FUNDAMENTALS OF GEOTECHNICAL ENGINEERING

Lesson 6. Shear strength of soils.

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6. SHEAR STRENGTH OF SOILS.

LESSON OVERVIEW

In this lesson, the mechanisms that give rise to failure in soils are presented. First, the Mohr-Coulomb failure criterion is introduced and the shear strength parameters, friction angle and cohesion, are presented. Then, the different laboratory test to determine these parameters are explained. Finally, the expected values for different soils are presented and some correlations to in-situ tests are defined.

LEARNING OUTCOMES

On completion this lesson, the student will be able to:

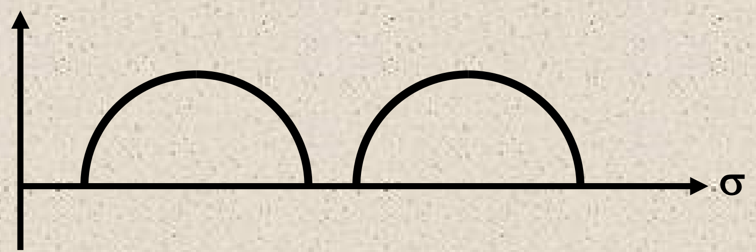
- ✓ Know and understand the concept of failure in soils.
- ✓ Know and understand the Mohr-Coulomb failure criterion and obtain the mathematical expressions of this criterion for different types of soils.
- ✓ Know and understand the laboratory tests used to obtain the strength parameters of soils: direct shear test, triaxial compression tests and unconfined compression test.
- ✓ Interpret the results of these tests and compare them with those expected from experience.
- ✓ Know and apply different expressions to correlate results from in-situ tests to strength parameters .

CONTENTS

INTRODUCTION: FAILURE IN SOILS (I)

➔ Lesson 4: Stresses

- Self weight + external loading.
- Mohr circles (effective stresses and total stresses).



➔ The question is: can the soil resist those stresses?

- YES ⇒ The construction can be done safely.
- NO ⇒ The construction has to be redesigned to reduce stresses.
- NO ⇒ If the construction is done as it is projected, the soil under it will collapse. FAILURE.

INTRODUCTION: FAILURE IN SOILS (II)

➔ When a soil fails, an internal failure surface appears and one part of the soil mass (usually including a construction) slides over a still part of the soil mass. ULS – Ultimate Limit State.

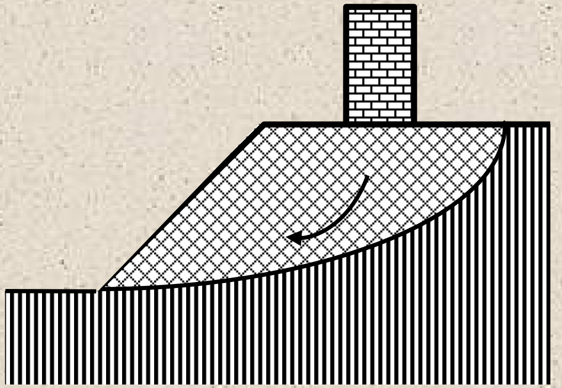
➔ Strength of soils is directly related to its strength against sliding.

➔ It depends on:

❶ Normal force between sliding and still soil masses.

❷ Friction among particles.

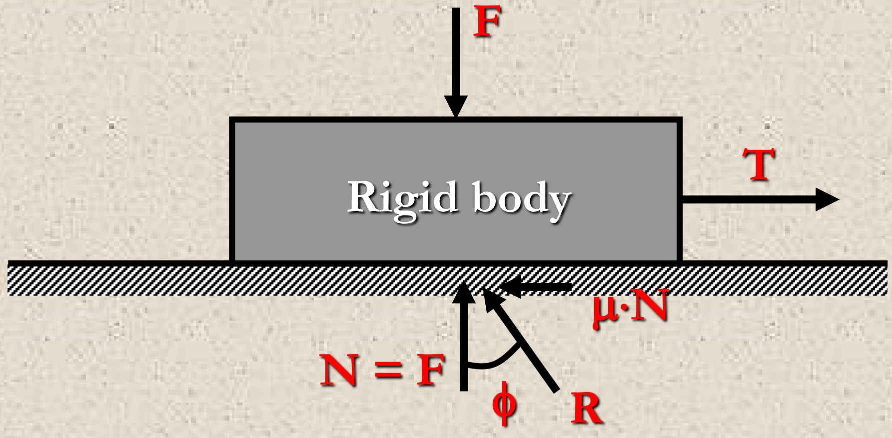
❸ Cohesion.



Landslide in Norway

MOHR-COULOMB FAILURE CRITERION (I)

Coulomb's frictional law



➔ The horizontal (T) force required to initiate the movement is $T \geq \mu \cdot N$.

