Cambridge Self-Bore Pressuremeter

Session 8 – Reconciling pressuremeter data with other techniques

Reconciling the Data

- In this session we will discuss:
  - The purpose of the geotechnical site investigation
  - How we use the data we obtain
  - Differences in the strength of clays in the lab and *insitu*
  - Evaluation of the stiffness of clays in the lab and *insitu*
  - Evaluation of consolidation parameters in the lab and *insitu*

Purpose of Site Investigations

- The immediate purposes associated to a geotechnical investigation programme is to:
    a) Determine the general nature and sequence of the subsurface strata
    b) Locate the water table and groundwater conditions and
    c) Measure or assess specific properties of the ground
- Understanding laboratory and *insitu* tests and the constitutive relationships that link material behaviour is therefore considered essential to optimise engineering geotechnical design

Use of Data for Site Investigations

- Geophysical methods give a qualitative picture of the site which does not substitute the need for direct measurements attained by *insitu* tests
- CPT, DMT and SBPM are designed to reveal 1-D information of the ground that, under some simplified assumptions, can be interpreted to assess average properties of soil profiles
- Laboratory tests deal with a close examination of an elemental material property under ideal conditions

Use of Data for Site Investigations

- Existing field techniques can be broadly divided into two main groups:
  a) Non-destructive or semi-destructive tests that are carried out with minimal overall disturbance of soil structure and little modification of the initial mean effective stress during the installation process
  b) Invasive, destructive tests were inherent disturbance is imparted by the penetration or installation of the probe into the ground
- Pressuremeters fall into the first category and are classified as ‘semi-destructive’ (Schnaid, 2005)

Table 1: Commercial in situ testing techniques (modified from Schnaid et al, 2004)

Category	Test	Designation	Measurements	Common Applications
Non-destructive or semi-destructive tests	Geophysical tests: Seismic refraction Surface waves Crosshole test Downhole test	SR SASW CHT DHT	P-waves from surface R-waves from surface P & S waves in boreholes P & S waves with depth	Ground characterisation Small strain stiffness, G_o
	Pressuremeter test Pre-bored Self-boring	PMT SBPM	G, (ψ x ε) curve G, (ψ x ε) curve	Shear modulus, G Shear strength *In situ* horizontal stress Consolidation properties
	Plate loading test	PLT	(L x δ) curve	Stiffness and strength
Invasive penetration tests	Cone penetration test Electric Piezocone	CPT CPTU	q_c, f_s q_c, f_s, u	Soil profiling Shear strength Relative density Consolidation properties
	Standard Penetration Test (energy control)	SPT	Penetration (N value)	Soil profiling Internal friction angle, φ′
	Flat dilatometer test	DMT	p_o, p_1	Stiffness Shear strength
	Vane shear test	VST	Torque	Undrained shear strength, s_u
Combined tests (Invasive + Non-destructive)	Cone pressuremeter	CPMT	q_c, f_s, (+u), G, (ψ x ε)	Soil profiling Shear modulus, G Shear strength Consolidation properties
	Seismic cone	SCPT	q_c, f_s, V_p, V_s, (+u)	Soil profiling Shear strength Small strain stiffness, G_o Consolidation properties
	Resistivity cone	RCPT	q_c, f_s, ρ	Soil profiling Shear strength Soil porosity
	Seismic dilatometer		p_o, p_1, V_p, V_s	Stiffness (G and G_o) Shear strength

Use of Data for Site Investigations

- Jamiolkowsky et al (1985) summarized the advantages and limitations of both laboratory and *insitu* methods
- There is an inherent bias of practitioners to use only one or the other;
  - We should all be open to using both where they are useful and then still back analyzing the field results in accordance with Peck (1969)
- Laboratory tests are able to determine initial and evolving anisotropy of both strength and deformability, the effects of stress and/or strain reversal, time effects, the influence of intermediate principal stress, etc

Use of Data for Site Investigations

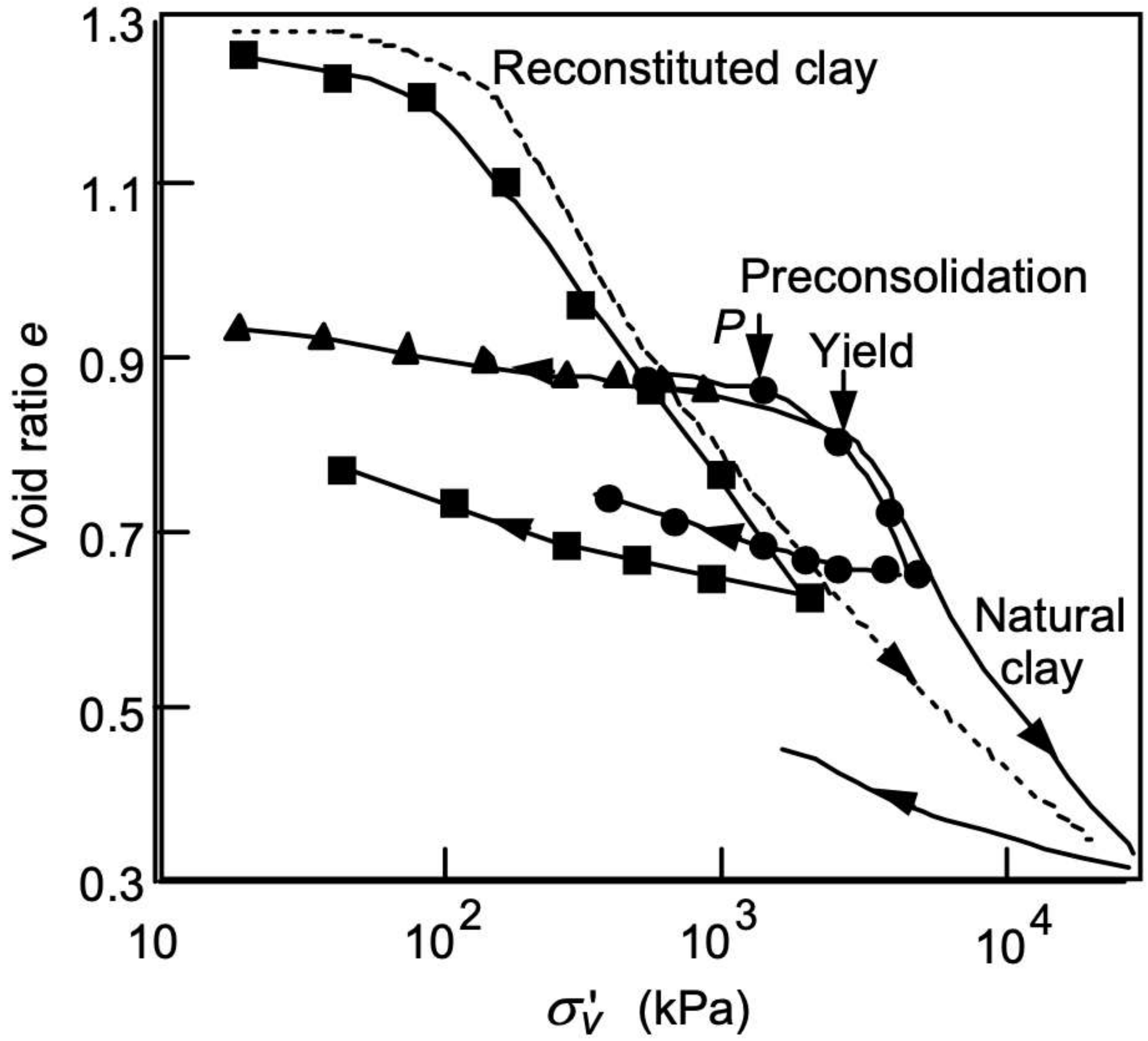
- The role of *insitu* tests in soil mechanics consists mainly in the assessment of:
  - Initial state variables and particularly detailed soil profiles, but also the *insitu* initial lateral stress
  - Drained and undrained soil stiffness, especially at small and moderate strain levels
  - Flow and consolidation properties, especially in cohesionless deposits and cohesive soils with a well-developed macro-fabric

Use of Data for Site Investigations

- The laboratory and *insitu* data should then feed into a theoretical model that then forms the basis for site instrumentation and monitoring
  - Once construction begins, then the data is regularly checked against the assumed constitutive models and the performance evaluated in light of the predicted model
  - Back analysis forms the basis of model validation and recalibration if it is needed
- Only after the above is completed is it likely that the micro and macro structure and scale effects of every aspect may be reasonably ascertained

