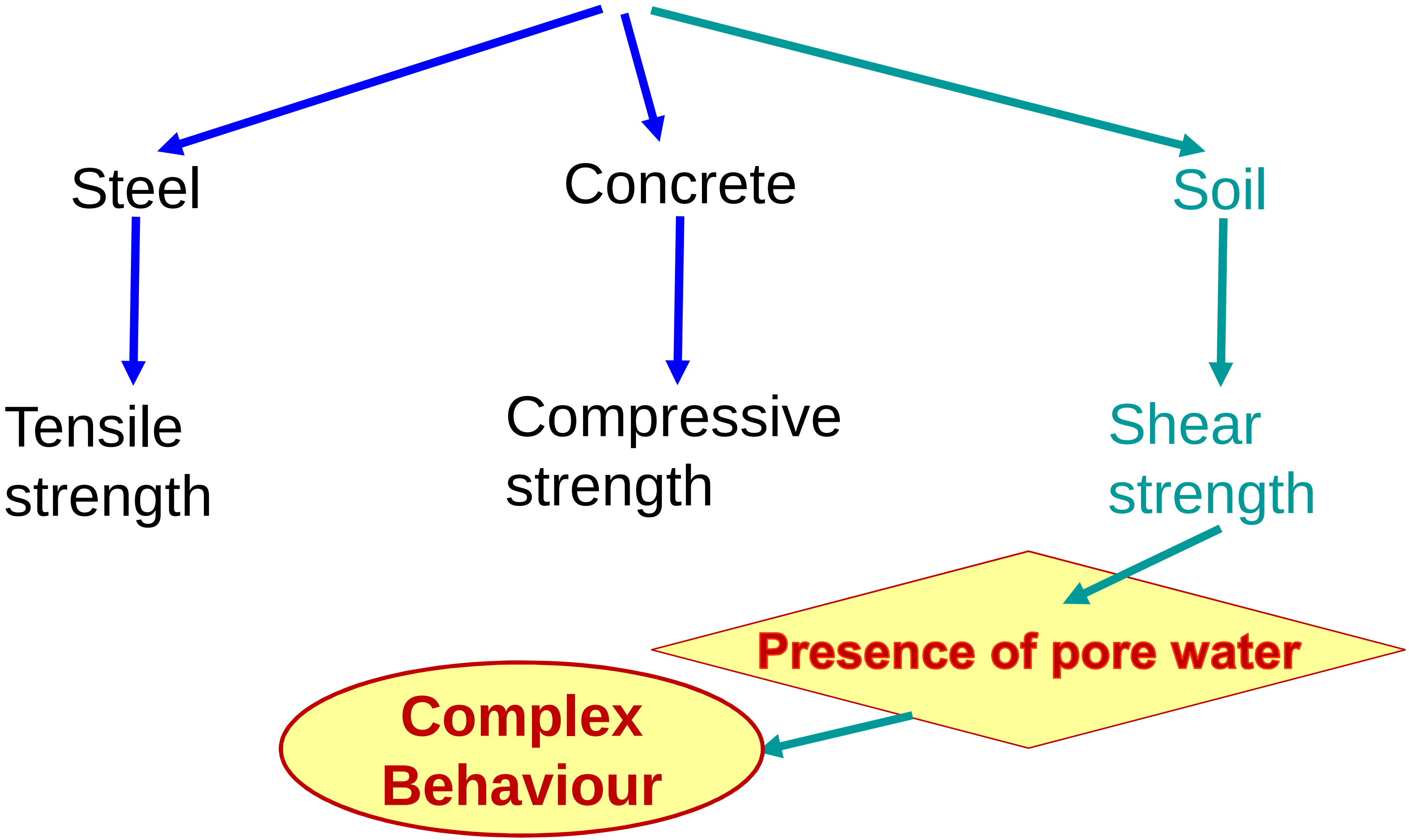
SHEAR FAILURE IN SOILS

Strength of different materials



What is Shear Strength?

- Shear strength in soils is the resistance to movement between particles due to physical bonds from:
  a. Particle interlocking
  b. Atoms sharing electrons at surface contact points
  c. Chemical bonds (cementation) such as crystallized calcium carbonate

Influencing Factors on Shear Strength

- The shearing strength, is affected by:
  - ***soil composition***: mineralogy, grain size and grain size distribution, shape of particles, pore fluid type and content, ions on grain and in pore fluid.
  - ***Initial state*:** State can be describe by terms such as: loose, dense, over-consolidated, normally consolidated, stiff, soft, etc.
  - ***Structure*:** Refers to the arrangement of particles within the soil mass; the manner in which the particles are packed or distributed. Features such as layers, voids, pockets, cementation, etc, are part of the structure.

Shear Strength of Soil

- In reality, a complete shear strength formulation would account for all previously stated factors.

- Soil behavior is quite complex due to the possible variables stated.

- Laboratory tests commonly used:
  - Direct Shear Test
  - Triaxial Test
  - Unconfined Compression Test.

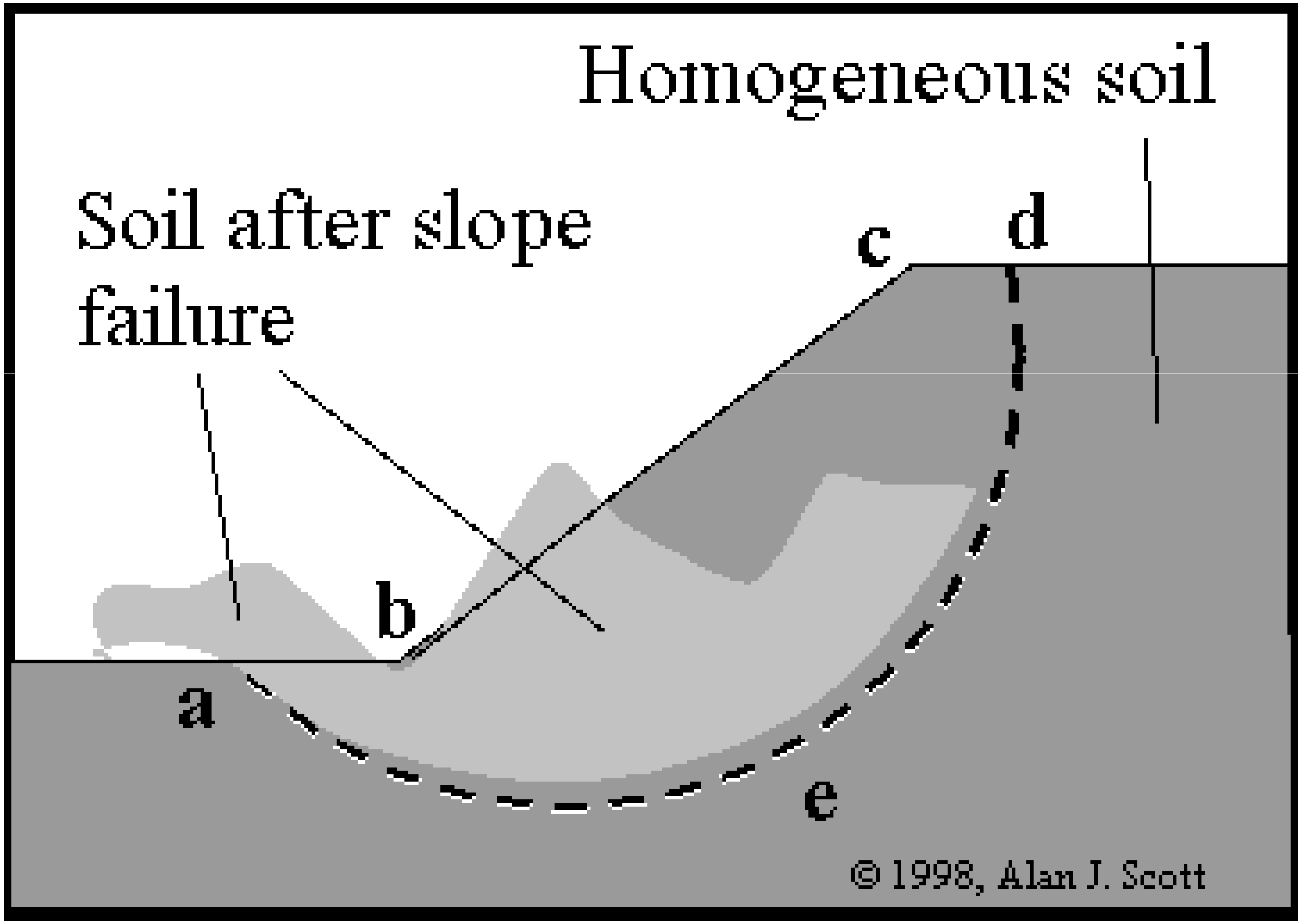
Soil Failure and shear strength.

- Soil failure usually occurs in the form of “shearing” along internal surface within the soil.

- Thus, structural strength is primarily a function of shear strength.

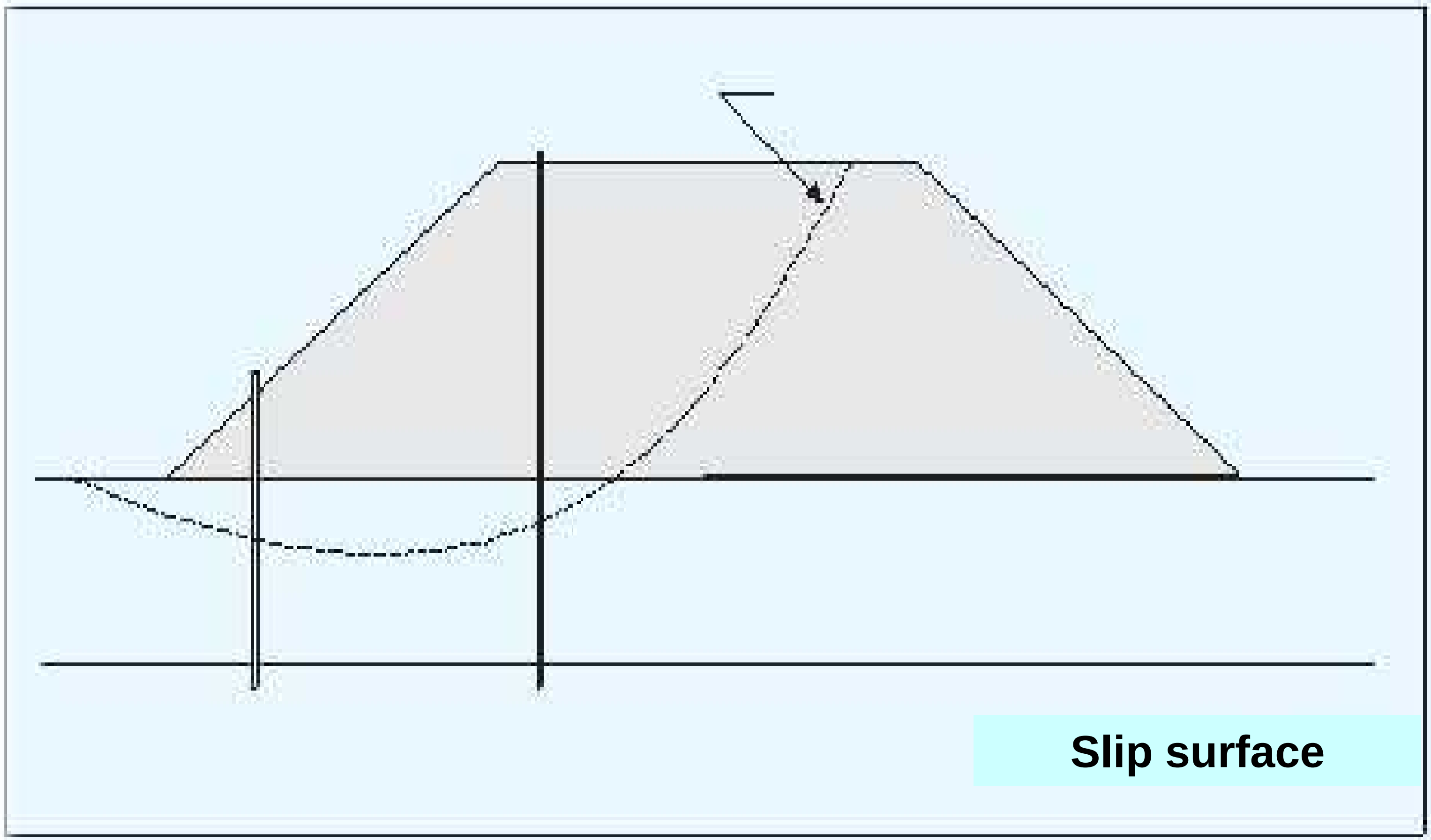
- Shear strength is a soils’ ability to resist sliding along internal surfaces within the soil mass.

Slope Stability:Failure is an Example of Shearing Along Internal Surface

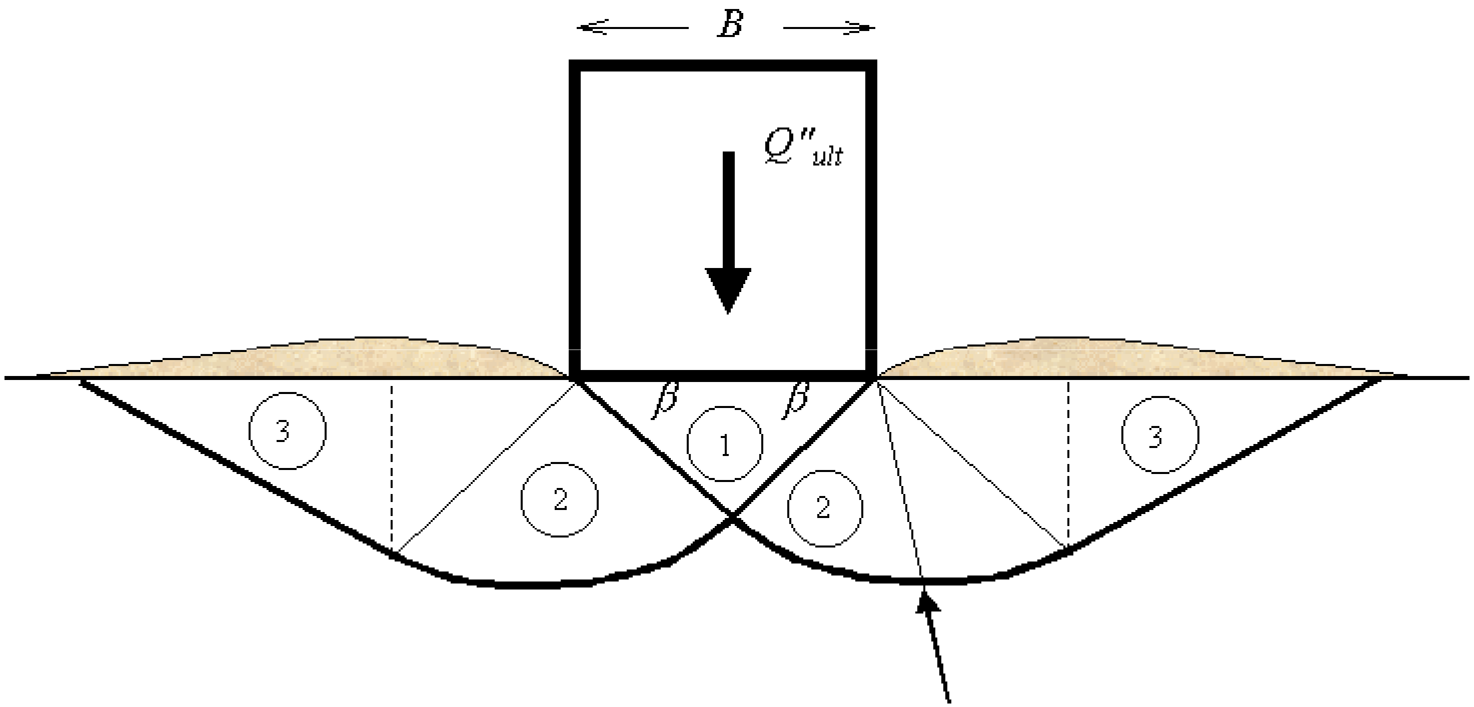


Mass Wasting: Shear Failure

Shear Failure: Earth Dam

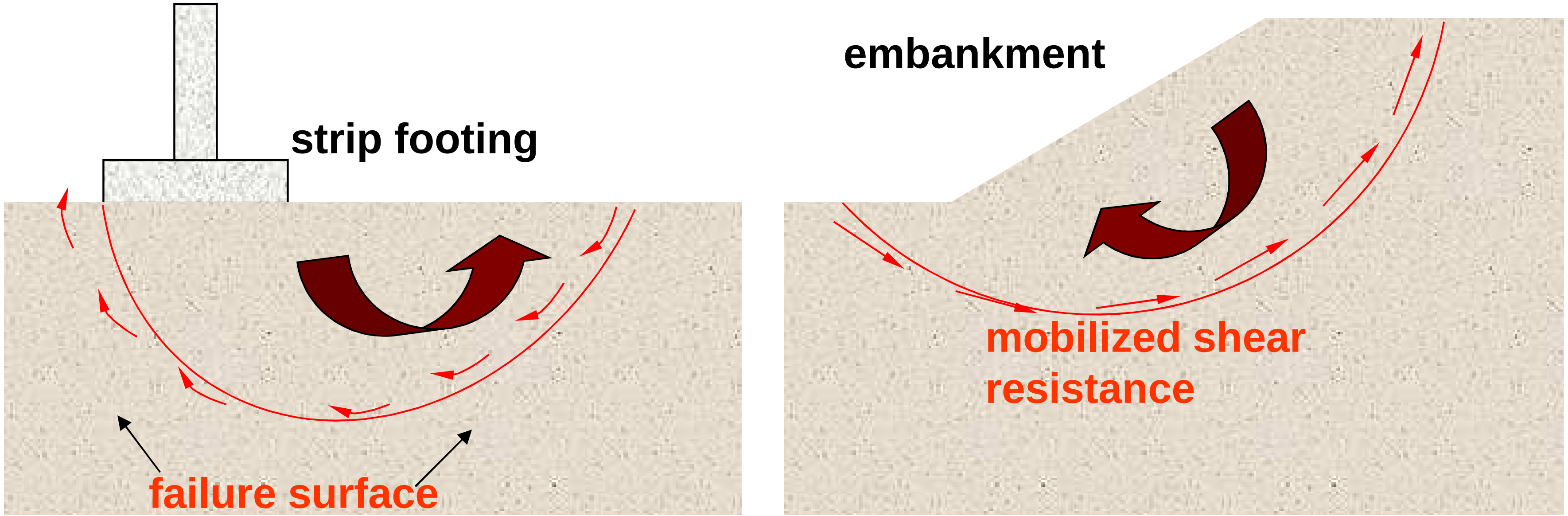


Shear Failure Under Foundation Load



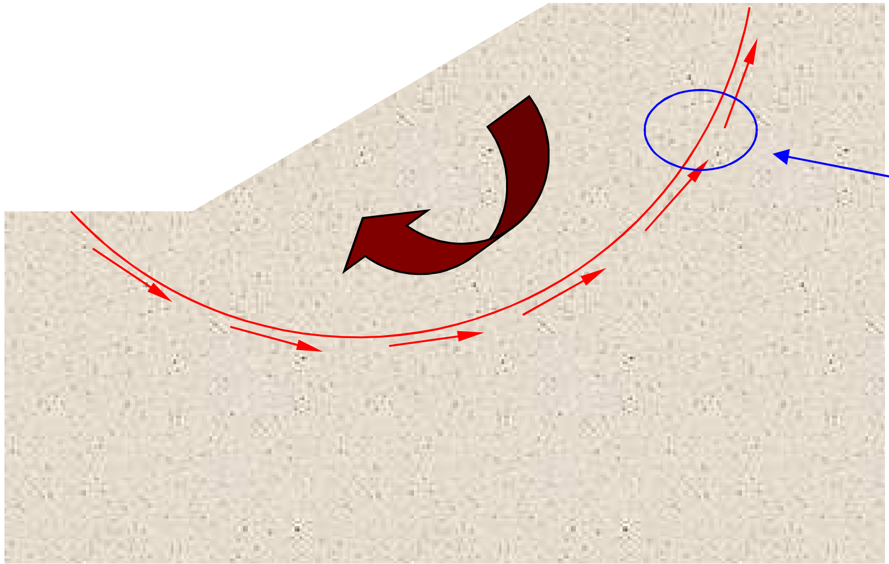
Shear failure

Soils generally fail in **shear**



At failure, shear stress along the failure surface reaches the shear strength.

Shear failure

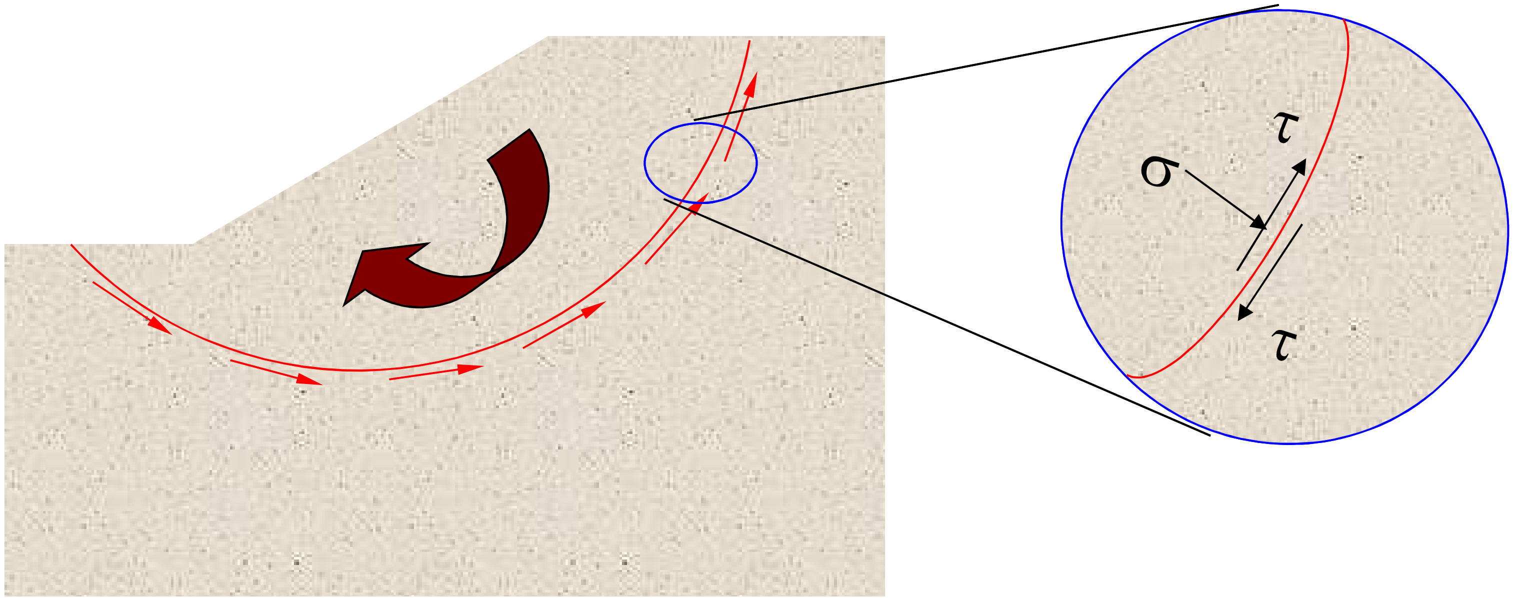


failure surface

The soil grains slide over each other along the failure surface.

No crushing of individual grains.

Shear failure mechanism



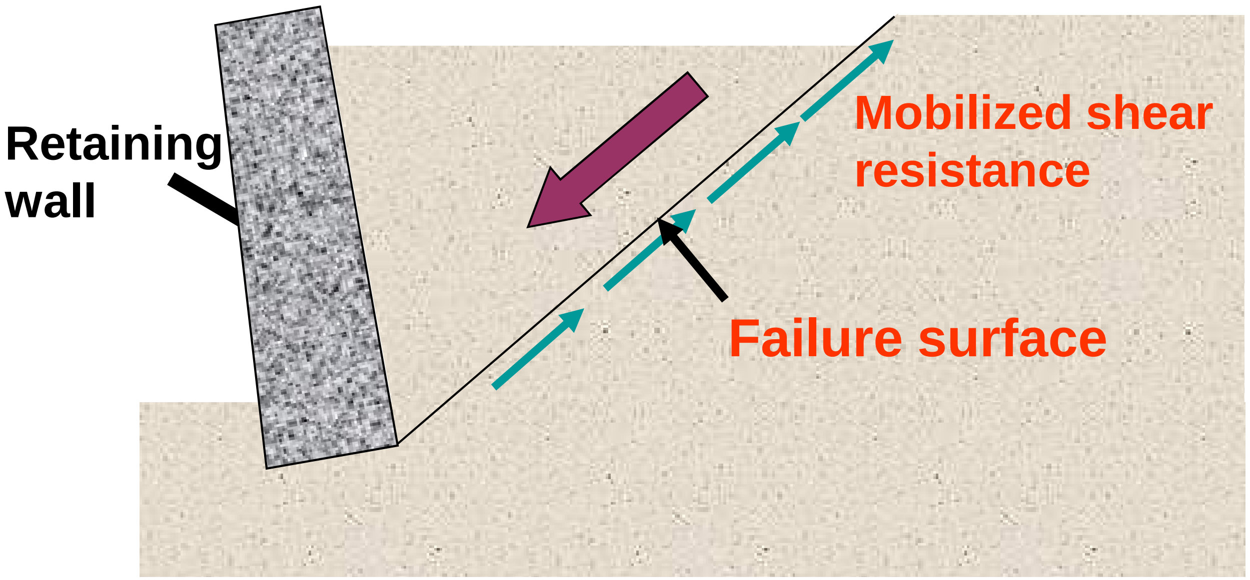
At failure, shear stress along the failure surface (τ) reaches the shear strength (τ_f).

Shear failure of soils

Soils generally fail in **shear**

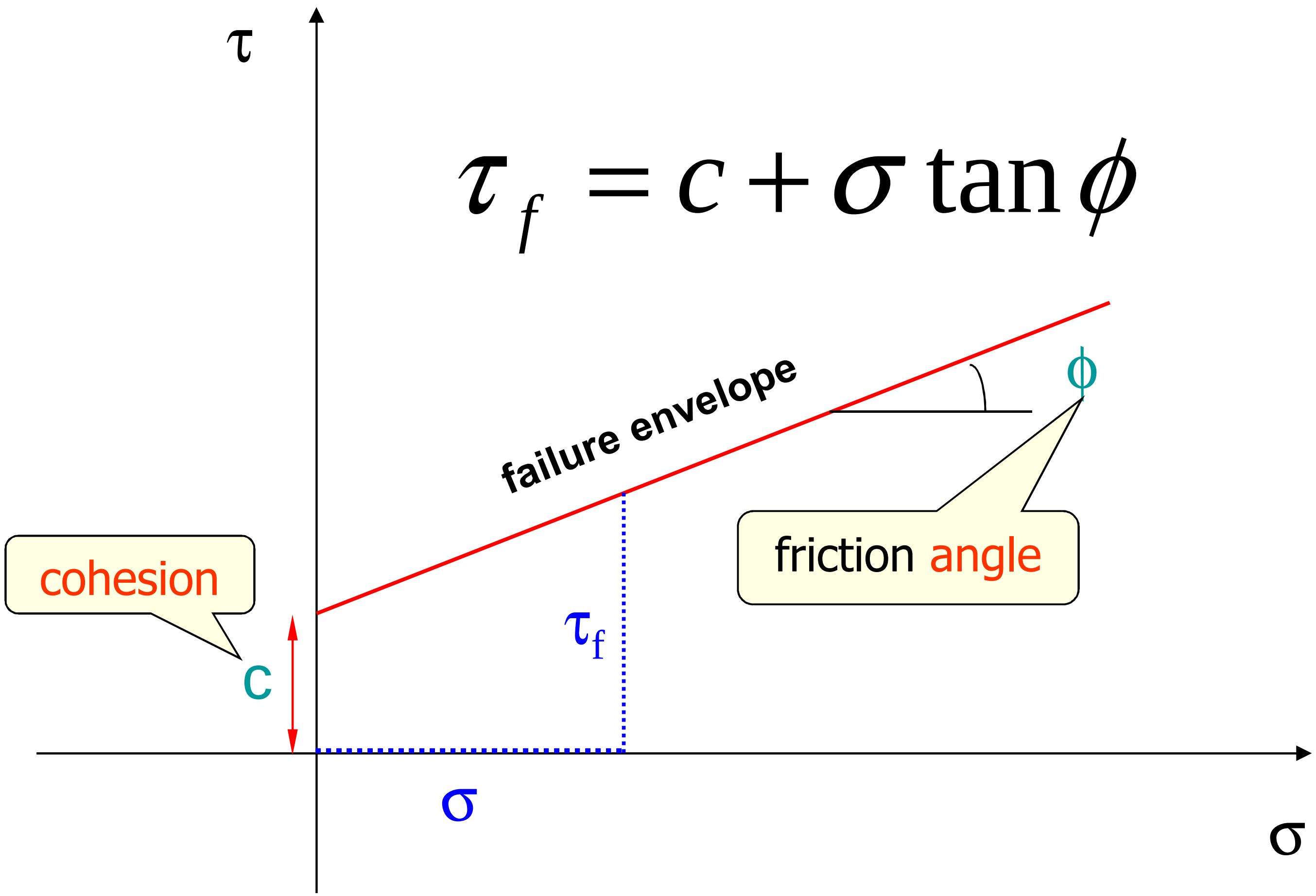
Shear failure of soils

Soils generally fail in **shear**



At failure, shear stress along the failure surface (mobilized shear resistance) reaches the shear strength.

