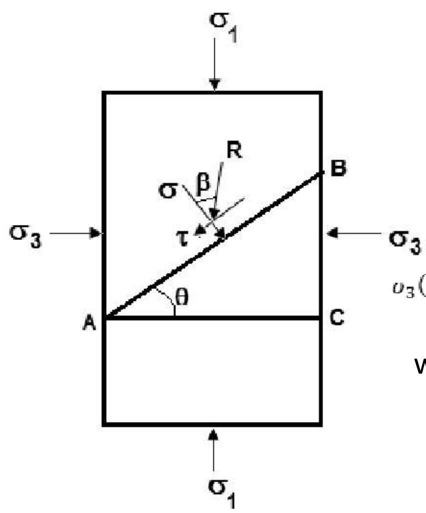
SHEAR STRENGTH

- The shear strength of a soil is its maximum resistance to shear stresses just before failure.
- Soils are seldom subject to direct shear. However, shear stresses develop when the soil is subjected to direct compression.
- The shear failure of a soil mass occurs when the shear stresses induced due to applied compressive loads exceed the shear strength of the soil.
- Failure in soils occurs by the relative movements of soil particles.

STRESS SYSTEMS WITH PRINCIPAL PLANES PARALLEL TO COORDINATE AXES

- At every point in a stressed body, there exist three mutually perpendicular planes on which the shear stresses are zero.
- These planes are known as principal planes.
- The plane with maximum compressive stress (σ_1) is known as the major principal plane, and that with minimum compressive stress (σ_3) is known as minor principal plane.
- The third plane is subjected to a stress value in between σ_1 and σ_3, and is known as the intermediate principal plane.
- The critical stress values generally occur on planes normal to the intermediate plane.

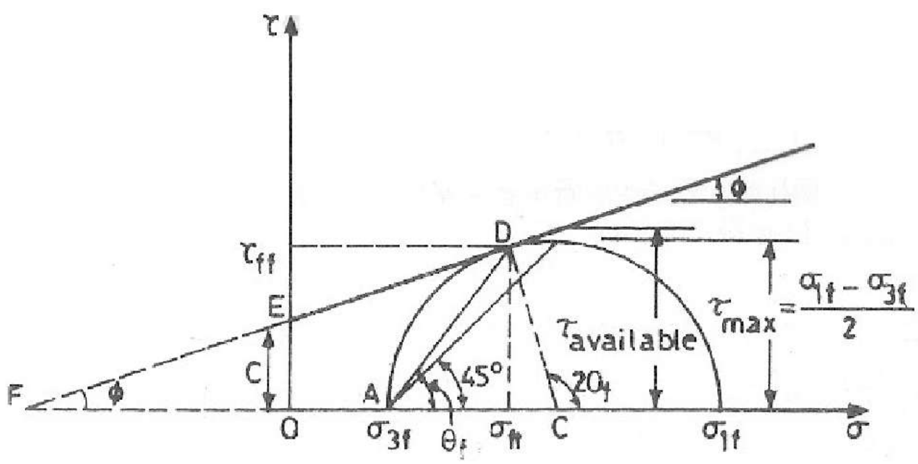


AB is a plane of unit width perpendicular to the plane of the paper, inclined at θ to the major principal plane.

Resolving the forces on the wedge ABC in the horizontal direction

$$\sigma_3(BC \times 1) = \sigma\,(AB \times 1)\sin\theta - \tau\,(AB \times 1)\cos\theta$$

where σ = normal stress on AB
τ = shear stress on AB

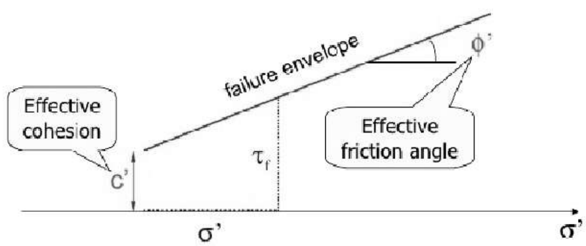


Mohr-Coulomb Failure Criterion

(in terms of effective stresses)