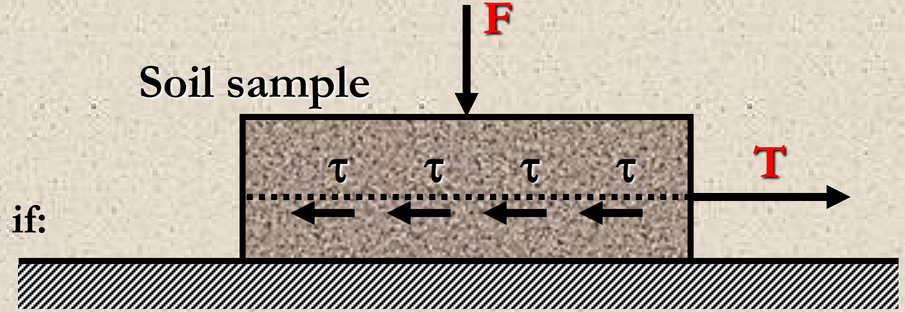
➔ μ is the coefficient of static sliding friction between the block and the surface.

➔ The greater the force F, the greater the friction force $\mu \cdot N$.

➔ The angle between the resultant force R and the normal force N is called the friction angle $\phi = \tan^{-1} \mu$.

MOHR-COULOMB FAILURE CRITERION (II)

What would happen to a soil sample?



➔ The upper part slides over the lower part if:

$$\underbrace{\frac{T_{máx}}{A} = \frac{F_{R\phi}}{A} = \frac{\mu_\phi \cdot F}{A} = \mu_\phi \cdot \sigma = \sigma \cdot tg\phi \qquad \frac{T_{máx}}{A} = \tau_{máx} = \tau_f}$$

τ_f is the shear stress when slip starts.

$$\boxed{\tau_f = \sigma \cdot tg\phi}$$

σ is the normal stress on the plane where slip starts.

ϕ is the "angle of shearing resistance" or "friction angle" (a constant of the soil).

MOHR-COULOMB FAILURE CRITERION (III)

➔ In addition, some clayey soils show "cohesion", an electrical attraction force between particles.

"Cohesion" is represented by letter c and it is a constant of the soil, too.

➔ Then, the general expression that governs the shear strength of any soil would be:

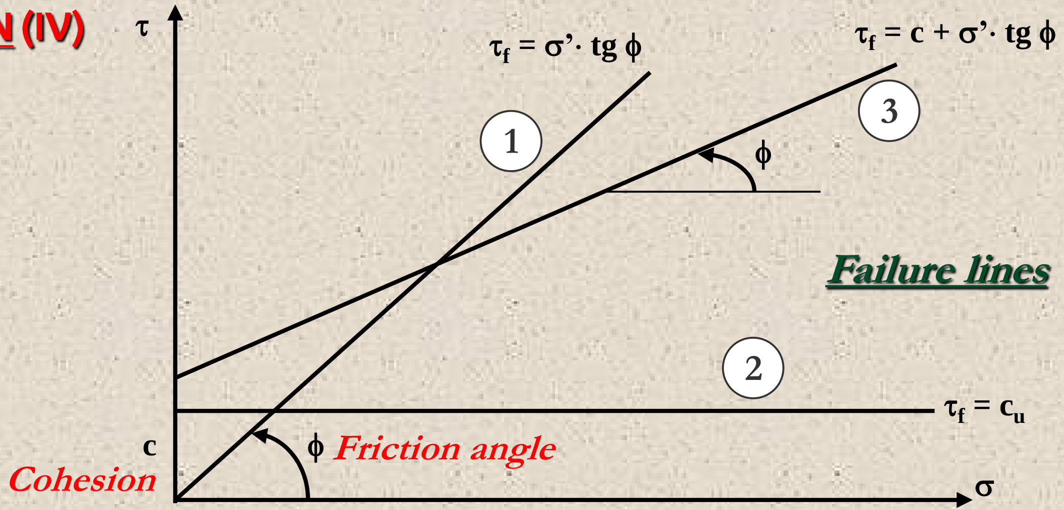
$$\boxed{\tau_f = c + \sigma \cdot tg\,\phi}$$

➔ In 1925, Terzaghi found different results on real cases and modified the expression:

$$\boxed{\tau_f = c + \sigma' \cdot tg\,\phi}$$

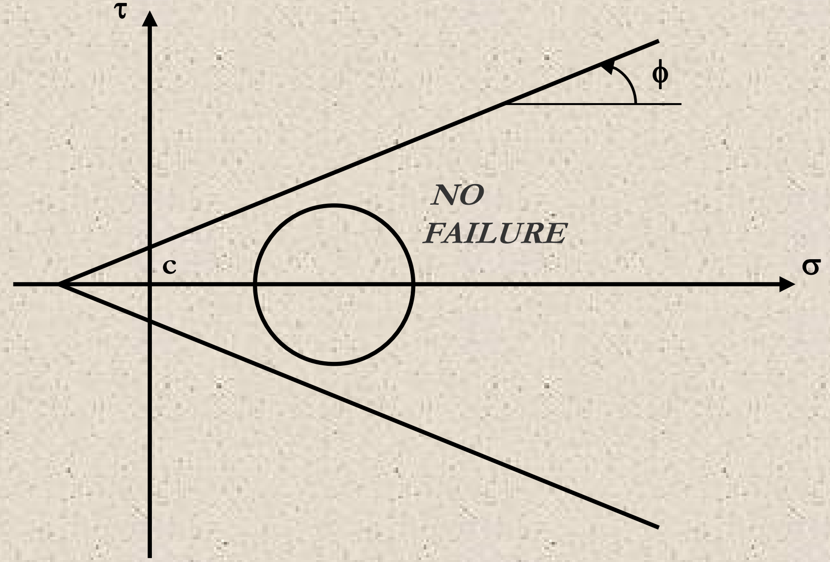
➔ Also, due to the consolidation process, effective stresses change over time. Therefore, there will be a "short-term" or "undrained" behaviour and a "long-term" or "drained" behaviour.

