

# Shear Strength Testing

Text: Das, 2010. Chapter 12.3 - 12.18

There are several laboratory methods to determine shear strength parameters  $c'$  and  $\phi'$ :

- Direct Shear Test
- Triaxial Test
- Unconfined Compression Test
- Vane Shear Test



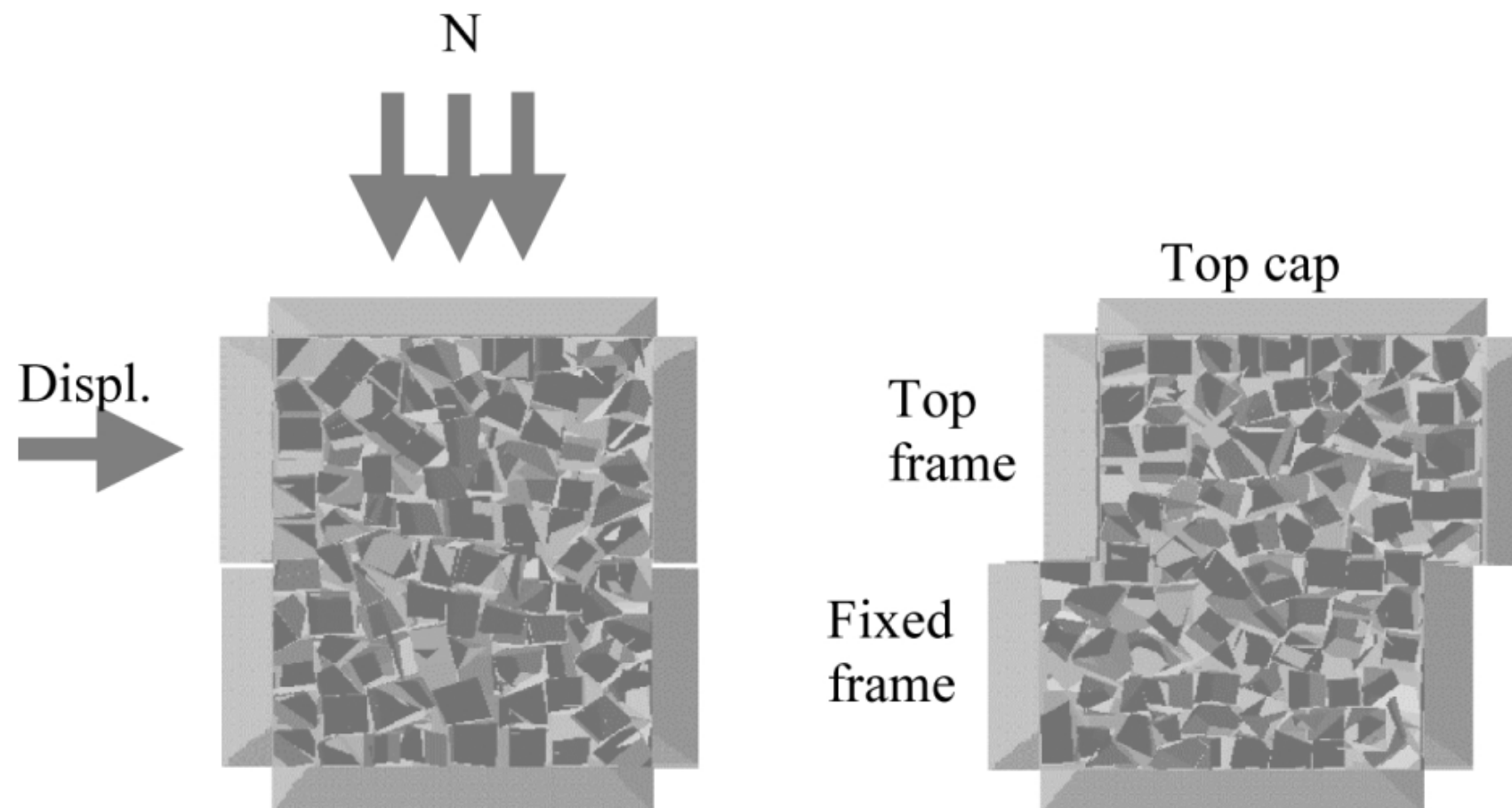
Of these, the Triaxial test is the most commonly performed. This test will be demonstrated in the intensive school.

# Direct Shear Test

The direct shear test is the oldest and simplest form of shear test, but has some fundamental limitations.

Test equipment consists of a split metal "shear box" in which the soil specimen is placed. Normal pressure is applied vertically, and shear stress horizontally across the line of the split.

Shear failure is induced by displacing the top half of the box and specimen relative to the bottom half. The specimen is usually kept saturated to reflect pore pressure effects.



# Direct Shear Test

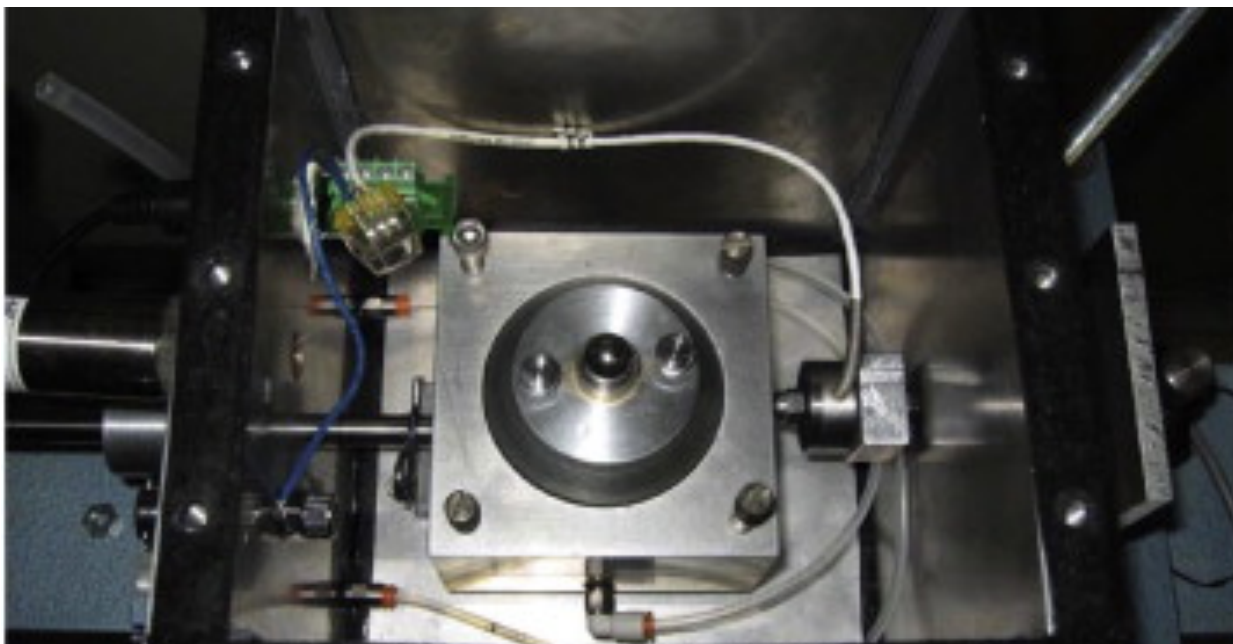
Depending on the equipment, the direct shear test can be either stress-controlled or strain-controlled.

In stress-controlled tests, the shear force is applied in equal increments until the specimen fails. After application of each increment the shear displacement of the top half of the box is measured by a horizontal dial gauge. Volume change can also be measured by vertical displacement.

In strain-controlled tests a constant rate of shear displacement is applied to the specimen, and the resisting shear is measured by a horizontal proving ring or load cell.

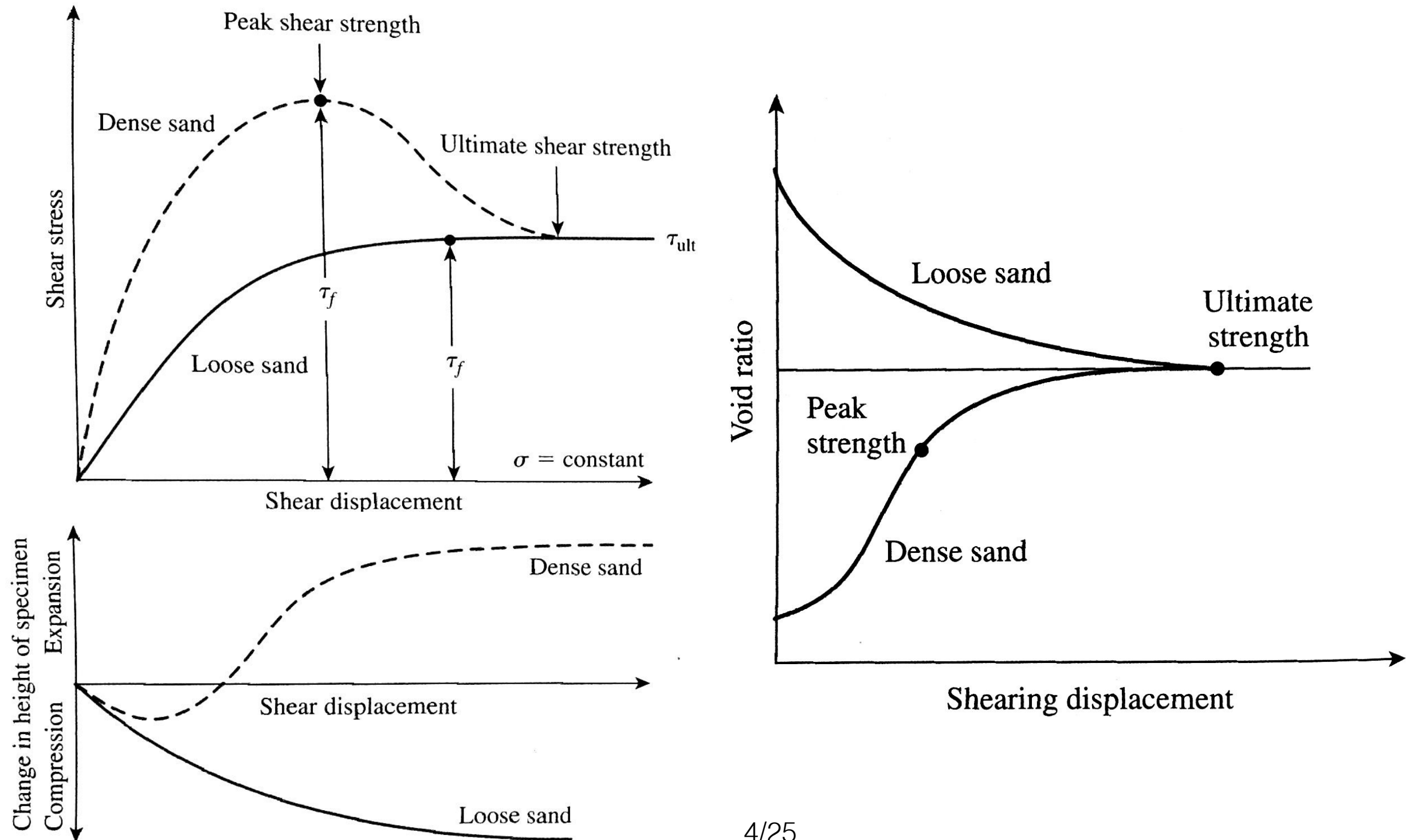
The advantage of the strain-controlled test is that in Type II soils both the peak shear resistance at failure and the residual or ultimate shear resistance after failure can be measured.

Stress-controlled tests tend to model the field situation more realistically, but do not provide complete data.