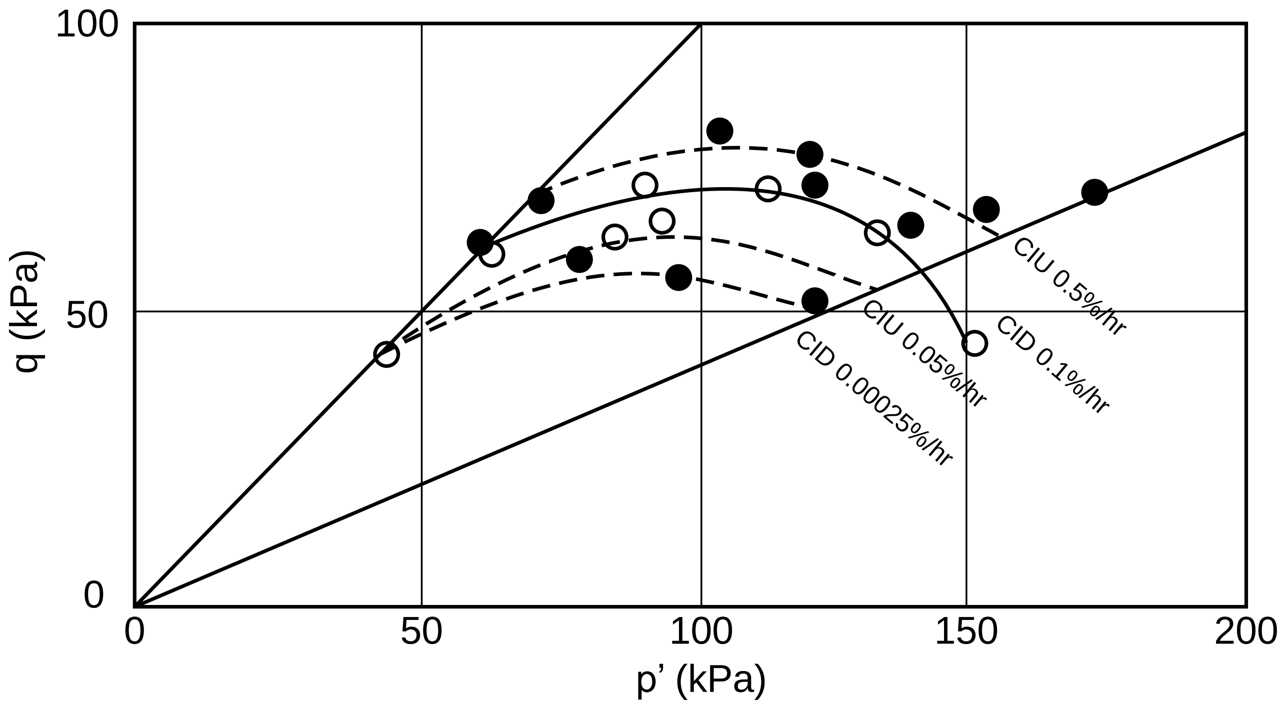
Evaluation of Clays

- Evaluating clays is extremely complex both in the lab or in the field
  - Often anisotropy is neglected
  - Fabric and its role in the assess parameters is either destroyed or misunderstood
  - Strain rate is also often mis-understood and/or neglected
  - Coupled with sampling and preparation errors…



Evaluation of Clays

- Evaluation of strain rates in the laboratory demonstrated that the limit state was pushed outward resulting in higher strengths
- Therefore the assumption of strain rate and a consistent undrained shear strength must be understood
- The influence on the actual elastic deformations or post-yield deformations were not considered



After Lo and Morin, 1972

Evaluation of Clays

- Wroth (1984) illustrated the difficulties in interpreting the undrained results of pressuremeters in clays relative to laboratory tests
- The issues with direct comparison are related to:
  - Strain path of the samples in the lab
  - Rate of strain
  - Consolidation during the pressuremeter tests

Strain *Path* of Clays

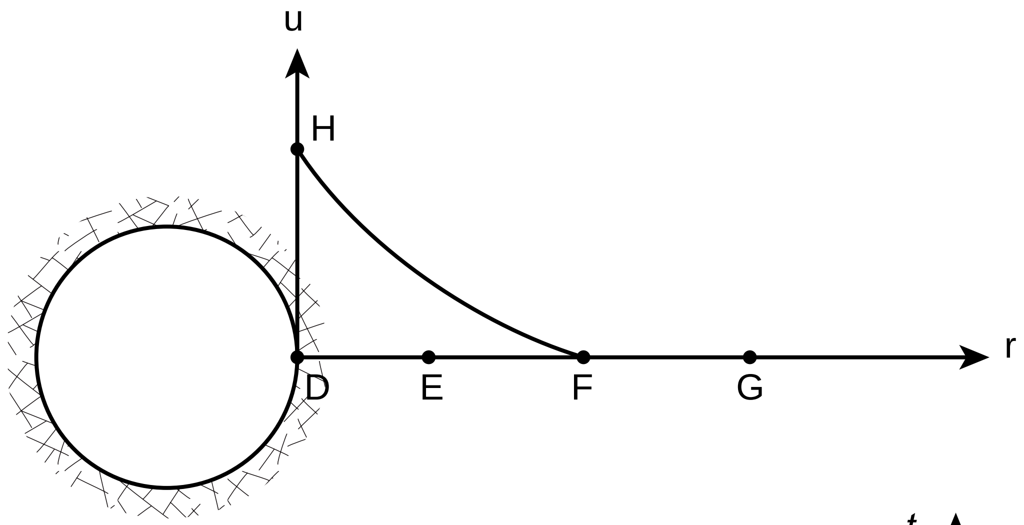
- Strain path tests were attempted by Wood and Wroth (1977) and compared to complex plane strain triaxial tests by Eden and Ladd (1972)
- Using the modified Cam-Clay model, Wroth was unimpressed with the model for the interpretation of a pressuremeter test relative to the triaxial results
- Normalized shear strength ratios from the MCCM obtained from PMT were approximately 75% of those found in the lab

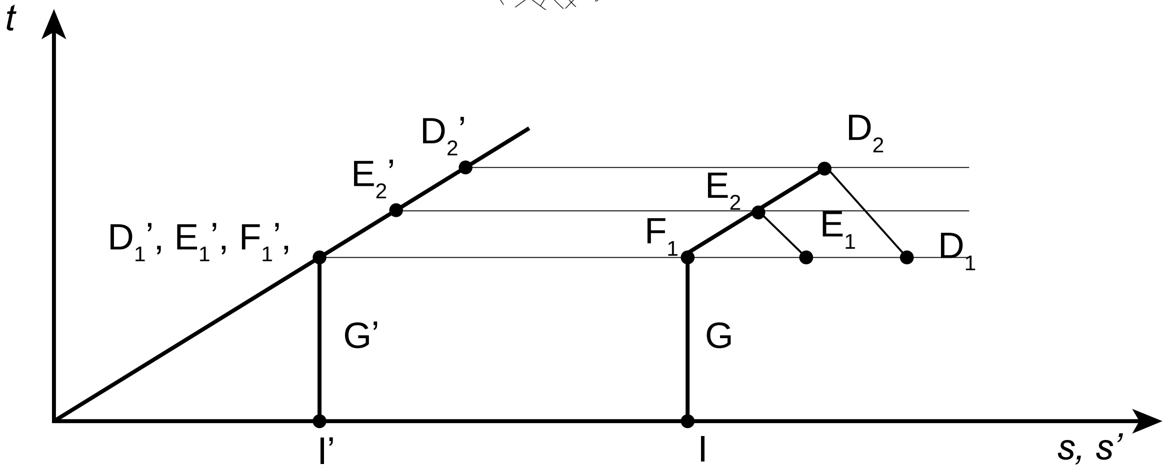
Strain *Rate* of Clays During PM

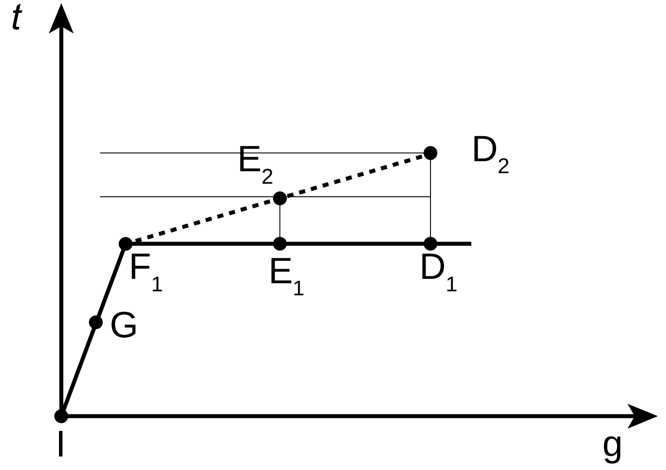
- The rate of strain plays a crucial role in the interpretation of the pressuremeter

- Even at 1%/min (similar to triaxial tests), the rate can increase the measured undrained shear strength
  - If a test is done too quickly, then the test is hindered by the increased "viscosity" of the soil
  - If a test is conducted too slowly, then drainage of the soil around the probe can occur and the effective stress is increasing with loading