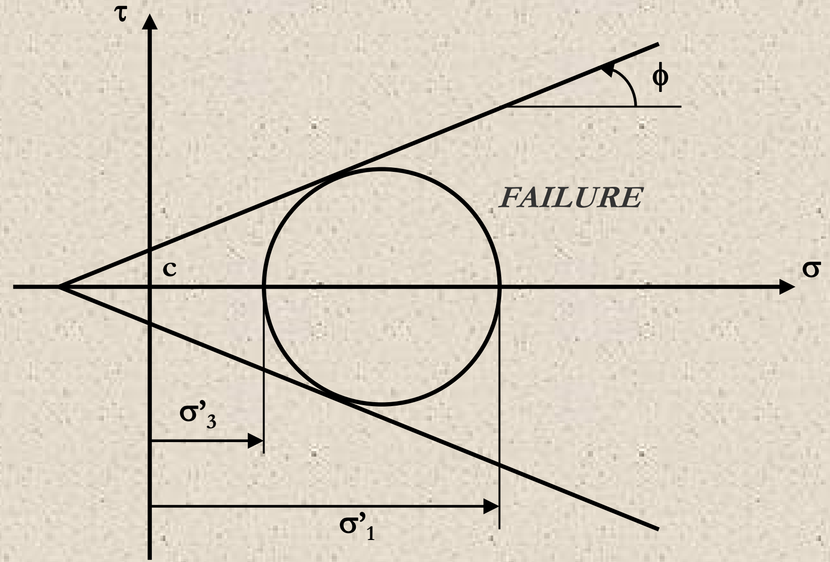
MOHR-COULOMB FAILURE CRITERION (IV)



1. Granular soils and normally consolidated clays under drained conditions (long-term).
2. Clayey soils under undrained conditions (short-term).
3. Overconsolidated clays under drained conditions (long-term) and soils having all types of particles.

MOHR-COULOMB FAILURE CRITERION (V)





$$\sigma_3' = \sigma_1' \cdot tg^2\left(\frac{\pi}{4} - \frac{\phi}{2}\right) - 2 \cdot c \cdot tg\left(\frac{\pi}{4} - \frac{\phi}{2}\right)$$

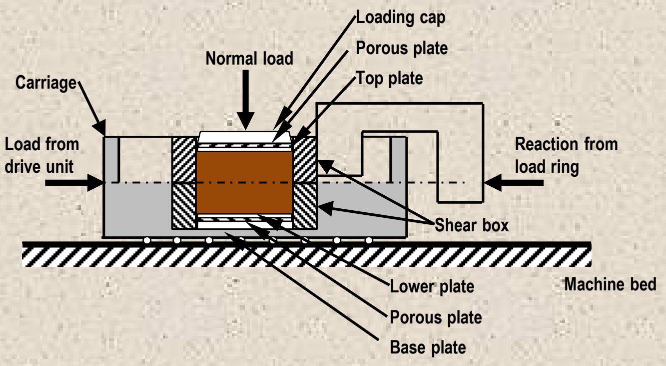
$$\sigma_1' = \sigma_3' \cdot tg^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) + 2 \cdot c \cdot tg\left(\frac{\pi}{4} + \frac{\phi}{2}\right)$$

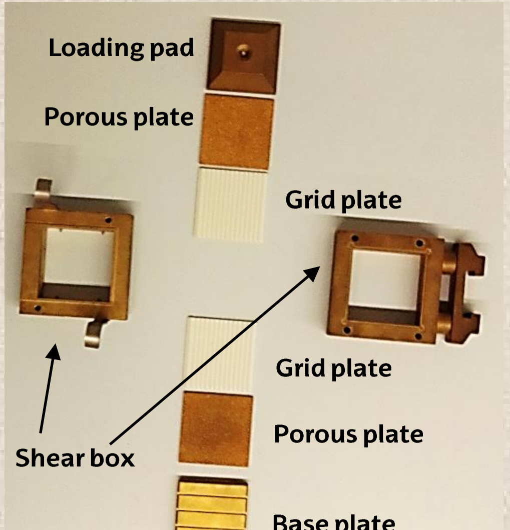
Video: drained and undrained shear strength.

DIRECT SHEAR TEST (I) – UNE 103401:1998 and ASTM D3080 standards

- It is especially recommended to determine shear strength parameters in sand and sandy silts.

(Image from www.controls-group.com)





(Own work)

Video: Direct shear test.

DIRECT SHEAR TEST (II)

➢ It is especially recommended to determine shear strength parameters in sand and sandy silts.