# Direct Shear Test

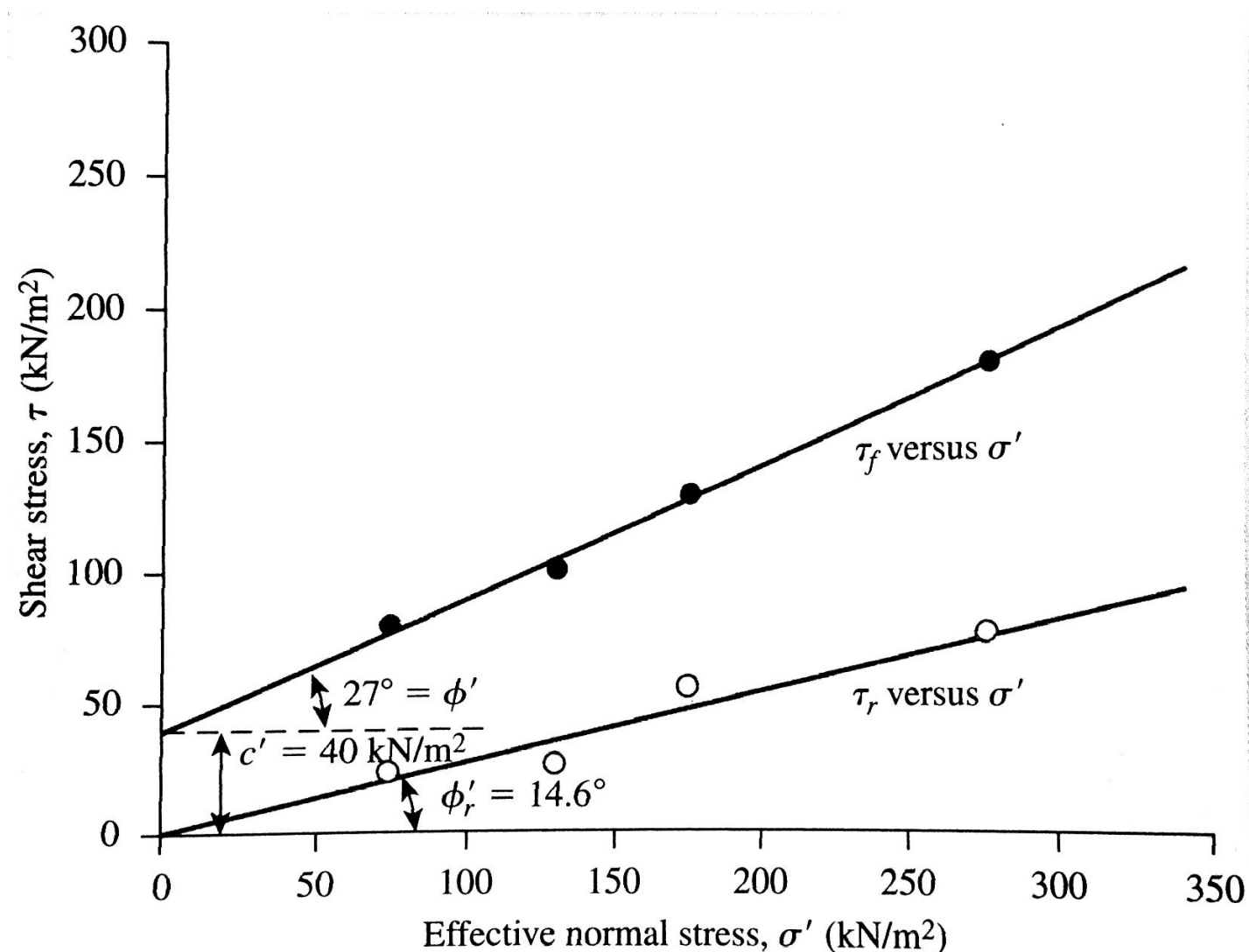
The overall shear response of Type I and Type II soils can be determined by a strain-controlled direct shear test:



# Direct Shear Test

The ultimate or residual shear stress is a separate stress state in which a Type II soil continues to carry a reduced shear force after failure.

The residual state has its own set of stress parameters. In general the residual shear stress resembles a Type I soil with  $c' = 0$ :

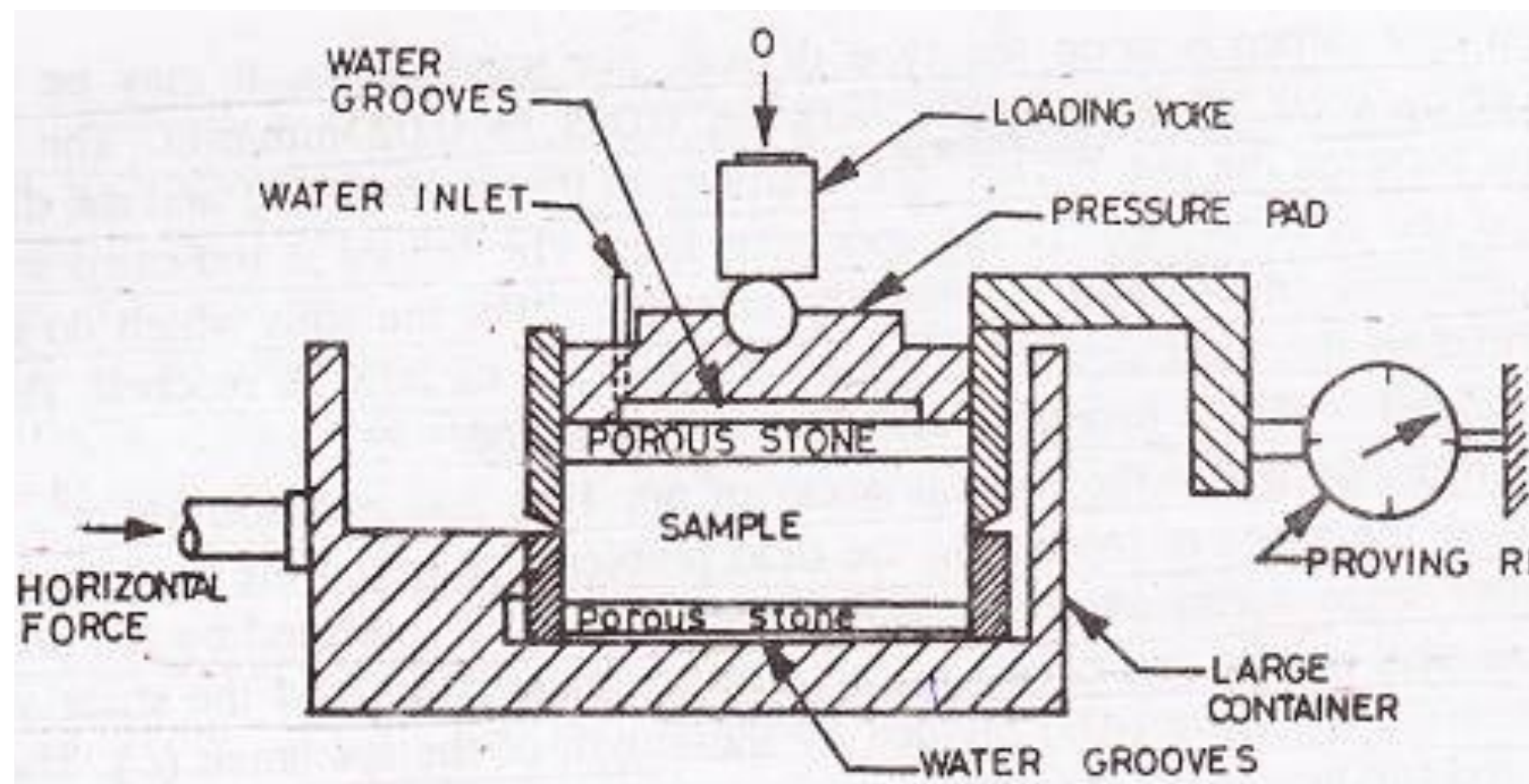


# Drained Direct Shear Test

A drained direct shear test is made on a saturated specimen by ensuring that the rate of loading is sufficiently low to allow excess pore pressures to dissipate. This reflects the effect of shear during consolidation.

Pore water from the specimen is drained through two porous stone membranes as per a consolidation test.

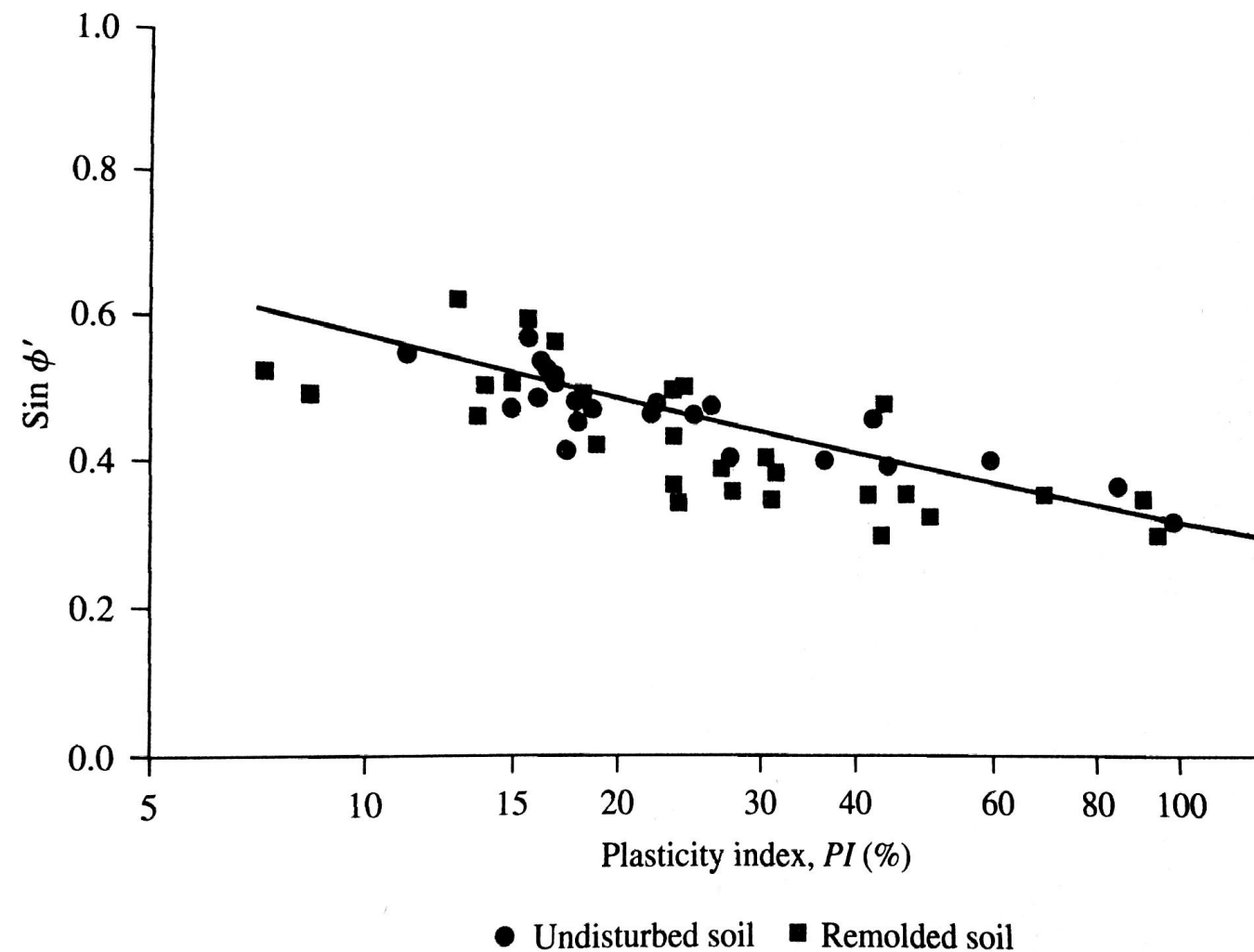
Coarse and fine grained soils exhibit very different responses due to the large difference in hydraulic conductivity. In clays the shearing load must be applied very slowly, over two to five days.



