SKAA 1713
SOIL MECHANICS

- **Laboratory Testing**
- **Total & Effective Stress Analysis**

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Mohr Coulomb failure criterion with Mohr circle of stress

$$\left[c'Cot\phi' + \left(\frac{\sigma_1' + \sigma_3'}{2}\right)\right]Sin\phi' = \left(\frac{\sigma_1' - \sigma_3'}{2}\right)$$

$$\left(\sigma_1' - \sigma_3'\right) = \left(\sigma_1' + \sigma_3'\right)Sin\phi' + 2c'Cos\phi'$$

$$\sigma_1'\left(1 - Sin\phi'\right) = \sigma_3'\left(1 + Sin\phi'\right) + 2c'Cos\phi'$$

$$\sigma_1' = \sigma_3'\frac{\left(1 + Sin\phi'\right)}{\left(1 - Sin\phi'\right)} + 2c'\frac{Cos\phi'}{\left(1 - Sin\phi'\right)}$$

$$\sigma_1' = \sigma_3' Tan^2\left(45 + \frac{\phi'}{2}\right) + 2c'Tan\left(45 + \frac{\phi'}{2}\right)$$

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

Laboratory tests

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

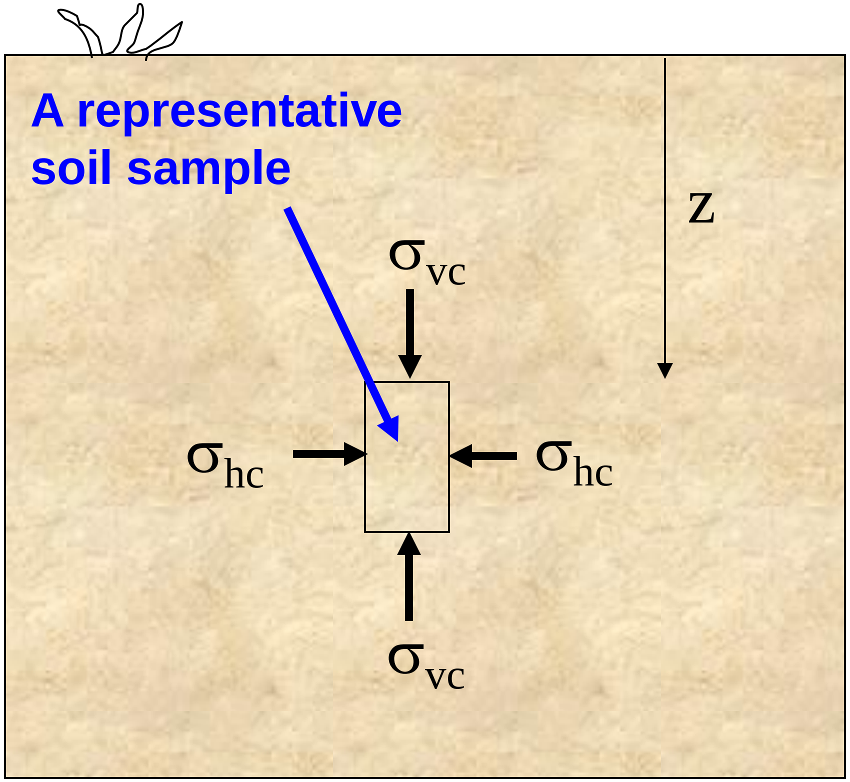
1. Direct shear test
2. Unconfined Compressive Strength test
3. Triaxial shear test

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

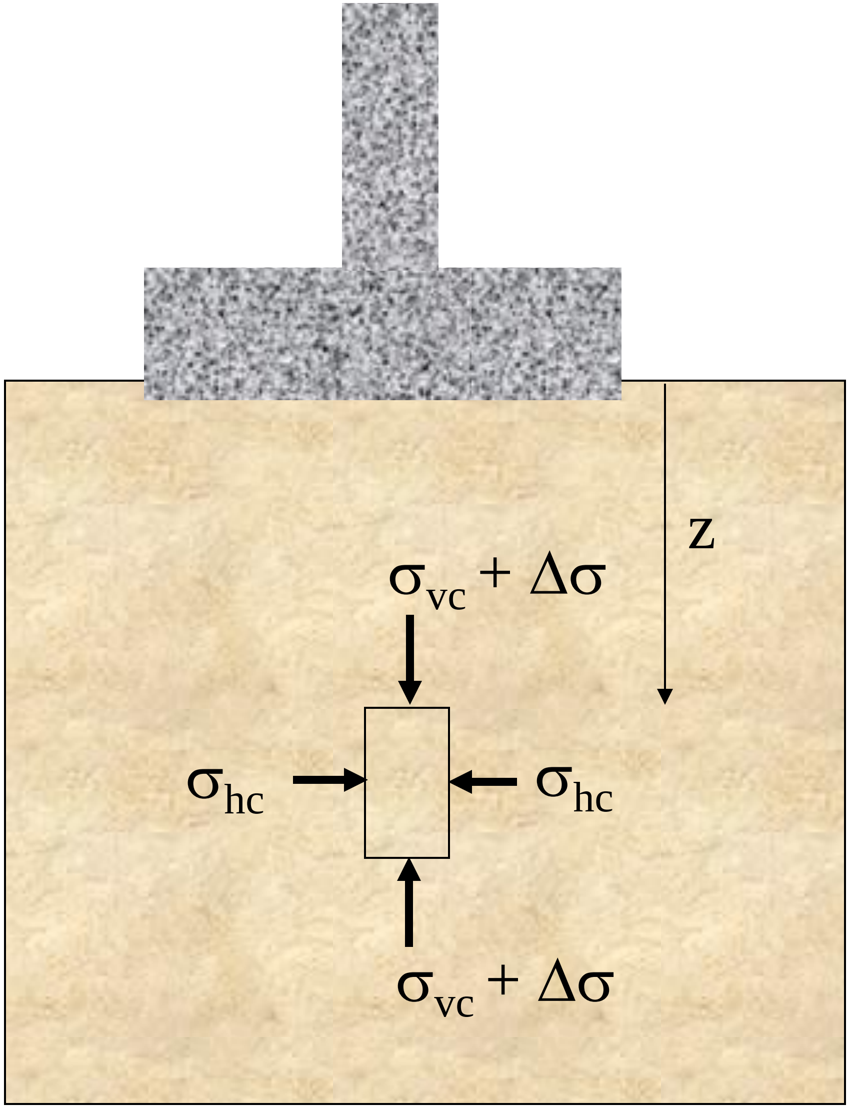
Field tests

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

Field conditions

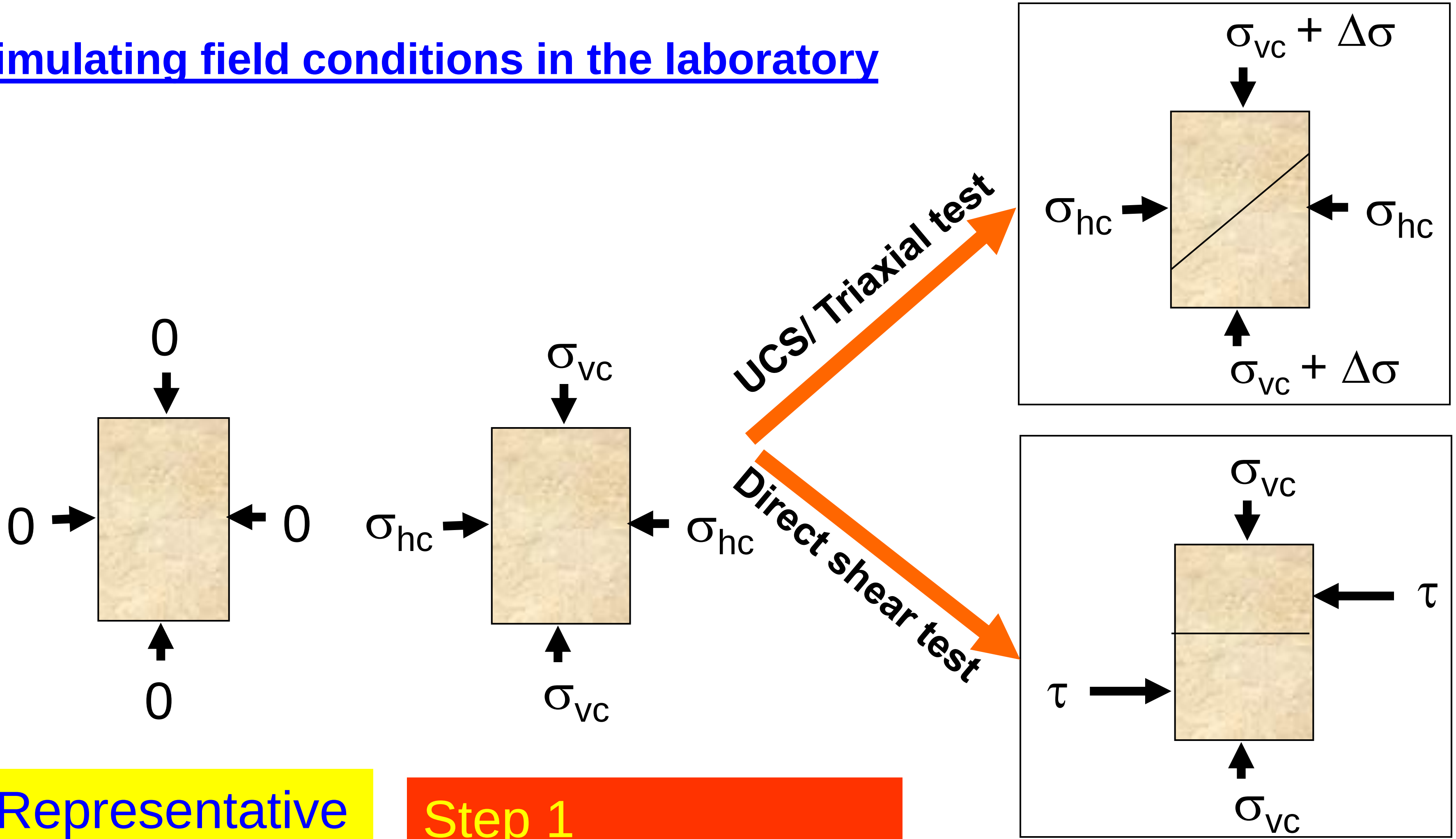


Before construction



After and during construction

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

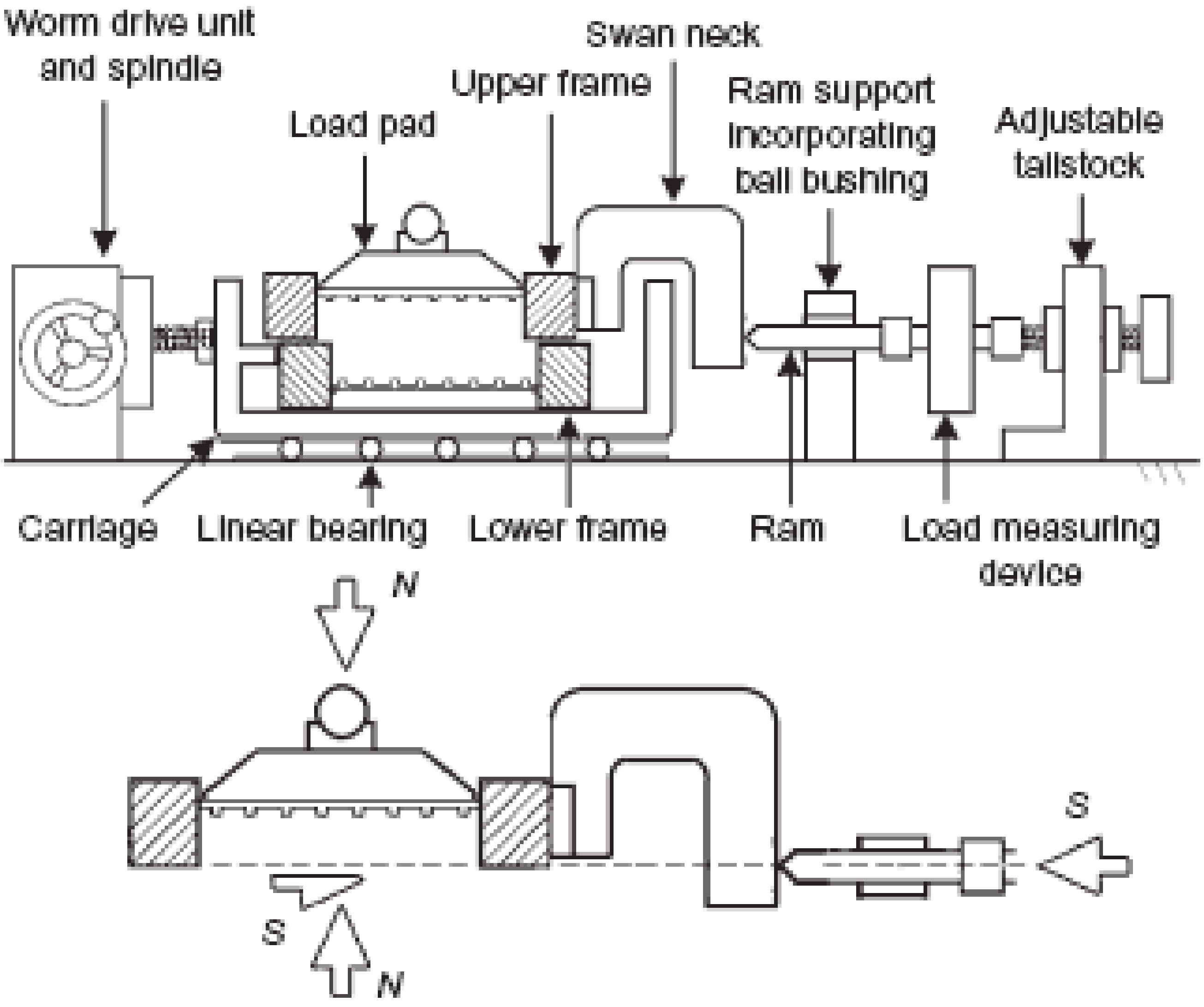
Step 2

Apply the corresponding field stress conditions

DIRECT SHEAR TEST

Direct shear test

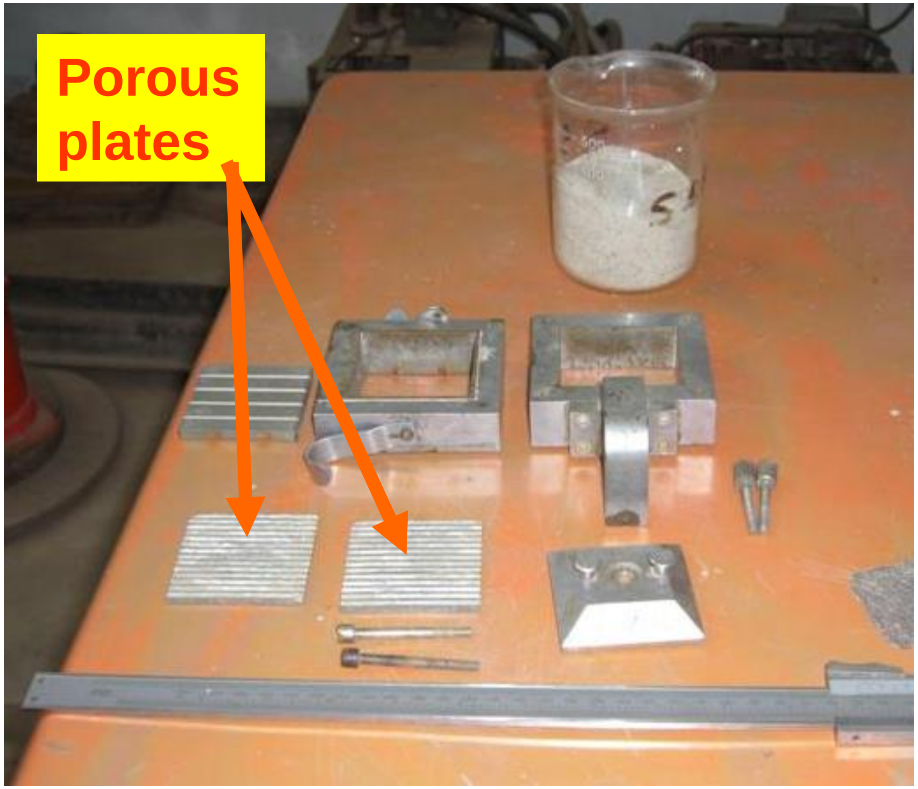
Schematic diagram of the direct shear apparatus



