Strength of Soils

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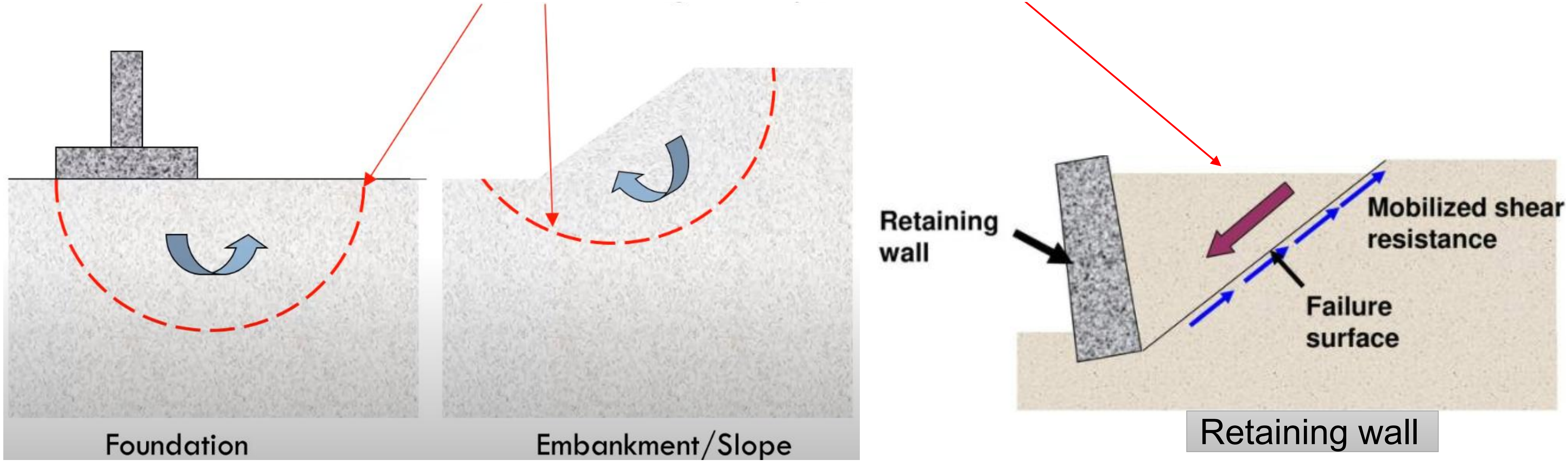
Outline

- General introduction
- Mohr-Coulomb failure criterion
- Shear strength test
- Pore pressure coefficient in the triaxial compression test
- Shear strength characteristics of soils

General introduction

Shear strength reached along failure plane



Schematic diagram of shear resistance and typical failure

General introduction

Main reason for the shear failure

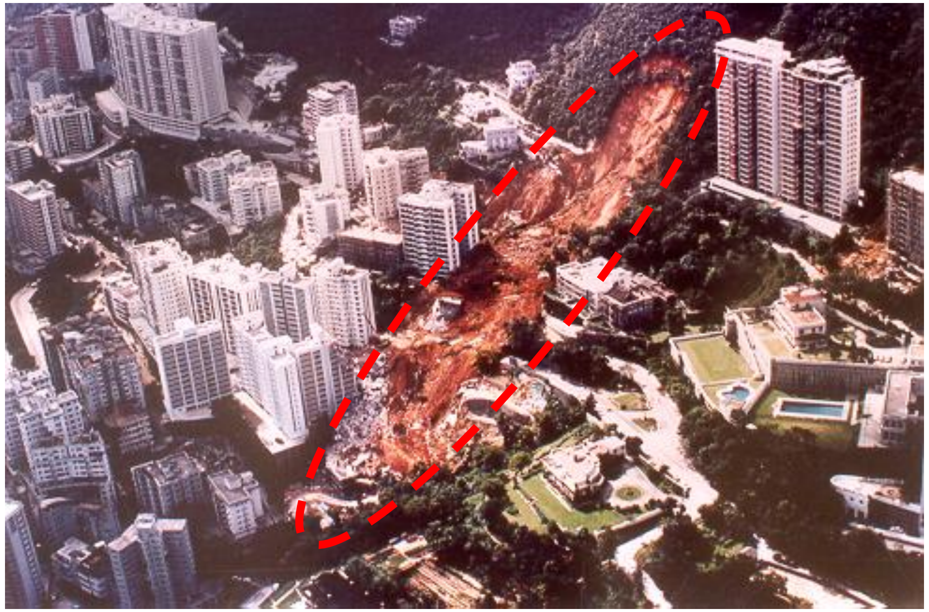
Shear stress > Shear strength

Contribution

Either total or effective → **Stress** at a point within soils

1. Friction resistance
2. Cohesive resistance

General introduction



The strength of the residual soil is low and the rainwater infiltration further reduces its strength

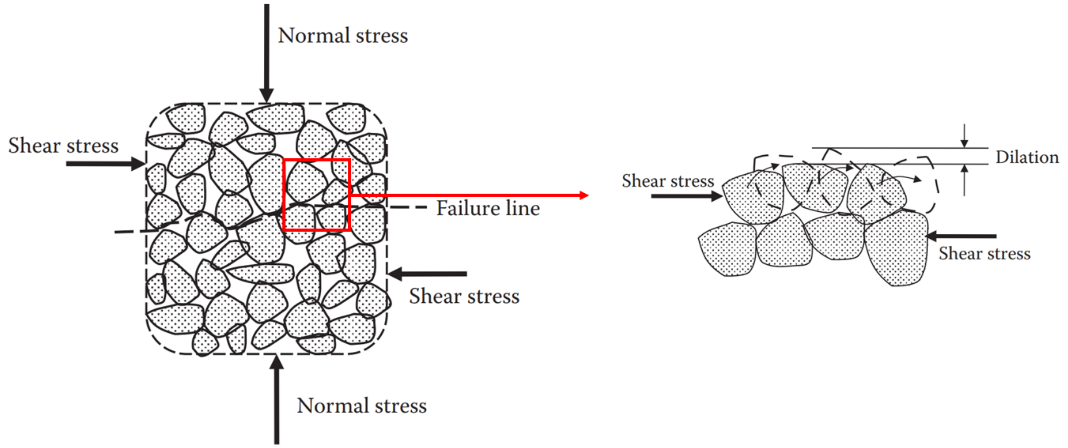
The liquefaction of soil results in almost zero shear strength of soils and bearing capacity

General introduction

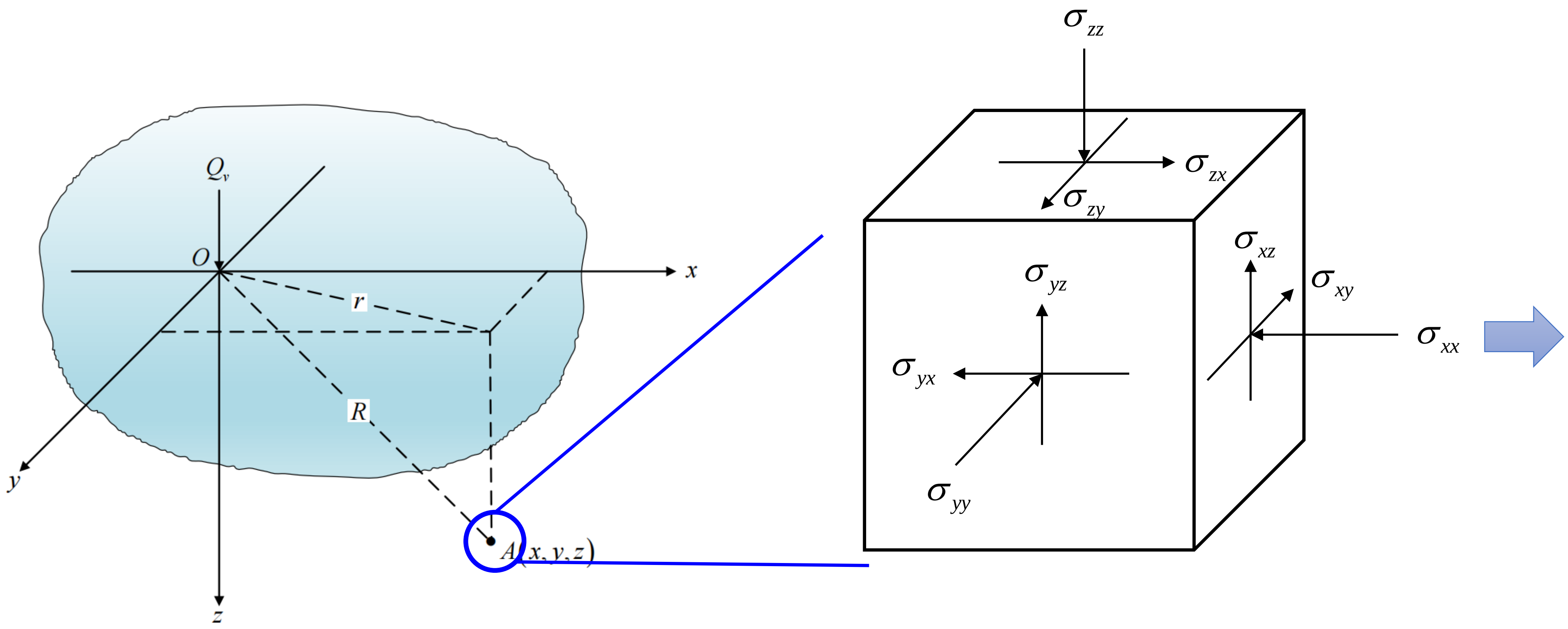
Failure mechanism

The particles of most soils are essentially incompressible, **normal stress cause no failure of soil mass**

Main mode of failure: soils fail **when one block of soil moves relative to another block and the soil particles at the failure plane move over each other**. This is what is known as **shear**



Mohr-Coulomb failure criterion



Stress tensors

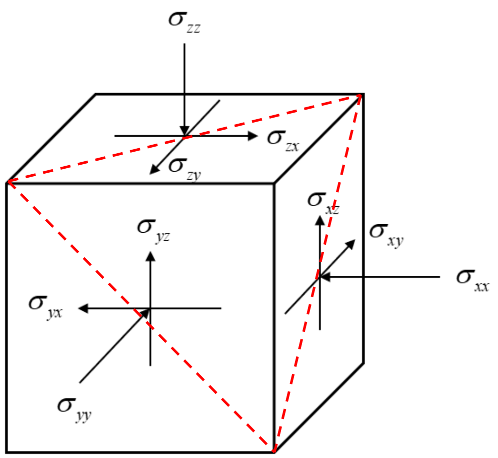
$$\sigma = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix}$$

General stress state at any point in soils

Mohr-Coulomb failure criterion

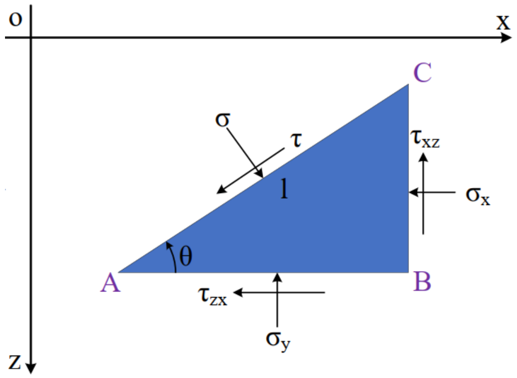
Stress vector acts on a plane

3D



$$\begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix} \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix}$$

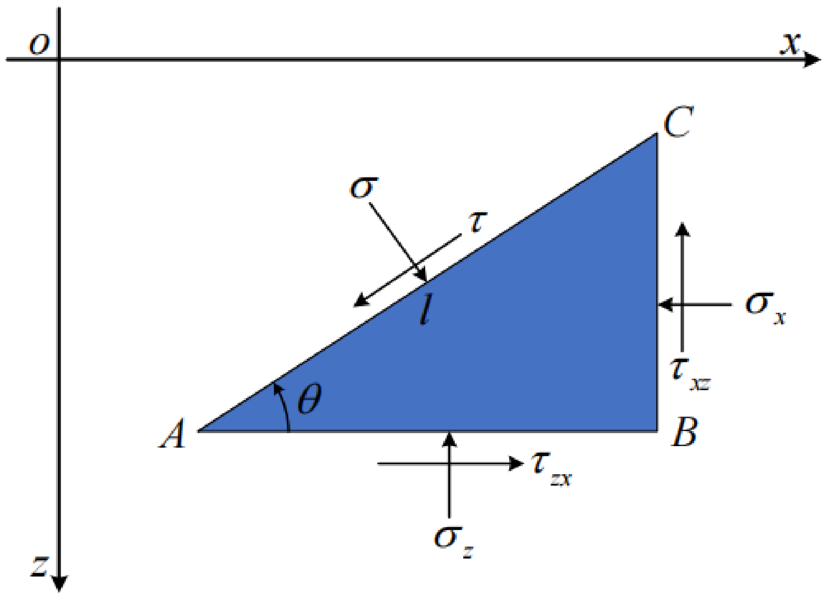
2D



$$\begin{bmatrix} \sigma_{xx} & \sigma_{xz} \\ \sigma_{zx} & \sigma_{zz} \end{bmatrix} \begin{bmatrix} n_x \\ n_z \end{bmatrix}$$