# Drained Direct Shear Test

The drained angle of friction  $\phi'$  for normally consolidated clays tends to decrease with Plasticity Index.

| Soil          | Clay-size fraction (%) | Residual friction angle, $\phi'_r$ (deg) |
|---------------|------------------------|------------------------------------------|
| Selset        | 17.7                   | 29.8                                     |
| Wiener Tegel  | 22.8                   | 25.1                                     |
| Jackfield     | 35.4                   | 19.1                                     |
| Oxford clay   | 41.9                   | 16.3                                     |
| Jari          | 46.5                   | 18.6                                     |
| London clay   | 54.9                   | 16.3                                     |
| Walton's Wood | 67                     | 13.2                                     |
| Weser-Elbe    | 63.2                   | 9.3                                      |
| Little Belt   | 77.2                   | 11.2                                     |
| Biotite       | 100                    | 7.5                                      |



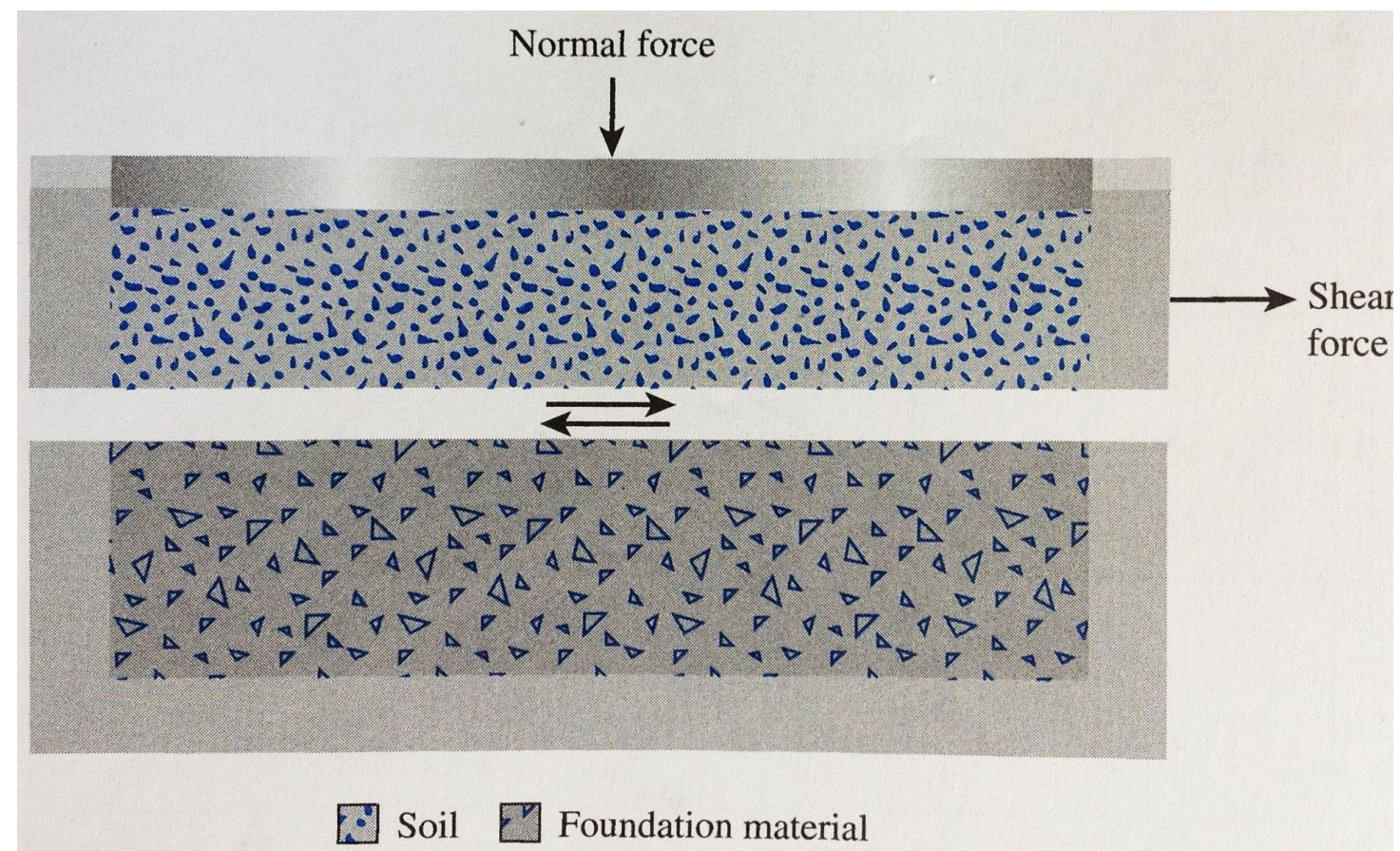
# Direct Shear Test

The reliability of the direct shear test can be questioned because of some inherent shortcomings, but is still used for its simplicity and flexibility.

The soil is not allowed to fail along the weakest plane but is forced to fail along the split of the shear box.

Also the shear stress distribution along the plane of the shear surface is not uniform but varies by accumulation of shear force across the face.

A significant advantage of the direct shear test is that it can be used to measure the friction parameters between a soil and a foundation material, so that the risk of failure by sliding against a constructed surface can be assessed.

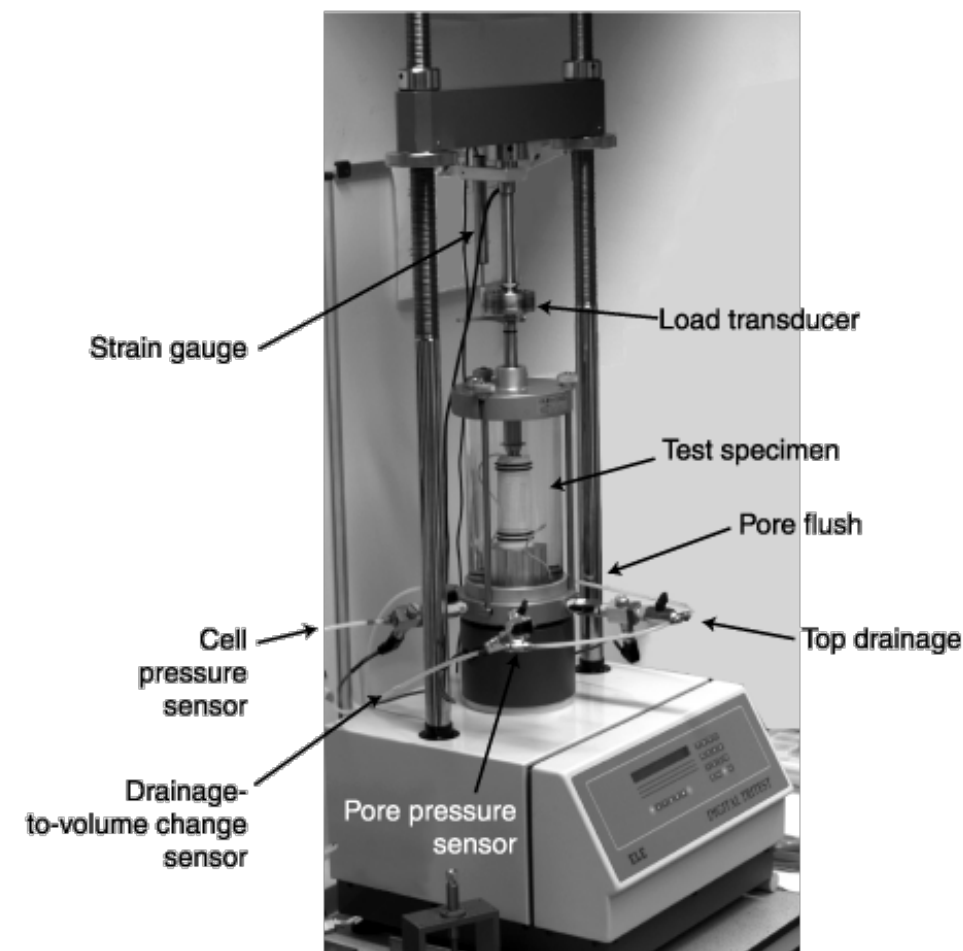
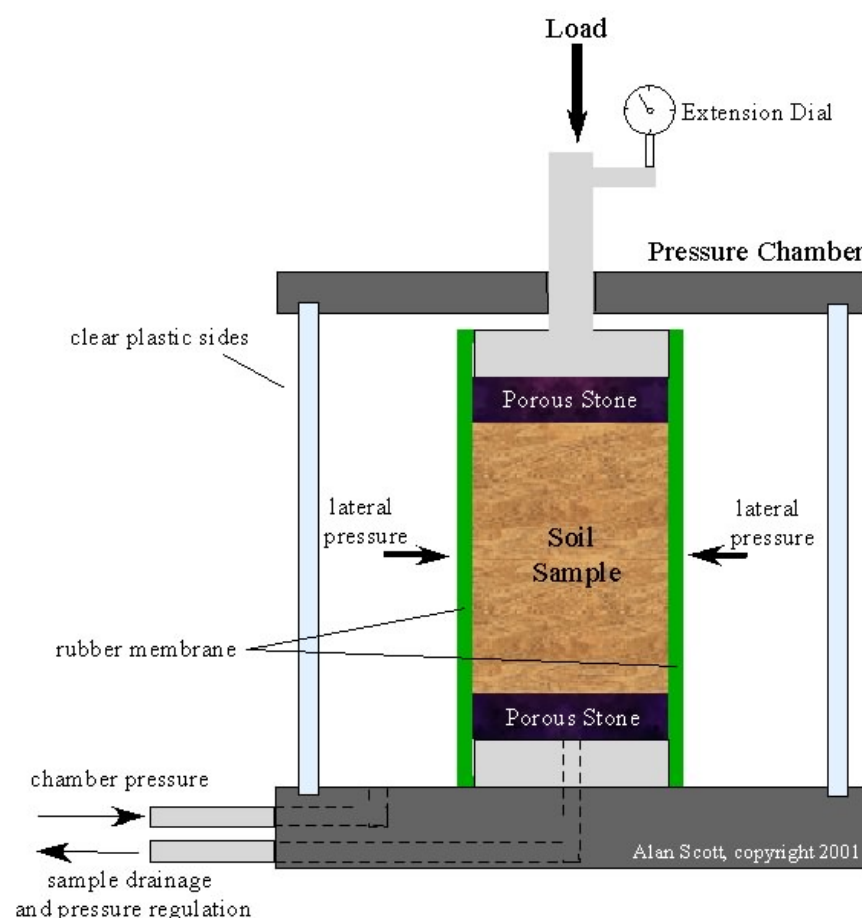


# Triaxial Shear Test

The Triaxial shear test is one of the most reliable methods available for determining shear strength parameters. It is widely used for research and conventional testing.

The specimen is encased in a thin rubber membrane and placed inside a clear plastic or glass cylinder filled with water or even glycerine. The specimen is subjected to a confining pressure by pressurisation of the fluid medium.

Axial and shear stress (sometimes called deviator stress) are induced in the specimen by a vertical loading ram. As with the direct test either stress- or strain-controlled methods are available.