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

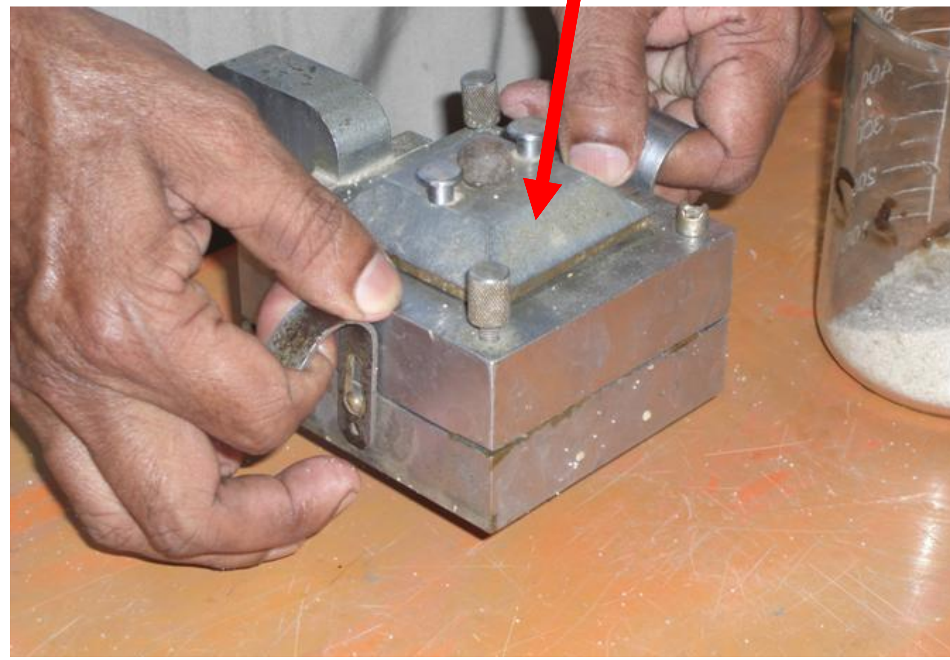
Preparation of a sand specimen

Direct shear test

Preparation of a sand specimen

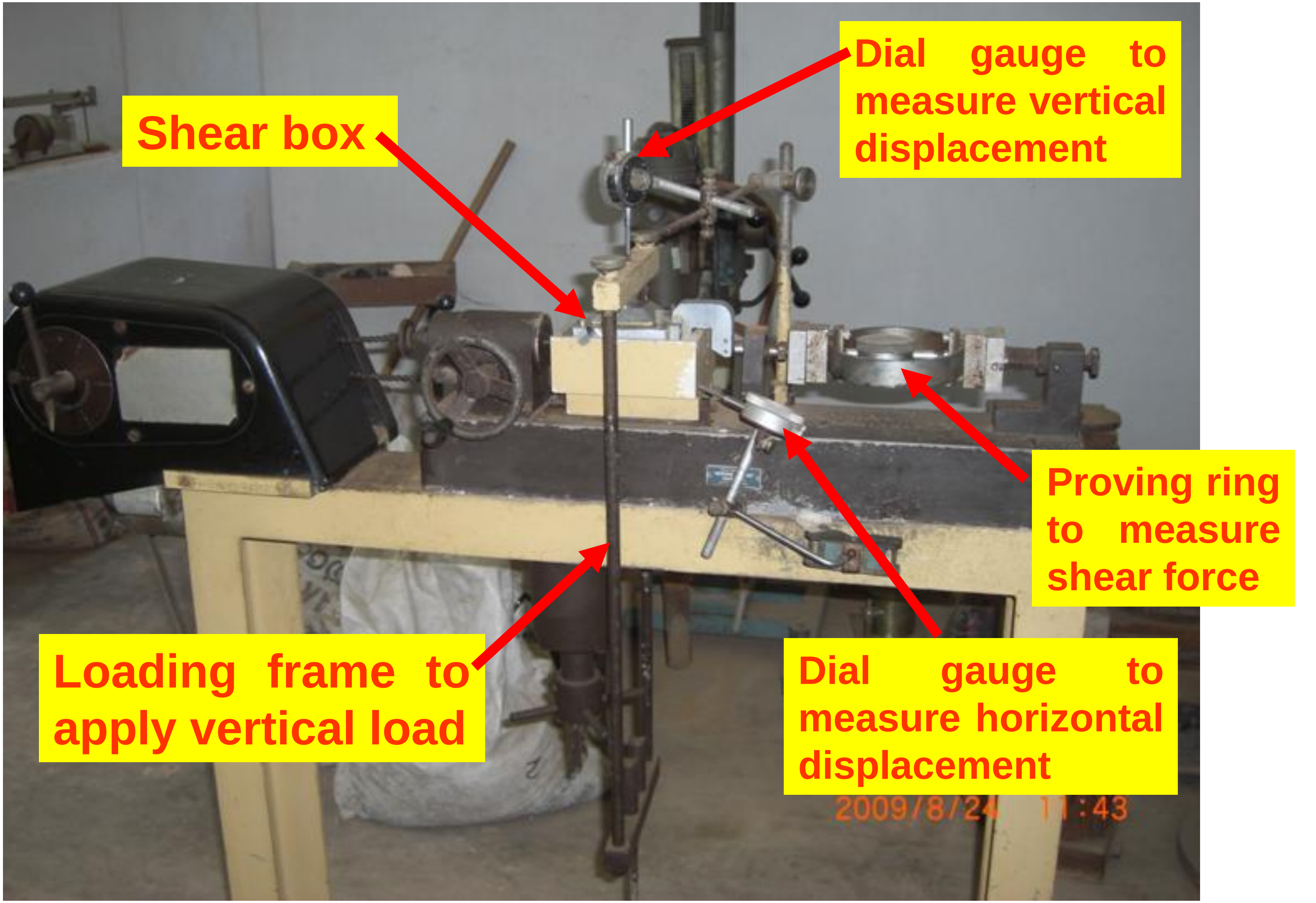
Leveling the top surface of specimen

Pressure plate



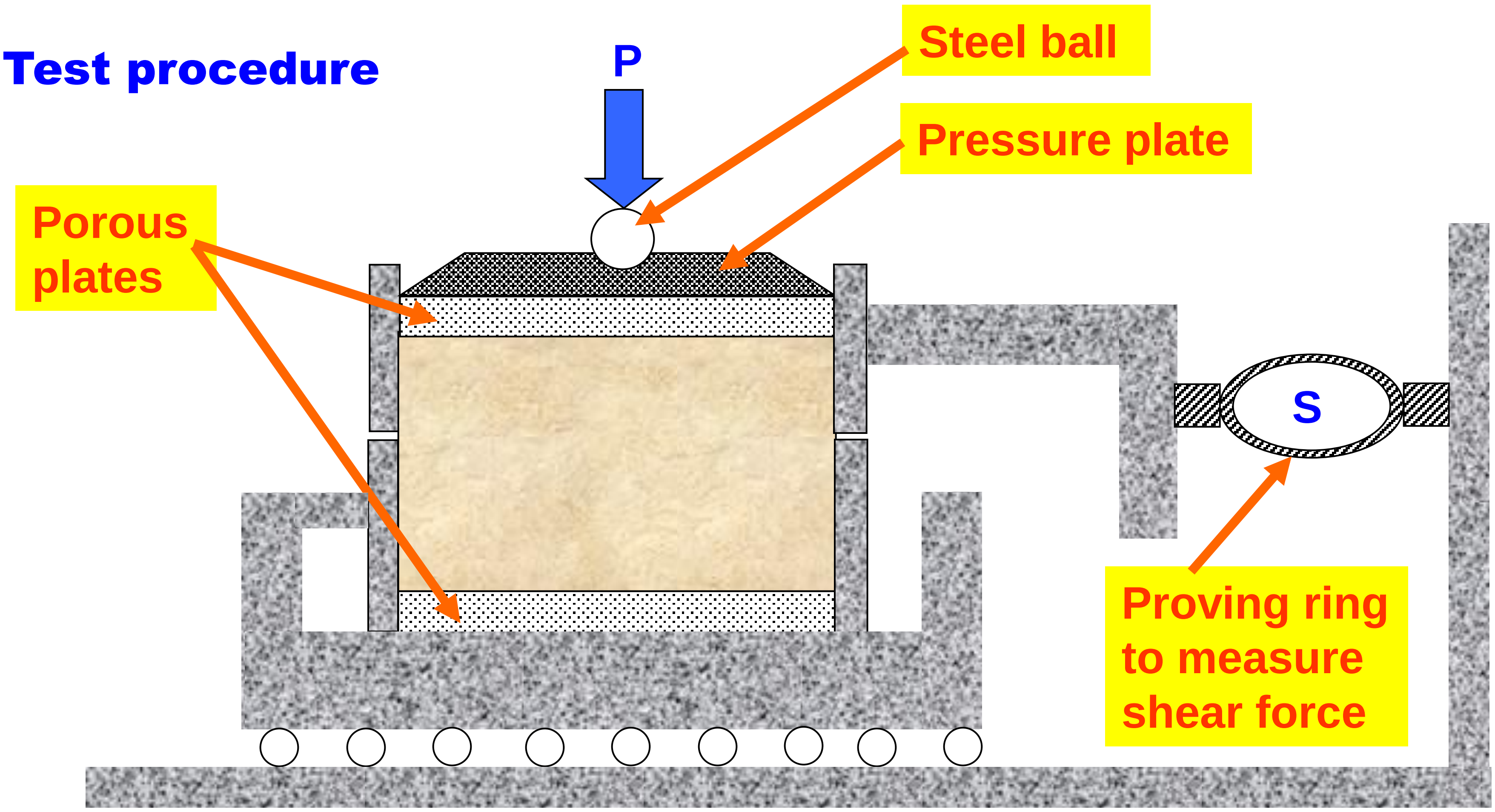
Specimen preparation completed

Direct shear test



Direct shear test

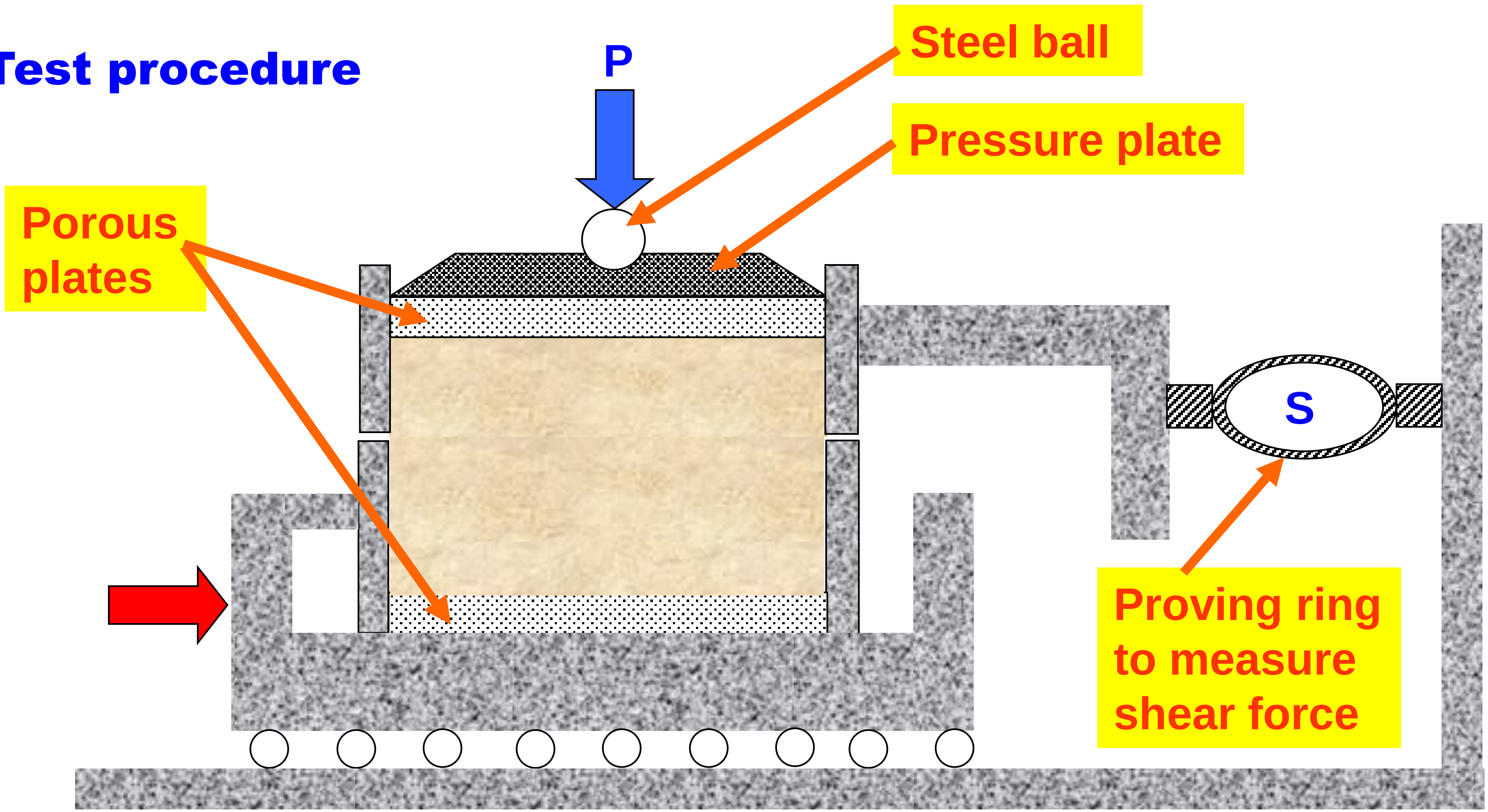
Test procedure



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

Analysis of test results

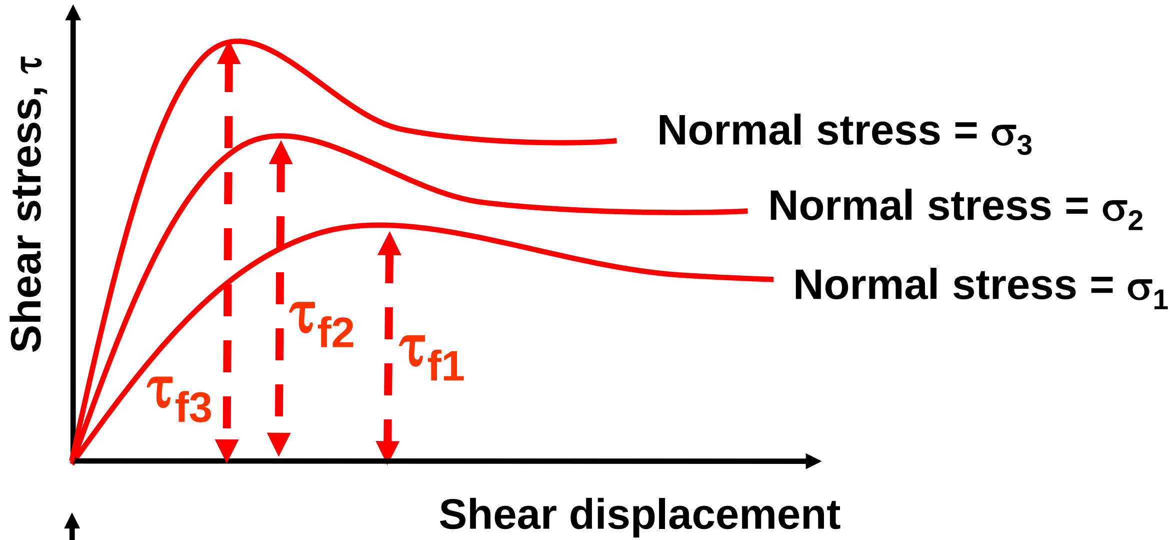
$$\sigma = \text{Normal stress} = \frac{\text{Normal force (P)}}{\text{Area of cross section of the sample}}$$

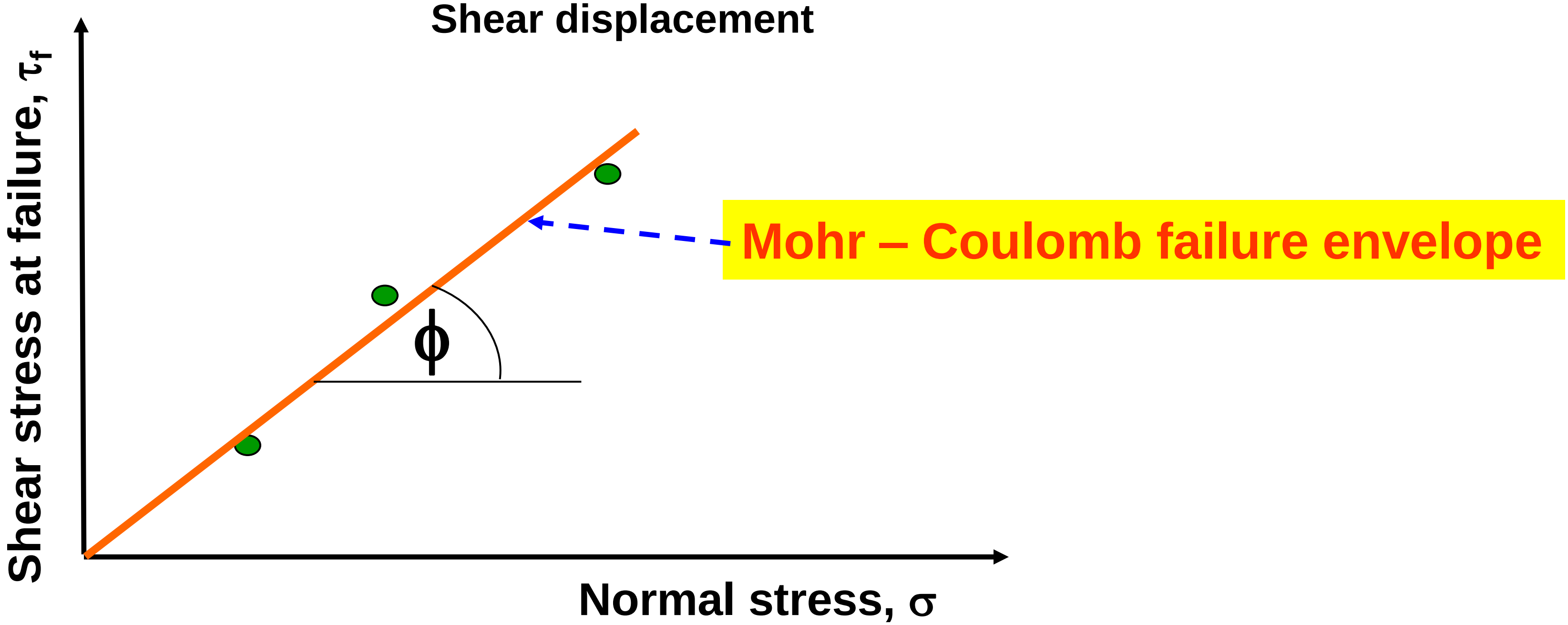
$$\tau = \text{Shear stress} = \frac{\text{Shear resistance developed at the sliding surface (S)}}{\text{Area of cross section of the sample}}$$

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

Direct shear tests on sands

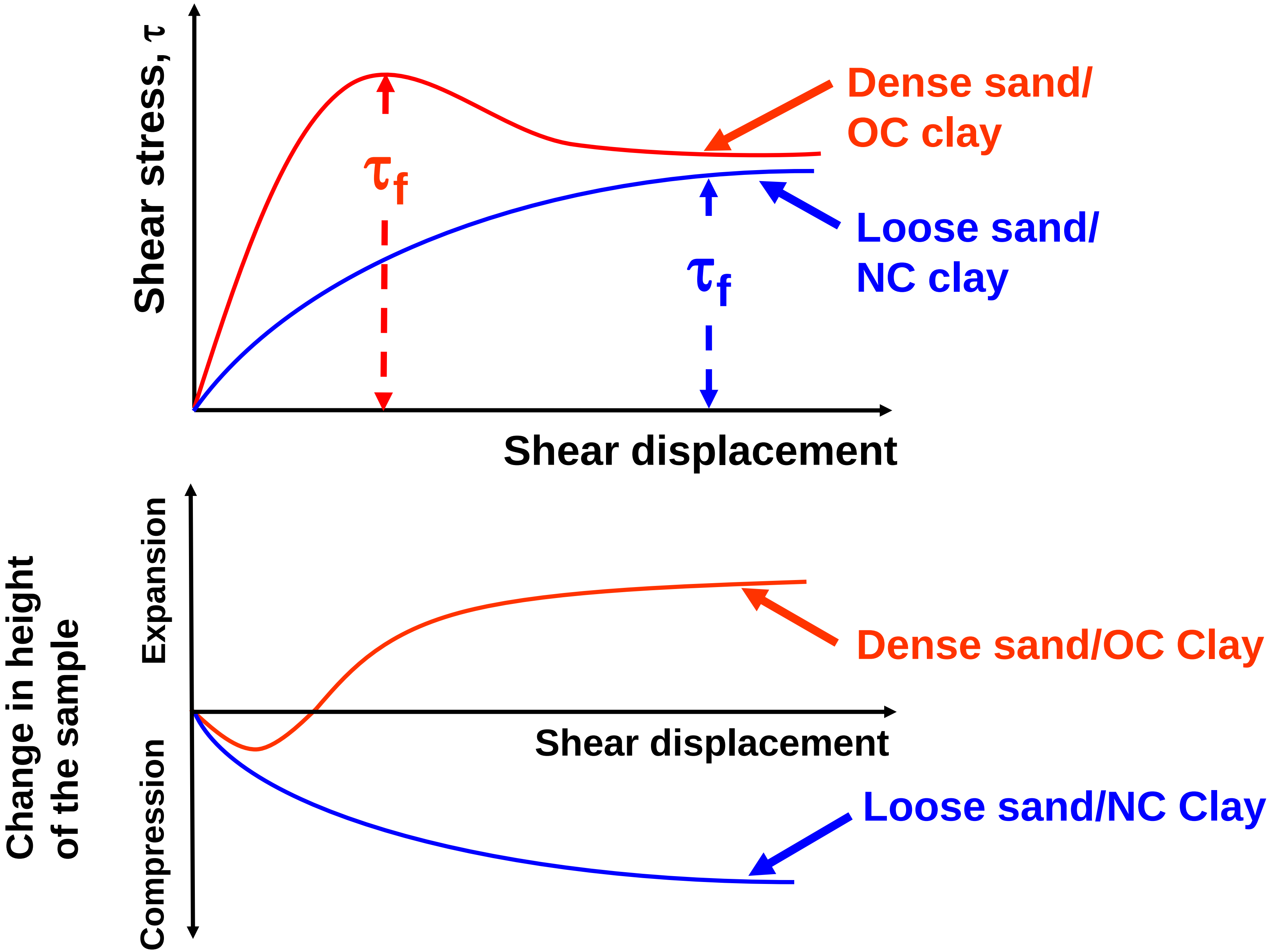
How to determine strength parameters c and ϕ





