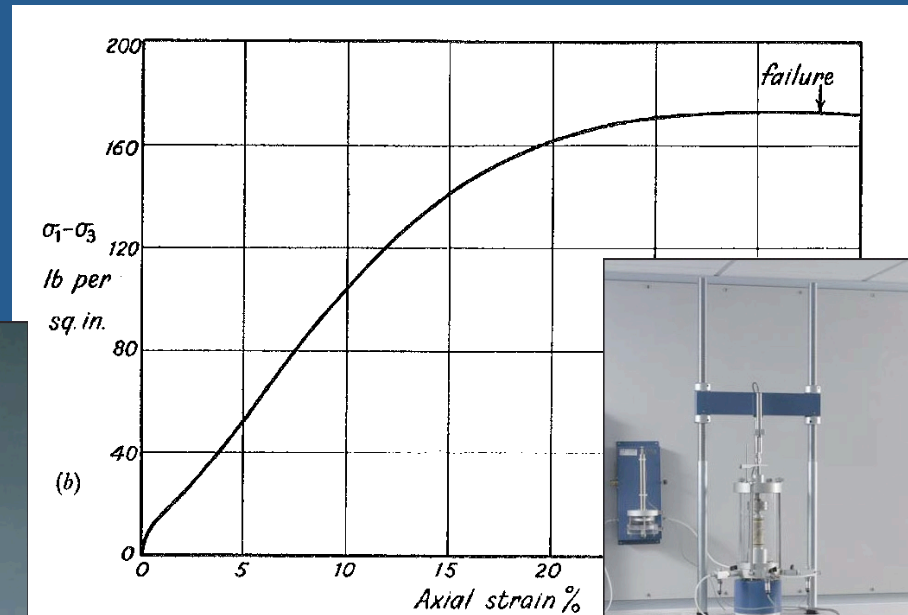
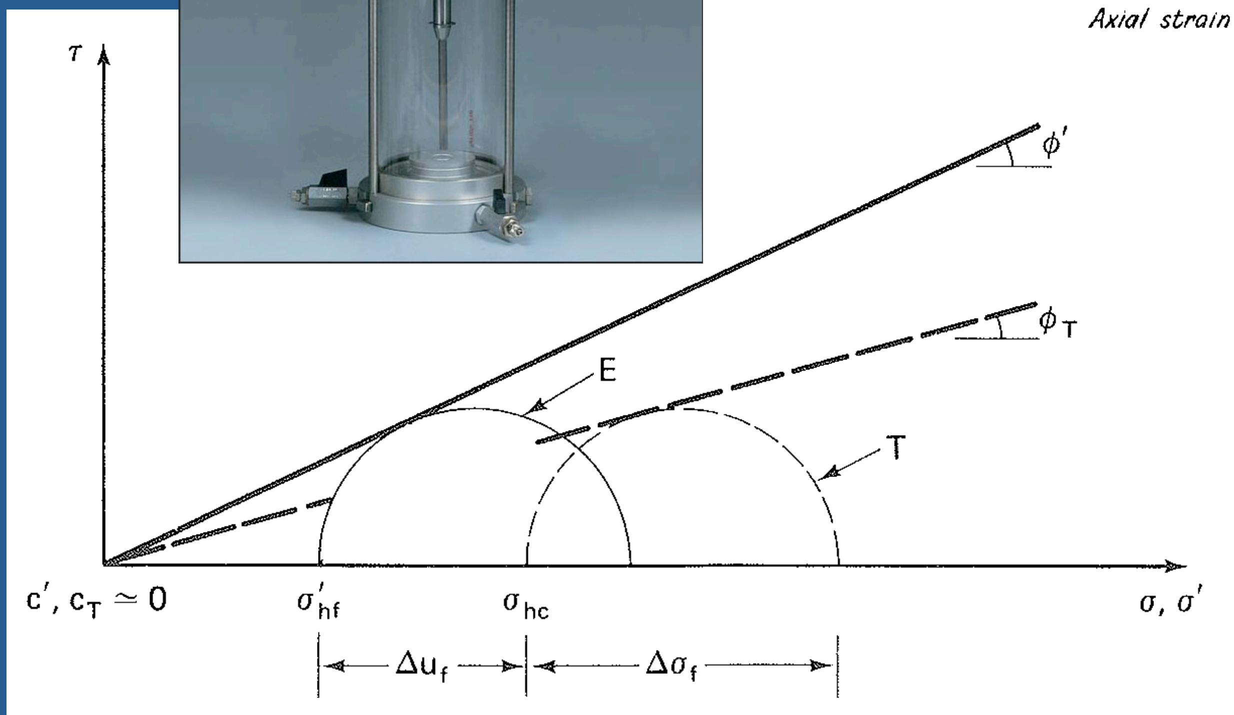
Triaxial Testing





Laboratory Tests to Determine Shear Strength of Soils

Geotechnical Engineering II
(ENGI 6723)

Presented by Rodney P. McAffee, Ph.D., P.Eng.

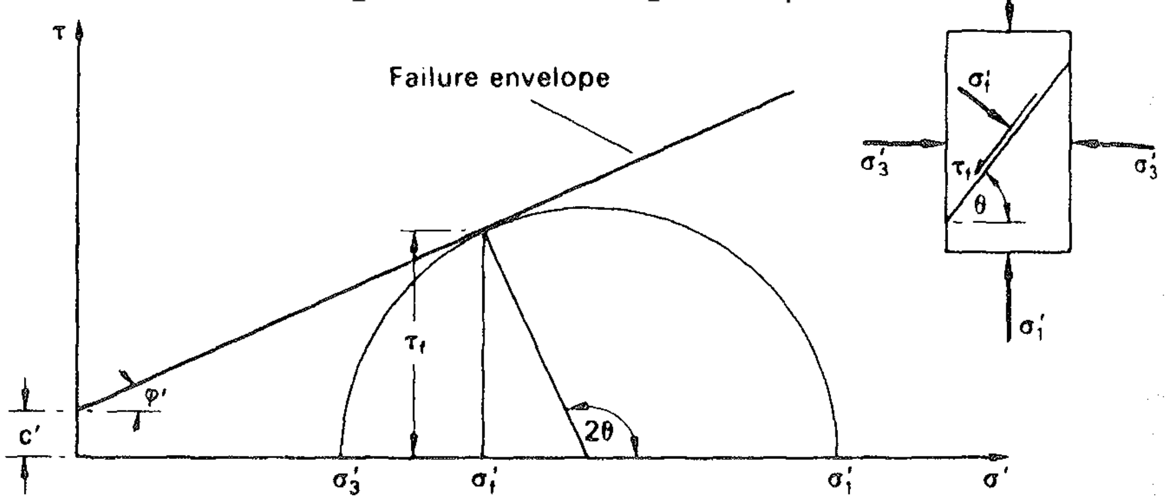
Laboratory Tests to Determine Shear Strength of Soils

- Lecture Topics
  - Brief overview of direct shear test
  - Determine soil shear strength parameters from triaxial testing:
    - Unconsolidated – Undrained
    - Consolidated – Undrained
  - Triaxial test setup and behaviour
  - Use of results in engineering practice
  - Examples of triaxial test results

Shear Strength

- Shear strength of soils is required to solve problems of stability
  - Bearing capacity, earth pressures, slope stability, etc.
- Shear strength is a function of effective normal stress

$$\tau_f = c' + \sigma_f' \tan \phi'$$



Stress conditions at failure.

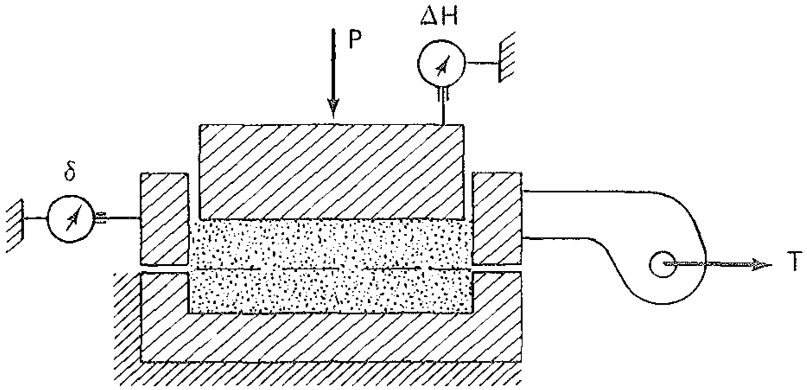
Laboratory Tests to Determine Shear Strength of Soils

- Direct Shear Test

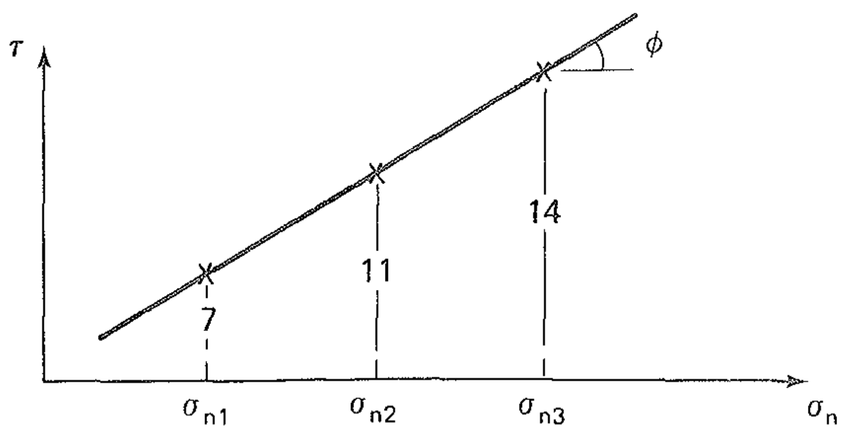
- Triaxial Tests
  - Pore water pressure measurement
  - Testing under back pressure

- Types of Triaxial Tests
  - Unconsolidated – Undrained
  - Consolidated – Undrained
  - Consolidated – Drained

