SOIL MECHANICS (CE-505)

Lecture 15:

Shear Strength of Soil

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SHEAR STRENGTH OF SOIL

The *shear strength* of a soil mass is the internal resistance per unit area that the soil mass can offer to resist failure and sliding along any plane inside it.

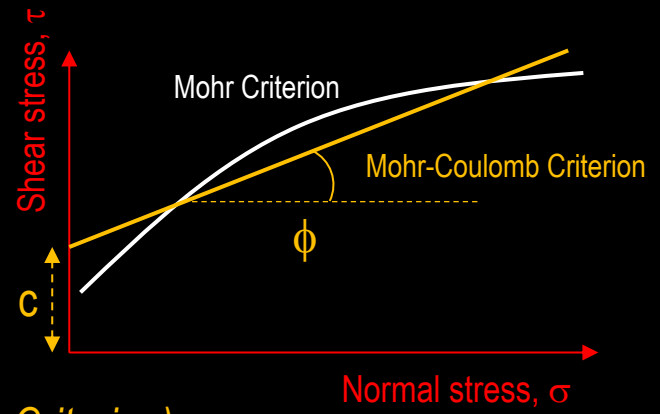
- The safety of any geotechnical structure is dependent on the strength of the soil.
- If the soil fails, a structure founded on it can collapse, endangering lives and causing economic damage. The strength of soils is therefore of paramount importance to geotechnical engineers.
- Shear strength is required to make estimates of the load-bearing capacity of soils and the stability of geotechnical structures, and in analyzing the stress–strain characteristics of soils.

MOHR-COULOMB FAILURE CRITERION

As per Mohr (1900), a material fails because of a critical combination of normal stress and shearing stress and not from either maximum normal or shear stress alone.

The functional relationship between normal stress and shear stress on a failure plane can be expressed in the following form:

$$\tau_f = f(\sigma)$$



This failure envelope defined by a curved line.

For most soil mechanics problems:

- It is approximated to straight line
- Modified by using Coulomb criterion

$$\tau_f = c + \sigma \tan\phi \text{ (Mohr-Coulomb Criterion)}$$

where, ϕ = angle of internal friction

c = cohesion

σ = normal stress on the failure plane

τ_f = shear strength

MOHR-COULOMB FAILURE CRITERION (CONTD.)

In saturated soils, $\sigma = \sigma' + u$

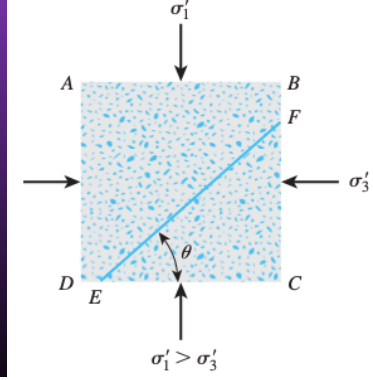
The Mohr-Coulomb Criterion in terms of effective stress:

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

where, c' = cohesion, and ϕ' = angle of internal friction based on effective stress

The value of c' for sand and inorganic silt is 0. For normally consolidated clays, *c'* can be approximated at 0. Over-consolidated clays have values of *c'* that are greater than 0. The angle of friction, ϕ', is sometimes referred to as the *drained angle of friction.*

INCLINATION OF FAILURE PLANE CAUSED BY SHEAR



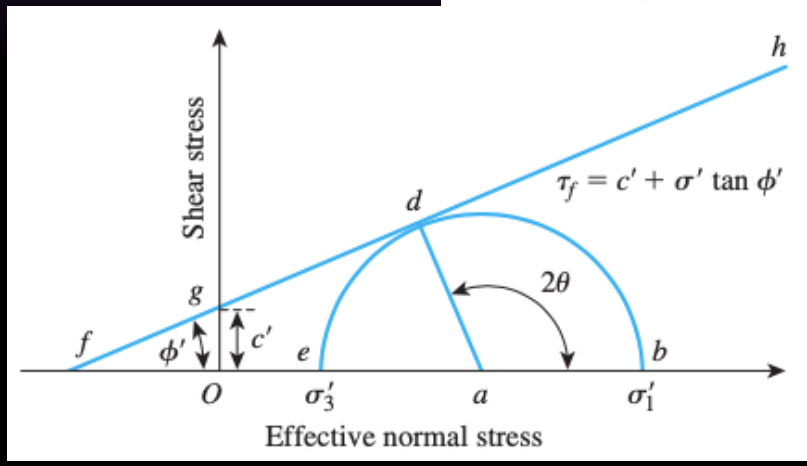
$$2\theta = 90 + \phi' \rightarrow \theta = 45 + \frac{\phi'}{2}$$

$$\sin\phi' = \frac{ad}{fa}$$

$$fa = fO + Oa = c'\cot\phi' + \frac{\sigma'_1 + \sigma'_3}{2}$$

$$ad = \frac{\sigma'_1 - \sigma'_3}{2}$$

$$\therefore \sin\phi' = \frac{\frac{\sigma'_1 - \sigma'_3}{2}}{c'\cot\phi' + \frac{\sigma'_1 + \sigma'_3}{2}}$$



$$\sigma'_1 = \sigma'_3\left(\frac{1+\sin\phi'}{1-\sin\phi'}\right) + 2c'\left(\frac{\cos\phi'}{1-\sin\phi'}\right)$$