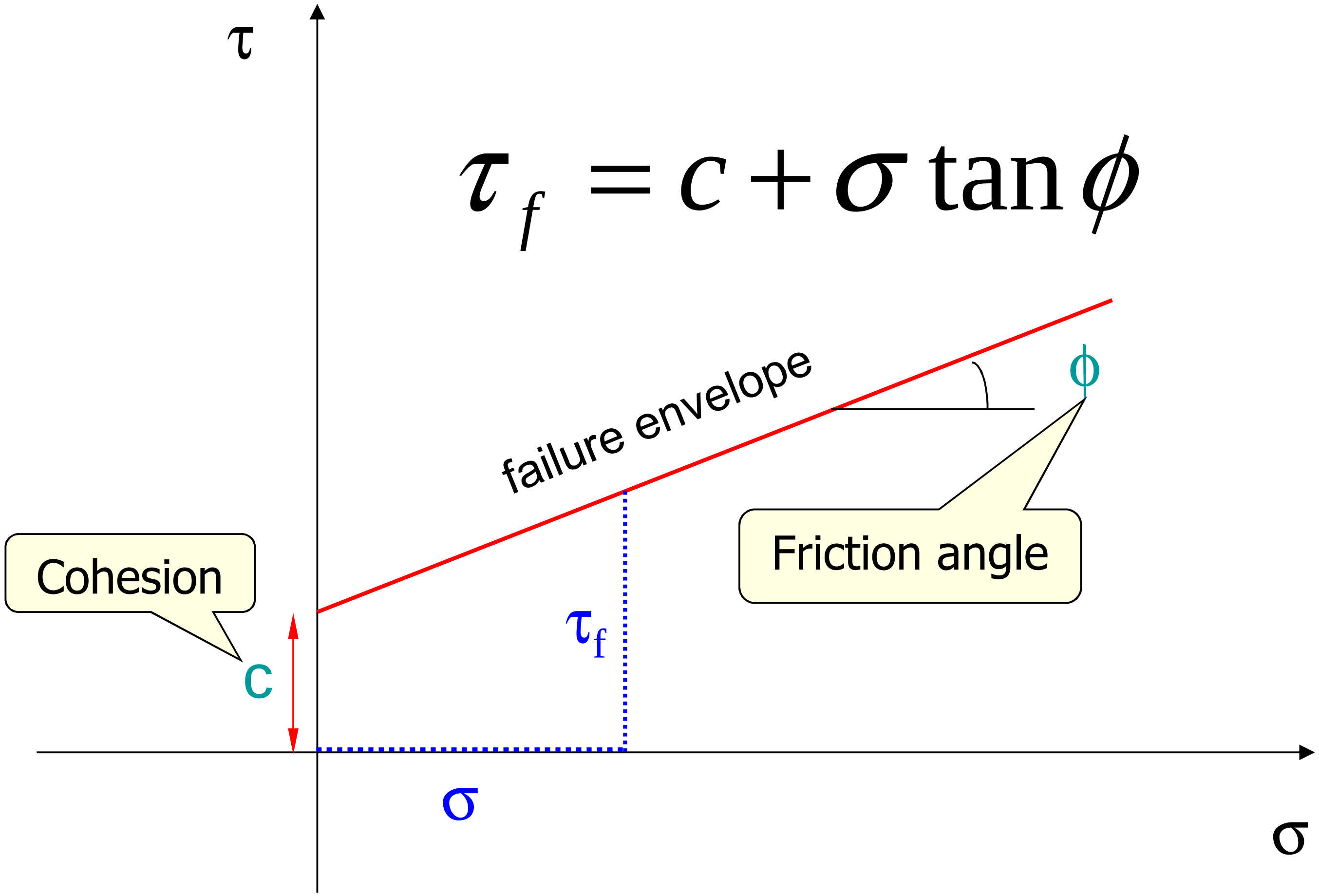
Mohr-Coulomb Failure Criterion



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

Mohr-Coulomb Failure Criterion

(in terms of **total stresses**)



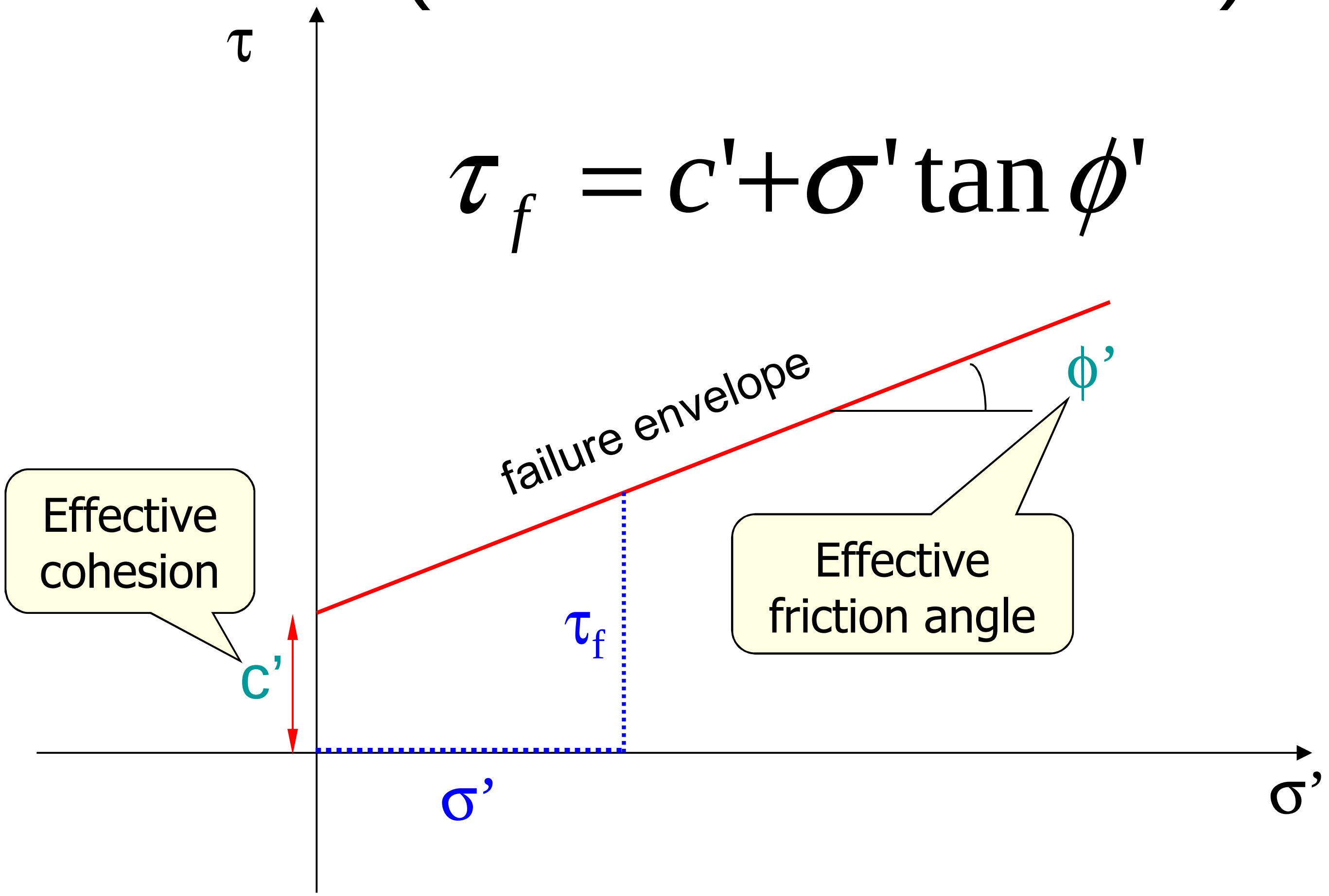
$$\tau_f = c + \sigma \tan \phi$$

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

Mohr-Coulomb Failure Criterion

(in terms of effective stresses)

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



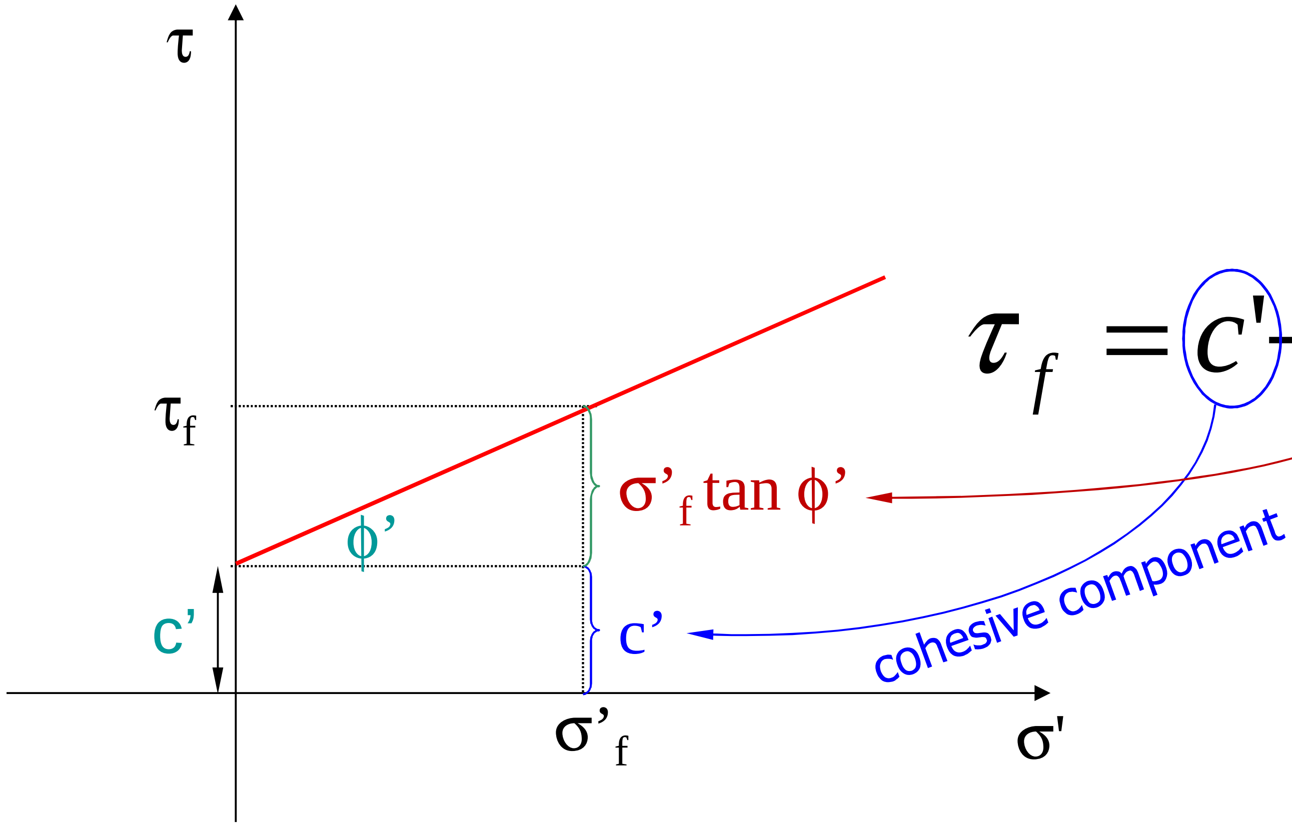
$$\sigma' = \sigma - u$$

u = pore water pressure

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

Mohr-Coulomb Failure Criterion

Shear strength consists of two components:
cohesive and **frictional**.

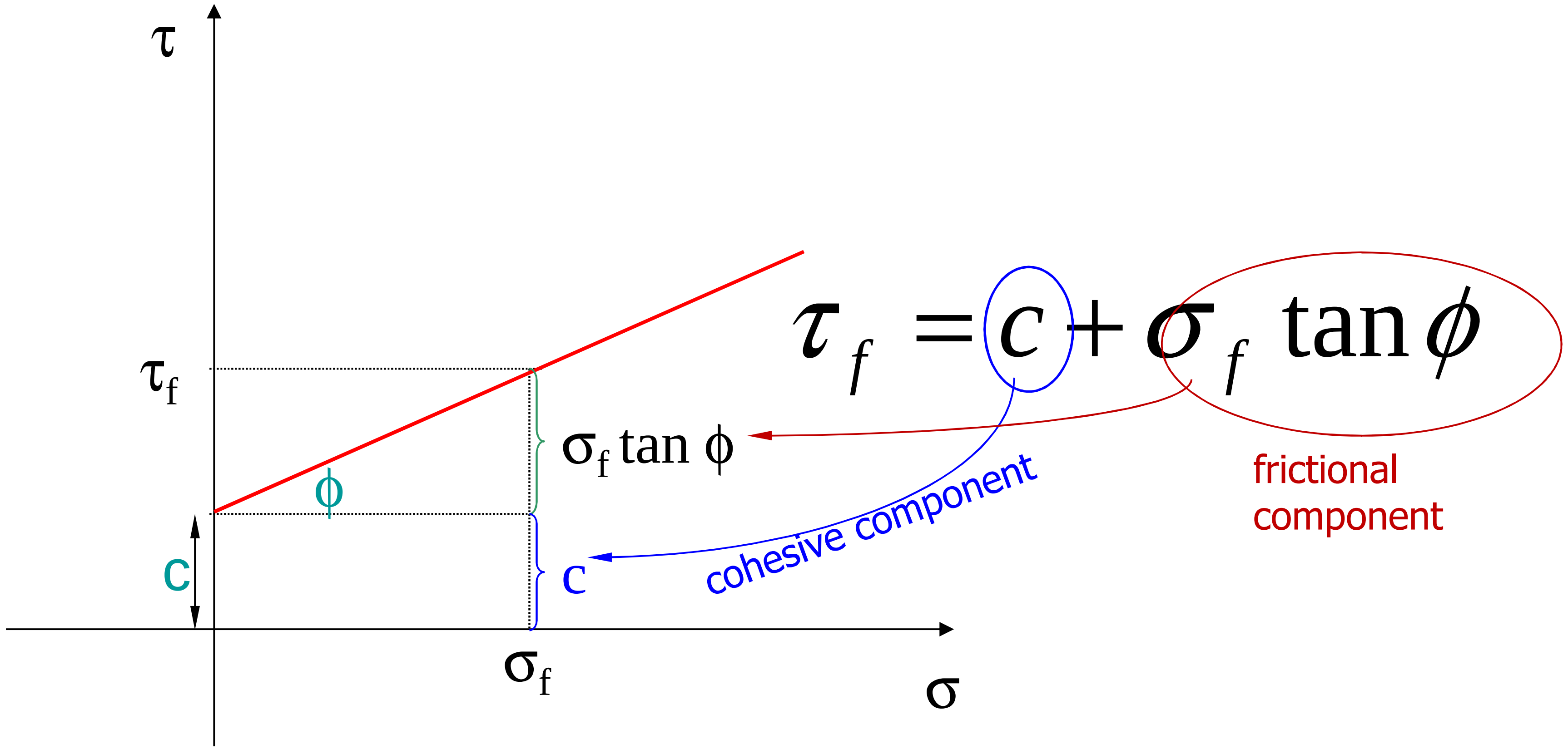


$$\tau_f = c' + \sigma'_f \tan\phi'$$

frictional component

Mohr-Coulomb Failure Criterion

Shear strength consists of two components: **cohesive** and **frictional**.

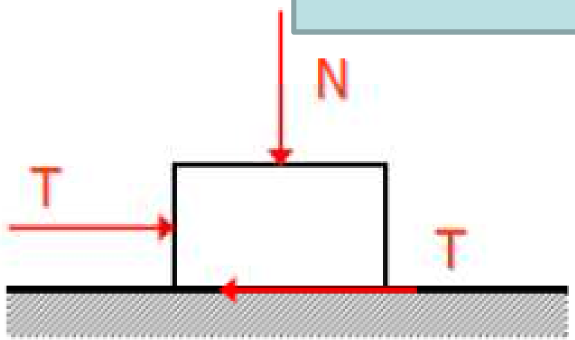


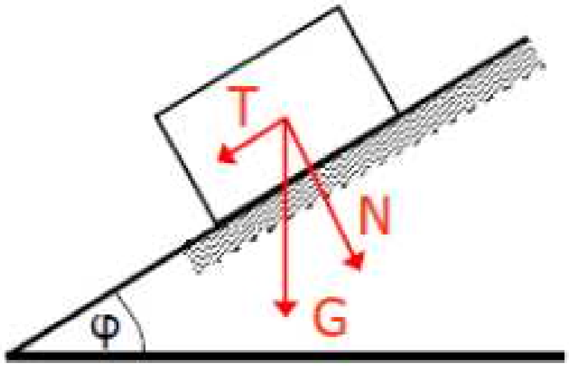
$$\tau_f = c + \sigma_f \tan\phi$$

- c and ϕ are measures of shear strength.
- Higher the values, higher the shear strength.

Shear strength of soils

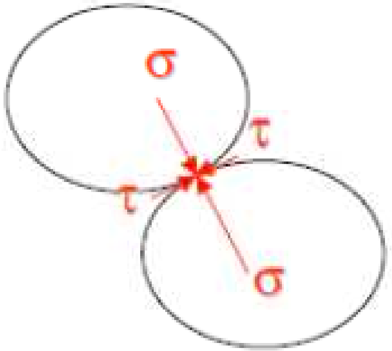
T=N.Tanφ





Granular soils

$\tau = \sigma' \tan\varphi$

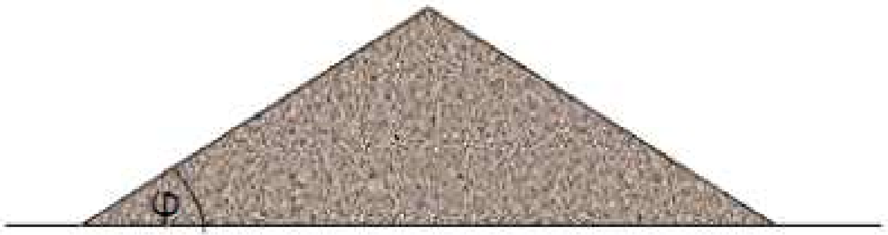


For soils this φ angle is called:

angle of internal friction or

friction angle

Angle of repose = φ



Shear strength of soils

Fine grained soils:

Their strength is, apart from friction, due to internal forces holding the particles together

This propertiy is called cohesion, and soils possessing it are cohesive soils

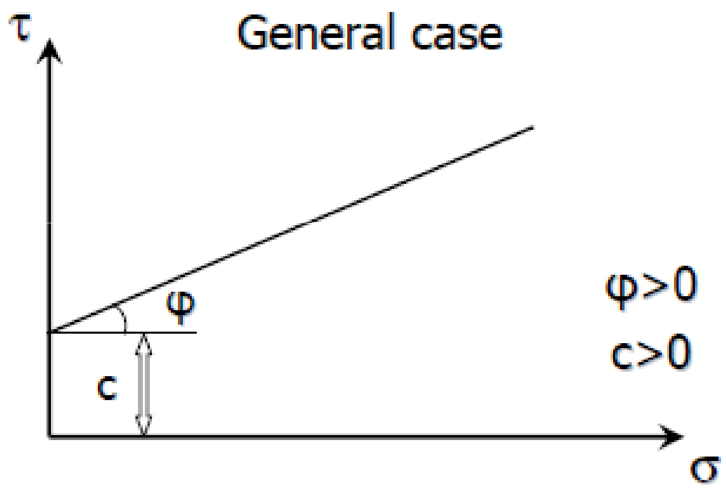
Coulomb's law extended to cohesive soils:

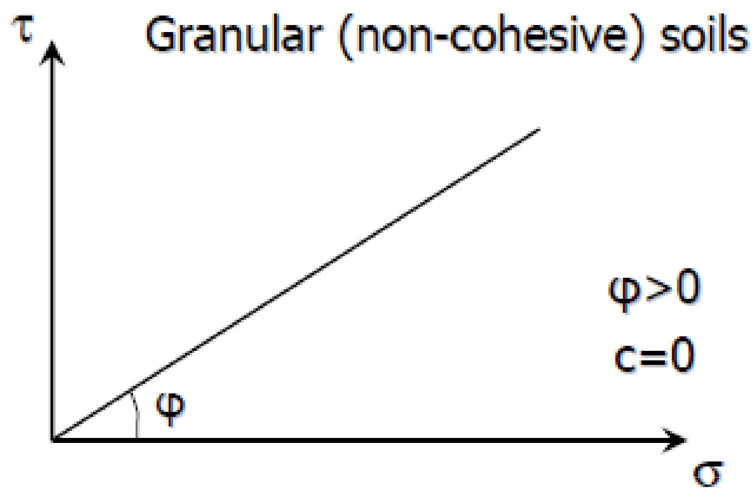
$$\tau = \sigma \cdot \tan\varphi + c$$

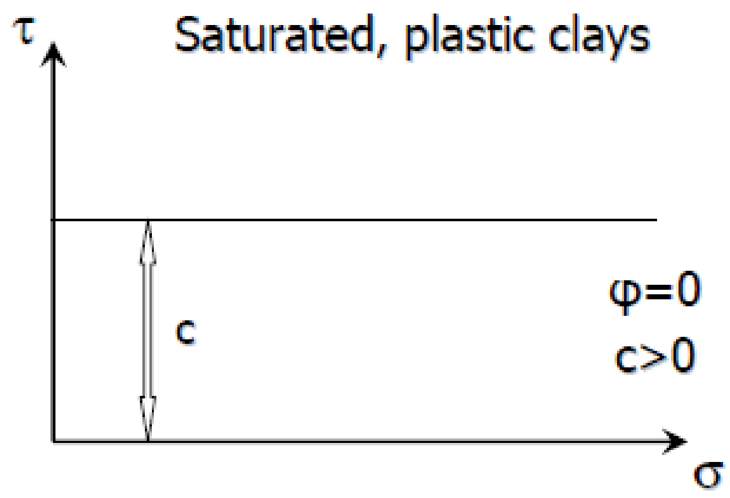
In case of saturated soils this can be expressed as:

$$\tau = (\sigma - u) \cdot \tan\varphi + c$$

Graphical represantation of Mohr Coulomb failure criteria







Determination of shear strength parameters of soils (c, ϕ or c', ϕ')

Laboratory tests on specimens taken from representative undisturbed samples

Most common laboratory tests to determine the shear strength parameters are,

1. **Direct shear test**
2. **Triaxial shear test**

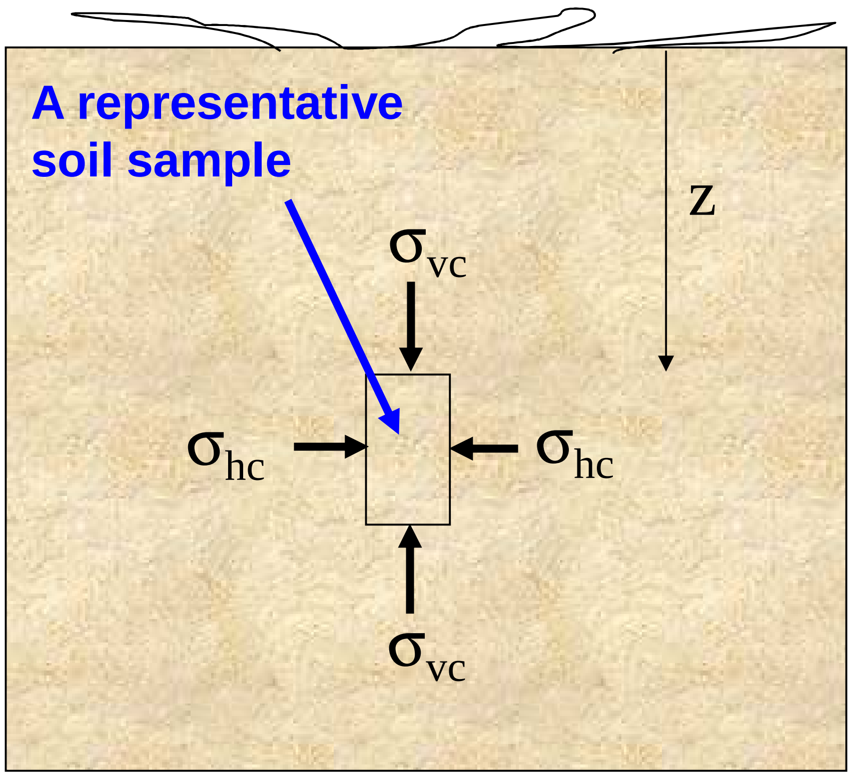
Other laboratory tests include, Direct simple shear test, torsional ring shear test, True triaxiaal, plane strain triaxial test, laboratory vane shear test, laboratory fall cone test

Field tests

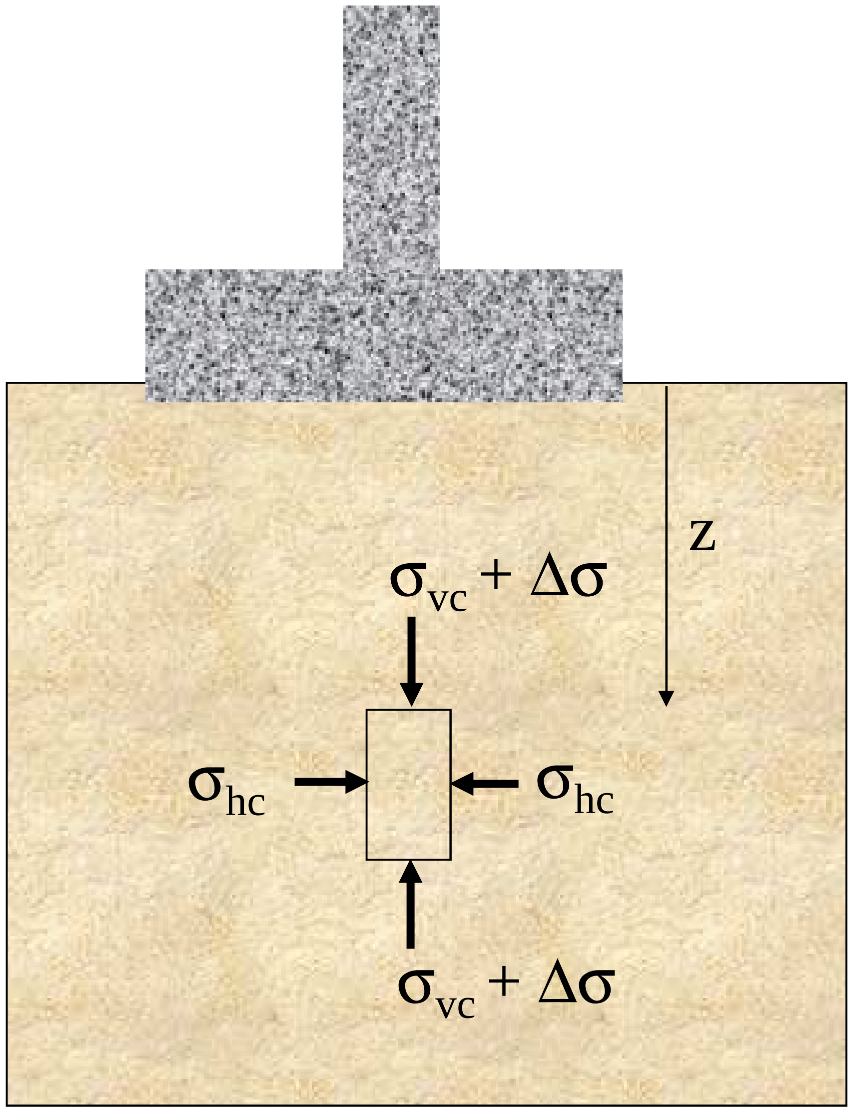
1. **Vane shear test**
2. **Pocket penetrometer**
3. **Fall cone**
4. **Pressuremeter**
5. **Static cone penetrometer**
6. **Standard penetration test**

Laboratory tests

Field conditions



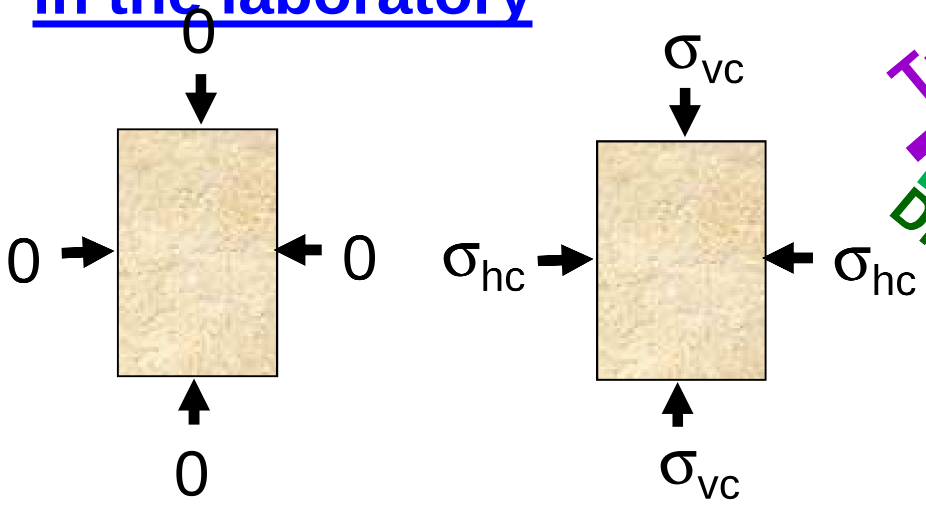
Before construction

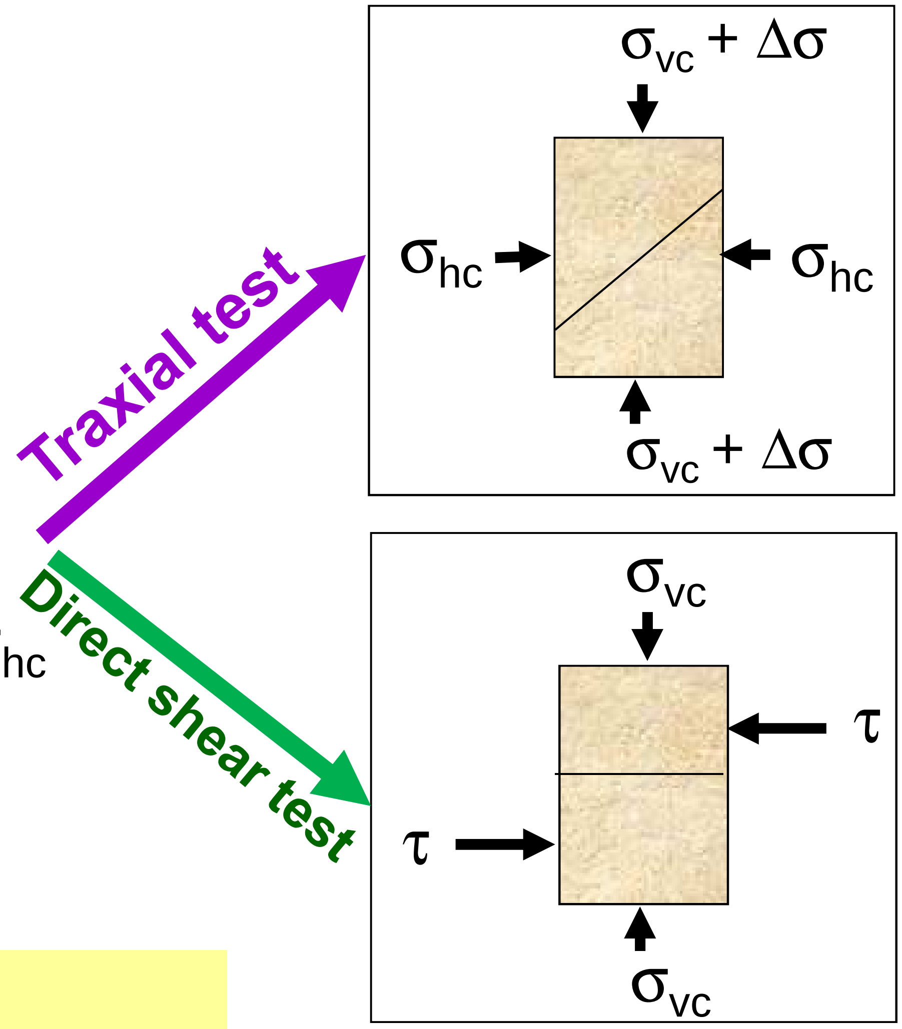


After and during construction

Laboratory tests

Simulating field conditions in the laboratory





Representative soil sample taken from the site

Step 1

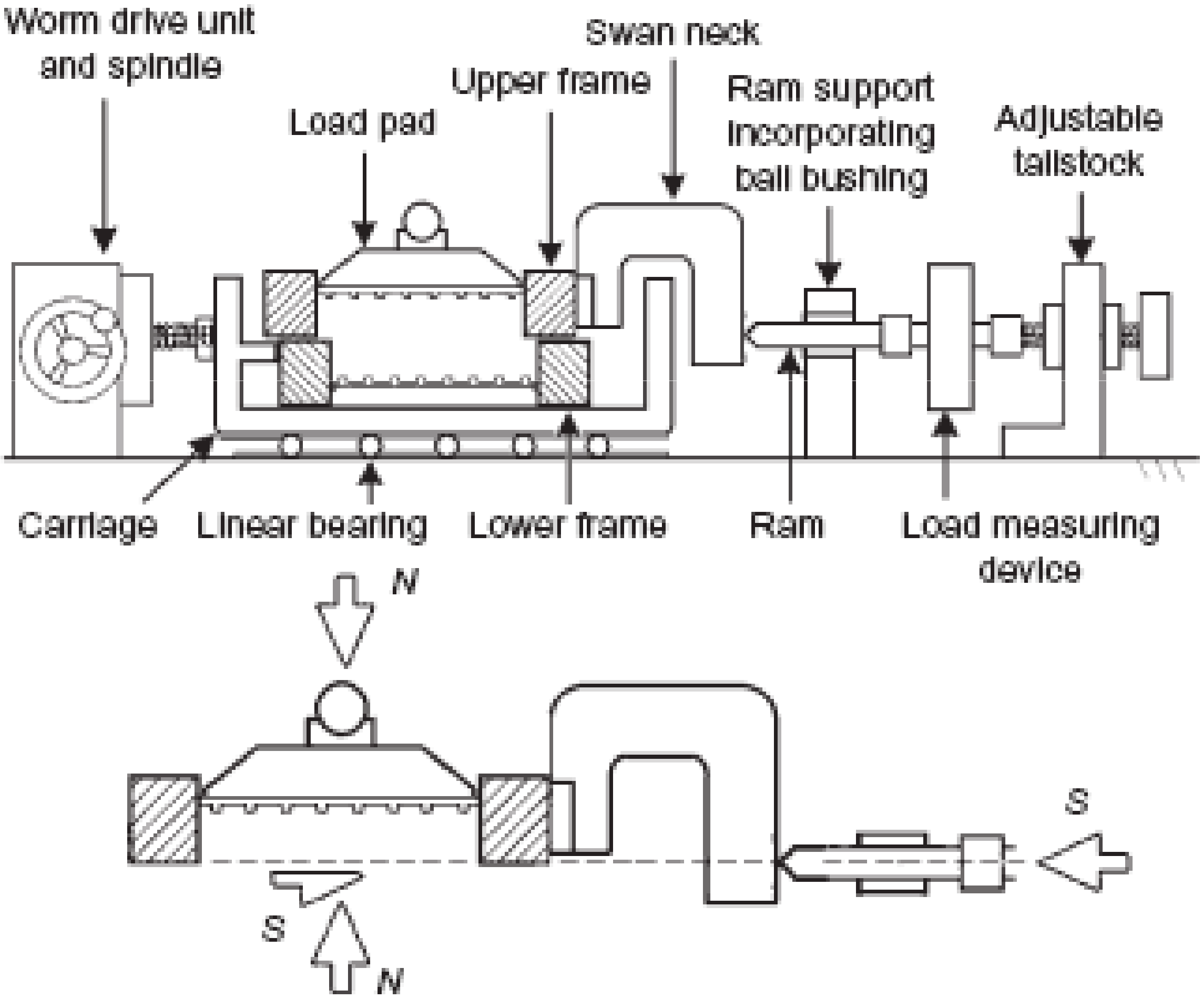
Set the specimen in the apparatus and apply the initial stress condition