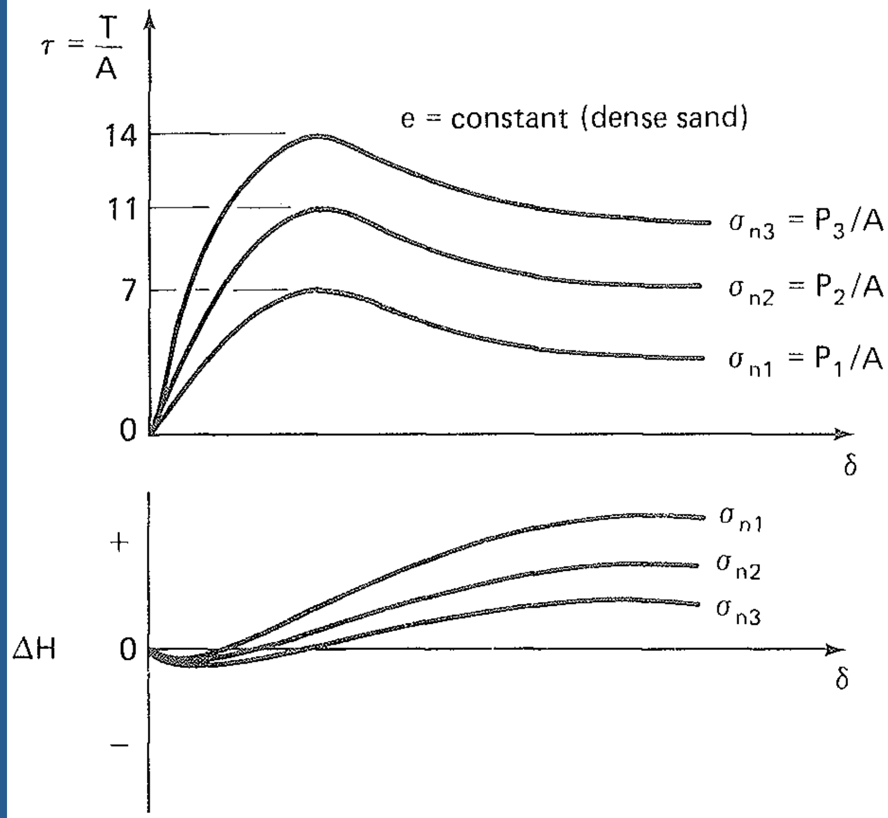
Direct Shear Test



(a) Apparatus



(c) Mohr diagram



(b) Test results

Direct Shear Test

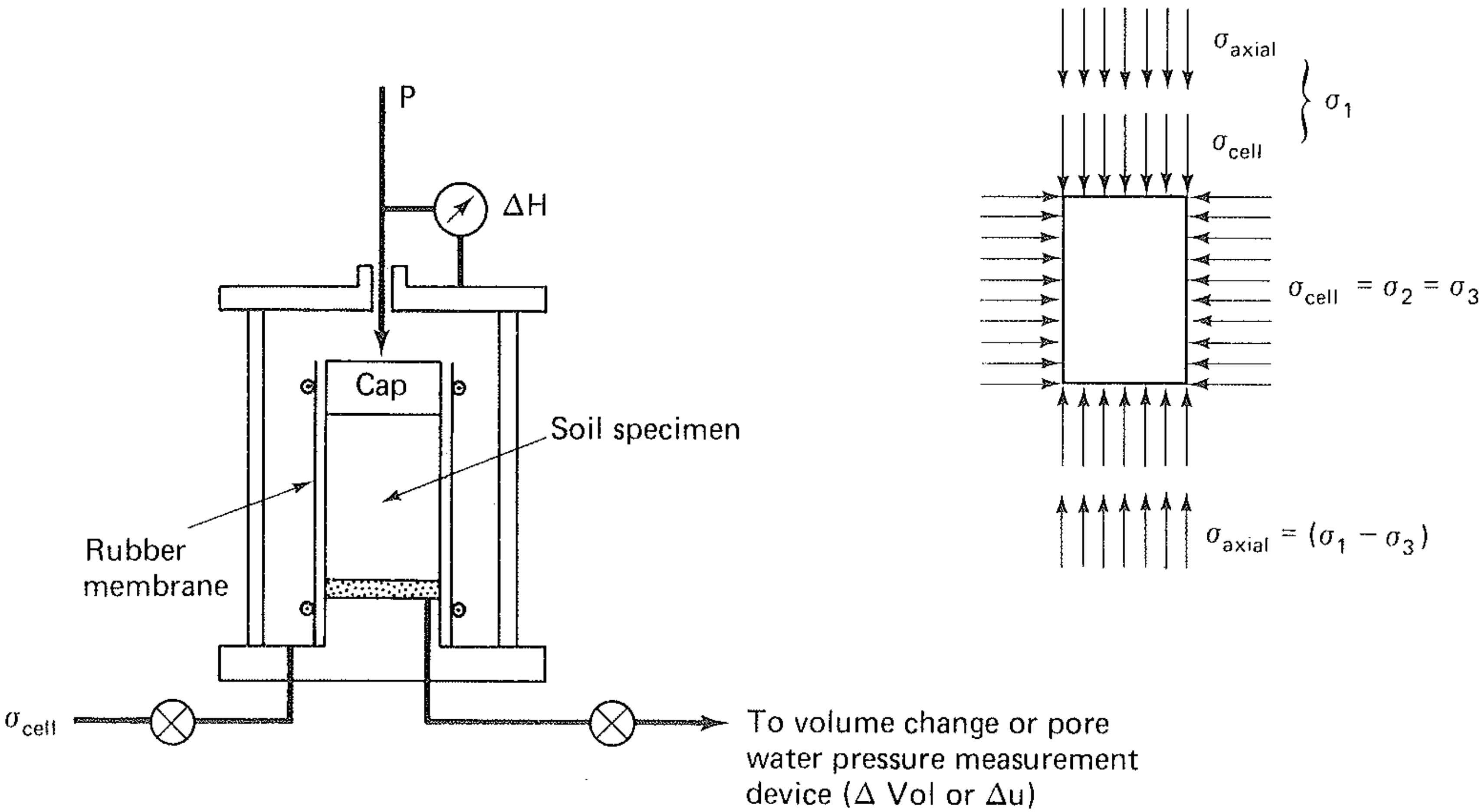
- Disadvantages
  - Failure plane is forced to be horizontal
  - Cannot control drainage
  - Stress concentrations at the sample boundaries
  - Uncontrolled rotation of principal planes and stresses

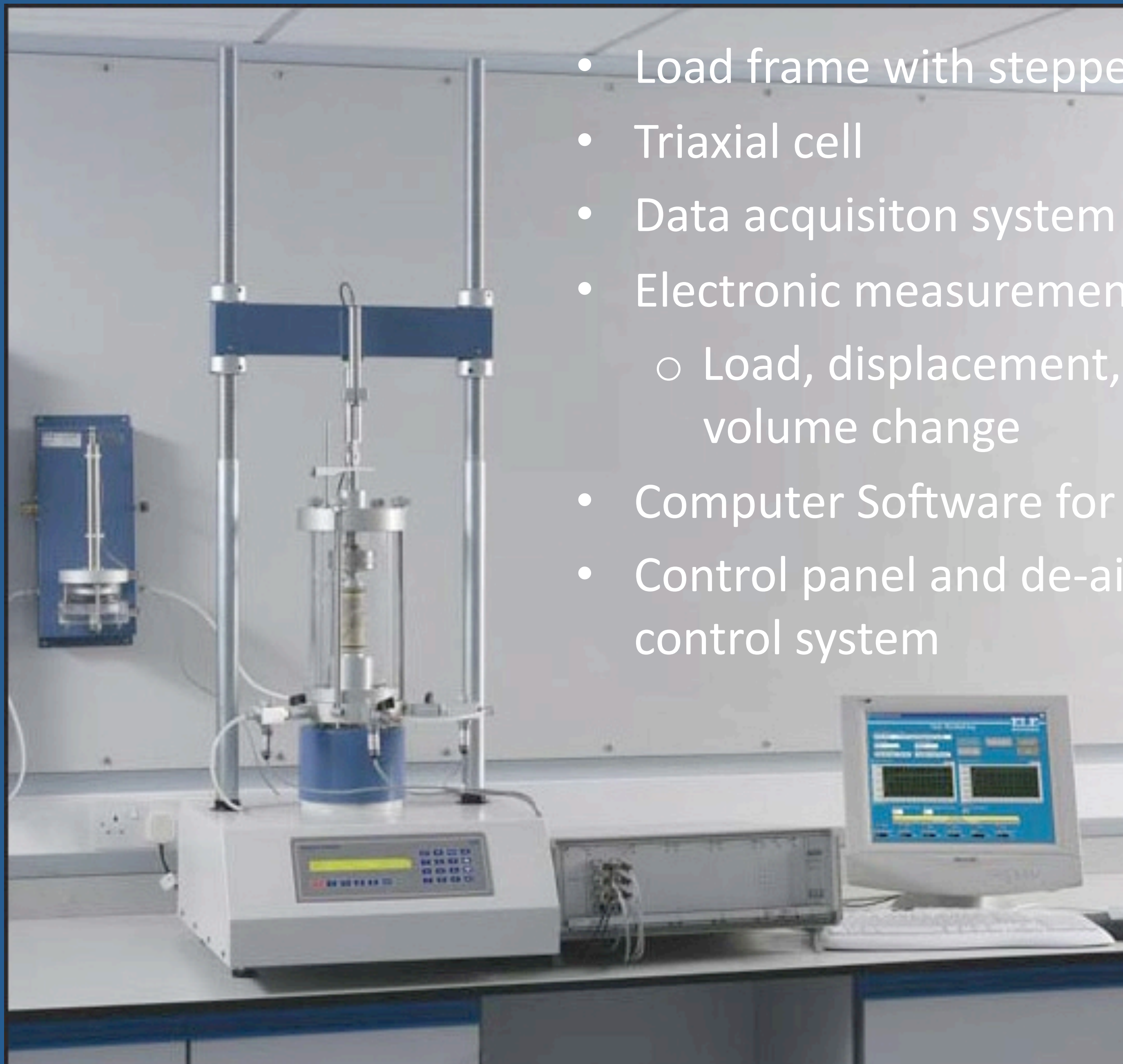
- Advantages
  - Test in inexpensive
  - Fast and simple
  - Easy to prepare for cohesionless samples