However, $\frac{1+\sin\phi'}{1-\sin\phi'} = tan^2\left(45 + \frac{\phi'}{2}\right)$, and $\frac{\cos\phi'}{1-\sin\phi'} = tan\left(45 + \frac{\phi'}{2}\right)$

Thus

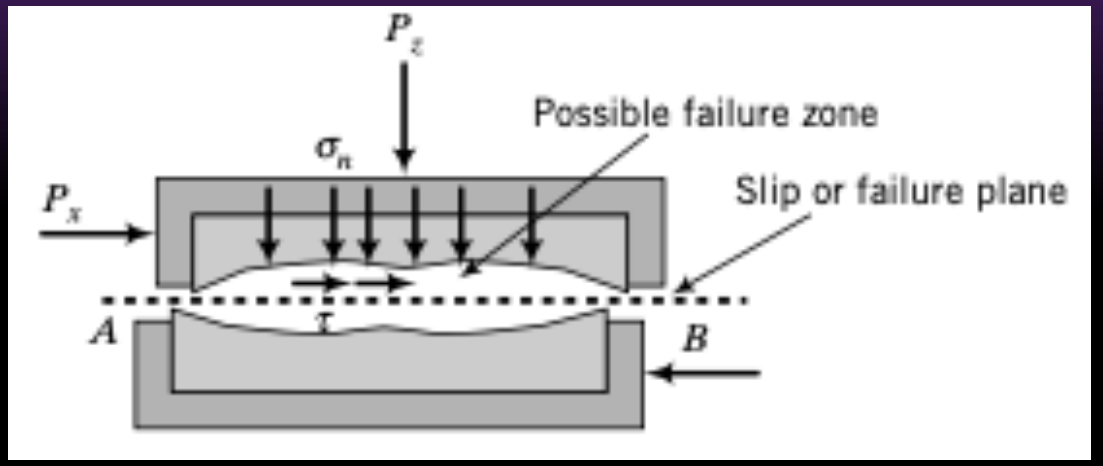
$$\boldsymbol{\sigma'_1 = \sigma'_3 tan^2\left(45 + \frac{\phi'}{2}\right) + 2c' tan\left(45 + \frac{\phi'}{2}\right)}$$

LABORATORY TEST FOR DETERMINATION OF SHEAR STRENGTH PARAMETERS

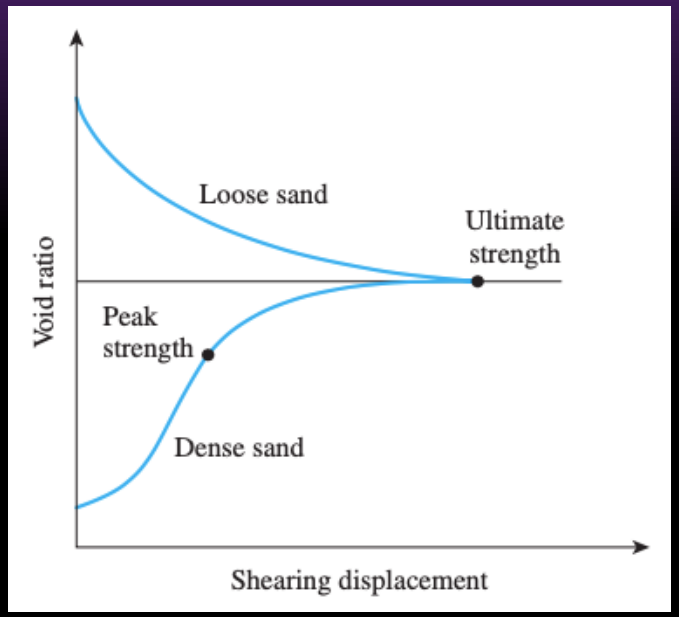
- Direct Shear Test
- Triaxial Shear Test (Sample Preparation, De-Airing Procedure, Triaxial Shear Test)
- Unconfined Compression Test
- Vane Shear Test