Mohr-Coulomb failure criterion

Sign convention



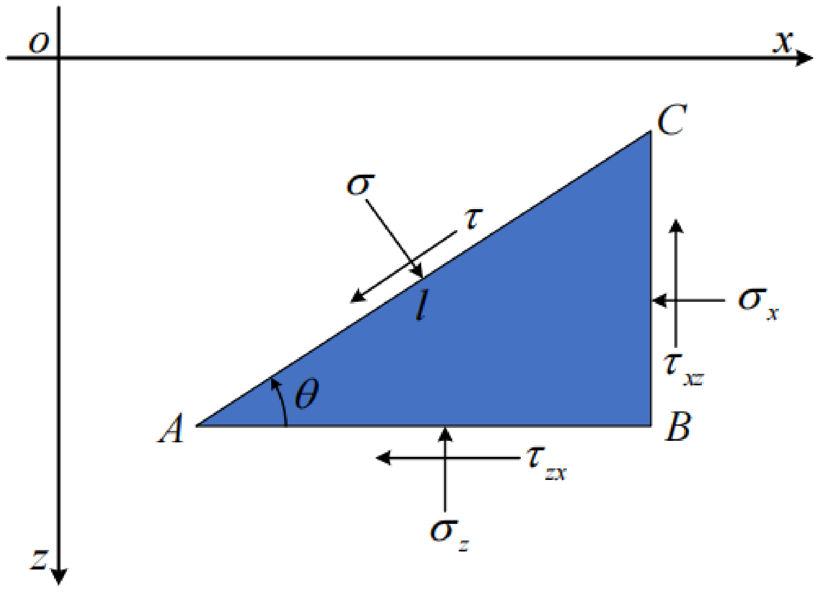
Positive stresses on each face

The signs of σ, τ and θ are defined as

1) **Compressive normal stress** is considered as **positive**;
2) The shear stress, which has the tendence to rotate the material **counterclockwise**, is considered to be **positive**;
3) **Counterclockwise rotate** from the horizontal plane θ is treated as **positive**

Mohr-Coulomb failure criterion

Normal stress and shear stress on a plane—2D case



Equilibrium analysis

The force equilibrium in horizontal direction

$$\sigma \cdot l \cdot \sin\theta - \tau \cdot l \cdot \cos\theta - \tau_{zx} \cdot l \cdot \cos\theta - \sigma_x \cdot l \cdot \sin\theta = 0$$

The force equilibrium in vertical direction

$$\sigma \cdot l \cdot \cos\theta + \tau \cdot l \cdot \sin\theta - \tau_{xz} \cdot l \cdot \sin\theta - \sigma_z \cdot l \cdot \cos\theta = 0$$

$$\sigma = \frac{\sigma_x + \sigma_z}{2} + \frac{\sigma_z - \sigma_x}{2}\cos 2\theta + \tau_{xz}\sin 2\theta$$

$$\tau = \frac{\sigma_z - \sigma_x}{2}\sin 2\theta - \tau_{xz}\cos 2\theta$$

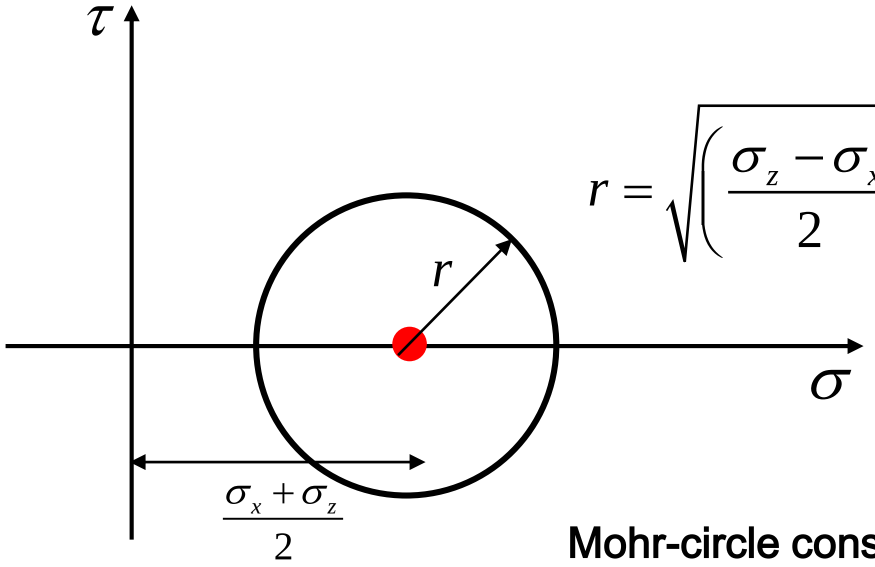
Mohr-Coulomb failure criterion

Mohr's circle

$$\sigma = \frac{\sigma_x + \sigma_z}{2} + \frac{\sigma_z - \sigma_x}{2}\cos 2\theta + \tau_{xz}\sin 2\theta$$

$$\tau = \frac{\sigma_z - \sigma_x}{2}\sin 2\theta - \tau_{xz}\cos 2\theta$$

$$\Rightarrow \left(\sigma - \frac{\sigma_x + \sigma_z}{2}\right)^2 + \tau^2 = \left(\frac{\sigma_z - \sigma_x}{2}\right)^2 + \tau_{xz}^2$$



$$r = \sqrt{\left(\frac{\sigma_z - \sigma_x}{2}\right)^2 + \tau_{xz}^2}$$

Mohr-circle constructioin

Mohr-Coulomb failure criterion

Construction of Mohr's circle

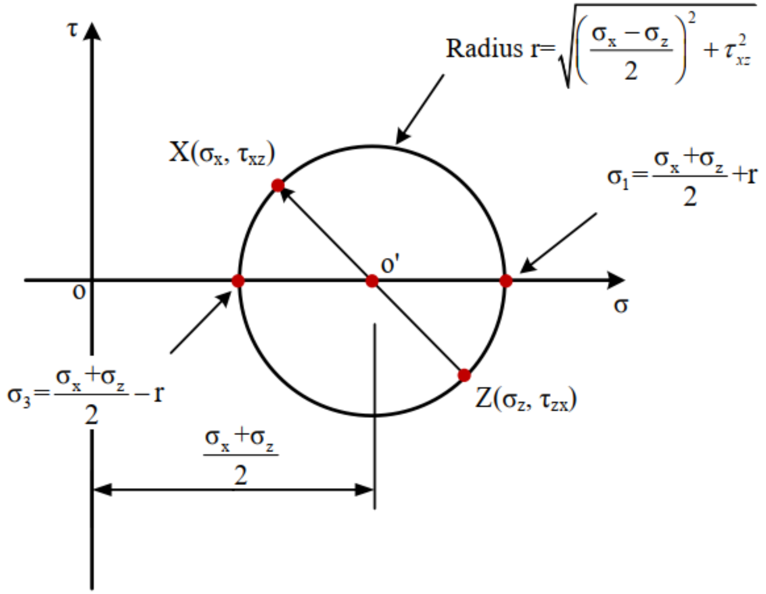


Illustration of Mohr-circle construction

Procedures

1) Plot the corresponding stresses state on x-plane and z-plane, on the $\sigma - \tau$ coordinate system
2) Connect the two points with a straight line. Since $\tau_{zx} = \tau_{xz}$, the straight line passes the center of the circle
3) Draw Mohr's circle

Mohr-Coulomb failure criterion

Construction of Mohr's circle

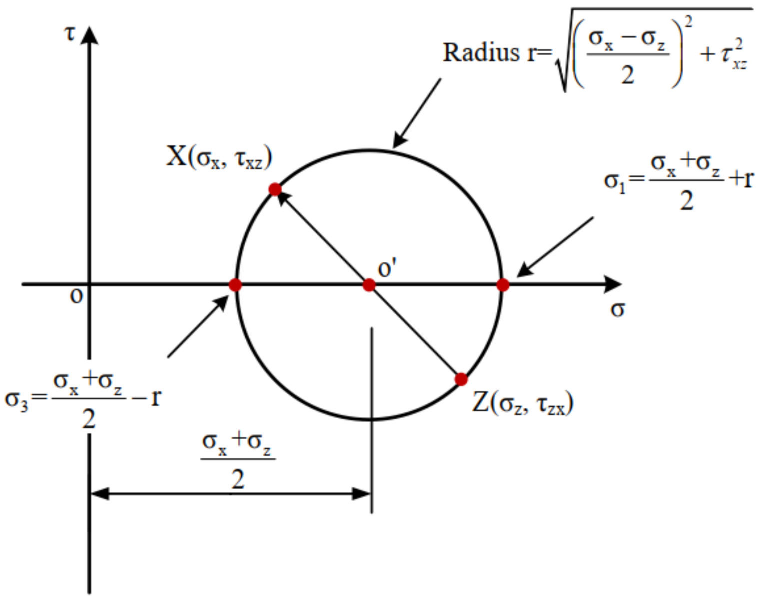


Illustration of Mohr-circle construction

Two intersection points of the Mohr's circle with horizontal axis

$$\begin{cases} \sigma_{\max} = \dfrac{\sigma_x+\sigma_z}{2} + \sqrt{\left(\dfrac{\sigma_x-\sigma_z}{2}\right)^2 + \tau_{xz}^2} \\ \sigma_{\min} = \dfrac{\sigma_x+\sigma_z}{2} - \sqrt{\left(\dfrac{\sigma_x-\sigma_z}{2}\right)^2 + \tau_{xz}^2} \end{cases}$$

The planes corresponds to the stress state at the rightmost point or the leftmost point is called **principal planes**. The normal stress on the principal plane is termed as **principal stress**.

Mohr-Coulomb failure criterion

Principal stresses

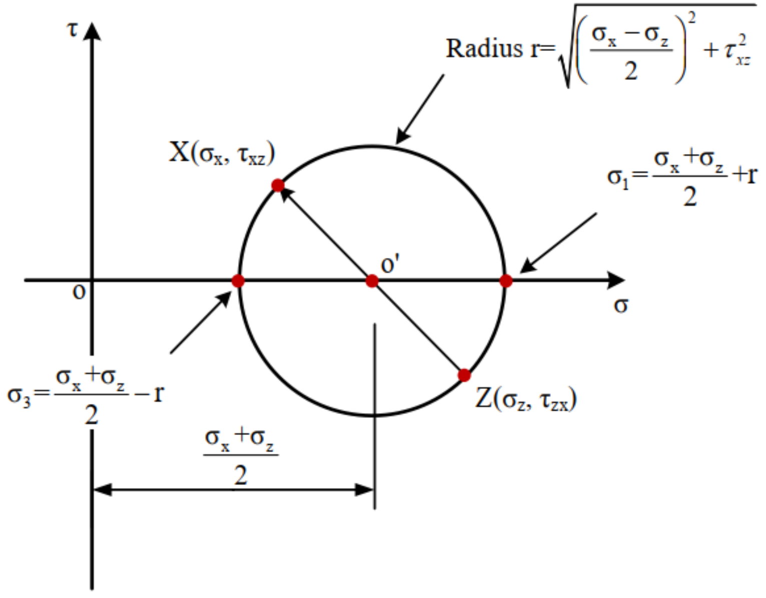


Illustration of Mohr-circle construction

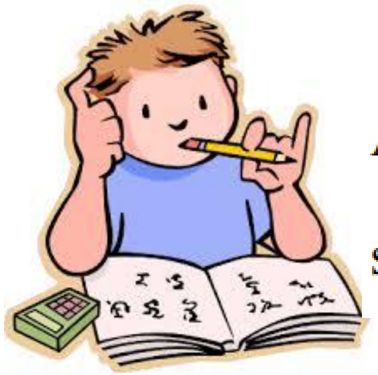
The maximum value σ_{max} is designated as the major principal stress σ_1, and the minimum one σ_{min} as the minor principal stress σ_3.

$$\begin{cases} \sigma_1 = \sigma_{\max} \\ \sigma_3 = \sigma_{\min} \end{cases}$$

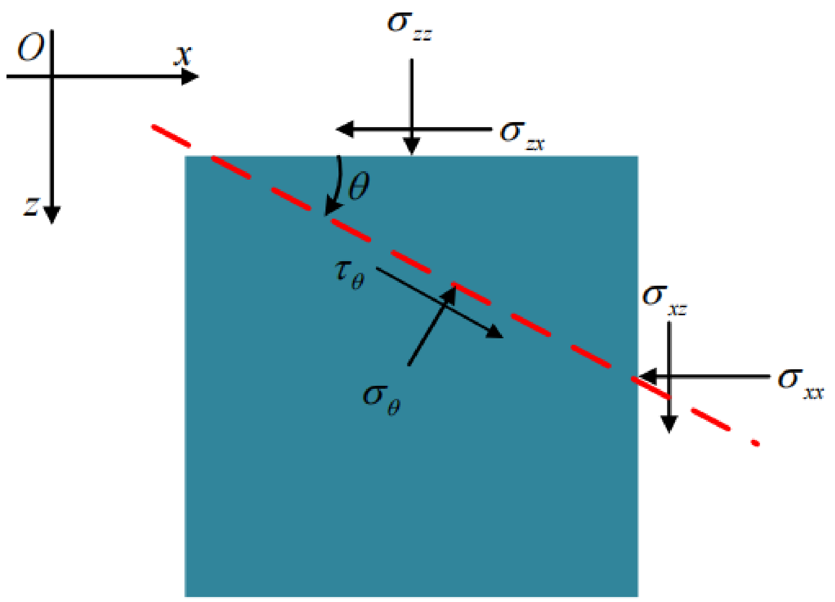
Mohr-Circle in principal stresses form

$$\left[\sigma - \frac{\sigma_1 + \sigma_3}{2}\right]^2 + \tau^2 = \left(\frac{\sigma_1 - \sigma_3}{2}\right)^2$$

Exercises

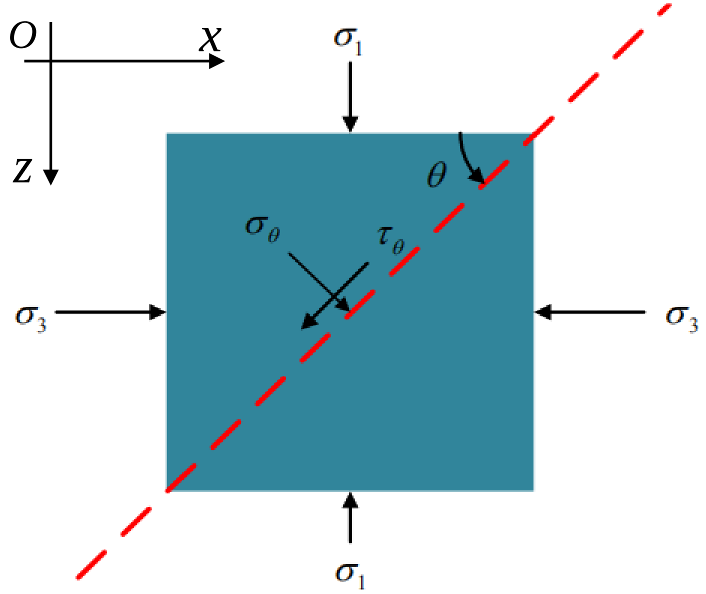


The normal stress and shear stress act on x-plane and z-plane are as Fig.1 shows. And $\sigma_{xx} = 50\text{ kPa}$, $\sigma_{xz} = -12.5\text{ kPa}$, $\sigma_{zz} = 25\text{ kPa}$, $\theta = 20^{\circ}$. Determine the normal stress σ_{θ} and shear stress τ_{θ} on the plane, which is clockwise from the horizontal plane.