τ

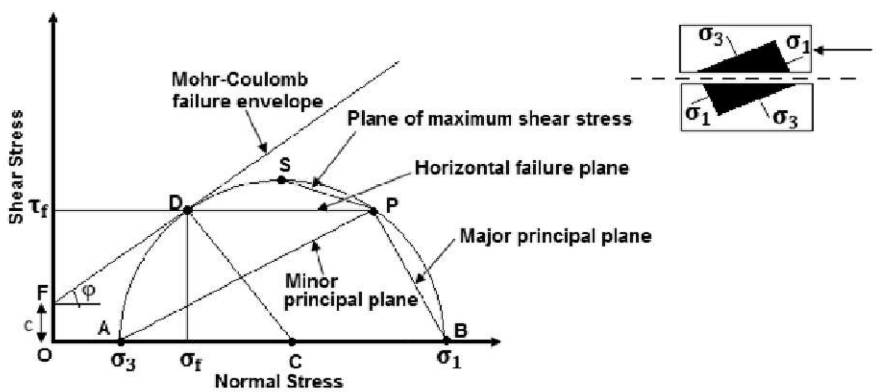
$$\tau_f = c' + \sigma' \tan \phi'$$

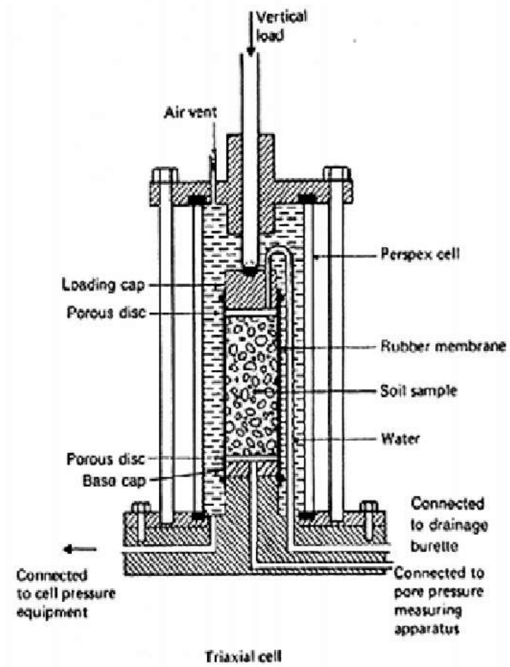


$$\sigma' = \sigma - u$$

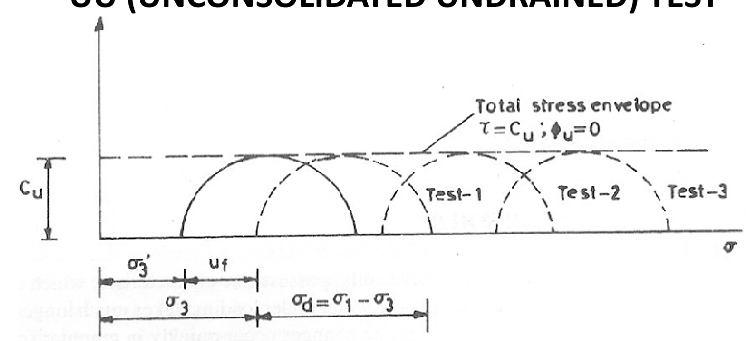
u = pore water pressure

τ_f is the maximum shear stress the soil can take without failure, under normal effective stress of σ'.





UU (UNCONSOLIDATED UNDRAINED) TEST



If three tests are conducted on identical samples, each with an increasing confining pressure, **the Mohr circles at failure for all the tests will have the same diameter**.

The total stress failure envelope (line tangential to all the Mohr circles) will have a zero slope (horizontal line) and intersects the τ-axis at c_u. This is known as the $\varphi = 0$ condition.