Increasing s_u and Consolidation



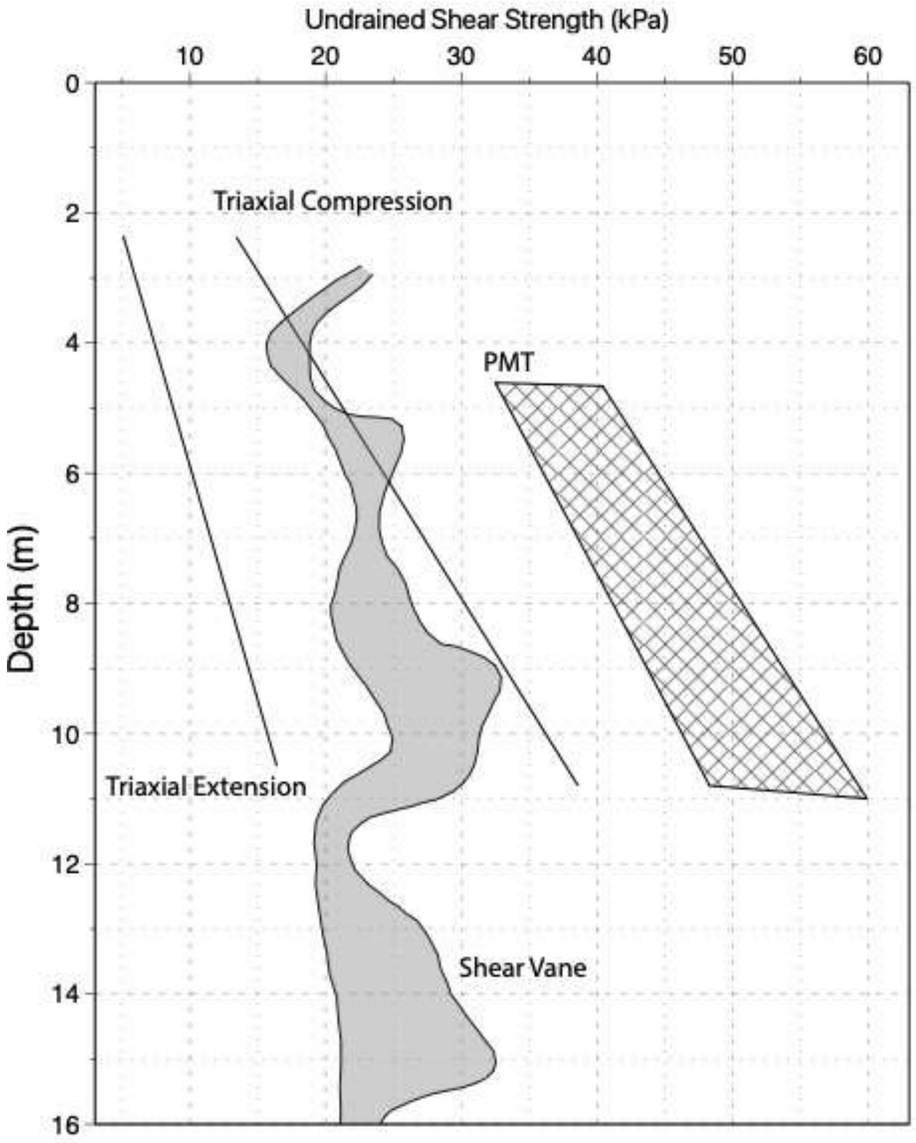




After Wroth, 1984

s_u and Other Tests

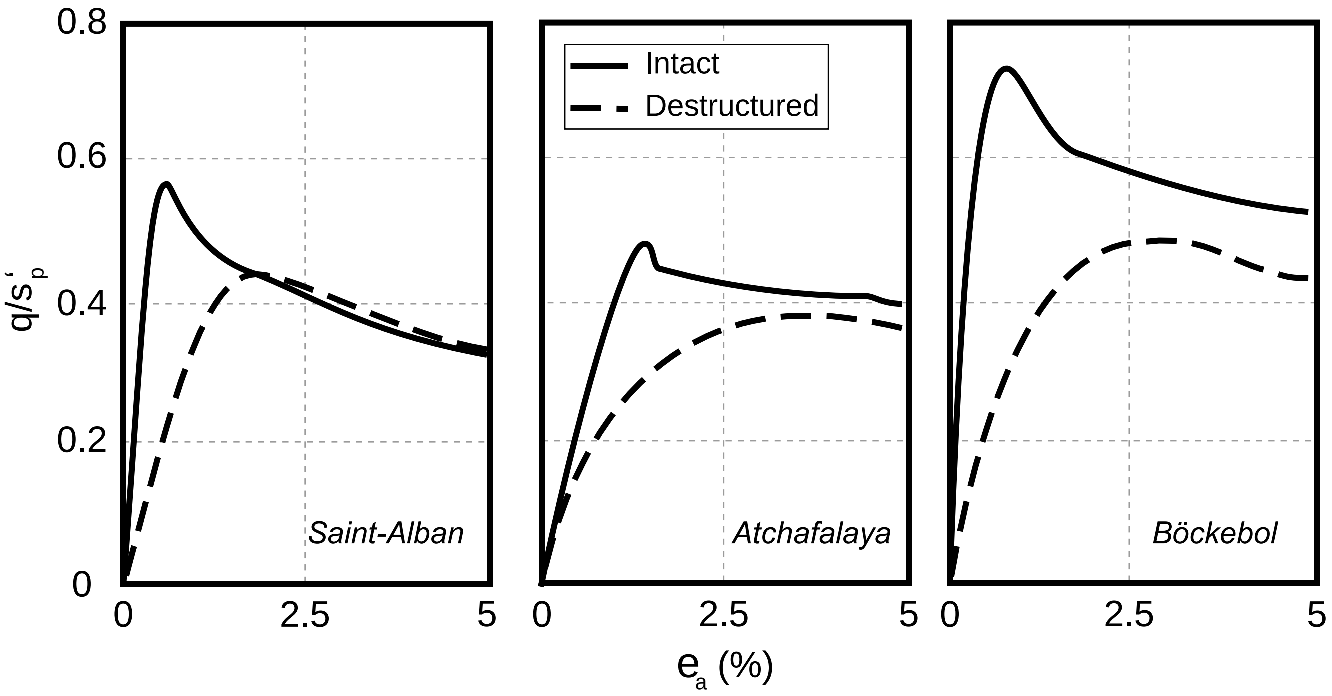
- Lacasse et al, 1981 assessed the undrained shear strength of two sites using laboratory and *insitu* testing methods
- They found that the PMT 'overestimated' the undrained shear strength using simple analysis methods
- The authors noted the importance of disturbance on their analysis and the lack of extending the cavity strain beyond 10% may have been an issue
- Back analysis of an embankment was ***not*** provided to validate their assumed model



After Lacasse et al., 1981

s_u and Other Tests

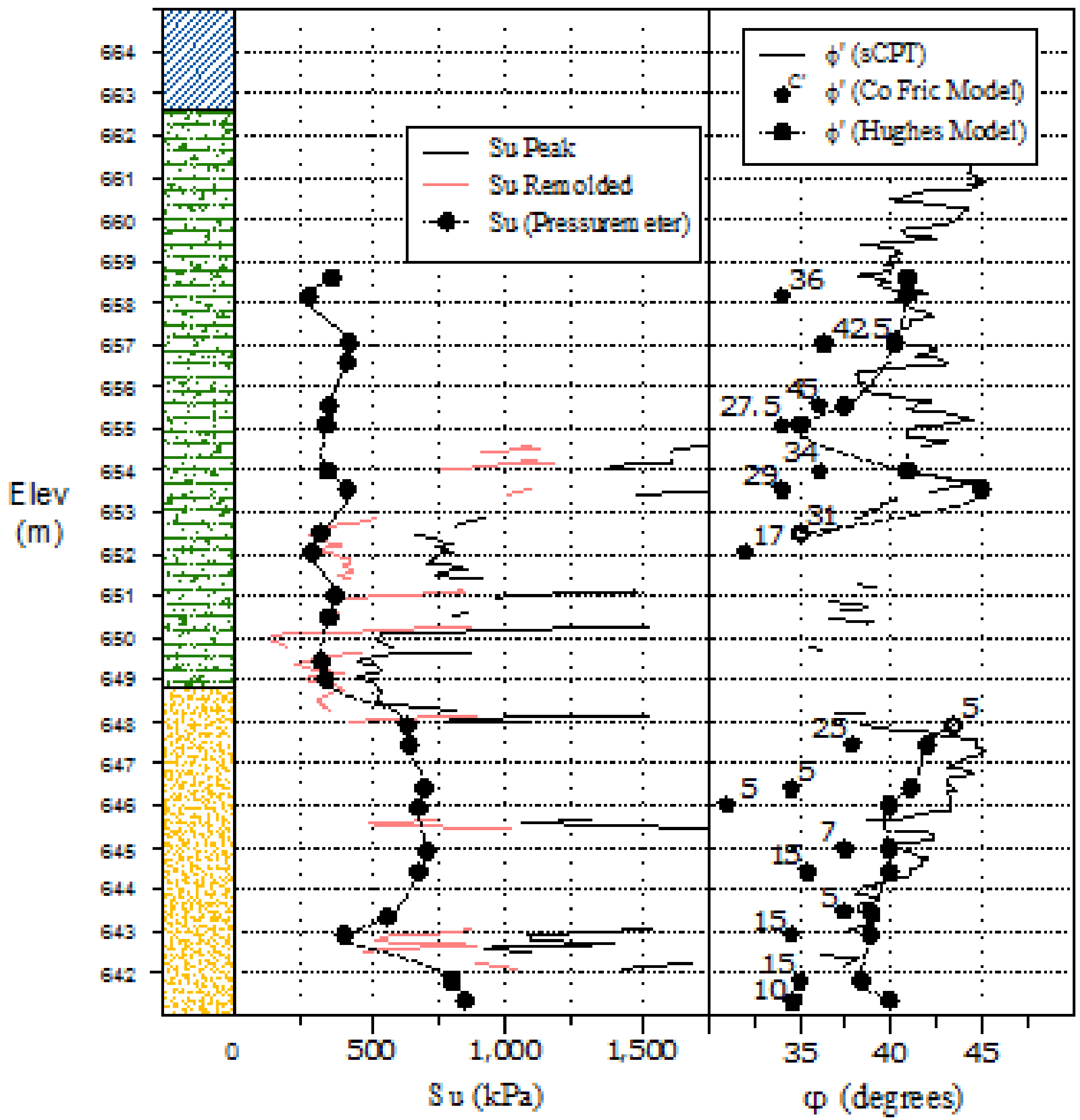
- Historically, the s_u obtained from the PM is considered to be high
  - Wroth (1984); Lacasse et al.(1981); Jamiolkowsky et al (1985); Schnaid (2005) all document the many reasons ***why***
  - Is it possible that the other methods are maybe low?
  - Tavenas & Leroueil (1985), Burland (1990) discuss the role of de-structuring on measured strength



