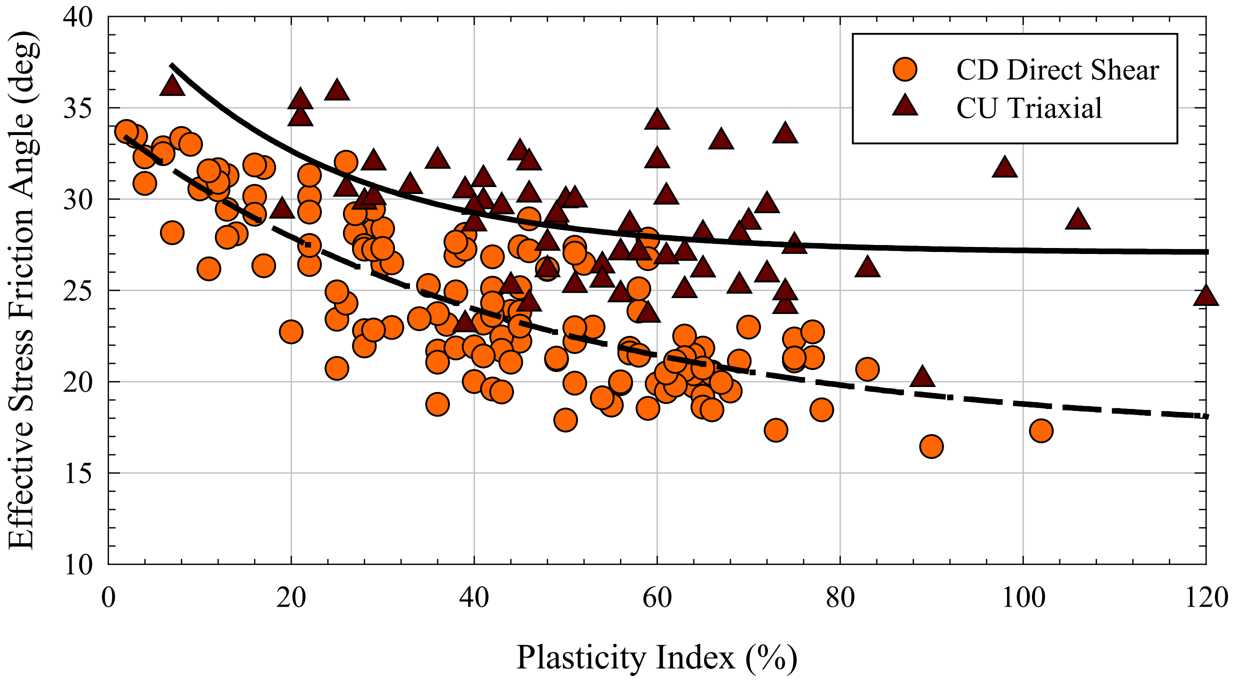
Measurement of the FSSS

- Triaxial vs direct shear
  - Five different soils were tested.
  - Consolidation pressures ranged from 500 psf to 10,000 psf.
  - **In all cases, no significant difference was observed in the results.**



Measurement of the FSSS

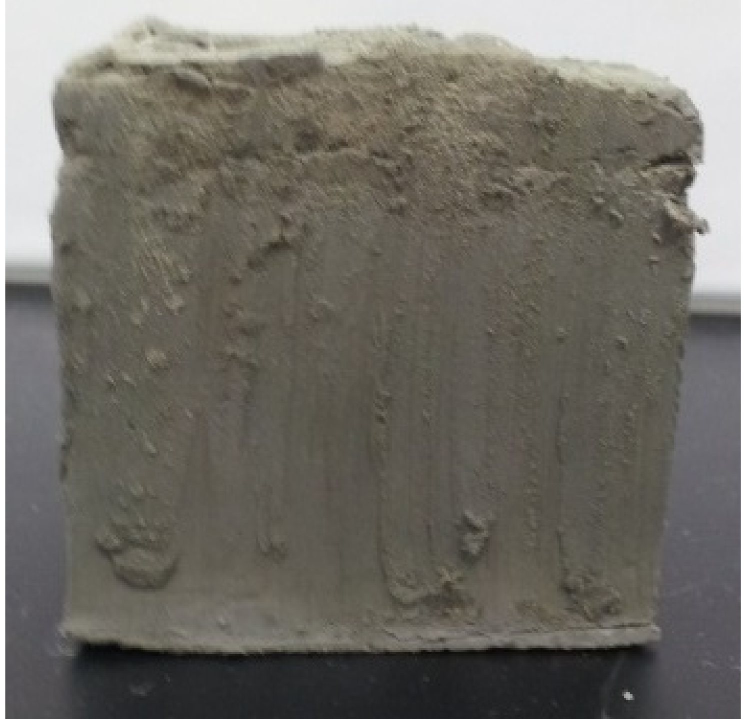
- Triaxial vs direct shear – Inherent anisotropy