Triaxial Testing

- Casagrande developed triaxial testing in the 1930s
- More complicated than direct shear testing
  - But more versatile
- Drainage can be controlled
- No rotation of principal stresses
  - Some small shear stresses do act on the boundaries
- Stress concentrations are limited
- Failure plane can occur anywhere
- Stress paths to failure can be controlled

Triaxial Test Apparatus and assumed Stress Conditions





- Load frame with stepper motor drive
- Triaxial cell
- Data acquisiton system
- Electronic measurement transducers
  - Load, displacement, pressure, and volume change
- Computer Software for triaxial testing
- Control panel and de-aired water control system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- Control Panel to regulate pressure and flows during testing

Drainage Paths in Triaxial Testing

- The 3 permissible drainage paths are:

Drainage Path Before Shear-During Shear	Symbol
Unconsolidated-Undrained	UU
Consolidated-Undrained	CU
Consolidated-Drained	CD

Q-Test
(for “quick” test)

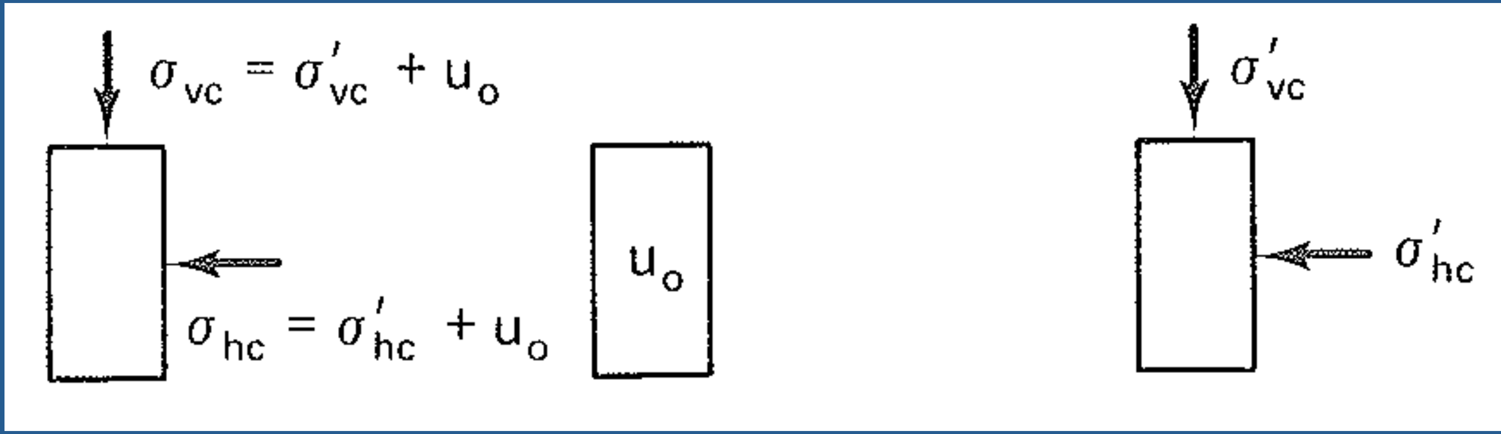
S-test
(for “slow” test)

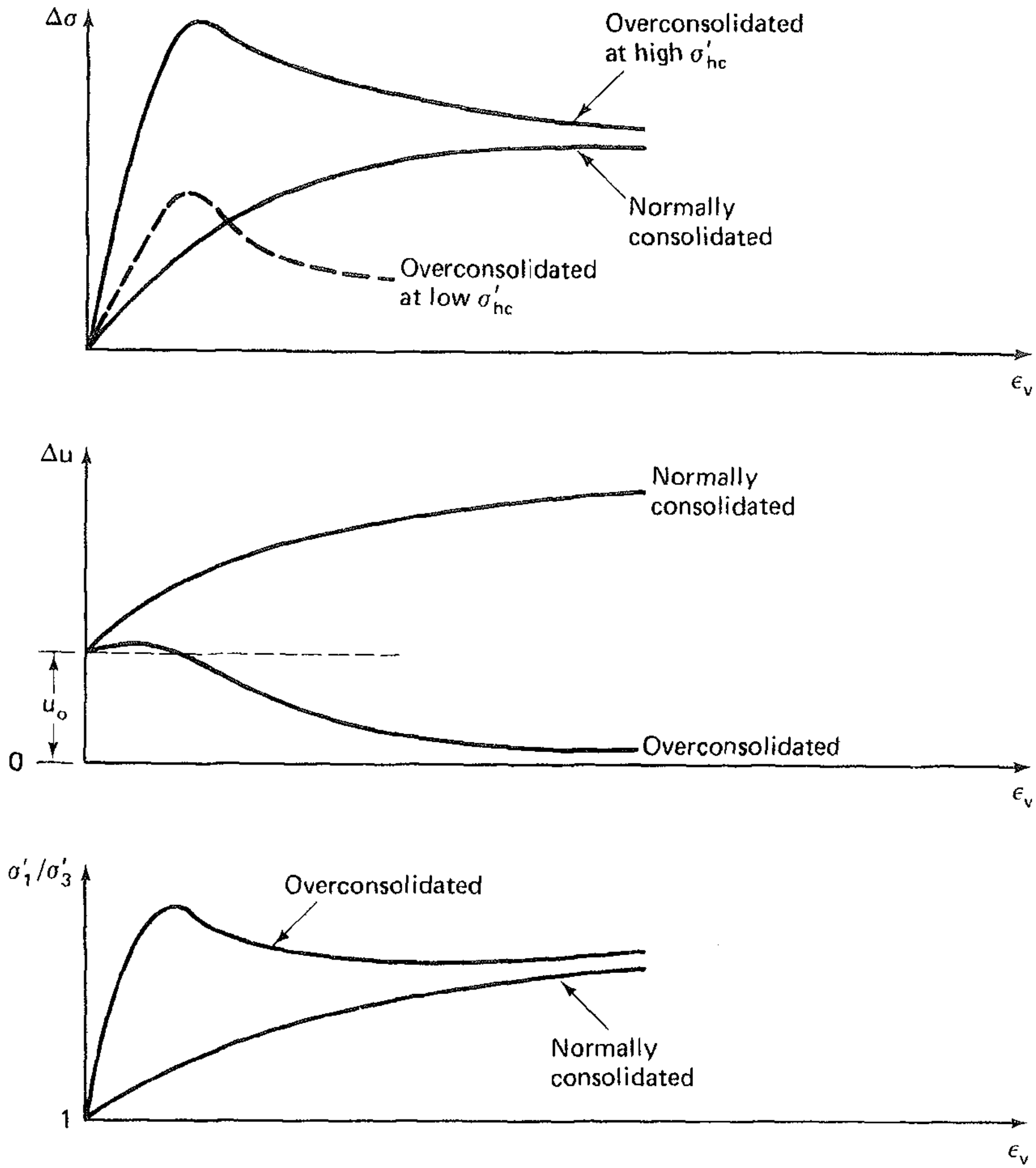
Consolidated – Undrained (CU) Test Behaviour

- Sample is first consolidated under desired stresses
- After consolidation complete, drainage valves closed
- Typically, pore water pressures are measured
  - Calculate total and effective stresses
- Excess pore water pressure (Δu) can either:
  - Increase (+ive): specimen contracts or consolidates
  - Decrease (-ive): specimen expands or swells
- Axial stress increased incrementally or at constant rate of strain

Back Pressure during Testing

- To ensure 100% saturation (necessary to give accurate pore water pressures), a back pressure is applied to the pore water
- Cell pressure also increased by same amount to maintain the same effective consolidation stresses