Step 2

Apply the corresponding field stress conditions

Direct shear test

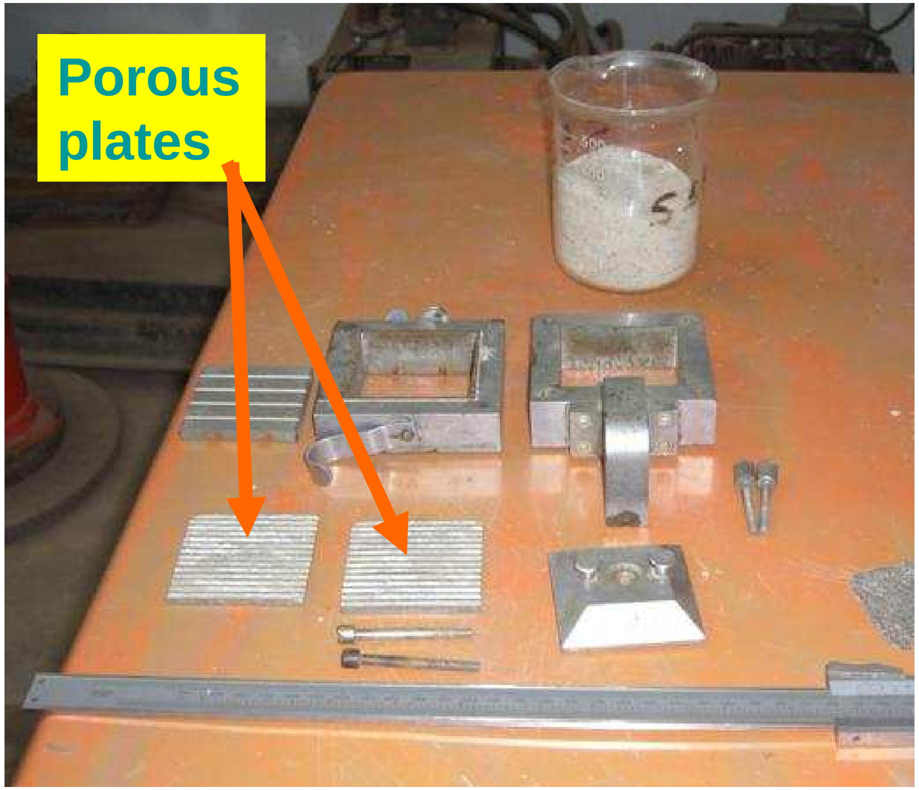
Schematic diagram of the direct shear apparatus



Direct shear test

Direct shear test is most suitable for <u>consolidated drained</u> tests specially on granular soils (e.g.: sand) or stiff clays

Preparation of a sand specimen



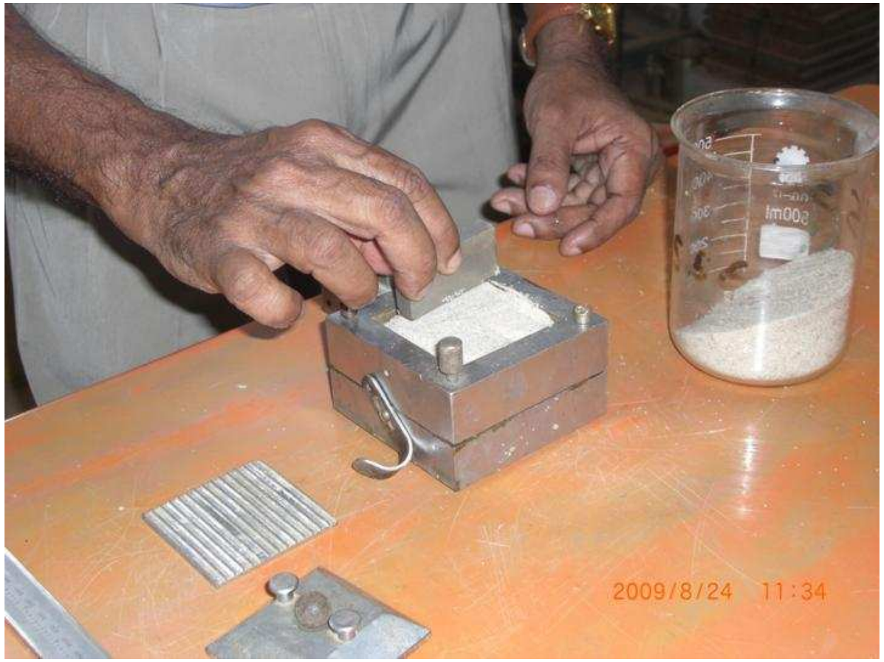
Components of the shear box

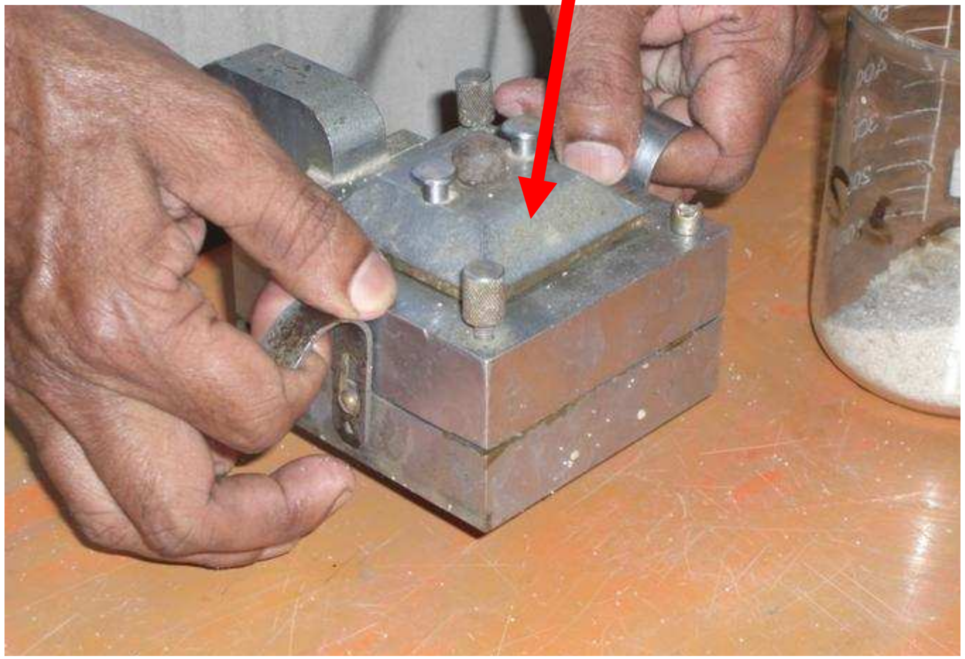
Preparation of a sand specimen

Direct shear test

Preparation of a sand specimen

Pressure plate

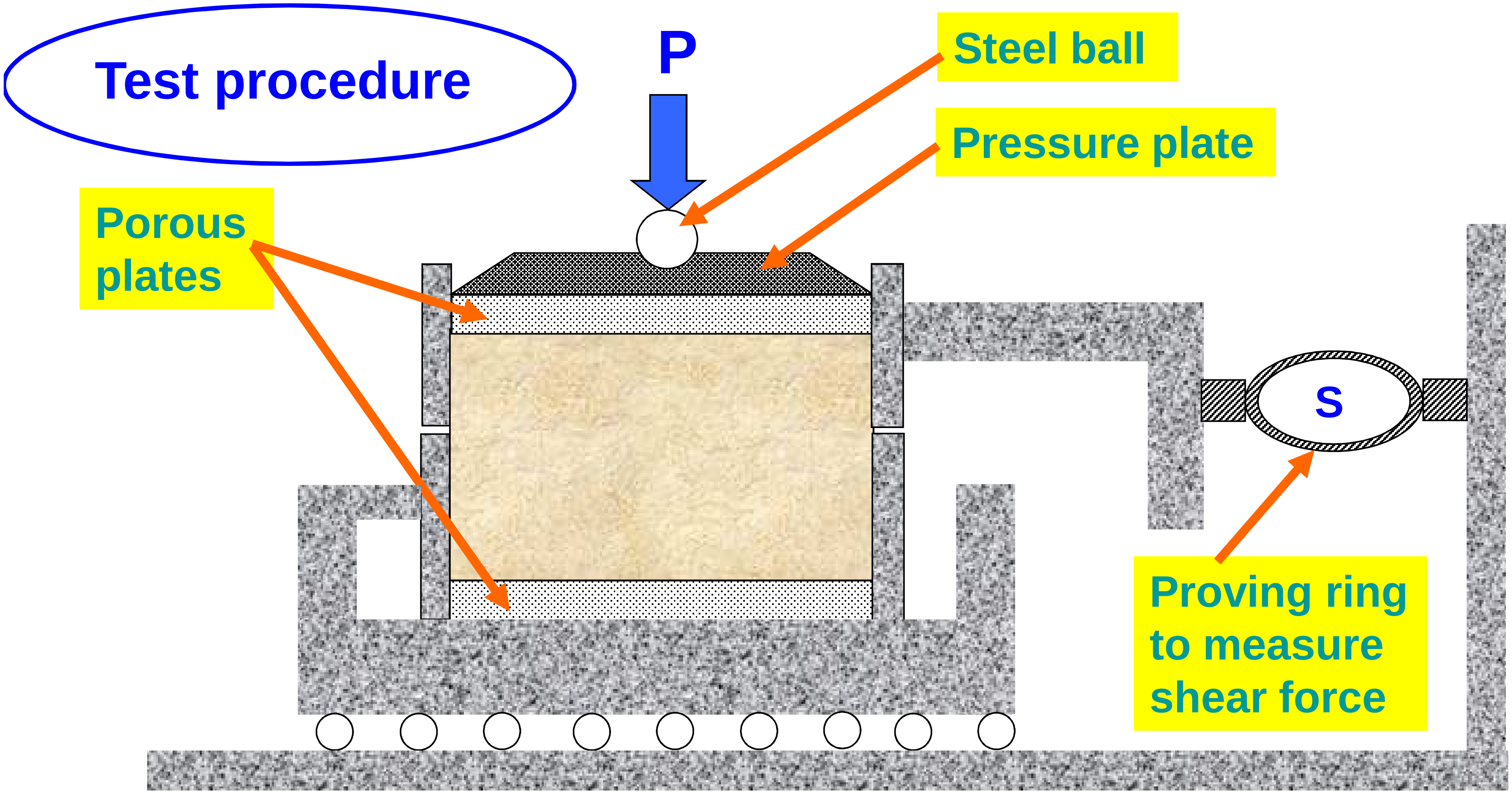




Leveling the top surface of specimen

Specimen preparation completed

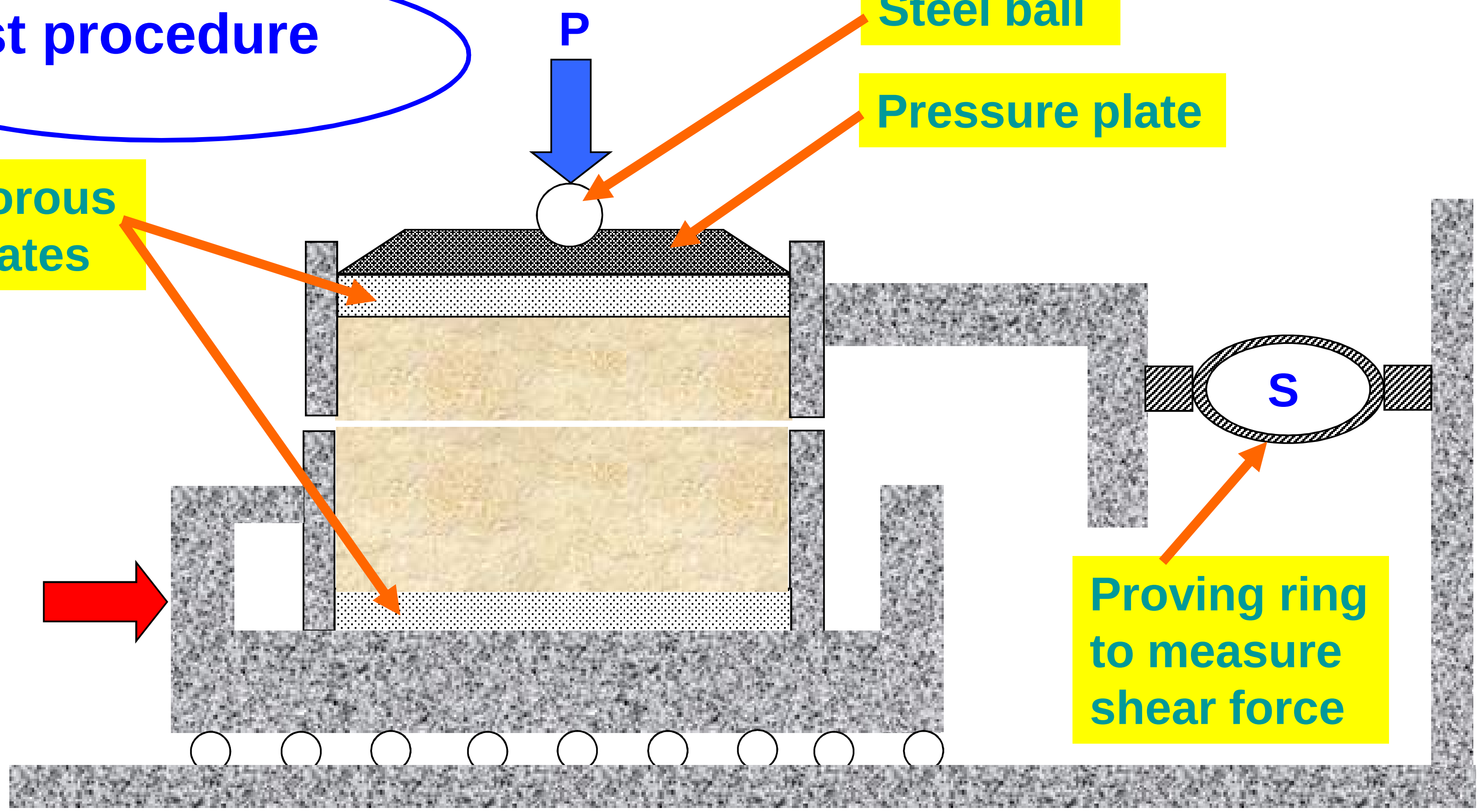
Direct shear test



Step 1: Apply a vertical load to the specimen and wait for consolidation

Direct shear test

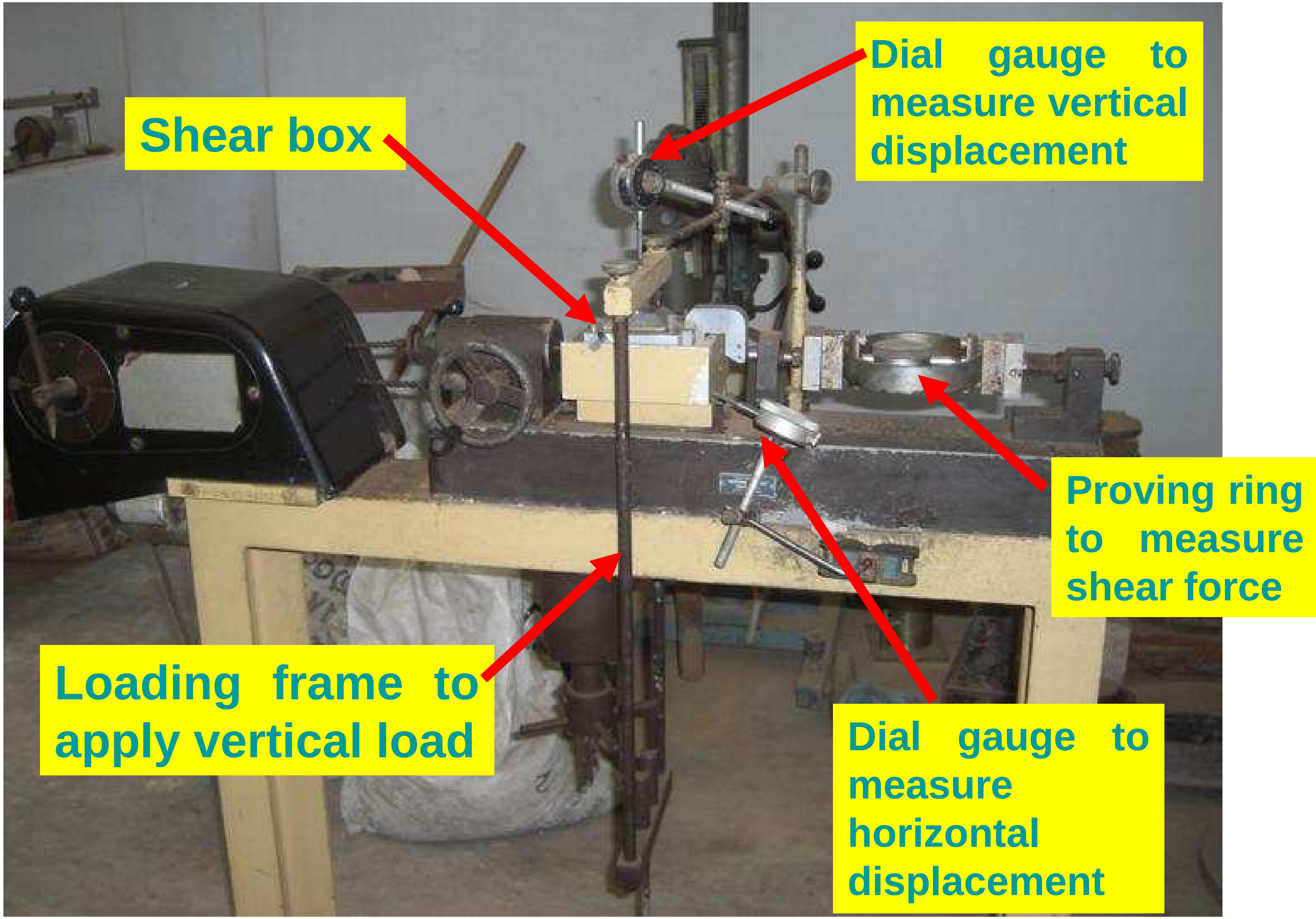
Test procedure



Step 1: Apply a vertical load to the specimen and wait for consolidation

Step 2: Lower box is subjected to a horizontal displacement at a constant rate

Direct shear test



Direct shear test

Analysis of test results

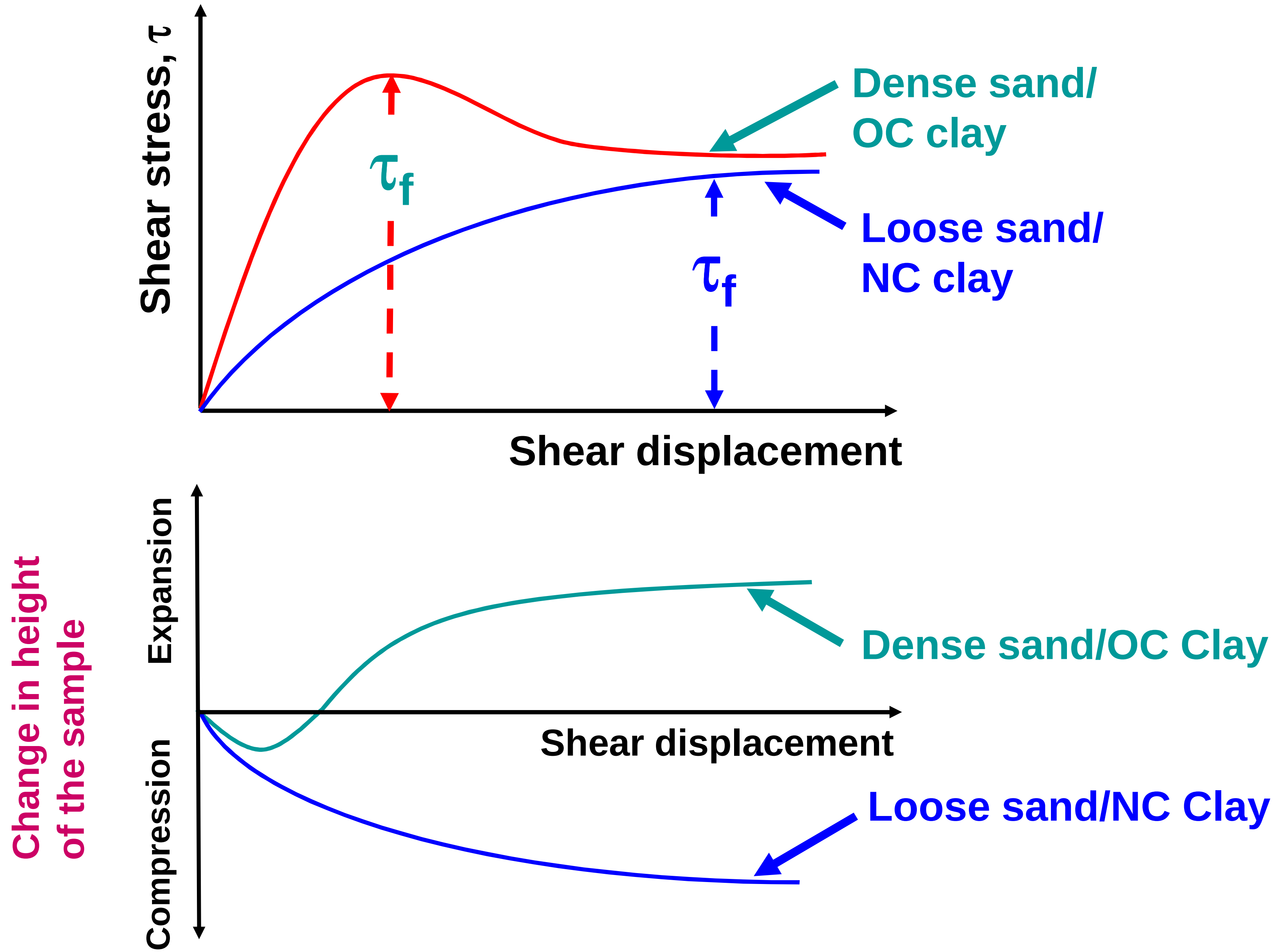
$$\sigma = \text{Normal stress} = \frac{\text{Normal force (P)}}{\text{Area of cross section of the sample}}$$

$$\tau = \text{Shear stress} = \frac{\text{Shear resistance developed at the sliding surface (S)}}{\text{Area of cross section of the sample}}$$

Note: Cross-sectional area of the sample changes with the horizontal displacement

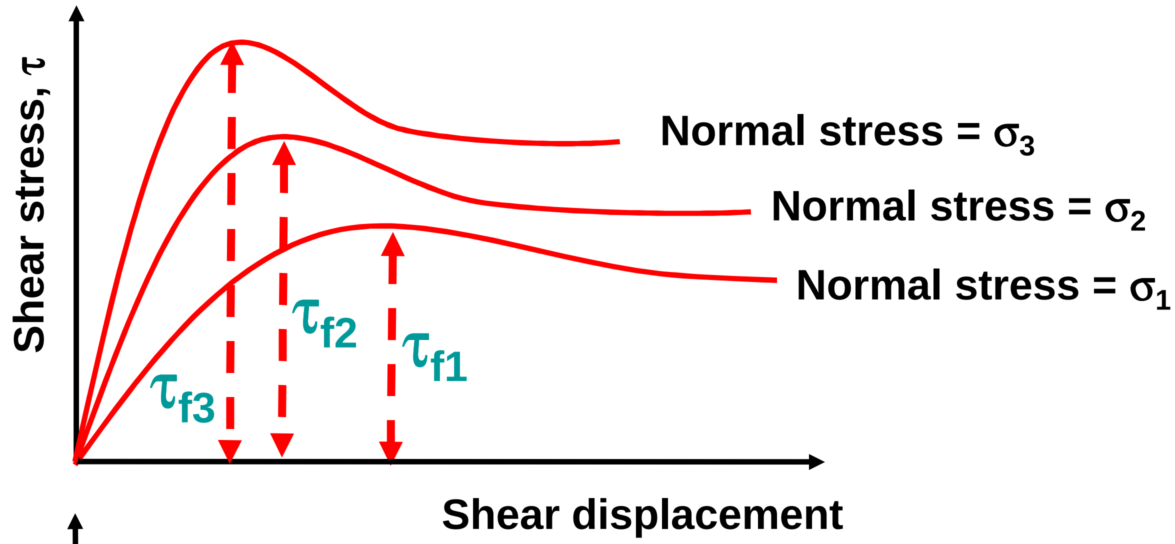
Direct shear tests on sands

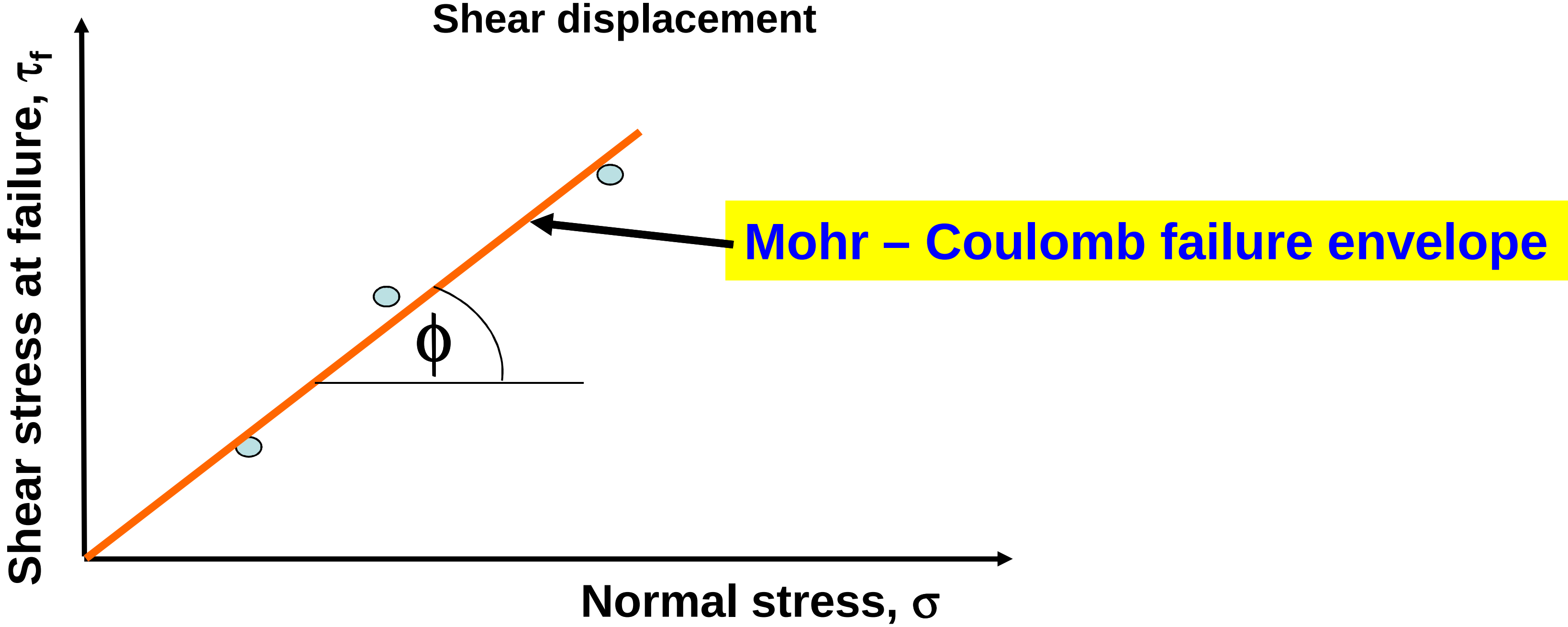
Stress-strain relationship



Direct shear tests on sands

How to determine strength parameters c and ϕ





Direct shear tests on sands

Some important facts on strength parameters c and ϕ of sand

Sand is cohesionless hence c = 0

Direct shear tests are drained and pore water pressures are dissipated, hence u = 0