- ➤ Undisturbed samples were tested.
- ➤ Lacustrine and riverine alluvial deposits.
- ➤ Deposited in horizontal layers, which can represent plane of weakness.

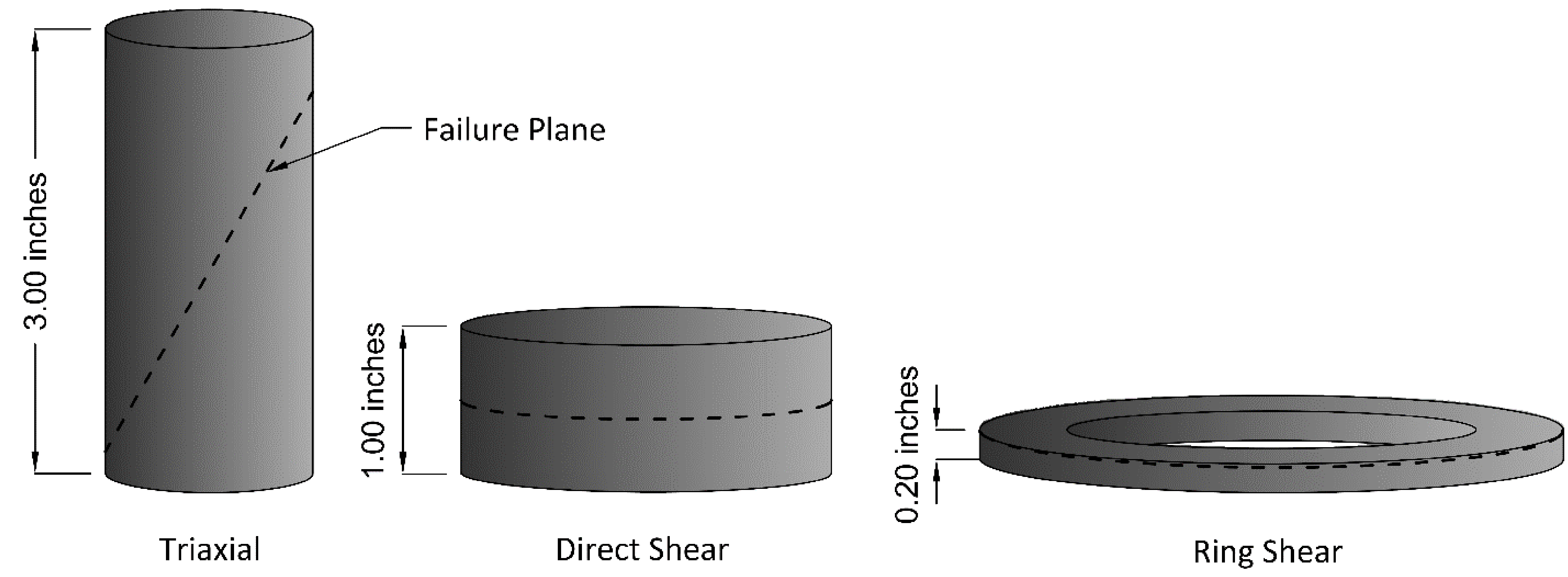
Measurement of the FSSS

- Triaxial vs direct shear



Measurement of the FSSS

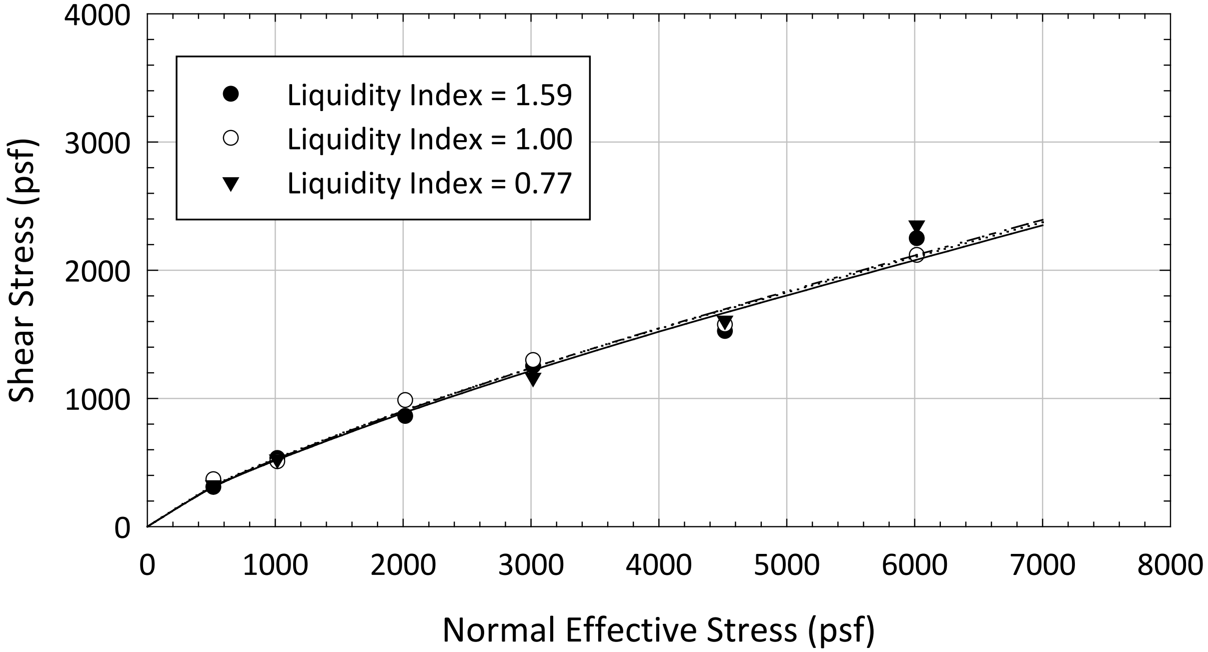