DIRECT SHEAR TEST

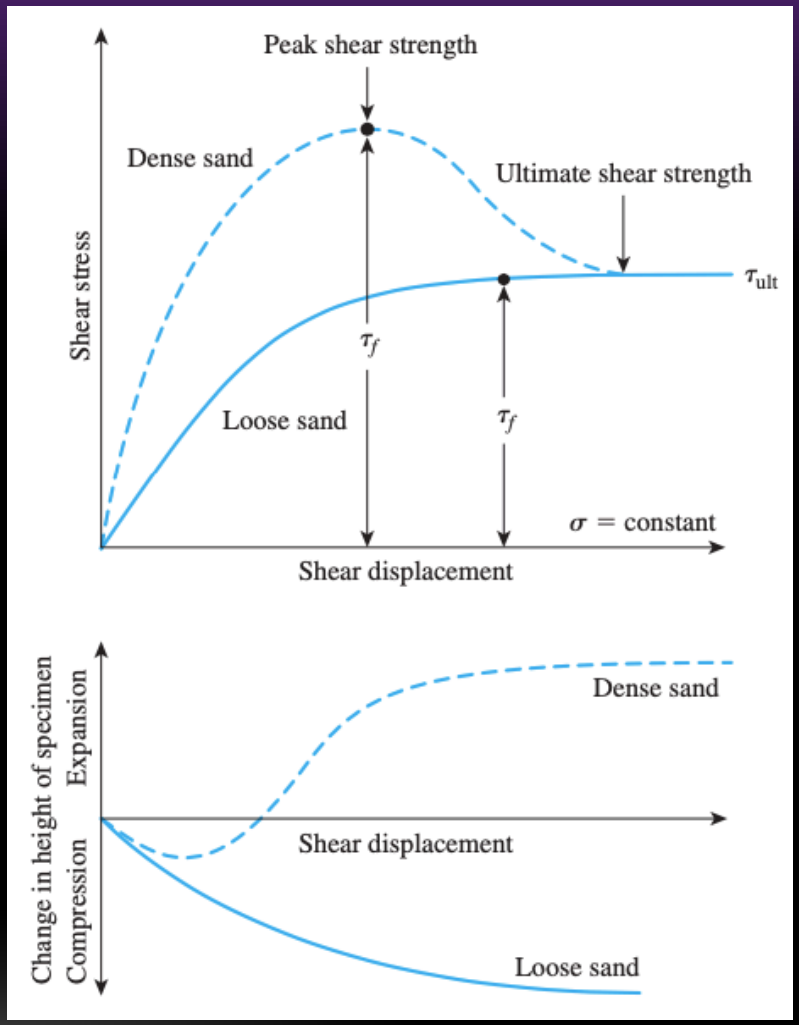
- Shear box



DIRECT SHEAR TEST PLOTS

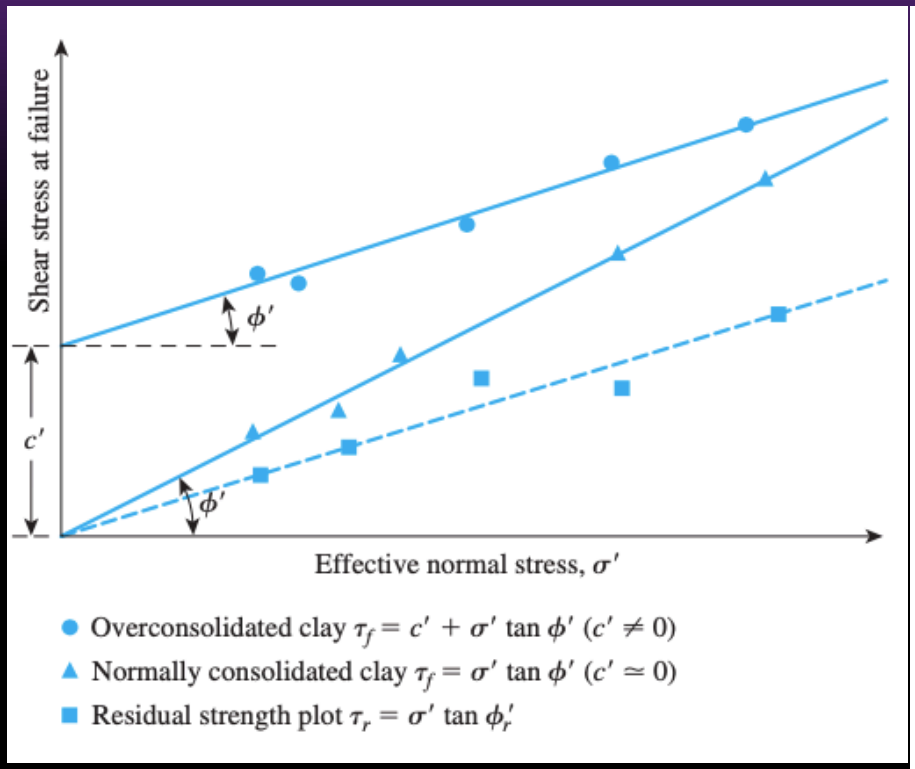


Nature of variation of void ratio with shearing displacement

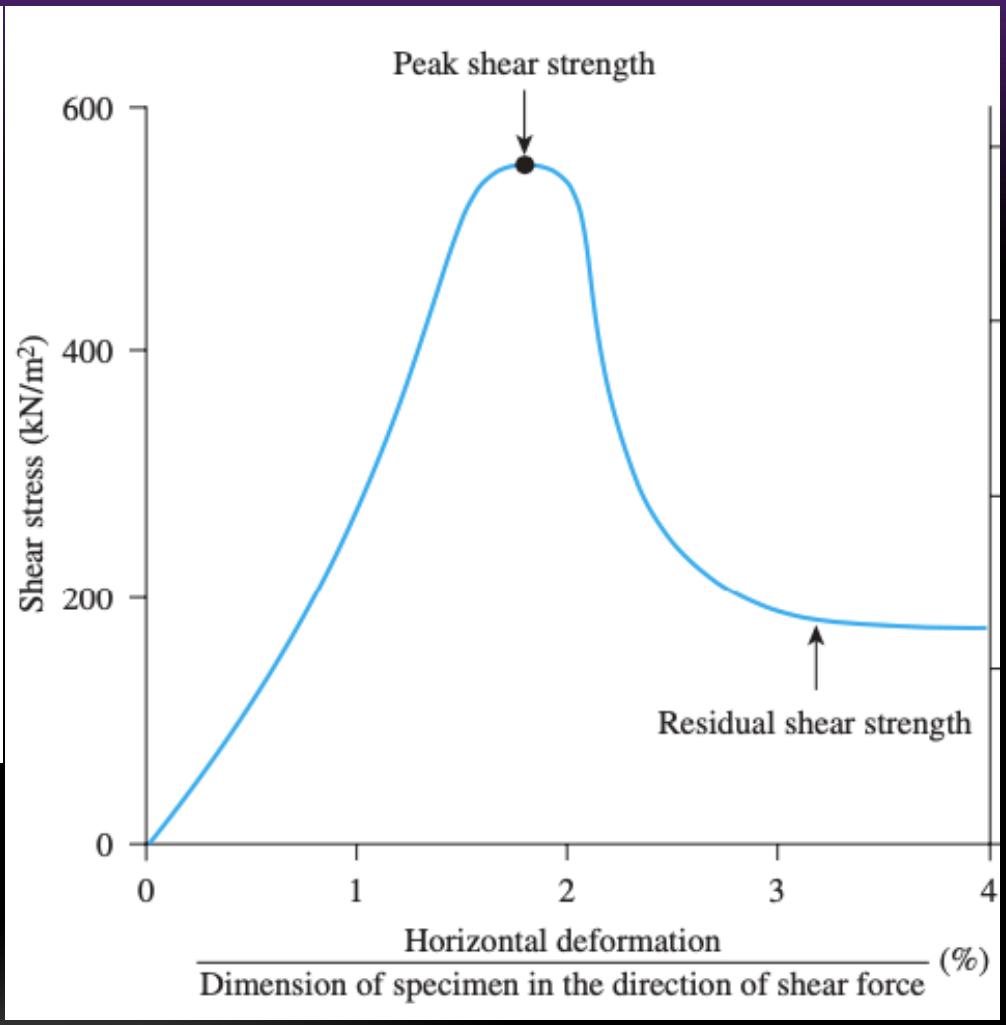


Plot of shear stress and change in height of specimen against shear displacement for loose and dense dry sand (direct shear test)

DIRECT SHEAR TEST PLOTS



Failure envelope for clay obtained from drained direct shear tests



Results of a drained direct shear test on an overconsolidated clay

PROBLEMS

Following are the results of four drained direct shear tests on an *overconsolidated clay:*

- Diameter of specimen = 50 mm
- Height of specimen = 25 mm

Test No.	Normal Force, N (N)	Shear Force at Failure, S_{peak} (N)	Residual Shear Force, $S_{residual}$ (N)
1	150	157.5	44.2
2	250	199.9	56.6
3	350	257.6	102.9
4	550	363.4	144.5