(Image from www.controls-group.com)

Steps:

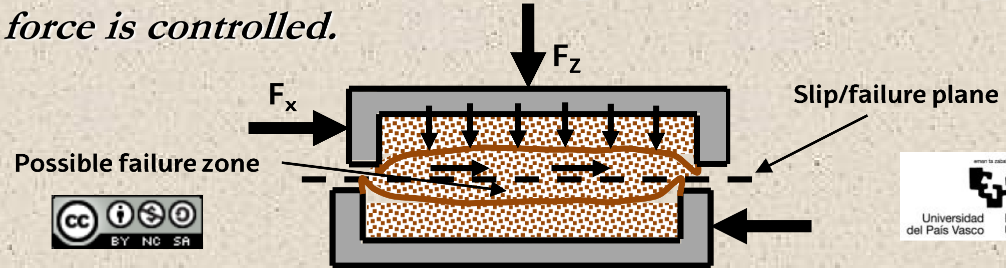
❶ Apply a normal compressive load.

❷ Move a half of the apparatus laterally by a recorded shearing force.

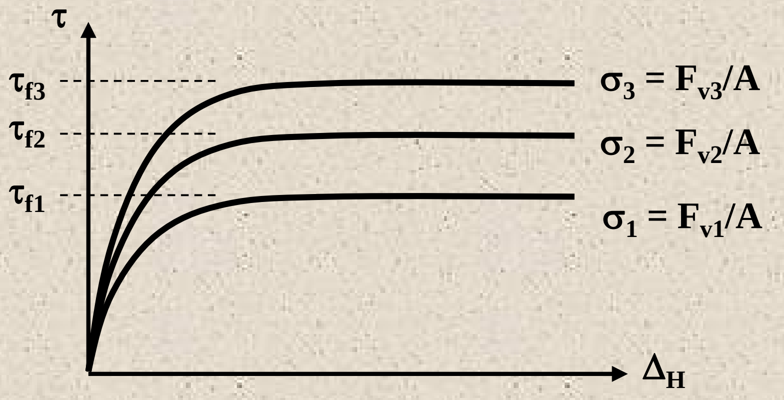
Options:

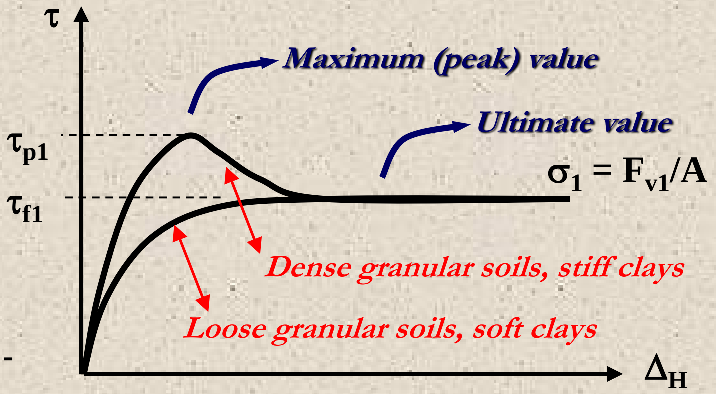
❶ *Strain-controlled test: the shearing deformation occurs at a controlled rate.*

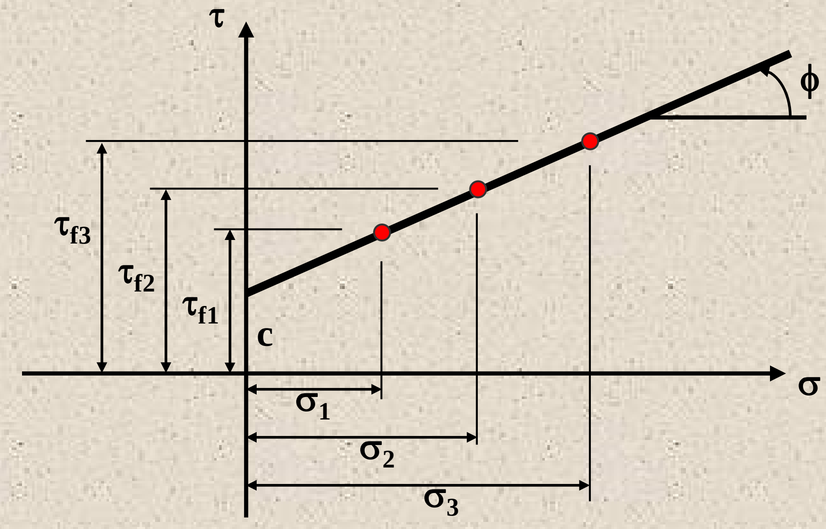
❷ *Stress-controlled test: the magnitude of the shearing force is controlled.*