After Tavenas & Leroueil, 1987

PMT and CPT Strength

- When properly calibrated, the values obtained from the CPT agree quite well with those found from curve fitting of PMT data
- In the HOC tills in Edmonton, the PBPMT tended to reflect the residual shear strength of the CPT, while the Hughes Model and the ϕ' obtained from the CPT were in close agreement

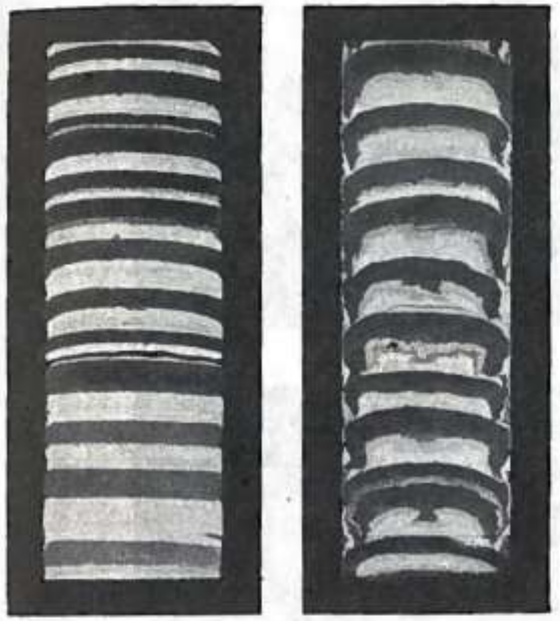


- As a final note on strength; when compared to other *insitu* methods like the CPTu, the values obtained may give misleading results
  - It is potentially from an assumed N_k value used to determine the undrained shear strength
  - The stress paths for the PMT and CPTu are highly complex and not completely defined, so direct calculation and determination of the 'correct' value are not always clear
  - The influence of L/D ratios in the PMT also should not be ignored (Yeung & Carter, 1990; Houlsby & Carter, 1993; Charles et al, 1999)
  - Use of the SVT also may be problematic as Wroth (1984) detailed the differences in shear relative to the laboratory and outlined the potential errors in the shearing assumption

Stiffness in the Lab and Field

- It is well understood that of all of the parameters obtained for geotechnical design, the stiffness is the first to degrade during sampling and testing
- Wroth (1984); Jamliokowsky et al (1985); Tavenas & Leroueil (1987); Burland (1990); Clayton (2010); Hight et al. (2007); Lim et al (2019) (and countless others) all demonstrate the issues with sampling and testing of modulus in the lab
- Many practitioners often neglect the anisotropy of stiffness and either assume isotropic or transversely isotropic conditions Leroueil and Hight (2003)
- As far back as 1949, the damage of even sharpened Shelby tubes were well documented