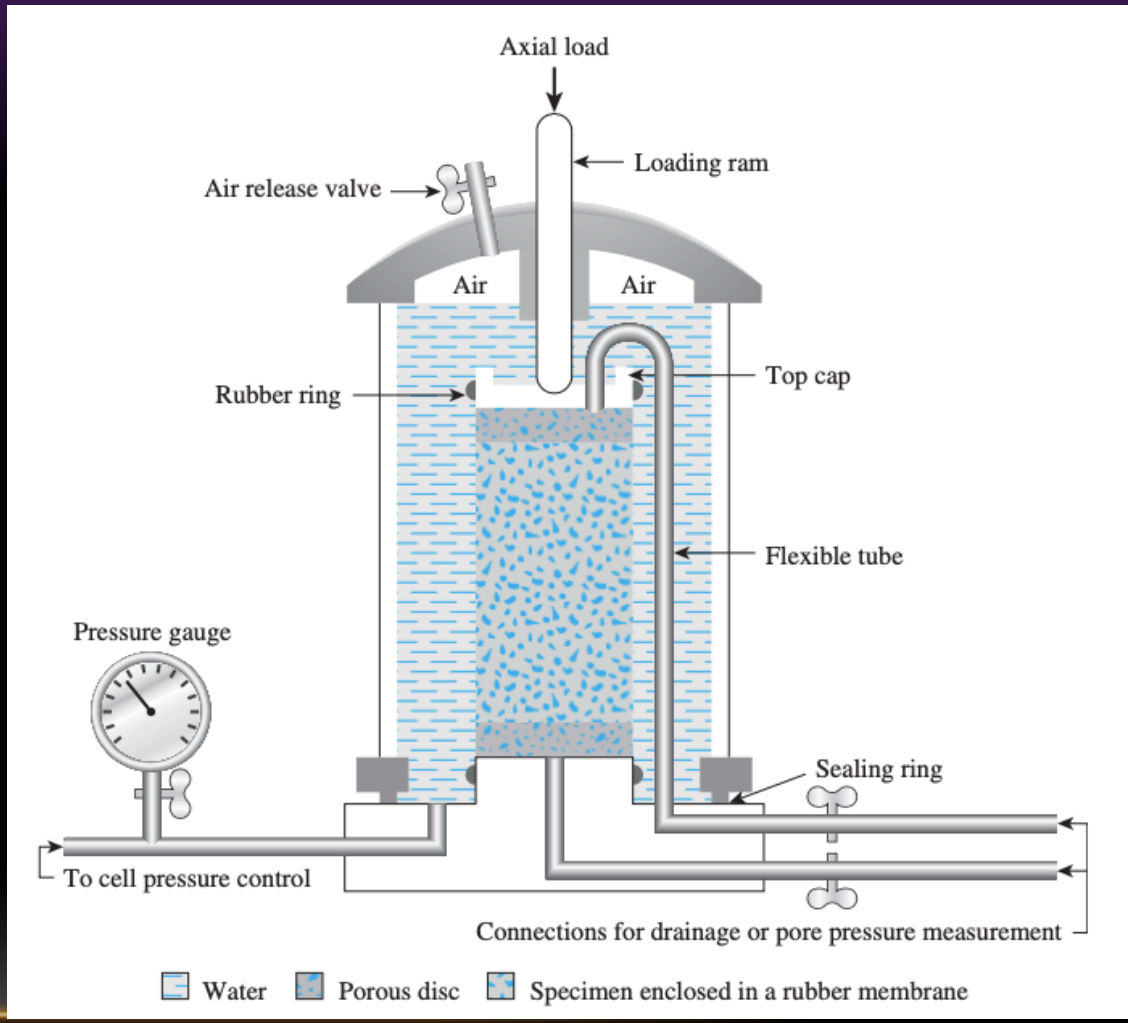
Determine the relationships for *peak shear strength* (τ_f) and *residual shear strength* (τ_r).

TRIAXIAL SHEAR TEST

Triaxial Setup

Drainage Conditions:

- Consolidated-drained test or drained test (CD test)
- Consolidated-undrained test (CU test)
- Unconsolidated-undrained test or undrained test (UU test)



CONSOLIDATED DRAINED TEST (CD TEST)

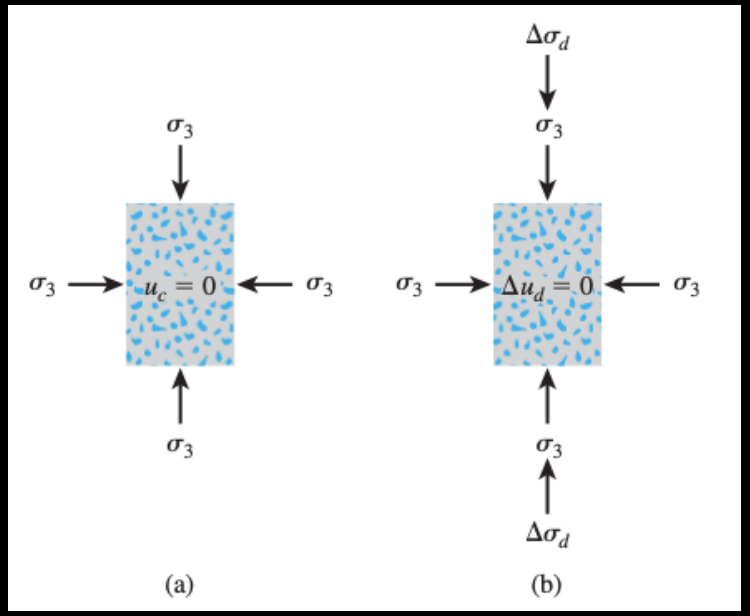
The saturated specimen first is subjected to an all around confining pressure, σ_3, by compression of the chamber fluid. As confining pressure is applied, the pore water pressure of the specimen increases by u_c (if drainage is prevented). This increase in the pore water pressure can be expressed as a nondimensional parameter in the form