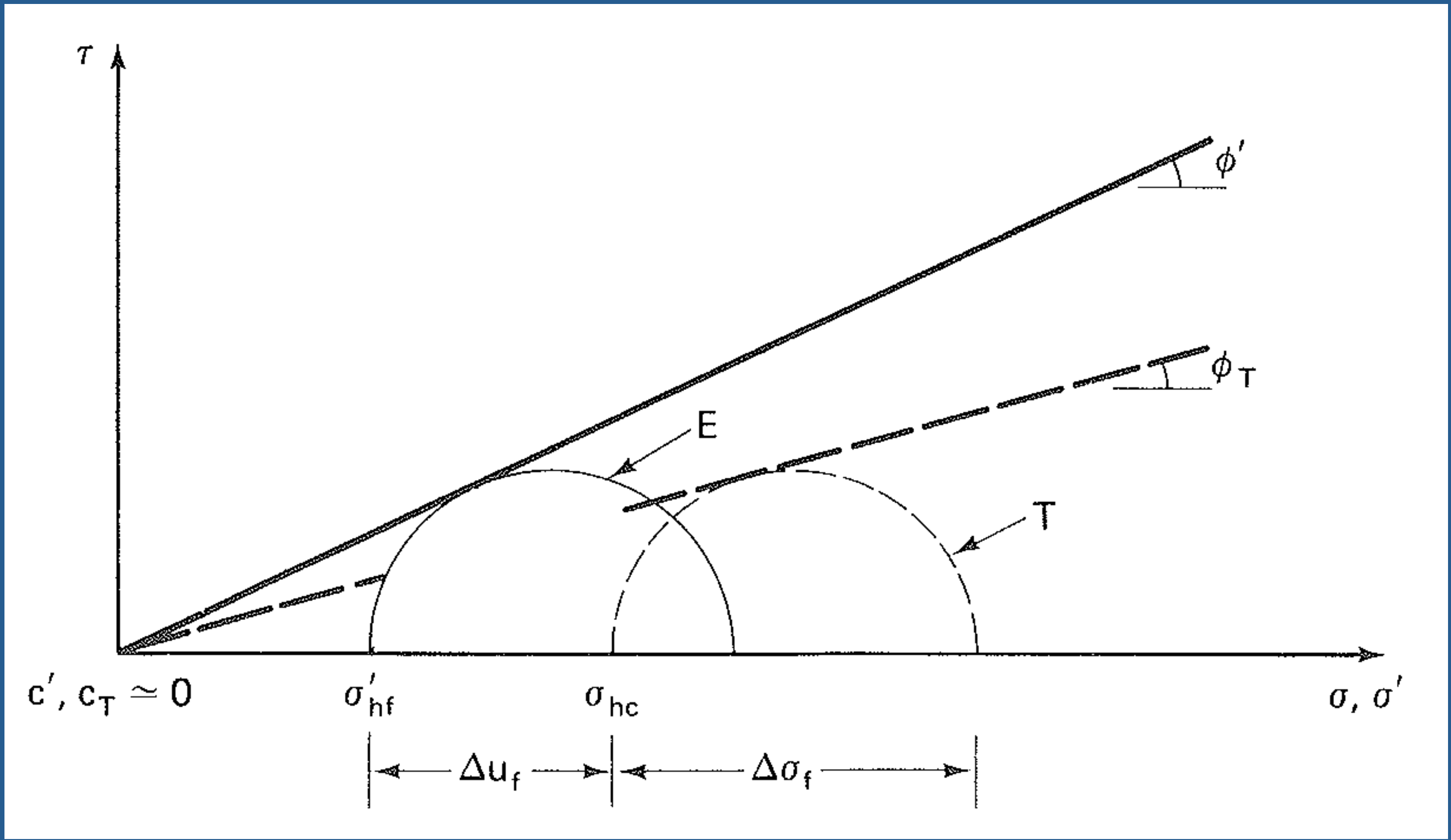


Note: For hydrostatic consolidation, $\sigma'_1/\sigma'_3 = 1$ at the start of the test; for non-hydrostatic consolidation, $\sigma'_1/\sigma'_3 > 1$.

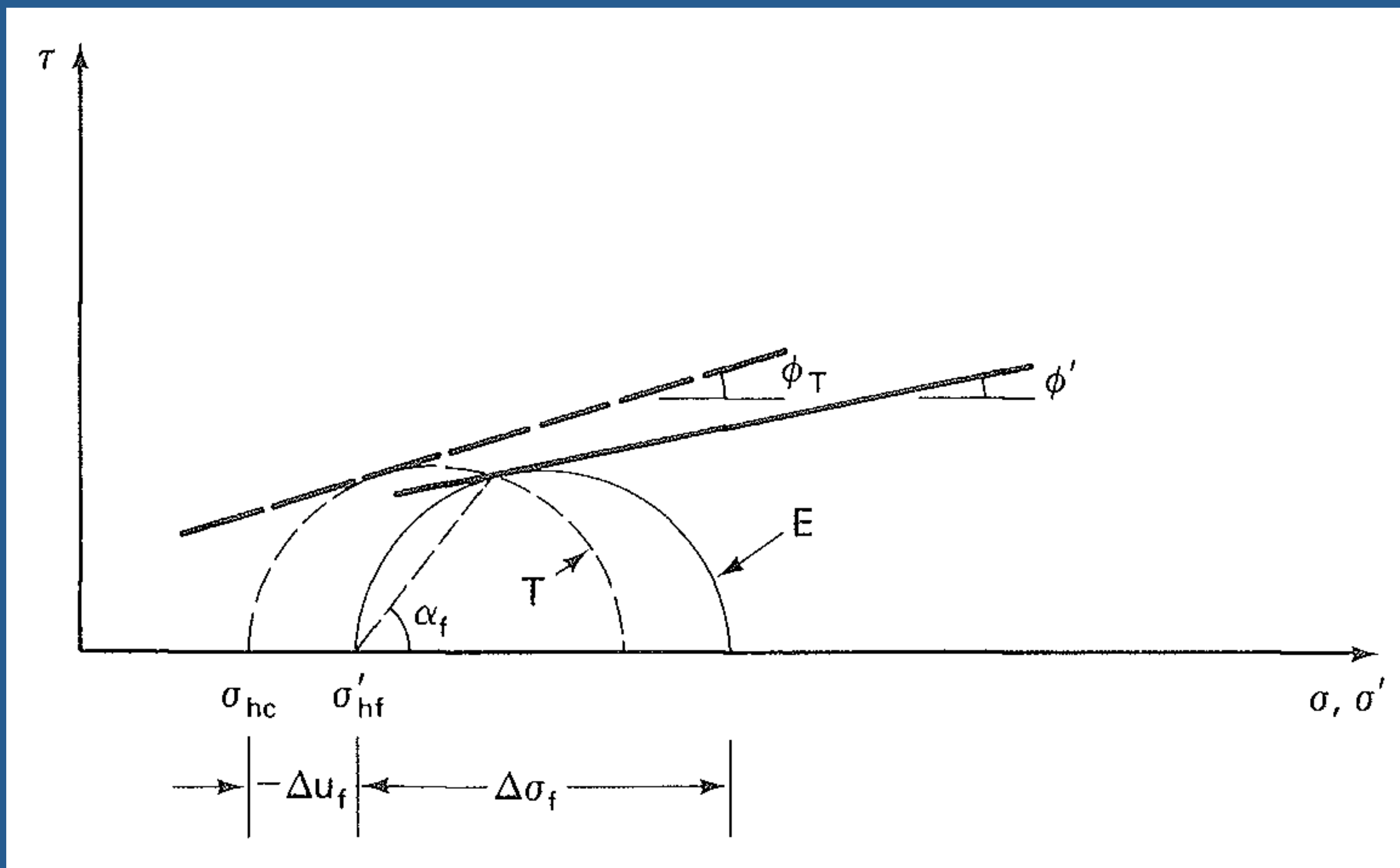
Typical Stress-Strain Curves for CU Tests

Principal (effective) stress ratio is a simple way to normalize the stress behaviour with respect to σ'_3 during the test

- With pore water pressures measured, we can calculate both total and effective stresses at failure
- Typically, a number of tests over a range of stresses is carried out
- **NC clay** specimens develop positive pore water pressures ($\sigma' = \sigma - \Delta u$)



- **OC clays** tend to expand during shear causing decreased pore water pressures
($\sigma' = \sigma - (-\Delta u)$)