Stiffness in the Lab and Field



A

SPECIFIC RECOVERY 100% - 115%

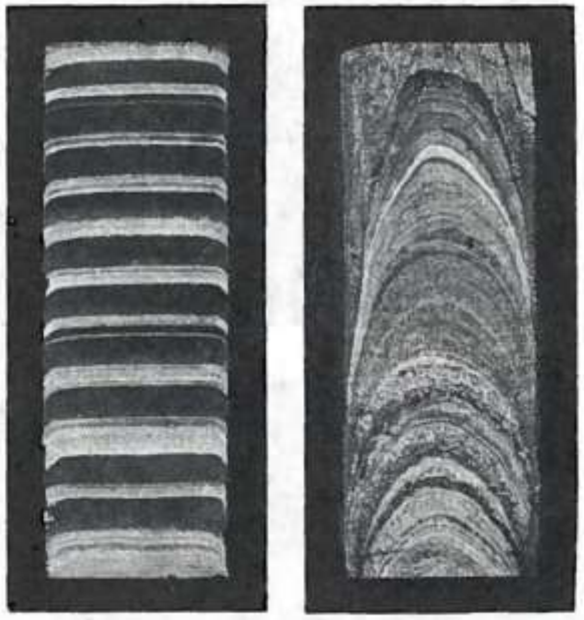
B

SPECIFIC RECOVERY 140% - 154%

VARVED CLAY - DEPTH 4' - 2" PIGGOT SAMPLER - SLOW JACKING

DISTORTIONS BY ENTRANCE OF EXCESS SOIL

FIG. 89



A

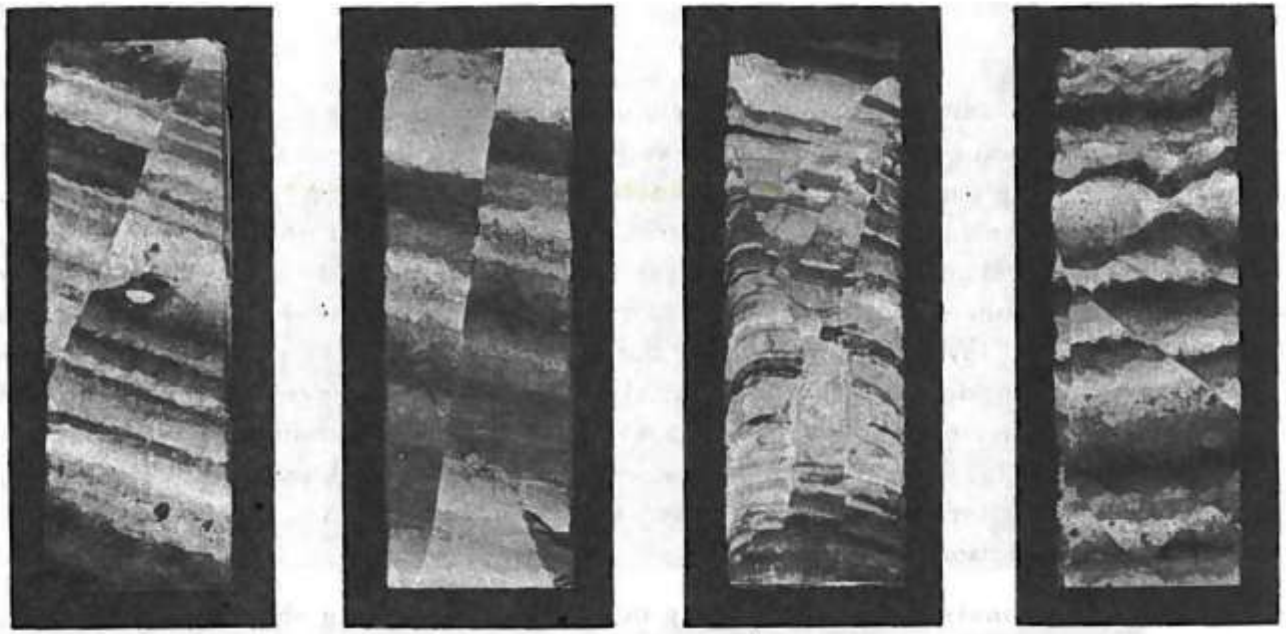
VARVED CLAY - DEPTH 5'
2" PIGGOT SAMPLER
SHOOTING

B

SANDY AND SILTY CLAY
DEPTH 18' - 2" SHELBY TUBING
HAMMERING

DRAG AND DISTORTION BY INSIDE FRICTION

FIG. 90



A - SINGLE INCLINED PLANE

B - SINGLE VERTICAL PLANE

C - FORMATION OF WEDGE

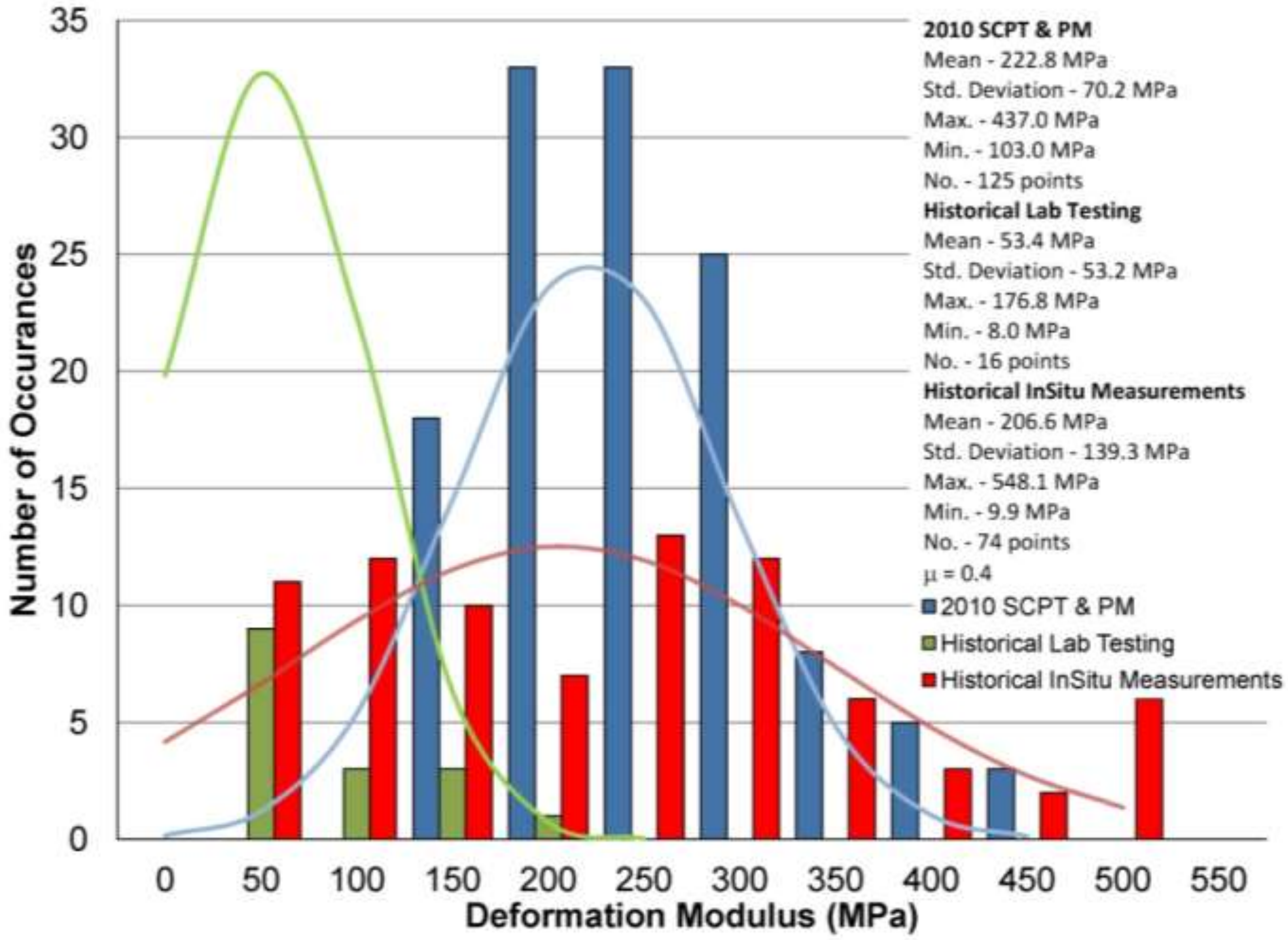
D - MULTIPLE SHEAR PLANES

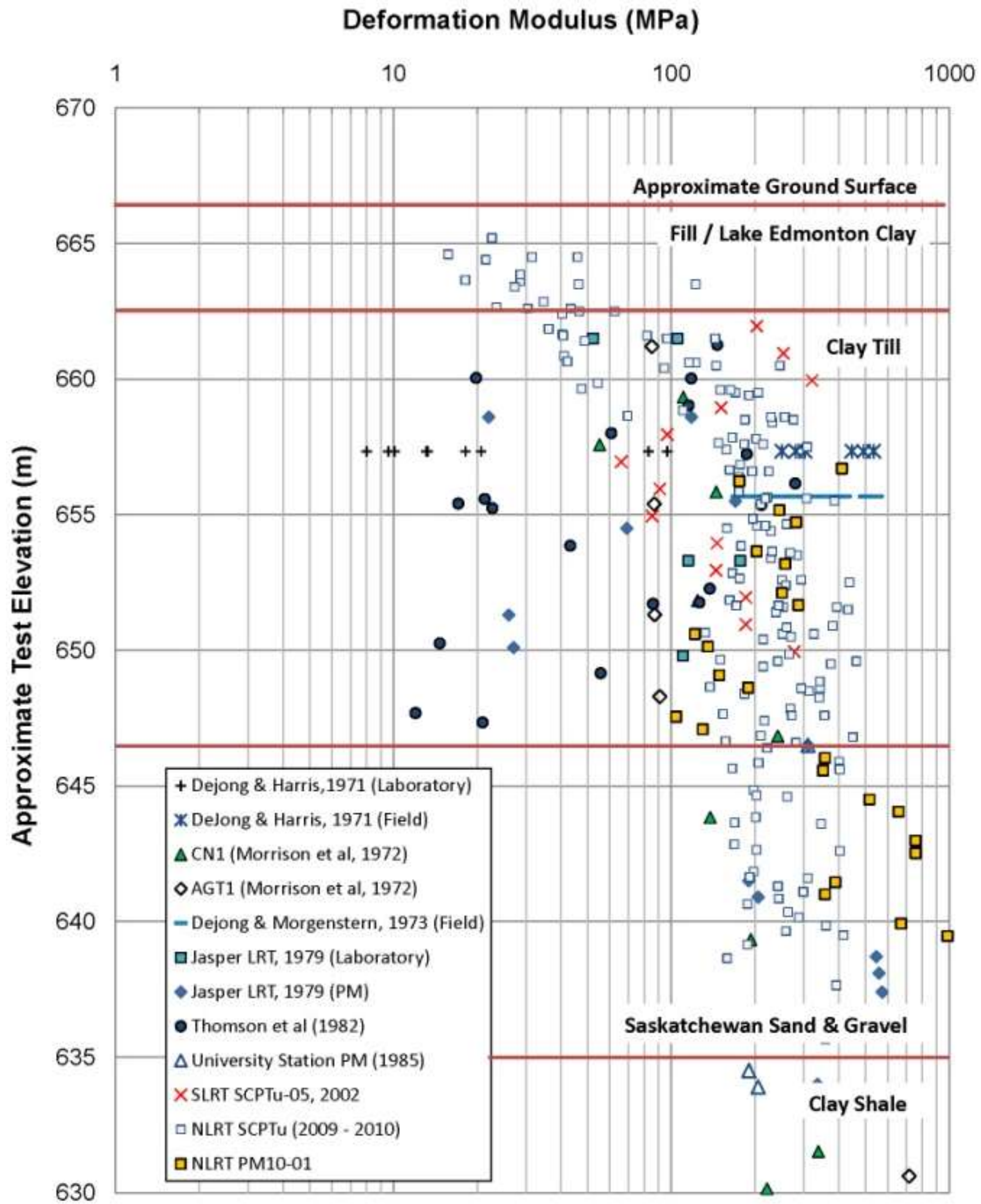
MEDIUM SOFT SILTY CLAY - DEPTH 22' TO 47' - 2" SHELBY TUBING - PUSHING - PENETRATION 42" TO 44" - RECOVERY 80% TO 85%