Exercises

Major and minor principal stresses are given as $\sigma_1 = 120$ kPa and $\sigma_3 = 50$ kPa as shown in Fig. 2. Determine the normal stress and shear stress on the plane, which is inclined 45° counterclockwise from the horizontal plane.



Mohr-Coulomb failure criterion

Pole (origin of plane) of Mohr's circle

Usage: The pole of Mohr’s circle is a point so special that it can help to readily find stresses on any specified plane by using graphical technique instead of complicated computation.

Key point: Starting from the pole, **a straight line, which is in parallel with the plane**, is draw to intersect with the Mohr’s circle. The coordinate of the intersection point represents the stress state on that plane.

Mohr-Coulomb failure criterion

Pole of Mohr's circle

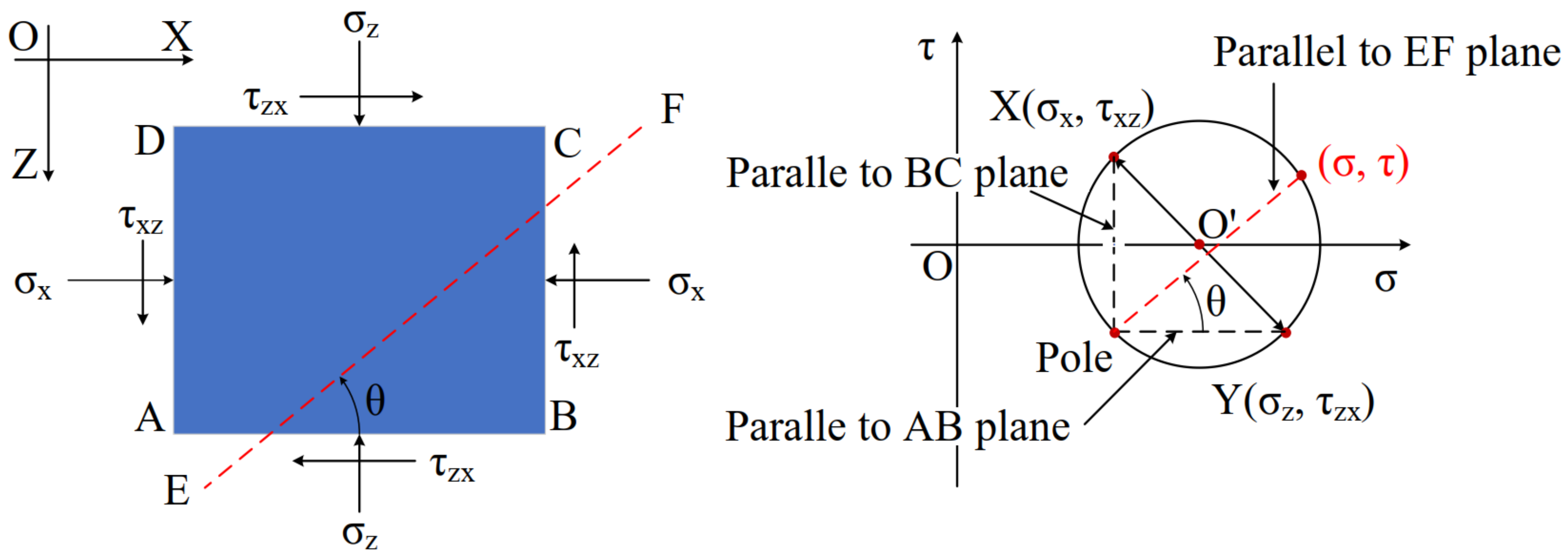
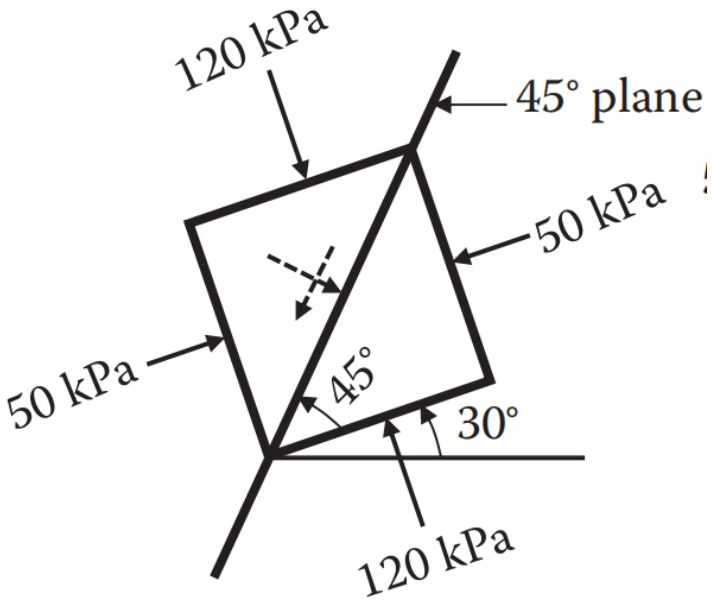


Illustration of Pole of Mohr's circle determination

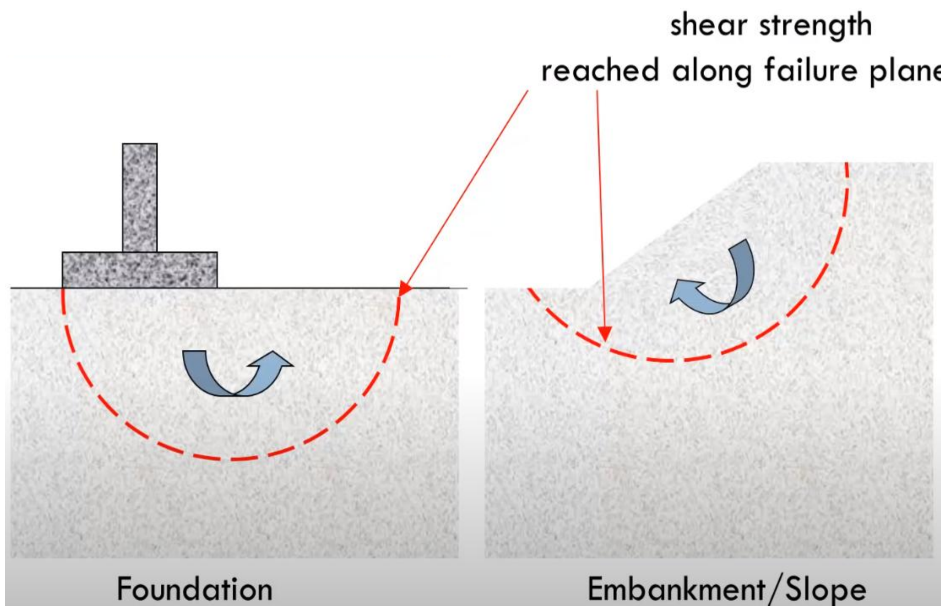
Exercises

The principal stresses on an element is known. By using the pole, determine stresses on the plane with 45° counterclockwise inclined from the major principal stress plane by using the pole.

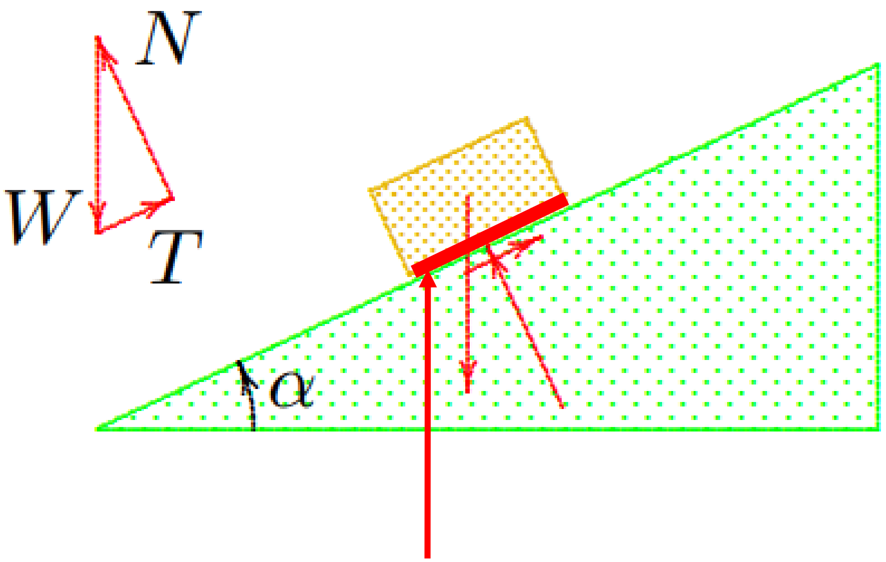


Mohr-Coulomb failure criterion

Coulomb's theory



Thought model

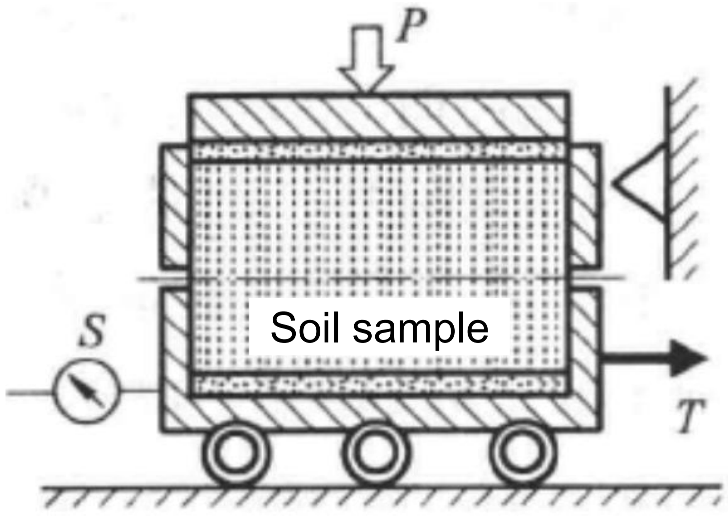


1. Friction resistance
2. Cohesive resistance

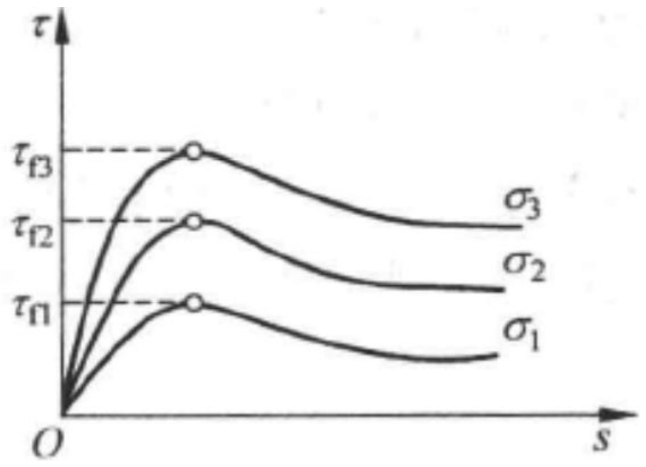
Mohr-Coulomb failure criterion

Coulomb's theory

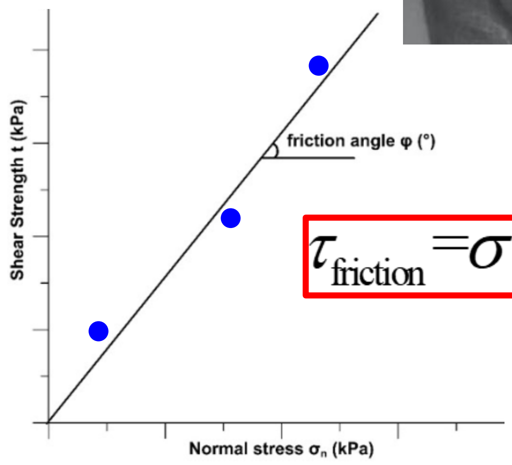
C. A. Coulomb (1773) did a series test on sand by direct shear test.