- Device comparison



Measurement of the FSSS

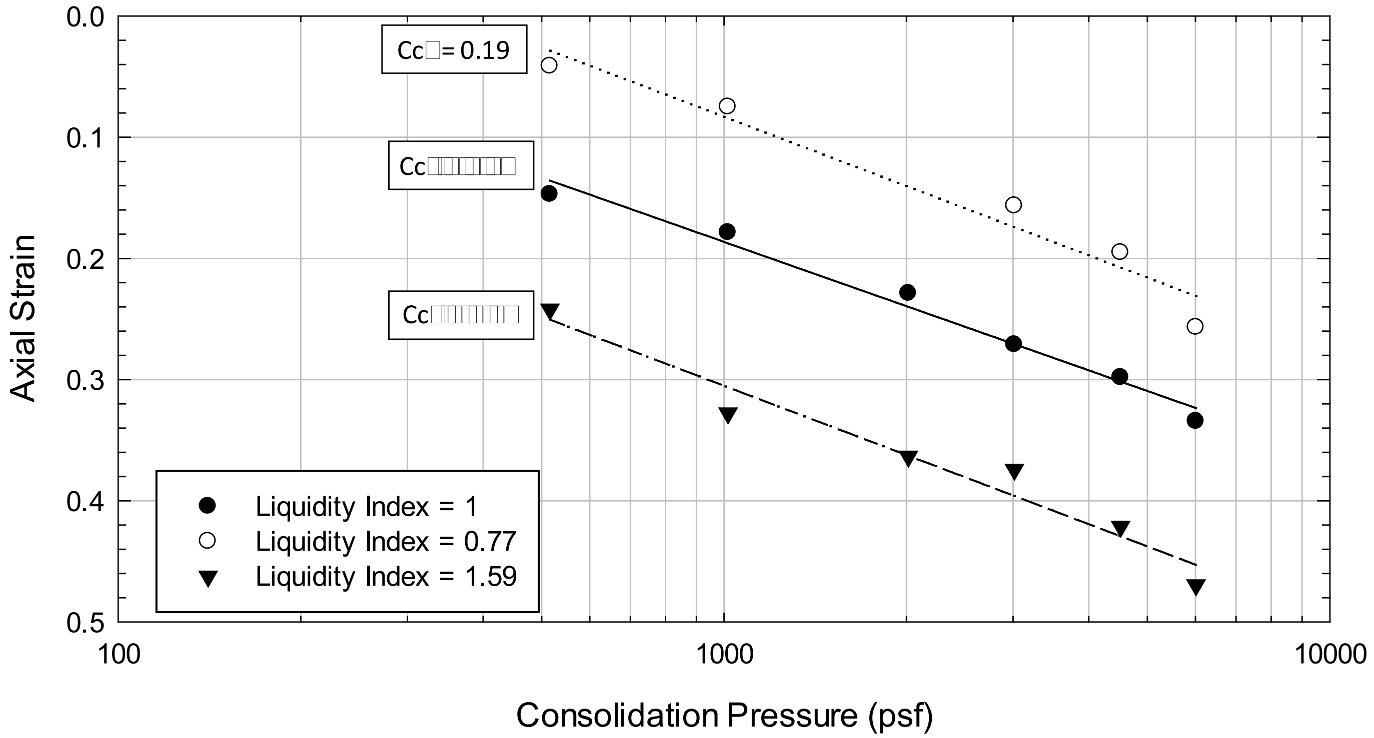
Effect of initial water content

- Two different soils were tested at initial water contents corresponding to liquidity indices ranging from 0.6 to 1.6.