Saturated clays loaded under undrained conditions fail under $\varphi = 0$ condition.

UU (UNCONSOLIDATED UNDRAINED) TEST

The **failure envelope cannot be drawn in terms of effective stresses for a saturated soil under undrained conditions** due to the fact that:

An increase in confining pressure results in an equal increase in pore water pressure and hence **only one Mohr circle can be drawn in terms of effective stresses and it has the same diameter as the total stress Mohr circle.**

In the UU test, if pore water pressure is measured, the test is designated by $\overline{UU}$

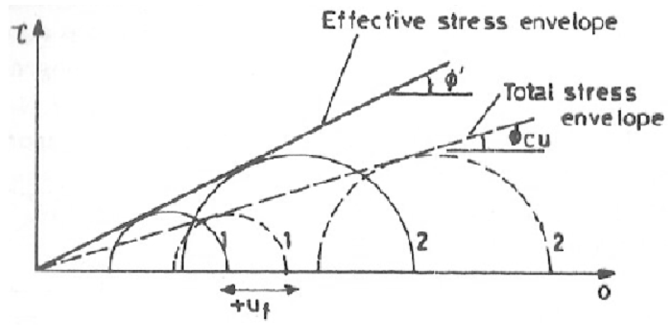
The shear strength equation may be written as $\tau_f = c_{uu} = \frac{\sigma_1 - \sigma_3}{2}$

CU (CONSOLIDATED UNDRAINED) TEST

- Drainage is allowed during cell pressure application or consolidation phase.
- At the end of the first stage there is no excess pore water pressure in the specimen.
- During the second phase or shearing phase, without allowing further drainage, deviator stress is increased keeping cell pressure constant. It is also called as an **R-test.**
- The pore pressure is measured during the deviator stress application.
- When the specimen is sheared under undrained condition, the excess pore water that develops can be positive or negative.

CU (CONSOLIDATED UNDRAINED) TEST

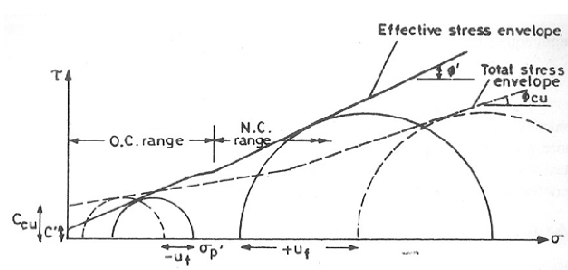
NORMALLY CONSOLIDATED CLAYS



- There is a **tendency towards volume decrease** under undrained conditions during shear (that is, for pore water to escape).
- **If this volume change is not allowed to occur, positive pore water pressures develop.** Consequently, effective stress Mohr circles lie to the left of total stress circles (i.e**. effective stress < total stress**).
- **Both effective stress and total stress failure envelopes for the normally consolidated clays are straight lines that pass through the origin** i.e. $c_{cu} = c' = 0$. Also, $\varphi_{cu} \cong 1/2\ \varphi'$.

CU (CONSOLIDATED UNDRAINED) TEST

OVER CONSOLIDATED CLAYS



- There **is tendency towards volume increase** under undrained conditions during shear.
- If this **volume increase** is **not allowed** to occur, **negative pore water pressures develop.**

- **Consequently, effective stress Mohr circles lie to the right of total stress circles (i.e. effective stress > total stress).**
- **The failure envelope for an overconsolidated clay is not a straight line but a curve.** An overconsolidated clay shows a cohesion intercept c_{cu} in terms of total stresses and c' in terms of effective stresses. $\mathbf{c_{cu}}$ **is always greater than c'.** φ_{cu} can be slightly greater than or smaller than φ'.