$$B = \frac{u_c}{\sigma_3}$$

where B = Skempton's pore pressure parameter

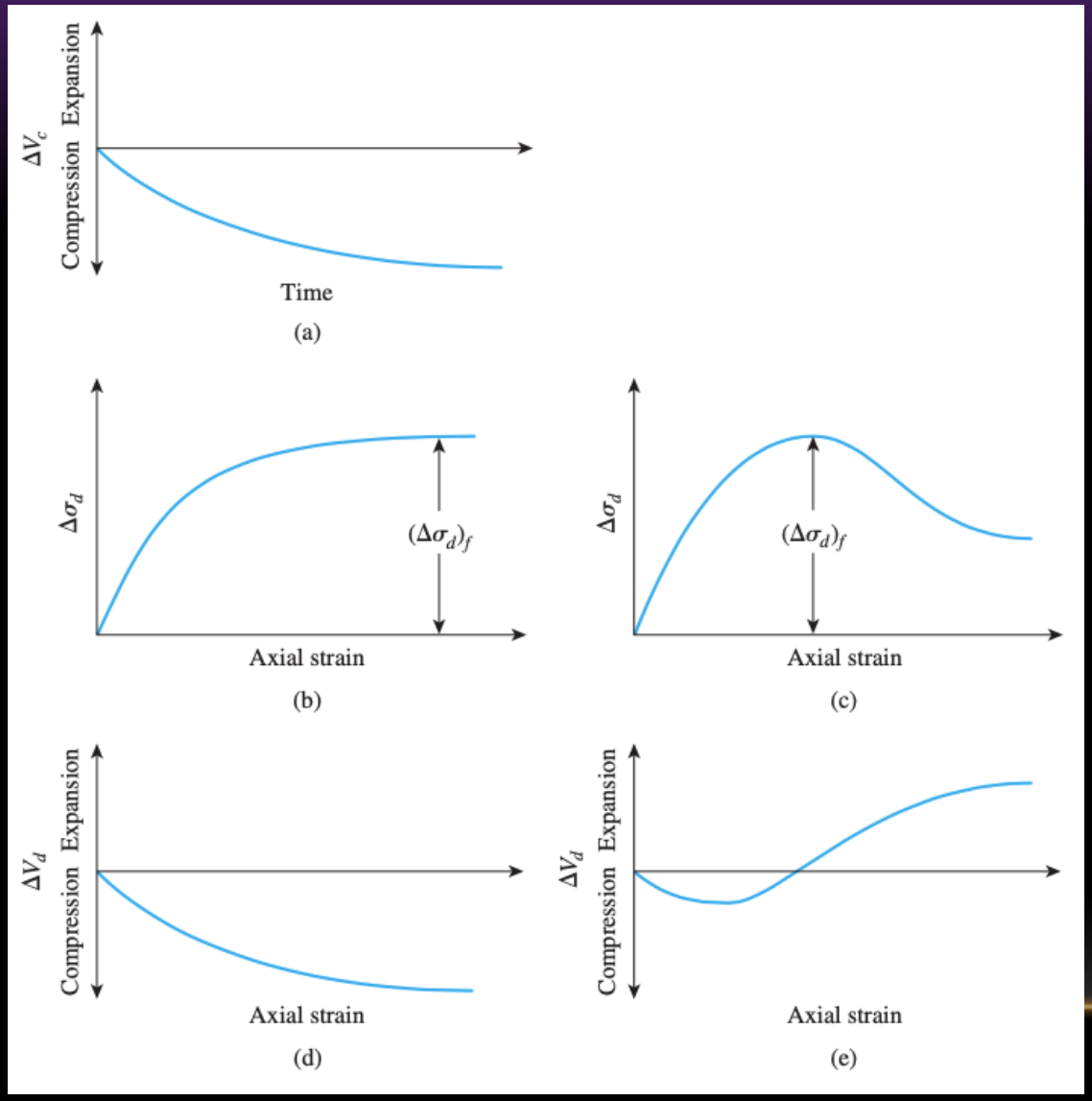
For saturated soft soils, B ≃1;

For saturated stiff soils, B can be less than 1.