- **In all cases, no significant difference was observed in the FSS failure envelope.**



Measurement of the FSSS

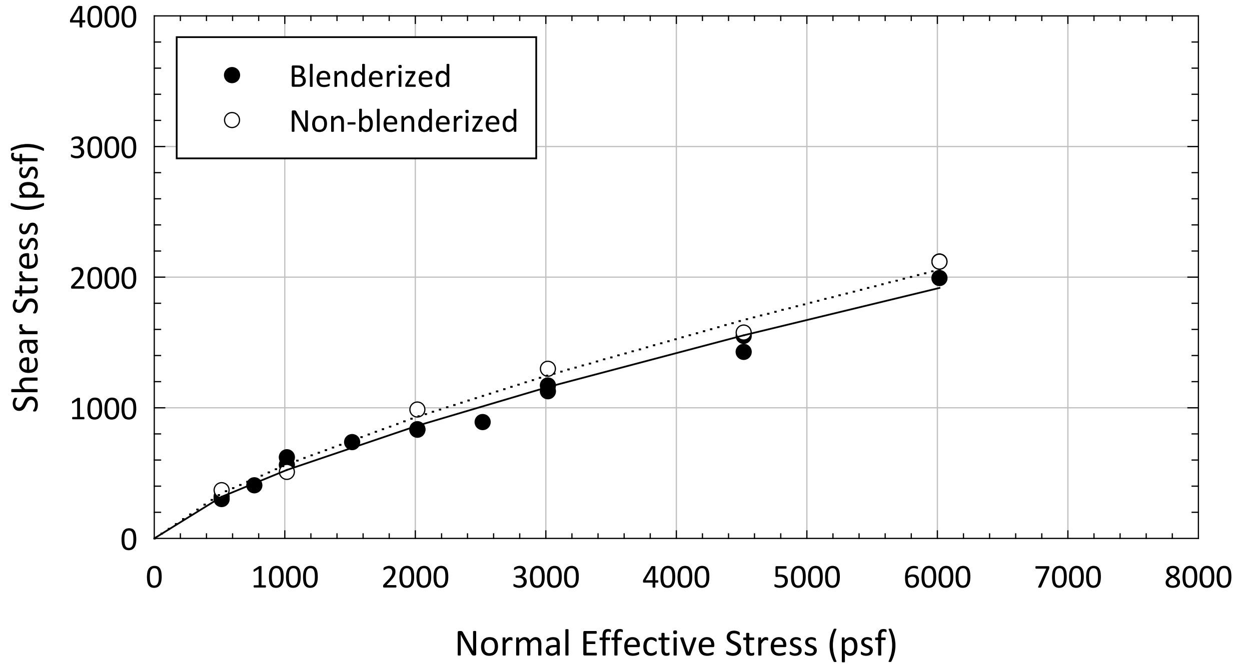
- Effect of initial water content
  - Compression during consolidation increases with increasing initial water content.
  - No significant difference in the modified compression index.