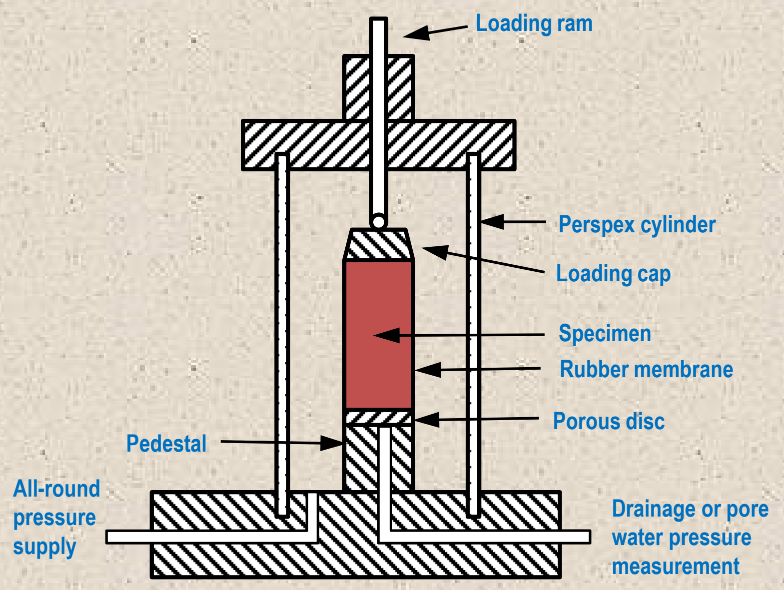
DIRECT SHEAR TEST (III)







TRIAXIAL COMPRESSION TESTS (I) – UNE 103402:1998, ASTM D4767 and ASTM D2850 standards



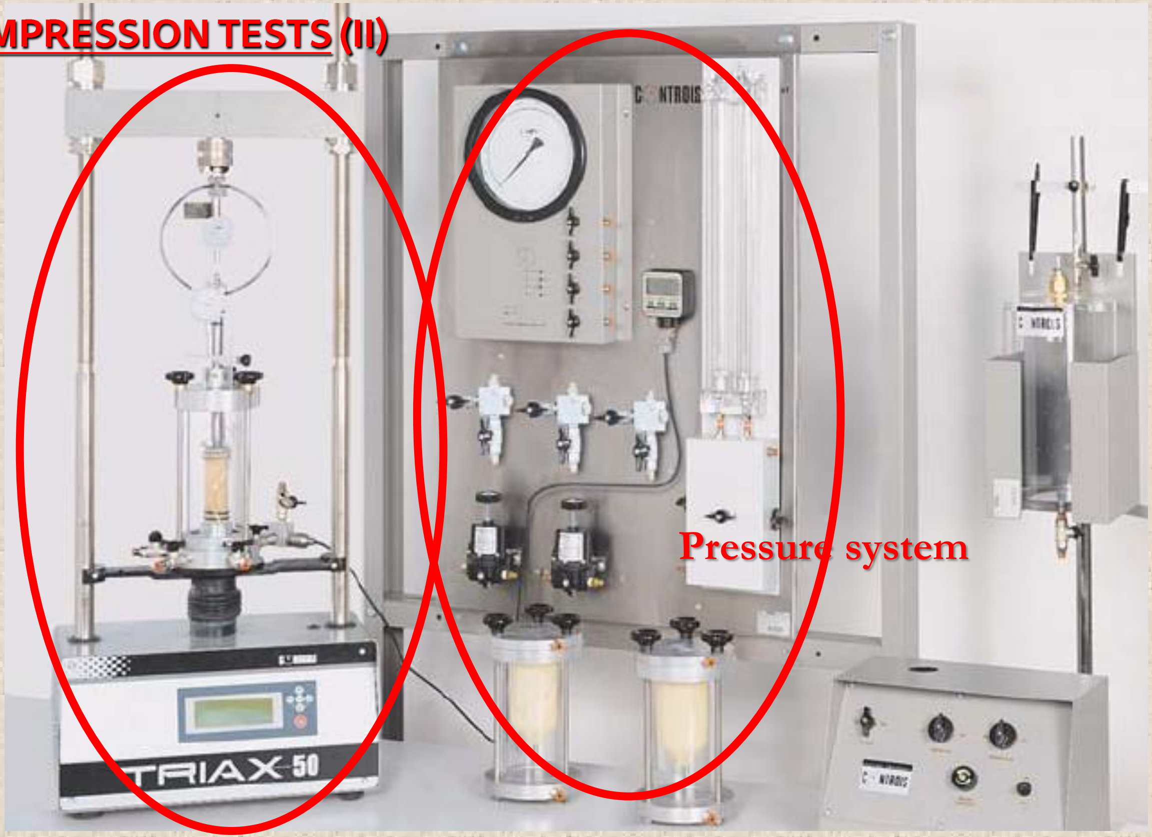
Schematic representation of the triaxial apparatus

Advantages

- ***Loading conditions in triaxial tests simulate more accurately the loading conditions that the soil was (or will be) subjected to in its natural state.***
- ***Failure is not forced to occur across a predetermined plane, as occurs for the direct shear test.***

Video: Triaxial compression tests.

TRIAXIAL COMPRESSION TESTS (II)



Triaxial apparatus

(Image from www.controls-group.com)

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TRIAXIAL COMPRESSION TESTS (III)

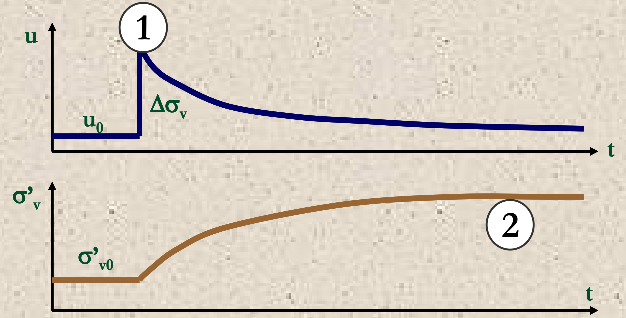
Stage I: Isotropic consolidation phase.