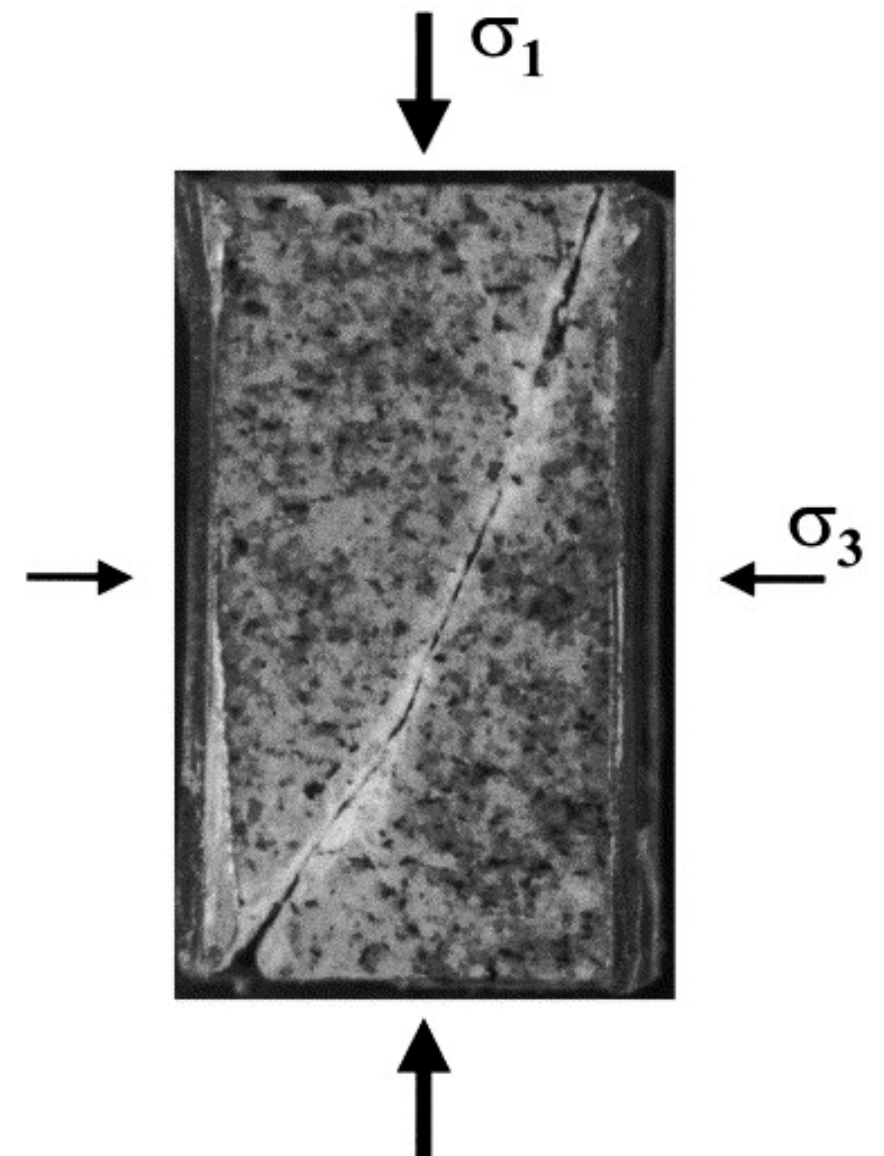
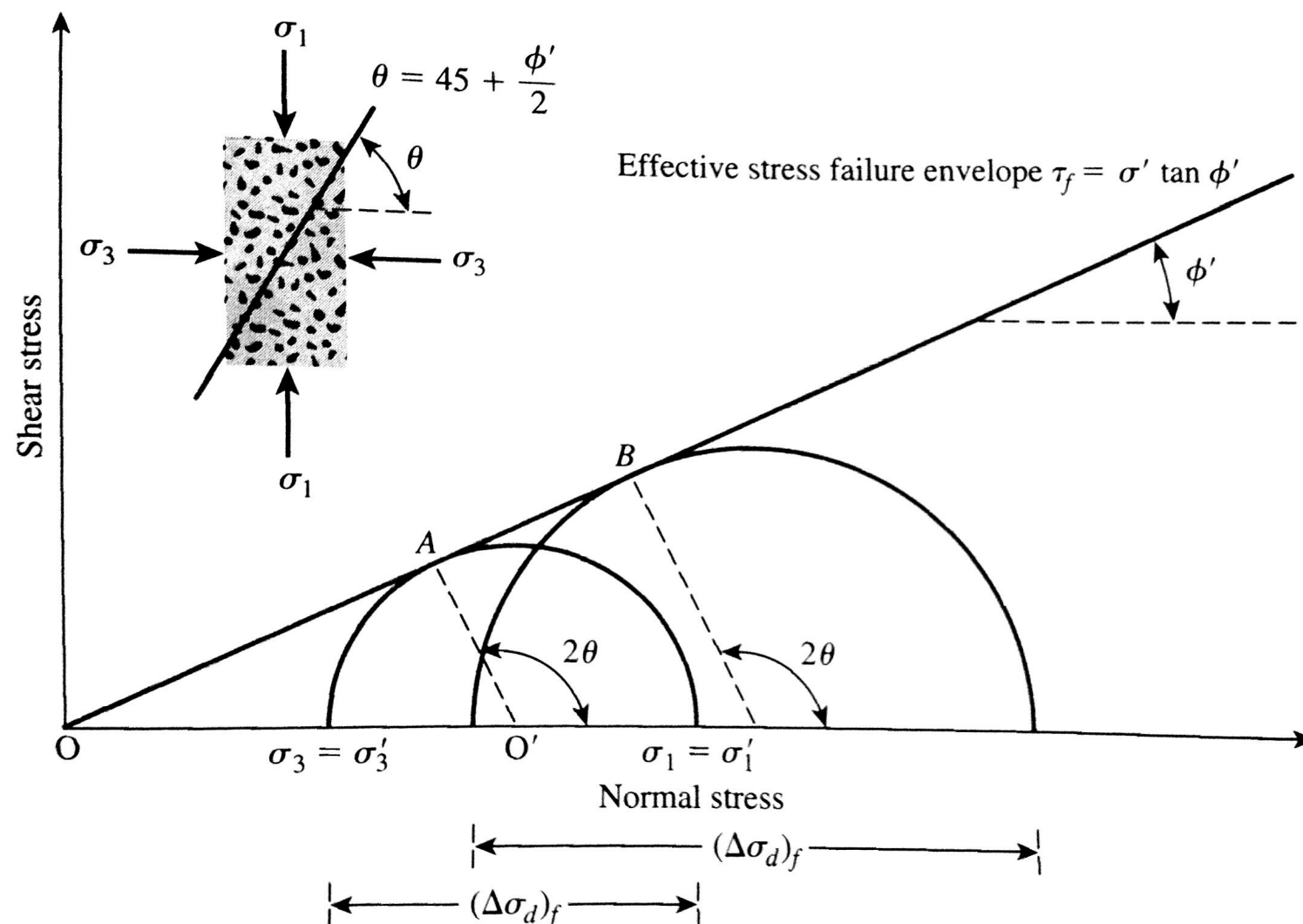


# Triaxial Shear Test

The specimen fails by shearing along a plane at the failure angle  $\theta_f$

Several tests on similar specimens can be carried out by varying the confining pressure  $\sigma_x$  and axial stress  $\sigma_z$ . Depending on the state of drainage-consolidation these may reflect total or effective stresses.

With the major and minor principal stresses at failure identified (at failure  $\sigma_z = \sigma_1$ ,  $\sigma_x = \sigma_3$ ), Mohr's circles can be drawn and the failure envelopes obtained:

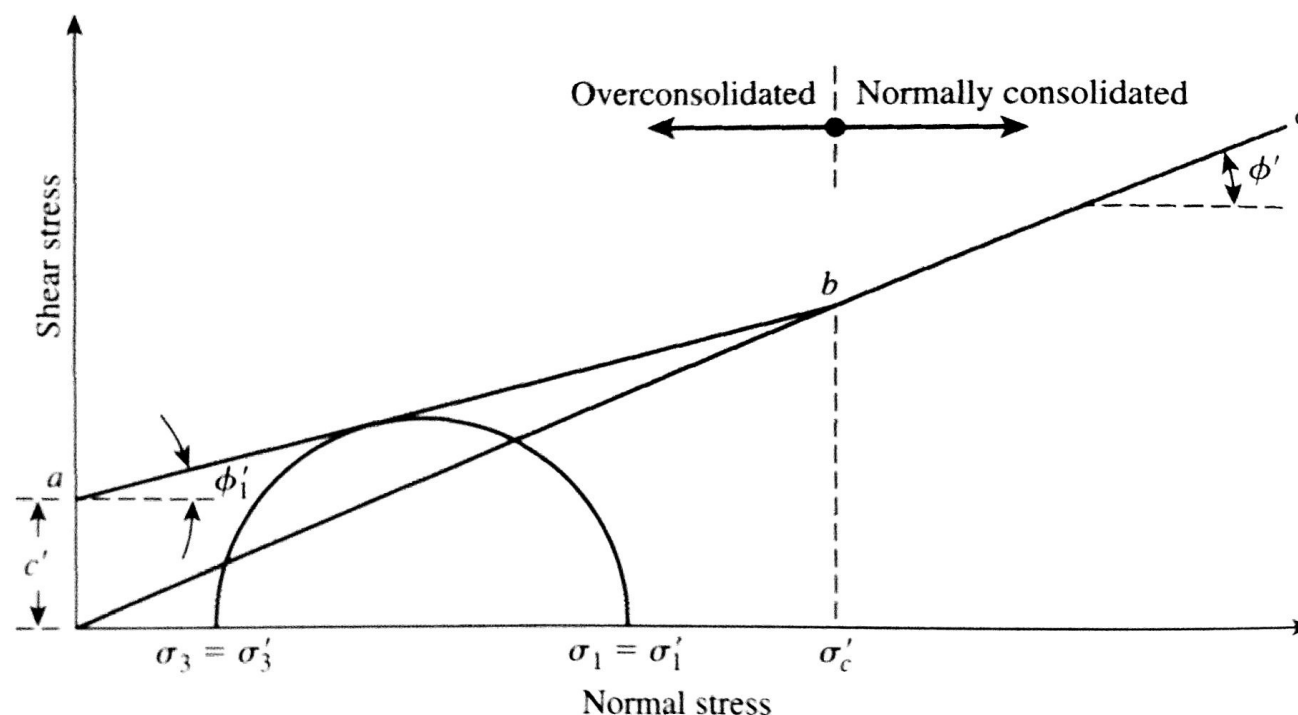


# Triaxial Shear Test

The following three standard types of Triaxial tests provide a range of information about shear parameters in different field conditions:

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

In the CD test, loads are applied slowly so that drainage and consolidation take place. The confining fluid pressure is then equal to the lateral stress  $\sigma_x$  or  $\sigma_3$ , and the principal stress  $\sigma_z$  or  $\sigma_1$  is the sum of axial and confining stresses. CD test is used in identifying the consolidation stress  $\sigma'_c$ .



A CD test on a clay soil may take several days to complete.