CU (CONSOLIDATED UNDRAINED) TEST

SHEAR STRENGTH

The shear strength equation may be written as

For normally consolidated clay

In terms of total stresses, $\tau_f = \sigma \tan \varphi_{cu}$

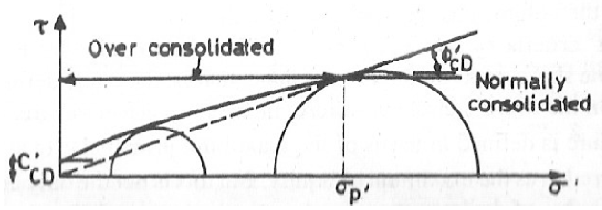
In terms of effective stresses, $\tau_f = \sigma' \tan \varphi'_{cu}$

For over consolidated clay

In terms of total stresses, $\tau_f = c_{cu} + \sigma \tan \varphi_{cu}$

In terms of effective stresses, $\tau_f = c'_{cu} + \sigma' \tan \varphi'_{cu}$

CD (CONSOLIDATED DRAINED) TEST



For NC clay

$\tau_f = c_{cu} + \sigma \tan \varphi_{cu}$

For OC clay

$\tau_f = c'_{cu} + \sigma' \tan \varphi'_{cu}$

- The drainage valve is kept open in both the phases of the test.
- During the shearing phase, the rate of loading must be slow enough to ensure no excess pore water pressure develops.
- Therefore, **at any stage of the test, the total stresses are the effective stresses**. Thus, **this is an effective stress test**. It is also called an **S- or Slow test**.
- For the normally consolidated clay, the failure envelope is a straight line that passes through the origin.
- For the over-consolidated clays, the failure envelope is curved and gives an a value of effective cohesion.

UNCONFINED COMPRESSION TEST

- This is a special case of triaxial test carried out at zero cell pressure ($\sigma_3 = 0$). The Perspex cell and latex membrane are not required.
- A cylindrical soil sample is subjected to gradually increasing axial stress until it fails.
- **Since the specimen is laterally unconfined, the test is known as unconfined compression test.**
- The axial or vertical compressive stress is the major principal stress and the other two principal stresses are zero.
- Since the test is quick, water is not allowed to drain out of the sample. Hence it is undrained test or quick test.
- The test applicable only to soils for which $\varphi_u = 0$ (fully saturated non-fissured clays).
- **The test produces only one Mohr circle which is tangential to the τ-axis.**

The relationship between principal stresses at failure is given by

$$\sigma_{1f} = \sigma_{3f}\left(\frac{1+\sin\varphi}{1-\sin\varphi}\right) + 2c\sqrt{\frac{1+\sin\varphi}{1-\sin\varphi}}$$

As $\sigma_{3f} = 0$

$$\sigma_{1f} = 2c_u\sqrt{\frac{1+\sin\varphi}{1-\sin\varphi}}$$

c_u indicates that the test is undrained.

As saturated clays loaded under undrained conditions fail under $\varphi = 0$ condition

$$\sigma_{1f} = 2c_u$$

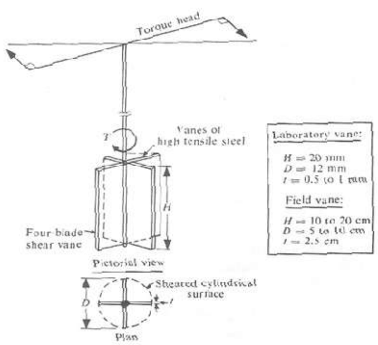
σ_{1f} is called the unconfined compressive strength and is denoted by q_u.

$$\therefore\ q_u = 2c_u$$

The undrained shear strength of saturated clay is $\tau = c_u = \dfrac{q_u}{2}$

VANE SHEAR TEST

- Used for determining the shear strength of soft saturated clay deposits in the field as undisturbed sampling of such soils is not possible.
- Shear vane consists of four steel blades welded at right angles to a steel rod. The vane pushed gently into the soil up to the required depth or at the bottom of the bore hole.
- Torque is gradually applied to the upper end of the torque rod until the soil fails in shear, due to rotation of the vane.
- Torque is measure by noting the angle of twist.
- Shear failure occurs over the surface and ends of the cylinder having a diameter "d" equal to the diameter of the vane.