Measurement of the FSSS

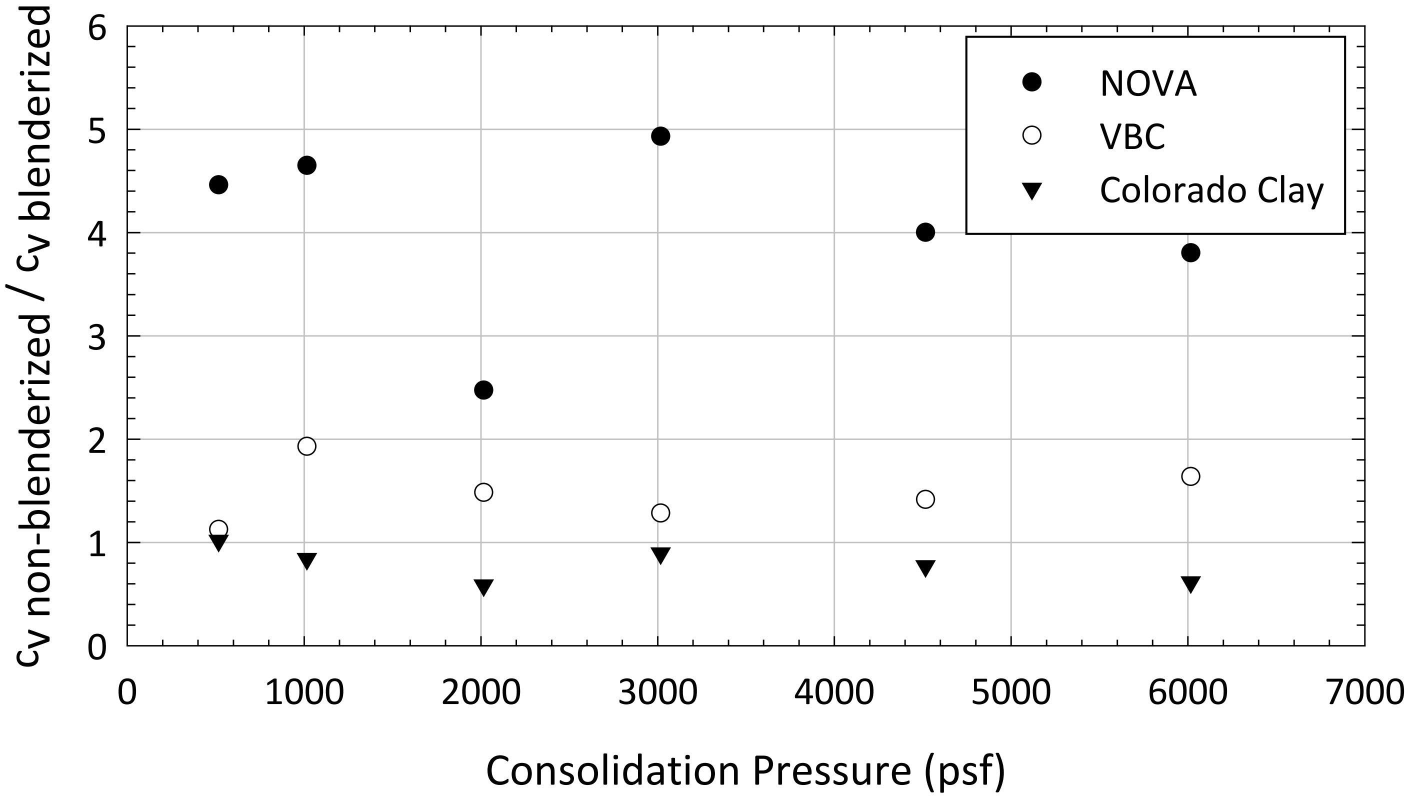
Effect of sample preparation procedure

- Three different soils were tested usingblenderized and non-blenderized samples.
- Blenderizing might increase the measured liquid limit and clay-sized fraction.
- **Results showed only a slight decrease in the measured FS failure envelope.**



Measurement of the FSSS

- Effect of sample preparation procedure
  - Increase in testing time.



Measurement of the FSSS

- Testing advices and tips
  - Sieve the soil sample as received.
  - Mix the soil sample to a water content close to the liquid limit.
  - For high consolidation stresses, a lower water content will reduce the compression during consolidation and might prevent the specimen from compressing too much before shear.
  - Start the consolidation stage with a stress of around 100 psf to prevent extrusion and use a load increment ratio of one until the desired stress is achieved.
  - For specimens mixed at liquidity indices above 1, a initial consolidation stress of 50psf might be needed.
  - **Take your time forming the test specimen and running the test.**