Coulomb's test on sand



Stress-strain relation



$$\tau_{friction} = \sigma \cdot \tan\varphi$$

Mohr-Coulomb failure criterion

Coulomb's theory

Cohesive resistance $\left\{ \begin{array}{l} \text{electrostatic force} \\ \text{Chemical bond} \\ \text{Capillary force} \\ \text{Other force between particles} \end{array} \right.$

$$\tau_f = \tau_{friction} + c = \sigma \cdot \tan\varphi + c$$

c and φ

strength parameters

Mohr-Coulomb failure criterion

Modified Coulomb's theory

Terzaghi (1925) modified Mohr-Coulomb's theory by including the effective stress concept

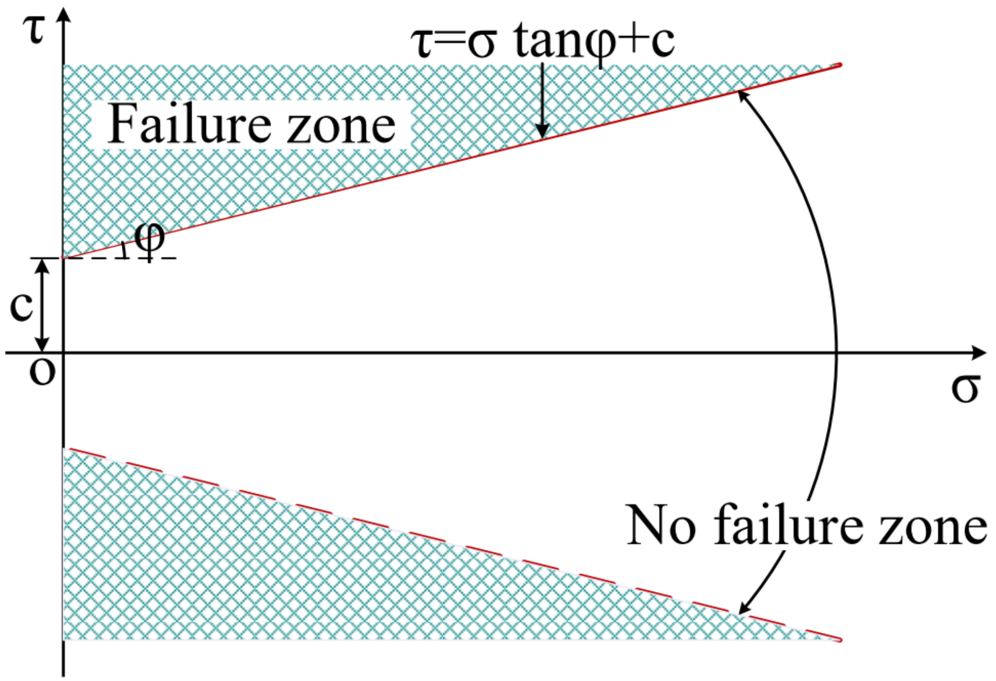
$$\tau_f = (\sigma - u) \cdot \tan\varphi' + c'$$

c' and φ' are effective strength parameters

Karl Terzaghi

Mohr-Coulomb failure criterion

Failure criteria

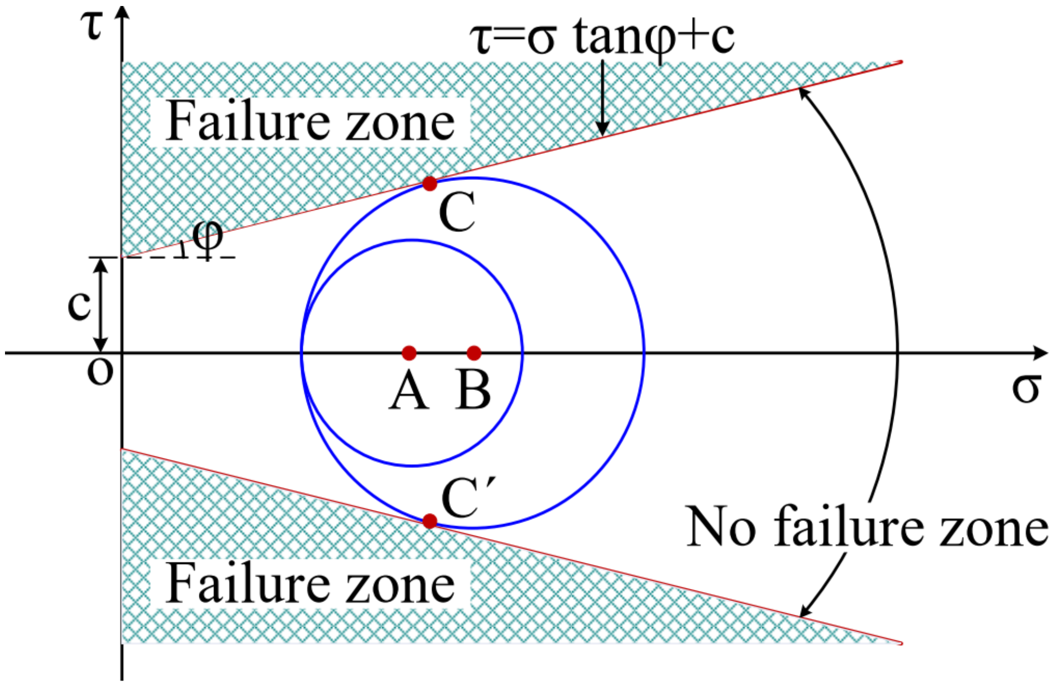


Failure criteria

1) The relationship between τ and σ is linear. The straight line is called envelop, which implies that if any stress combination of τ and σ below the failure envelope locus, there is no failure
2) Two envelops are plotted, as negative shear stress merely means the same magnitude of shear stress in the opposite direction. In this case, the sliding direction also changes.
3) These two failure envelopes define the safe limits of the stress combination of τ and σ

Mohr-Coulomb failure criterion

Mohr-Coulomb’s failure criterion



Mohr-Coulomb’s Failure criteria

Mohr-Coulomb’s failure criterion

$\tau < \tau_f$ Steady state

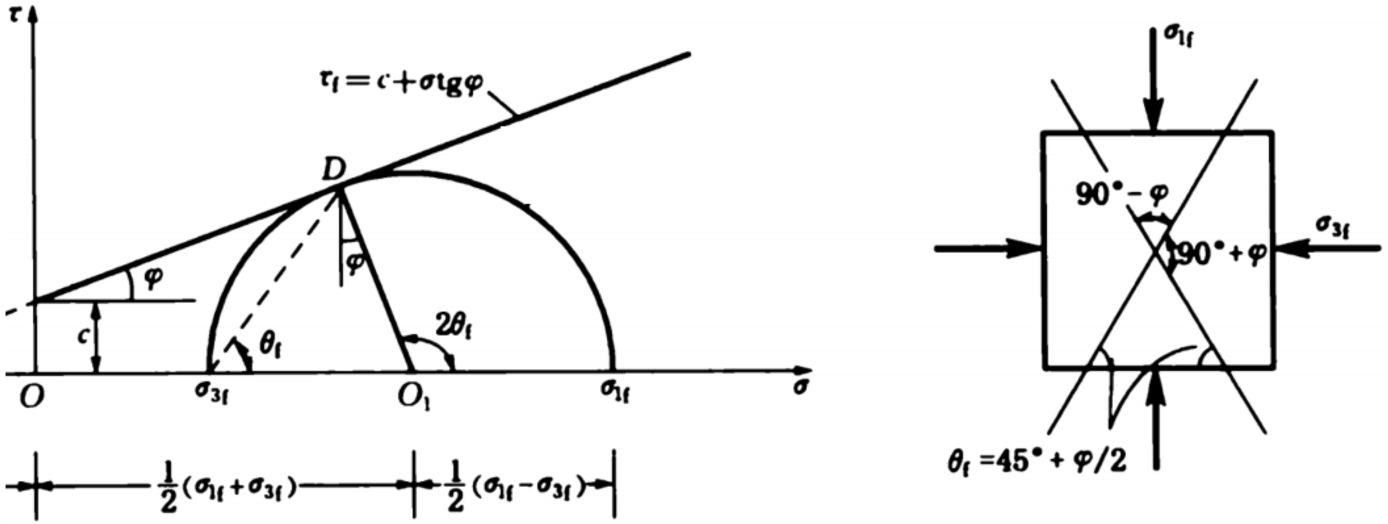
$\tau = \tau_f$ Limit state

$\tau > \tau_f$ Failure state

Mohr-Coulomb failure criterion

Limit state of soils-qualitative description

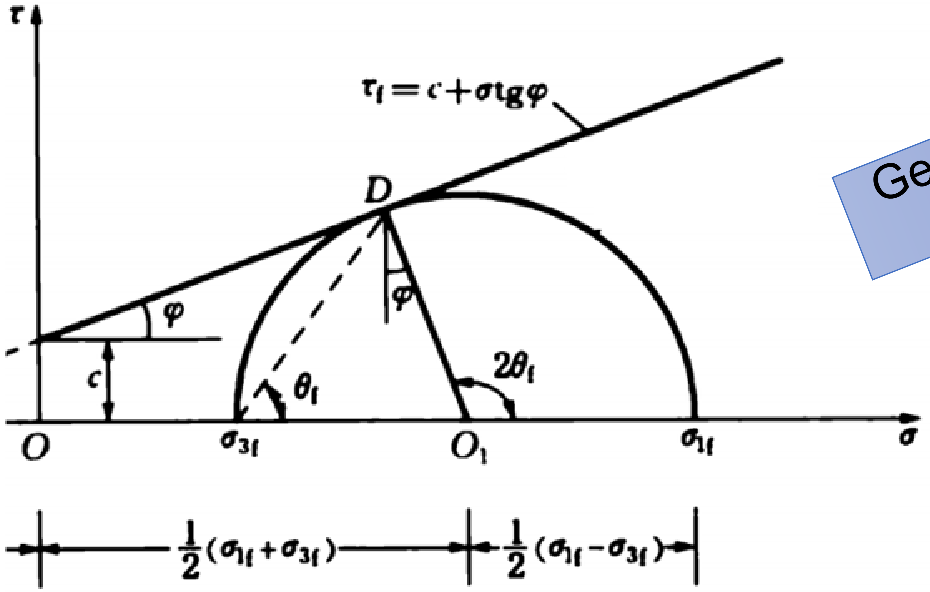
In a limit state of soil, the real angle θ_f between any critical plane and the major principal plane appeared $2\theta_f$ on Mohr's circle



Limit equilibrium state of soil

Mohr-Coulomb failure criterion

Limit state of soils-quantitative description



Limit equilibrium state of soil

Geometrical relation

$$\sin\varphi = \frac{\dfrac{\sigma_1 - \sigma_3}{2}}{\dfrac{\sigma_1 + \sigma_3}{2} + c\cdot\cot\varphi}$$

$$\sigma_1 = \sigma_3 \tan^2\left(45^\circ + \frac{\varphi}{2}\right) + 2c\cdot\tan\left(45^\circ + \frac{\varphi}{2}\right)$$

$$\sigma_3 = \sigma_1 \tan^2\left(45^\circ - \frac{\varphi}{2}\right) - 2c\cdot\tan\left(45^\circ - \frac{\varphi}{2}\right)$$

Exercises

The major principal stresses at certain point within a cohesionless soil mass is σ_1 =300 kPa. The shear strength parameters $\varphi = 20^{\text{o}}$. Determine the minor principal stresses at failure.

Exercises

Major and minor principal stresses at certain point are $\sigma_1 = 480\ \text{kPa}$ and $\sigma_3 = 210\ \text{kPa}$ respectively. The shear strength parameters are $c = 20\ \text{kPa}$ and $\varphi = 20^\circ$.

Determine the state of the point.

Shear strength test

Shear strength test

- **In the laboratory**
  - Direct shear test
  - Triaxial compression test
  - Unconfined compression test
- **In situ**
  - Vane shear test

Shear strength test

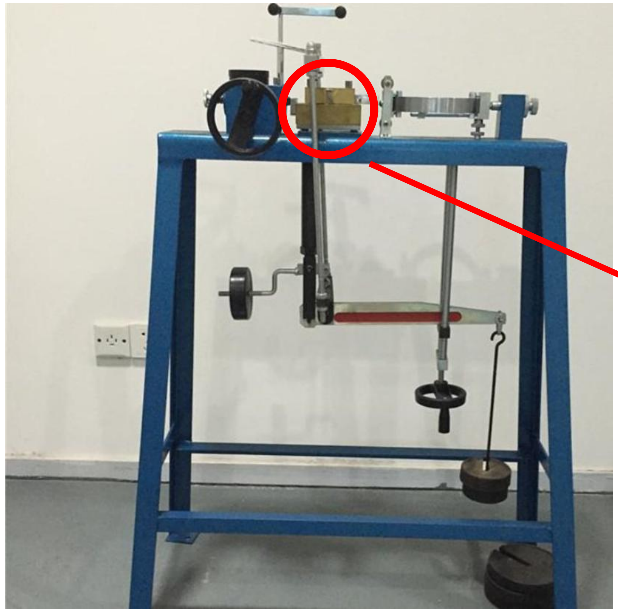
Direct shear test

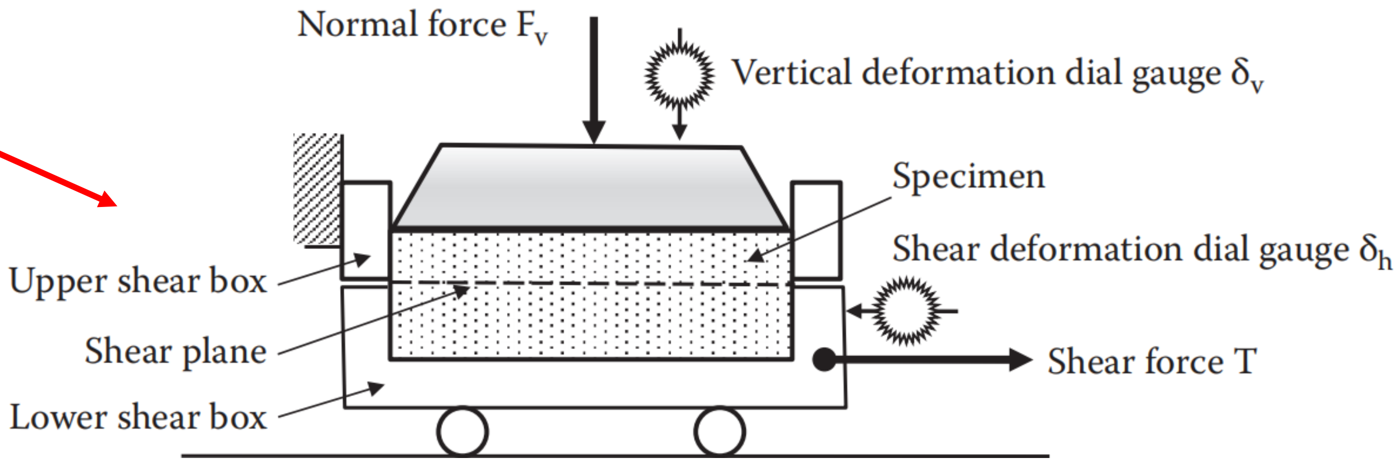
Factors affecting the shear strength of soils