Shear failure occurs over the surface and the ends of a cylinder having a diameter *D*, equal to the diameter of the vane.

The total shearing resistance of the soil at failure is

$$= \pi D H c_u + 2\int_0^{D/2} (2\pi r\, dr) c_u$$

where is the unit undrained shearing resistance and *r* is the radius of the sheared surface.

The moment of the total shearing resistance about the centre is the torque *T* at failure

$$T = \pi D H c_u . \frac{D}{2} + 2\int_0^{D/2} (2\pi r\, dr) c_u . r$$

$$T = c_u \pi \left[\frac{D^2 H}{2} + \frac{D^3}{6}\right] \quad \text{or} \quad c_u = \frac{T}{\pi D^2 \left[\frac{H}{2} + \frac{D}{6}\right]}$$

If the test is carried out such that the top end of the vane does not shear the soil (as in the case of a test in a borehole)

$$T = c_u \pi \left[\frac{D^2 H}{2} + \frac{D^3}{12}\right]$$

SKEMPTON'S PORE PRESSURE PARAMETERS

- These are empirical coefficients which are used to express the response of pore pressure to changes in total stress under *undrained conditions*.
- They are dimensionless and indicate the part of total stress that manifests as excess pore water pressure for no drainage condition.
- In one-dimensional loading situation, the excess pore water pressure that is induced initially is equal to the applied vertical stress.
- But **in the case of triaxial test when the deviator stress is applied and shear stresses develop, the pore water pressure that is induced will not be equal to the applied deviator stress.** Its magnitude will depend on the type of soil, and its stress history. It can be positive or negative.

Skempton's equation may be written in the following form.

$$\Delta u = B[\Delta\sigma_3 + A(\Delta\sigma_1 - \Delta\sigma_3)]$$

where,

$\Delta u =$ increase in pore water pressure when no drainage is permitted

$A, B =$ Skempton's pore pressure parameters

The above equation can be split into two parts as

$$\Delta u_1 = B\Delta\sigma_3$$

$$\Delta u_2 = BA(\Delta\sigma_1 - \Delta\sigma_3)$$

$$\Delta u = \Delta u_1 + \Delta u_2$$

Δu_1 is the change in pore pressure due to an increase in cell pressure $\Delta\sigma_3$

Δu_2 is the change in pore pressure due to an increase in deviator stress $(\Delta\sigma_1 - \Delta\sigma_3)$.
B varies from 0 to 1 depending on the degree of saturation (S). For S = 100 %, B = 1. The relation between S and B is not linear.

For B =1,

$$\Delta u = \Delta\sigma_3 + A(\Delta\sigma_1 - \Delta\sigma_3)$$

For a partially saturated sample,

$$\Delta u = B\Delta\sigma_3 + \bar{A}(\Delta\sigma_1 - \Delta\sigma_3)$$

where $\bar{A} = AB$

For a completely saturated sample, $\bar{A} = A$

Parameter B varies with the stress range. Hence, while evaluating A from $\bar{A}$, the value of B corresponding to appropriate deviator stress range must be used.

Parameter B can be determined from a $\overline{UU}$ test (UU test in which pore pressure is measured). The cell pressure is increased by $\Delta\sigma_3$ and the corresponding increase in pore pressure Δu_1 is measured in the first stage of the triaxial test.

$$B = \frac{\Delta u_1}{\Delta\sigma_3}$$

Parameter $\bar{A}$ is measured during the second stage of the triaxial test. If Δu_2 is the pore pressure increase due to an increase in deviator stress of $(\Delta\sigma_1 \quad \Delta\sigma_3)$ with cell pressure being constant.