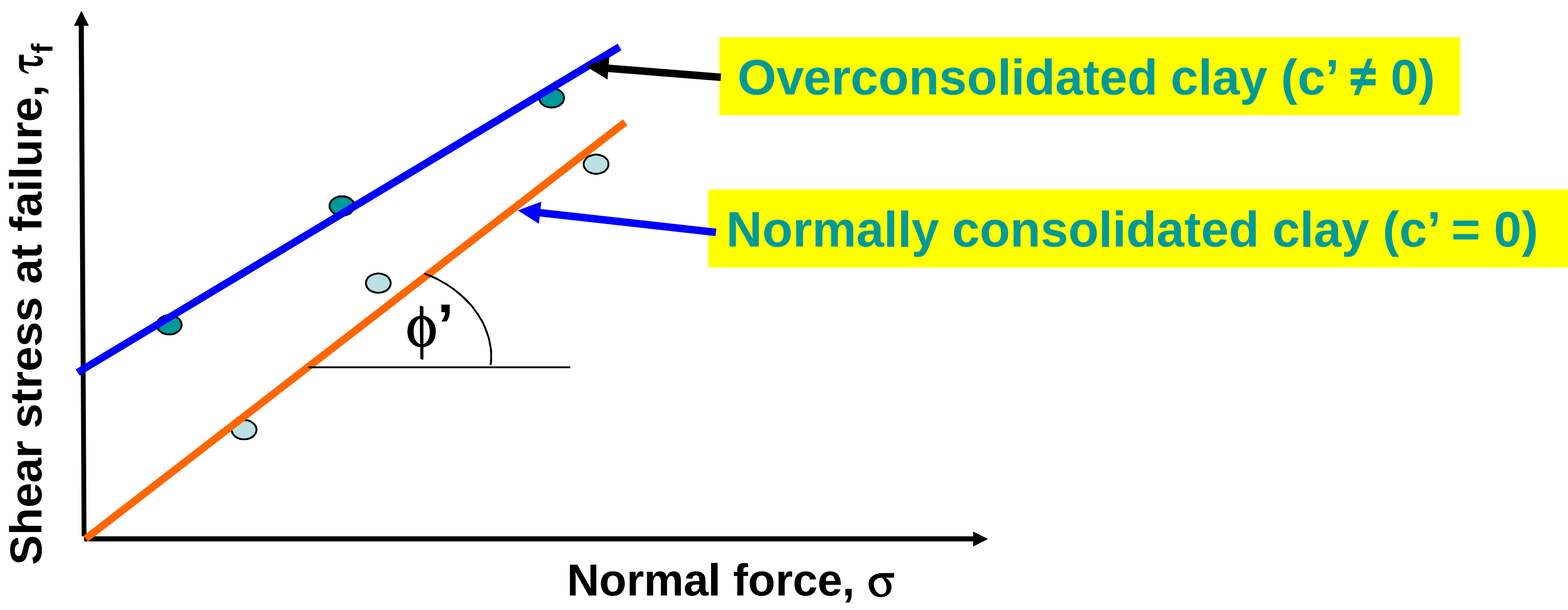
Therefore,

$\phi' = \phi$ and $c' = c = 0$

Direct shear tests on clays

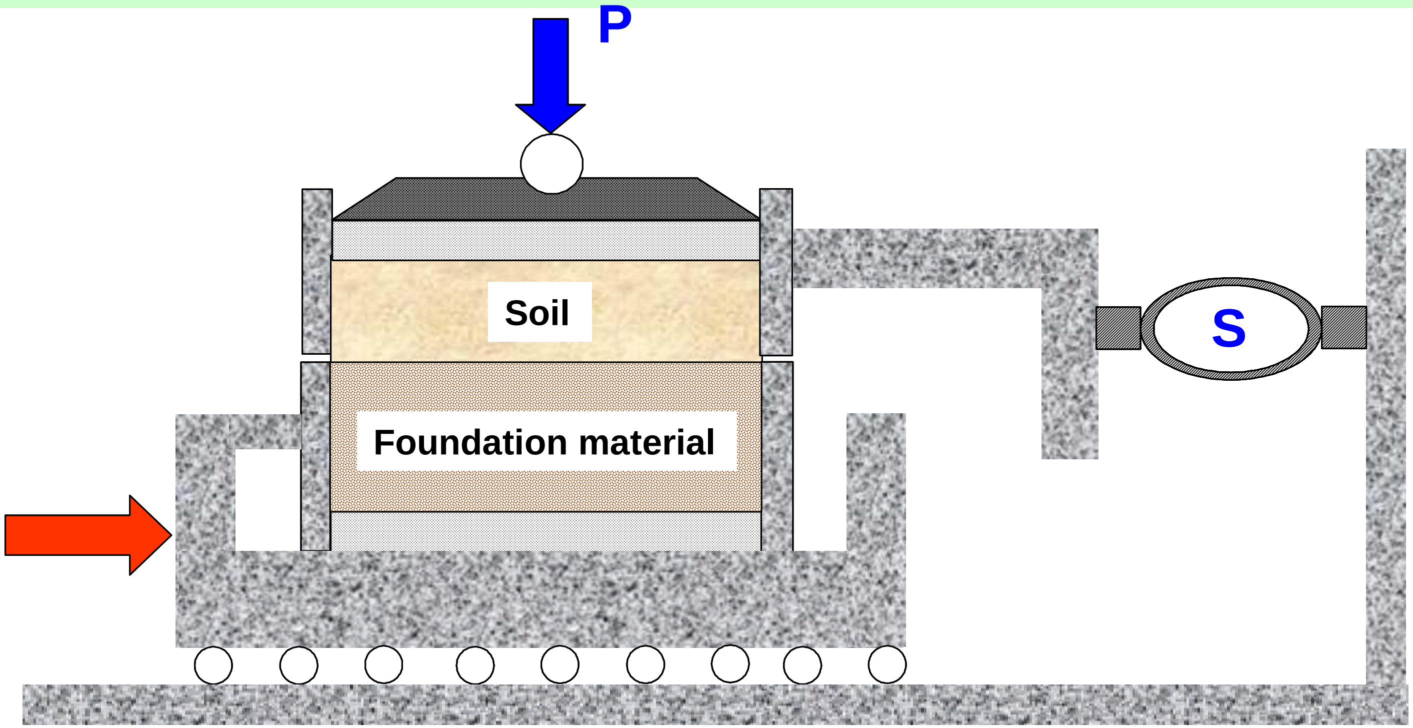
In case of clay, horizontal displacement should be applied at a very slow rate to allow dissipation of pore water pressure (therefore, one test would take several days to finish)

Failure envelopes for clay from drained direct shear tests



Interface tests on direct shear apparatus

In many foundation design problems and retaining wall problems, it is required to determine the angle of internal friction between soil and the structural material (concrete, steel or wood)



$$\tau_f = c_a + \sigma' \tan \delta$$

Where,

c_a = adhesion,

δ = angle of internal friction

Two basic definitions of clay based on stress history:

1. **Normally consolidated,** whose present effective overburden pressure is the maximum pressure that the soil was subjected to in the past. **NC**

2. **Overconsolidated**, whose present effective overburden pressure is less than that which the soil experienced in the past. The maximum effective past pressure is called the ***preconsolidation pressure.*** **OC**

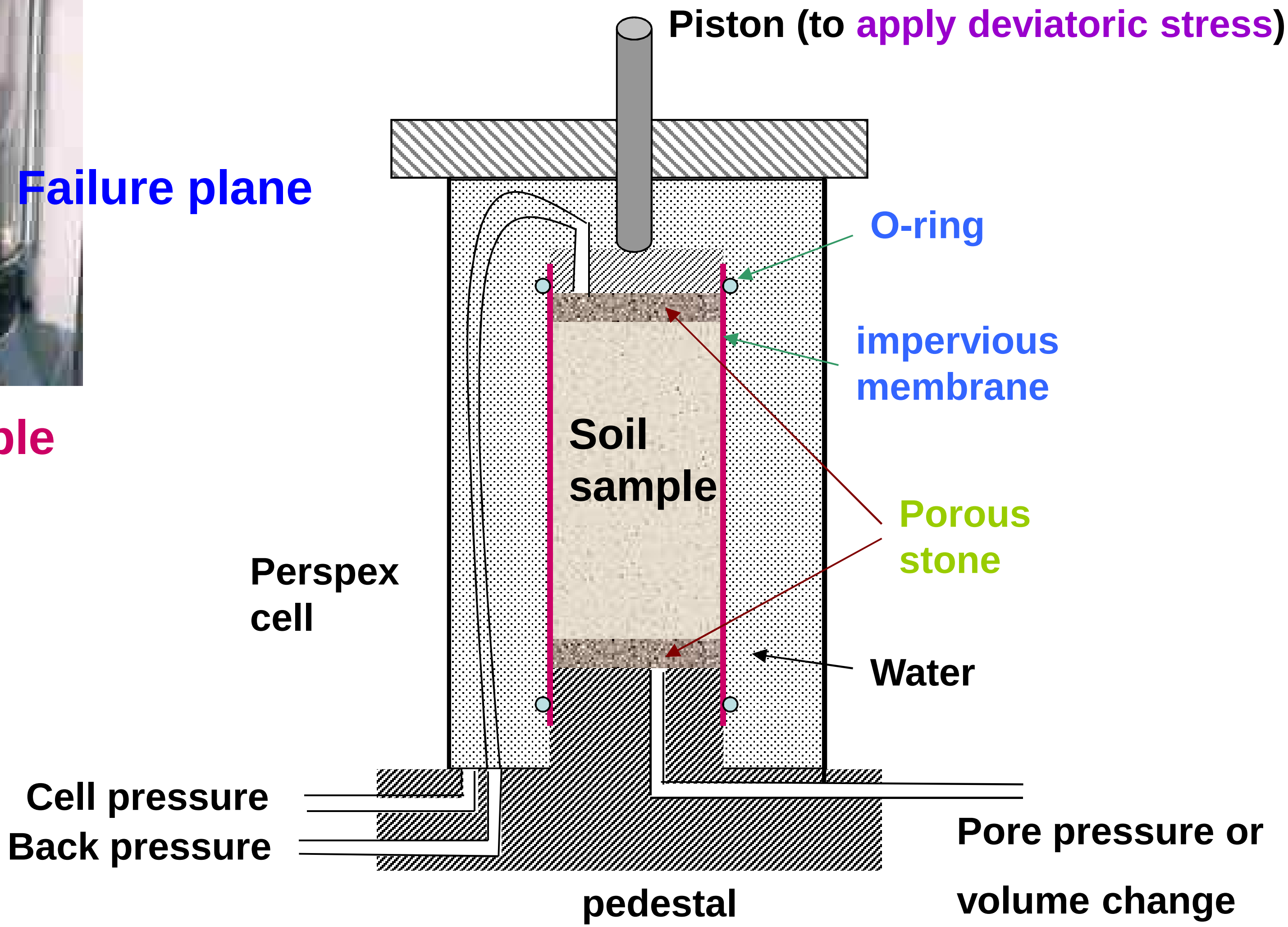
The overconsolidation ratio (OCR) for a soil can now be defined as

$$OCR = \frac{\sigma'_c}{\sigma'}$$

where σ'_c = preconsolidation pressure of a specimen
σ' = present effective vertical pressure

Triaxial Shear Test

Soil sample
at failure



Triaxial Shear Test

Specimen preparation (undisturbed sample)

Sampling tubes

Sample extruder

Triaxial Shear Test

Specimen preparation (undisturbed sample)

Edges of the sample are carefully trimmed

Setting up the sample in the triaxial cell

Triaxial Shear Test

Specimen preparation (undisturbed sample)

Sample is covered with a rubber membrane and sealed

Cell is completely filled with water

Triaxial Shear Test

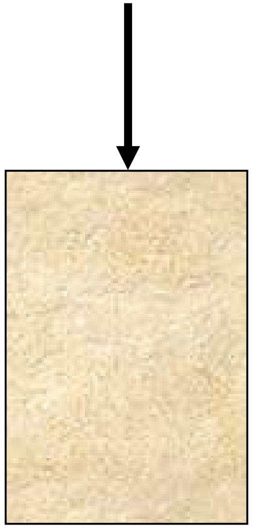
Specimen preparation (undisturbed sample)

Proving ring to measure the deviator load

Dial gauge to measure vertical displacement

Unconfined Compression Test (UC Test)

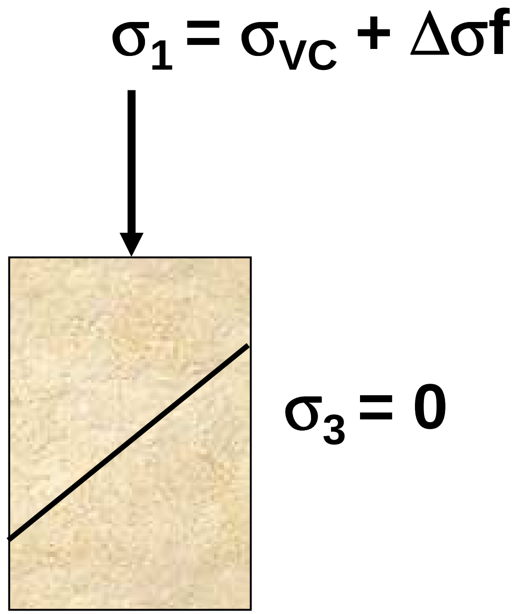
$$\sigma_1 = \sigma_{VC} + \Delta\sigma$$

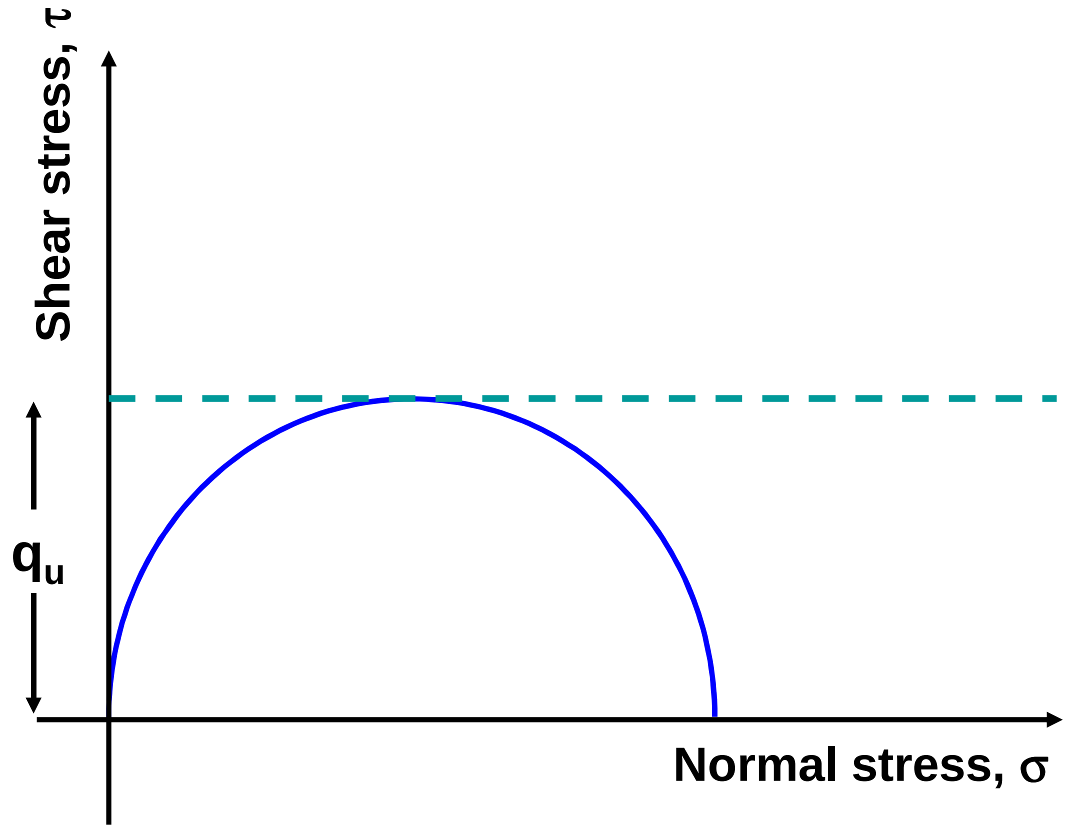


$$\sigma_3 = 0$$

Confining pressure is zero in the UC test

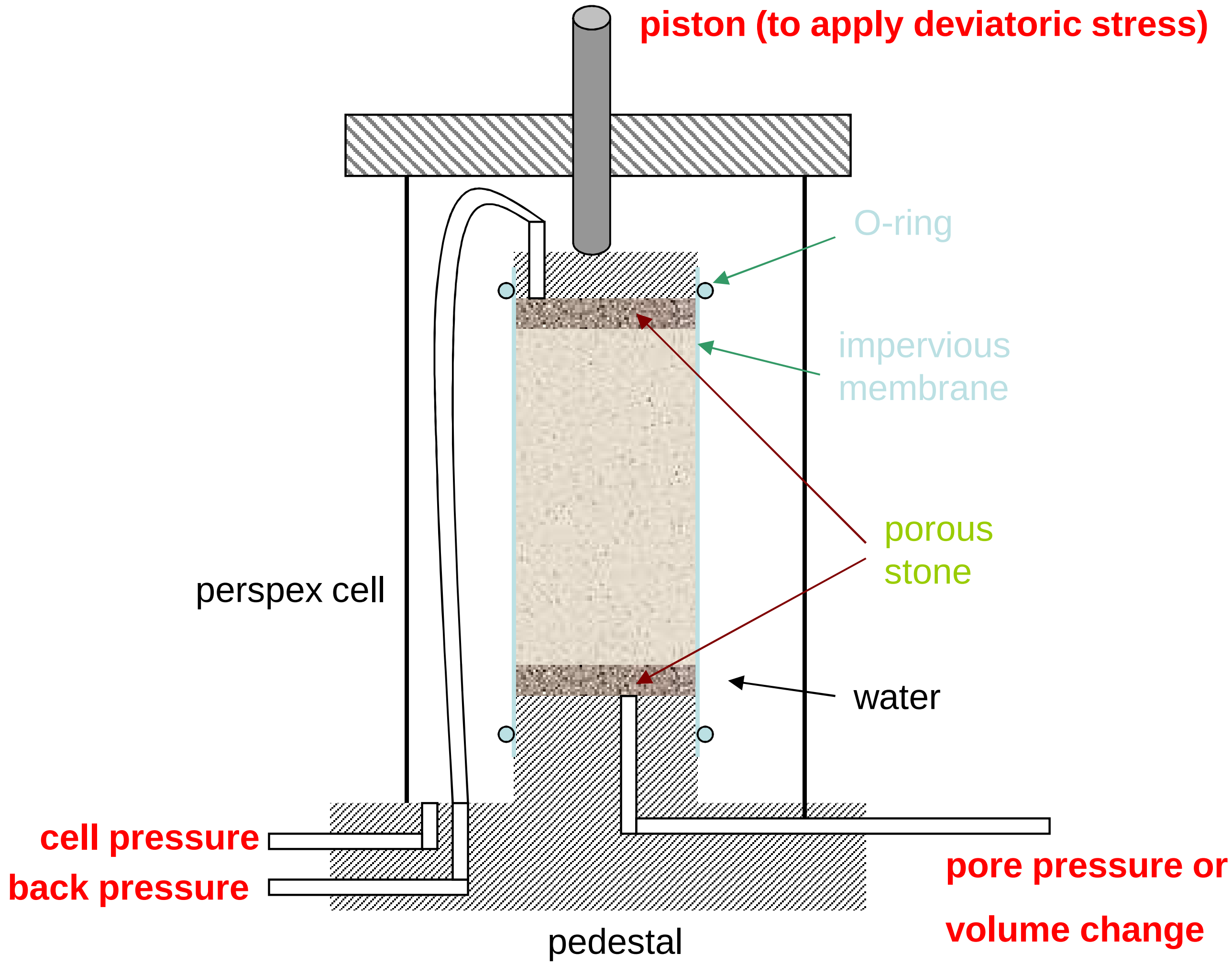
Unconfined Compression Test (UC Test)





$$\tau_f = \sigma_1/2 = q_u/2 = c_u$$

Triaxial Test Apparatus

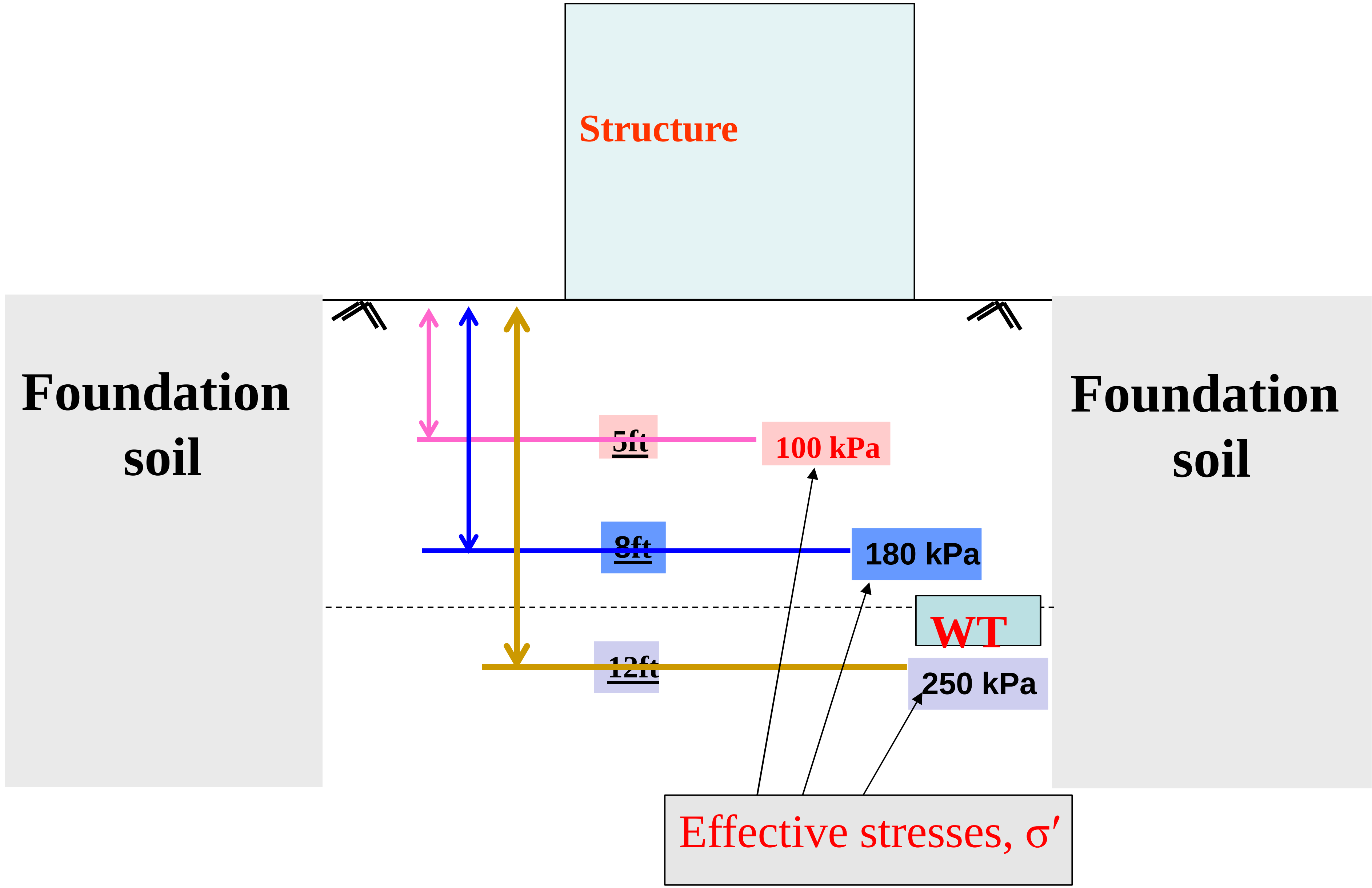


UNDRAINED TESTS

- **NO** drainage of pore water
- simulates short term condition (e.g. end of construction)
- excess pore water pressure, **Δu** is often finite

DRAINED TEST

- Drainage **ALLOW** for pore water
- simulates long term condition (e.g. *'many years'* after construction)
- excess pore water pressure, **$\Delta u = 0$;** however u is not necessarily = 0


Structure
Foundation soil
Foundation soil
5ft
100 kPa
8ft
180 kPa
WT
12ft
250 kPa
Effective stresses, σ′

Flashing

saturation- Worst condition

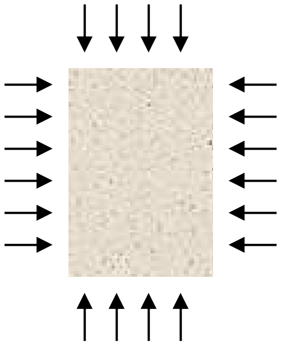
Consolidation - 250kPa

Shearing - Slow / High rate

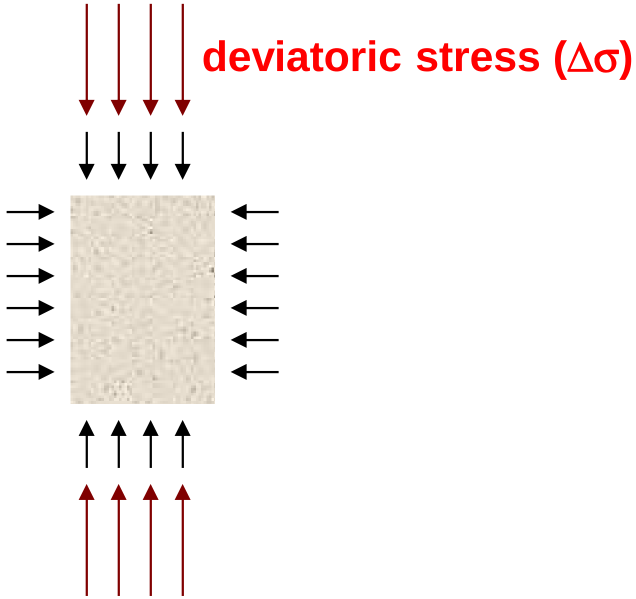
plotting./ calculating

c , ϕ or **c', ϕ'**

Types of Triaxial Tests



Under all-around cell pressure σ_c



Shearing (loading)

Is the drainage valve open?

yes → **Consolidated** sample

no → **Unconsolidated** sample

Is the drainage valve open?

yes → **Drained** loading

no → **Undrained** loading

Types of Triaxial Tests

Depending on whether drainage is allowed or not during

- ❖ initial isotropic cell pressure application, and
- ❖ shearing,

there are three special types of triaxial tests that have practical significances. They are:

Consolidated Drained (CD) test
Consolidated Undrained (CU) test
Unconsolidated Undrained (UU) test

For unconsolidated undrained test, in terms of total stresses, $\phi_u = 0$

Granular soils have no cohesion.
$c = 0$ & $c' = 0$

For normally consolidated clays,
$c' = 0$ & $c = 0$.

CD, CU and UU Triaxial Tests

Consolidated Drained (CD) Test

- no excess pore pressure throughout the test
- very slow shearing to avoid build-up of pore pressure

Can be days! ∴ not desirable

- **gives c′ and ϕ'**

Use c′ and ϕ' for analysing fully drained situations (e.g***., long term stability, very slow loading***)

CD, CU and UU Triaxial Tests

Consolidated Undrained (CU) Test

- pore pressure develops during shear

  Measure → σ'

- gives c′ and ϕ'

- faster than CD (∴ preferred way to find c′ and ϕ')

CD, CU and UU Triaxial Tests

Unconsolidated Undrained (UU) Test

❖ pore pressure develops during shear

Not measured

∴ σ' unknown

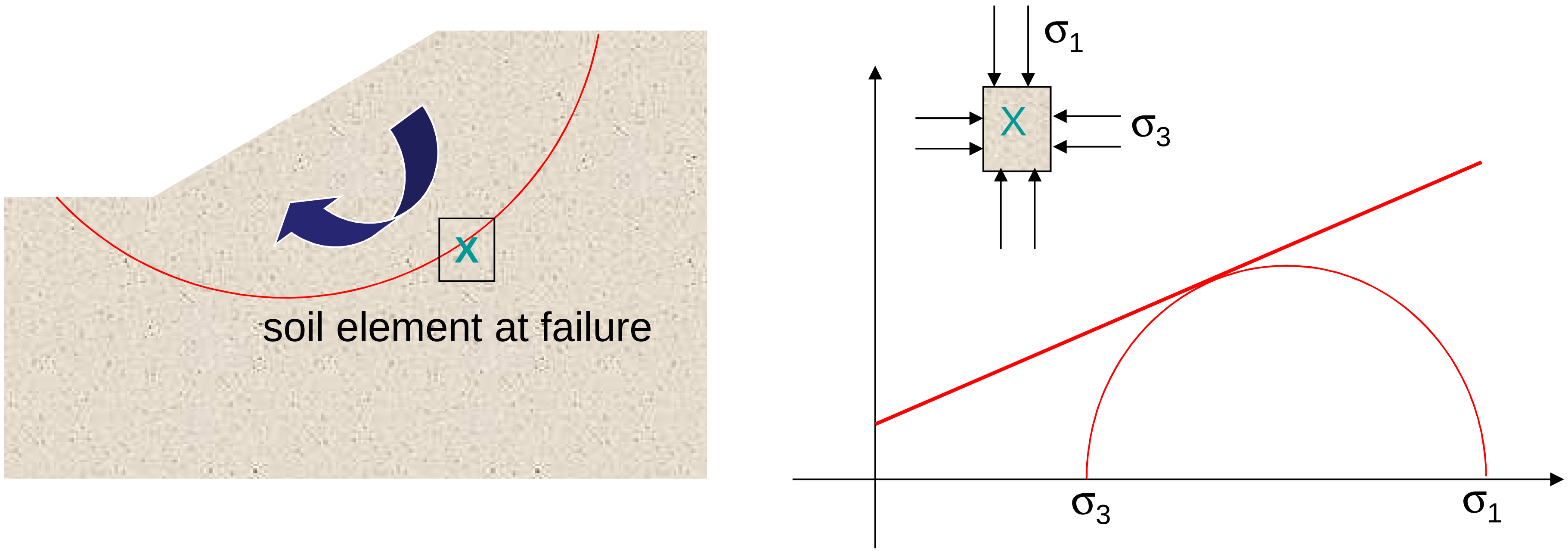
= 0; i.e., failure envelope is horizontal

❖ analyse in terms of σ ➔ **gives c_u and ϕ_u**

❖ very quick test

Use c_u and ϕ_u for analysing undrained situations (e.g., short term stability, quick loading)