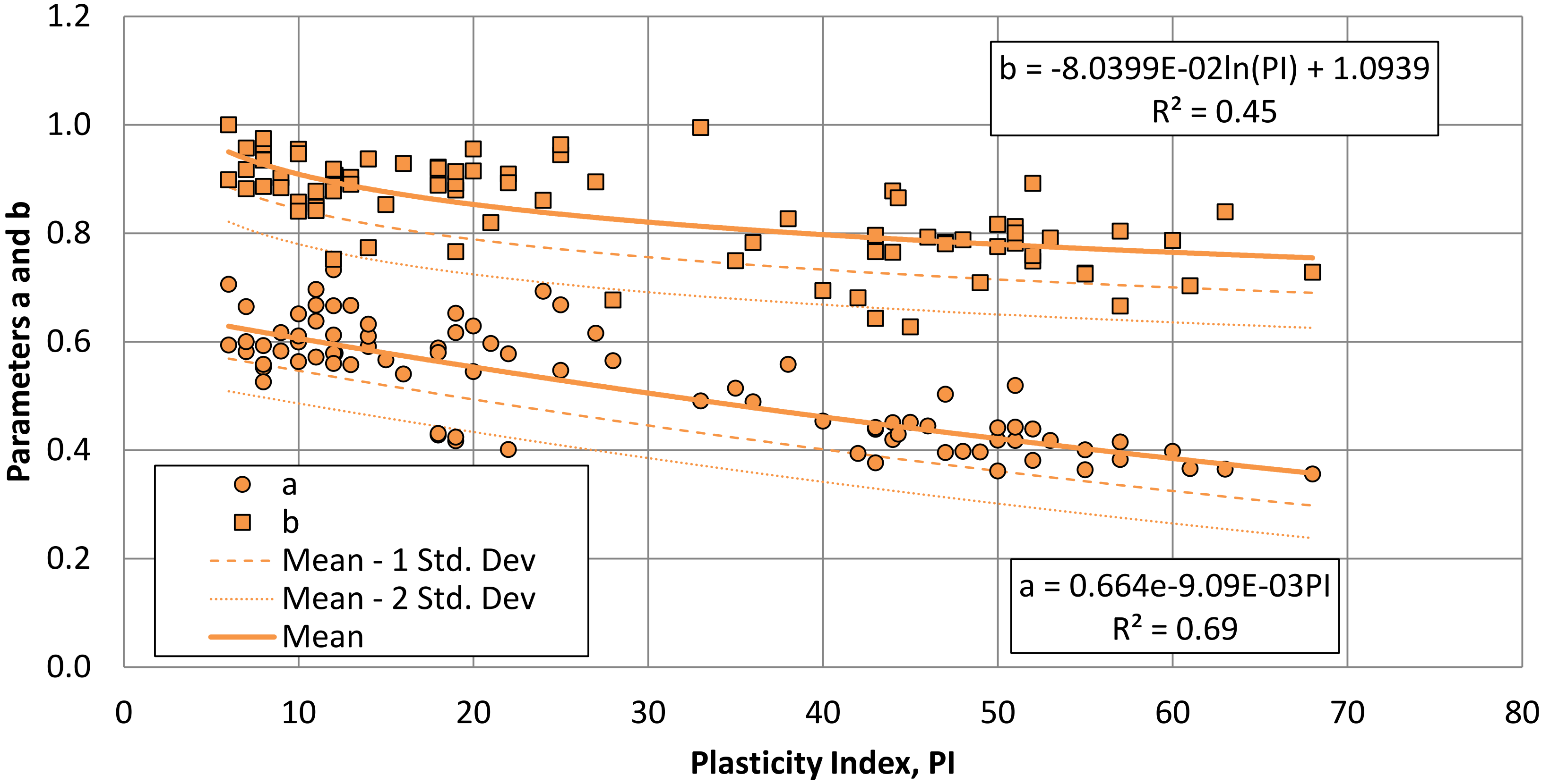
Measurement of the FSSS

- Lessons learned
  - The fully softened shear strength can be measured using remolded normally consolidated specimens.
  - Procedures like ball-milling and blenderizing are not recommended. Blenderizing is preferred over ball-milling, if required.
  - The direct shear device is recommended for this purpose. The triaxial device can be used but it is difficult and time consuming. The ring shear device is not recommended for this purpose.
  - The initial water content does not impact the FSSS measured. Use an initial water content equal to the liquid limit for most cases. A lower water content might be appropriate for tests at high stresses.