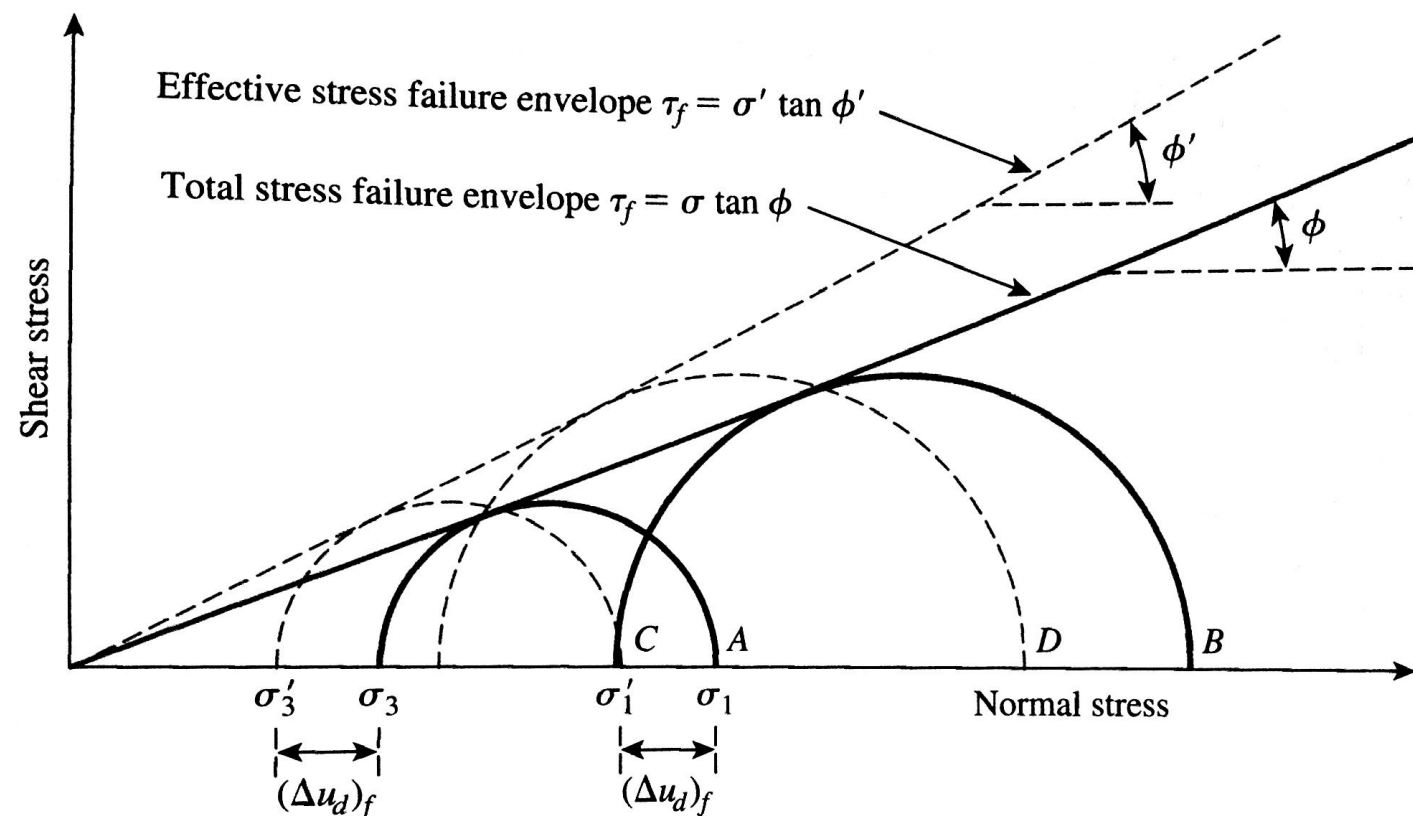
# Triaxial Shear Test

The Consolidated-Undrained CU test is the most common type of triaxial test. CU reflects the loading conditions of undrained or rapid construction on a previously drained consolidated soil.

In a CU test the specimen is pre-loaded with a confining pressure that is allowed to dissipate by drainage via apparatus drainage lines.

The drainage lines are then closed and the consolidated specimen is loaded with an axial stress that is increased until shear failure occurs. Because drainage is not permitted the deformation and failure are as for overconsolidated soil.

Also, as pore water pressure is not dissipated the total stress differs from the effective stress. Both conditions can thus be measured and plotted:



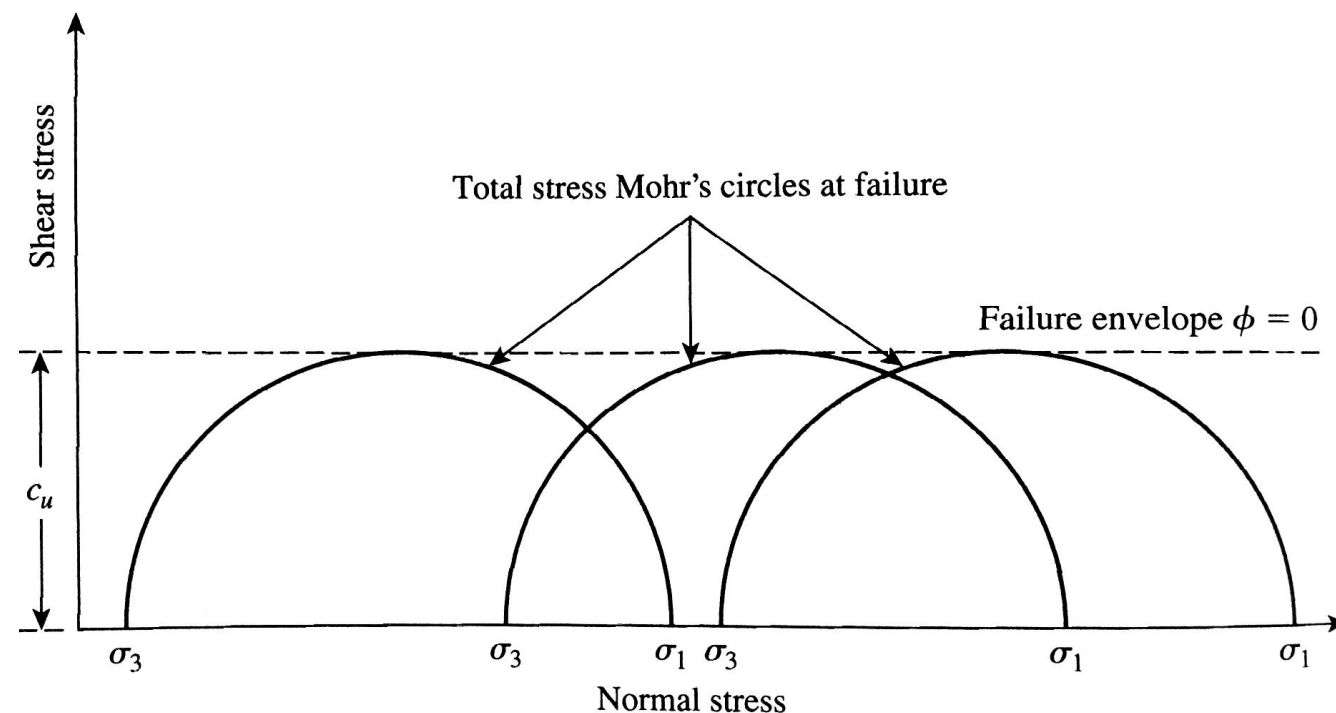
The diameters of total and effective stress circles are the same.

# Triaxial Shear Test

The Unconsolidated-Undrained UU test does not permit drainage or consolidation in either the confining pressure or axial stresses.

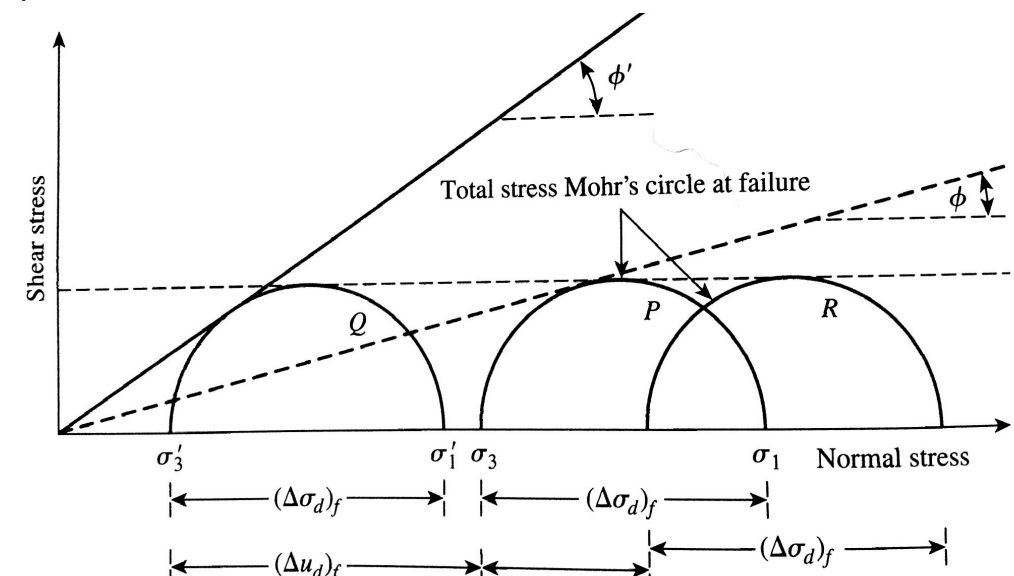
With variable confining pressure in place and no drainage, the axial stress is applied until shear failure occurs. It is found that the axial total stress is practically constant at failure, giving a flat shear failure line known as a  $\phi=0$  condition

This is an important principle of saturated cohesive soils under rapid loading:



Pore pressure includes both confining and axial pressures in such a way that total stress is constant.

Effective stress parameters are then determined by subtracting the instrumentally measured pore pressure:

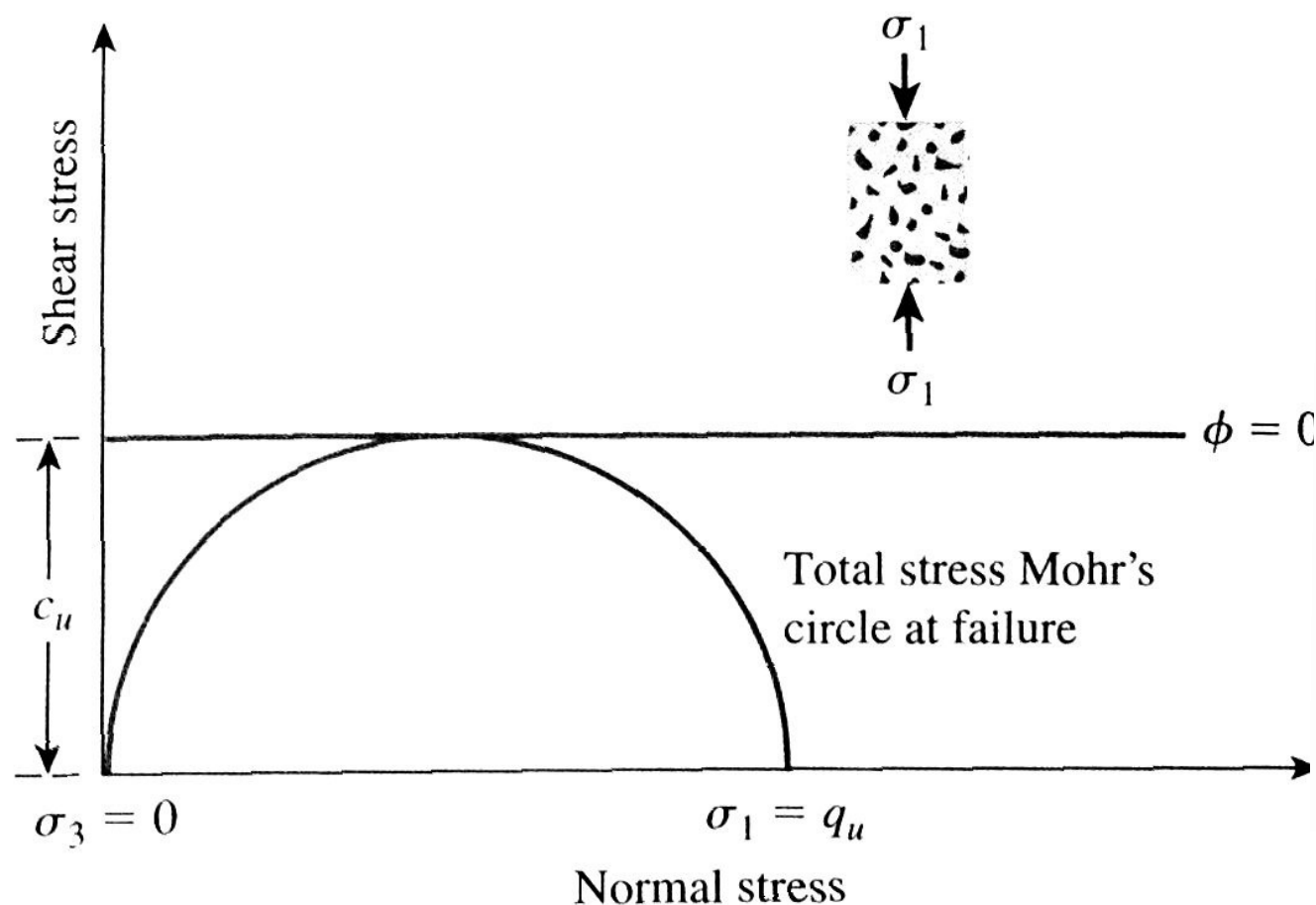


# Unconfined Compression Test

An Unconfined Compression UC test is a special type of Unconsolidated-Undrained test with a confining pressure of zero.