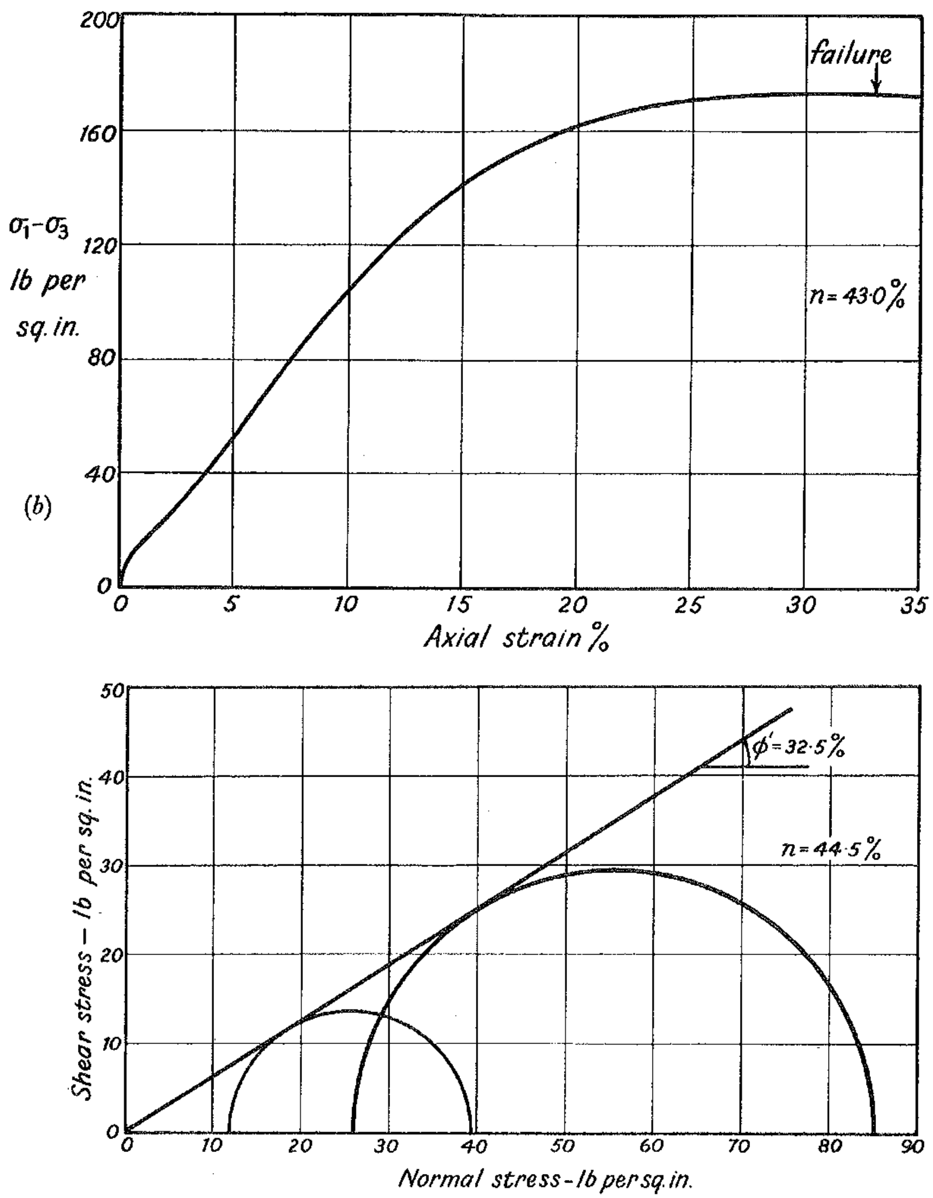
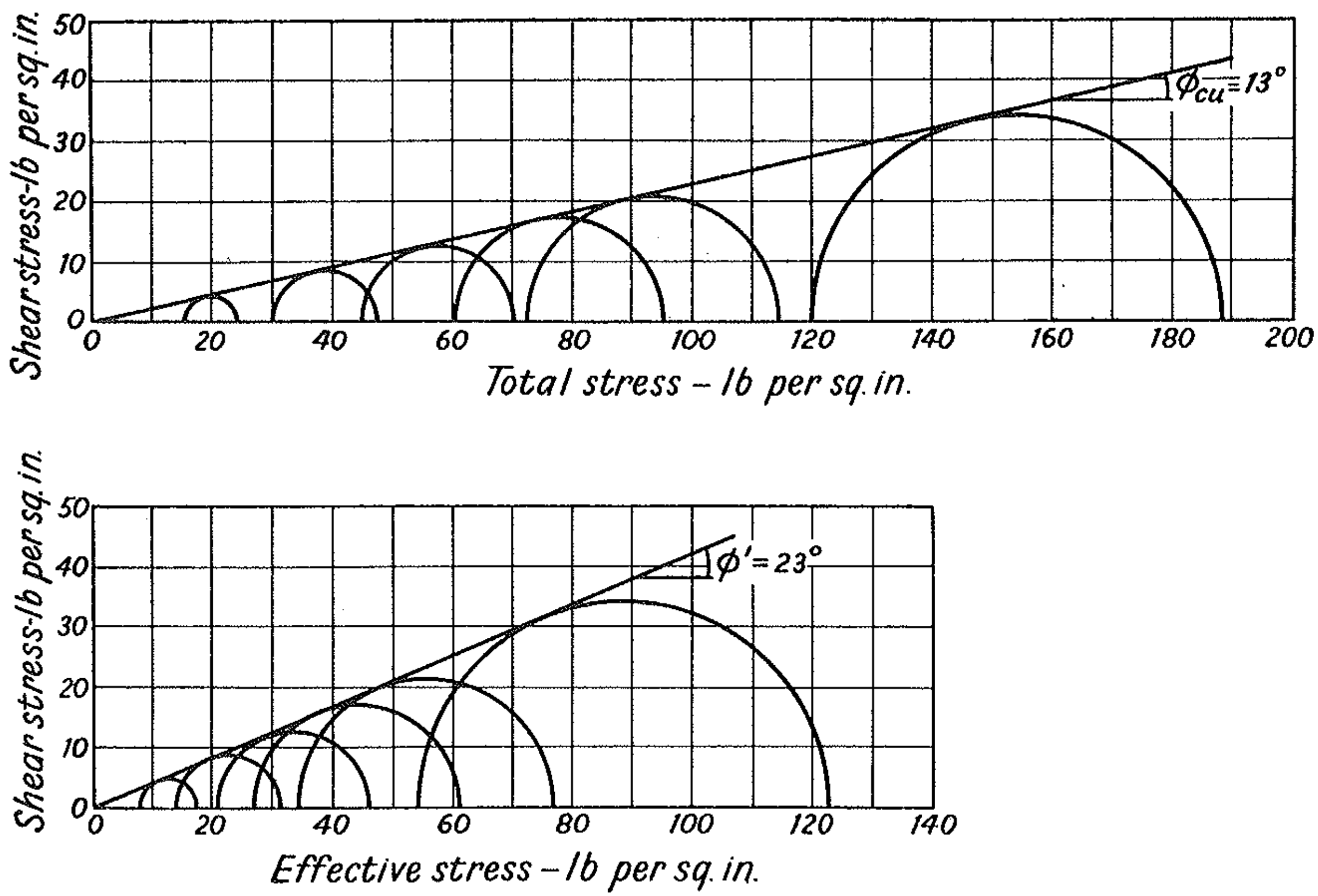
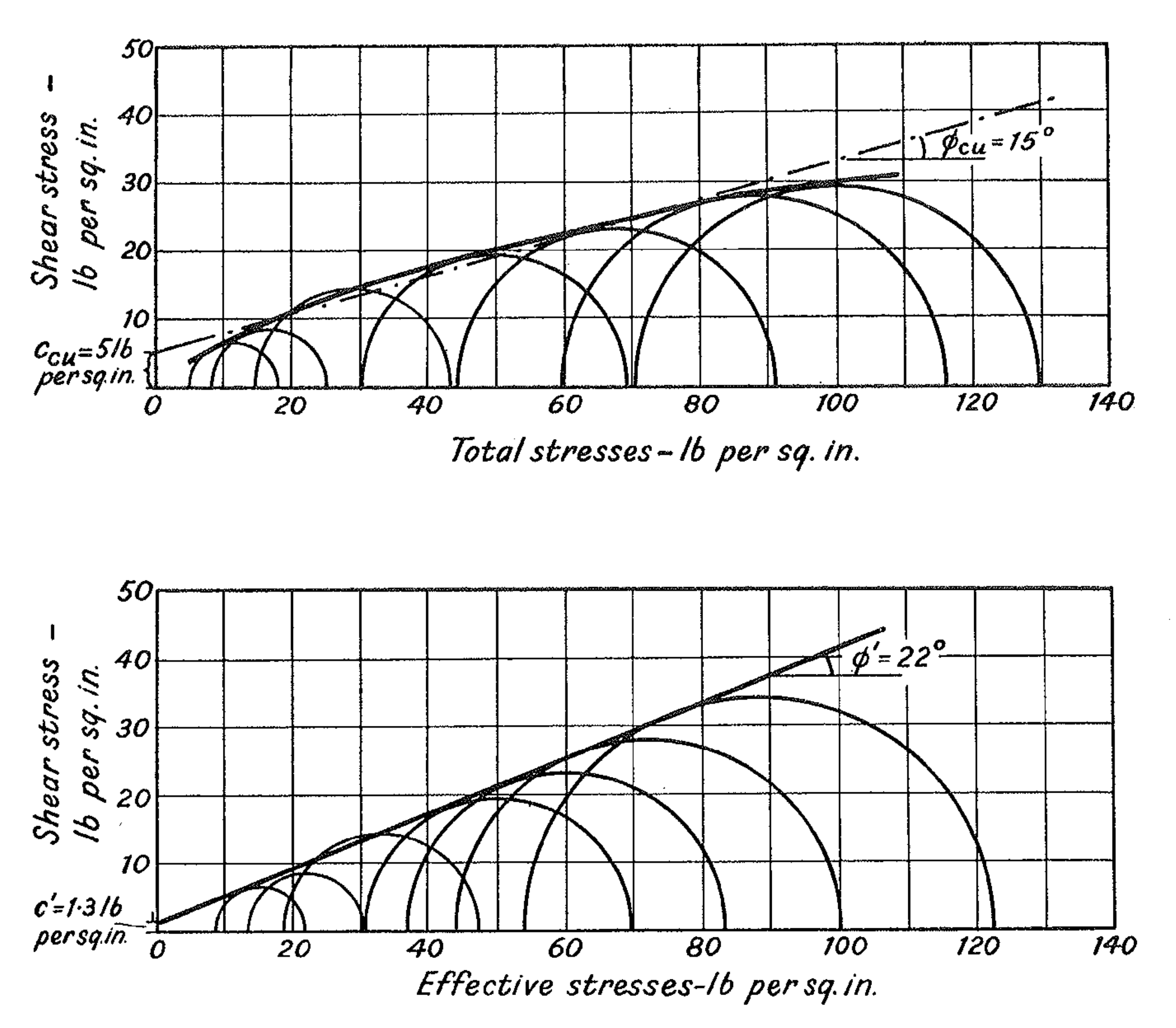


Fig. 75. Mohr envelope in terms of effective stress for consolidated-undrained tests on loose sand