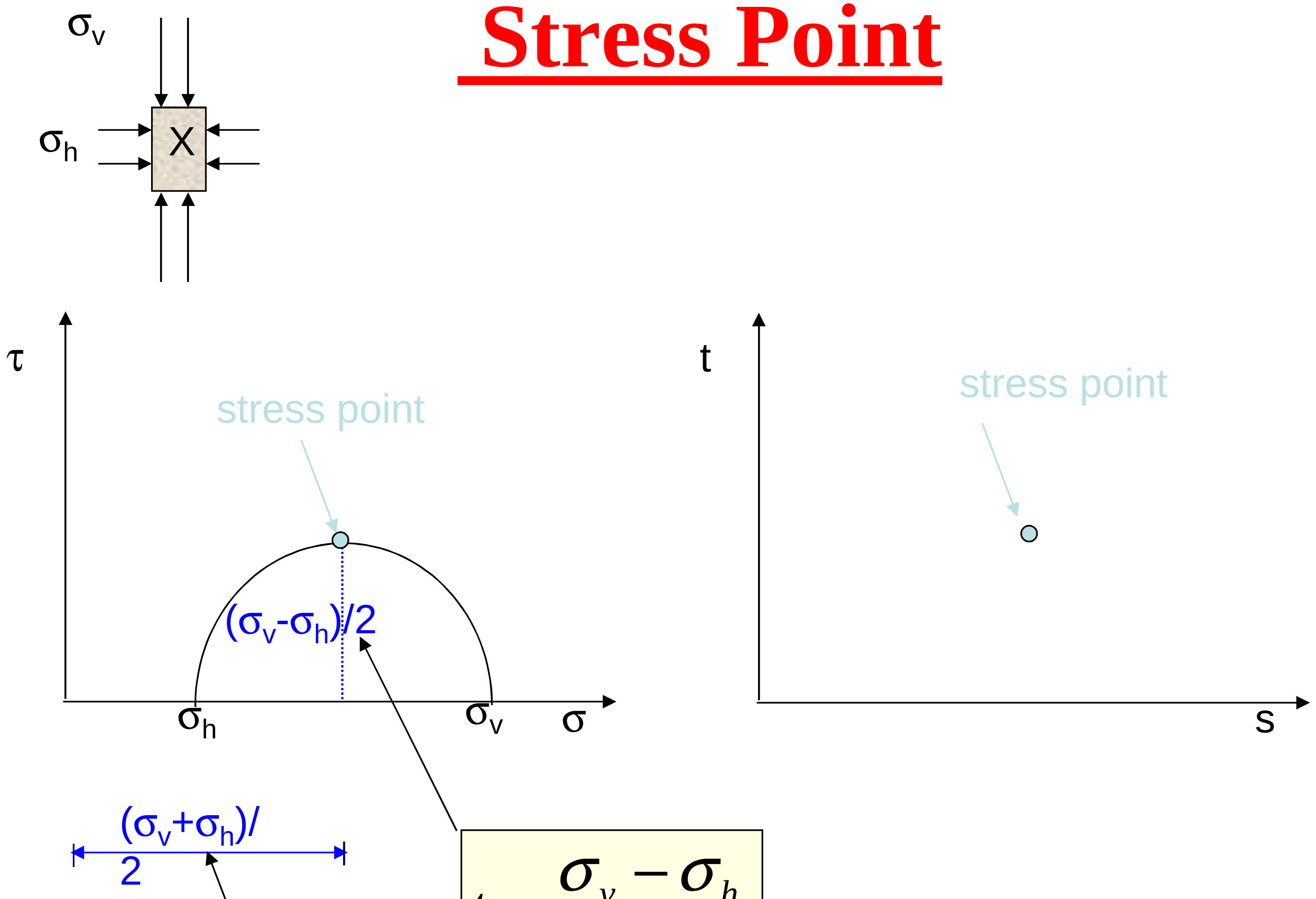
σ_1- σ_3 Relation at Failure



$$\sigma_1 = \sigma_3 \tan^2(45 + \phi/2) + 2c\tan(45 + \phi/2)$$

$$\sigma_3 = \sigma_1 \tan^2(45 - \phi/2) - 2c\tan(45 - \phi/2)$$

Stress Point

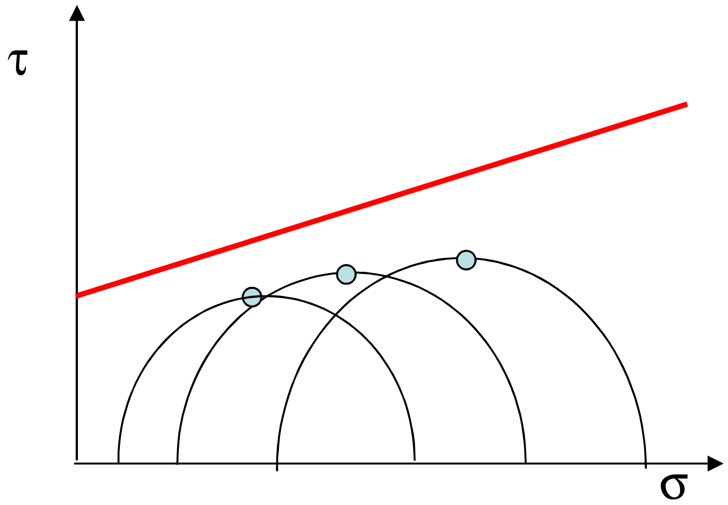


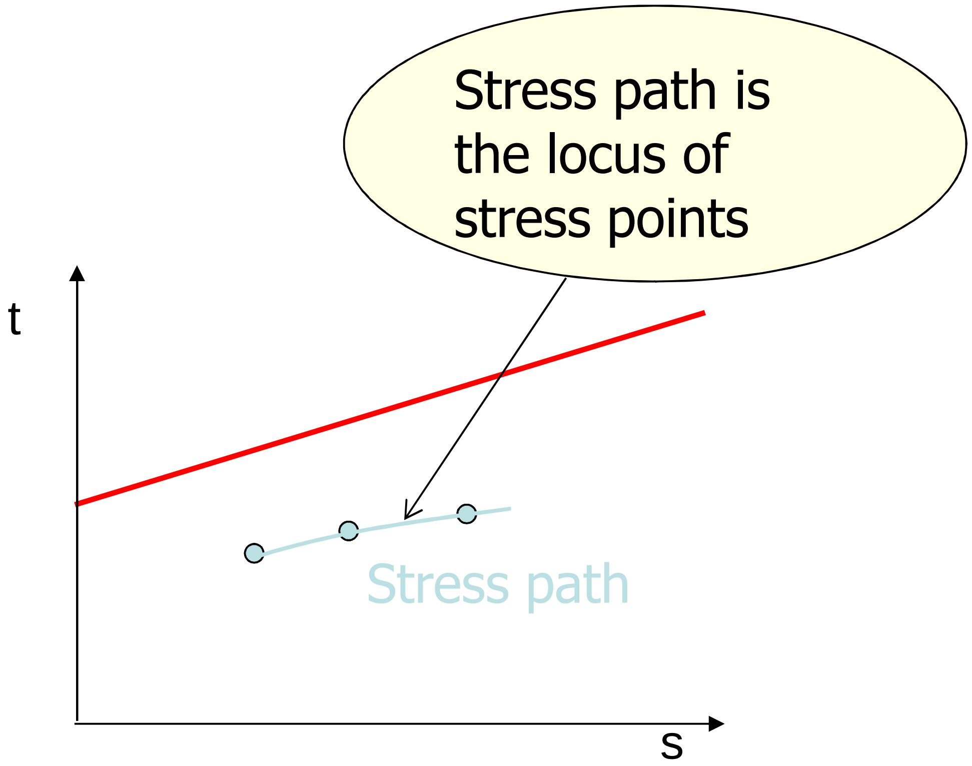
$$t = \frac{\sigma_v - \sigma_h}{2}$$

$$s = \frac{\sigma_v + \sigma_h}{2}$$

Stress Path

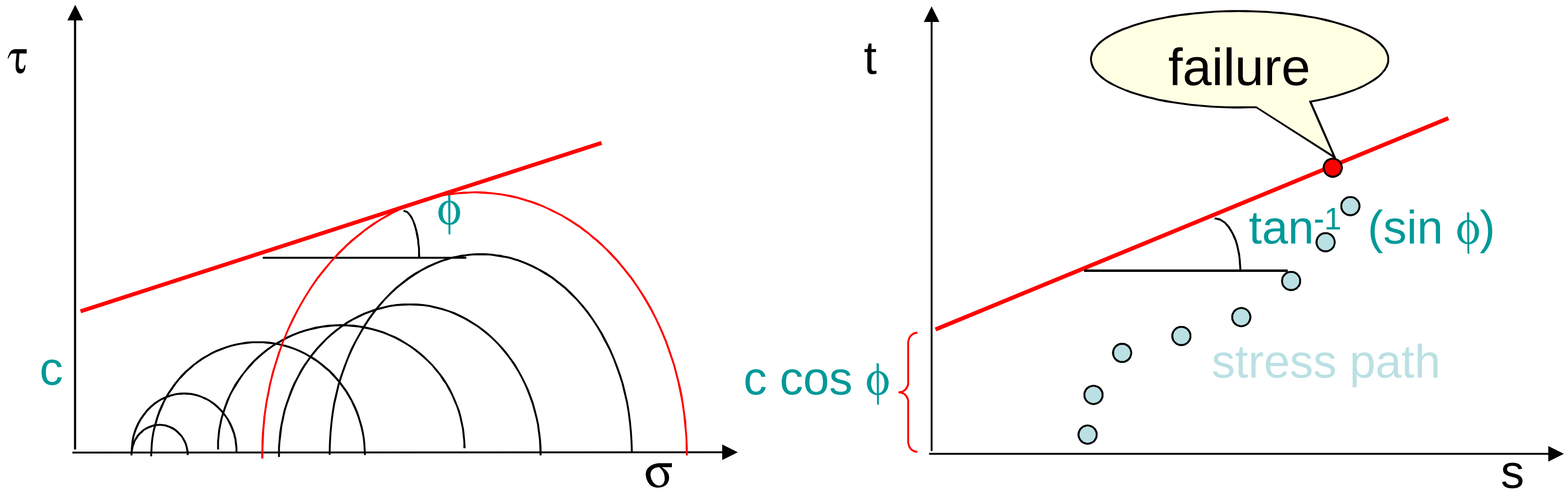
During loading…





Stress path is a convenient way to keep track of the progress in loading with respect to failure envelope.

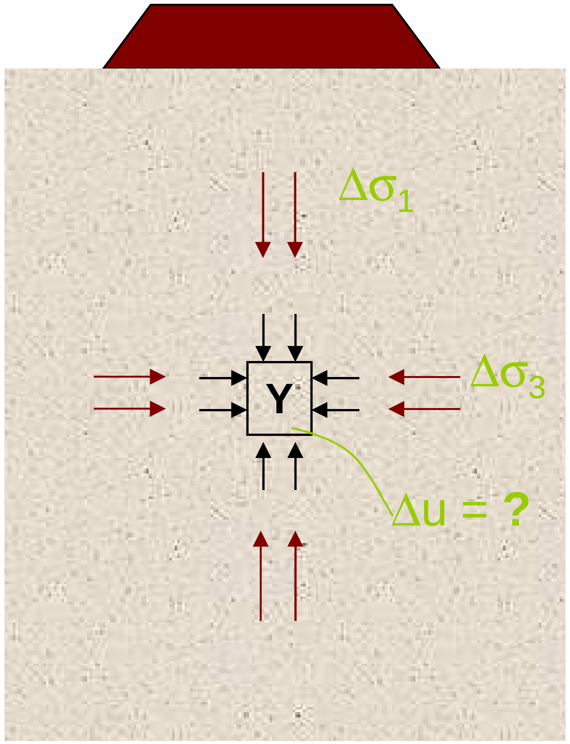
Failure Envelopes



During loading (shearing)….

<u>Pore Pressure Parameters</u>

A simple way to estimate the pore pressure change in undrained loading, in terms of <u>total stress</u> changes ~ after Skempton (1954)



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

Skempton's pore pressure parameters A and B

Pore Pressure Parameters

B-parameter

$B = f$ (saturation,..)

For saturated soils, $B \approx 1$.

A-parameter at failure (A_f)

$A_f = f(OCR)$

For normally consolidated clays $A_f \approx 1$.

For heavily overconsolidated clays A_f is negative.

Consolidated- drained test (CD Test)

Total, σ = Neutral, u + Effective, σ'

Step 1: At the end of consolidation

- Total: σ_{VC}, σ_{hC} (Drainage)
- Neutral: 0
- Effective: $\sigma'_{VC} = \sigma_{VC}$, $\sigma'_{hC} = \sigma_{hC}$

Step 2: During axial stress increase

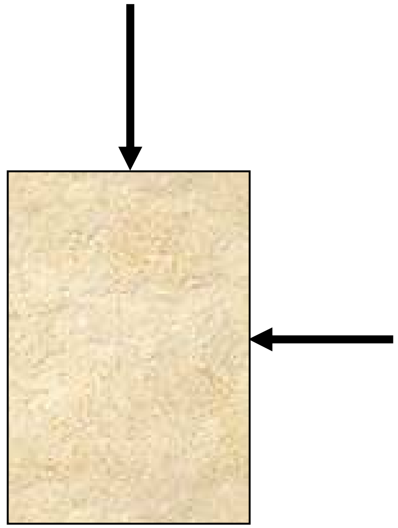
- Total: $\sigma_{VC} + \Delta\sigma$, σ_{hC} (Drainage)
- Neutral: 0
- Effective: $\sigma'_{V} = \sigma_{VC} + \Delta\sigma = \sigma'_{1}$, $\sigma'_{h} = \sigma_{hC} = \sigma'_{3}$

Step 3: At failure

- Total: $\sigma_{VC} + \Delta\sigma_{f}$, σ_{hC} (Drainage)
- Neutral: 0
- Effective: $\sigma'_{Vf} = \sigma_{VC} + \Delta\sigma_{f} = \sigma'_{1f}$, $\sigma'_{hf} = \sigma_{hC} = \sigma'_{3f}$

Consolidated- drained test (CD Test)

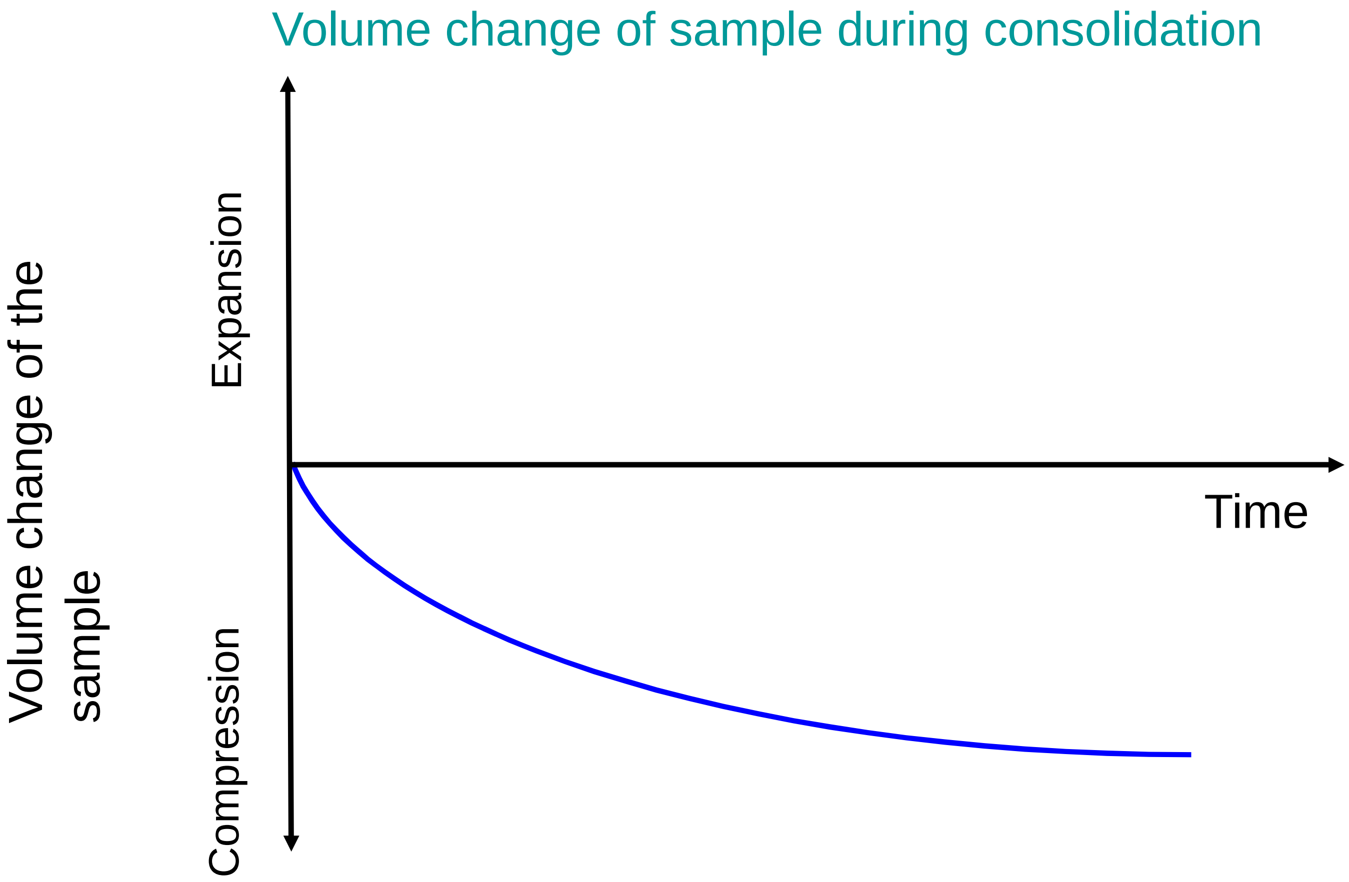
$\sigma_1 = \sigma_{VC} + \Delta\sigma$



$\sigma_3 = \sigma_{hC}$

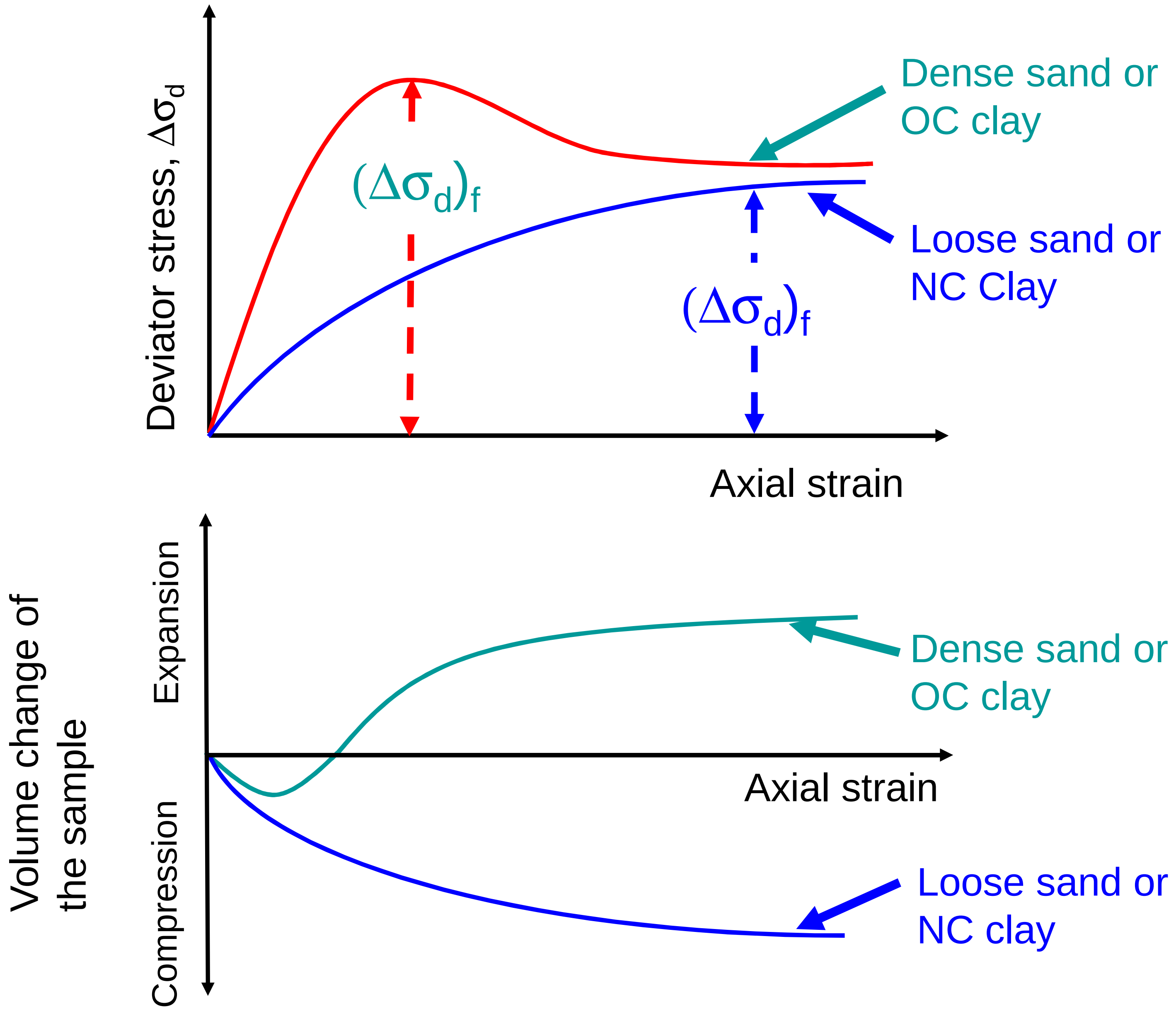
Deviator stress (q or $\Delta\sigma_d$) = $\sigma_1 - \sigma_3$

Consolidated- drained test (CD Test)



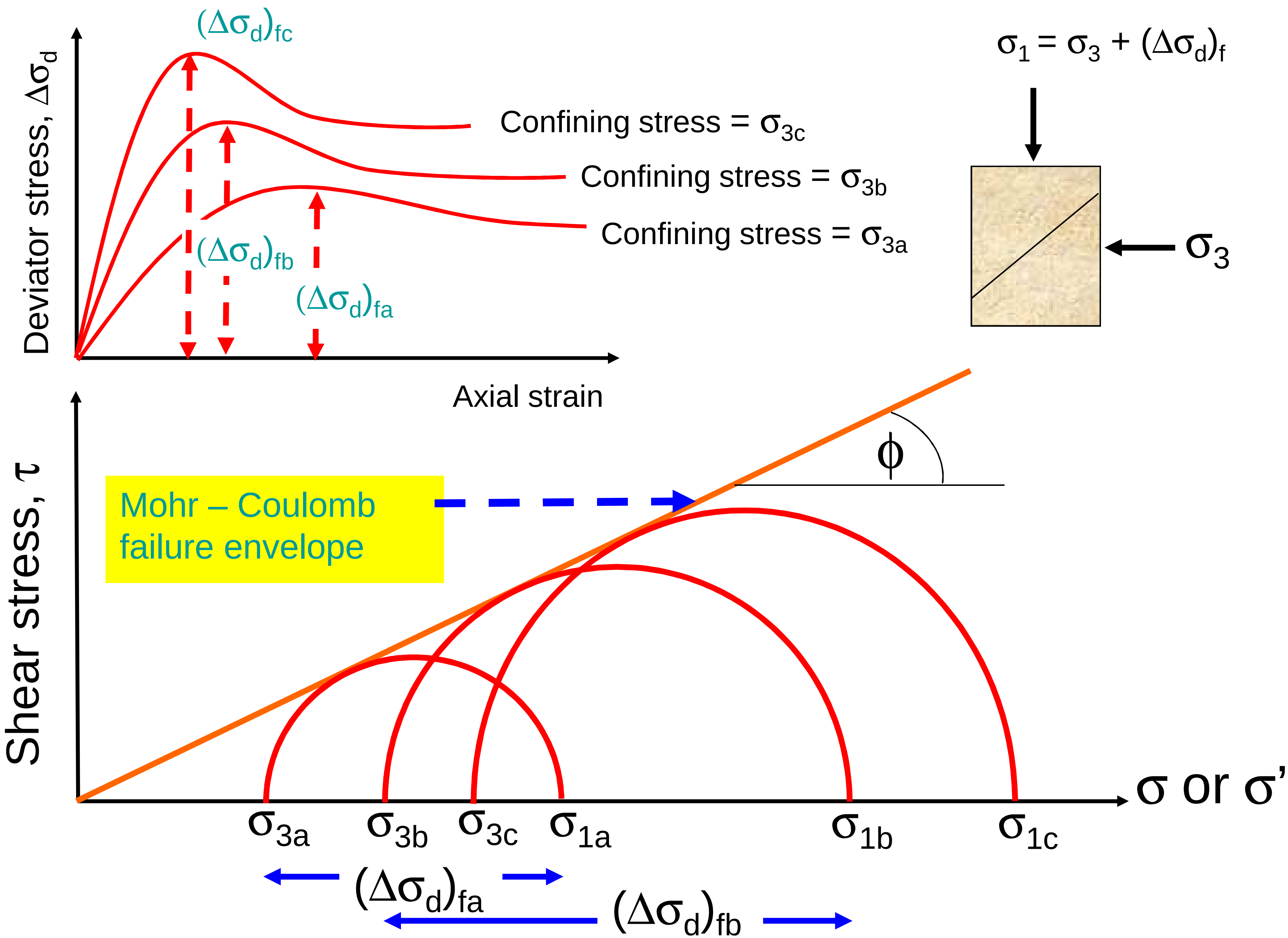
Consolidated- drained test (CD Test)

Stress-strain relationship during shearing



CD tests

How to determine strength parameters c and ϕ



CD tests

Strength parameters c and ϕ obtained from CD tests

Since u = 0 in CD tests, $\sigma = \sigma'$

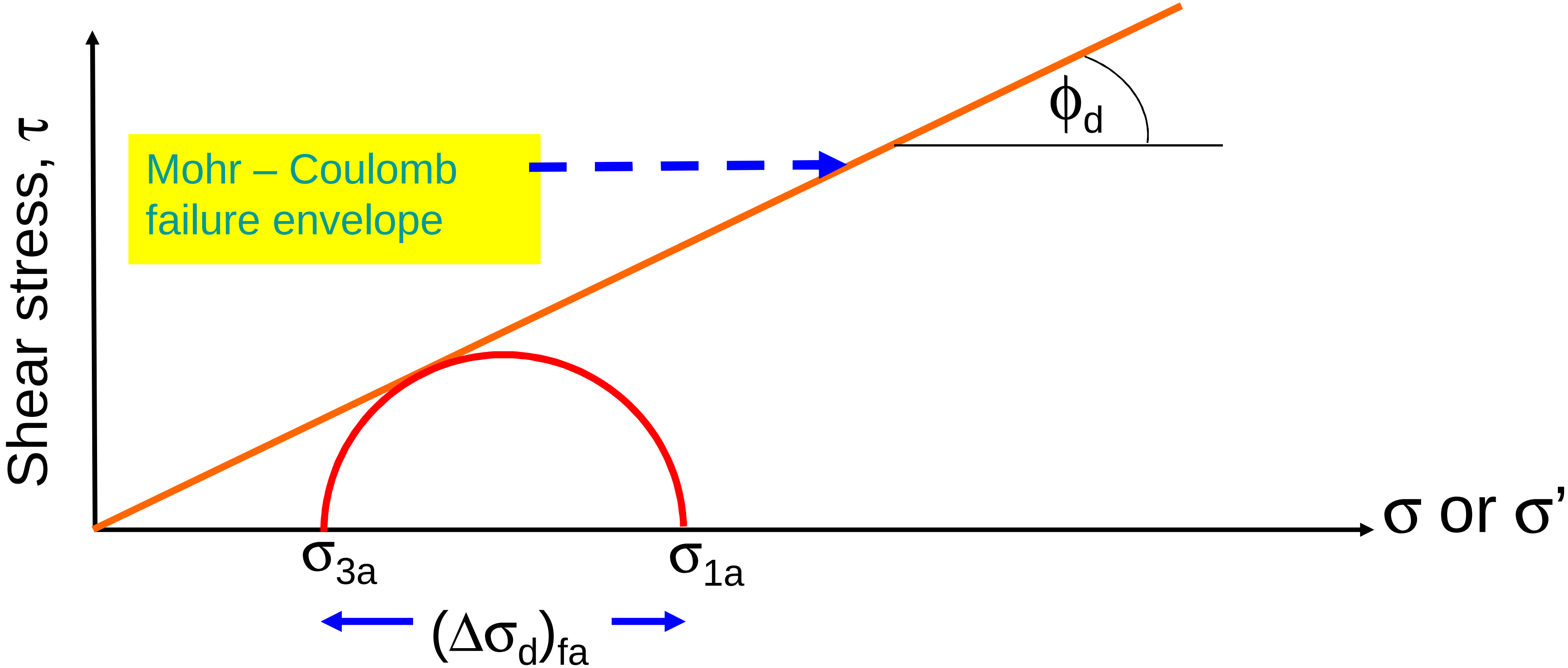
Therefore, $c = c'$ and $\phi = \phi'$

c_d and ϕ_d are used to denote them

CD tests

Failure envelopes

For sand and NC Clay, $c_d = 0$

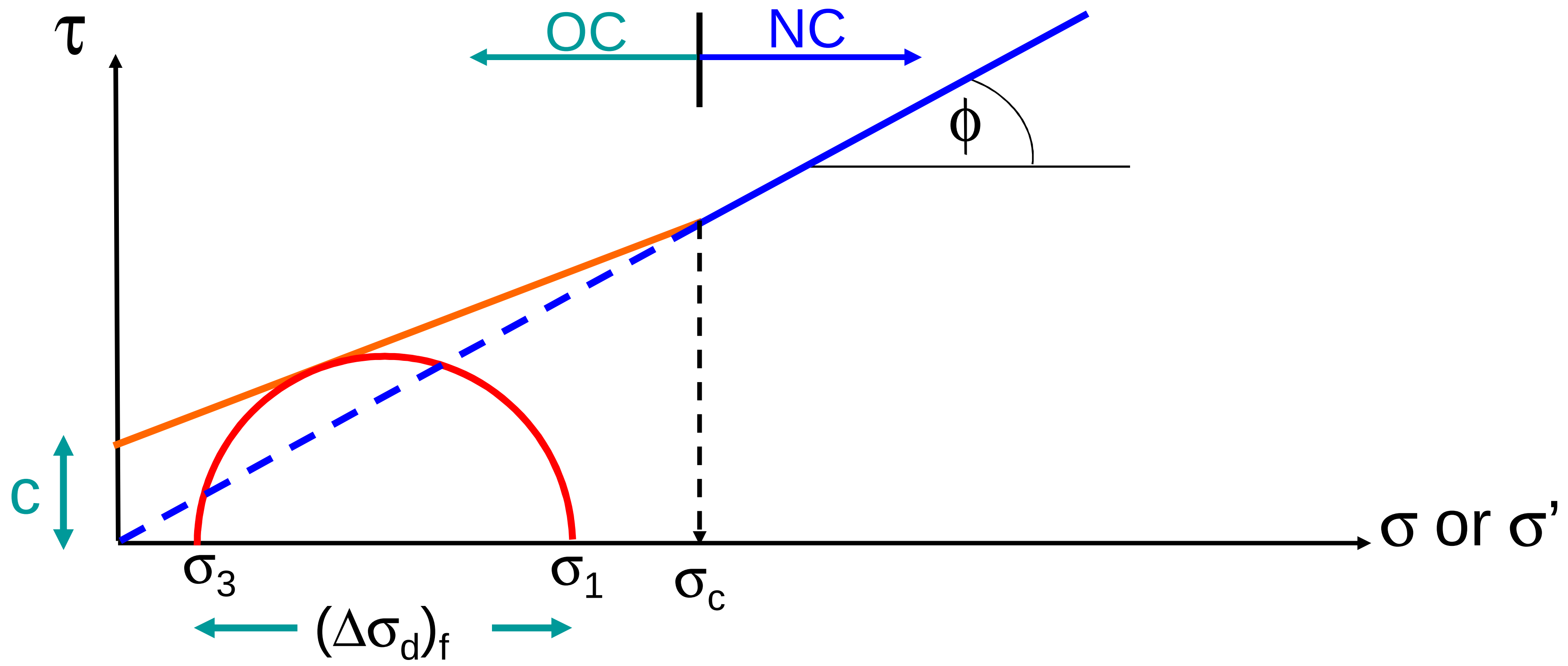


Therefore, one CD test would be sufficient to determine ϕ_d of *sand or NC clay*

CD tests

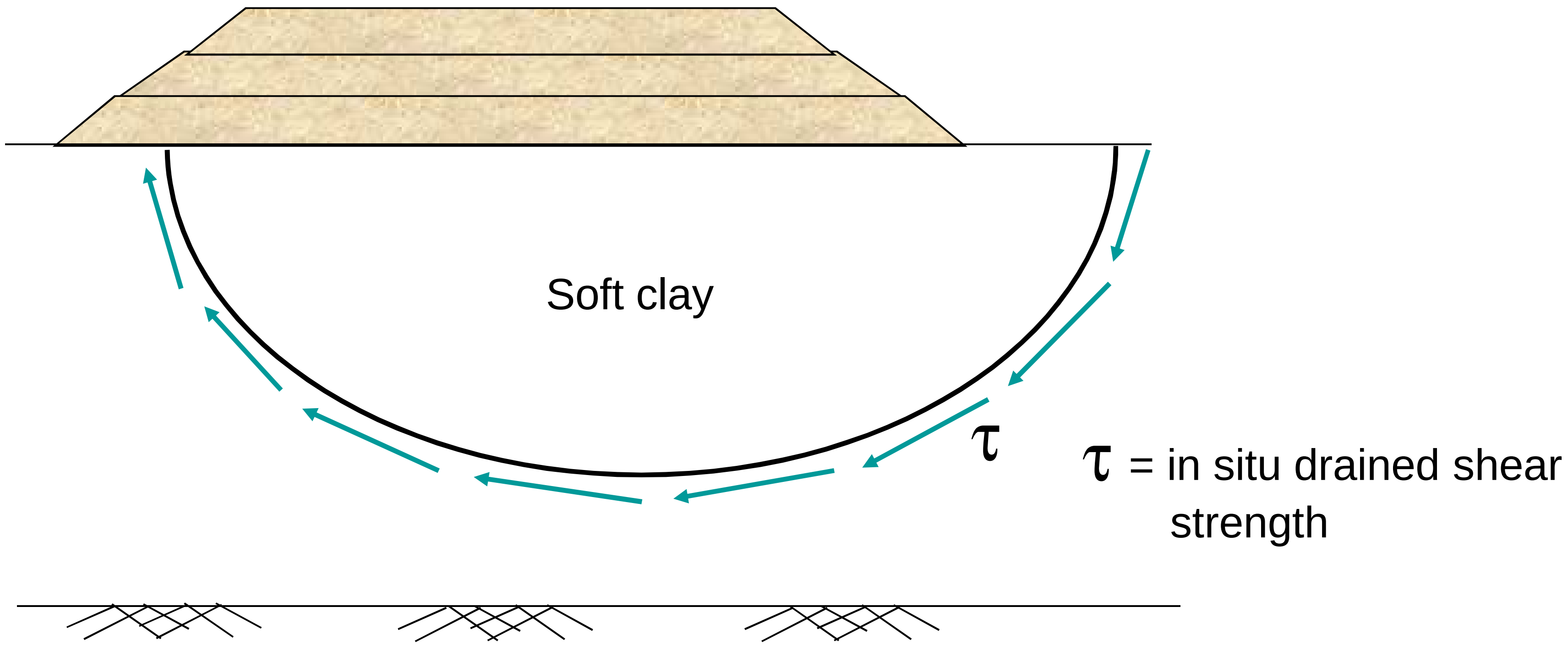
Failure envelopes

For OC Clay, $c_d \neq 0$



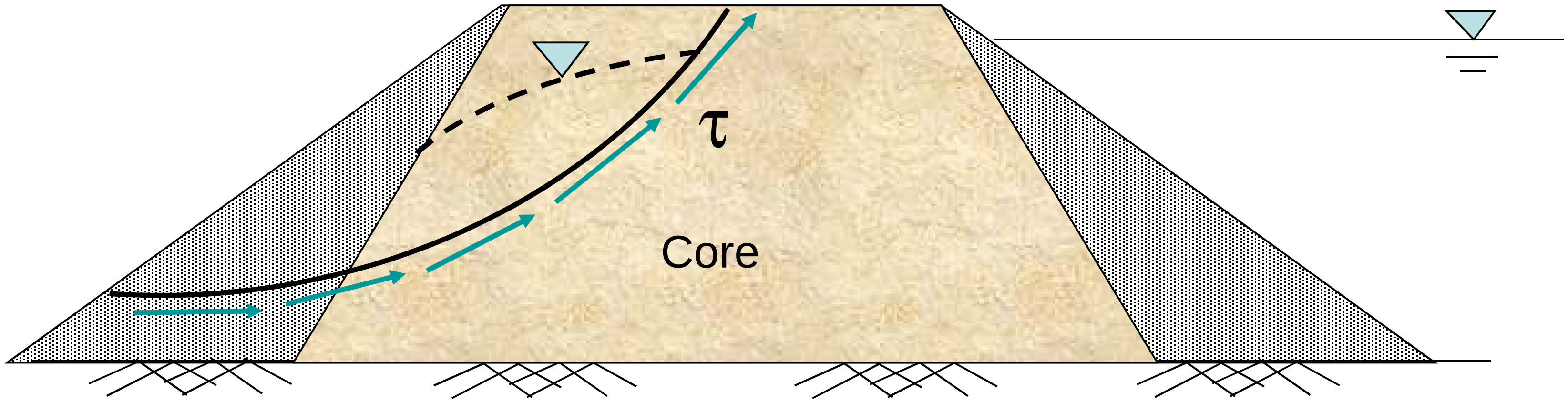
Some practical applications of CD analysis for clays