The unconfined compression test requires relatively simple apparatus: a cohesive specimen is simply loaded axially in a confining medium of air at atmospheric pressure (ie no confining apparatus required).

Because of the  $\phi=0$  condition, the failure shear stress is measured directly by the axial stress:  $\tau_f = \sigma_1/2 = q_u/2$  where  $q_u$  is the unconfined compression strength of the soil:



**Table 12.4** General Relationship of Consistency and Unconfined Compression Strength of Clays

| Consistency | $q_u$<br>kN/m <sup>2</sup> |
|-------------|----------------------------|
| Very soft   | 0–25                       |
| Soft        | 25–50                      |
| Medium      | 50–100                     |
| Stiff       | 100–200                    |
| Very stiff  | 200–400                    |
| Hard        | >400                       |

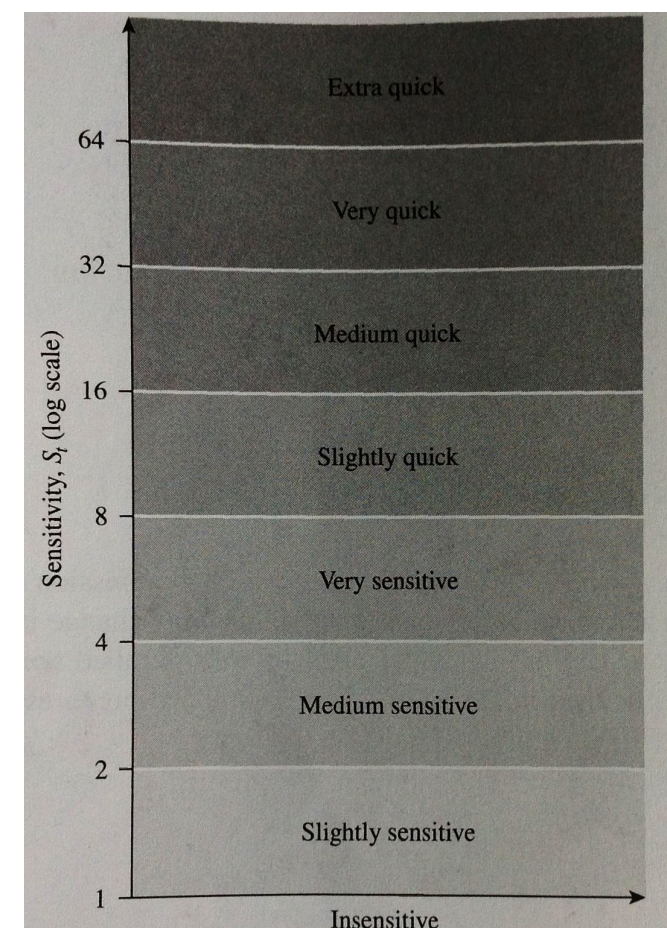
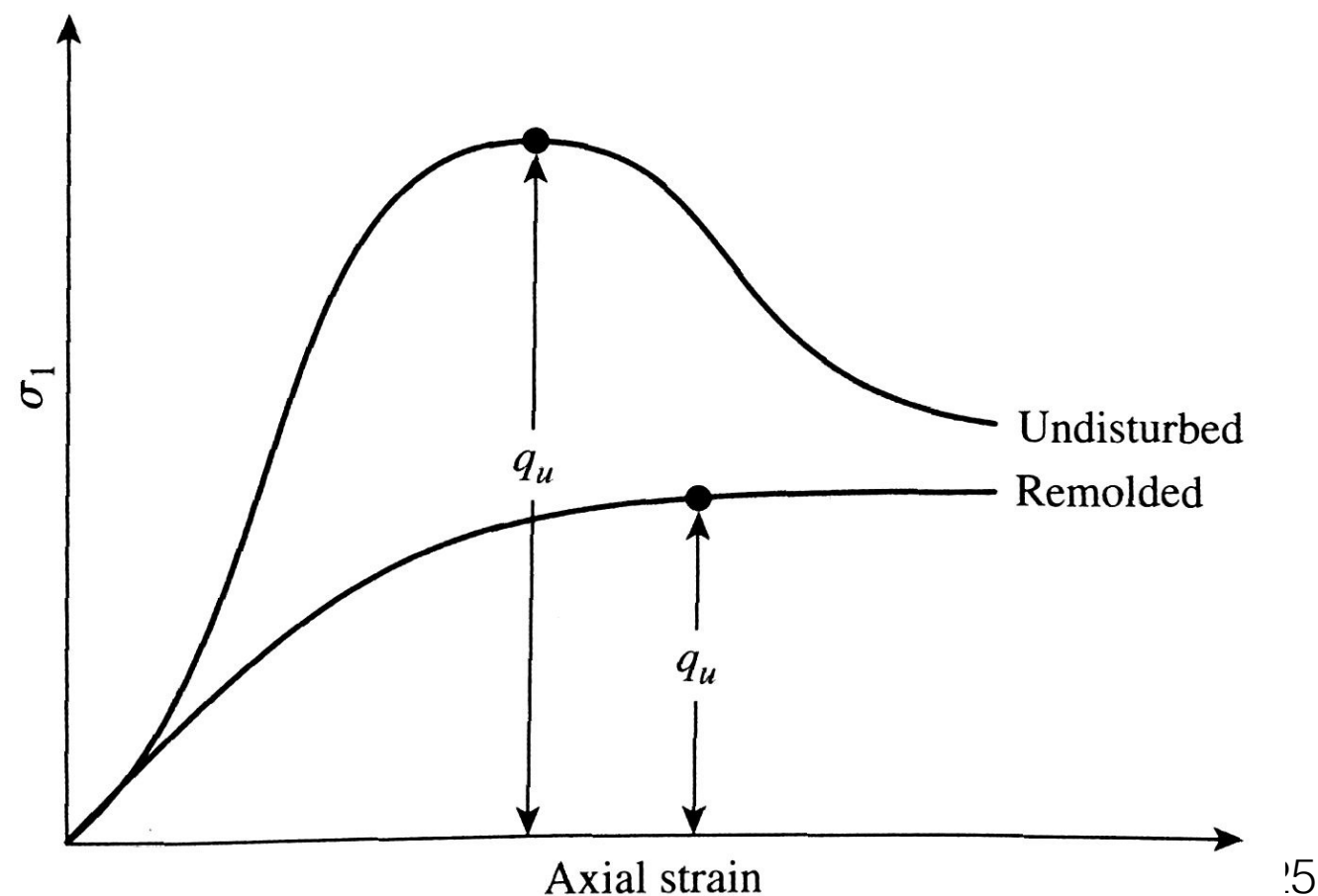
# Thixotropy and Strength Anisotropy

Many soils lose strength on remoulding, ie disturbance that obliterates the natural bedding structure of the soil.

This is known as *thixotropy*, or more commonly as *sensitivity*.

The unconfined compression strength of bedding structures may be higher but only in one principal load direction, with weaker planes in other load directions. This is known as *strength anisotropy*.

Sensitivity is measured as the ratio of  $q_u$  in undisturbed and remoulded conditions.



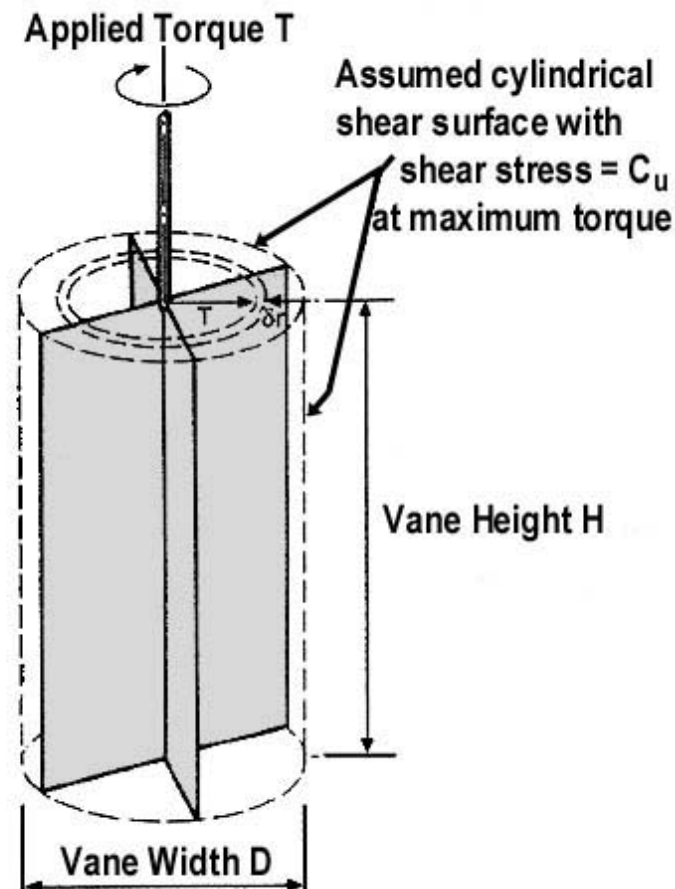
# Vane Shear Test

A shear vane is an apparatus consisting of four thin, equal sized steel plates on an axis. The plates are embedded in a soil and the vane torqued to produce a shearing action with shear strain and failure observed directly.

Vane shear provides an estimate of undrained shear strength.

An estimate of the distribution of shear across the face of a vane is required, but works out in a very narrow range of values so a guess of  $\beta=0.55$  is acceptable

Because of its simplicity and portability, vane shear tests are commonly used for assessment of soils in the field. Other types of shear tests are described in the text.



$$c_u = \frac{T}{\pi \left[ \frac{D^2 H}{2} + \beta \frac{D^3}{4} \right]}$$

Where  $\beta$  is a parameter between 0.5 and 0.6 depending on the assumed stress distribution



# Angle of Repose

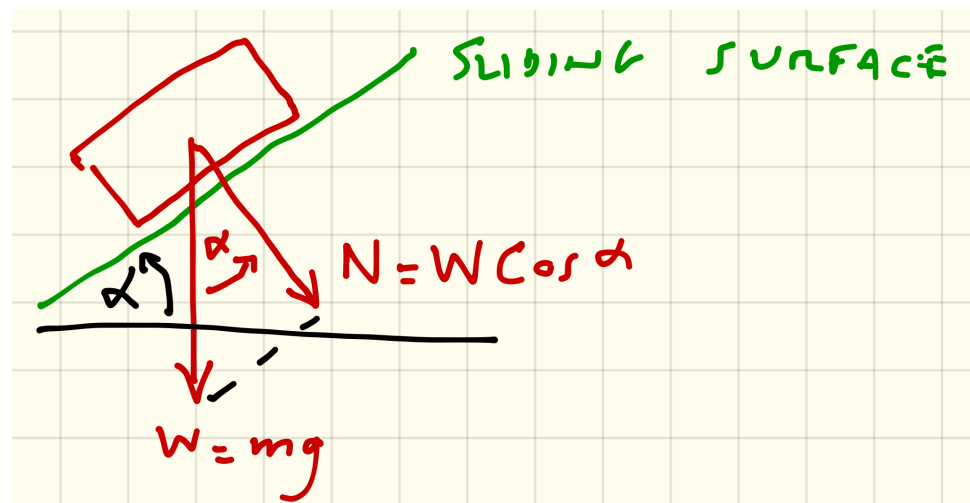
A useful application of shear failure theory is to determine the angle of repose, ie the maximum angle or slope at which a soil can rest without failure. In granular soils this is a direct measure of the friction angle  $\phi'$ .