- Testing on saturated sand with measurement of pore water pressure

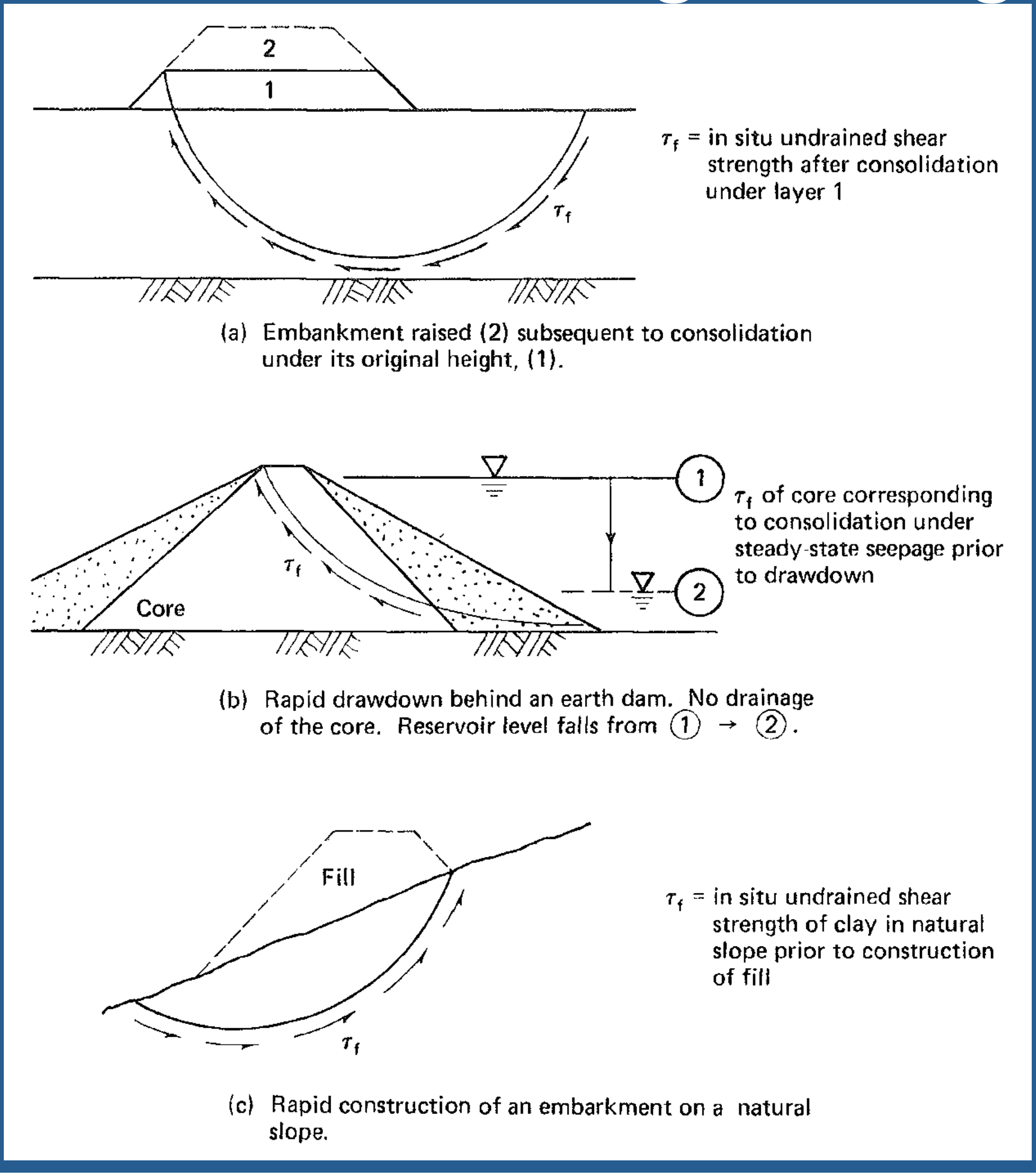


- Mohr envelopes in terms of both total and effective stresses for consolidated undrained tests on **normally consolidated clay** samples



- Mohr envelopes in terms of both total and effective stresses for consolidated undrained tests on **over-consolidated clay** samples

Use of CU Strength in Engineering Practice



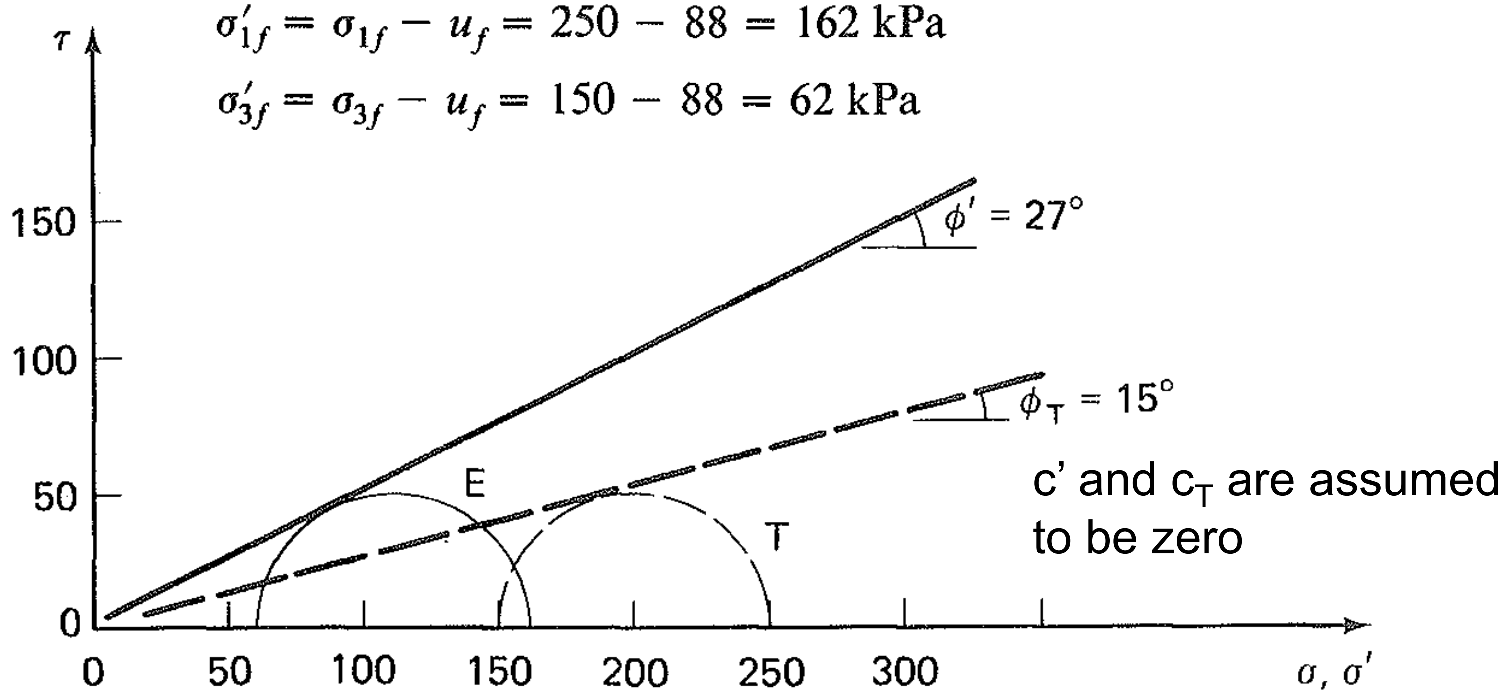
- Soils are fully consolidated and at equilibrium with the existing stress system
- Then, additional stresses are applied quickly

- Example Test for NC Clay:
  - Consolidated under a stress of 150 kPa
  - Then sheared undrained in axial compression
  - Principal stress difference at failure = 100 kPa
  - Induced pore water pressure at failure = 88 kPa

$$\sigma_{1f} = (\sigma_1 - \sigma_3)_f + \sigma_{3f} = 100 + 150 = 250\ \text{kPa}$$

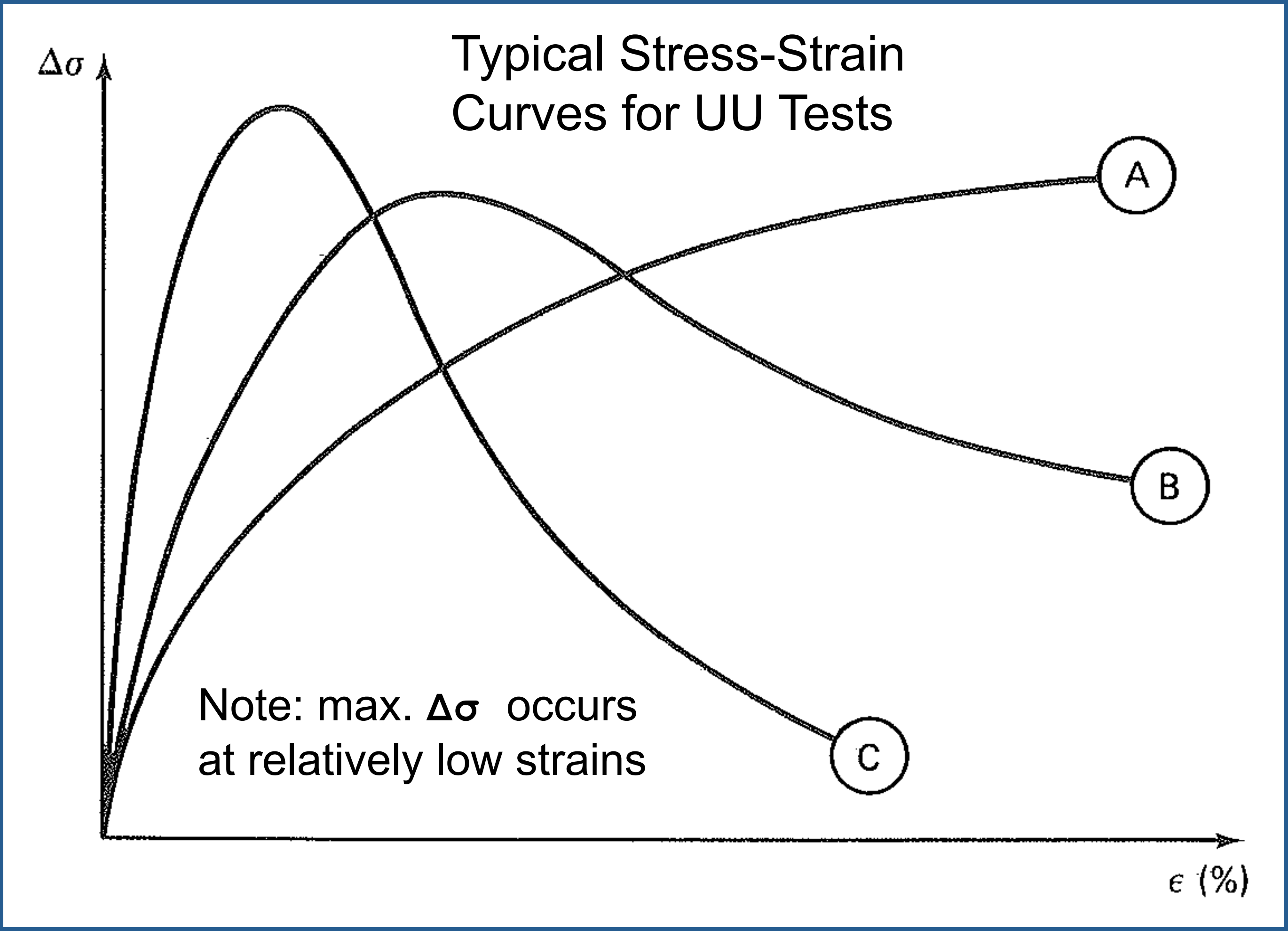
$$\sigma'_{1f} = \sigma_{1f} - u_f = 250 - 88 = 162\ \text{kPa}$$