1. Embankment constructed very slowly, in layers over a soft clay deposit



Some practical applications of CD analysis for clays

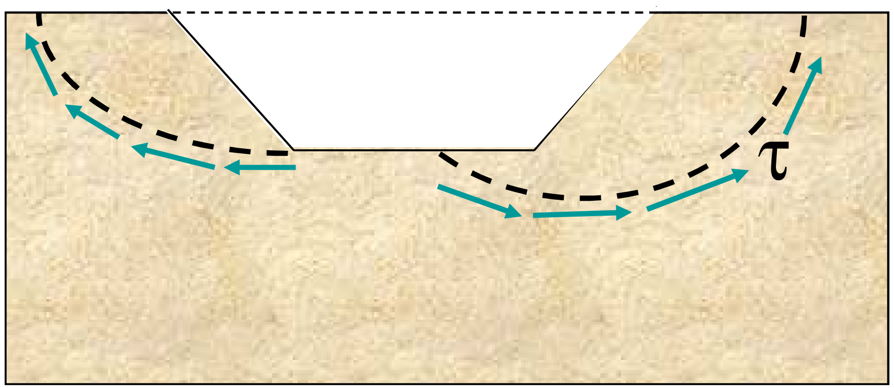
2. Earth dam with steady state seepage

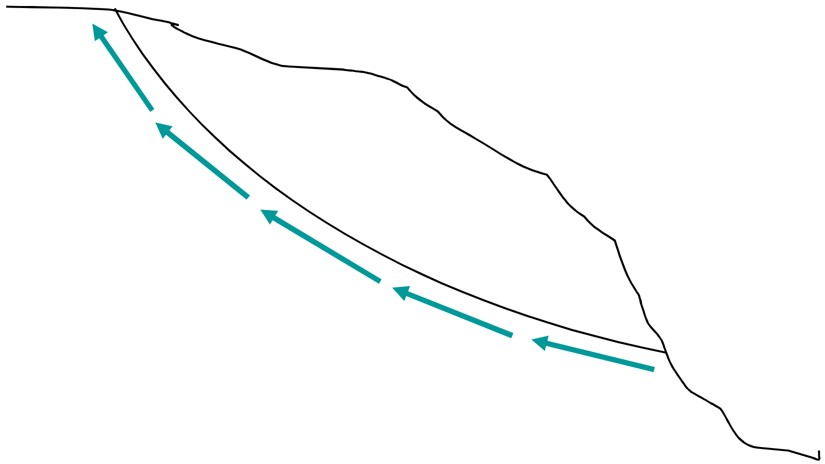


τ = drained shear strength of clay core

Some practical applications of CD analysis for clays

3. Excavation or natural slope in clay





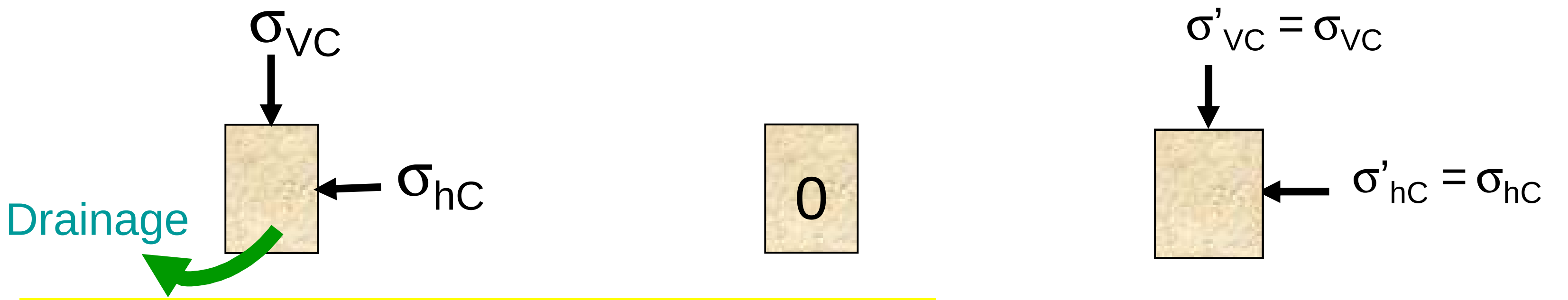
τ = In situ drained shear strength

Note: CD test simulates the long term condition in the field. Thus, c_d and ϕ_d should be used to evaluate the long term behavior of soils

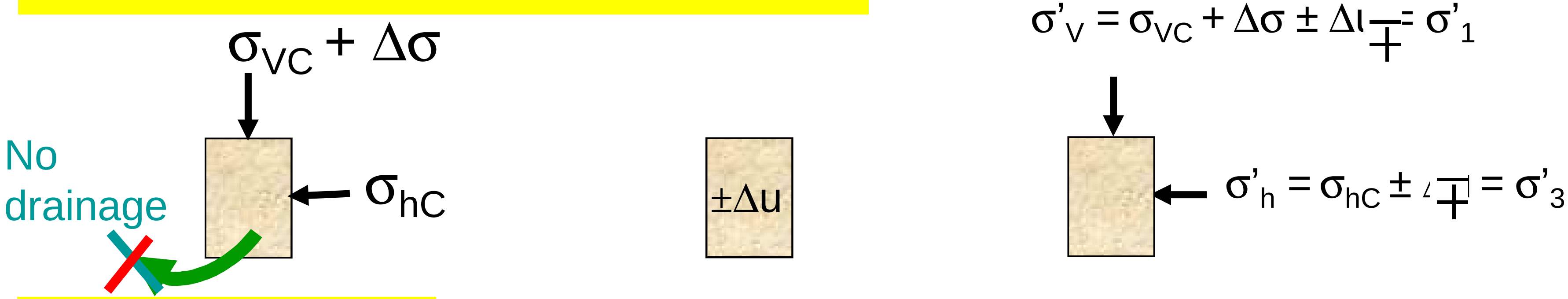
Consolidated- Undrained test (CU Test)

Total, σ = Neutral, u + Effective, σ'

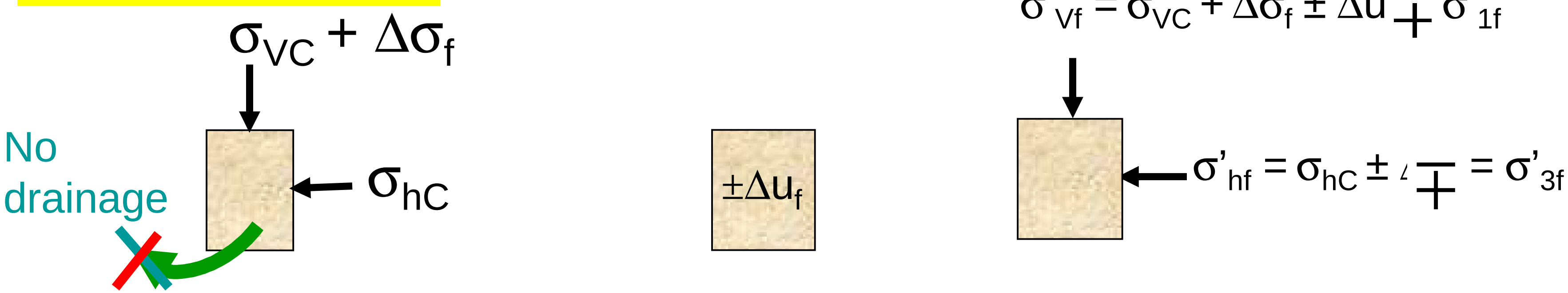
Step 1: At the end of consolidation



Step 2: During axial stress increase

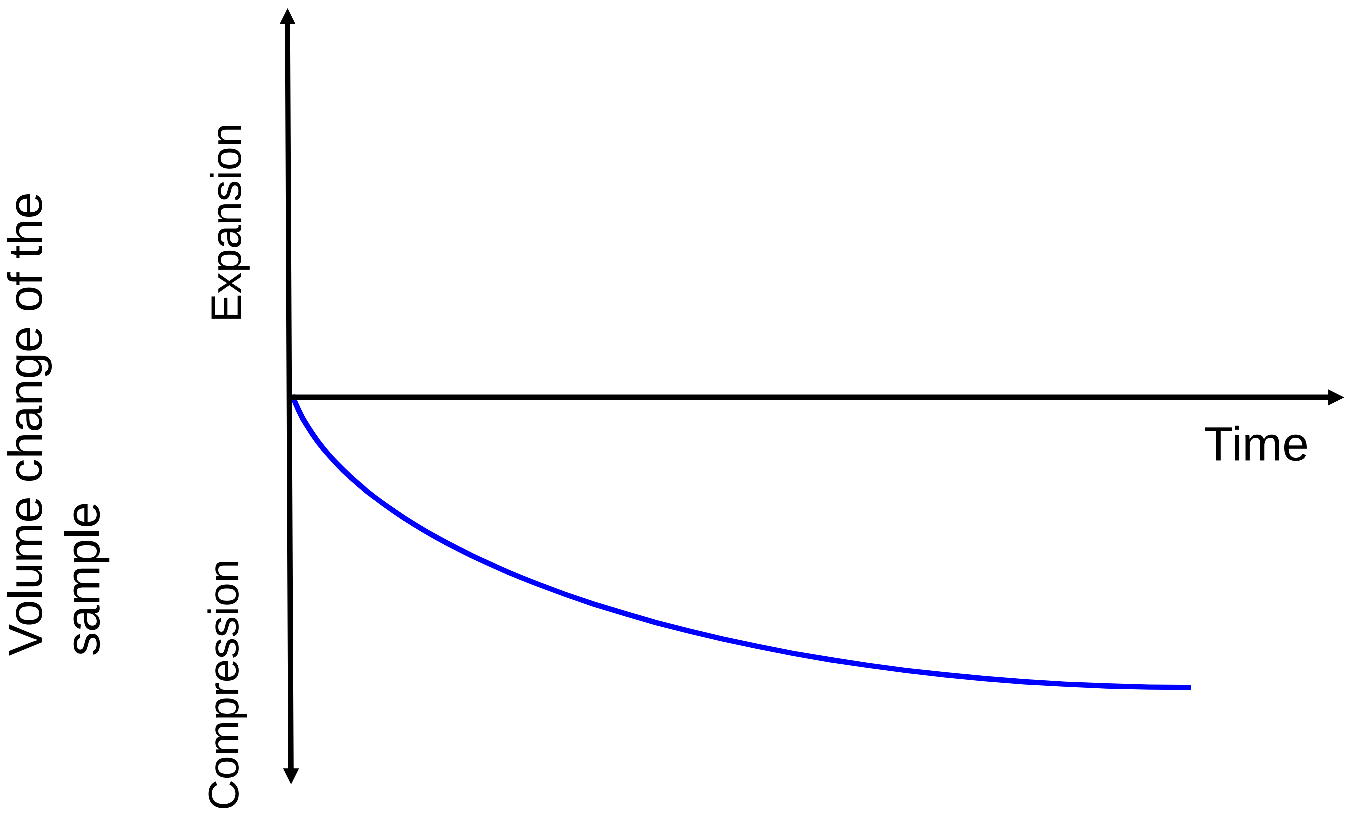


Step 3: At failure



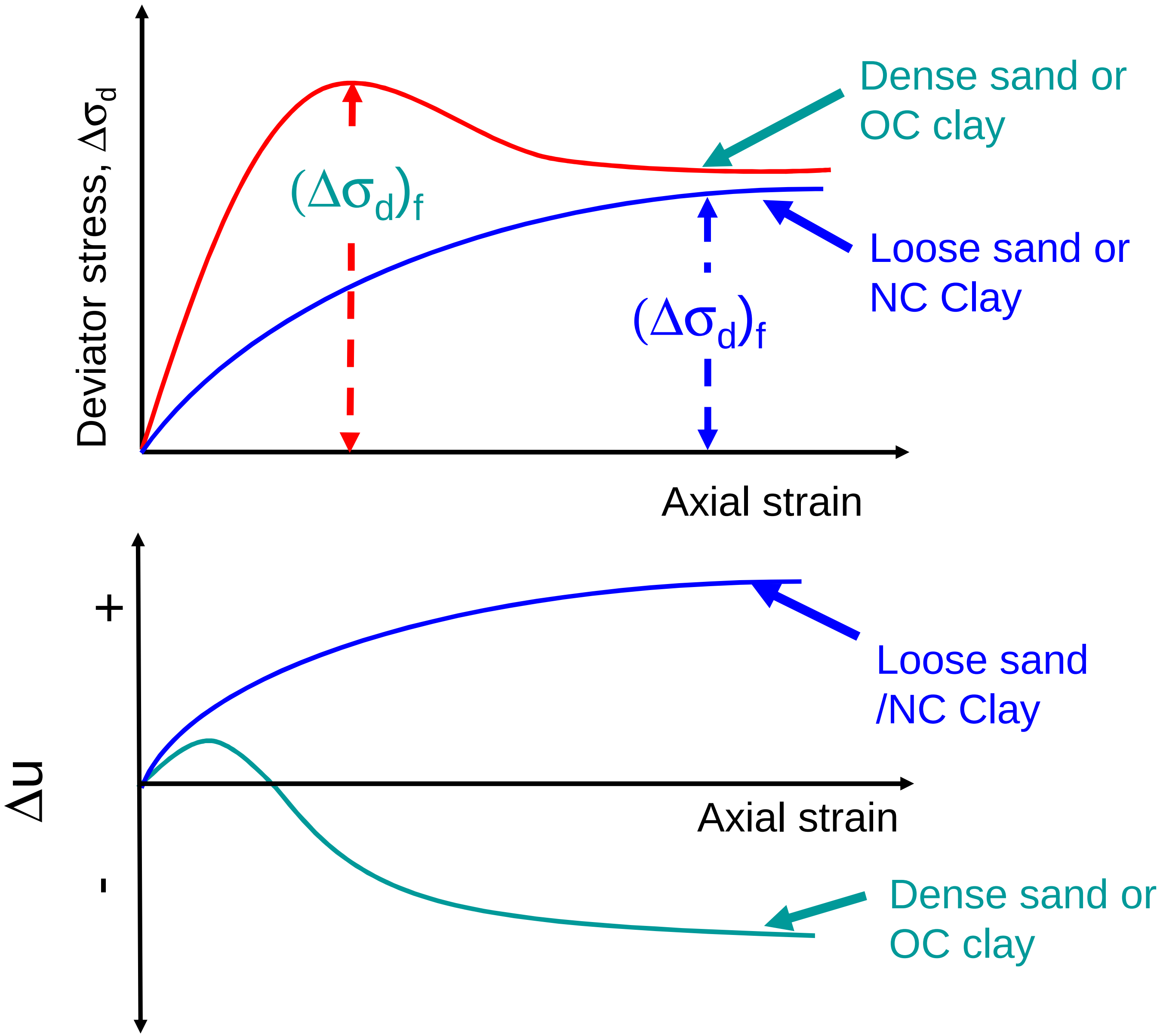
Consolidated- Undrained test (CU Test)

Volume change of sample during consolidation



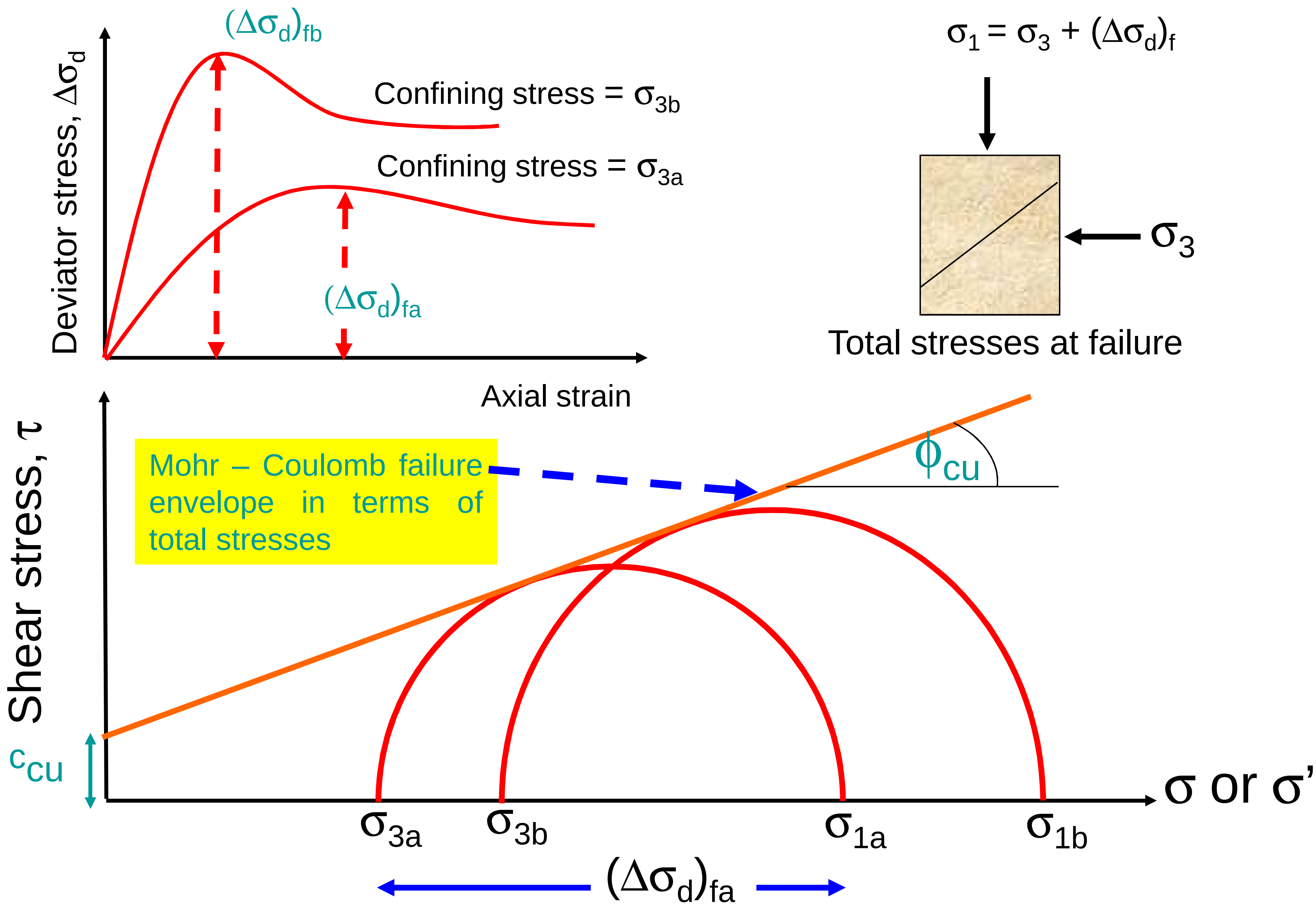
Consolidated- Undrained test (CU Test)

Stress-strain relationship during shearing



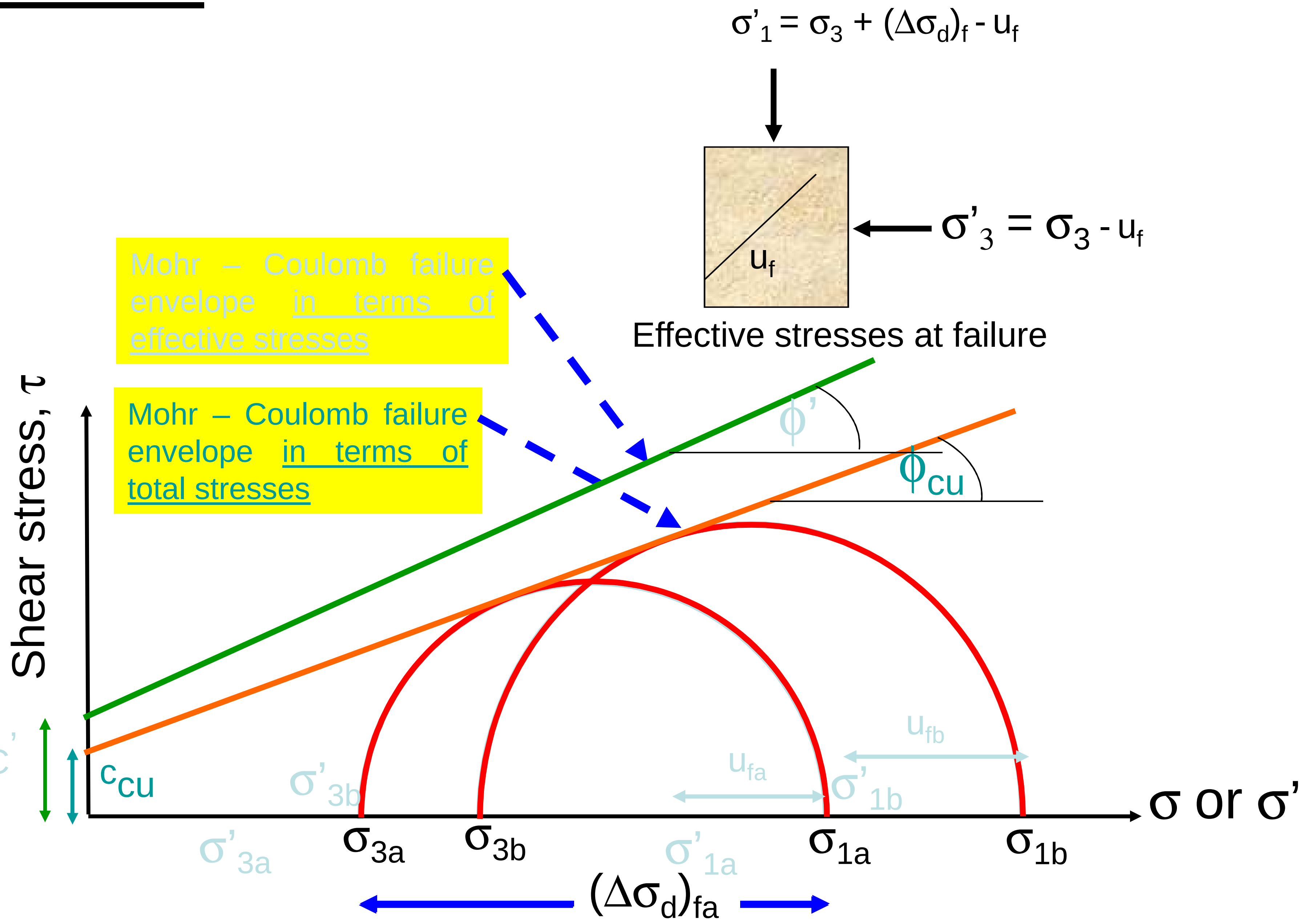
CU tests

How to determine strength parameters c and ϕ



CU tests

How to determine strength parameters c and ϕ



CU tests

Strength parameters c and ϕ obtained from CD tests

Shear strength parameters in terms of total stresses are c_{cu} and ϕ_{cu}

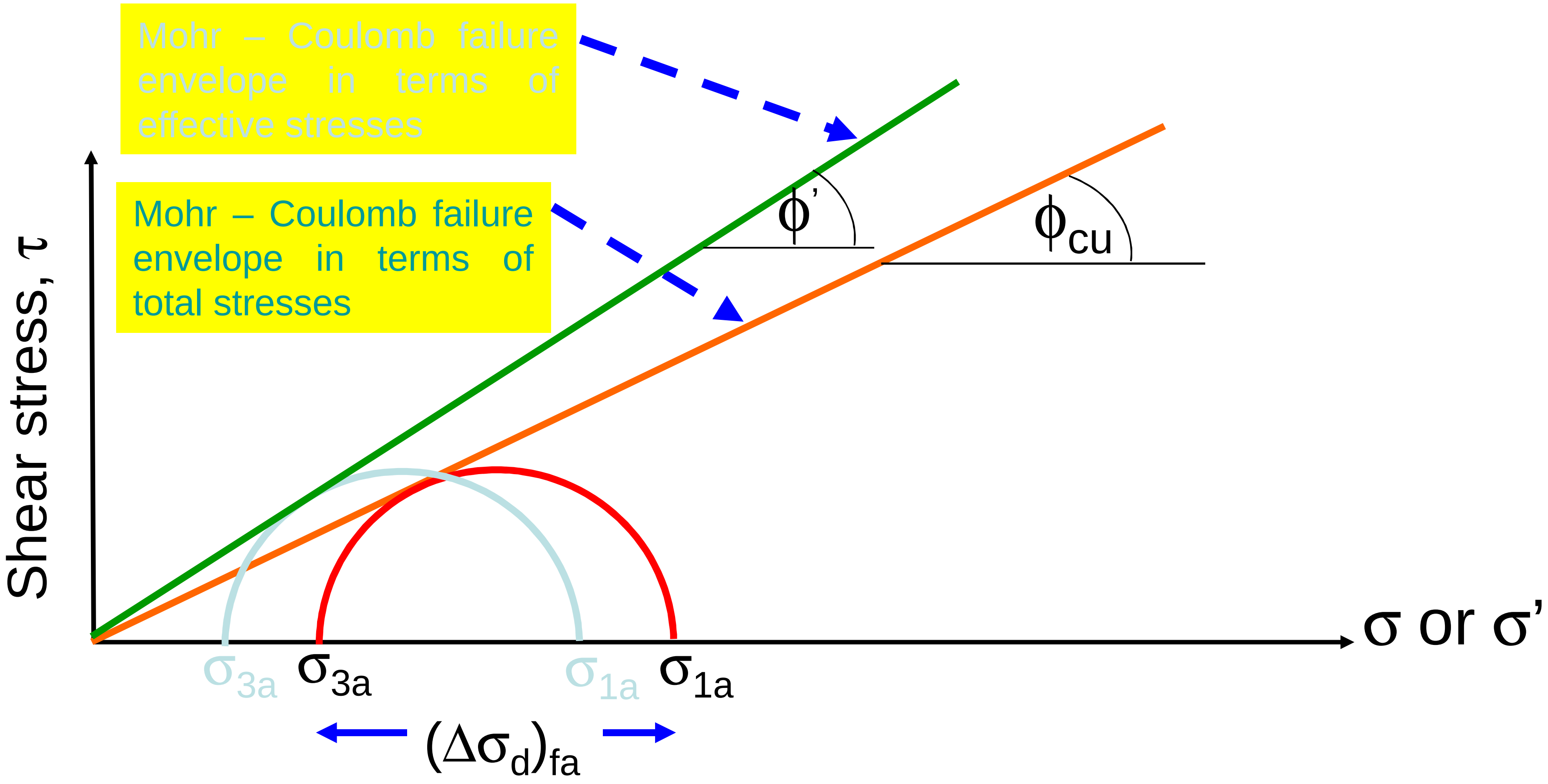
Shear strength parameters in terms of effective stresses are c' and ϕ'

$c' = c_d$ and $\phi' = \phi_d$

CU tests

Failure envelopes

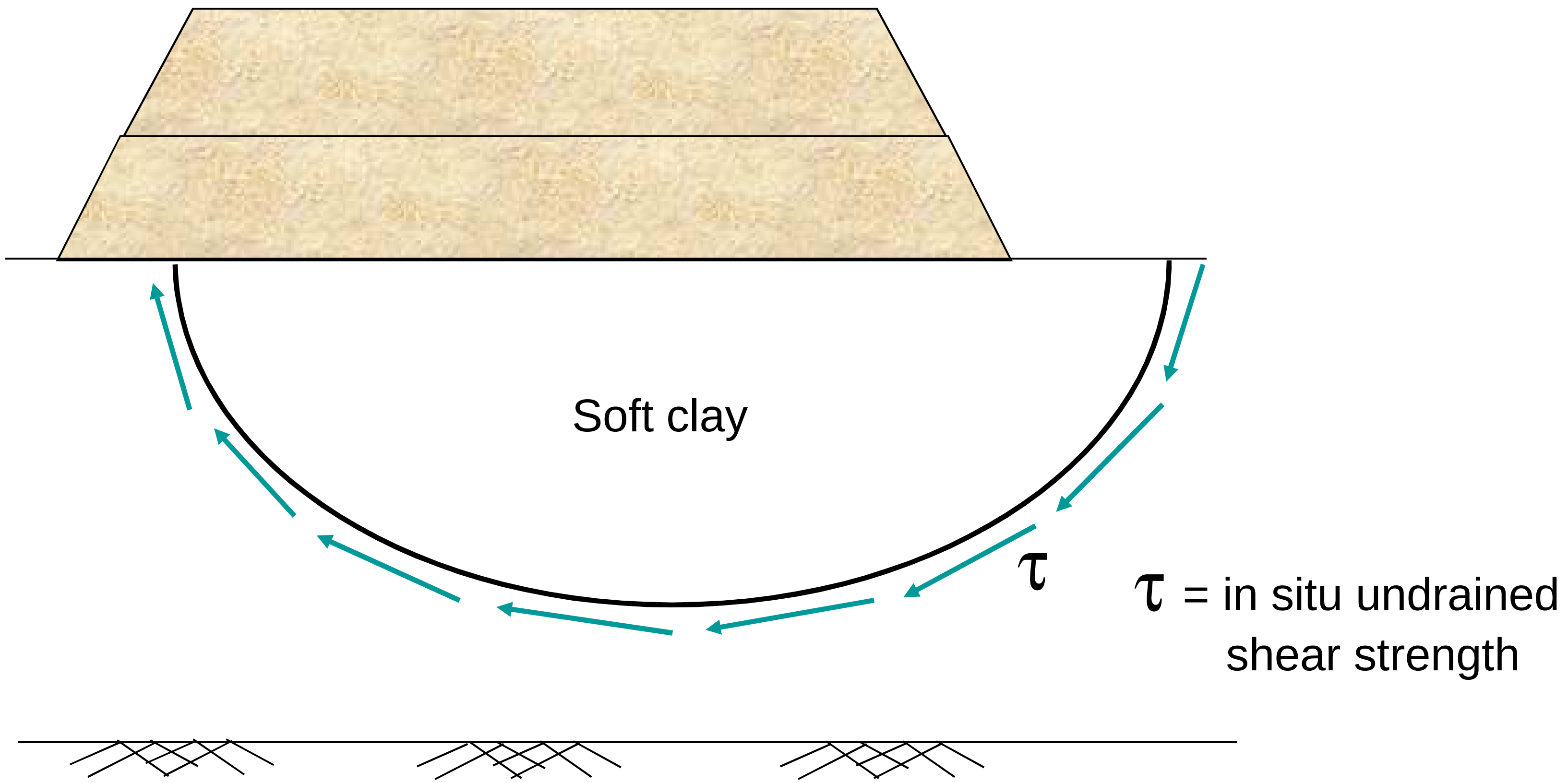
For sand and NC Clay, c_{cu} and $c' = 0$