The Mohr-Coulomb criteria can be recognised as Normal friction:

Shear Stress:  $\tau_f = \sigma'_f \tan(\phi')$

Shear Force:  $\tau_f A = \sigma'_f A \tan(\phi') = N \mu_s$

where  $\sigma'_f A = N$  is the normal force and  $\tan \phi' = \mu_s$  is a static friction coefficient. For example, the classic sliding block experiment:



The block exerts a shear force down the surface. For slopes less than a critical angle  $\alpha_c$  the shear force is resisted by the friction force:

A hand-drawn diagram on a grid background showing a red rectangular block on a green inclined plane. The angle of the incline is labeled  $\alpha$ . To the right of the diagram, the following equations are written in green:  $D = W \sin \alpha$ ,  $F_f = \mu_s N$ , and  $= \mu_s W \cos \alpha$ . A red arrow points down the incline, representing the shear force.

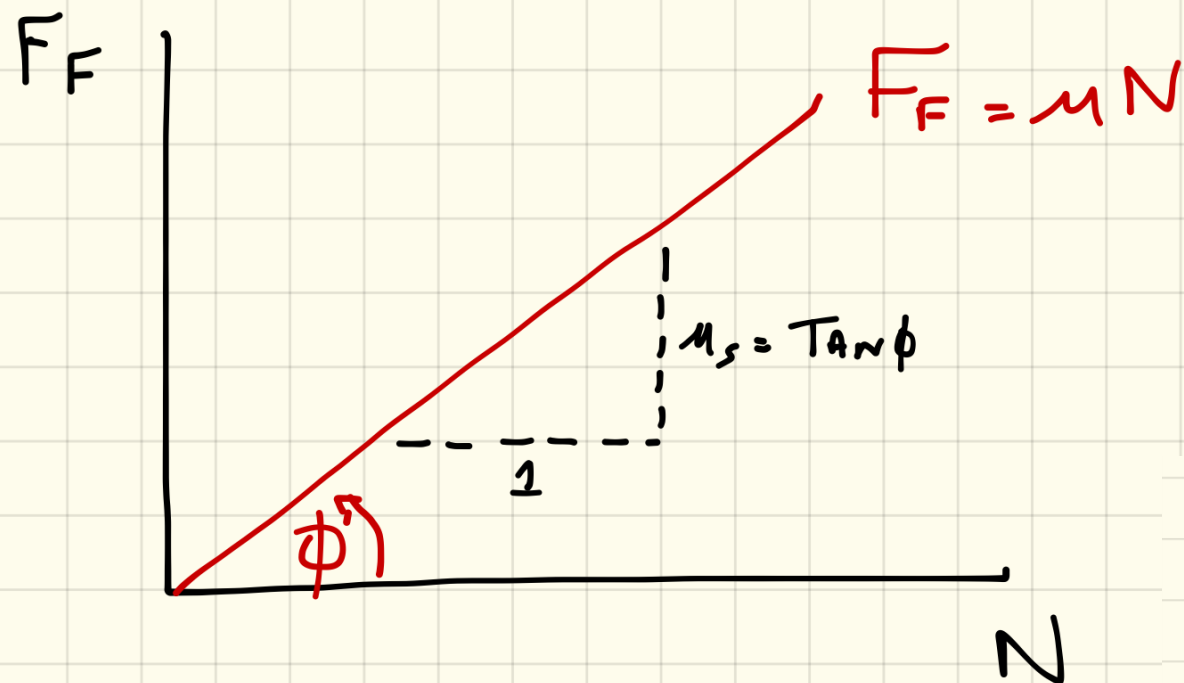
# Angle of Repose

At the critical slope the downward shear just equals the friction force, ie

$$D = F_f:$$

$$W \sin \alpha_c = \mu_s W \cos \alpha_c$$

$$\text{or } \tan \alpha_c = \mu_s$$



$\mu_s$  HAS THE SAME  
STRUCTURE AS THE FRICTION  
SLOPE  $\tan \phi'$ .

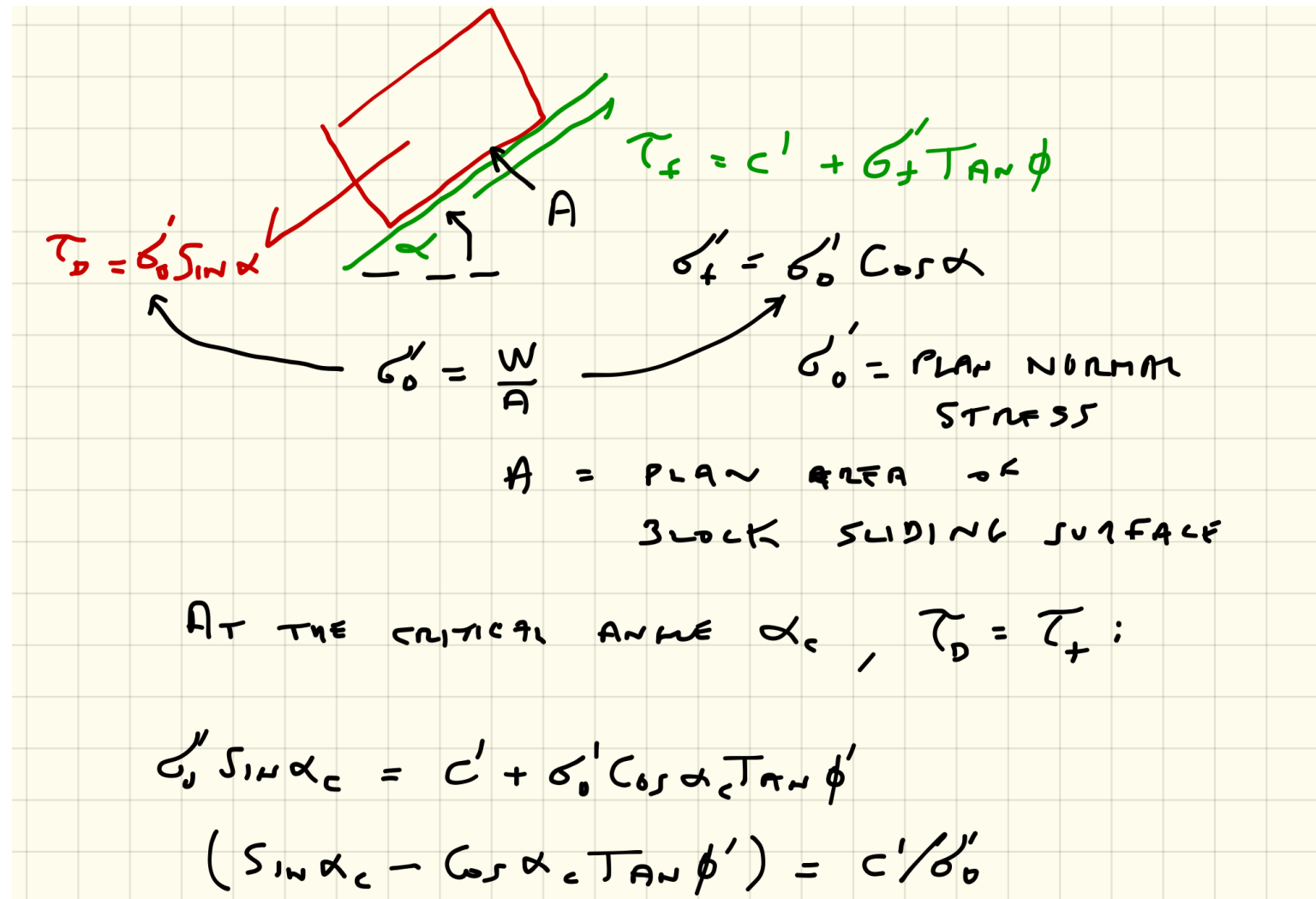
$$\text{Thus } \tan \alpha_c = \tan \phi'$$

$$\text{or } \alpha_c = \phi'$$

THE CRITICAL SLOPE  $\tan \phi'$  DOES NOT  
DEPEND ON THE LOAD  $W$ : SURFACE  
LAYERS OF LOOSE SAND WILL FLIP WHEN  
SLOPE ANGLE OF  $\alpha_c = \phi' = \underline{\underline{\text{ANGLE OF REPOSE}}}$

# Angle of Repose

Let's try that again with the full cohesive shear failure model:



Note that when  $c' = 0$ ,  $\alpha_c = \phi'$  since  $\cos(x)\tan(x) = \sin(x)$ .

Also note that when  $\sigma'_0 \gg c'$  the same condition applies since  $c' / \sigma'_0 \sim 0$

In this case the angle of repose *does* depend on stress, but for cohesive soils in normal applications under vertical stress, the angle of repose is essentially equal to the friction angle.

Angle of repose  $\alpha_c = \text{Friction angle } \phi'$

# Repose Angle and Slip Plane

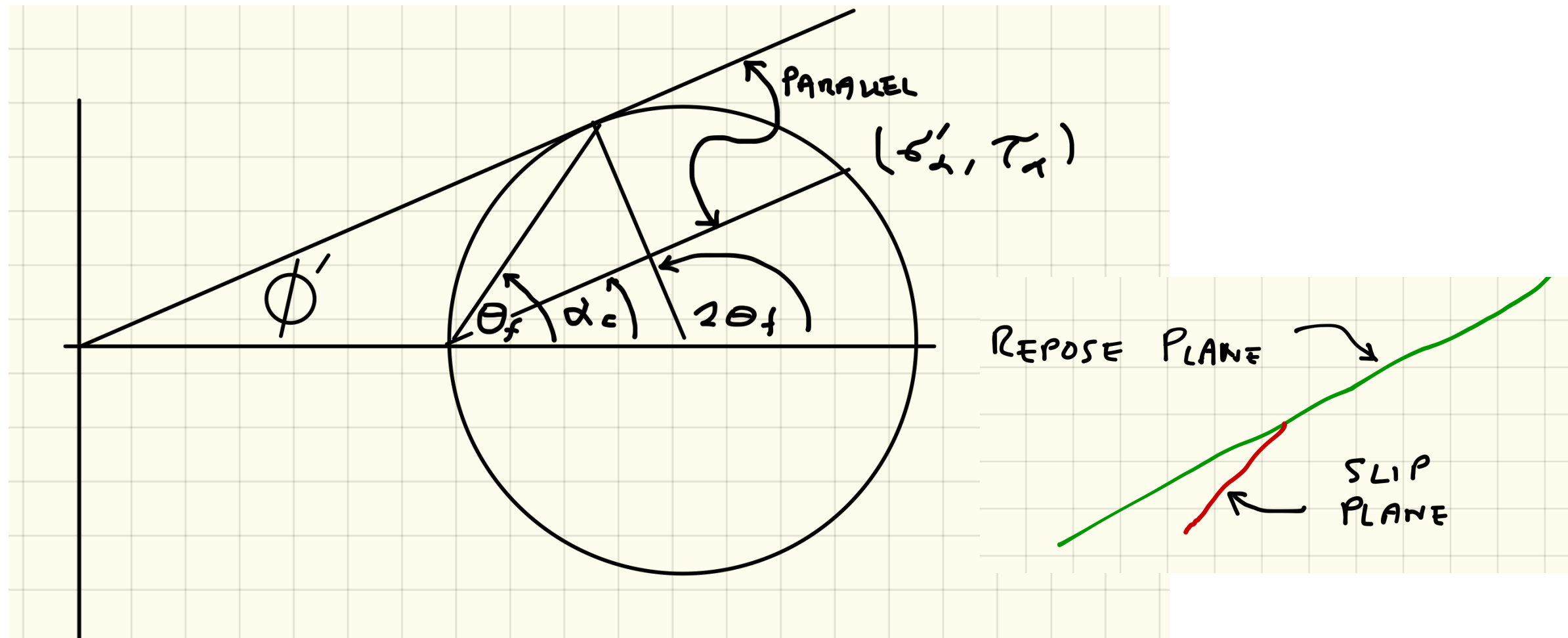
Coulomb's model  $\tau_f = c' + \sigma'_f \tan \phi'$  strictly speaking only applies to soil failures that occur along a slip plane such as a joint or the interface of two soils or between a structure and a soil.