Direct shear tests

Stress-strain relationship



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

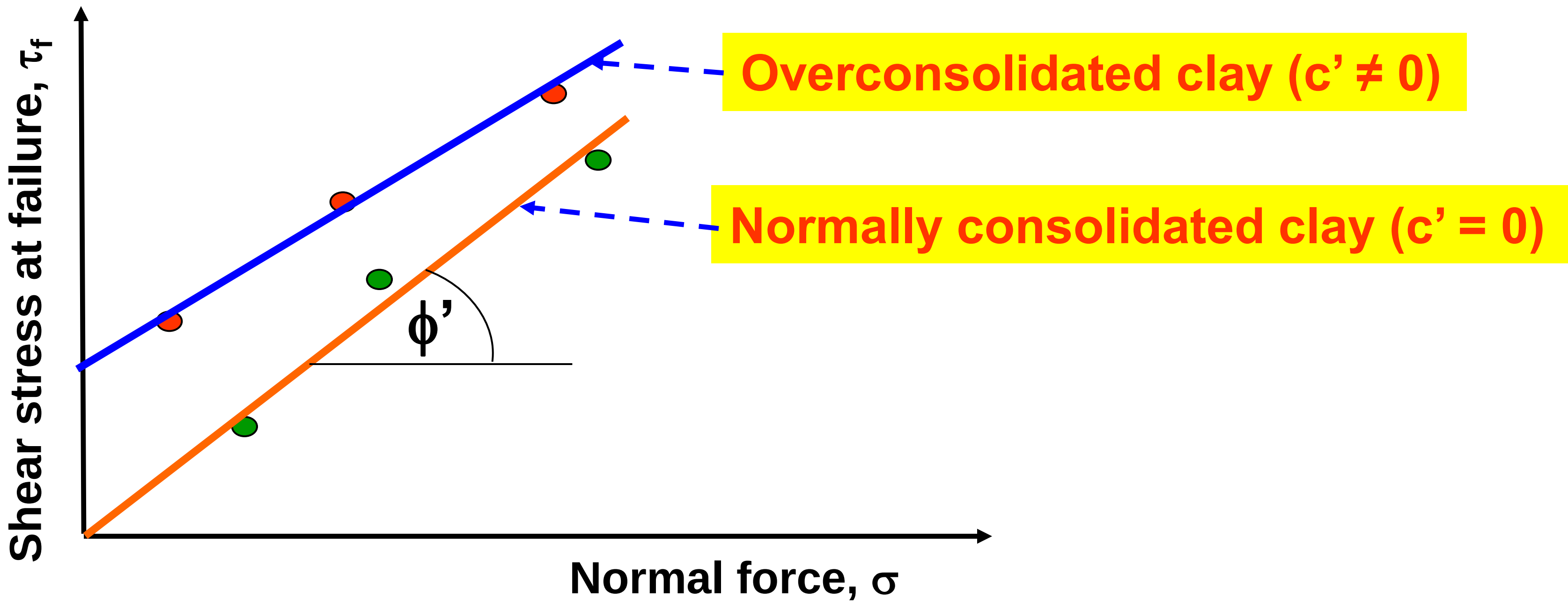
Therefore,

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

Direct shear tests on clays

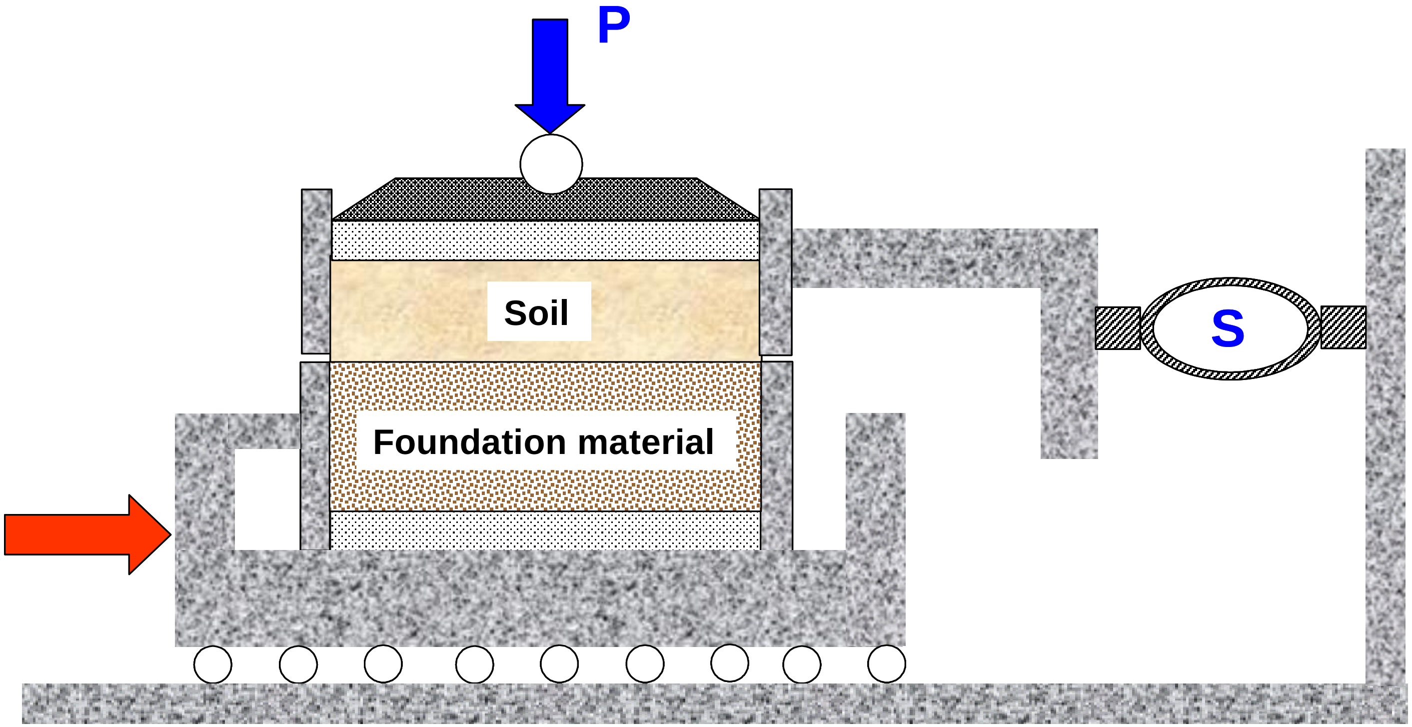
In case of clay, *horizontal displacement* should be applied at a very slow rate to allow dissipation of pore water pressure (therefore, one test would take several days to finish)

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

Advantages of direct shear apparatus

- Due to the smaller thickness of the sample, rapid drainage can be achieved
- Can be used to determine interface strength parameters
- Clay samples can be oriented along the plane of weakness or an identified failure plane

Disadvantages of direct shear apparatus

- Failure occurs along a predetermined failure plane
- Area of the sliding surface changes as the test progresses
- Non-uniform distribution of shear stress along the failure surface

Example

A direct shear test when conducted on a remolded sample of sand, gave the following observations at the time of failure; Normal force = 288 N; shear force = 173 N. The cross sectional area of the sample = 36cm^2.

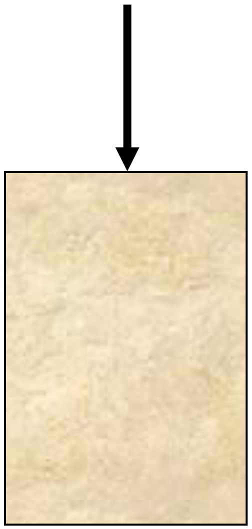
Determine the angle of frictional. Solved in 2 ways, namely graphically and analytically

(31 degrees)

UNCONFINED COMPRESSIVE STRENGTH (UCS) TEST

Unconfined Compression Test (UCS Test)

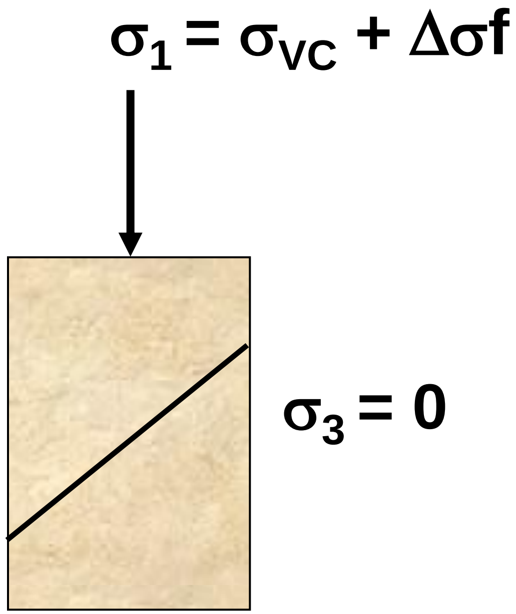
$$\sigma_1 = \sigma_{VC} + \Delta\sigma$$

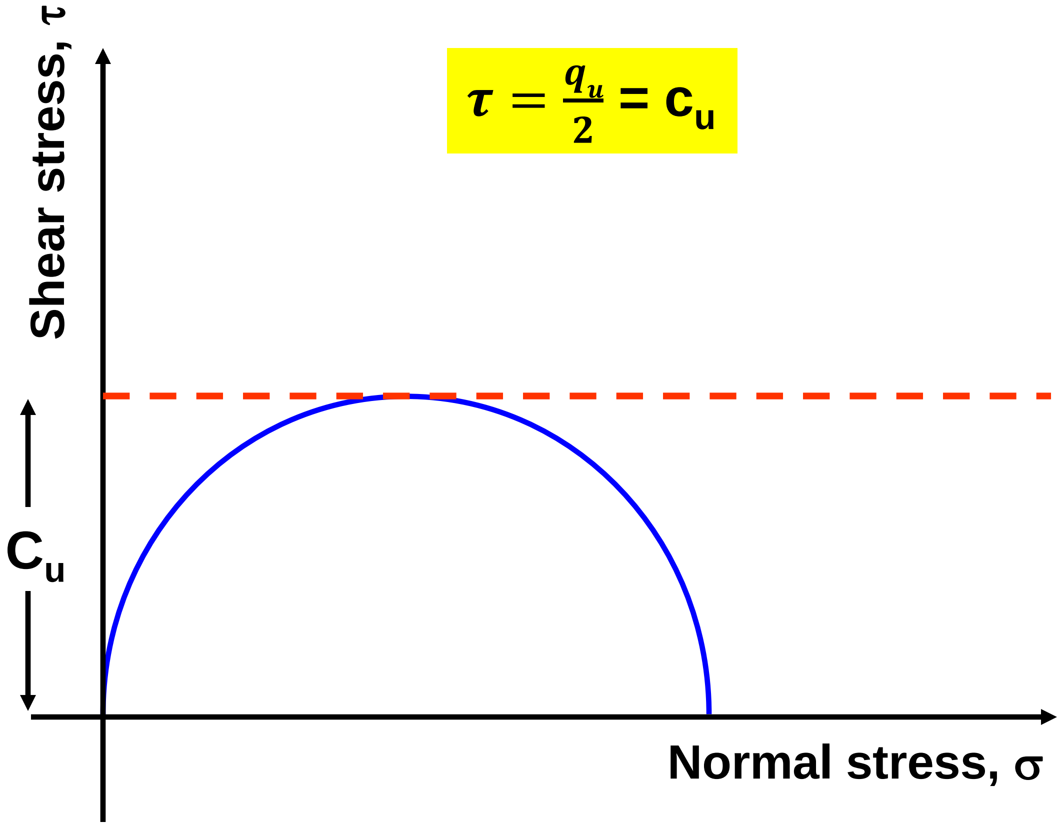


$$\sigma_3 = 0$$

Confining pressure is zero in the UCS test

Unconfined Compression Test (UC Test)

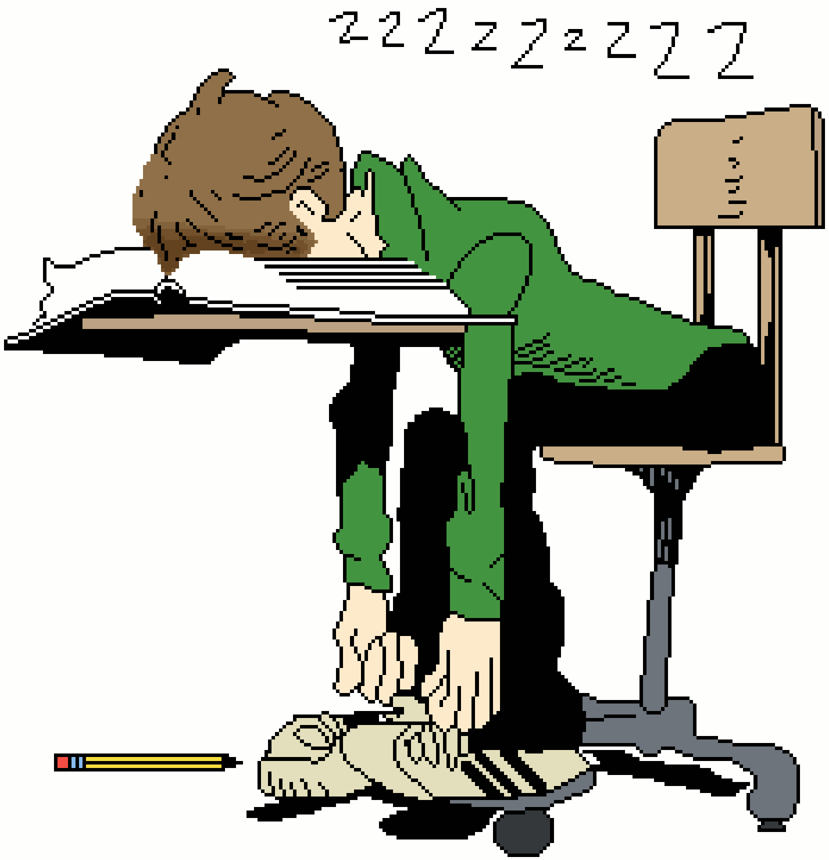




$$\tau = \frac{q_u}{2} = c_u$$

Note: Theoritically $q_u = c_u$, However in the actual case $q_u < c_u$ due to premature failure of the sample

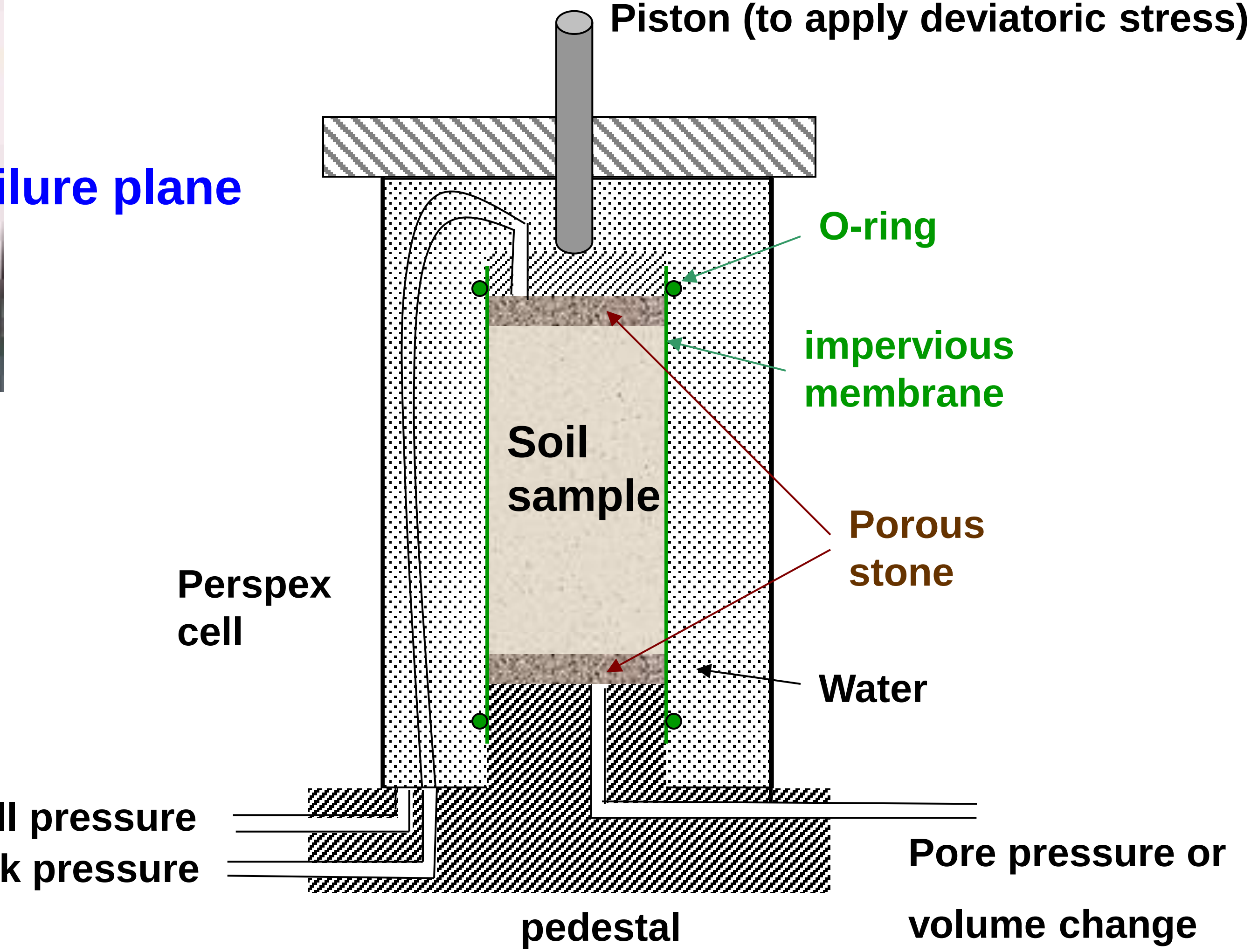
Lets continue later....