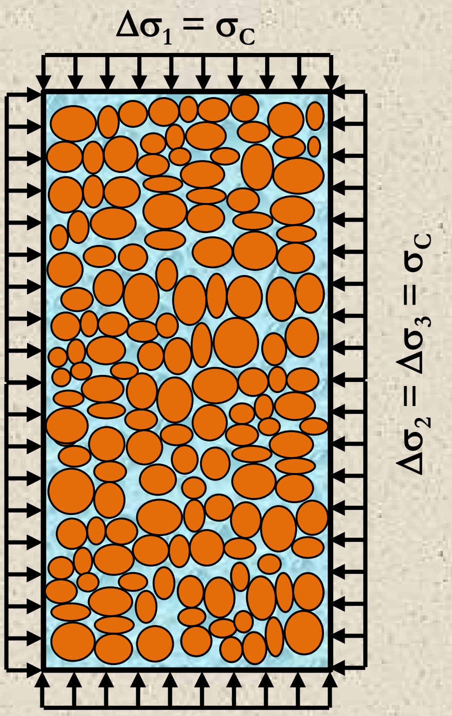
① *A specific and constant all-around pressure is applied.*

- ➔ *Specimen drainage valves are closed. (equalization).*
- ➔ *All-around pressure is completely taken by water.*

② *Drainage valves are opened.*

- ➔ *Until $\Delta u = 0$.*
- ➔ *All -around pressure is completely taken by solid particles, so it is an effective stress.*

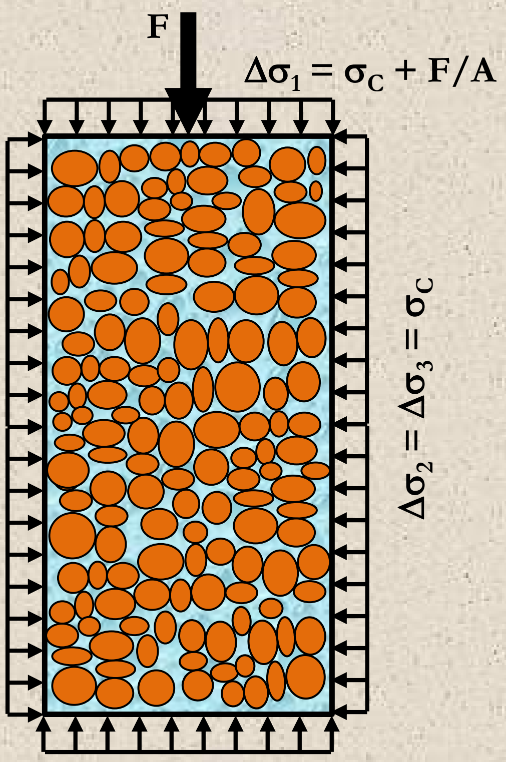




TRIAXIAL COMPRESSION TESTS (IV)

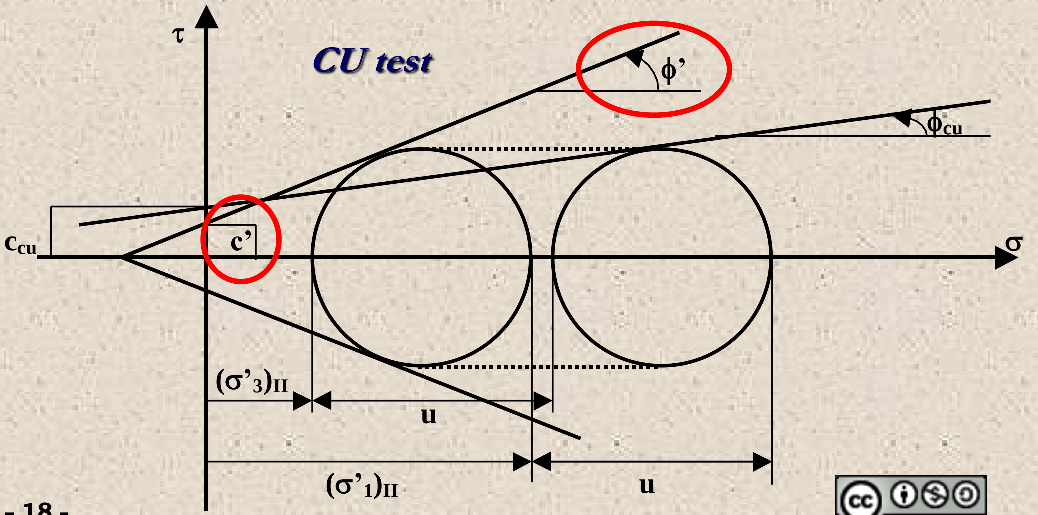
Stage II: Axial loading (shearing) phase.