Correlations for FSSS Parameters

- Eighty six soils tested

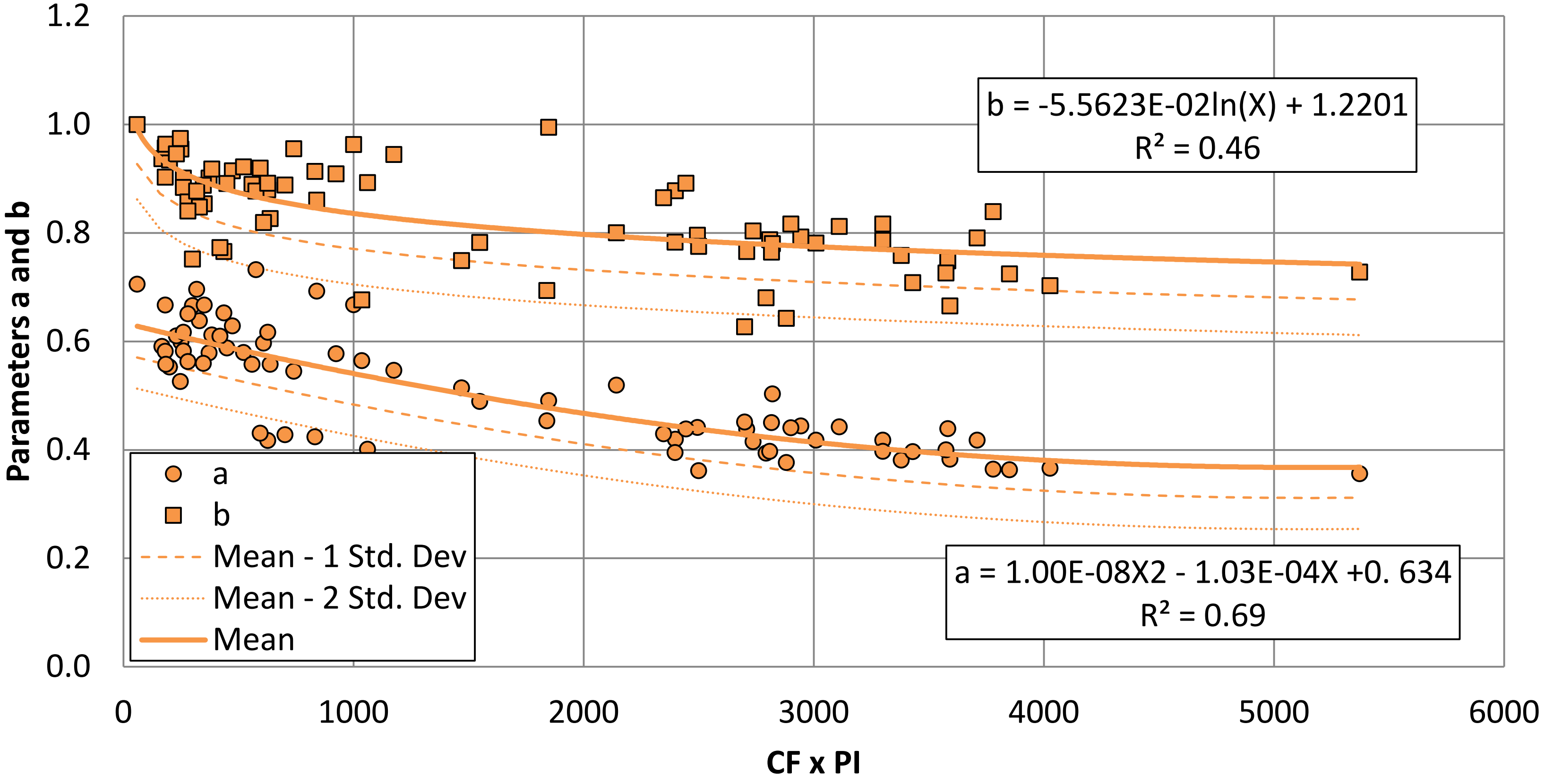
$$s = a\,P_a\left(\frac{\sigma'}{P_a}\right)^b$$