TRIAXIAL TEST

Triaxial Shear Test

Soil sample at failure



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

In some tests

Triaxial Shear Test

- **Consists of 3 stages:**

1. Saturation
2. Consolidation
3. Shearing

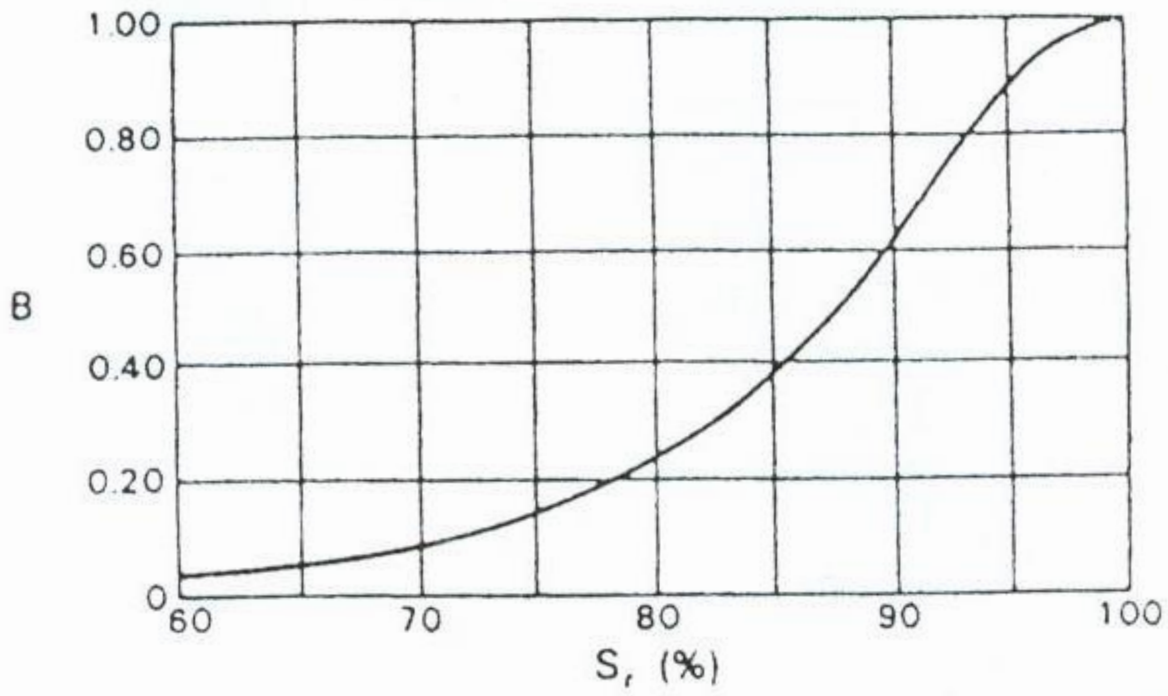
Main stages (Consolidation and Shearing)

Triaxial Shear Test

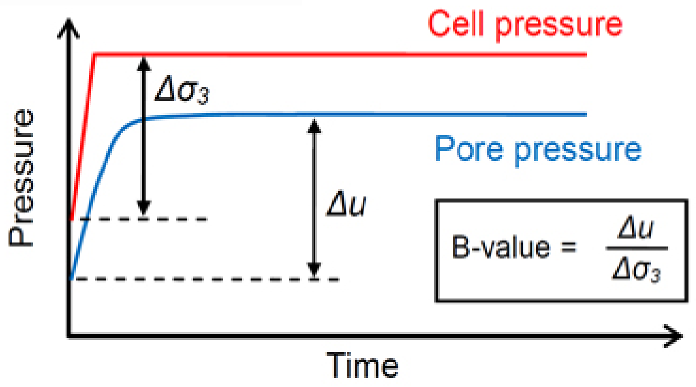
Saturation & use of back pressure

1. Reason for saturation
2. Principle of saturation
3. Maintaining saturation
4. Advantages of saturation

Typical values for parameter B



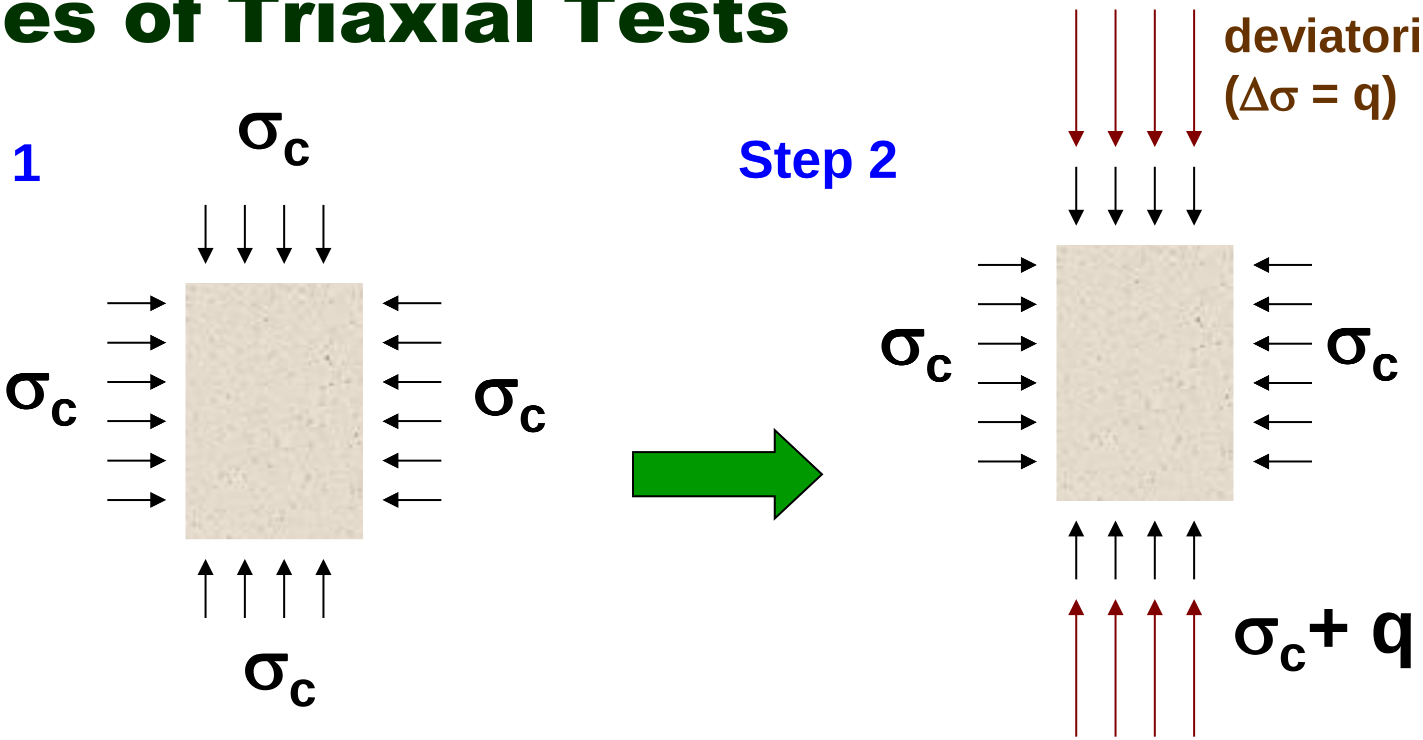
Typical relationship between B and degree of saturation.



Triaxial Shear Test

Test Condition	Stage 1	Stage 2
Unconsolidated Undrained (UU)	Apply confining pressure σ_3 while the drainage line from the specimen is kept closed (drainage is not permitted), then the initial pore water pressure ($u=u_o$) is not equal to zero	Apply an added stress $\Delta\sigma$ at axial direction. The drainage line from the specimen is still kept closed (drainage is not permitted) ($u=u_d \neq 0$). At failure state $\Delta\sigma=\Delta\sigma_f$; pore water pressure $u=u_f=u_o+u_{d(f)}$
Consolidated Undrained (CU)	Apply confining pressure σ_3 while the drainage line from the specimen is opened (drainage is permitted), then the initial pore water pressure ($u=u_o$) is equal to zero	Apply an added stress $\Delta\sigma$ at axial direction. The drainage line from the specimen is kept closed (drainage is not permitted) ($u=u_d \neq 0$). At failure state $\Delta\sigma=\Delta\sigma_f$; pore water pressure $u=u_f=u_o+u_{d(f)}=u_{d(f)}$
Consolidated Drained (CD)	Apply confining pressure σ_3 while the drainage line from the specimen is opened (drainage is permitted), then the initial pore water pressure ($u=u_o$) is equal to zero	Apply an added stress $\Delta\sigma$ at axial direction. The drainage line from the specimen is opened (drainage is permitted) so the pore water pressure ($u=u_d$) is equal to zero. At failure state $\Delta\sigma=\Delta\sigma_f$; pore water pressure $u=u_f=u_o+u_{d(f)}=0$

Types of Triaxial Tests



Under all-around cell pressure σ_c

Shearing (loading)

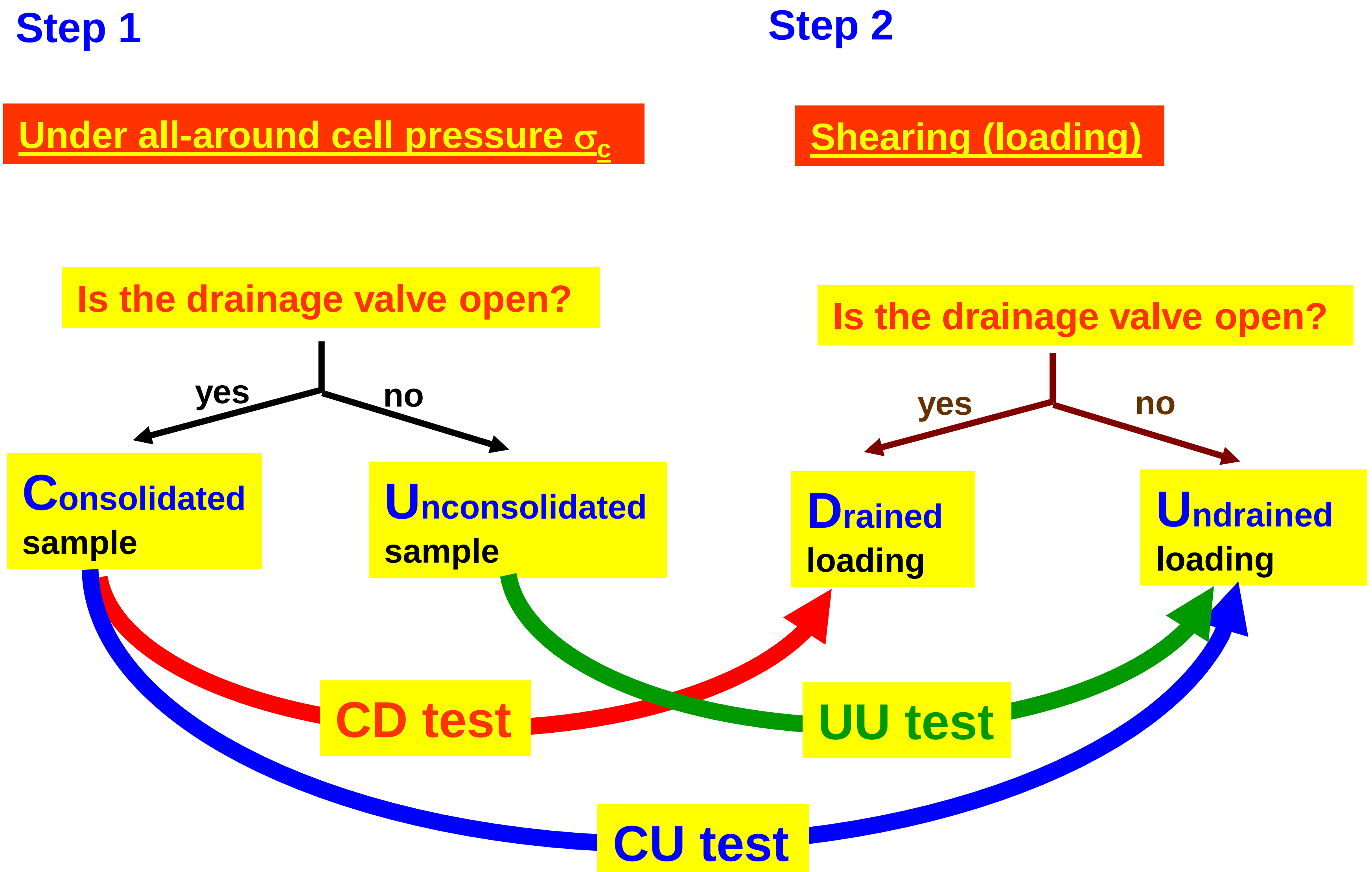
Is the drainage valve open?

- yes → **Consolidated sample**
- no → **Unconsolidated sample**

Is the drainage valve open?

- yes → **Drained loading**
- no → **Undrained loading**

Types of Triaxial Tests



Consolidated- drained test (CD Test)

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

Step 1: At the end of consolidation

σ_{VC}

σ_{hC}

Drainage

0

$\sigma'_{VC} = \sigma_{VC}$

$\sigma'_{hC} = \sigma_{hC}$

Step 2: During axial stress increase

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

σ_{hC}

Drainage

0

$\sigma'_{V} = \sigma_{VC} + \Delta\sigma = \sigma'_{1}$

$\sigma'_{h} = \sigma_{hC} = \sigma'_{3}$

Step 3: At failure

$\sigma_{VC} + \Delta\sigma_{f}$

σ_{hC}

Drainage

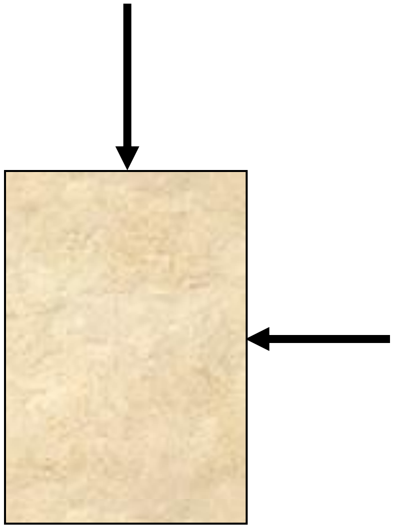
0

$\sigma'_{Vf} = \sigma_{VC} + \Delta\sigma_{f} = \sigma'_{1f}$

$\sigma'_{hf} = \sigma_{hC} = \sigma'_{3f}$

Consolidated- drained test (CD Test)