$$\sigma'_{3f} = \sigma_{3f} - u_f = 150 - 88 = 62\ \text{kPa}$$



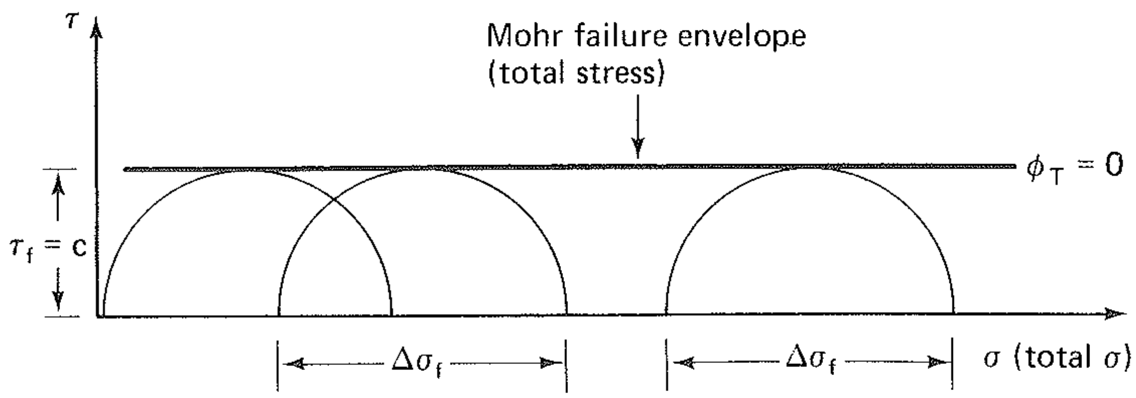
Unconsolidated – Undrained (UU) Test Behaviour

- Sample is placed in the triaxial cell with the drainage valves closed
- No consolidation occurs when confining pressure is applied
- Usually, pore water pressures are not measured
- Sample is loaded to failure in 10 to 20 minutes
    - Called Q-test (for “quick)
- Test is a total stress test and it yields the strength in terms of total stresses

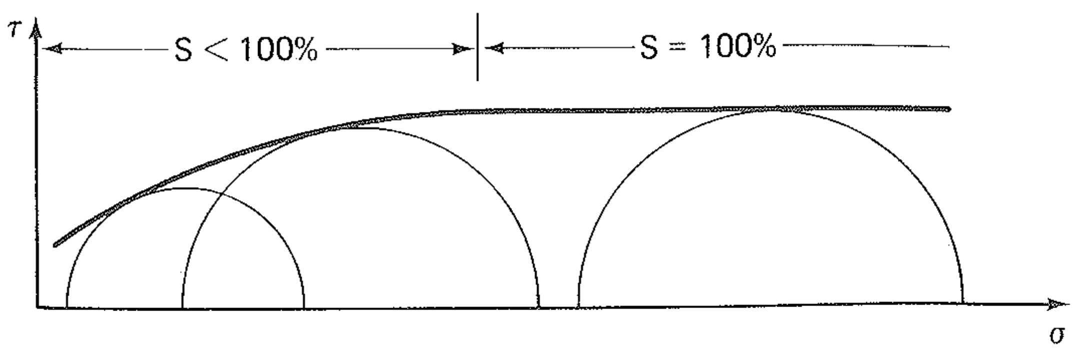


a) Remolded and some compacted clays
b) Medium sensitive undisturbed clay
c) Highly sensitive undisturbed clay

Typical Mohr failure envelopes for UU Tests



100% saturated clay



Partially saturated clay

All samples have same water content and void ratio – therefore the same undrained shear strength

Increased cell pressure compresses any air voids

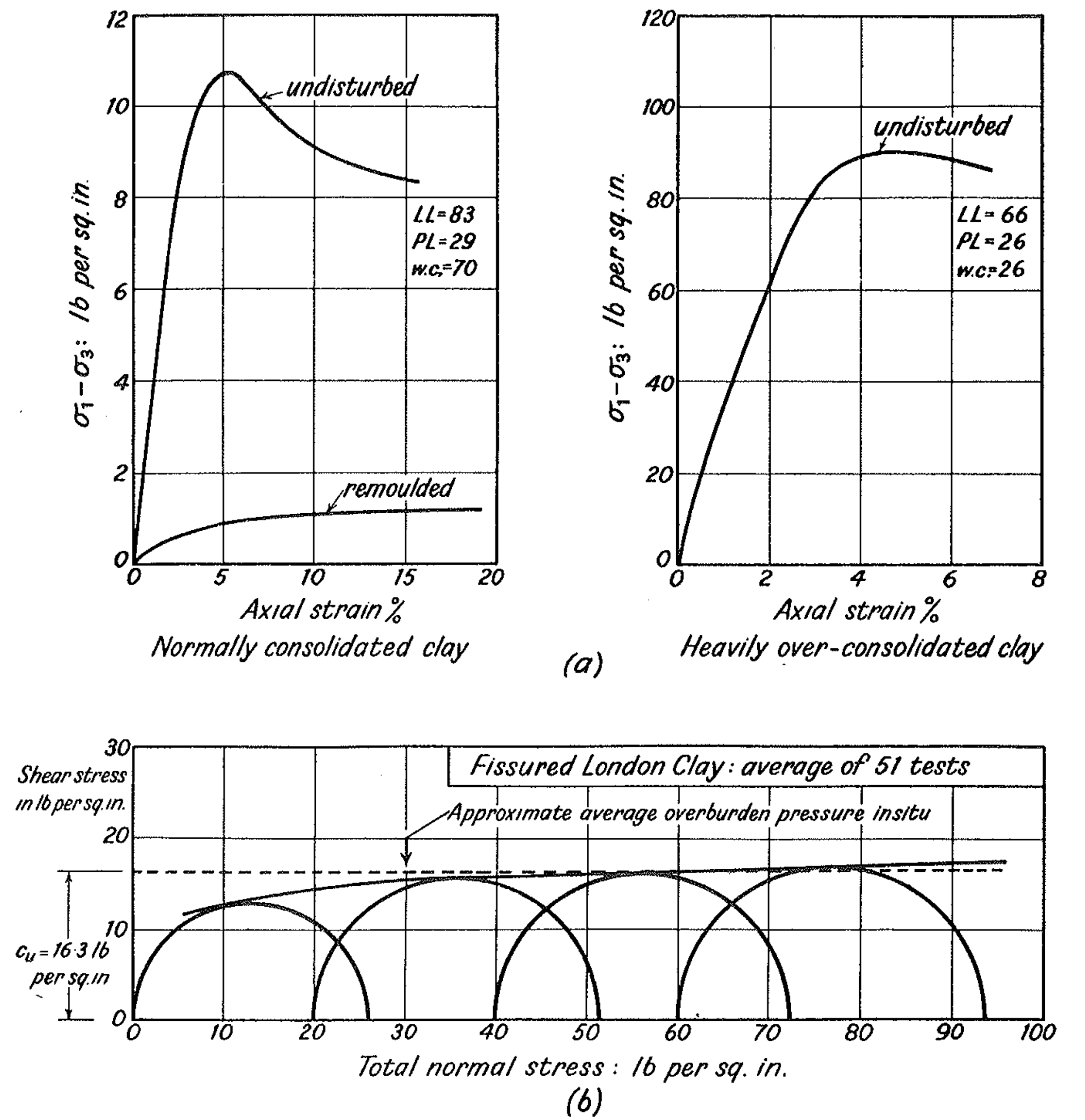
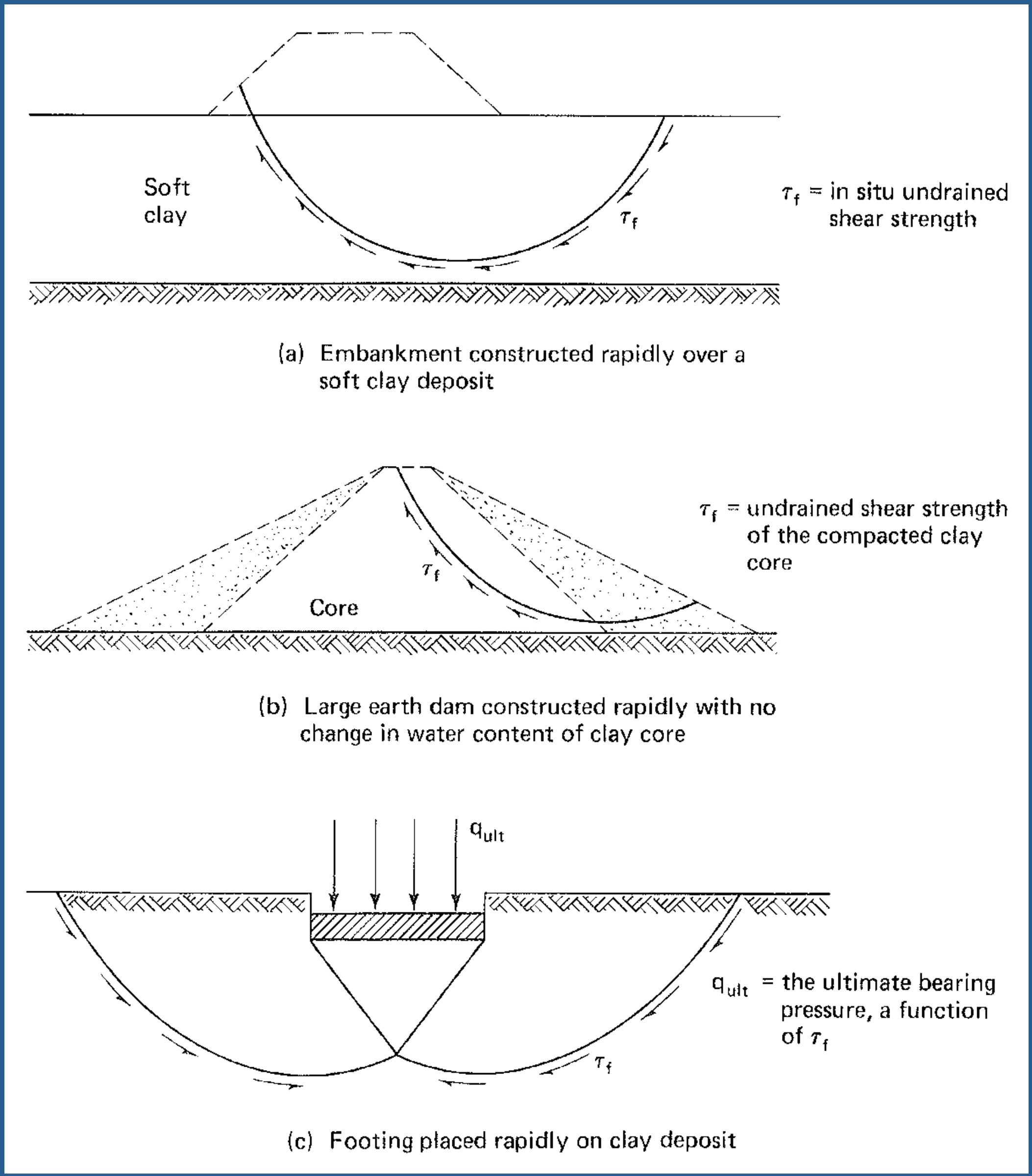