FIG. 94 - EXAMPLES OF SHEAR FAILURES CAUSED BY SAMPLING

Hvorslev, 1949

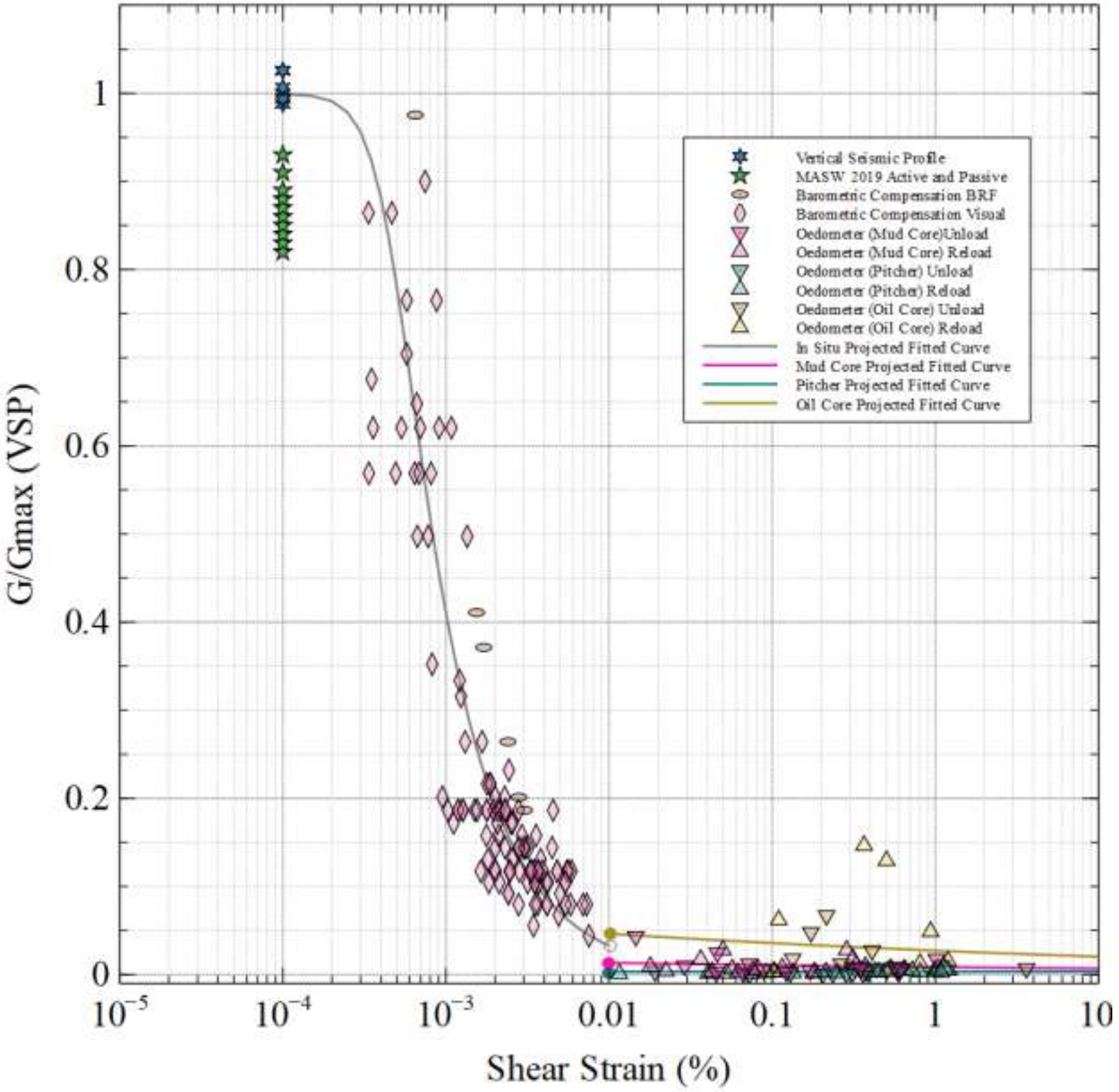
Stiffness in the Lab and Field





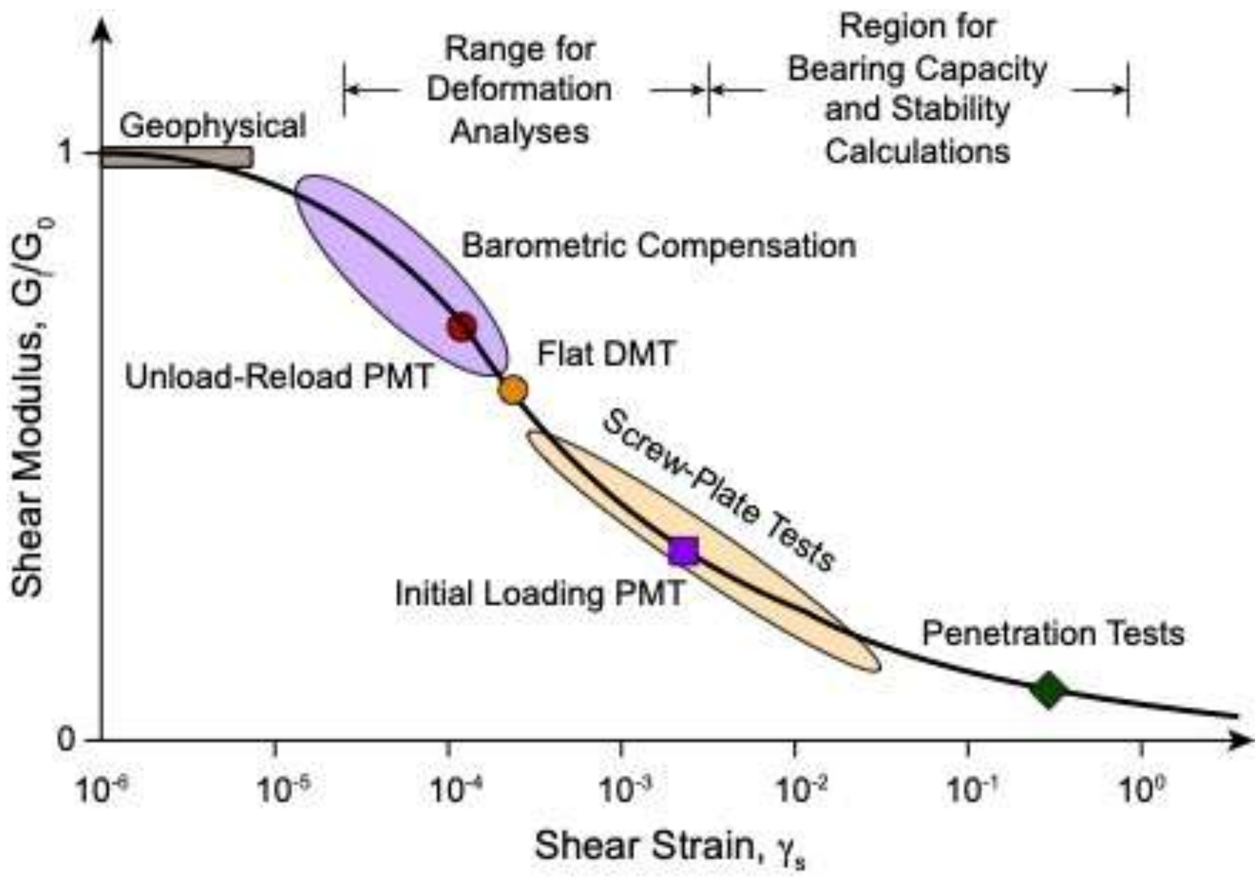
Stiffness

- Currently, the best method of determining sample damage is a comparison of G_0 values in the field vs lab
- Modulus decay is complex and is crucial to determine and map
- Use of multiple modulus determinations can vastly clarify the 'correct' modulus at a given strain increment



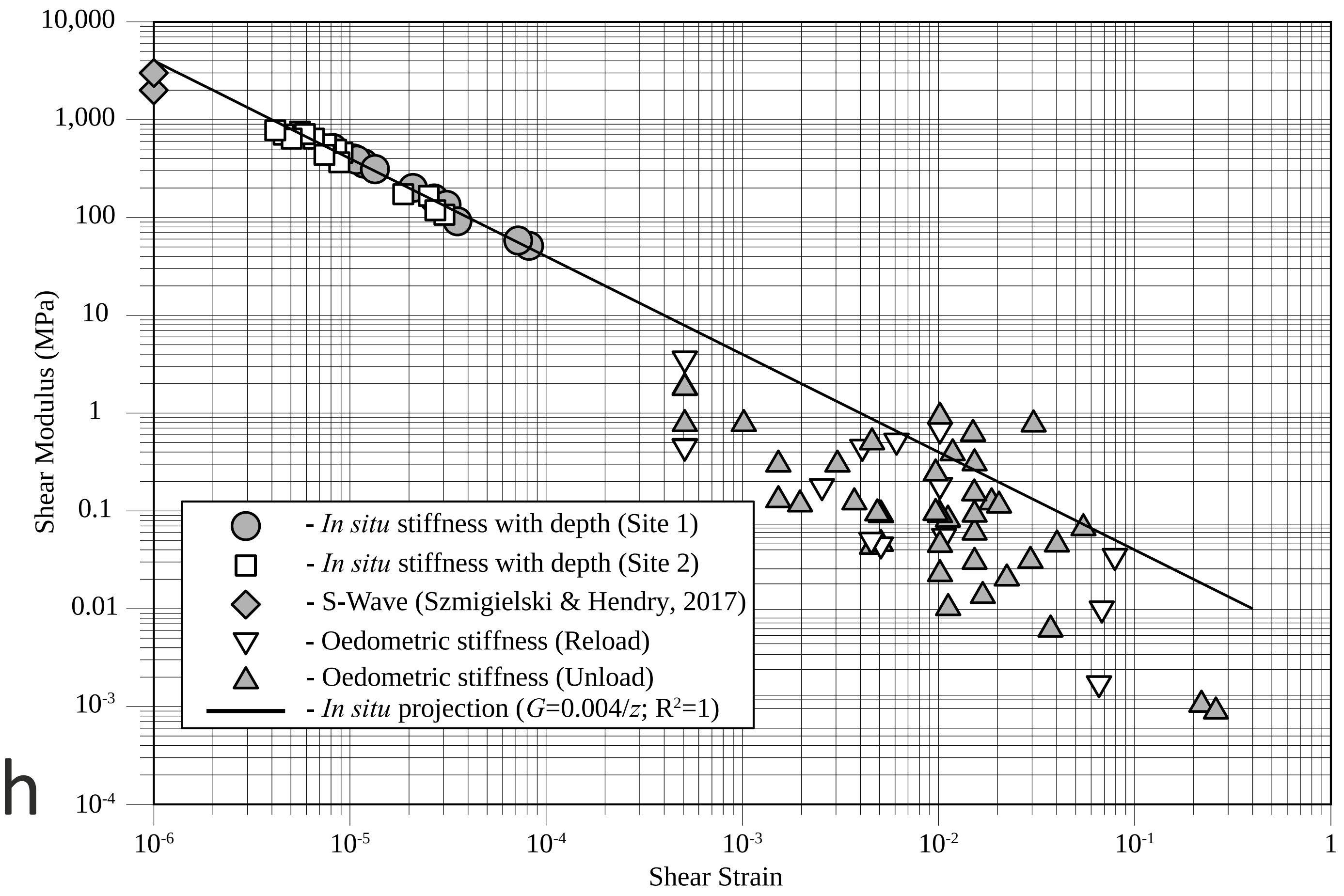
Stiffness in the Lab and Field

- Clearly the selection of modulus should be based on the anticipated strain increment
- This makes the use of non-linear evaluation of the U-R loops during the PMT so important
- Coupled with sCPTu and barometric compensation, the complete stiffness decay may be determined at any depth