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

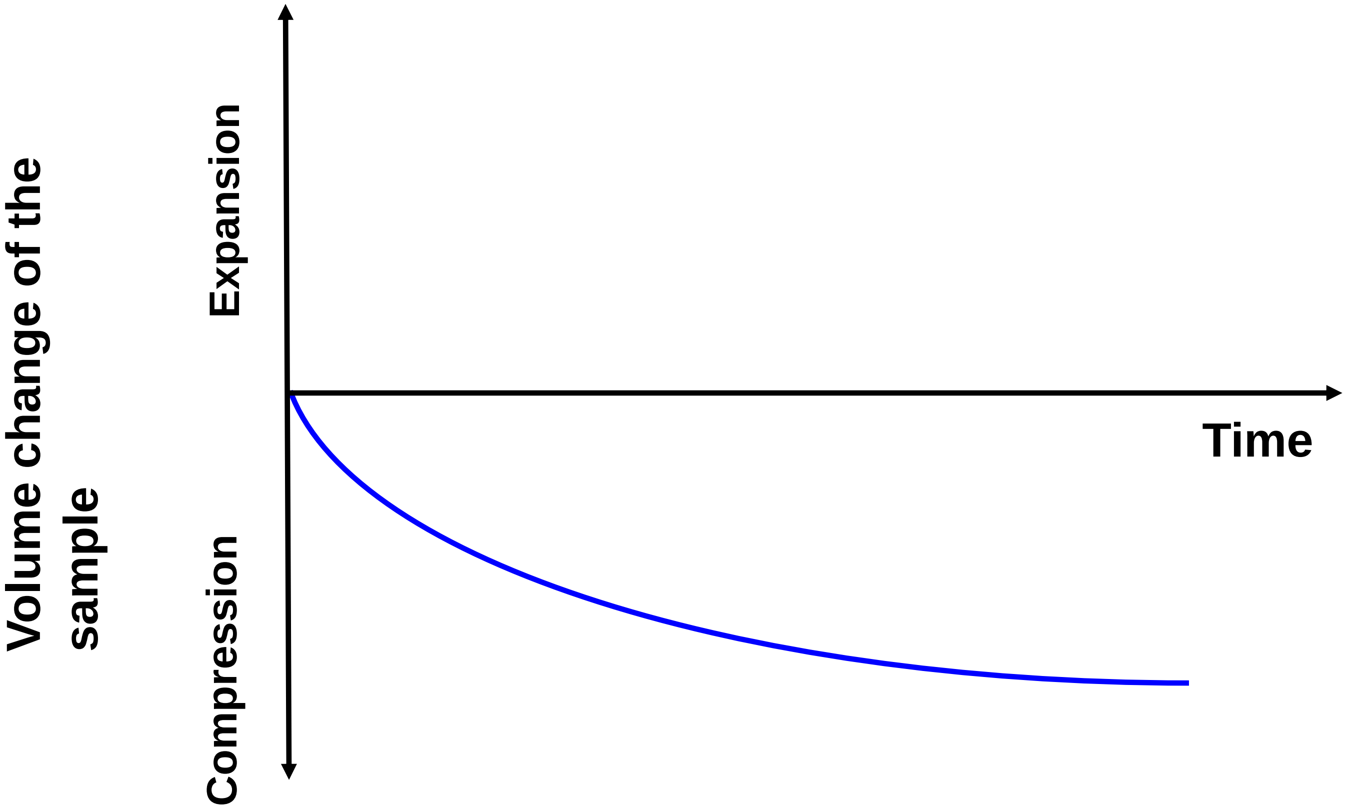


$$\sigma_3 = \sigma_{hC}$$

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

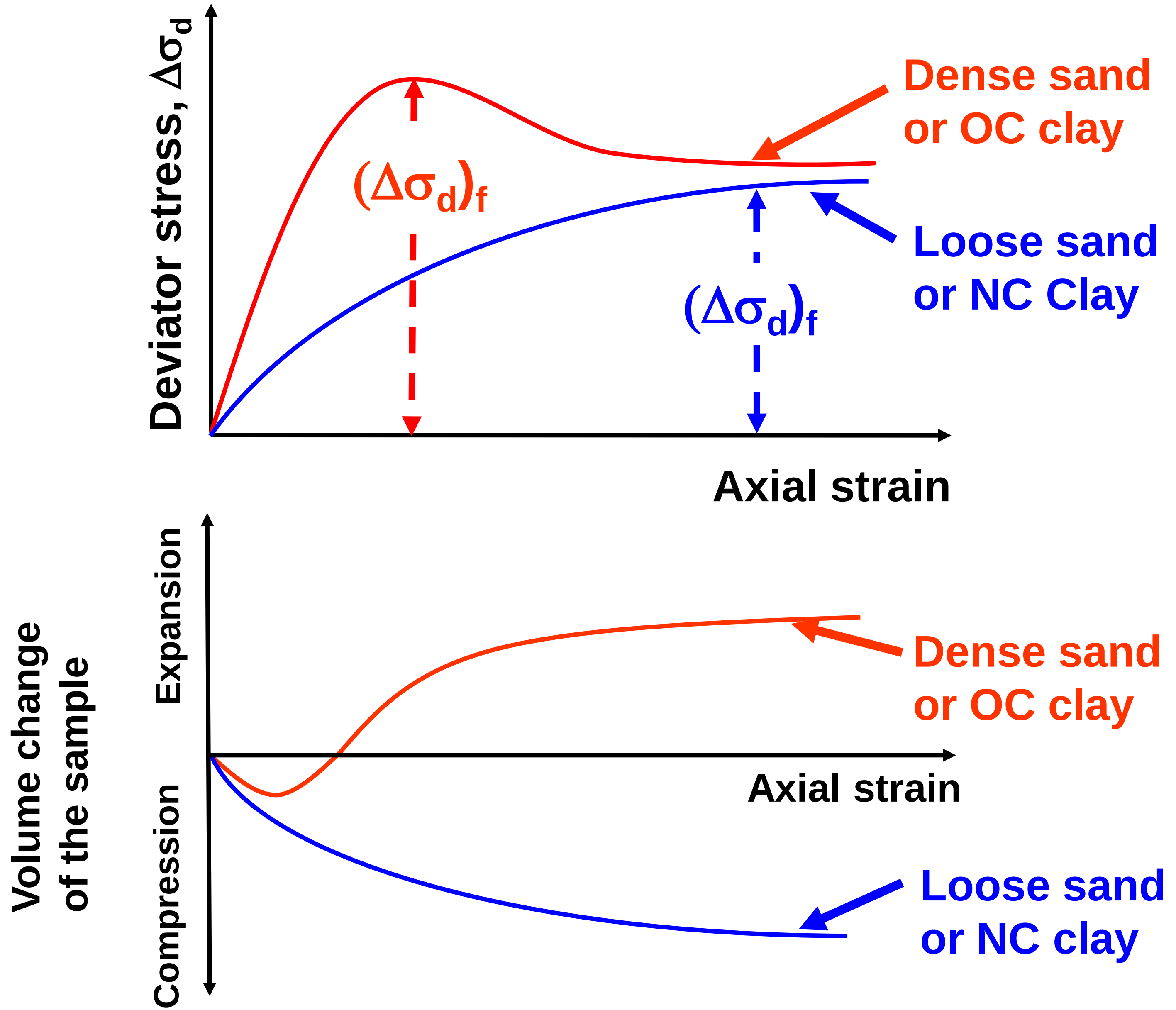
Consolidated- drained test (CD Test)

Volume change of sample during consolidation

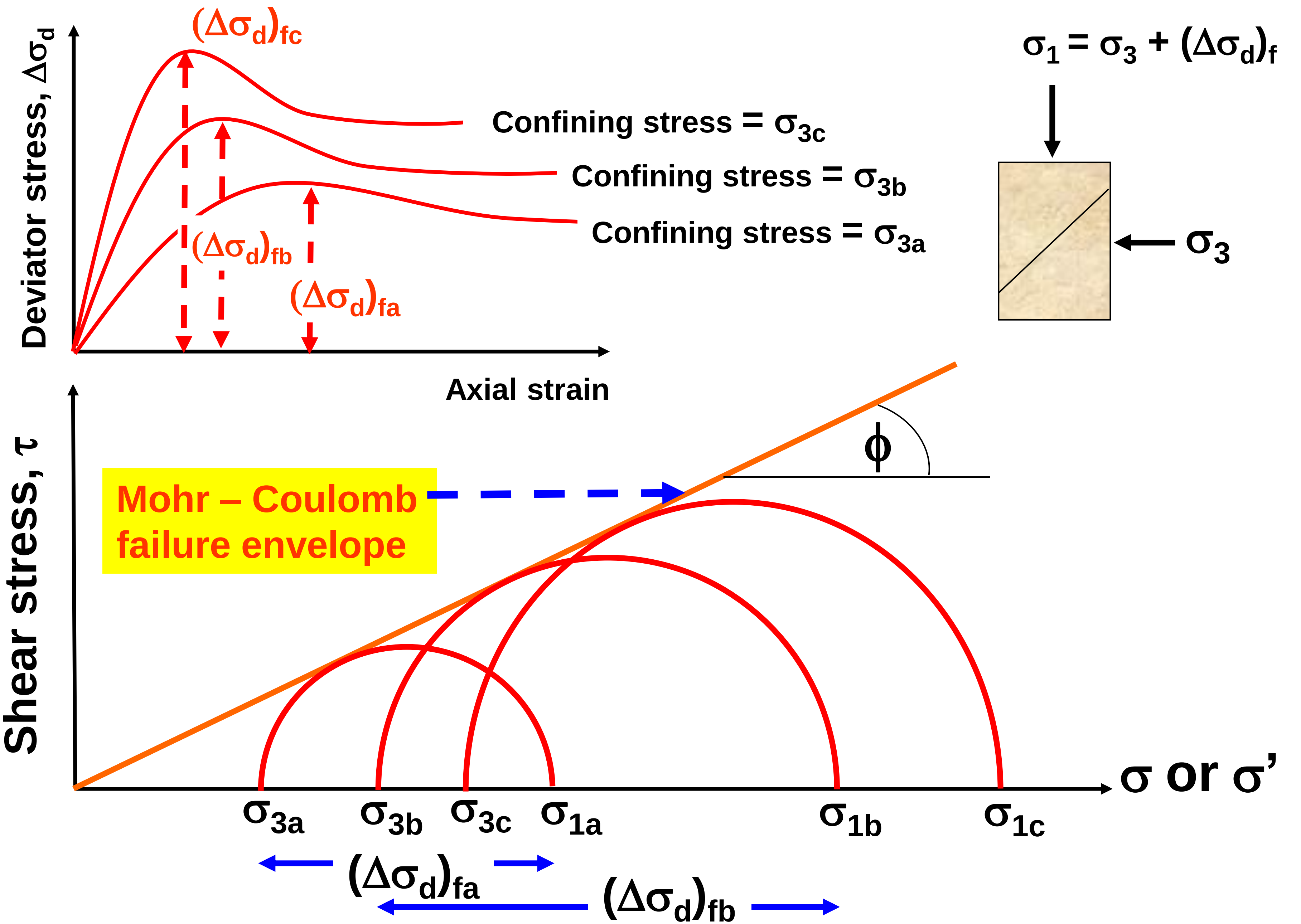


Consolidated- drained test (CD Test)

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

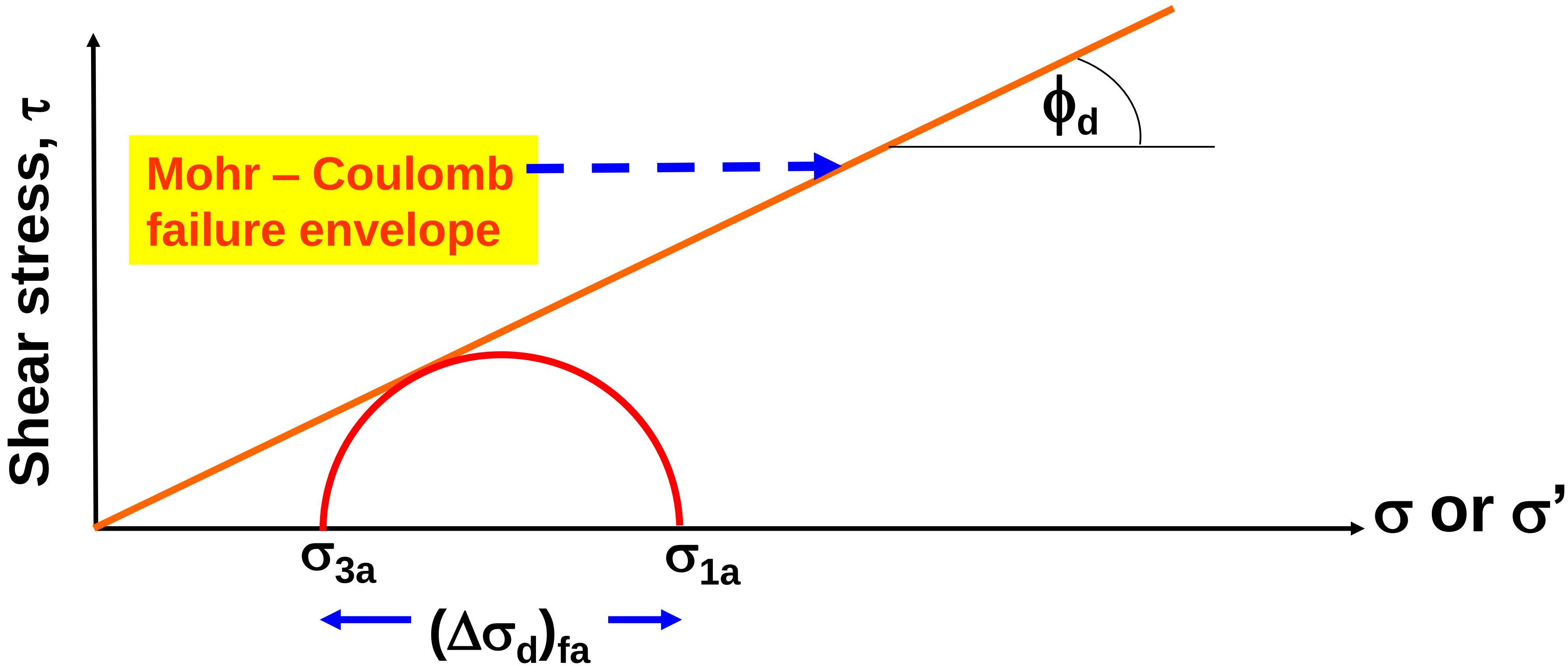
Since u = 0 in CD tests, $\sigma = \sigma'$

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

c_d and ϕ_d are used to denote them

CD tests Failure envelopes

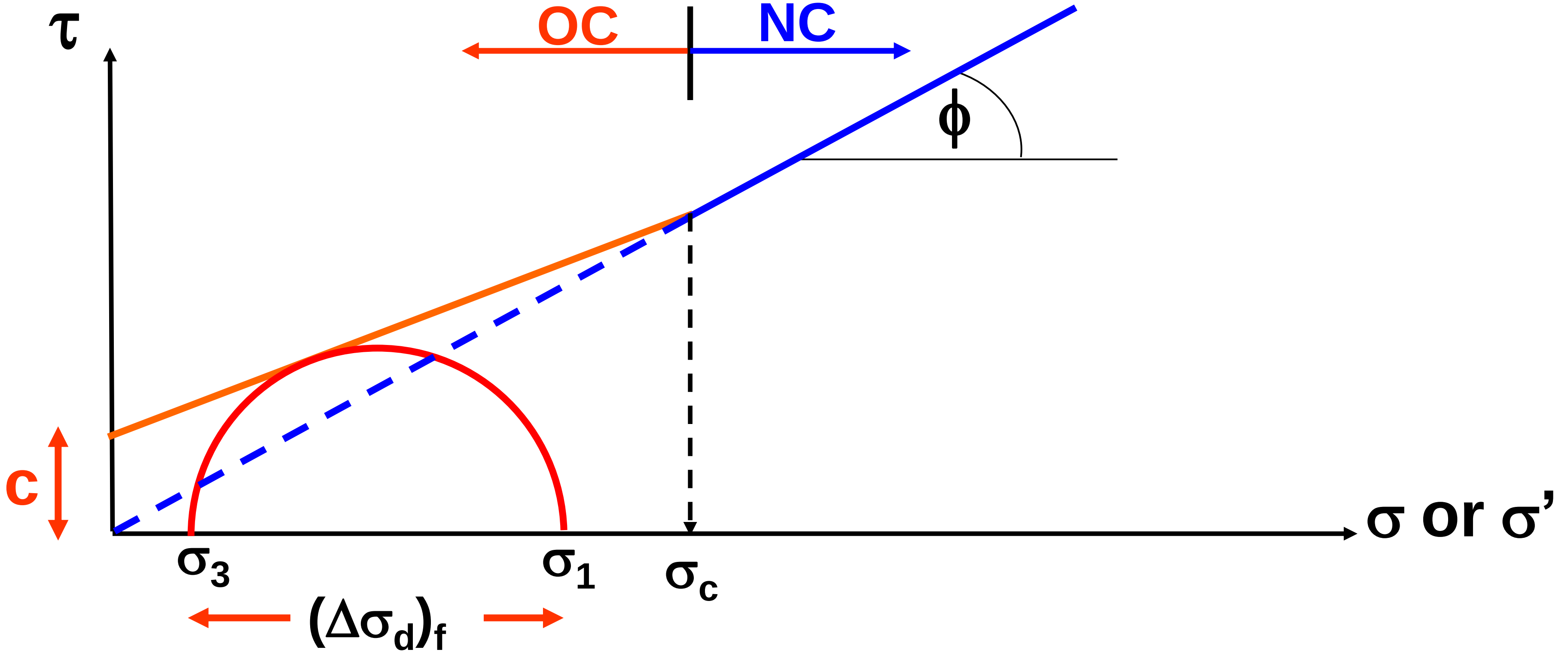
For sand and NC Clay, $c_d = 0$



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

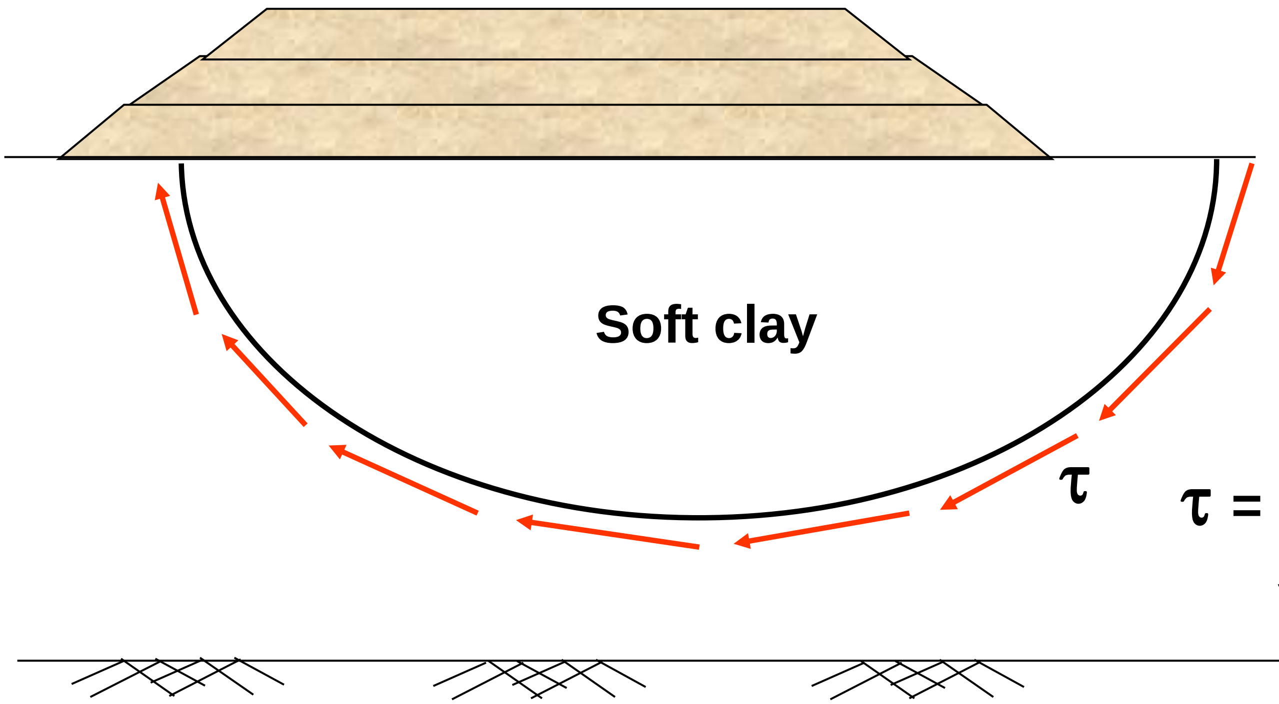
CD tests Failure envelopes

For OC Clay, $c_d \neq 0$



Some practical applications of CD analysis for clays

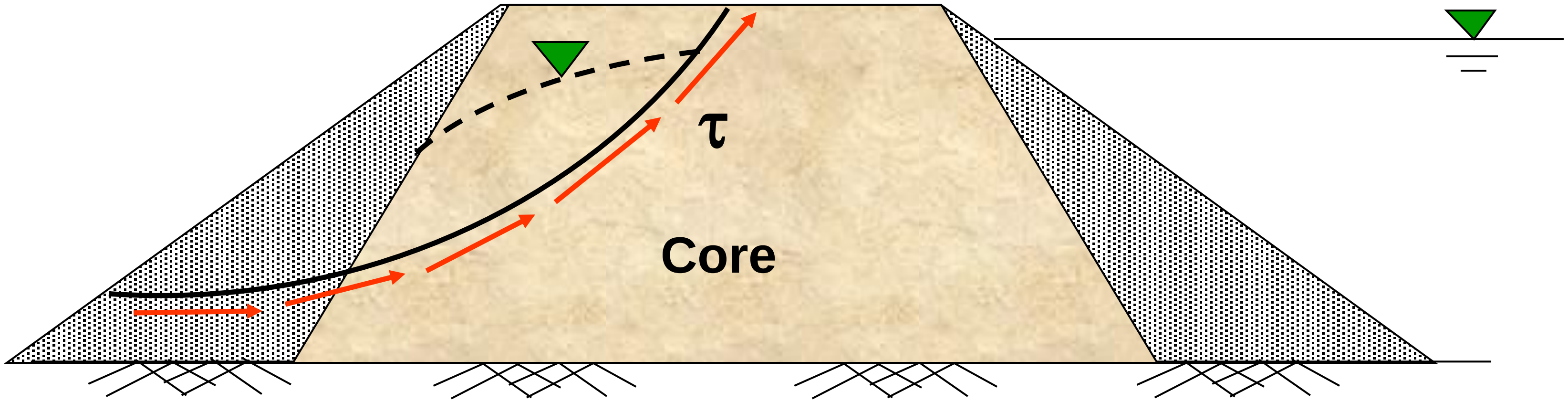
1. Embankment constructed very slowly, in layers over a soft clay deposit