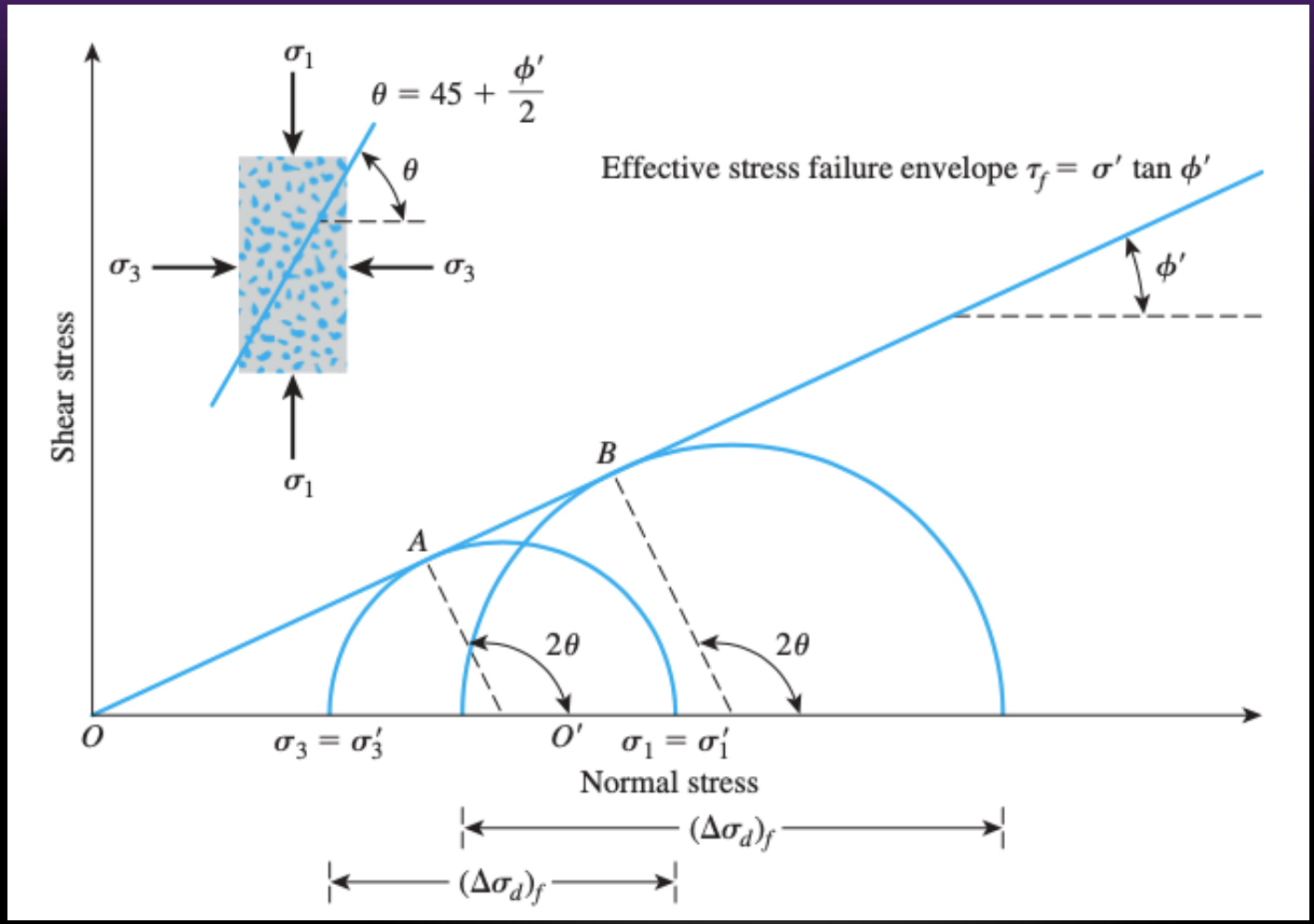
(a) specimen under chamber- confining pressure; (b) deviator stress application