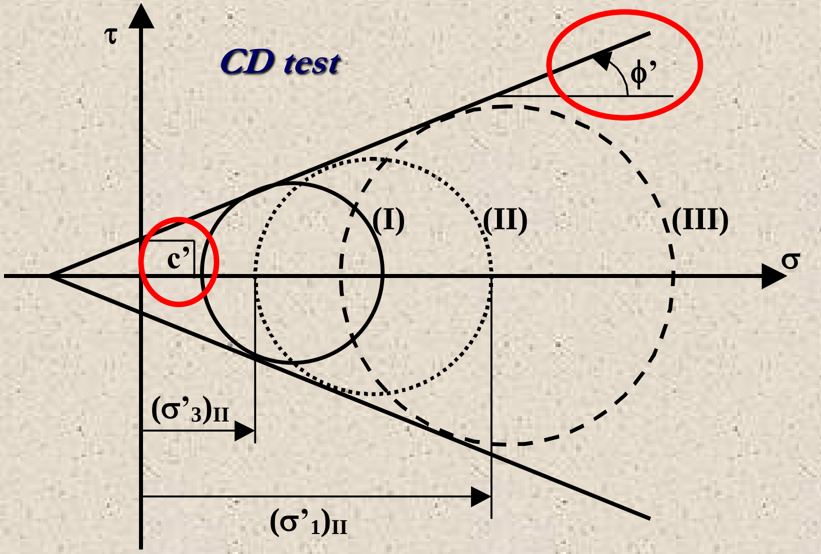
- *A vertical (axial) load F is applied by a piston ...*
  - ➔ *There is not an isotropic stress state.*
- *Option 1: drainage of water is allowed.*
  - ➔ *Until $\Delta u = 0$.*
  - ➔ *All the pressure is taken by solid particles, so it is an effective stress.*
  - ➔ *Consolidated Drained Test (CD).*
- *Option 2: drainage of water is NOT allowed.*
  - ➔ *Pore water pressure (u) is not zero.*
  - ➔ *Pore water pressure (u) can be recorded.*
  - ➔ *Consolidated Undrained Test (CU).*
- *… and steadily increased until the specimen fails.*
- *Principal stresses at failure are obtained.*



TRIAXIAL COMPRESSION TESTS (V)

CD and CU tests provide information about the long-term shear strength parameters (effective stresses)