τ = in situ drained shear strength

Some practical applications of CD analysis for clays

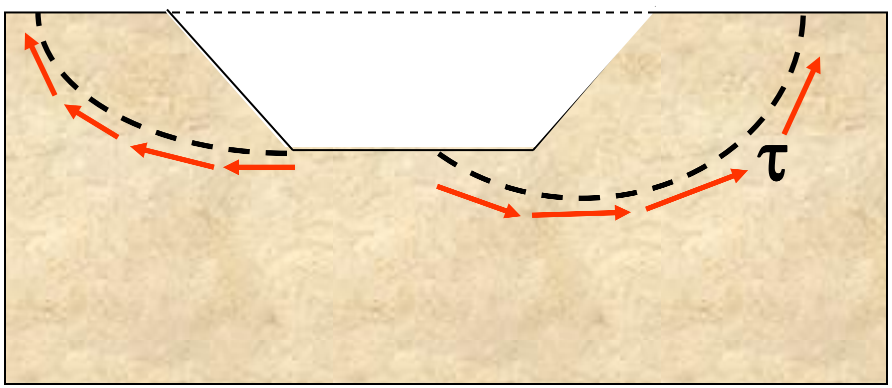
2. Earth dam with steady state seepage

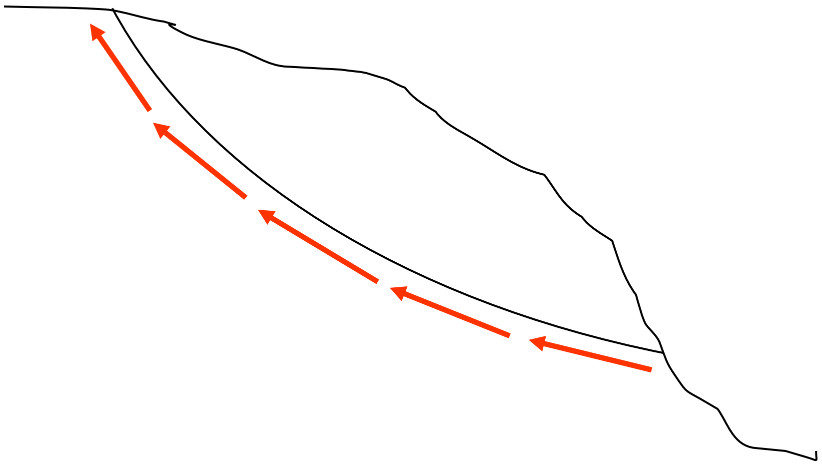


τ = drained shear strength of clay core

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 <u>long term condition</u> 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

Total: σ_{VC} (vertical), σ_{hC} (horizontal)

Drainage

Neutral: **0**

Effective: $\sigma'_{VC} = \sigma_{VC}$

$\sigma'_{hC} = \sigma_{hC}$

Step 2: During axial stress increase

Total: $\sigma_{VC} + \Delta\sigma$ (vertical), σ_{hC} (horizontal)

No drainage

Neutral: $\pm\Delta u$

Effective: $\sigma'_V = \sigma_{VC} + \Delta\sigma \mp \Delta u = \sigma'_1$

$\sigma'_h = \sigma_{hC} \mp \Delta u = \sigma'_3$

Step 3: At failure

Total: $\sigma_{VC} + \Delta\sigma_f$ (vertical), σ_{hC} (horizontal)

No drainage

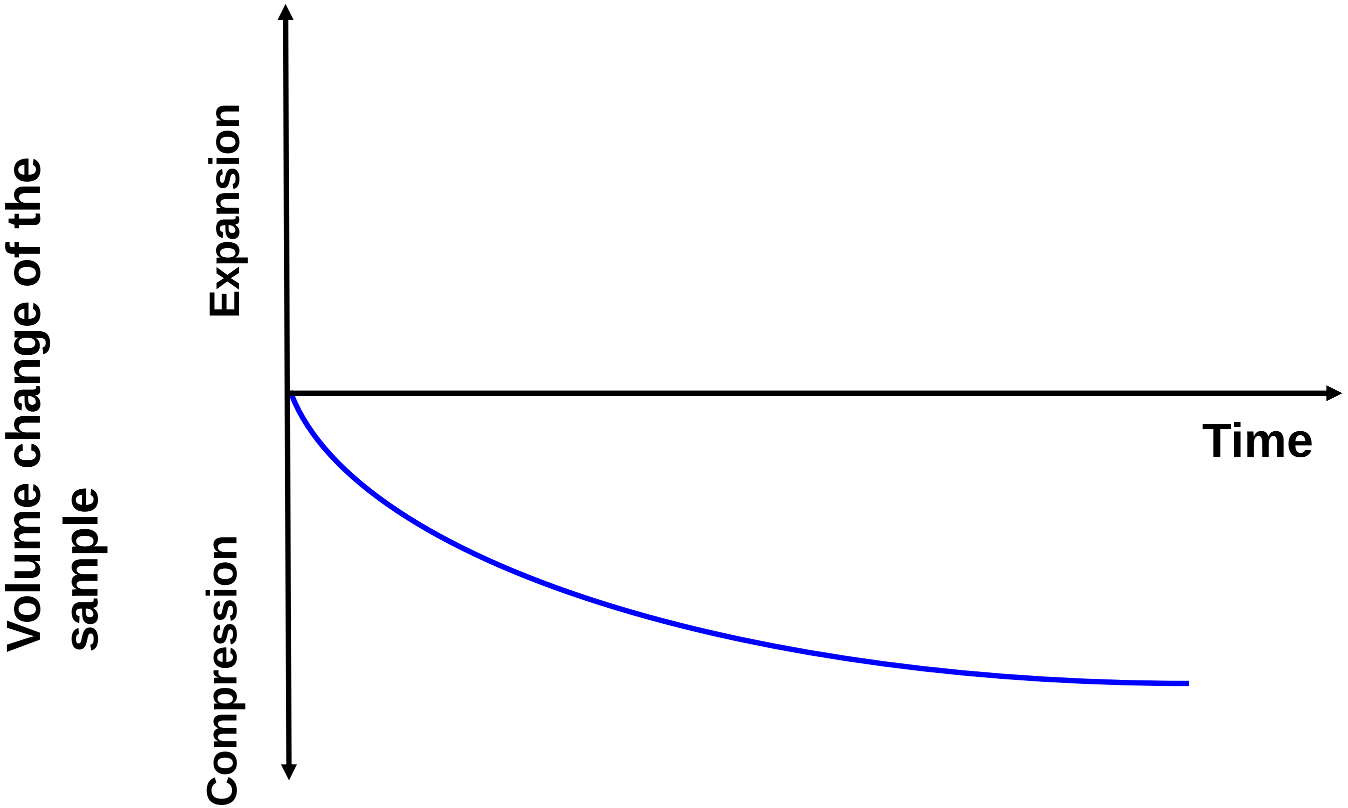
Neutral: $\pm\Delta u_f$

Effective: $\sigma'_{Vf} = \sigma_{VC} + \Delta\sigma_f \mp \Delta u_f = \sigma'_{1f}$

$\sigma'_{hf} = \sigma_{hC} \mp \Delta u_f = \sigma'_{3f}$

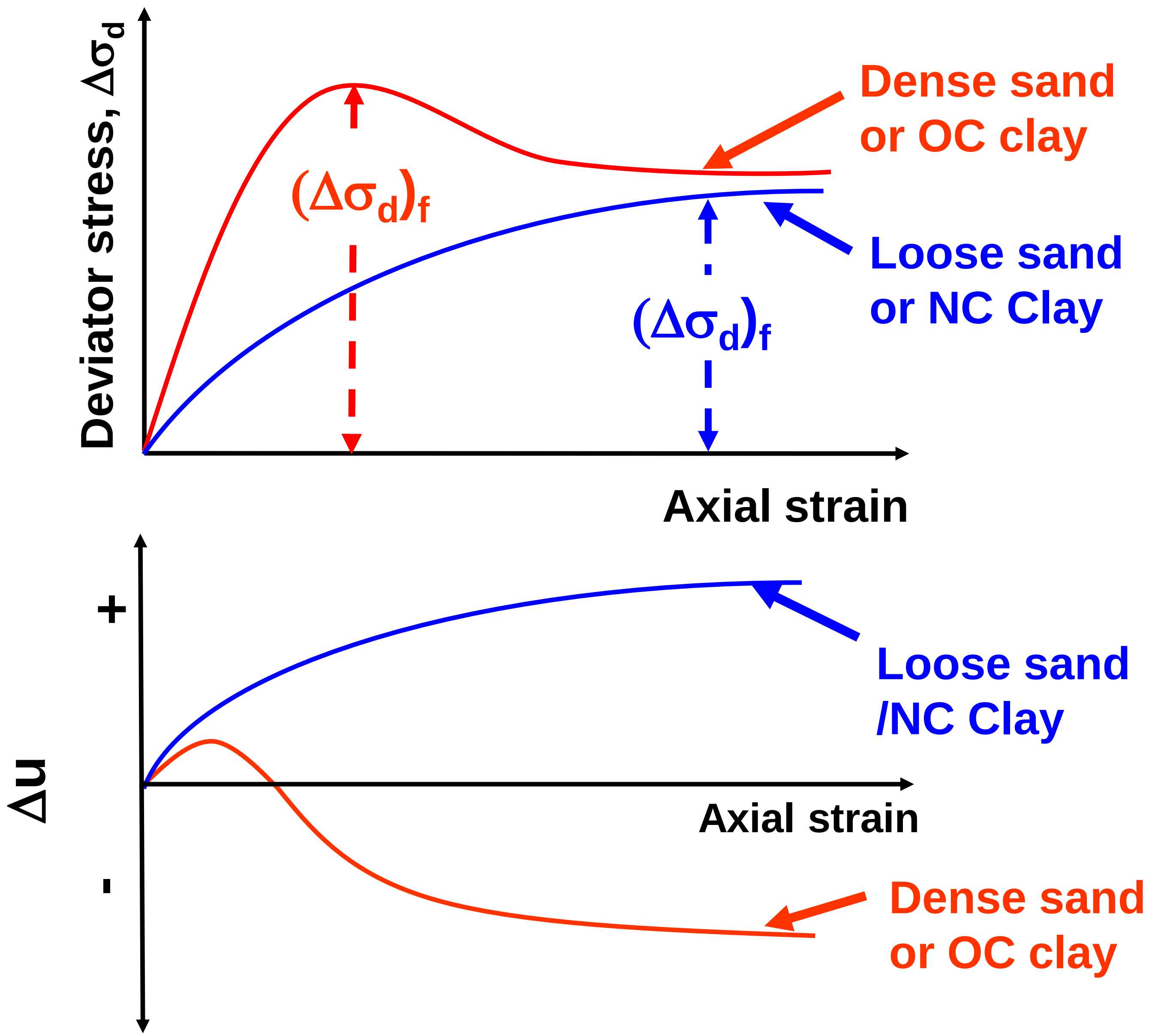
Consolidated- Undrained test (CU Test)

Volume change of sample during consolidation

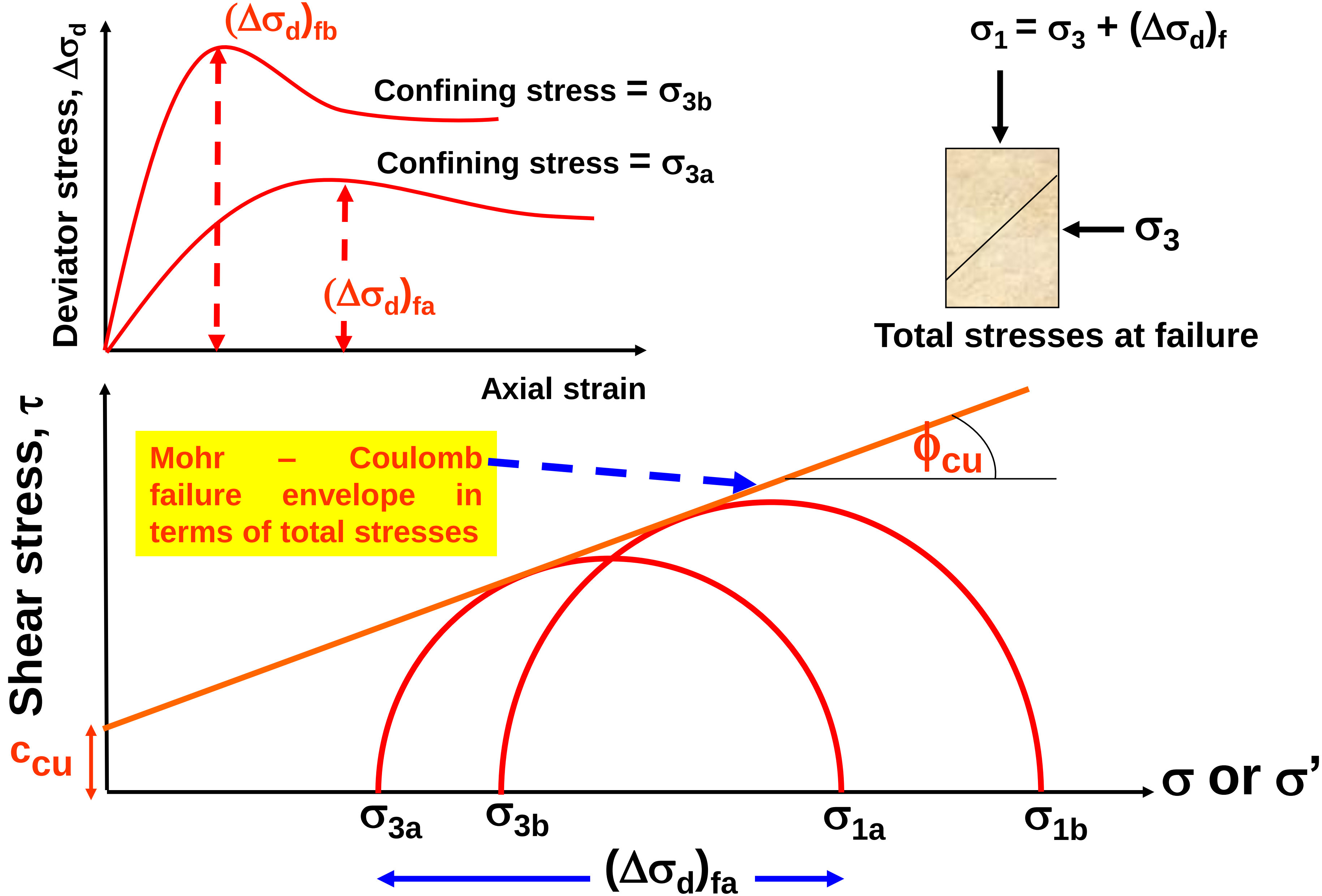


Consolidated- Undrained test (CU Test)

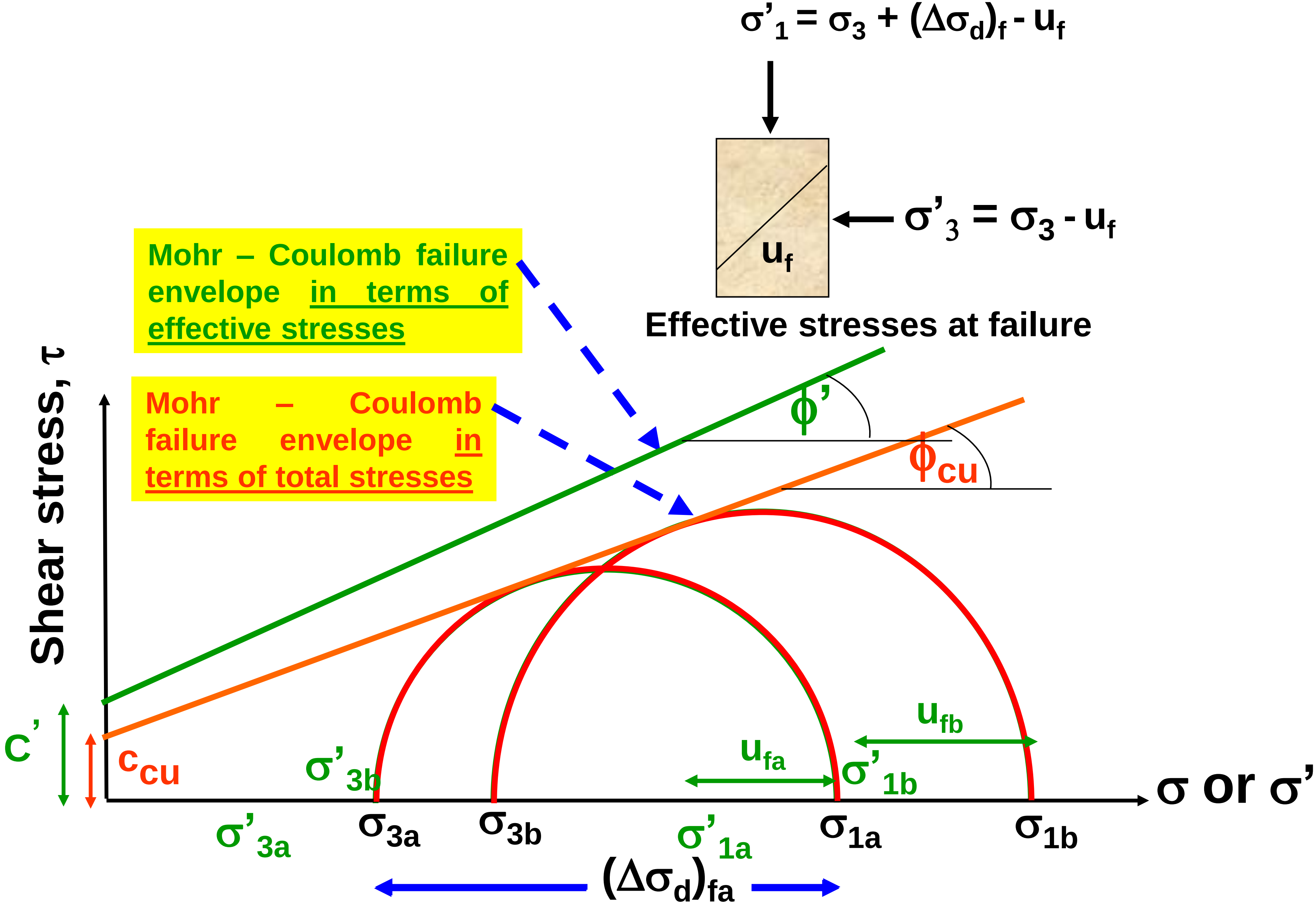
Stress-strain relationship during shearing