Fig. 66. Undrained tests

- Change in both strength and deformation after remolding an undisturbed sample of NC clay
- ϕ_u = 0 when results are plotted with respect to total stress

Use of UU Strength in Engineering Practice



- Engineering loading is assumed to take place so rapidly that Δu cannot dissipate or for consolidation to occur

- Change in total stress does not affect the in situ undrained shear strength

Designation: D 4767 – 04

Standard Test Method for
Consolidated Undrained Triaxial Compression Test for
Cohesive Soils[1]

Designation: D 2850 – 95 (Reapproved 1999)

Standard Test Method for
Unconsolidated-Undrained Triaxial Compression Test on
Cohesive Soils[1]

- Scope
- Terminology
- Significance of use
- Apparatus
- Test Specimens
- Procedure
- Calculation
- Report

ASTM D 2850: Unconsolidated - Undrained

- Terminology
  - Failure is defined as the maximum principal stress difference or that measured at 15% axial strain
- Test Specimens
  - Minimum diameter of 3.3 cm
  - Height to diameter ratio between 2 and 2.5
  - Procedures to prepare undisturbed and compacted samples
- Procedure
  - Axial strain: 1%/min for plastic and 0.3%/min for brittle
  - Test should last approximately 15 to 20 minutes

ASTM D 2850: Unconsolidated - Undrained

- Calculations
  - Axial strain, $\varepsilon = \Delta H/H_0$
  - Average cross-sectional area, $A = A_0/(1 - \varepsilon)$
  - Principal stress difference, $\sigma_1 – \sigma_3 = P/A$
  - Correction equations for:
    - If all around pressure changes specimen length
    - Correction for stiffness of the rubber membrane
- Report
  - Index properties of material being tested
  - Initial H_0, Diam., γ_d, void ratio, w.c., saturation, etc.
  - Rate of axial strain, strain and stresses at failure
  - Stress – strain curve and failure sketch

ASTM D 4767: Consolidated - Undrained

- Terminology
  - Failure is defined as the maximum principal stress difference or that measured at 15% axial strain, or
  - Maximum stress obliquity, σ'_1/σ'_3
- Test Specimens
  - Same as for UU test
- Procedure
  - Saturation procedure to ensure:
    Pore Pressure Parameter, $B > 0.95$ ($B = \Delta u/\Delta\sigma_3$)
  - Consolidation procedures to ensure specimen reaches equilibrium in a drained state at the effective consolidation stress required

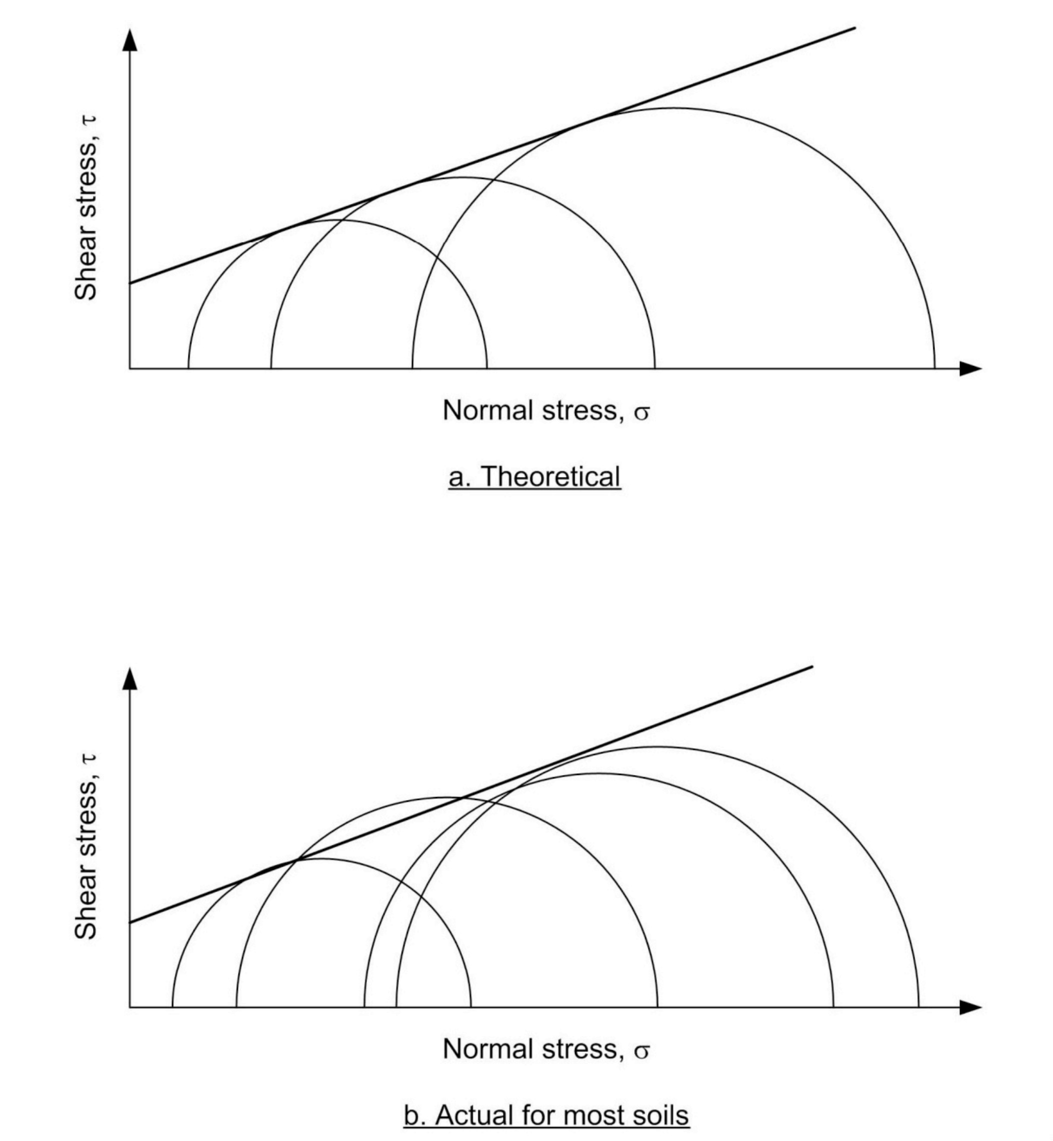
ASTM D 4767: Consolidated - Undrained

- Procedure
  - Axial loading to produce equalization of pore water pressures throughout the sample at failure
  - Assuming failure will occur at 4% axial strain
    - Rate of strain = 4% / (10 x t_{50})
  - Details for measuring pore water pressures
- Calculations
  - Equations for height and area after consolidation (H_c & A_c)
  - Axial strain, $\varepsilon = \Delta H/H_c$
  - Average cross-sectional area, $A = A_c/(1 - \varepsilon)$
  - Principal stress difference, $\sigma_1 - \sigma_3 = P/A$

ASTM D 4767: Consolidated - Undrained

- Calculations
  - Calculate effective stresses based on **Δu** measured
  - Correction equations for:
    - Correction for filter paper strips
    - Correction for stiffness of the rubber membrane
- Report
  - Index properties measured for material being tested
  - Effective consolidation stress, t_{50}
  - H_c , A_c ,Diam., γ_d, void ratio, w.c., saturation after consolidation
  - Rate of axial strain, strain and stresses at failure
  - Stress – strain curve and failure sketch

Interpreting Scatter in Test Results



- US Army Corps of Engineers Procedure: Draw strength envelope in a position such that data from two-thirds of the tests lie above the failure envelope

- Primary References:
  - A.W. Bishop and D.J. Henkel, 1962. **The Triaxial Test**
  - R.D. Holtz and W.D. Kovacs, 1981. **Introduction to Geotechnical Engineering**
  - US Army Corps of Engineers: **Engineering and Design Manual: Slope Stability, Appendix D Shear Strength Characteristics** (EM 1110-2-1902, Oct 31, 2003)
  - ASTM D2850 and D4767 **Standard Test Methods**

Summary / Questions

- Lecture Topics
  - Brief overview of direct shear test
  - Determine shear strength parameters from triaxial testing:
    - Unconsolidated – Undrained
    - Consolidated – Undrained
  - Triaxial test setup and behaviour
  - Use of results in practice
  - Examples of triaxial test results