CONSOLIDATED-DRAINED TRIAXIAL TEST



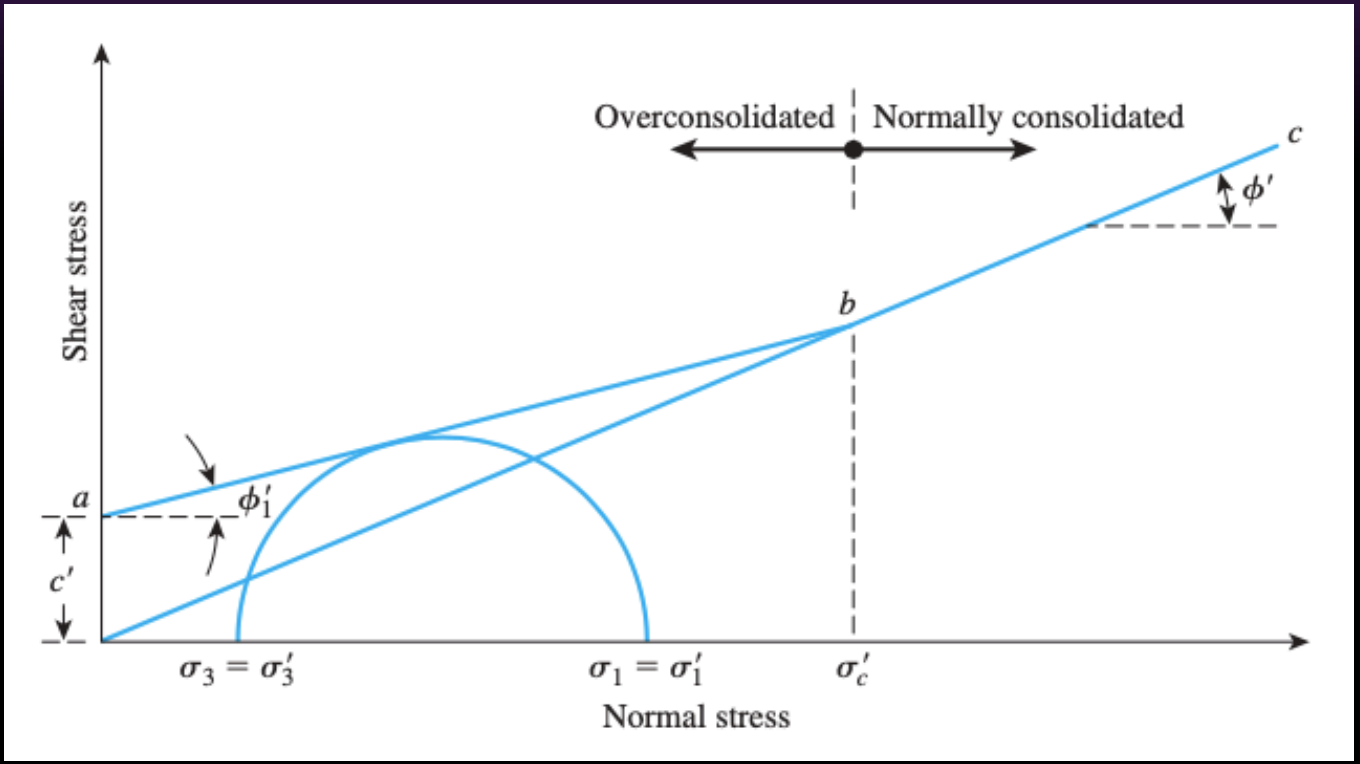
(a) volume change of specimen caused by chamber-confining pressure;
(b) deviator stress vs strain in the vertical direction for loose sand and normally consolidated clay;
(c) deviator stress vs strain in the vertical direction for dense sand and overconsolidated clay;
(d) volume change in loose sand and normally consolidated clay during deviator stress application;
(e) volume change in dense sand and overconsolidated clay during deviator stress application

CONSOLIDATED-DRAINED TRIAXIAL TEST



Effective stress failure envelope from drained tests on sand and normally consolidated clay

CONSOLIDATED-DRAINED TRIAXIAL TEST



Effective stress failure envelope for overconsolidated clay

PROBLEMS

Q.1. A consolidated-drained triaxial test was conducted on a normally consolidated clay. The results are as follows:

σ_3 = 110 kPa; $(\Delta\sigma_d)_f$ = 172 kPa

Determine (a) Angle of friction, ϕ', (**b)** Angle θ that the failure plane makes with the major principal plane.

Q.2. Refer to Q.1., (**a)** Find the normal stress σ' and the shear stress τ_f on the failure plane. **(b)** Determine the effective normal stress on the plane of maximum shear stress.

Q.3. The equation of the effective stress failure envelope for normally consolidated clayey soil is $\tau_f = \sigma'$ tan 30. A drained triaxial test was conducted with the same soil at a chamber-confining pressure of 70 kPa. Calculate the deviator stress at failure.

Q.4. The results of two drained triaxial tests on a saturated clay follow:

Specimen-I: σ_3 = 70 kPa; $(\Delta\sigma_d)_f$ = 130 kPa

Specimen-II: σ_3 = 160 kPa; $(\Delta\sigma_d)_f$ = 223.5 kPa

Determine the shear strength parameters.