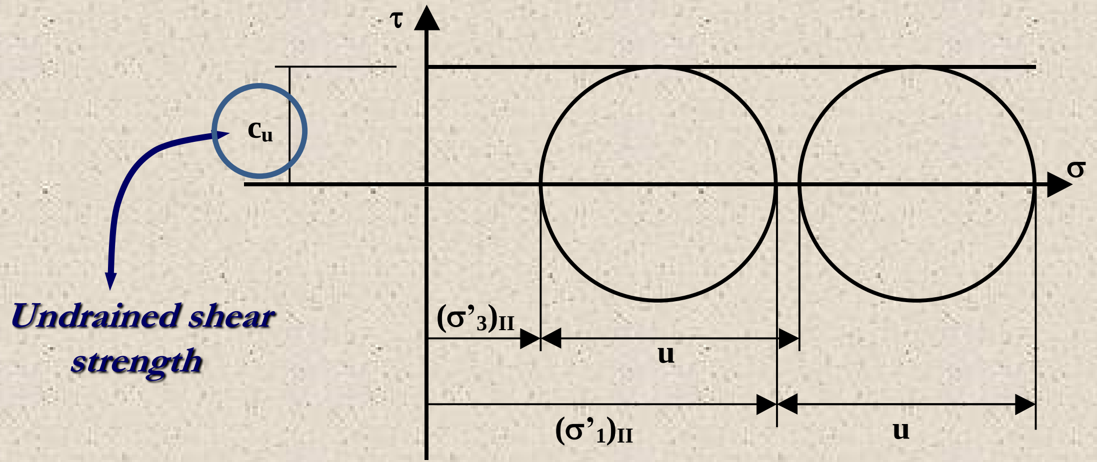




c', effective cohesion
φ', effective friction angle

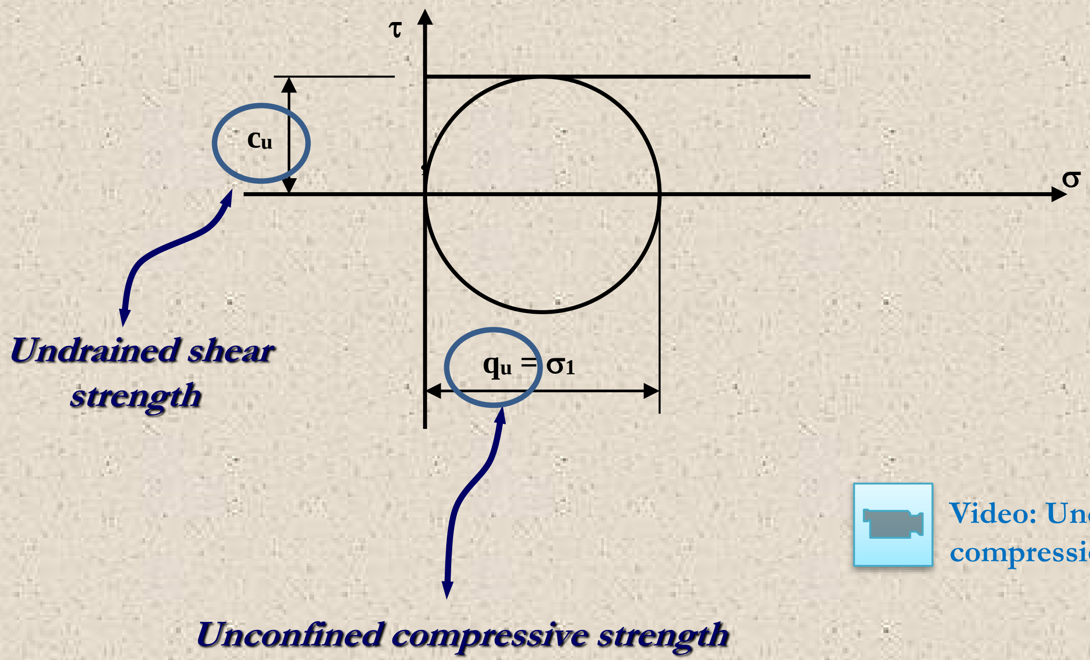
TRIAXIAL COMPRESSION TESTS (VI)

- ***Unconsolidated Undrained Test (UU) – "Quick Test or Q test".***
  - ***Specimen is not allowed to consolidate (1st stage) or drained (2nd stage).***
  - ***It provides information about the short-term or undrained strength parameters.***



UNCONFINED COMPRESSION TEST – UNE 103400:1993 and ASTM D2166

➔ *It is a triaxial compression test (UU) but a type where the all-around confining pressure is zero.*

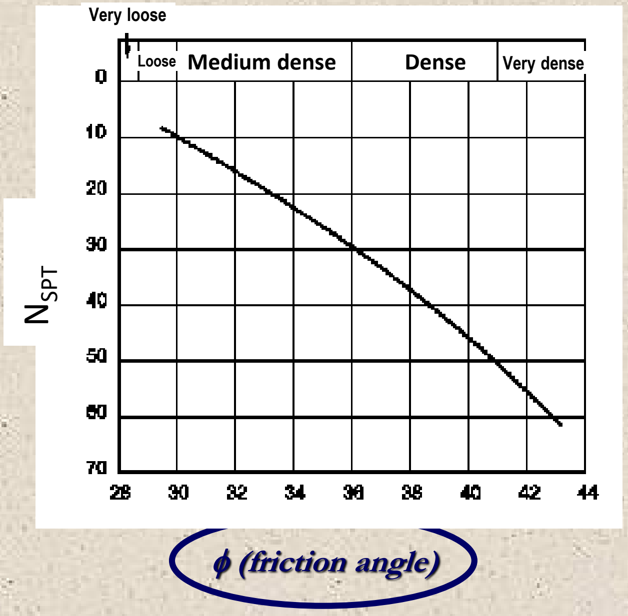


Video: Unconfined compression test.

VALUES OF SHEAR STRENGTH PARAMETERS (I)

	Soil type	Bulk unit weight (kN/m³)	Friction angle
Natural soils	Gravel	19 - 22	34º - 45º
	Sand	17 - 20	30º - 36º
	Silt	17 - 20	25º - 32º
	Clay	15 - 22	16º - 28º
Fill materials	Topsoil	17	25º
	Earthfill	17	30º
	Rockfill	18	40º

Technical Building Code. Foundations.



This chart is valid for granular soils without cohesion when the weight percentage of particles greater than 20 mm is less tan 30 %.

VALUES OF SHEAR STRENGTH PARAMETERS (II)

Clays	
N_{SPT}	q_u (kPa)
2	27
5	55
15	220
25	400

Table D.3 Consistency and strength for clays

Consistency	CI	Unconfined compressive strength (kPa)
Very soft	0 - 0.25	0 - 25
Soft	0.25 - 0.50	25 - 50
Medium	0.50 - 0.75	50 - 100
Stiff (firm)	0.75 - 1	100 - 200
Very stiff	1 - 1.5	200 - 400
Hard	> 1.5	> 400

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VALUES OF SHEAR STRENGTH PARAMETERS (III)

Type of soil	N_{SPT}	q_U (kN/m^2)	E (MN/m^2)
Very loose or very soft	< 10	0 - 80	< 8
Loose or soft	10 - 25	80 - 150	8 - 40
Medium	25 - 50	150 - 300	40 - 100
Dense or hard	50 - Refusal	300 - 500	100 - 500
Soft rocks	Refusal	500 - 5000	500 - 8000
Hard rocks	Refusal	5000 - 40000	8000 - 15000
Very hard rocks	Refusal	> 40000	> 15000

Technical Building Code. Foundations.

Relationship between N_{SPT} y N_{DPSH}

$$N_{SPT} = 1.5 \cdot N_{DPSH}$$

Old and simple expression. It is used extensively. These are better.

$$N_{SPT} = \frac{25 \cdot \log(1.22 \cdot N_{DPSH}) - 15.16}{1.27}$$

Sandy soils

$$N_{SPT} = (13 \cdot \log N_{DPSH}) - 2$$

Clayey soils