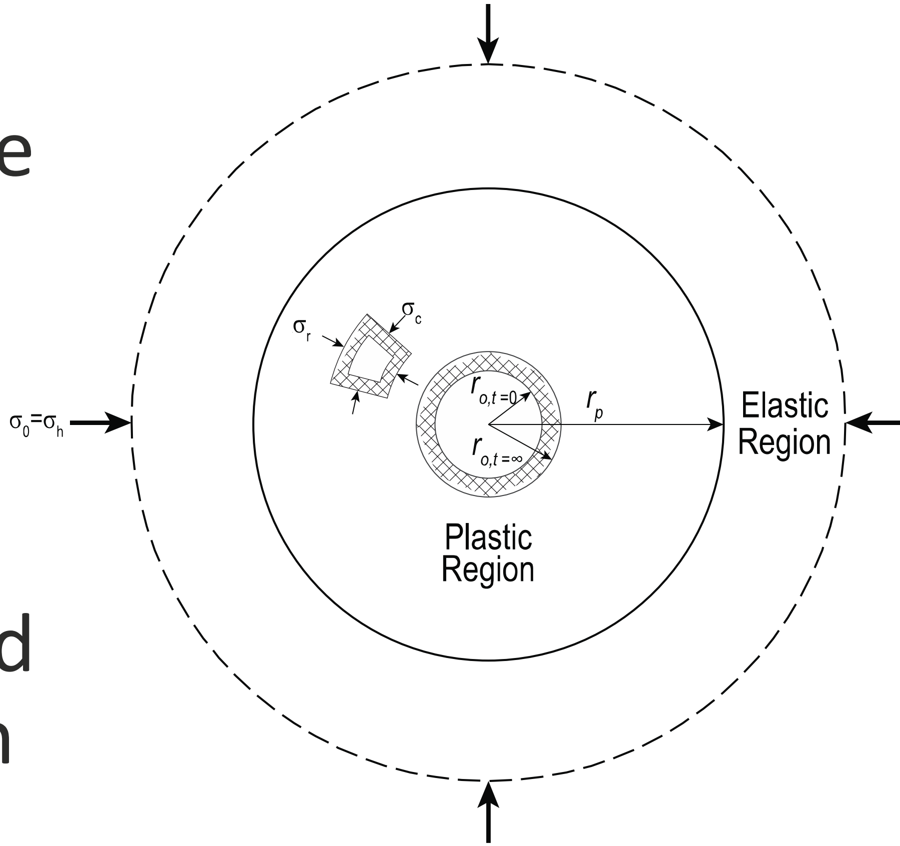
Stiffness in the Lab and Field

- Understanding that most geotechnical labs do not have access to bender elements or resonant column apparatus another method is needed
- The degree of sample disturbance may also be illustrated by using multiple methods as illustrated by Smith et al (2018)



Stiffness in the Lab and Field

- Schnaid (2005) noted that the stiffness measured in the unload-reload loops is not the same at all distances from the borehole; Houlsby (1998) justifies using the G_{UR} at the cavity wall
- Muir Wood (1990) evaluated the modulus degradation obtained from the PMT and found that the ***tangent*** modulus described by Bolton & Whittle (1999) is directly comparable to the ***secant*** modulus obtained from the laboratory

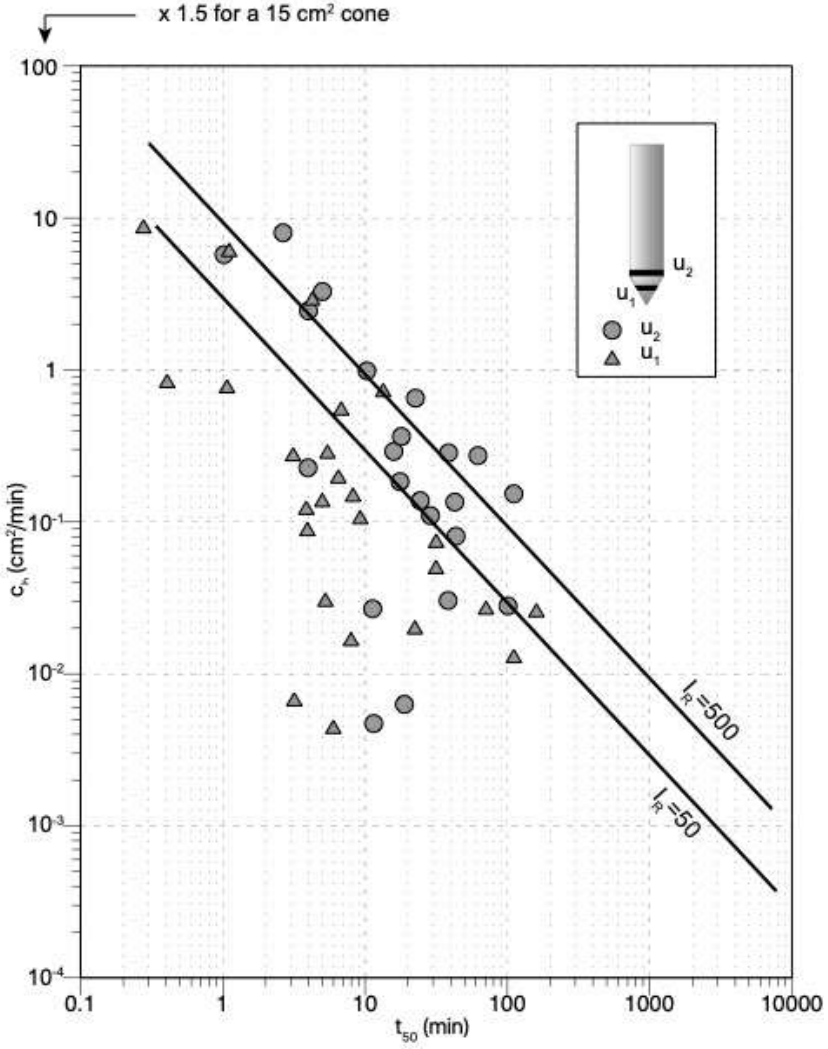


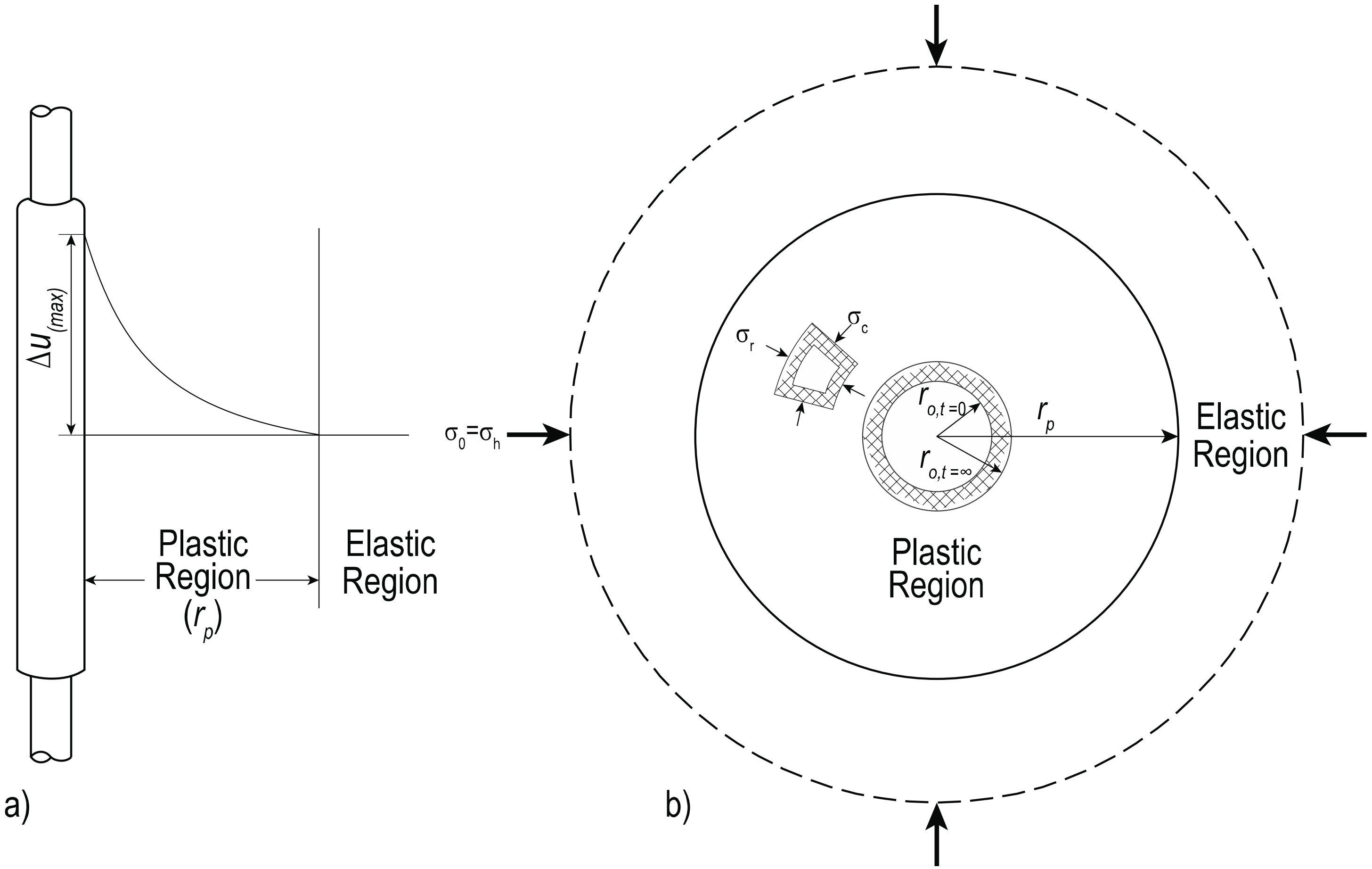
- As a final note on stiffness
  - Direct measurement of the modulus in unload-reload loops clearly illustrate the shear modulus at various stress and strain increments irrespective of the soil or rock type
  - Non-linear methods of interpretation provide a vital piece of the stiffness decay for a given soil and can clearly bridge the gap between geophysical methods and full scale deformation characteristics
  - Multiple unload-reload cycles throughout the test also can be an indicator of changes to the modulus with either the number of cycles, strain or stress levels