Stratified soil deposits and fissured clays are likely candidates for Coulomb's model, especially if the direction of shearing is parallel to the bedding plane.

Most soil failures are not like that:



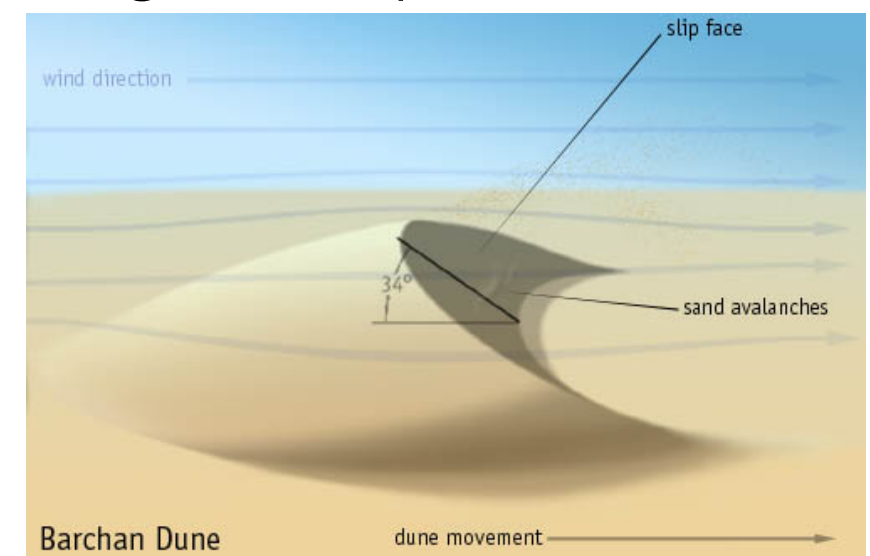
Mohr's circle indicates the direction of the slip plane:



A soil fails at an angle  $\theta_f$  which is larger than the angle of repose:

$$\theta_f = \frac{\pi}{4} + \frac{\phi'}{2} = \frac{\pi}{4} + \frac{\alpha_c}{2} \approx 60^\circ$$

But again, this is not always the case. For example a sand dune forms at the angle of repose:



# Dilation

Soils undergo volume expansions or contractions due to shear. A volume expansion is known as *dilation*.

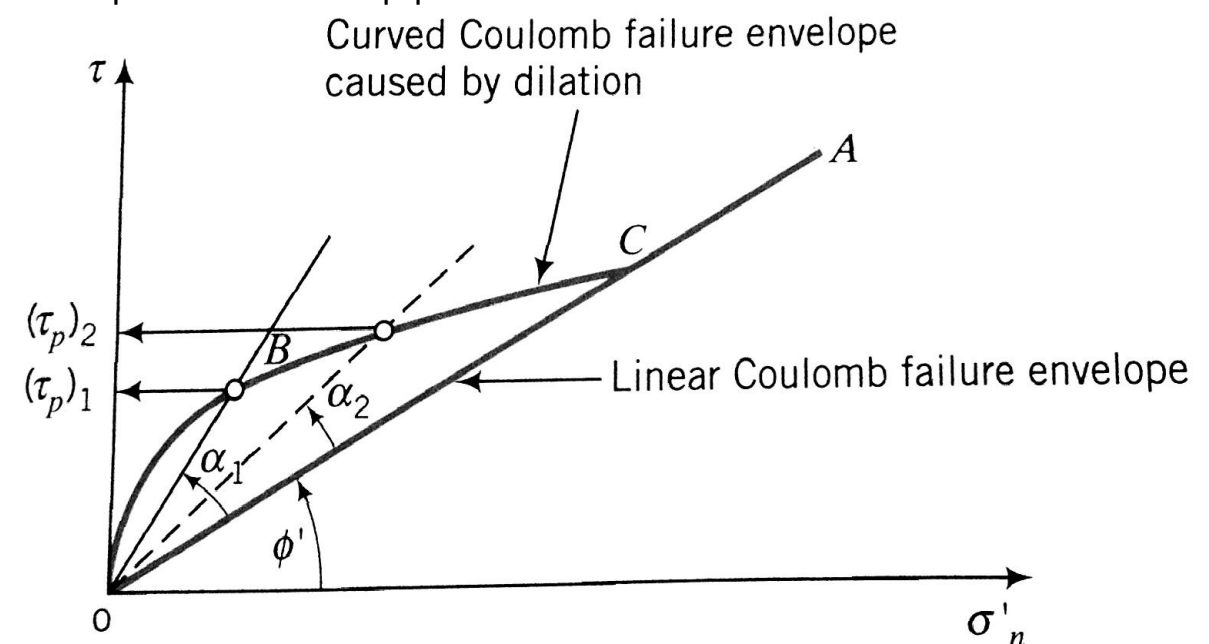
Dilation is measured as a ratio of volumetric strain to shear strain. It can be estimated by the ratio of vertical to horizontal strain:

$$\alpha = \tan^{-1} \left( \frac{-\Delta z}{\Delta x} \right)$$

Dilation is visible in the behaviour of compact wet sand such as after high tide on a beach: pressure on the sand causes shearing and volume expansion, which reduces the pore pressure and sucks water from the surrounding soil into the sheared region. When pressure is released, this dilation water is released as a pool of free water on the surface.



Dilation effects the strength of a cohesionless soil and explains the apparent cohesiveness of wet sand:



# Drained and Undrained Shear Strength

We have been introduced to the drained and undrained condition in the variants of the triaxial test which allow different degrees of drainage.

The drained condition occurs when the excess pore water developed during loading of a soil dissipates, ie  $\Delta u = 0$ .

The undrained condition occurs when excess pore water cannot drain quickly from the soil, thus  $\Delta u$  is not equal to zero and the effective stress is altered as  $\Delta \sigma' = \Delta \sigma - \Delta u$ .

Under different loading rates and soil types the stress responses of compression and shear failure will not be the same.

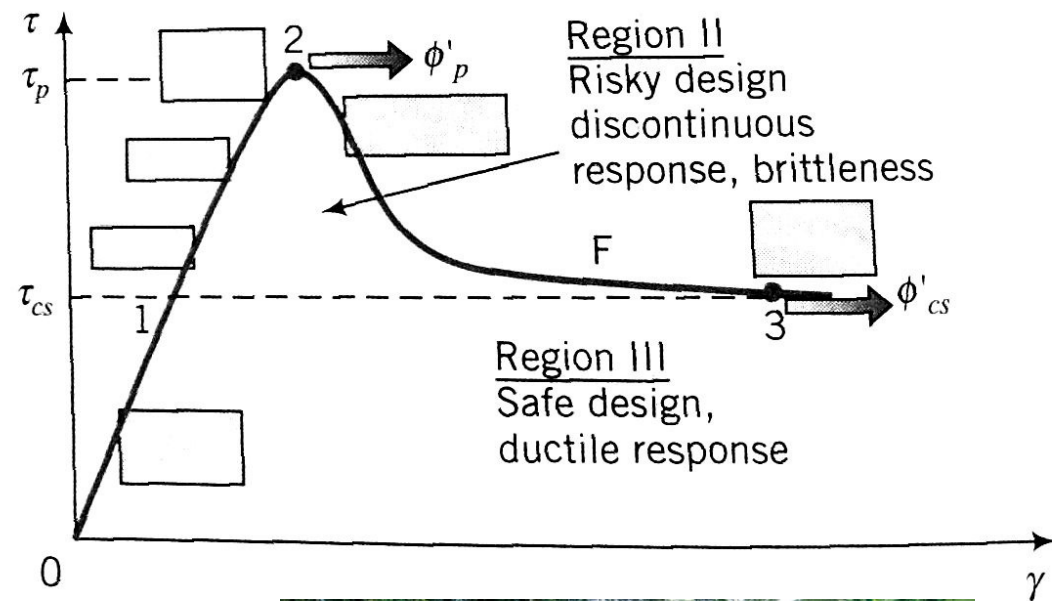
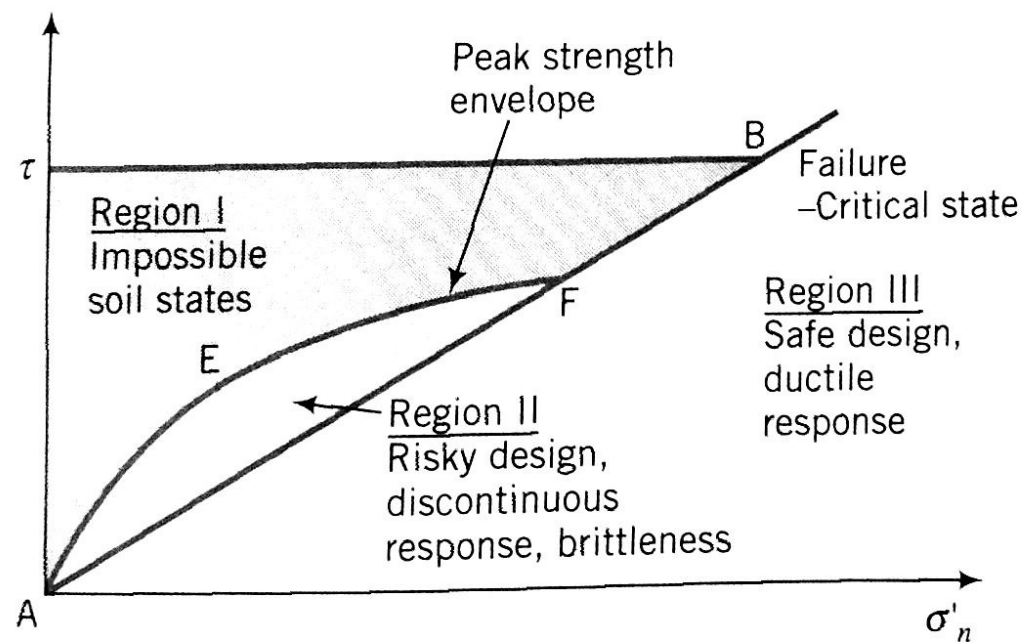
Soils with a tendency to dilate will cause a decrease in pore water pressure, ie  $\Delta u < 0$  resulting in an *increase* in effective stress.

Dynamic loading, such as during an earthquake, is so rapid that even coarse-grained soils do not have time to dissipate pore water pressure.

# Drained and Undrained Shear Strength

Over the life of a structure, soil conditions change from undrained to drained. Both cases must be considered.

For design purposes it is often conservative (and simpler) to assume that the cohesion  $c'$  is zero and to design all loads within a diagonal safety envelope:



# Readings

Chapter 12.3 -12.18 Das