- Density of soil
- Water content
- Stress history
- Degree of consolidation
- Boundary condition of drainage

Shear strength test

Direct shear test





Setup for direct shear test

Shear strength test

Direct shear test

Assumptions:

- The soil sample fails at predefined plane at mid height
- The area of cross section is a constant
- The distribution of stress at the failure plane is uniform

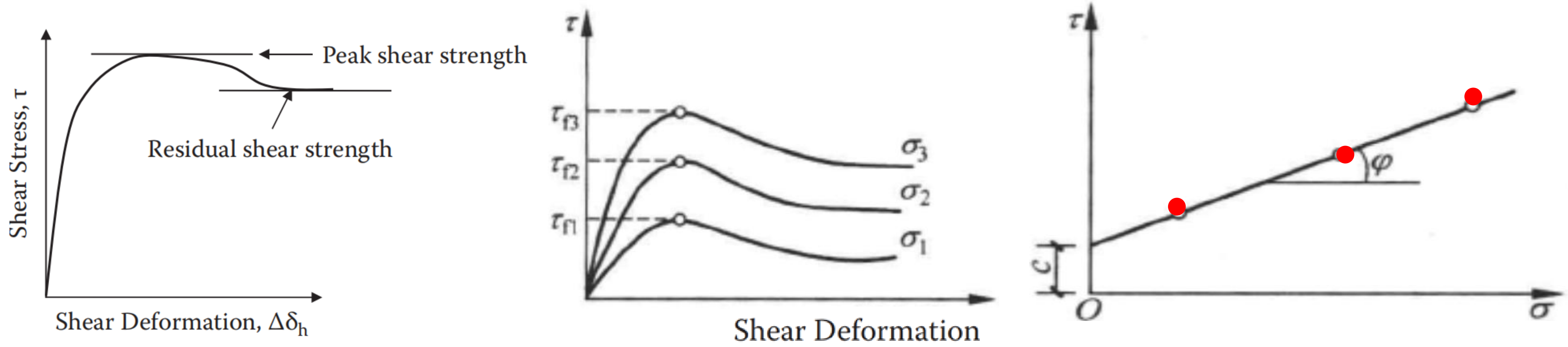
$$\sigma = \frac{F_v}{A} \qquad \tau = \frac{T}{A}$$

- The volume decrease of the soil sample

$$\delta V = \delta h \times A$$

Shear strength test

Direct shear test



Data of direct shear test

Shear strength test

Types of direct shear tests

Quick shear test (Q-test): During the normal loading process, incremental loading is applied without any interruption. The shear test is conducted just after the application of normal load. Moreover, the shear process should be so fast that water does not drain from the specimen. In these two stages, it can be assumed that no consolidation process has occurred.

Consolidated-quick shear test (R-test): After application of normal stress, the sample should be allowed to consolidate. The shear test should be conducted only after complete consolidation has occurred. In the shear test, no water is allowed to escape.

Shear strength test

Consolidated-slow shear test (S-test): After application of normal stress, the sample should be allowed to consolidate. During the second stage, the shear test should be done at such a slow rate that almost all excess pore pressure could dissipate.

Different direct shear test and associated strength parameters

Types of shear test	Quick-shear test (*Q*)	Consolidated-shear test (*R*)	Consolidated-slow shear test (*S*)
After applying the normal force	No consolidation	With consolidation	With consolidation
After applying the shear force	Without drainage	With drainage	With drainage
Shear strength parameters	c_Q, φ_Q	c_R, φ_R	c_S, φ_S

Shear strength test

Advantages and disadvantages

Advantages

- Almost all soil types can be tested
- Direct measurement of shear strength parameters
- The principles are easy to understand and the procedures are relatively easy to be carried out
- The strength parameters taking into account the effect of consolidation process can be roughly determined

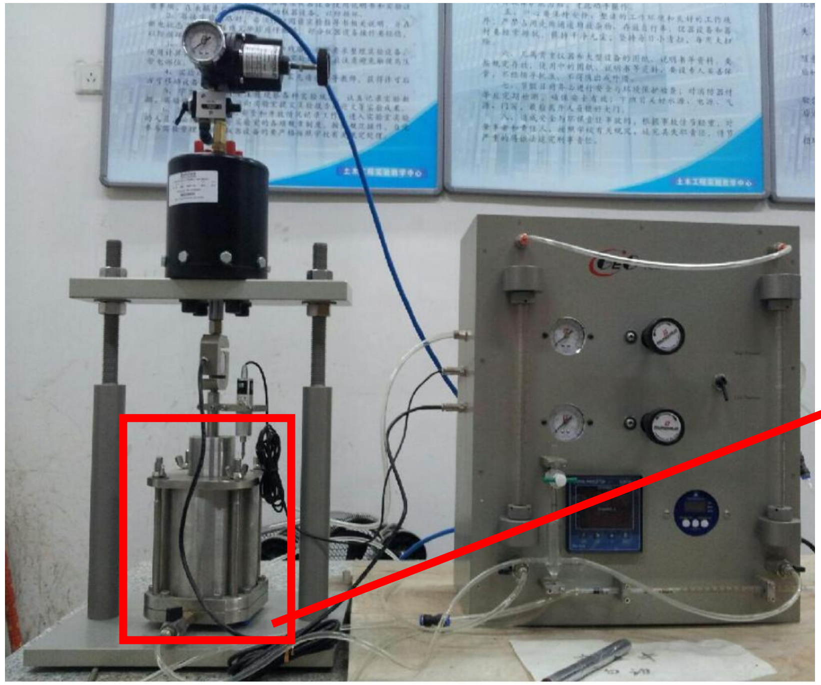
Shear strength test

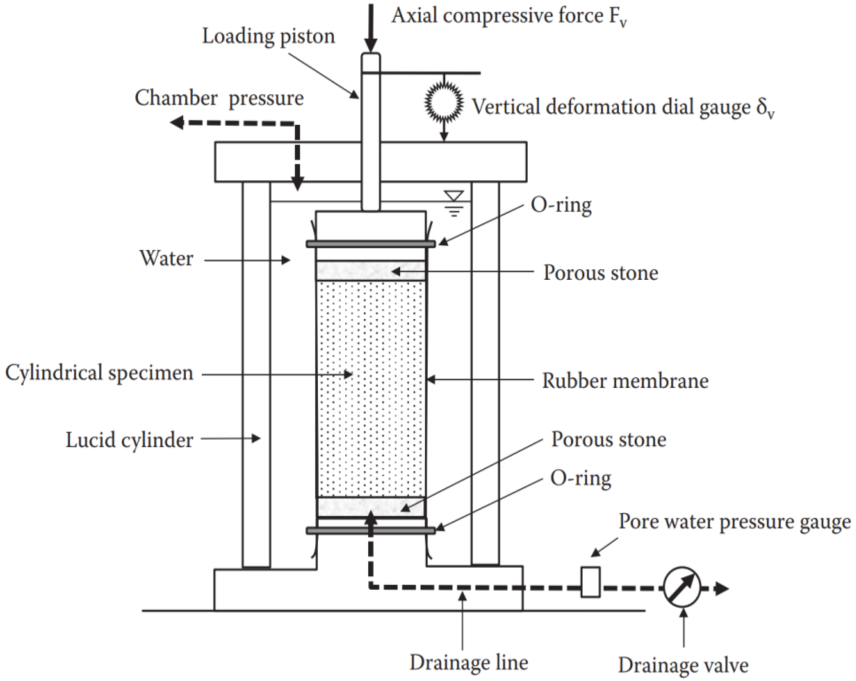
Disadvantages

- The failure plane is predetermined
- The drainage and measurement of the pore pressure could not be precisely controlled
- The assumption that the normal stress and shear stress are uniformly distributed on the failure plane is not reasonable

Shear strength test

Triaxial compression test

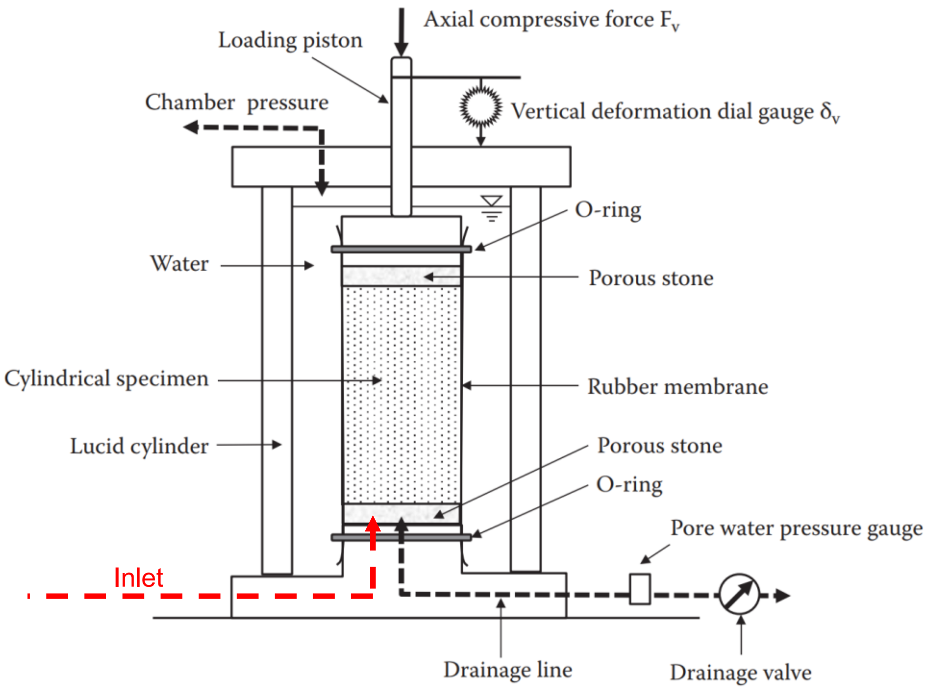




Setup for direct triaxial compression test

Shear strength test

Features of triaxial compression test



Triaxial cell

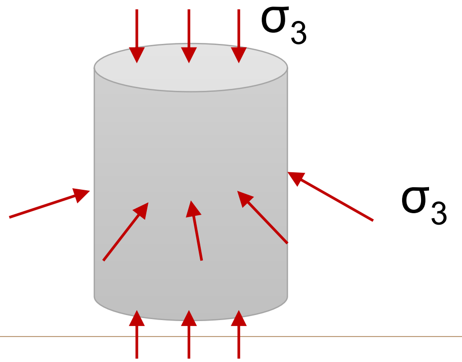
- Triaxial cell is a high-pressure cylindrical cell made of transparent materials.
- Soil sample usually have a height to diameter ratio 2 and enclosed in a rubber membrane between porous stones at top and bottom
- The triaxial cell is filled with fluid
- Water escapes through bottom drainage line and accordingly excess water pressure dissipate
- The O-rings prevent entry of cell fluid into the voids of the soil specimen
- Additional axial load is applied through the loading piston

Shear strength test

Triaxial compression test

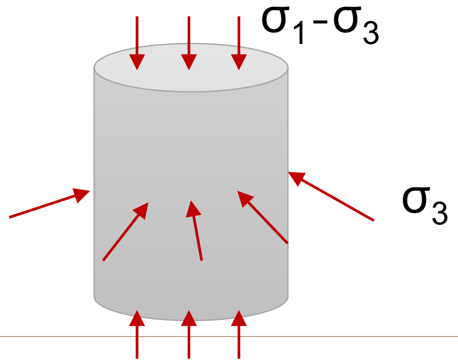
- **Stage one**

  The cell pressure (also called confining pressure) is increased to the desired value σ_3 by pumping in the liquid. In this stage, the soil sample subjected to hydrostatic pressure



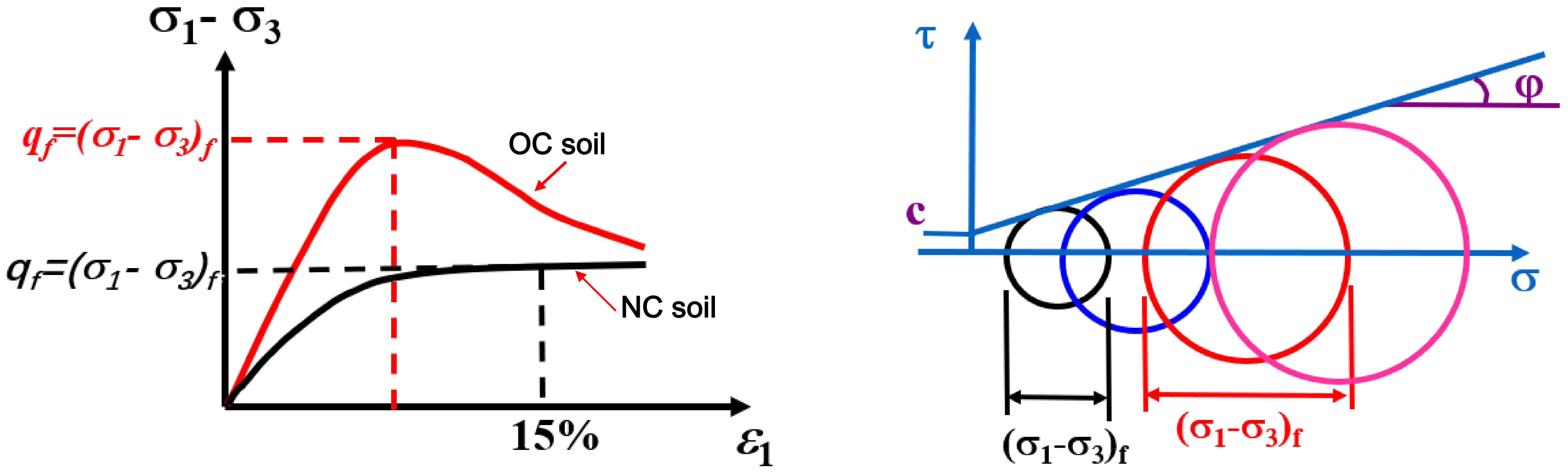
- **Stage two (principal stress difference)**

  By fixing cell pressure, additional axial load, usually at a constant rate, is applied to fail the soil sample. If the vertical stress at failure is σ_1, the additional stress induced in the second stage is $\sigma_1 - \sigma_3$, which is known as the deviator stress.