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

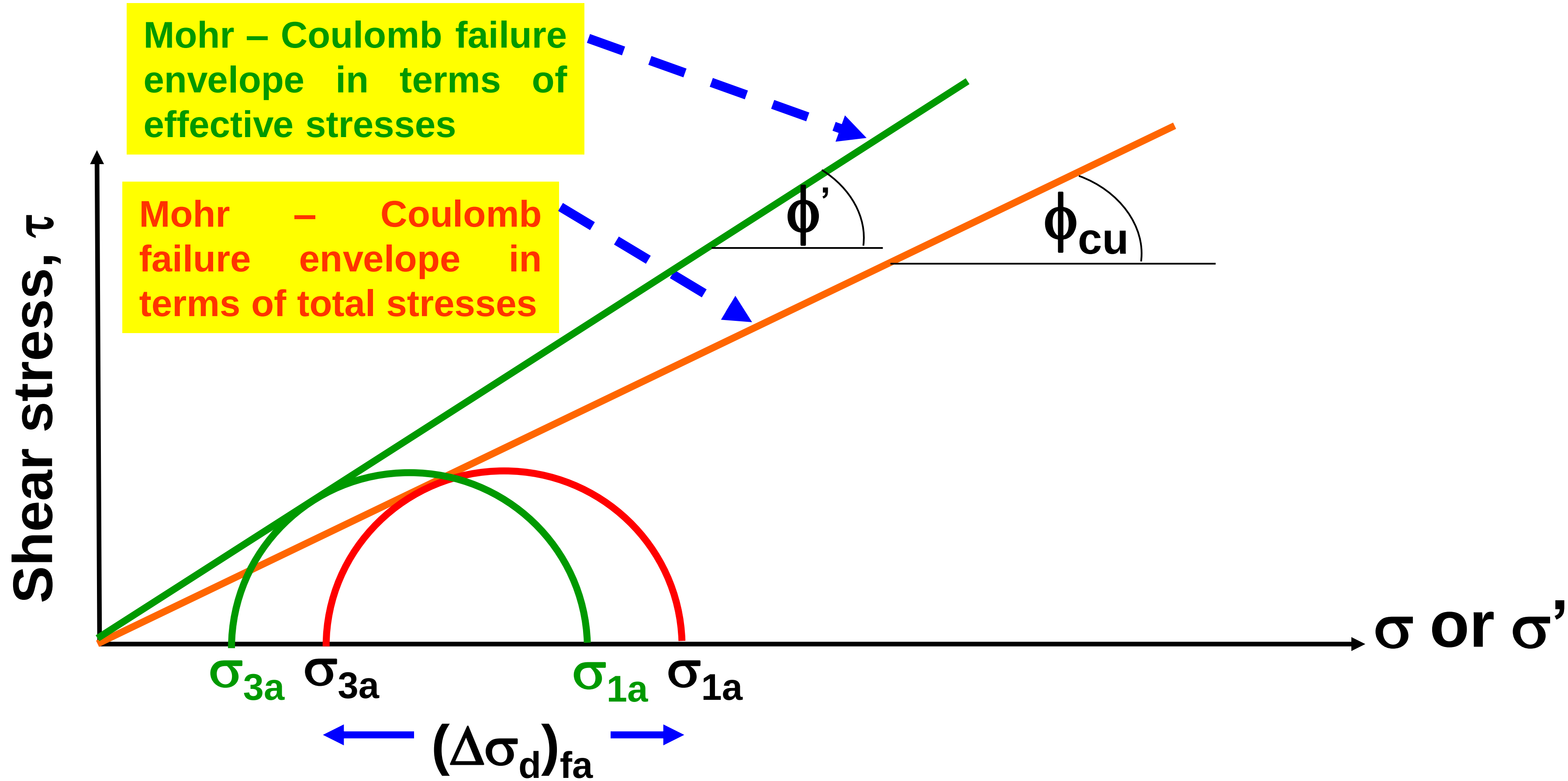
Shear strength parameters <u>in terms of total stresses</u> are c_{cu} and ϕ_{cu}

Shear strength parameters <u>in terms of effective stresses</u> are c' and ϕ'

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

CU tests Failure envelopes

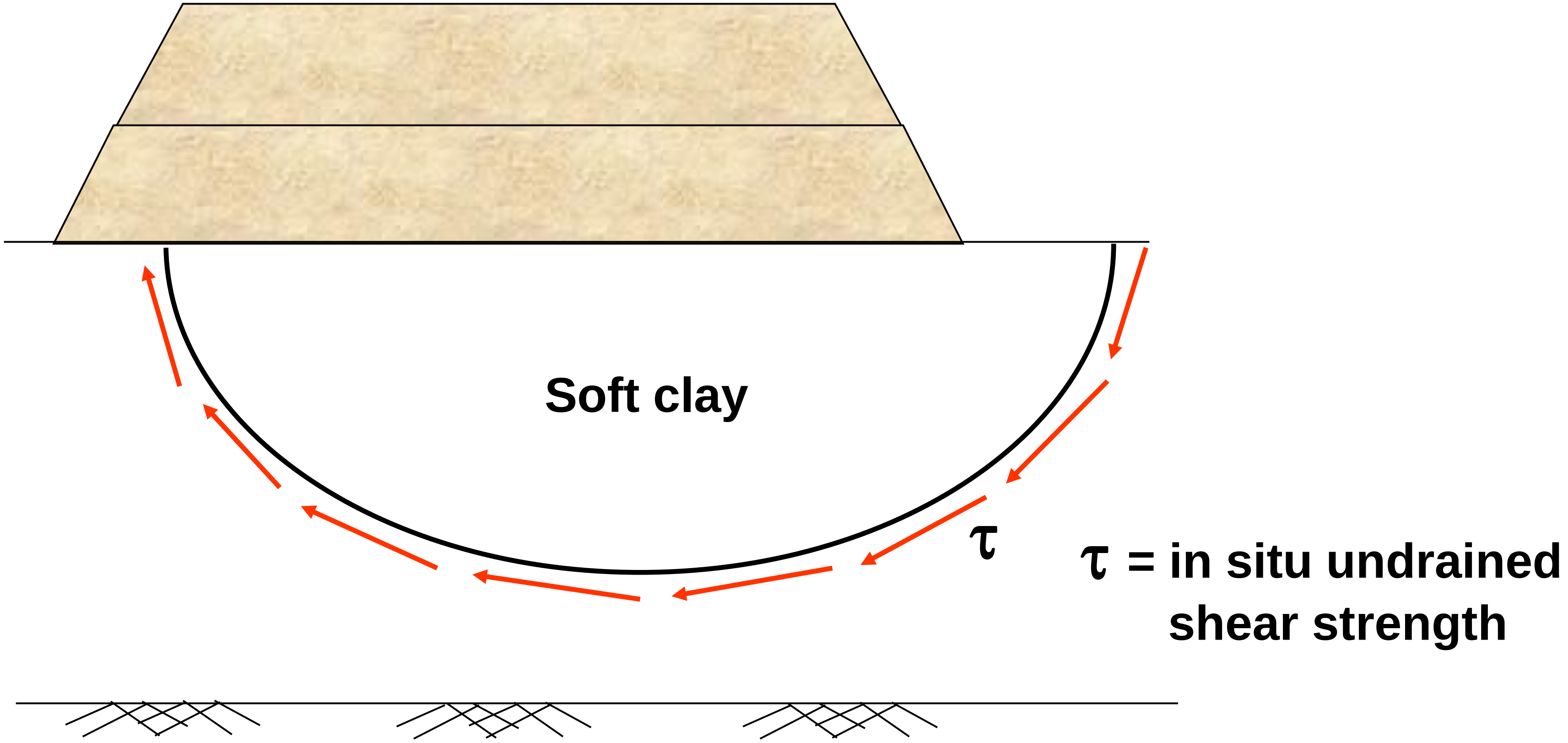
For sand and NC Clay, c_{cu} and c' = 0



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

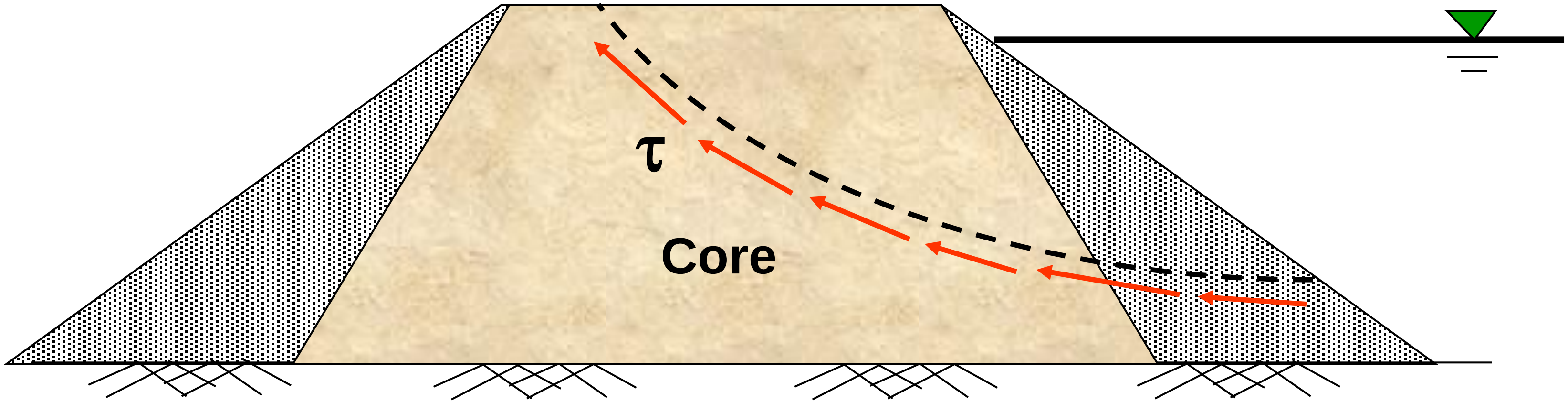
Some practical applications of CU analysis for clays

1. Embankment constructed rapidly over a soft clay deposit



Some practical applications of CU analysis for clays

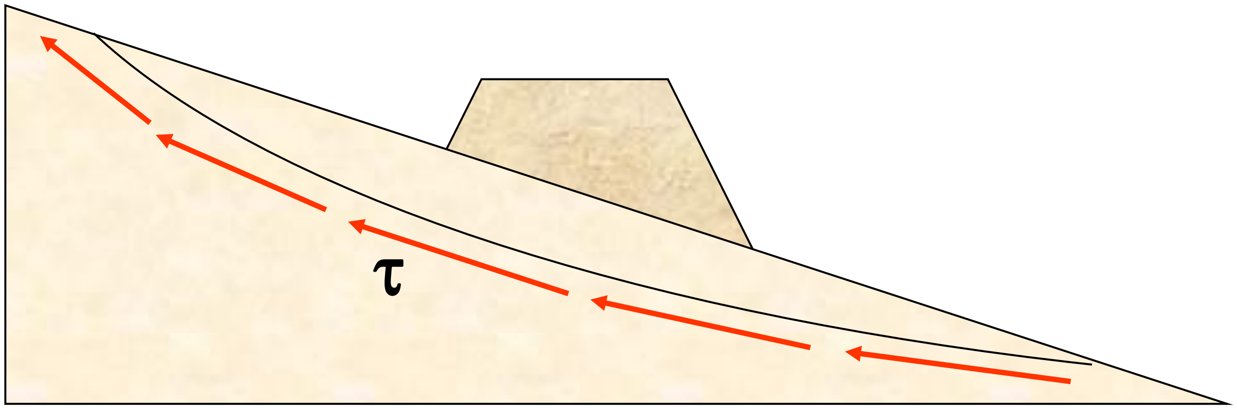
2. Rapid drawdown behind an earth dam



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,

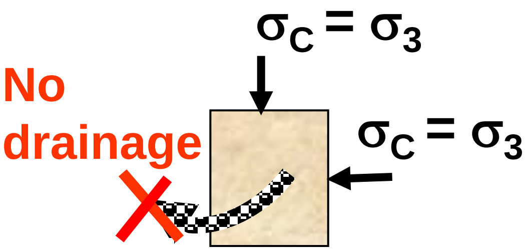
Soil have become fully consolidated and are at equilibrium with the existing stress state; Then for some reason additional stresses are applied quickly with no drainage occurring

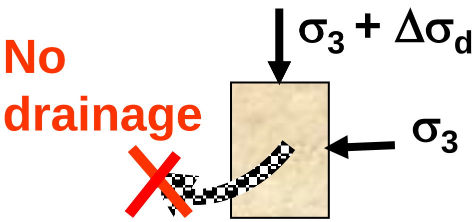
Unconsolidated- Undrained test (UU Test)

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,

$A \times H = A_0 \times H_0$

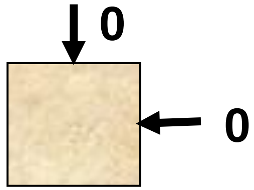
$A \times (H_0 - \Delta H) = A_0 \times H_0$

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

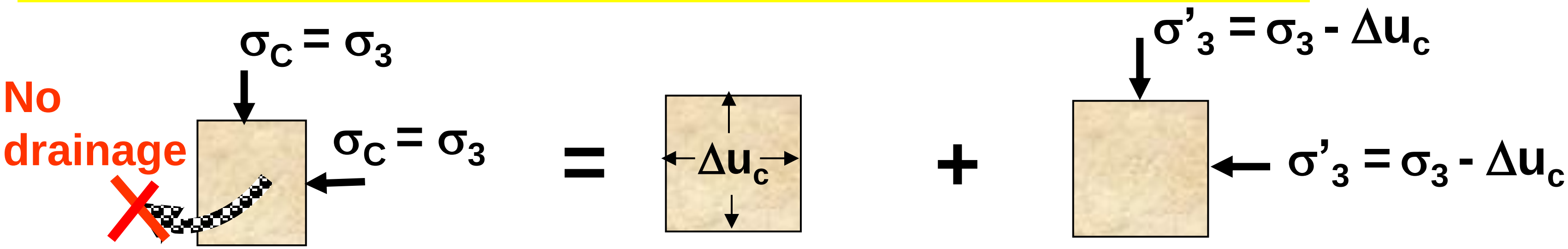
$$A = \frac{A_0}{1 - \varepsilon_z}$$

Unconsolidated- Undrained test (UU Test)

Step 1: Immediately after sampling



Step 2: After application of hydrostatic cell pressure

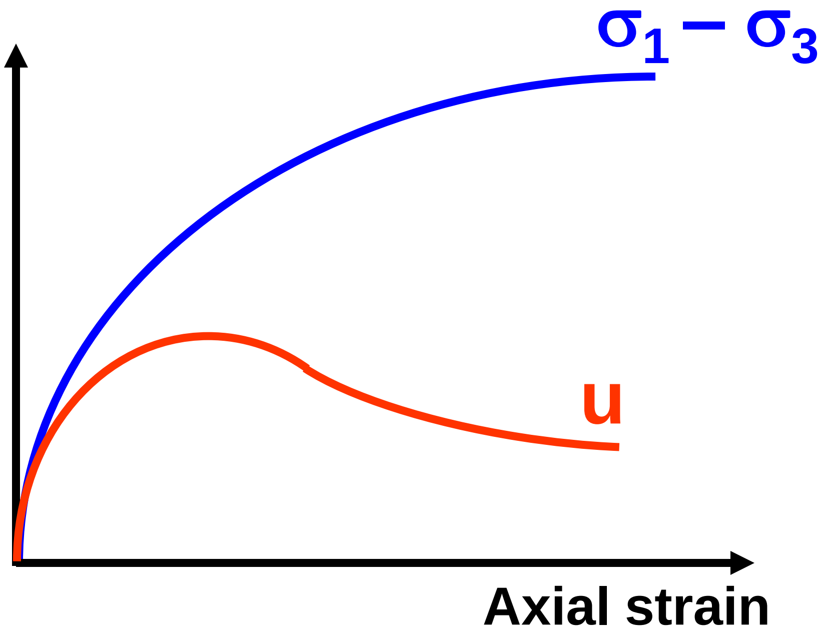


$$\Delta u_c = B \, \Delta\sigma_3$$

- Δu_c: Increase of pwp due to increase of cell pressure
- B: Skempton's pore water pressure parameter, B
- $\Delta\sigma_3$: Increase of cell pressure

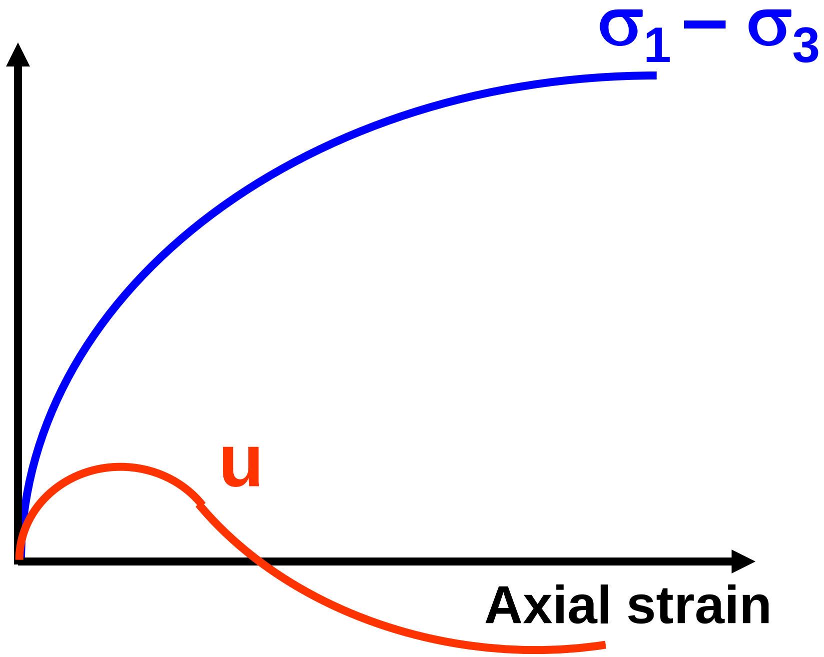
Note: If soil is fully saturated, then B = 1 (hence, $\Delta u_c = \Delta\sigma_3$)

Typical values for parameter A



OC Clay (Lightly overconsolidated)

(A = 0.0 – 0.5)



OC Clay (Heavily overconsolidated)

(A = -0.5 - 0.0)

During the increase of major principal stress pore water pressure can become negative in heavily overconsolidated clays due to dilation of specimen

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

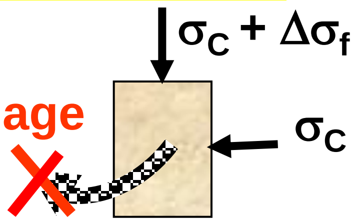
$\sigma'_{hf} = \sigma_C + u_r - \sigma_c \mp \Delta u_f = \sigma'_{3f}$