Consolidation in the Lab and Field

- Wroth (1984) and Schnaid (2005) provide a detailed evaluation of the consolidation obtained in the laboratory and from the PMT
- Coefficients of consolidation can be assessed *insitu* from observations of settlements under embankments or directly from in situ test results, preferably from piezocone dissipation tests and SBPM holding tests
  - Teh & Houlsby (1991) and Liu et al. (2018) illustrate the difficulty with assessing the non-dimensional time factor, T around a CPT and a PMT
  - Because consolidation is occurring at varying rates around the probe and within the plastic region, the effective stress is not a constant throughout

Consolidation in the Lab and Field





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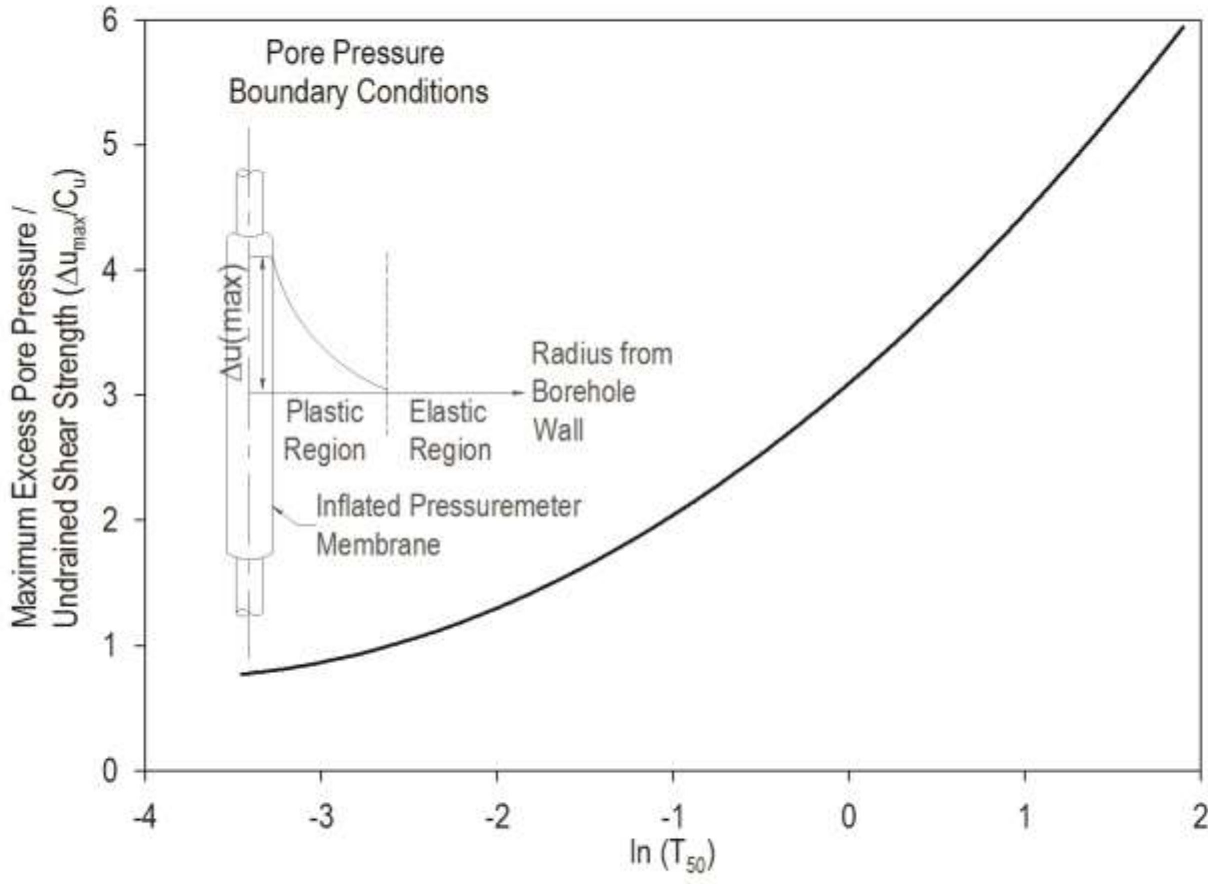
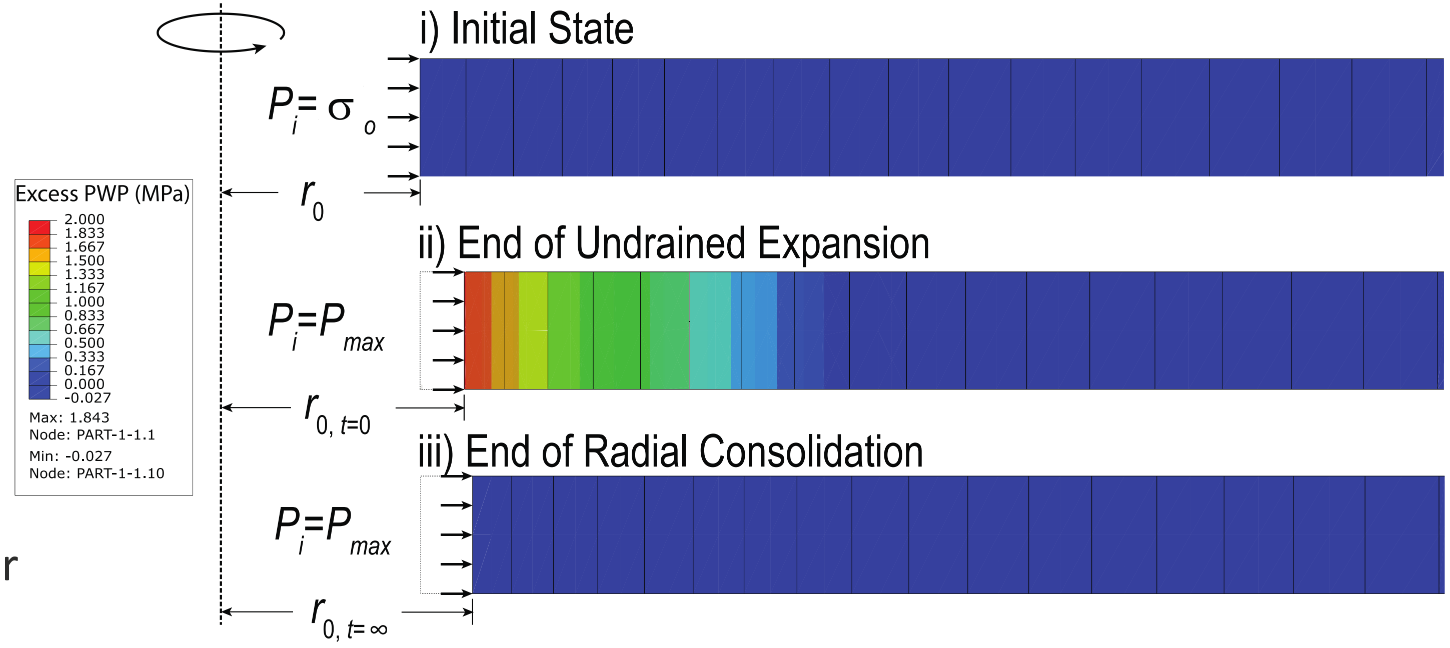
Consolidation in the Lab and Field

- Clarke et al. (1979) & Carter et al. (1979) developed a solution for the boundary conditions around the pressuremeter for the PMT considering a SHT
- Fahey (1986, 1988) attempted to solve the consolidation problem considering a PHT, but his results were unsatisfactory
- Lui et al. (2018) determined that part of the issue with Fahey's model was looking for t_{50} in the PHT



Consolidation in the Lab and Field

- Both the CPT dissipation tests and the PMT consolidation tests (PHT and SHT) are comparable to one another as they determine the k_h and c_h of the soil
  - Both methods also assume radial from from the probe to the plastic boundary
  - The main issue is determining the I_r for a given sample; because stiffness is not linear, I_r by definition cannot be either



Consolidation in the Lab and Field

- In the laboratory, it should not be expected that the c_v obtained from the oedometer test will be the same as those measured from *insitu* tests
  - This owes to sample damage during recovery and prep (de-structuring)
  - Anisotropic hydraulic conditions within the soil mass itself
  - Natural geologic conditions occurring *insitu* (macro-structure)

Final Thoughts…

- Understanding the data that is obtained in the field is critical to adequate design of high-risk/high-consequence project
- More often than not, we assume a number is correct without delving into the meaning of the data; the stress paths or strain paths taken to acquire this data
- Monitoring must be undertaken and back analysis of the results carried out to verify and validate the input into the predictive model

Final Thoughts…

- There is no reason why the parameters obtained in the laboratory *should* be the same as those obtained *insitu*
  - In fact, many researchers have outlined exactly *why* the values obtained in the lab will differ
  - It is important to understand the boundary conditions, the material responses to imposed loading or strain conditions and how they will influence the measured results
- Lastly, the use of advanced constitutive models for predicting scaling of data require realistic and consistent data as inputs; moreover, often the hardest to obtain parameters are the most critical (ie stiffness)