Shear strength test

Triaxial compression test



Data of triaxial compression test

Triaxial compression test

Advantages and disadvantages

Advantages

- Triaxial test has complete control over the drainage conditions.
- Pore pressure and volumetric changes are possible to be measured directly.
- Stress distribution is uniform on the failure plane.
- No pre-defined failure plane
- Any stress at intermediate stage up to failure is known and the corresponding Mohr’s circle can be drawn

Shear strength test

Disadvantages

- For soils with low hydraulic conductivity, the drained test takes long period of time
- It is impossible to calculate cross sectional area of the specimen accurately at large strains
- The test simulates only axis-symmetrical problems. In the real field, the problem is generally 3-dimentional
- Specimen consolidation in the triaxial test is isotropic; whereas in the real field, the consolidation is generally anisotropic
- Triaxial apparatus is expensive

Shear strength test

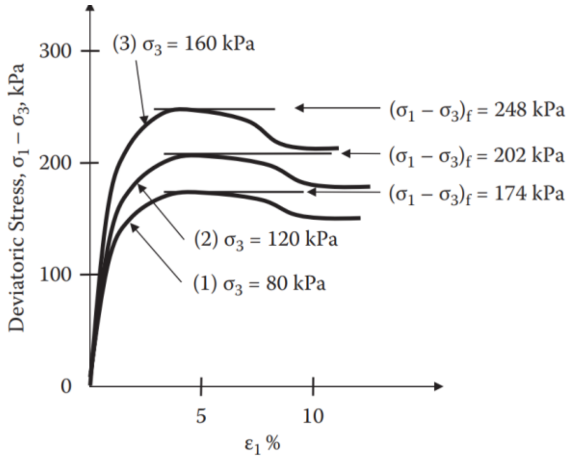
Triaxial compression test

Triaxial compression test and associated strength parameters

Types of shear tests	Unconsolidated undrained (UU) test	Consolidated undrained (CU) test	Consolidated drained test (*CD*)
σ_1	No consolidation	Consolidation	Consolidation
$\sigma_1 - \sigma_3$	Without drainage	Without drainage	With drainage
Shear strength parameters	c_u, φ_u	c_{cu}, φ_{cu}	c_d, φ_d

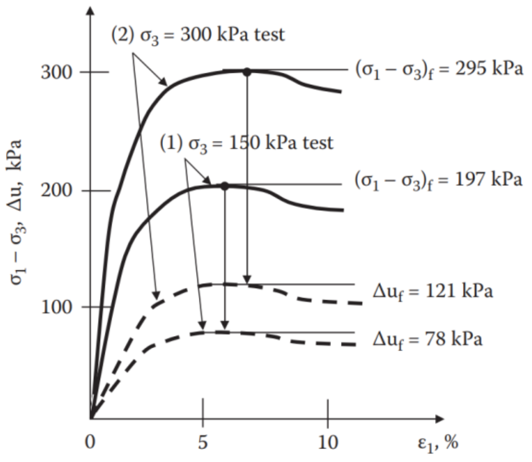
Exercises

Triaxial compression test data with three different confining pressures for a similar soil are shown in the following figure. The deviatoric stress ($\sigma_1 - \sigma_3$) is plotted with the vertical strain ε_1 and the failure strengths ($\sigma1 - \sigma3)_f$ are identified for those tests. After drawing Mohr's circles at failure for three specimens, determine cohesion component c and the angle of internal friction φ of this soil.



Exercises

Consolidated undrained triaxial tests for two similar specimens with different consolidation stresses were performed and the data in the figure, which includes pore water pressure measurements. Plot Mohr's circles at failure for two specimens in both the total stress and in the effective stress and determine the shear strength parameters c and φ from the total stress failure envelope and c′ and φ′ from the effective stress failure envelope.

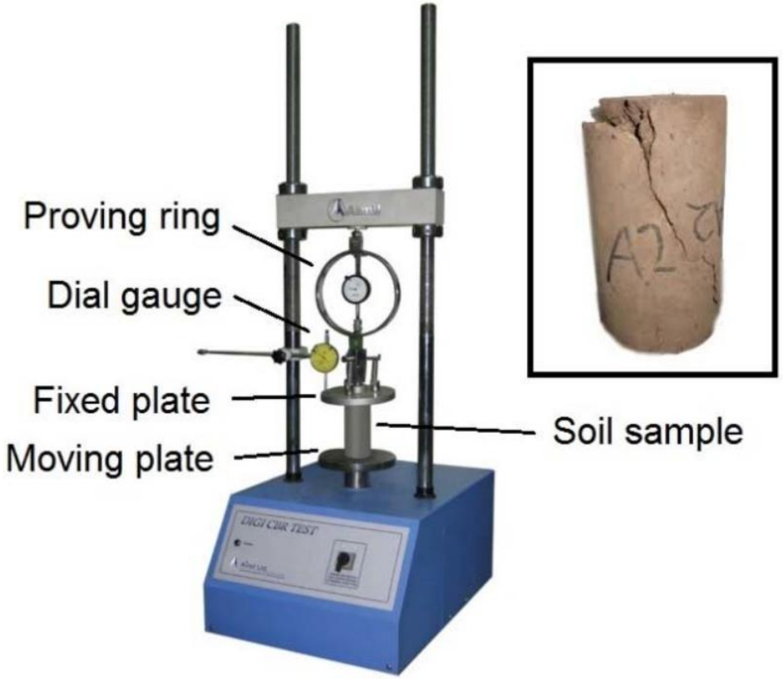


Exercises

For a normally consolidated specimen, it was found that $\varphi = 16°$ and $\varphi' = 28°$. If a similar specimen is sheared with $\sigma_3 = 120$ kPa in a CU test with pore water pressure measurement, estimate the deviatoric stress $(\sigma1 - \sigma3)_f$ and pore water pressure Δu_f at failure. (**Hints:** for NC soil, the failure envelop passes through the origin point)

Shear strength test

Unconfined compression test



Data of triaxial compression test

It is utilized to determine the **unconfined compressive strength** (UCS) of an undisturbed or a remoulded **cohesive soil sample.**

A soil specimen is trimmed to have a **cylindrical shape**. Axial compressive force F_v is gradually increased until failure with a measurement of axial deformation δv.

Shear strength test

Unconfined compression test

1) Axial strain

$$\varepsilon_v = {\delta v}/{H_0}$$

2) Variation of cross section (constant volume)

$$A = {A_0}/{1-\varepsilon}$$

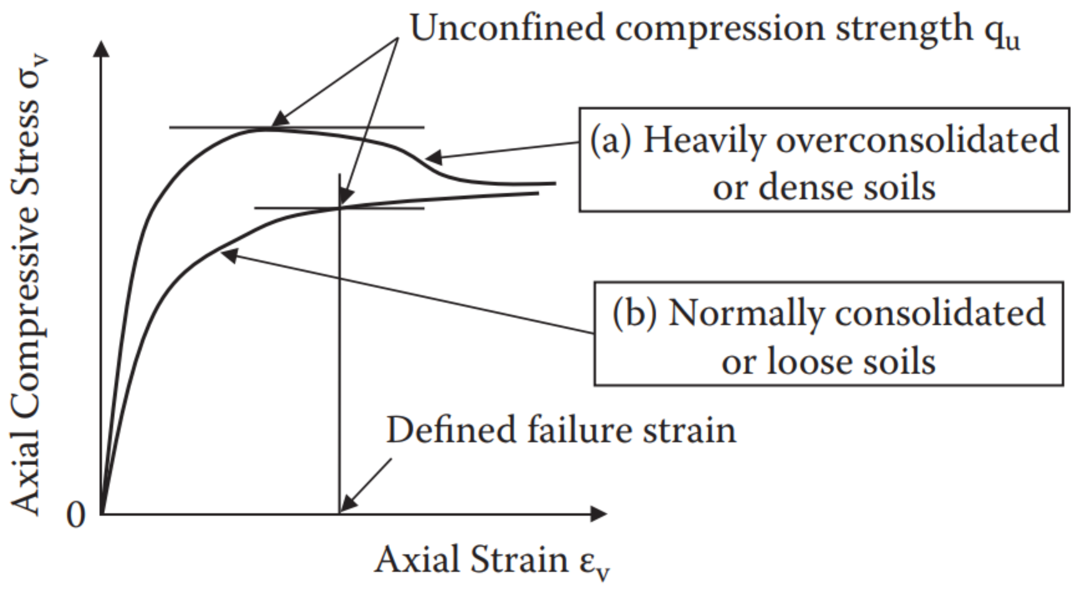
Initial cross section area

3) Compressive stress

$$\sigma_v = {F_v}/{A}$$

Shear strength test

Unconfined compression test



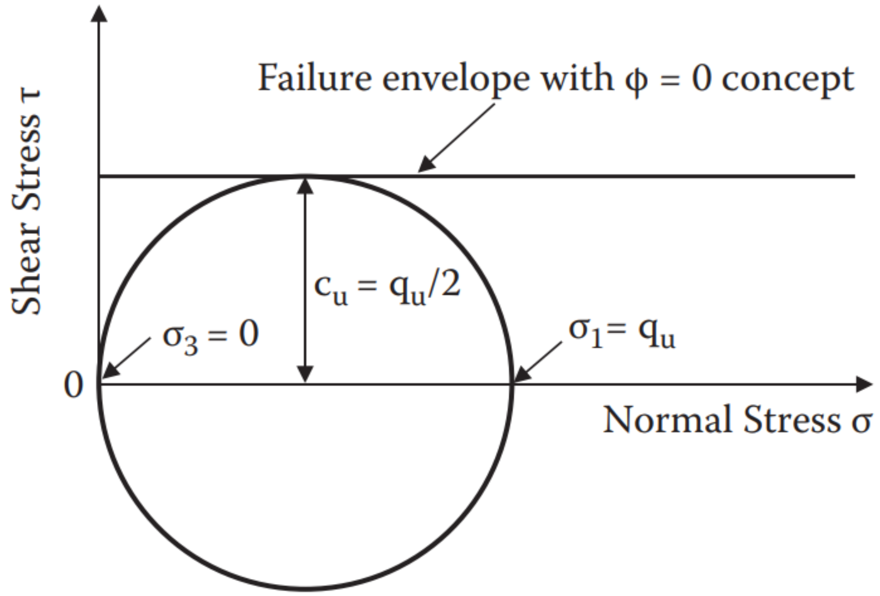
Stress-strain relation

Two curves for typical soils are seen: (a) overconsolidated or dense soils with a clear peak value, and (b) normally consolidated or loose soils without a clear peak value.

The UCS (q_u) corresponds to the peak value or certain defined failure strain ε_v (e.g., $\varepsilon_v = 10\%$ or $\varepsilon_v = 15\%$) depending on the code of design.

Shear strength test

Unconfined compression test



Failure criterion

As the loading process normally end within 10~20 minutes, the induced excess pore pressure may not have enough time to dissipate. Therefore, the **unconfined compression test is a special undrained shear test.**

The friction angle obtained from an undrained test would be always zero. Therefore, the undrained shear strength equals

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

Triaxial compression test

Advantages and disadvantages

Advantages

- It is readily to obtain the undrained strength
- Low cost of the apparatus

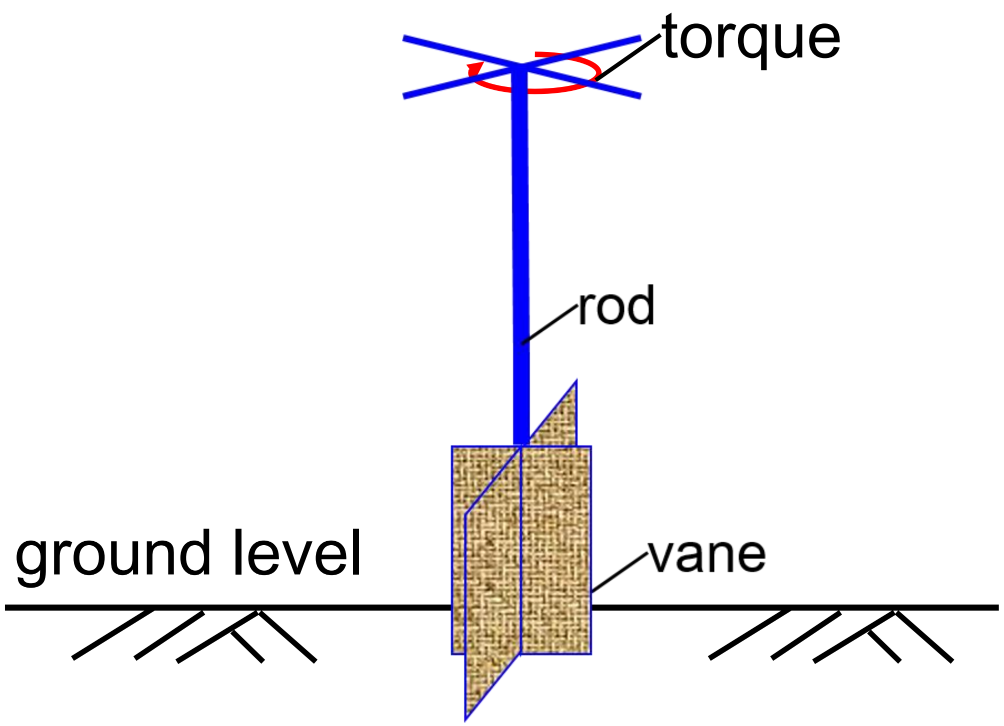
Disadvantages

- Total and effective stress conditions in the field can not be properly simulated
- It is impossible to calculate cross sectional area of the specimen accurately at large strains.