Therefore, one CU test would be sufficient to determine ϕ_{cu} and $\phi'(= \phi_d)$ of sand or NC clay

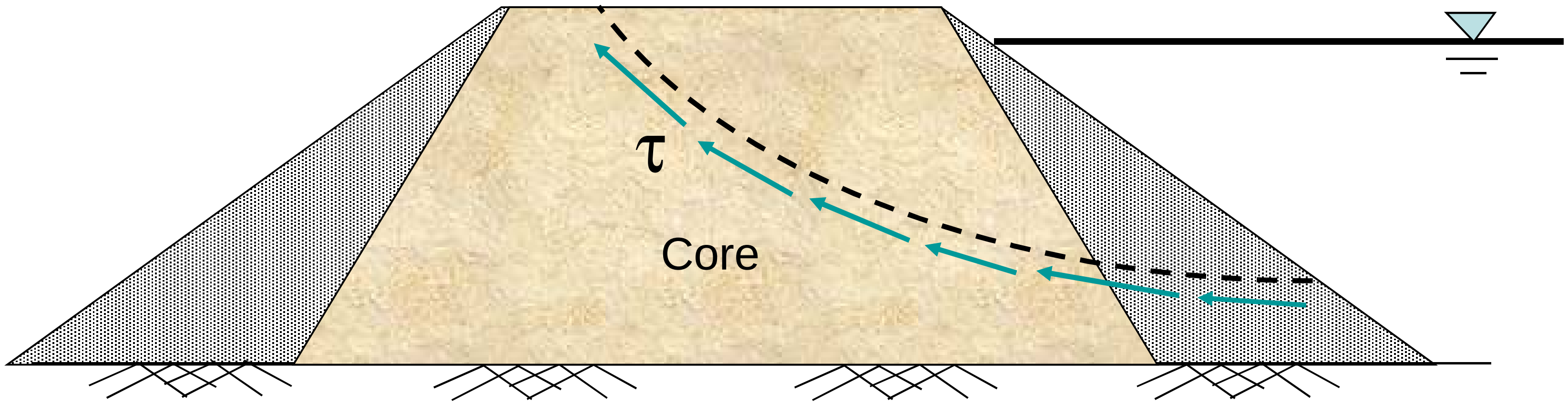
Some practical applications of CU analysis for clays

1. Embankment constructed rapidly over a soft clay deposit



Some practical applications of CU analysis for clays

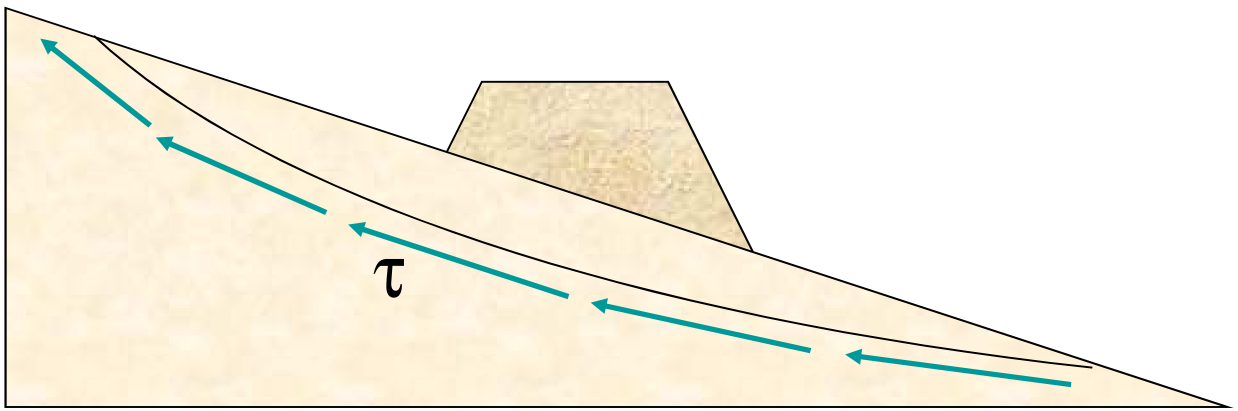
2. Rapid drawdown behind an earth dam



τ = Undrained shear strength of clay core

Some practical applications of CU analysis for clays

3. Rapid construction of an embankment on a natural slope



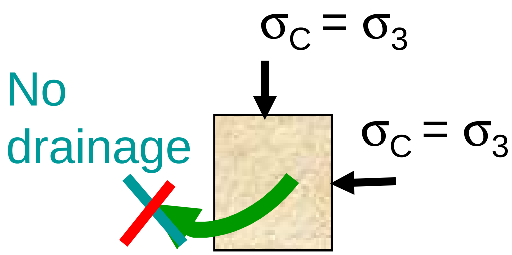
τ = In situ undrained shear strength

Note: Total stress parameters from CU test (c_{cu} and ϕ_{cu}) can be used for stability problems where, soil have become fully consolidated and are at equilibrium with the existing stress state; Then for some reason additional stresses are applied quickly with no drainage occurring

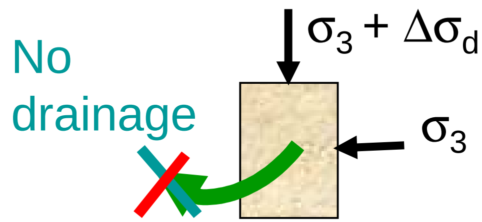
Unconsolidated- Undrained test (UU Test)

Data analysis

Initial specimen condition



Specimen condition during shearing



Initial volume of the sample = $A_0 \times H_0$

Volume of the sample during shearing = $A \times H$

Since the test is conducted under undrained condition,

$A \times H = A_0 \times H_0$

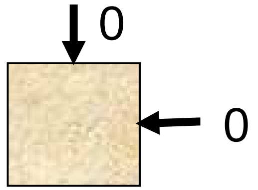
$A \times (H_0 - \Delta H) = A_0 \times H_0$

$A \times (1 - \Delta H / H_0) = A_0$

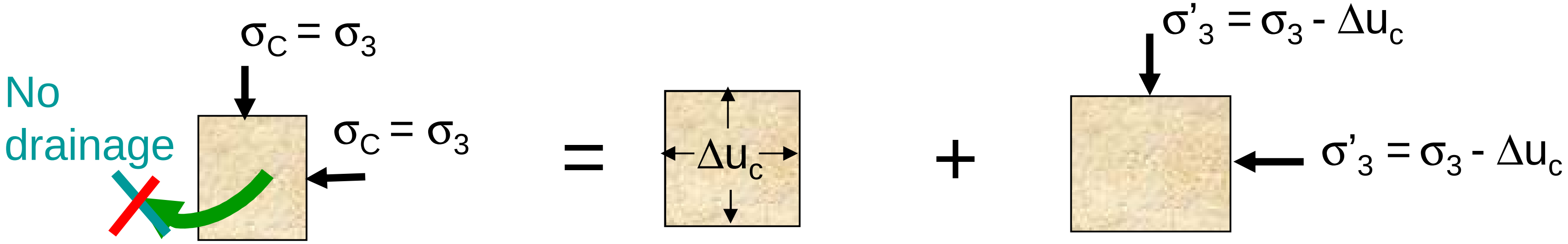
$$A = \frac{A_0}{1 - \varepsilon_z}$$

Unconsolidated- Undrained test (UU Test)

Step 1: Immediately after sampling



Step 2: After application of hydrostatic cell pressure



$$\Delta u_c = B \, \Delta\sigma_3$$

Increase of pwp due to increase of cell pressure

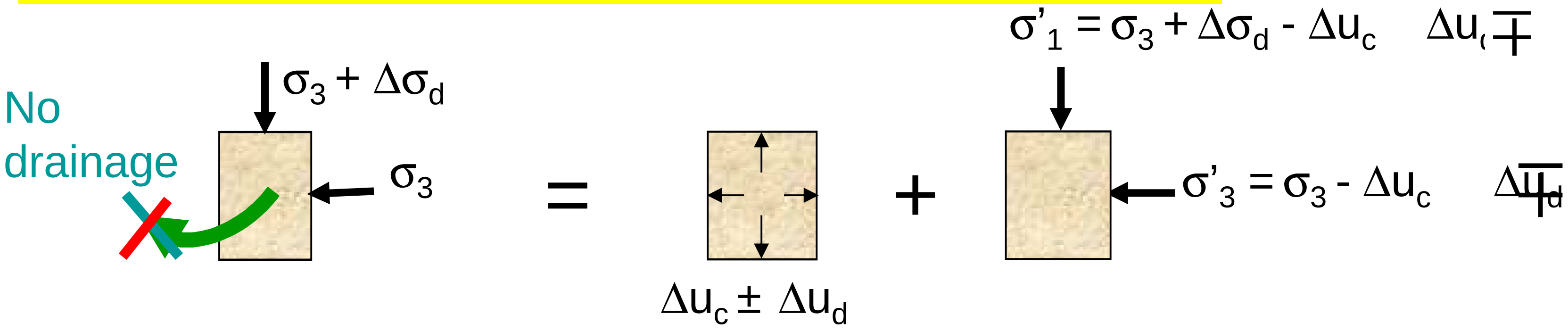
Skempton's pore water pressure parameter, B

Increase of cell pressure

Note: If soil is fully saturated, then B = 1 (hence, $\Delta u_c = \Delta\sigma_3$)

Unconsolidated- Undrained test (UU Test)

Step 3: During application of axial load



$$\Delta u_d = AB\Delta\sigma_d$$

Increase of pwp due to increase of deviator stress

Skempton's pore water pressure parameter, A

Increase of deviator stress

Unconsolidated- Undrained test (UU Test)

Combining steps 2 and 3,

$$\Delta u_c = B\,\Delta\sigma_3$$

$$\Delta u_d = AB\Delta\sigma_d$$

Total pore water pressure increment at any stage, Δu

$$\Delta u = \Delta u_c + \Delta u_d$$

$$\Delta u = B\,[\Delta\sigma_3 + A\Delta\sigma_d]$$

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

Skempton's pore water pressure equation

Unconsolidated- Undrained test (UU Test)

Total, σ = Neutral, u + Effective, σ'

Step 1: Immediately after sampling

- Total: vertical 0, horizontal 0
- Neutral: $-u_r$
- Effective: $\sigma'_{V0} = u_r$, $\sigma'_{h0} = u_r$

Step 2: After application of hydrostatic cell pressure

- No drainage
- Total: vertical σ_C, horizontal σ_C
- Neutral: $-u_r + \Delta u_c = -u_r + \sigma_c$ (S_r = 100% ; B = 1)
- Effective: $\sigma'_{VC} = \sigma_C + u_r - \sigma_C = u_r$, $\sigma'_h = u_r$

Step 3: During application of axial load

- No drainage
- Total: vertical $\sigma_C + \Delta\sigma$, horizontal σ_C
- Neutral: $-u_r + \sigma_c \pm \Delta u$
- Effective: $\sigma'_V = \sigma_C + \Delta\sigma + u_r - \sigma_c \mp \Delta u$, $\sigma'_h = \sigma_C + u_r - \sigma_c \mp \Delta u$

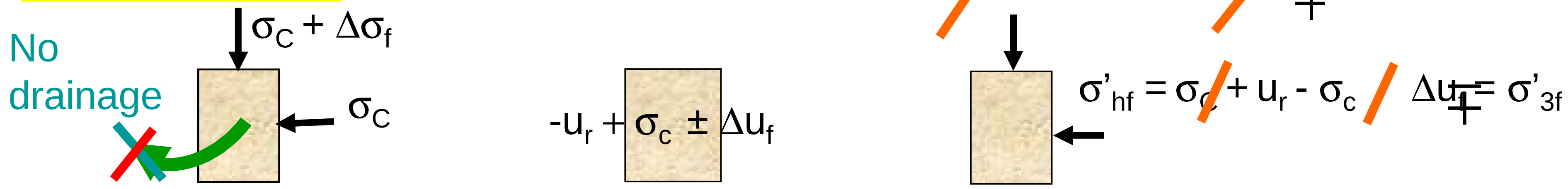
Step 3: At failure

- No drainage
- Total: vertical $\sigma_C + \Delta\sigma_f$, horizontal σ_C
- Neutral: $-u_r + \sigma_c \pm \Delta u_f$
- Effective: $\sigma'_{Vf} = \sigma_C + \Delta\sigma_f + u_r - \sigma_c \mp \Delta u_f = \sigma'_{1f}$, $\sigma'_{hf} = \sigma_C + u_r - \sigma_c \mp \Delta u_f = \sigma'_{3f}$

Unconsolidated- Undrained test (UU Test)

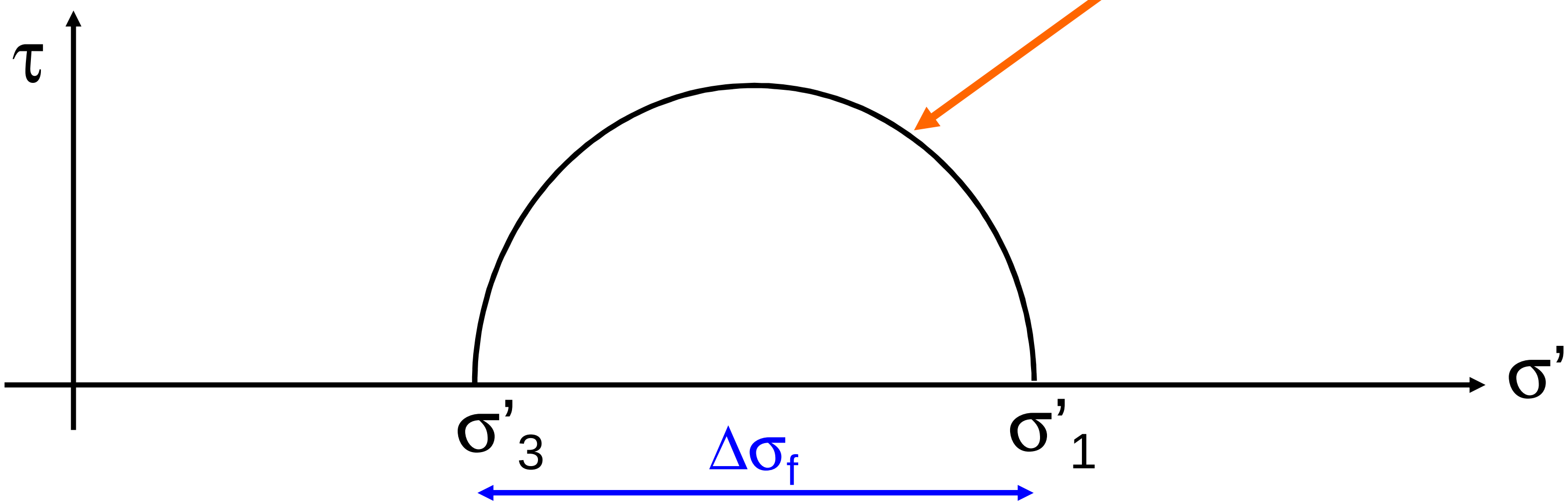
Total, σ = Neutral, u + Effective, σ'

Step 3: At failure



Mohr circle in terms of effective stresses do not depend on the cell pressure.

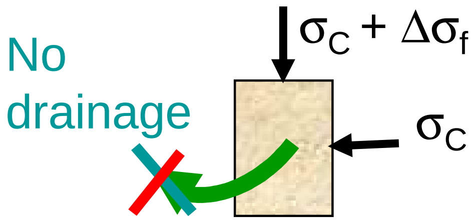
Therefore, we get only one <u>Mohr circle in terms of effective stress</u> for different cell pressures

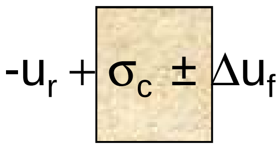


Unconsolidated- Undrained test (UU Test)

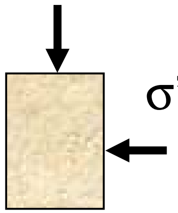
Total, σ = Neutral, u + Effective, σ'

Step 3: At failure



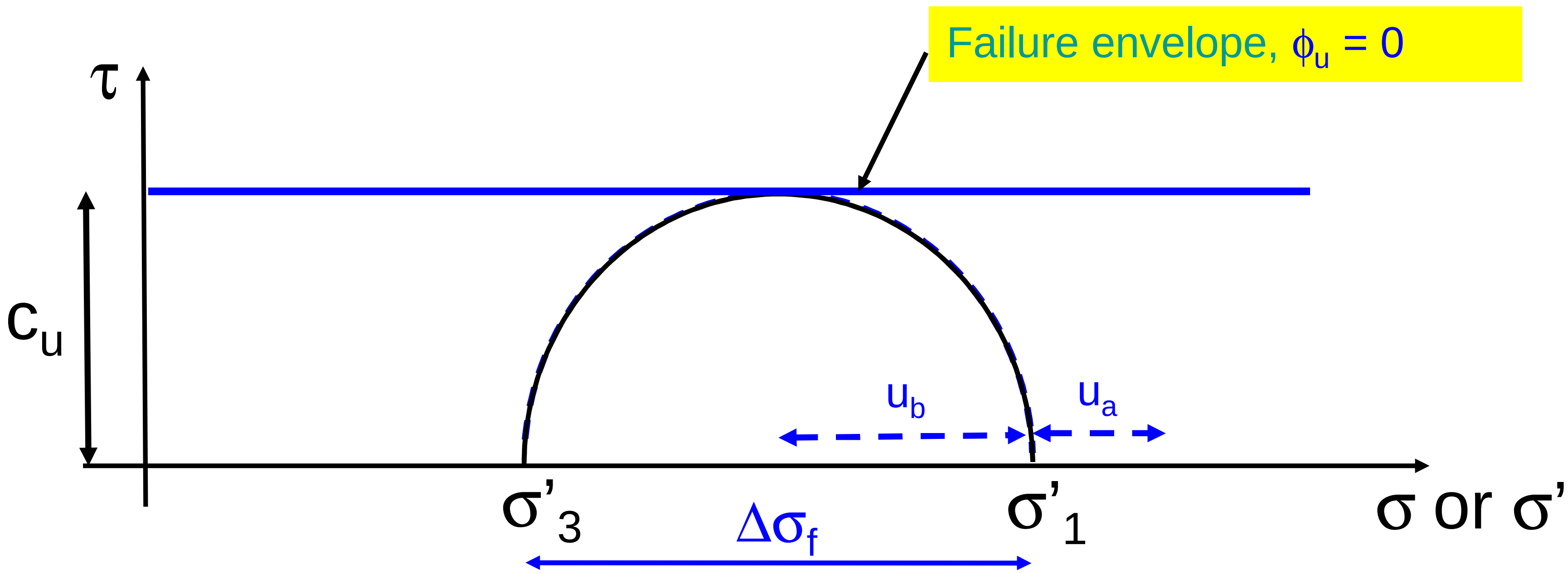


$\sigma'_{Vf} = \sigma_C + \Delta\sigma_f + u_r - \sigma_c \quad \Delta u_f = \mp \sigma'_{1f}$



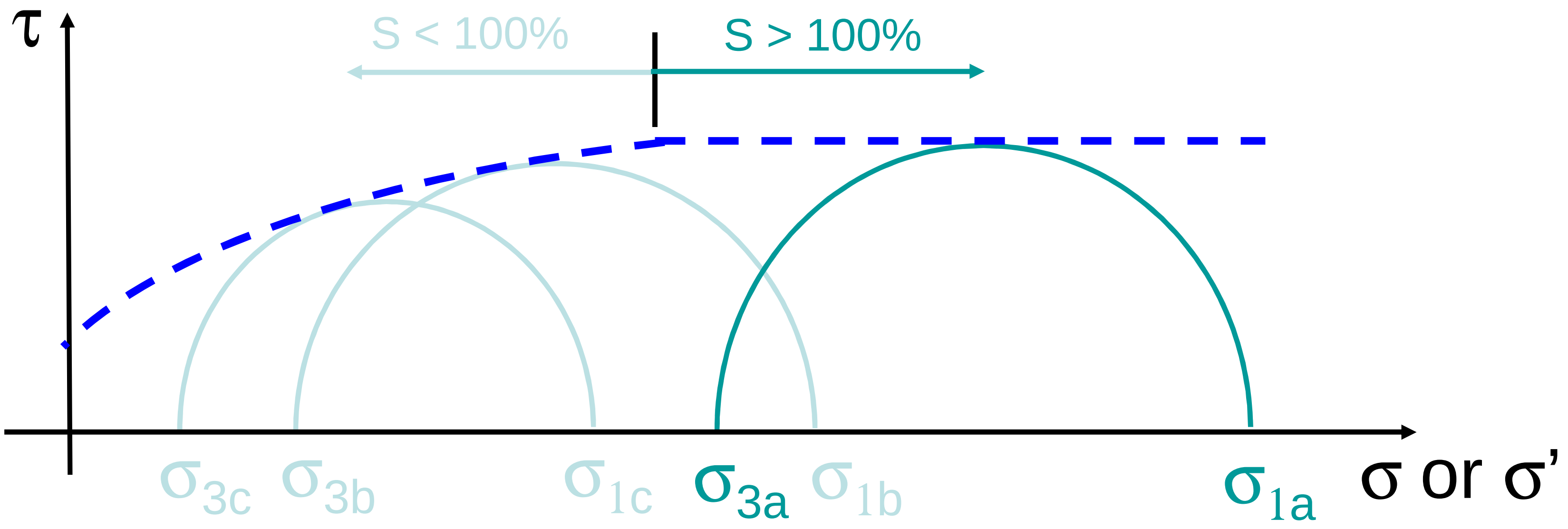
$\sigma'_{hf} = \sigma_C + u_r - \sigma_c \quad \Delta u_f = \mp \sigma'_{3f}$

Mohr circles in terms of total stresses



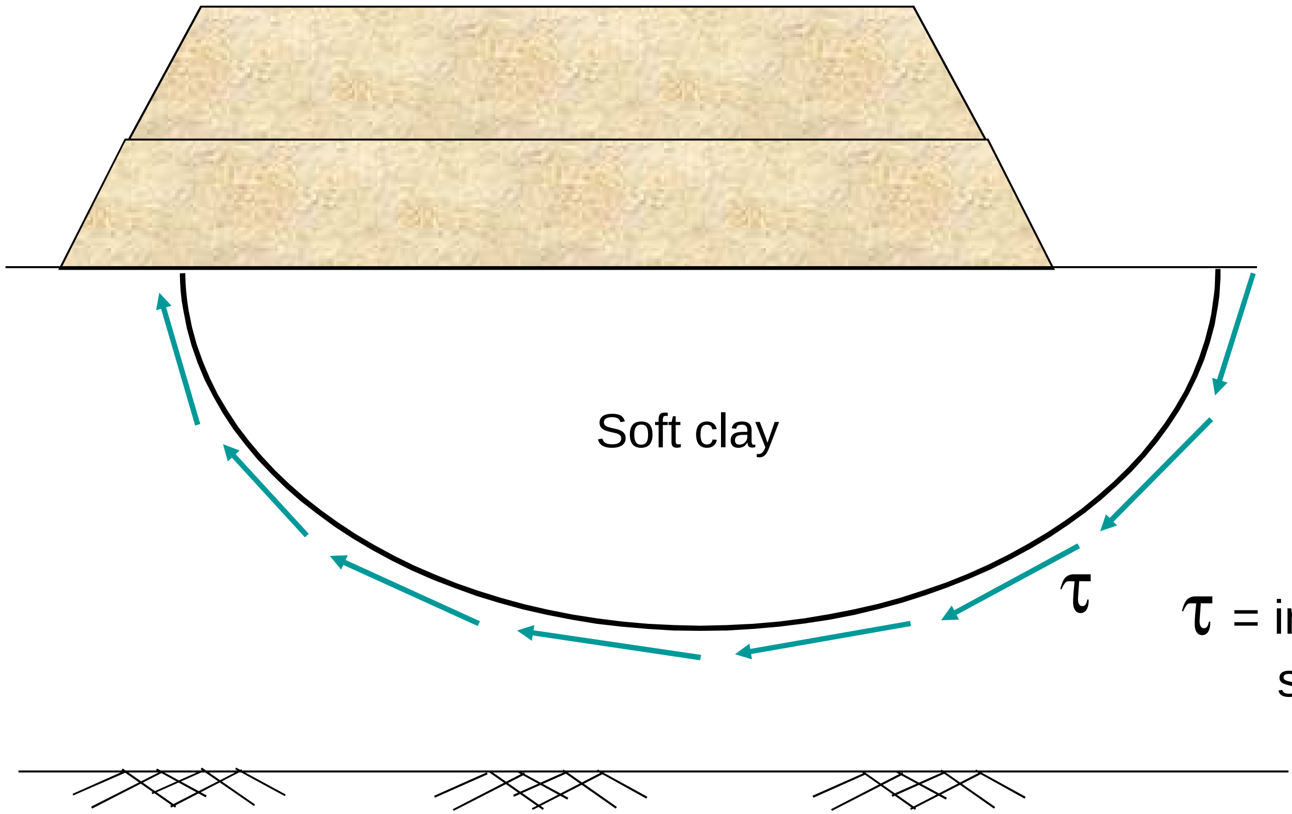
Unconsolidated- Undrained test (UU Test)

Effect of degree of saturation on failure envelope



Some practical applications of UU analysis for clays

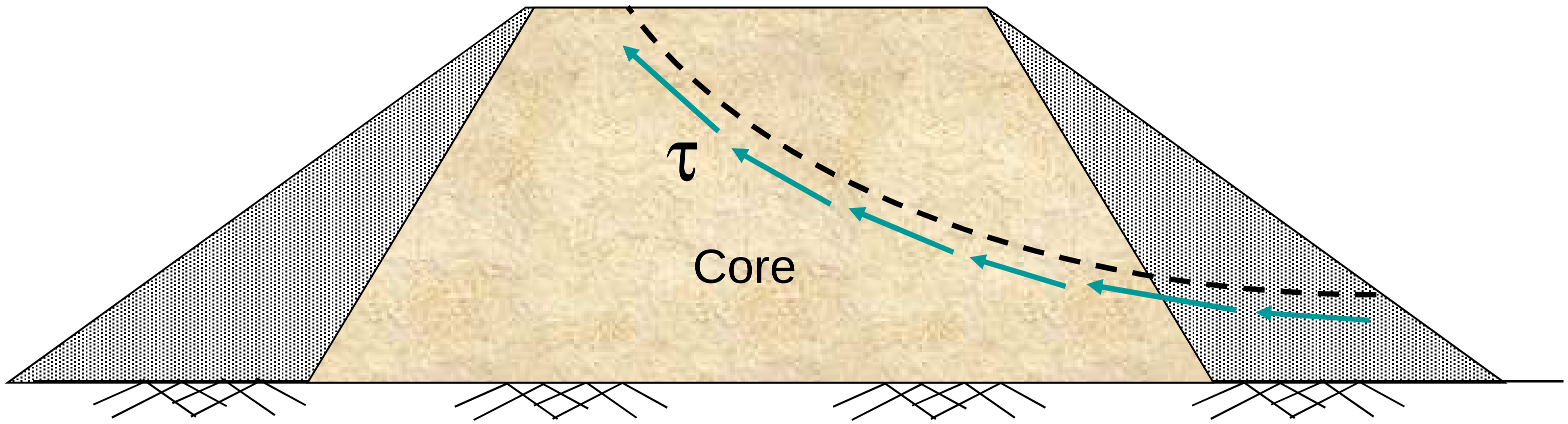
1. Embankment constructed rapidly over a soft clay deposit



τ = in situ undrained shear strength

Some practical applications of UU analysis for clays

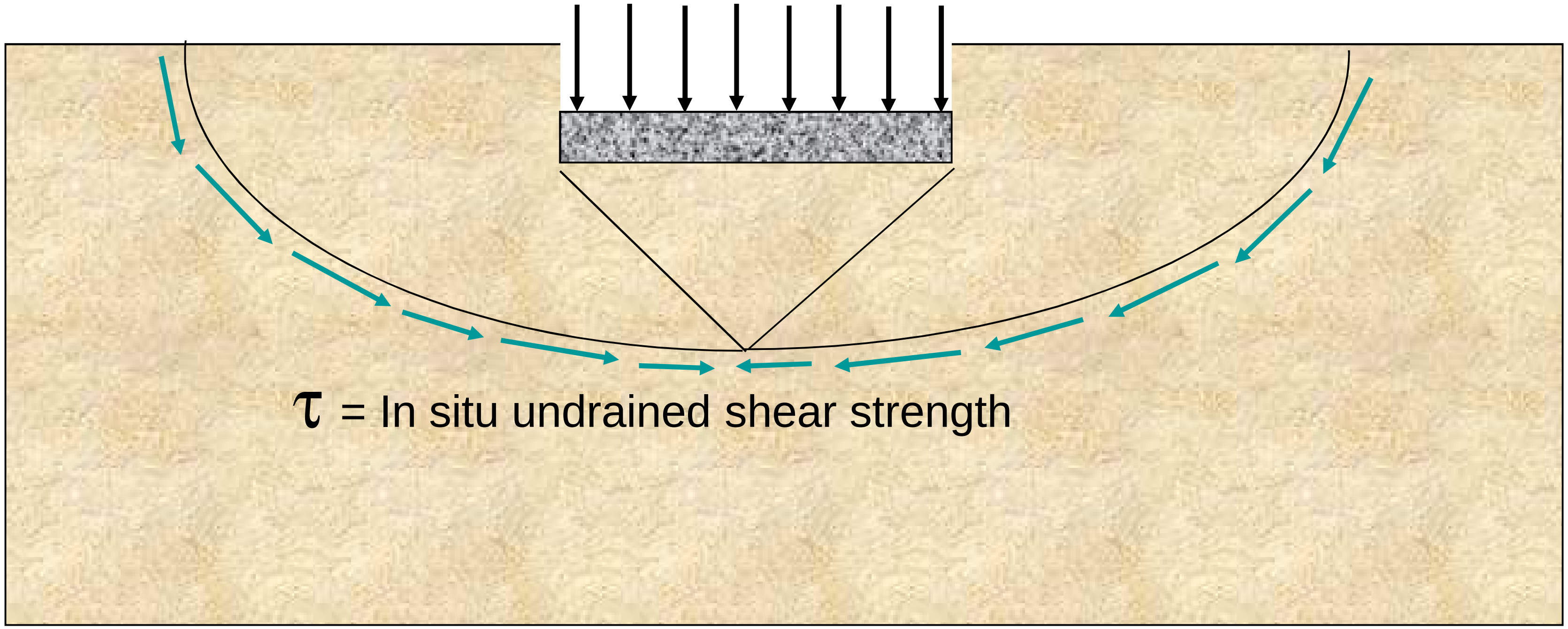
2. Large earth dam constructed rapidly with no change in water content of soft clay



τ = Undrained shear strength of clay core

Some practical applications of UU analysis for clays

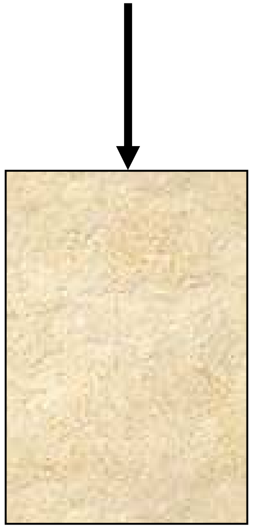
3. Footing placed rapidly on clay deposit



Note: UU test simulates the short term condition in the field. Thus, c_u can be used to analyze the short term behavior of soils