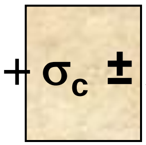
Unconsolidated- Undrained test (UU Test)

Total, σ = **Neutral, u** + **Effective, σ’**

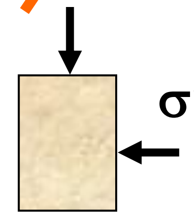
Step 3: At failure

No drainage





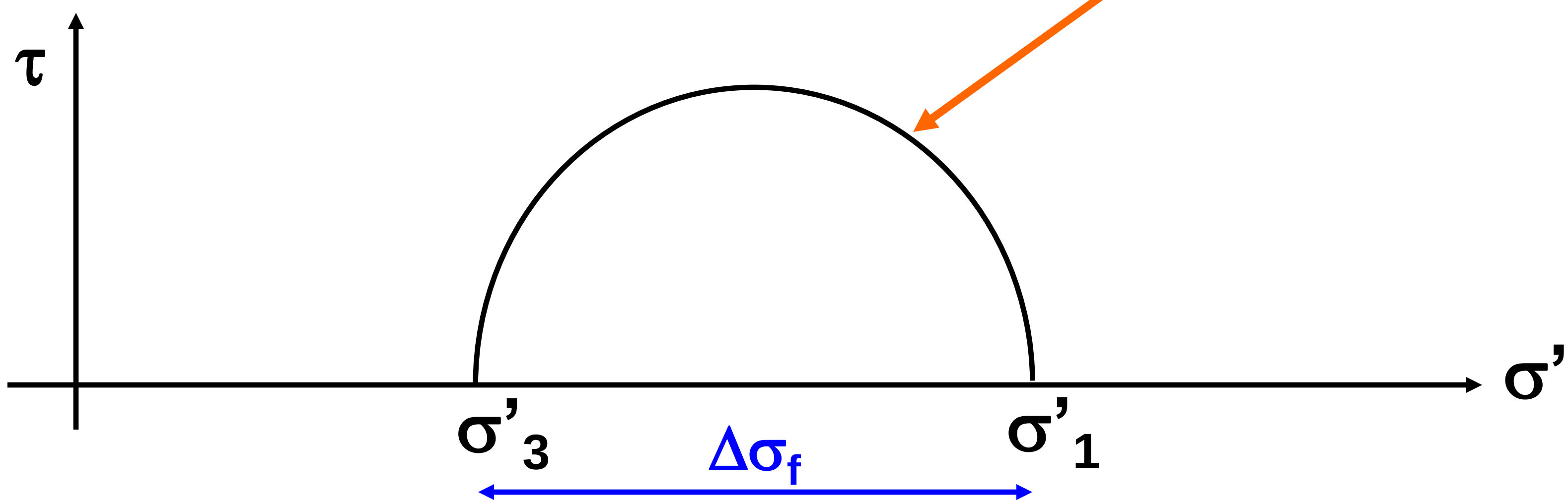
$$\sigma'_{Vf} = \cancel{\sigma_C} + \Delta\sigma_f + u_r - \cancel{\sigma_c} \mp \Delta u_f = \sigma'_{1f}$$



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

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

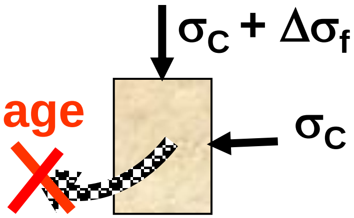


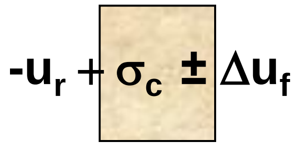
Unconsolidated- Undrained test (UU Test)

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

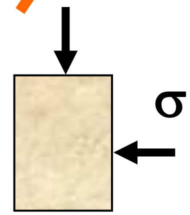
Step 3: At failure

No drainage



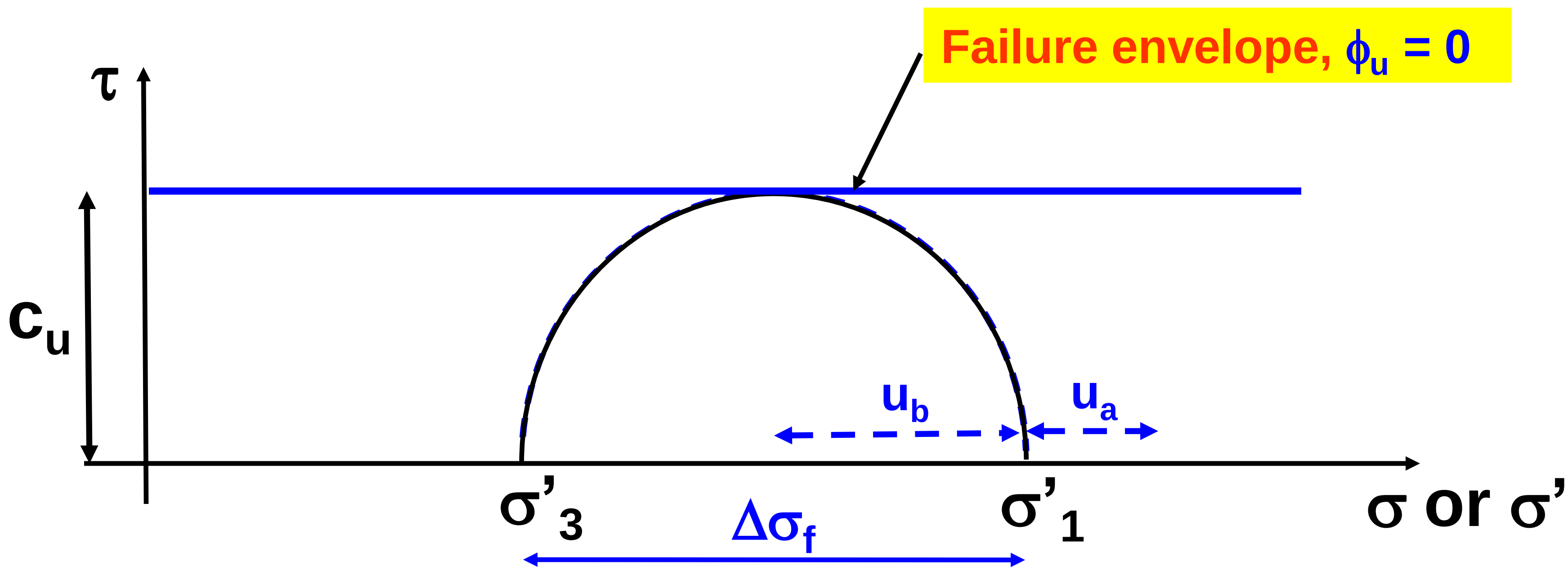


$$\sigma'_{Vf} = \cancel{\sigma_C} + \Delta\sigma_f + u_r - \cancel{\sigma_c} \mp \Delta u_f = \sigma'_{1f}$$



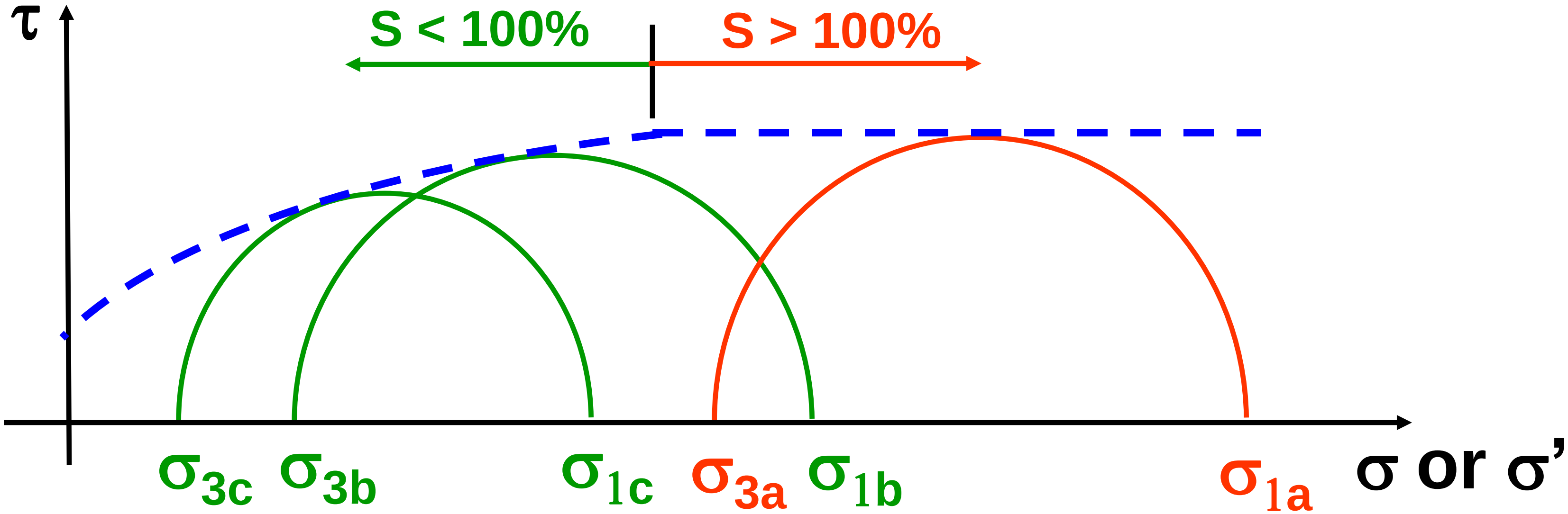
$$\sigma'_{hf} = \cancel{\sigma_C} + u_r - \cancel{\sigma_c} \mp \Delta u_f = \sigma'_{3f}$$

Mohr circles in terms of total stresses



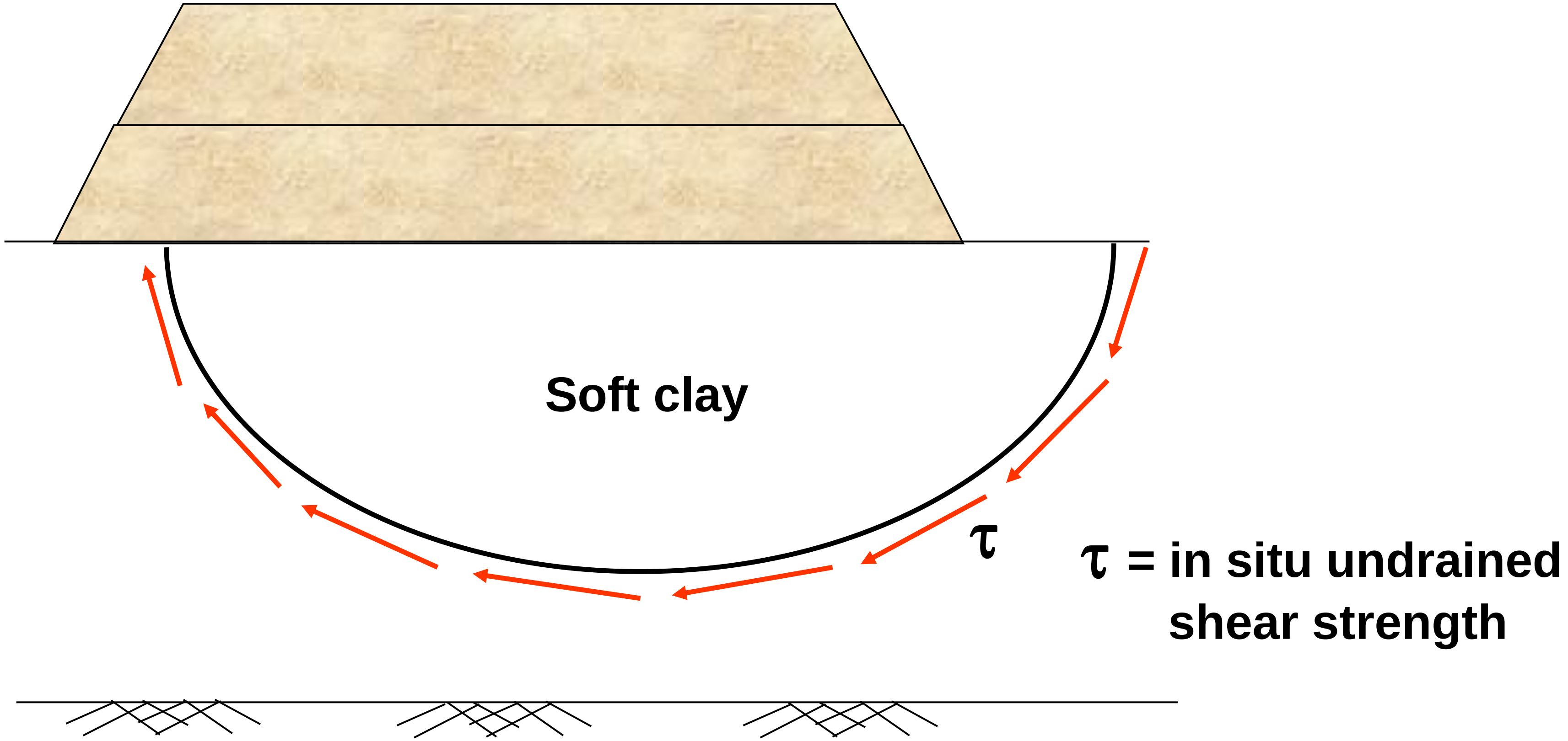
Unconsolidated- Undrained test (UU Test)

Effect of degree of saturation on failure envelope



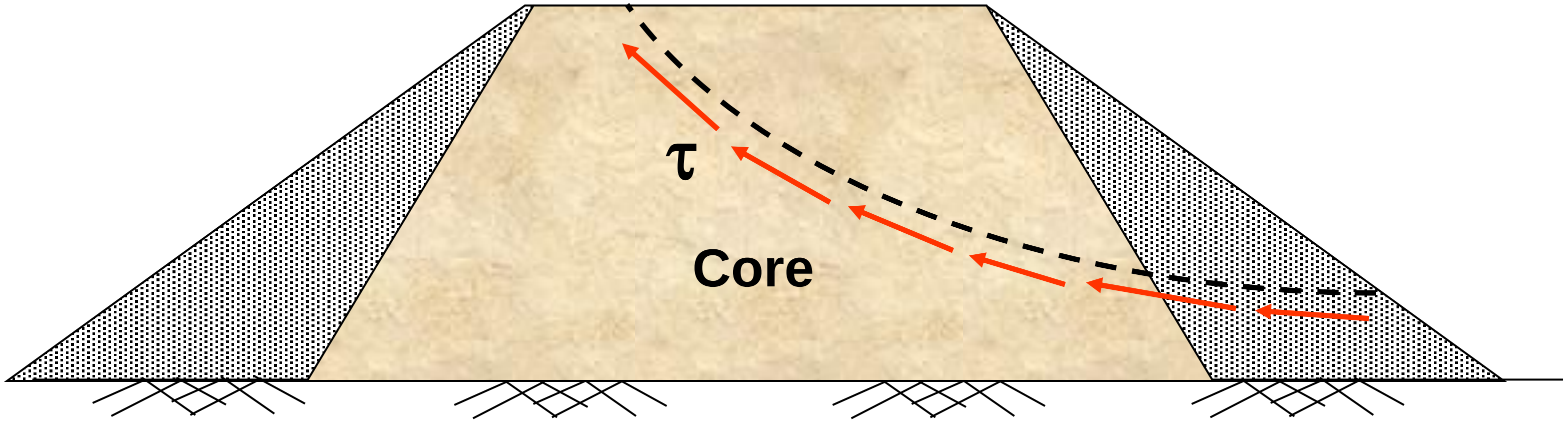
Some practical applications of UU analysis for clays

1. Embankment constructed rapidly over a soft clay deposit



Some practical applications of UU analysis for clays

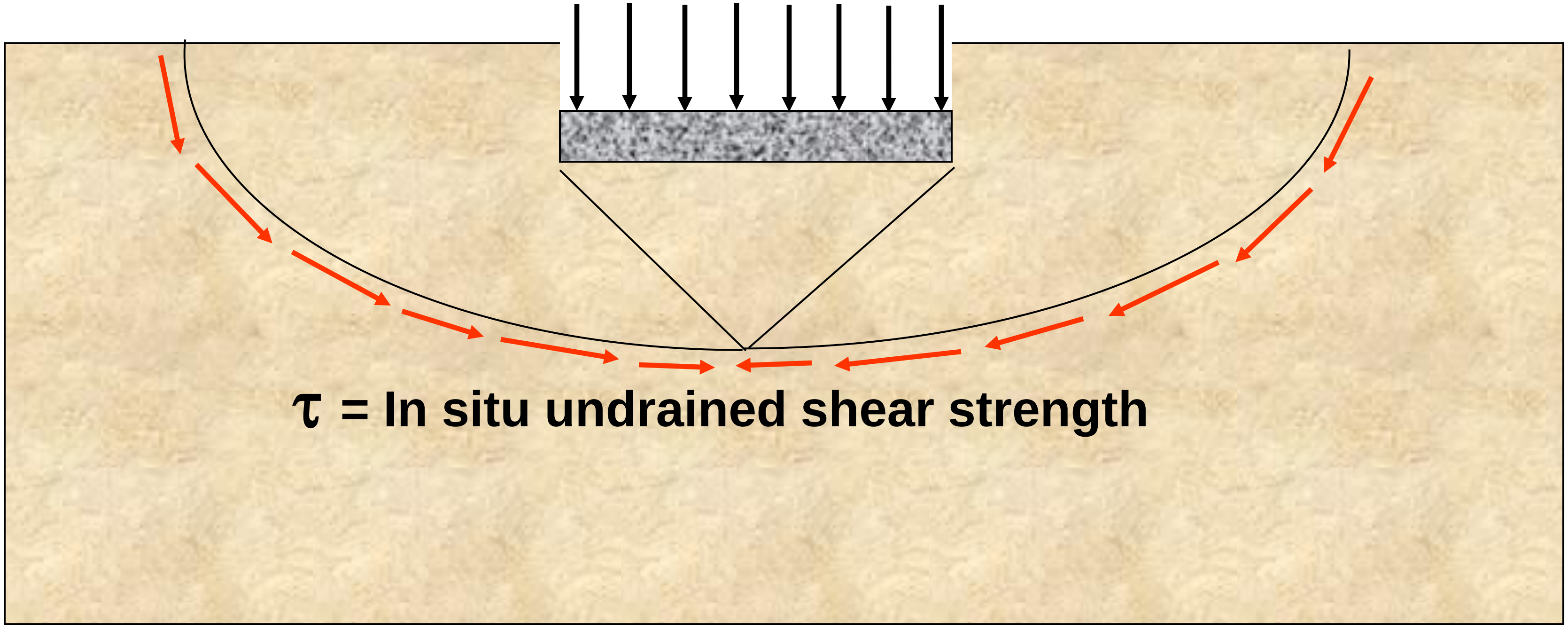
2. Large earth dam constructed rapidly with no change in water content of soft clay



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 <u>short term condition</u> in the field. Thus, c_u can be used to analyze the short term behavior of soils

THE END