Shear strength test

Vane shear test

The vane shear test is used for the *in-situ* to determine the undrained strength of saturated soft clay (other types of soils are not applicable). Moreover, reliable results may be unavailable if the clay contains sand or silt laminations and shell



Shear strength test

Assumptions:

1) Shear failure body is a cylinder having a diameter equal to the overall width of the vane and height equal to the length of the vane
2) The failure surface is made up of peripheral, top and bottom surfaces of the cylinder
3) Shear strength on lateral surface equals those on the top and bottom

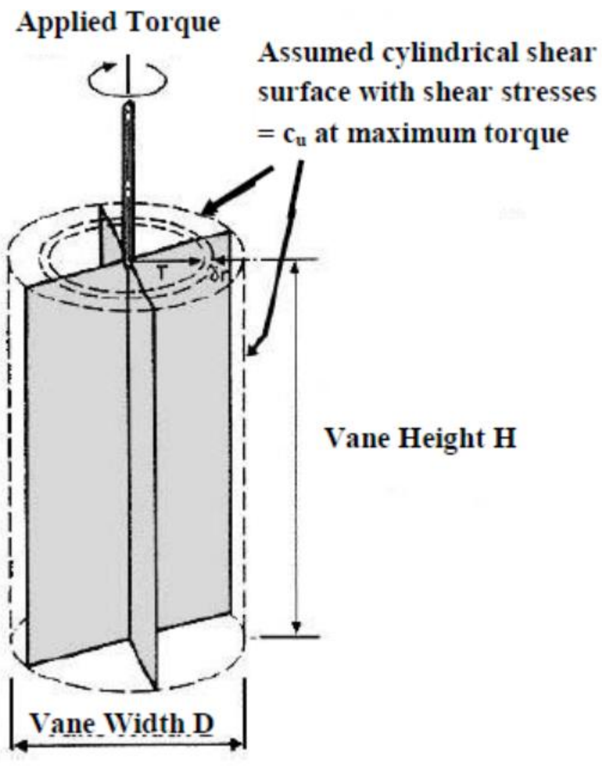
Shear strength test

$$\tau_f = \frac{T_f}{\frac{\pi D^2}{2}(H + \frac{D}{3})}$$

T_f — Torque to cause failure

D—overall vane diameter

H—vane height



Schematic diagram of the setup for Vane shear test

Pore pressure coefficients

Pore pressure coefficient: characterize the change in pore pressure caused by a change in total stress.

Skempton based on triaxial compression test firstly proposed two coefficients: A and B

During the application of confining pressure

$$B = {\Delta u_c}/{\Delta \sigma_3}$$

B=1 for fully saturated soil; B=0 for dry soil; 0<B<1 for partially saturated soil

A.W. Skempton

Pore pressure coefficients

During the application of axial additional load

$$B \cdot A = {\Delta u_d} \Big/ {\left(\Delta \sigma_1 - \Delta \sigma_3\right)}$$

The parameter A is also not a constant, and it varies with the over-consolidated ratio and the magnitude of deviatoric stress

The total induced stress equals

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

Pore pressure coefficients

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

For UU test: $A = 1$

$$\Delta u = \Delta\sigma_3 + B \cdot \left(\Delta\sigma_1 - \Delta\sigma_3 \right)$$

For CU test: $A = 1$, $\Delta u_c = 0$

$$\Delta u = B \cdot \left(\Delta\sigma_1 - \Delta\sigma_3 \right)$$

Pore pressure coefficients

Why shall we estimate the induced pore pressure

- The construction of an earth embankment or an earth dam over a soft clay deposit need to predict pore pressures caused by known changes in total stress
- The pore pressure parameters can be used to predict how the pore pressure changes as the total stresses increase as the height of the embankment/dam increases. As a result, the structure's stability can be ensured
- The construction engineer can recommend a reasonable construction rate in stages so that excess pore pressures can be controlled and stability can be maintained during and after construction

Exercises

In a CU test, the confining pressure on a specimen of saturated clay is 150kPa, the ultimate principal stress difference is 260kPa and the ultimate pore pressure is 50kPa. Determine the coefficients A and B.

Shear characteristics of cohesionless and cohesive soils

Cohesionless soils

The consolidation process finishes rapidly during loading due to relatively high hydraulic conductivity. As cohesionless soils normally have no cohesive resistance, **the strength envelop of cohesionless soils passes through the origin point**

$$\tau_f = \sigma' \tan \varphi_d$$

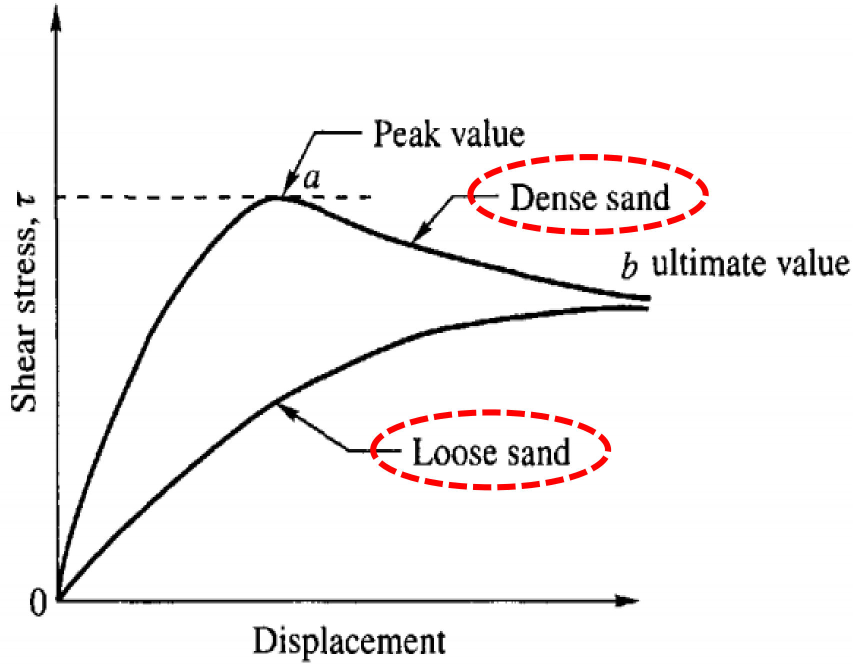
Factors influencing the strength of cohesionless soils:

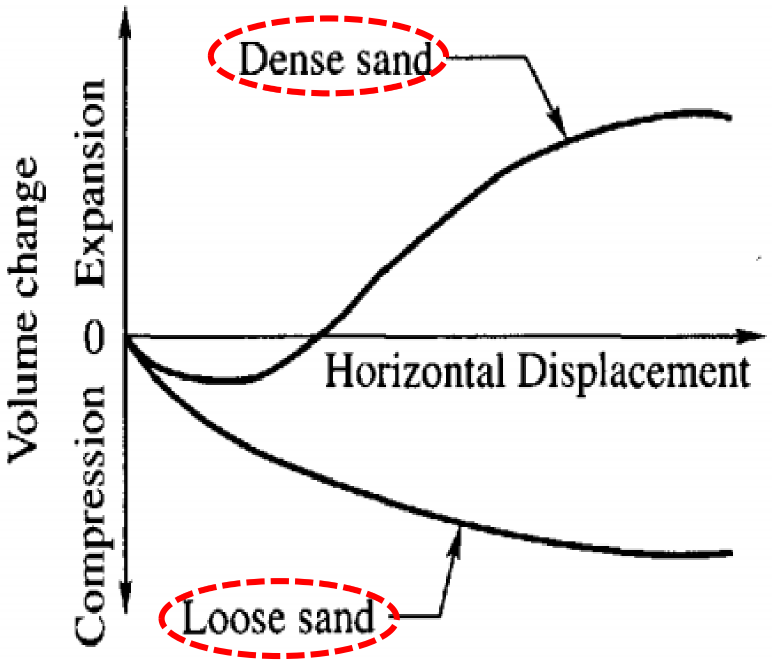
Key factors: relative density D_r (the higher the D_r, the higher the strength)

Other factors: mineralogy, grain size and gradation, shape of particle

Shear characteristics of cohesive and cohesionless soils

Cohesionless soils





Typical deformation stress-strain relation

Shear characteristics of cohesive and cohesionless soils

Liquefaction

When saturated loose cohesionless soils (e.g. silty sand) subjected to earthquake shaking or other rapid loading, the water within the soils may have not sufficient time to escape and the excess pore pressure increases rapidly.

When the excess pore pressure increases to a point, it results in the effective stress reducing to zero and accordingly zero strength of soils. In this case, soils behavior similar to liquid and can no longer bears any shear load.

Shear characteristics of cohesive and cohesionless soils

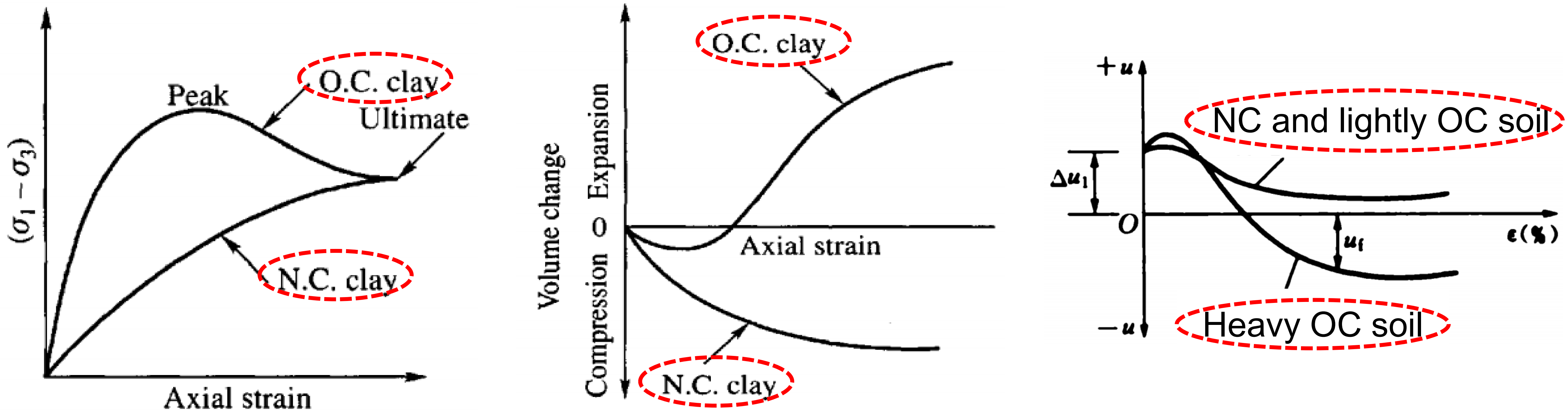
Cohesionsive soils

Apart from the degree of consolidation and drainage conditions, **the stress history** also play a fundamental role in the strength of cohesive soils.