Unconfined Compression Test (UC Test)

$$\sigma_1 = \sigma_{VC} + \Delta\sigma$$

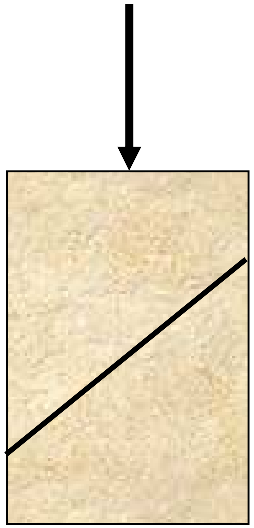


$$\sigma_3 = 0$$

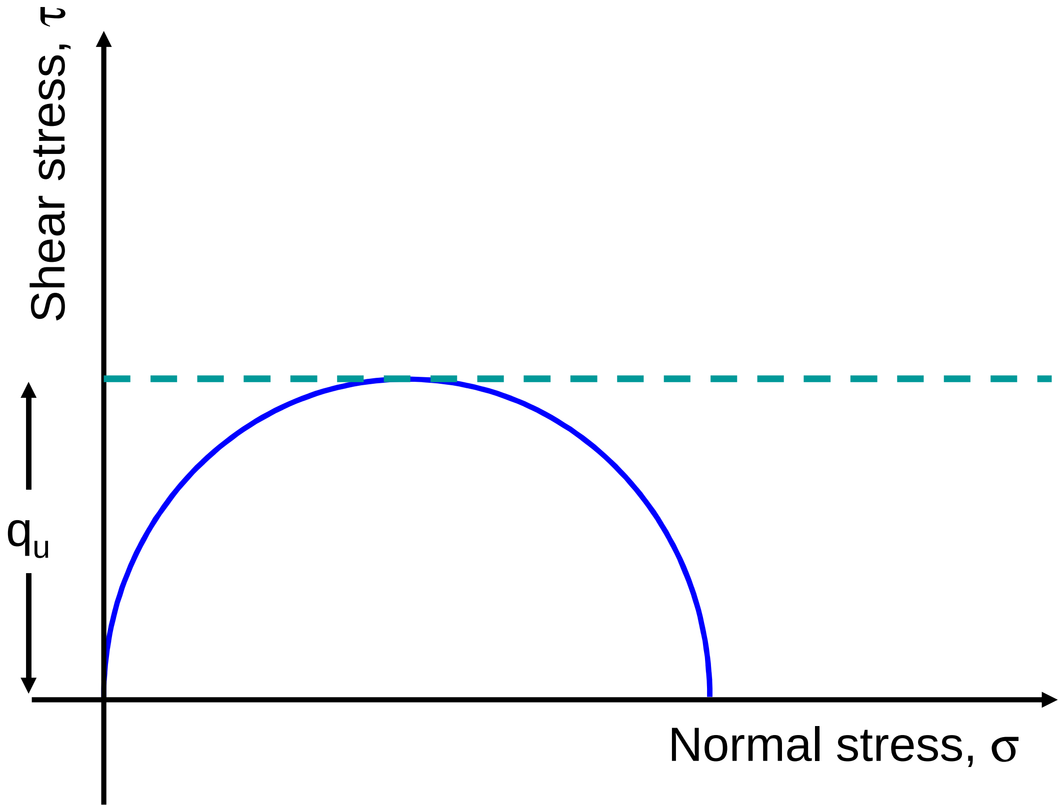
Confining pressure is zero in the UC test

Unconfined Compression Test (UC Test)

$\sigma_1 = \sigma_{VC} + \Delta\sigma f$



$\sigma_3 = 0$



$\tau_f = \sigma_1/2 = q_u/2 = c_u$

Various correlations for shear strength

For NC clays, the undrained shear strength (c_u) increases with the effective overburden pressure, σ'_0

$$\frac{c_u}{\sigma'_0} = 0.11 + 0.0037(PI)$$

Skempton (1957)

Plasticity Index as a %

For OC clays, the following relationship is approximately true

$$\left(\frac{c_u}{\sigma'_0}\right)_{Overconsolidated} \Big/ \left(\frac{c_u}{\sigma'_0}\right)_{Normally\,Consolidated} = (OCR)^{0.8}$$

Ladd (1977)

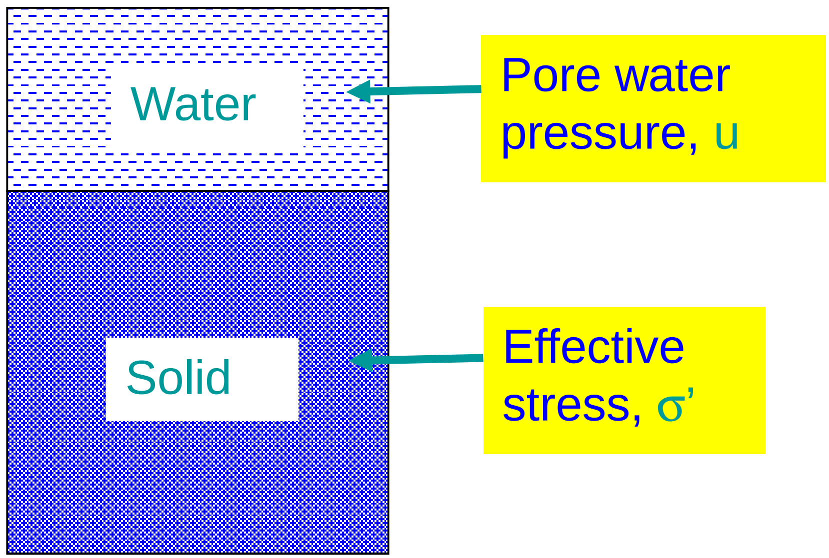
For NC clays, the effective friction angle (ϕ') is related to *PI* as follows

$$Sin\phi' = 0.814 - 0.234\log(IP)$$

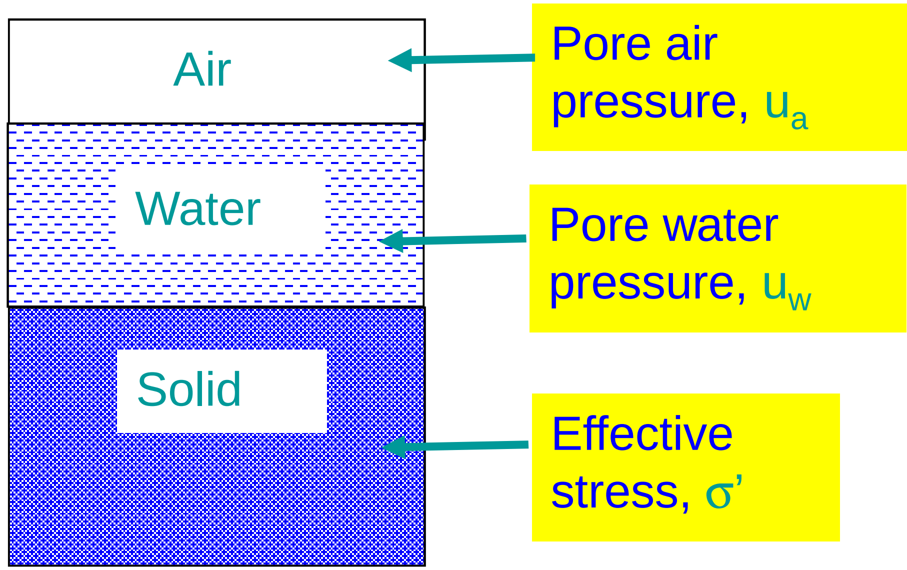
Kenny (1959)

Shear strength of partially saturated soils

In the previous sections, the shear strength of saturated soils is discussed. However, in most of the cases, it may encounter unsaturated soils



Saturated soils



Unsaturated soils

Pore water pressure can be negative in unsaturated soils

Shear strength of partially saturated soils

Bishop (1959) proposed shear strength equation for unsaturated soils as follows

$$\tau_f = c' + \left[(\sigma_n - u_a) + \chi(u_a - u_w)\right]\tan\phi'$$

Where,
$\sigma_n - u_a$ = Net normal stress
$u_a - u_w$ = Matric suction
χ= a parameter depending on the degree of saturation
(χ = 1 for fully saturated soils and 0 for dry soils)

Fredlund et al (1978) modified the above relationship as follows

$$\tau_f = c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b$$

Where, $\tan\phi^b$ = Rate of increase of shear strength with matric suction

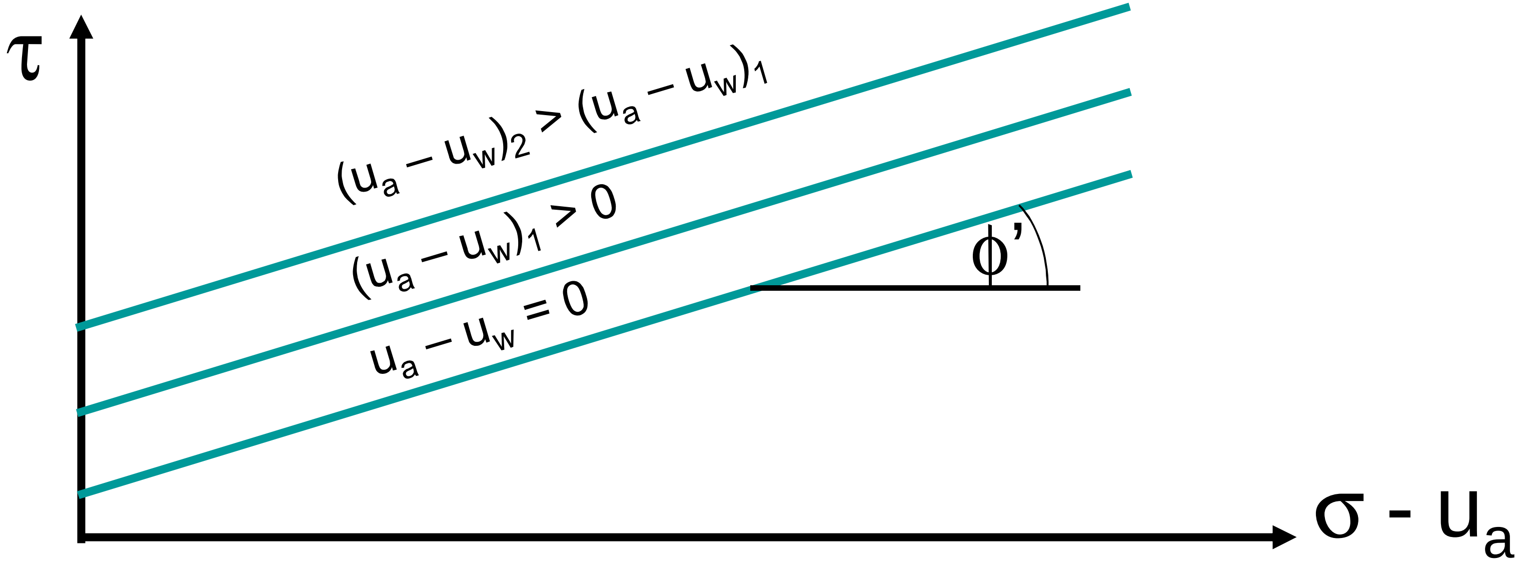
Shear strength of partially saturated soils

$$\tau_f = c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b$$

Same as saturated soils

Apparent cohesion due to matric suction

Therefore, strength of unsaturated soils is much higher than the strength of saturated soils due to matric suction



Example 1

A drained triaxial compression test carried out on three specimens of the same soil yielded the following results:

Test No.	1	2	3
Cell pressure (kPa)	100	200	300
Deviator stress at failure (kPa)	210	438	644

Draw the shear strength envelop and determine the shear strength parameters, C' & ϕ', assuming that the pore water pressure remain constant during the axial loading stage.

Example 2

Three consolidation undrained triaxial tests were carried out on 38mm diameter samples of the same clay. The applied axial force at failure of the samples were found to be as follows:-

Test No.	1	2	3
Cell pressure (kN/m^2)	25	75	120
Applied axial force at failure (kN)	0.086	0.120	0.149

Determine the shear strength parameters of the clay in term of total stress.

Example 3

The following results were obtained from undrained triaxial tests on specimens of a saturated normally consolidated clay.

Test No.	1	2	3
Cell Pressure (kN/m^2)	100	200	300
Ultimate Deviator Stress (kN/m^2)	137	210	283
Ultimate Pore Pressure (kN/m^2)	28	86	147

Determine the shear strength parameters of the clay in term of total and effective stress.

Example 4

The following results were obtained from undrained triaxial tests on specimens of an overconsolidated clay.

Test No.	1	2	3
Cell Pressure (kN/m^2)	100	250	400
Deviator Stress at failure (kN/m^2)	340	410	474
Deviator Pore Pressure (kN/m^2)	-42	64	177

Determine the shear strength parameters of the clay in term of total and effective stress.

Example 5

Referring to Example 2, if the shear strength parameters of the clay in term of effective stress were $C' = 10\ kN/m^2$ and $\Phi' = 30°$, determine the pore water pressure in each sample at failure.

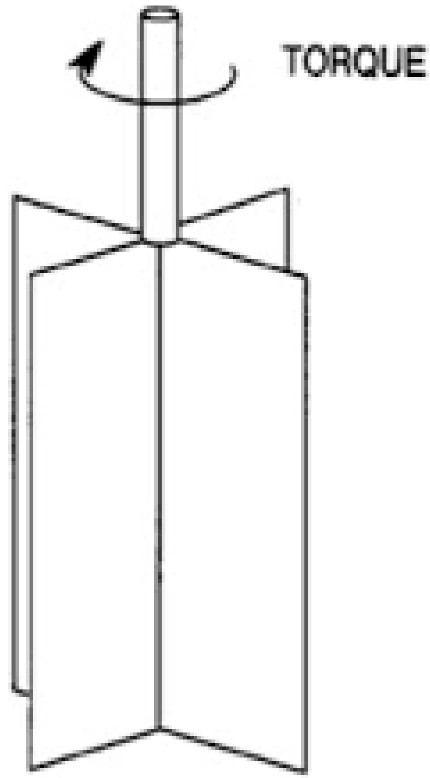
Example 6

Consolidated undrained triaxial tested were carried out on 3 samples of the same clay soil and the following results were obtained at the point of failure:-

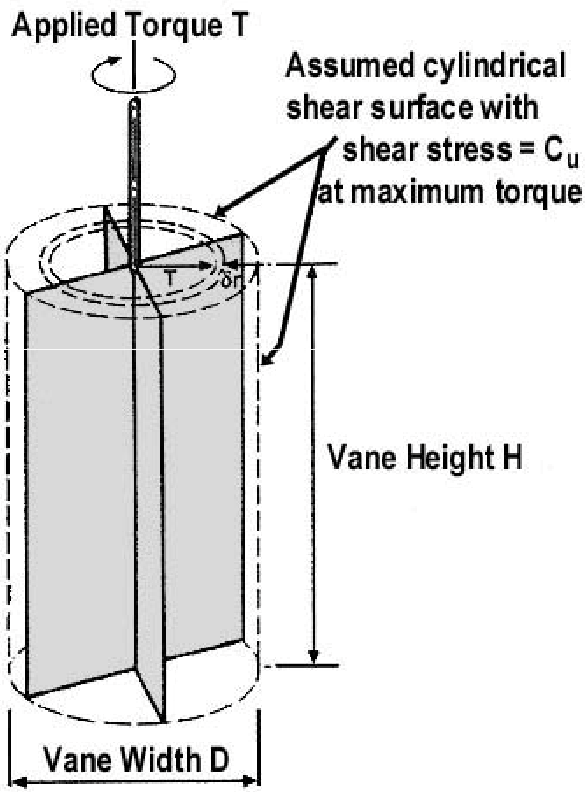
Sample No.	Cell Pressure (kN/m²)	Deviator Stress at failure (kN/m²)	Pore Water Pressure (kN/m²)	C_u (kN/m²)	Φ_u (°)	C' (kN/m²)	Φ' (°)
1	50	80.543	27.201				
2	100	?	57.879	10	?	?	?
3	?	158.514	?				

Determine the 6 unknown value (?) in the table by Calculation and Graphical method

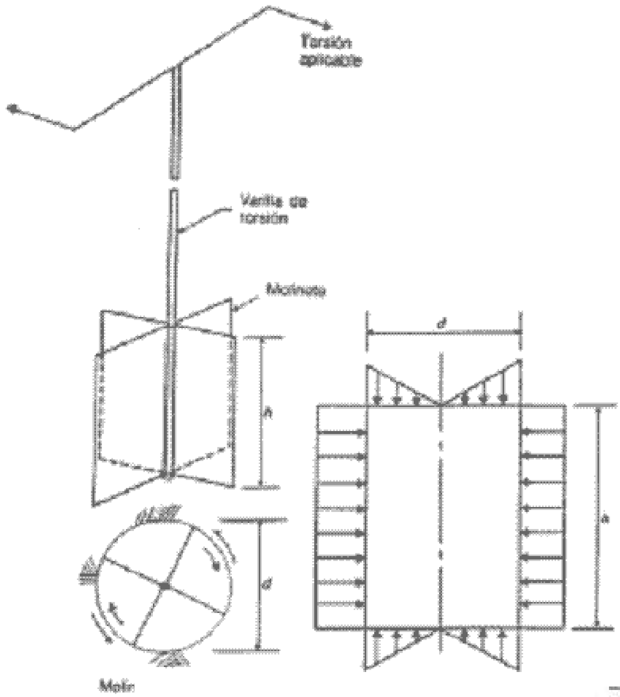
SHEAR-VANE TEST



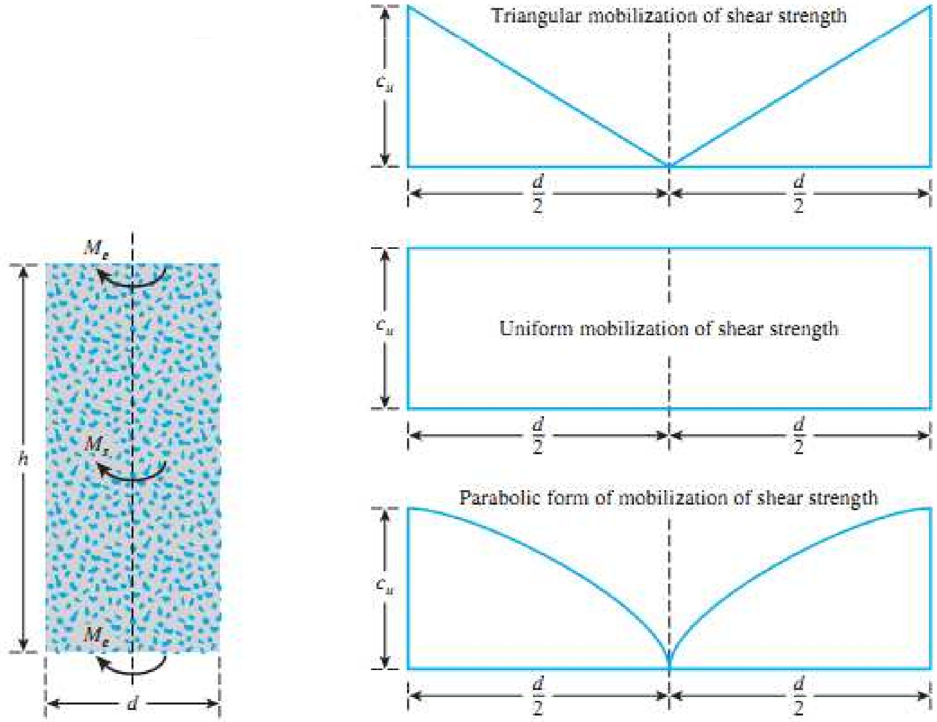
Vane shear apparatus



Applied Torque T
Assumed cylindrical shear surface with shear stress = Cu at maximum torque
T
δr
Vane Height H
Vane Width D



Torsión aplicable
Varilla de torsión
Molinete
d
h



Me
Ms
Me
h
d
Triangular mobilization of shear strength
Uniform mobilization of shear strength
Parabolic form of mobilization of shear strength
cu
d/2

(a) (b)

If **T** is the maximum torque applied at the head of the torque rod to cause failure, it should be equal to the sum of the resisting moment of the shear force along the side surface of the soilcylinder (Ms) and the resisting moment of the shear force at each end (Me)

$$T = M_s + \underbrace{M_e + M_e}_{\text{Two ends}}$$

$$M_s = \underbrace{(\pi d h) c_u}_{\text{Surface area}} \underbrace{(d/2)}_{\text{Moment arm}}$$

h = height of the shear vane
d = diameter of the shear vane

For the calculation of *Me*

1. *Triangular.* Shear strength mobilization is c_u at the periphery of the soil cylinder and decreases linearly to zero at the center.
2. *Uniform.* Shear strength mobilization is constant (that is, c_u) from the periphery to the center of the soil cylinder.
3. *Parabolic.* Shear strength mobilization is c_u at the periphery of the soil cylinder and decreases parabolically to zero at the center.

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

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

where $\beta = \frac{1}{2}$ for triangular mobilization of undrained shear strength

$\beta = \frac{2}{3}$ for uniform mobilization of undrained shear strength

$\beta = \frac{3}{5}$ for parabolic mobilization of undrained shear strength

- Suitable for determining the **in-situ** undrained shear strength of unfissured saturated clays and silts

- The vane consists of four rectangular blades in a cruciform at the end of a steel rod

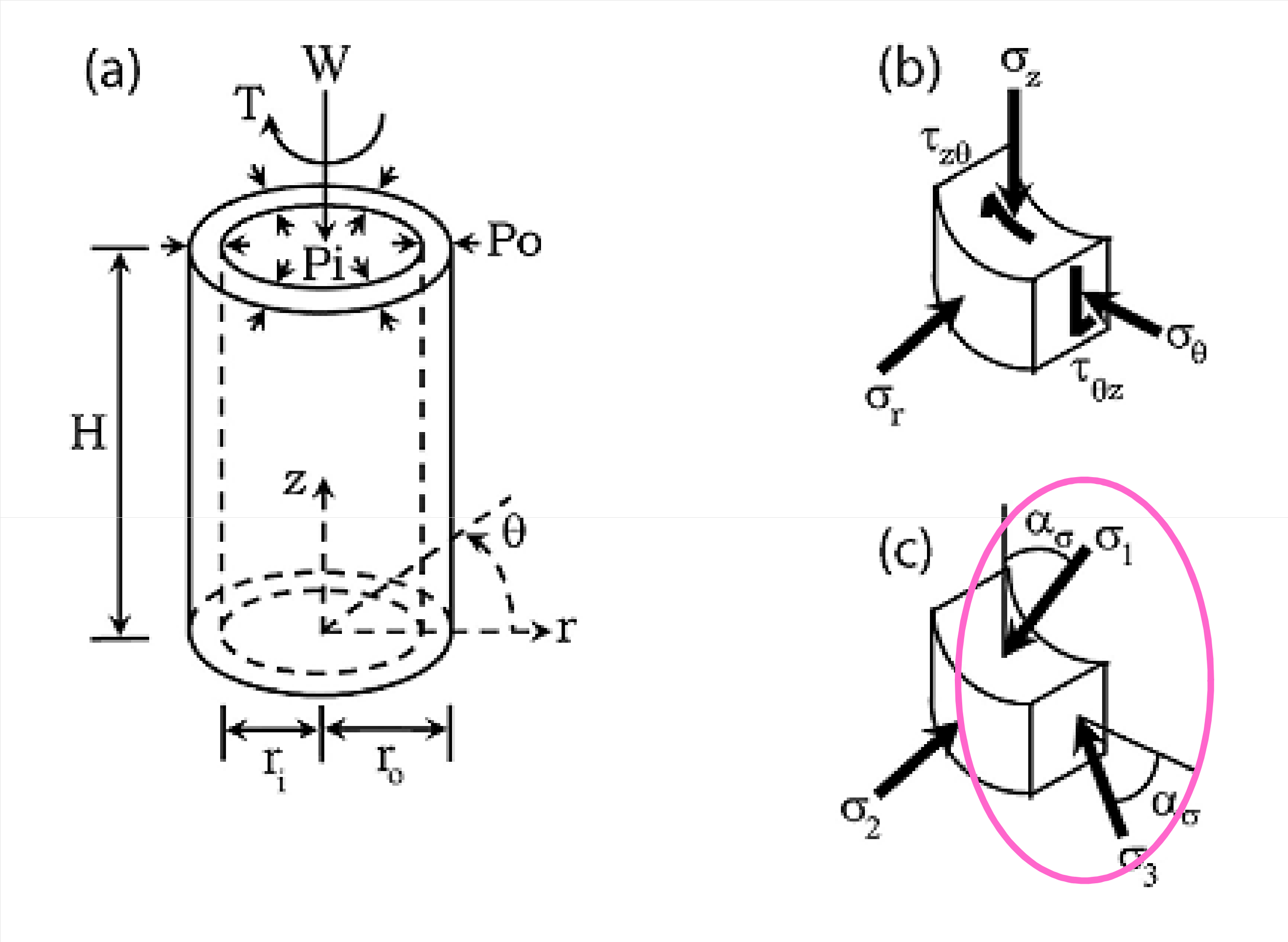
- Shear strength is measure by pushing the vane into the soil and rotated by applying a torque at the surface end of the rod

- The vane is first rotated at 6-12° per minute to determine the undisturbed shear strength and then the remoulded strength is measured by rotating the vane rapidly

Example 1

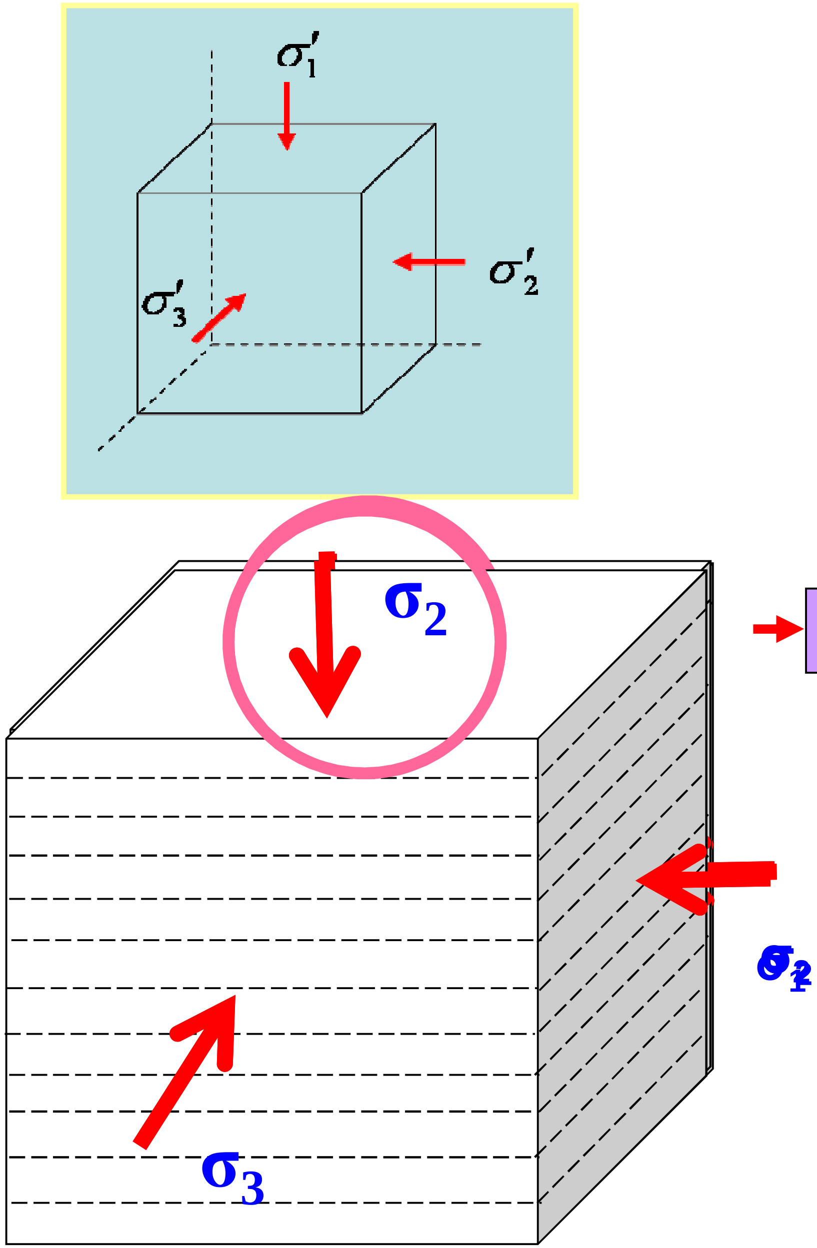
A shear vane used to test a soft clay had a diameter of 75mm and a length of 150mm. The average torques recorded after slow and then rapid rotations were 64 and 26 Nm respectively. Determine the undrained strength of the clay.

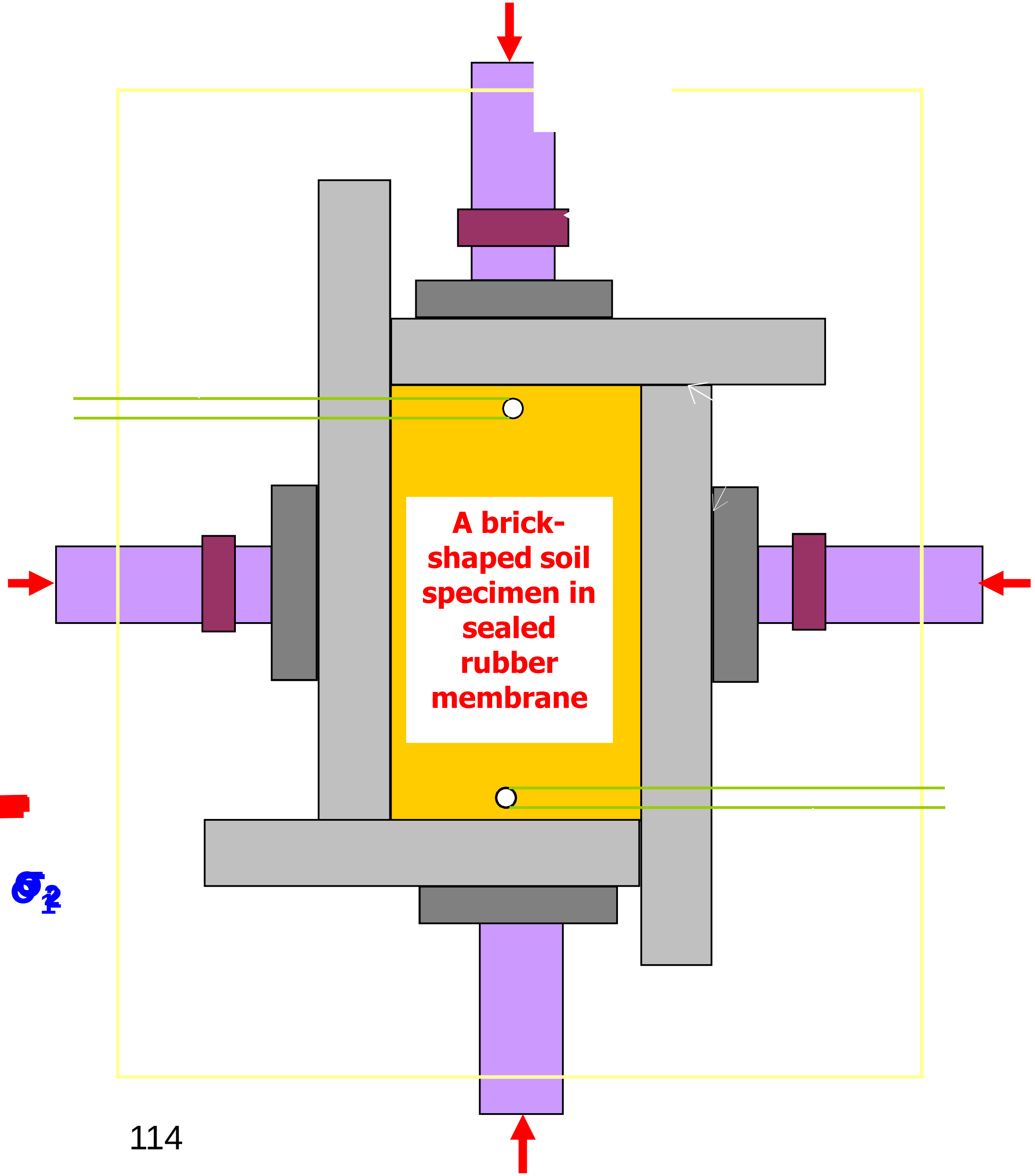
Hollow cylinder test…



Moving Vehicles on road, Beds of flowing river,…….etc

Truly Triaxial test, Plane strain test, simple shear test……





3 main types of triaxial tests:

a) Unconsolidated - Undrained
b) Consolidated – Drained
c) Consolidated – Undrained