Correlations for FSSS Parameters

- Seventy eight soils tested

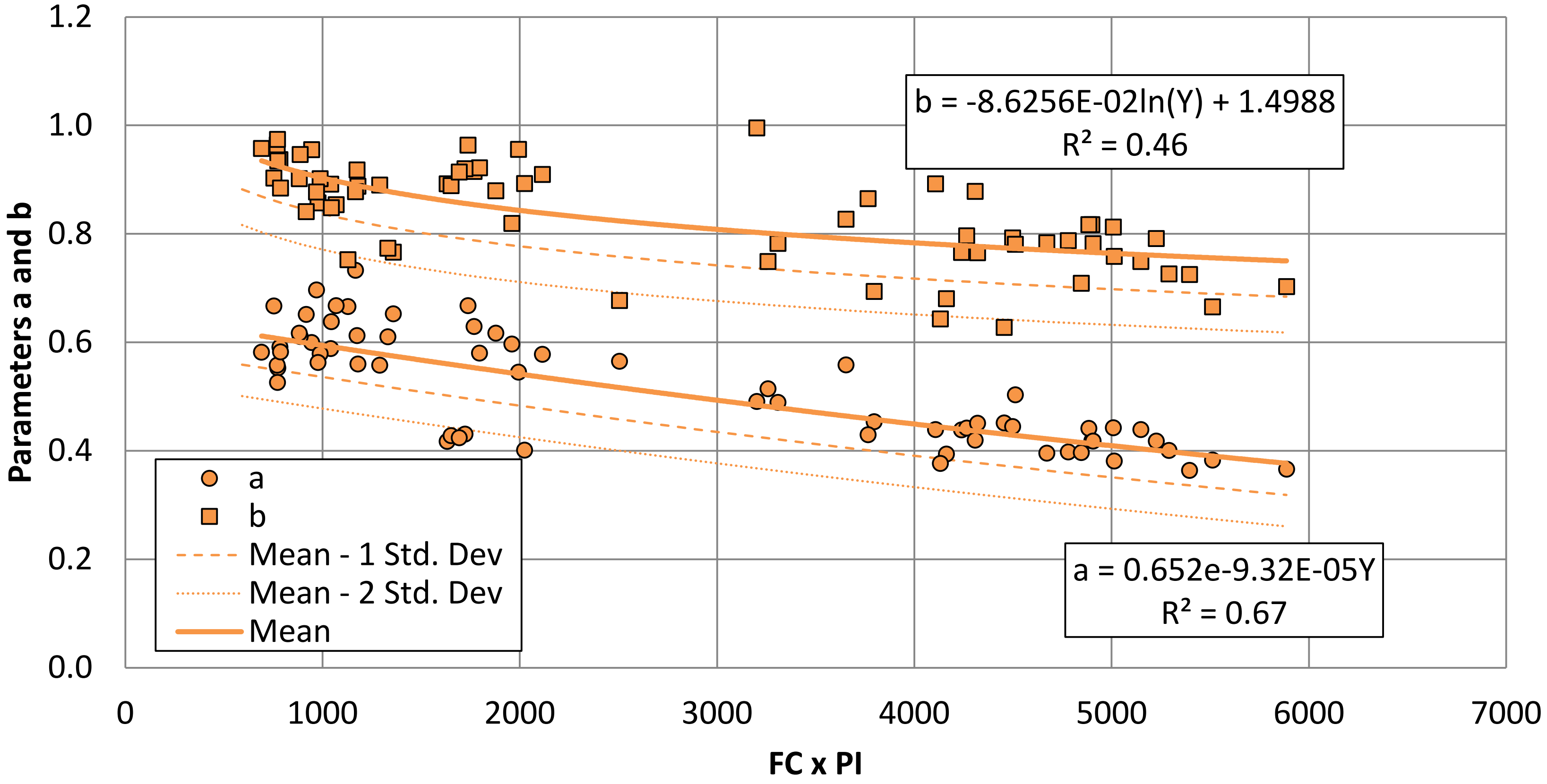
$$s = a\,P_a\left(\frac{\sigma'}{P_a}\right)^b$$



Correlations for FSSS Parameters

- Sixty nine soils tested

$$s = a\,P_a\left(\frac{\sigma'}{P_a}\right)^b$$



Closing Remarks

Closing Remarks

- The FSSS is an important engineering concept that should be considered in design of cut slopes in stiff clays and compacted embankments of high plasticity clays.
- Recommendations for its use are not readily available in design manuals.
- The ring shear device should not be used to measure the FSSS.
- Procedures like ball-milling and blenderizing should be avoided.
- Correlations are a good tools for engineers but should be used carefully.
- If your test results don’t match a correlation, check them. If you are confident about them, trust them above any correlation.


Muchas Gracias