The **nomral consolidated soils (NC)** in triaxial compression test is defined as if **the ratio of the pre-consolidation pressure over the confing pressure equals one** and **the overconsolidated soils (OC)** is defined as whether **the corresponding ratio is larger than one.**

Shear characteristics of cohesive and cohesionless soils

Cohesionsive soils



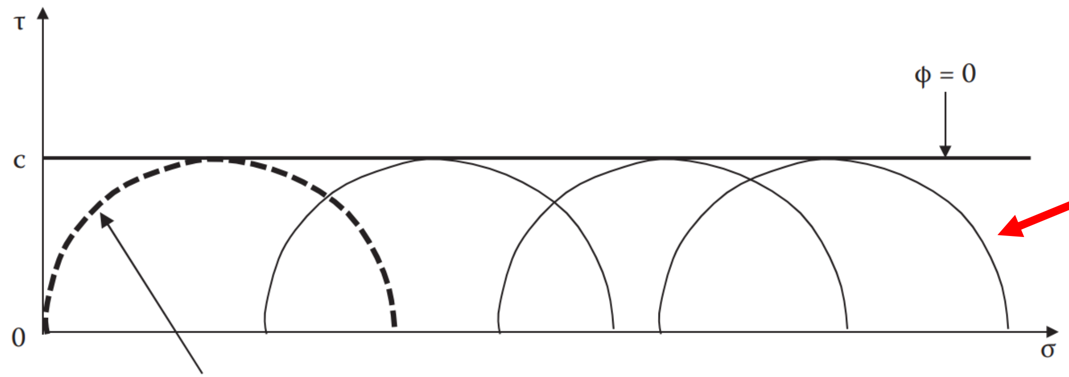
Typical deformation stress-strain relation

Shear characteristics of cohesive and cohesionless soils

Unconsolidated undrained (UU) test on NC soil

No consolidation indicates that the soil do not gain any strength. The failure envelop is an horizontal line.

$$\tau_f = C_u = \frac{q_u}{2}, \quad \varphi_u = 0$$



Typical Mohr's circles for UU test

The radius of the Mohr's circle is a constant

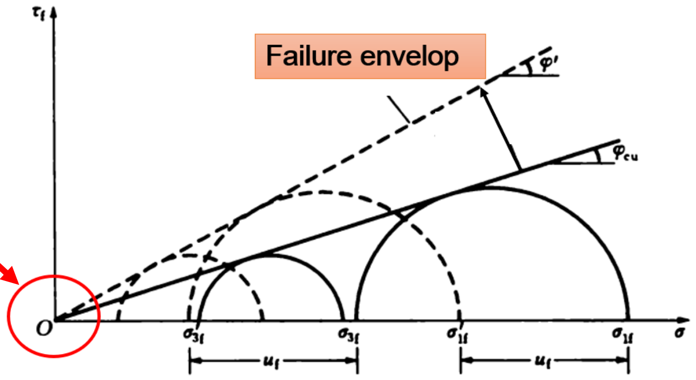
Shear characteristics of cohesive and cohesionless soils

Consolidated undrained (CU) test on NC soil

The strength increases due to consolidation process at increased confining pressure. The failure envelop passes through the origin point

$$\tau_f = \sigma \tan \varphi_{cu} \text{ and } \tau_f = \sigma' \tan \varphi'_{cu}$$

Note that zero cohesion component does not necessarily mean that soil is resisted purely by friction. In fact, shear resistance of clays is mostly contributed from cohesive resistance, but its expression merely implies that, when consolidation pressure is zero, there will be no strength.



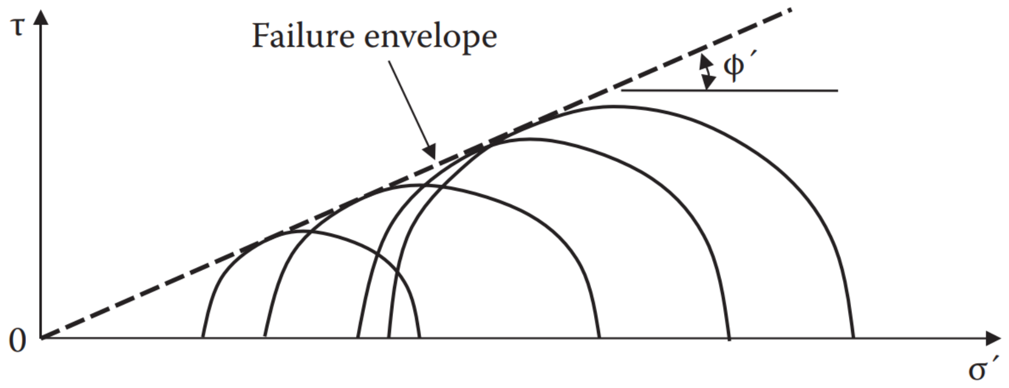
Typical Mohr's circles for CU test

Consolidated drained (CD) test on NC soil

The soils gain more strength within two loading stage. Total stress and effective stress are equal.

Only one failure envelop, which passes through the origin point

$$\tau_f = \sigma' \cdot \tan \varphi_d'$$

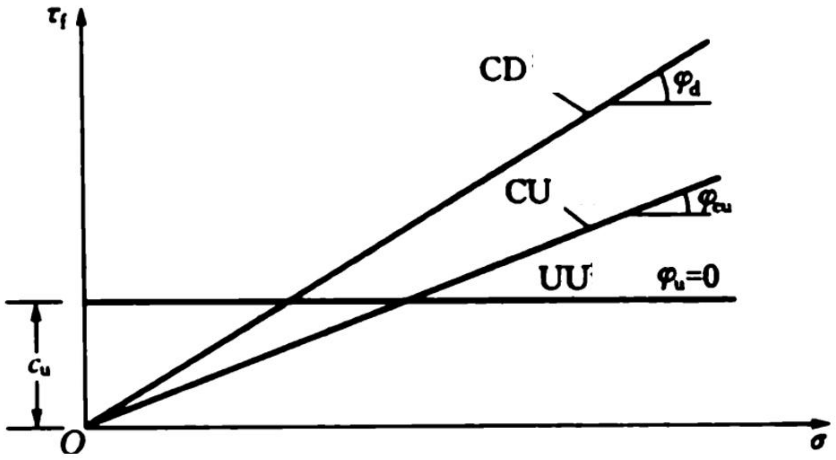


Typical Mohr's circles for CD test

Shear characteristics of cohesive and cohesionless soils

Comparisons of failure envelop for NC soil

The strength envelop from UU test is a horizontal line while the strength envelops from CU and CD tests are straight lines passing through the origin point.



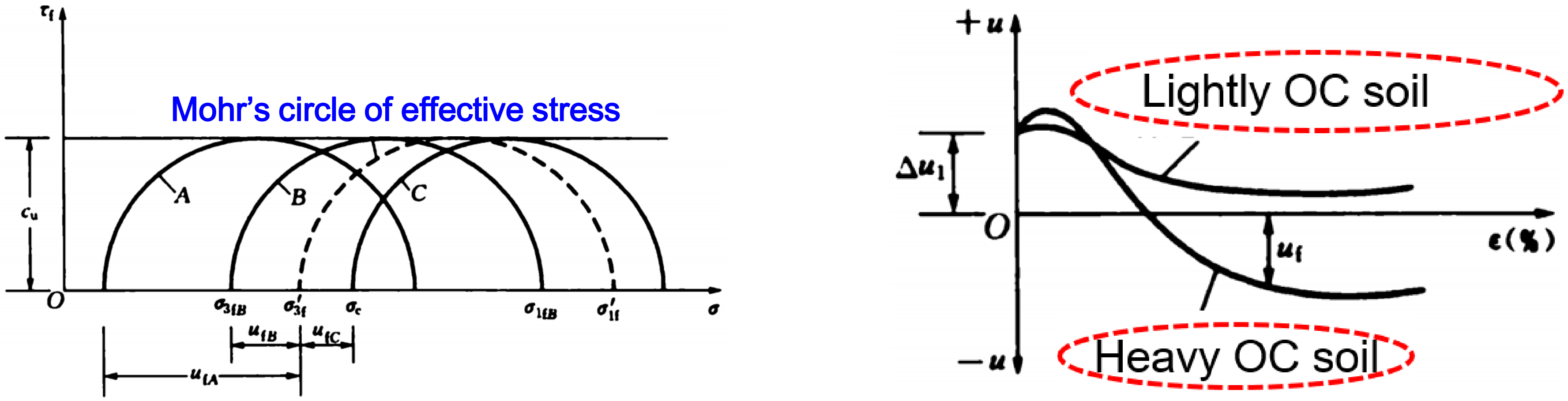
$$c_u > c_{cu} = c_d = 0$$

$$\varphi_d > \varphi_{cu} > \varphi_u = 0$$

Typical Strength envelops and relation between strength parameters

Unconsolidated undrained (UU) test on OC soil

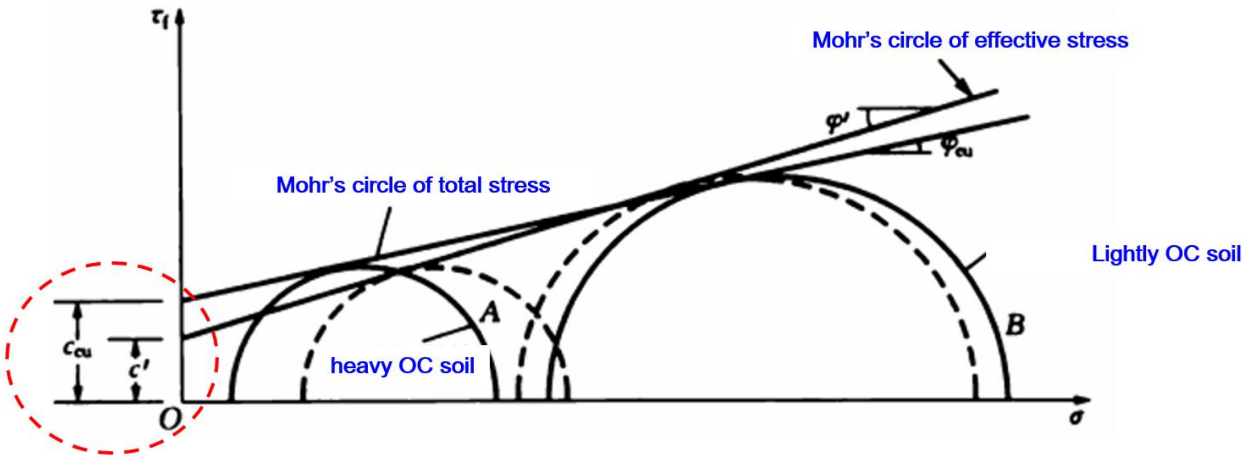
For heavy OC soil, the induced pore pressure is always negative. The Mohr's circles drawn according to effective principal stresses always locate to the right of the corresponding Mohr's circles drawn by total principal stresses. **While for lightly OC soil**, the induced pore pressure is postitive.



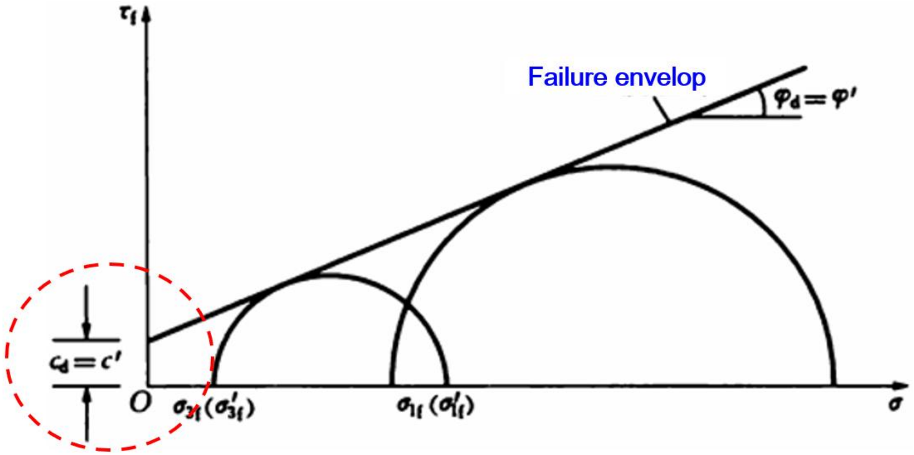
Mohr circle and variation of pore pressure during deformation for OC soils in UU test

Consolidated undrained (CU) and drained tests on OC soil

The stress history has significant impact on the strength of OC soil. The failure envelop never pass through the origin point as NC soil does.



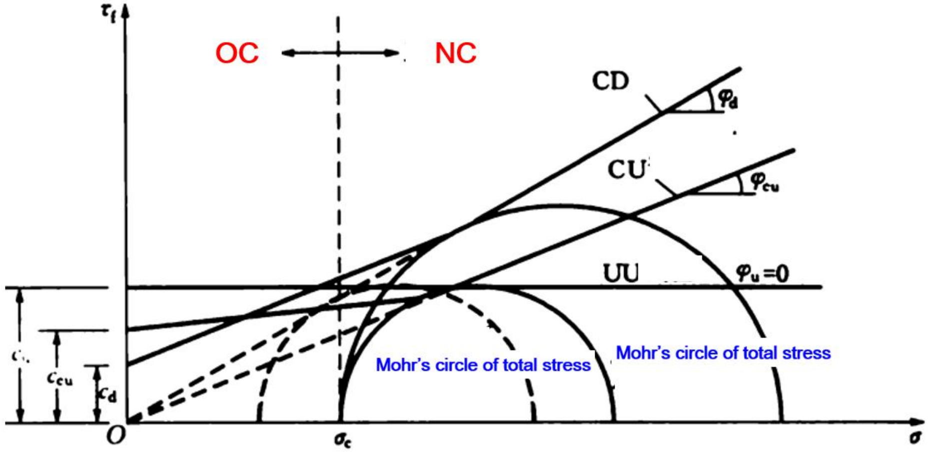
Mohr circle of OC soils in CU test



Mohr circle of OC soils in CD test

Comparisons of failure envelop for OC soil

The strength envelop from UU test is a horizontal line while the strength envelops from CU and CD tests are **piecewise straight lines**, which do not pass through origin point



$$c_u > c_{cu} > c_d$$

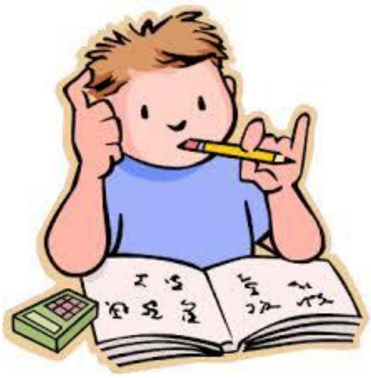
$$\varphi_d > \varphi_{cu} > \varphi_u = 0$$

Typical Strength envelop and relation between strength parameters

Exercises

A consolidated undrained test was conducted on a clay specimen.
The consolidation and chamber pressure was 50 kPa and the failure σ_1 was 86.2 kPa. If a similar specimen is first consolidated under 50 kPa consolidation pressure and then tested in an unconfined compression device, what will be the unconfined compression strength q_u?

Exercises



A normally consolidated clay had $\varphi' = 25^{\circ}$. The same specimen is tested in an unconfined compression device and obtains the unconfined compression strength q_u = 85 kPa. How much pore water pressure is generated in this unconfined compression specimen at the failure?

The End