Undrained and Drained Shear Strength

Lecture No. 11

October 22, 2002

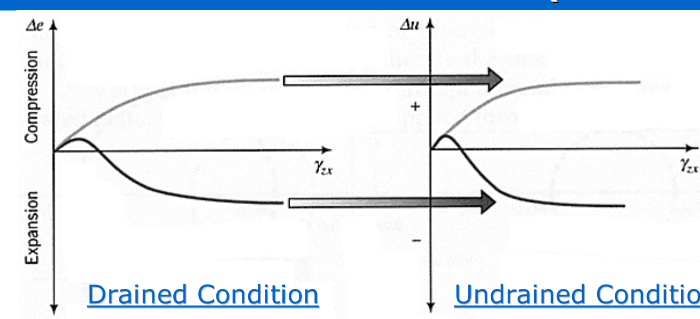
Drained and Undrained Conditions

- **Drained condition** occurs when there is no change in pore water pressure due to external loading.
- In a drained condition, the pore water can drain out of the soil easily, causing volumetric strains in the soil.
- **Undrained condition** occurs when the pore water is unable to drain out of the soil.
- In an undrained condition, the rate of loading is much quicker than the rate at which the pore water is able to drain out of the soil.
- As a result, most of the external loading is taken by the pore water, resulting in an increase in the pore water pressure.
- The tendency of soil to change volume is suppressed during undrained loading.

Drained and Undrained Conditions (Continued..)

- The existence of either a drained or an undrained condition in a soil depends on:
  - The soil type (e.g. fine-grained or coarse-grained)
  - Geological formation (fissures, sand layers in clays, etc.)
  - Rate of loading
- For a rate of loading associated with a normal construction activity, saturated coarse-grained soils (e.g. sands and gravels) experience drained conditions and saturated fine-grained soils (e.g. silts and clays) experience undrained conditions.
- If the rate of loading is fast enough (e.g. during an earthquake), even coarse-grained soils can experience undrained loading, often resulting in liquefaction.

Drained and Undrained Conditions (Continued..)

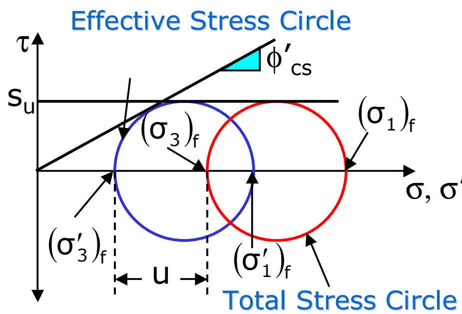


- A soil with a tendency to **compress** during drained loading will exhibit an **increase in pore water pressure** during undrained loading, resulting in a decrease in effective stress.
- A soil with a tendency to expand or **dilate** during drained loading will exhibit a **decrease in pore water pressure** during undrained loading, resulting in an increase in effective stress.

Undrained Shear Strength

- The shear strength of a **fine-grained** soil under **undrained condition** is called the **undrained shear strength** and is denoted by $\mathbf{s_u}$.
- $\mathbf{s_u}$ is the radius of the Mohr's Circle of Total Stress:

$$s_u = \frac{(\sigma_1)_f - (\sigma_3)_f}{2} = \frac{(\sigma'_1)_f - (\sigma'_3)_f}{2}$$

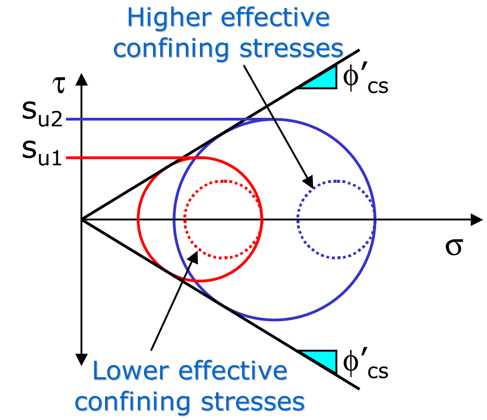


- The undrained shear strength depends only on the **initial void ratio** or the **initial water content** of the soil.

[Note that the horizontal tangent to the two circles is NOT a failure envelope.]

Undrained Shear Strength (Continued..)

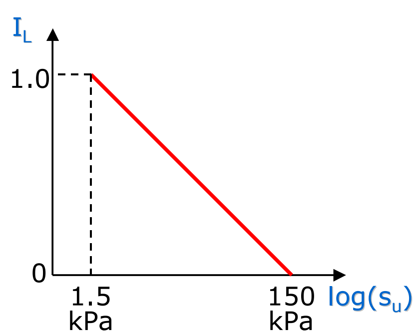
- Unlike the critical state angle of friction, the undrained shear strength is **not** a fundamental soil parameter.
- Its value depends on the values of the **effective confining stresses**.



- An **increase** in effective confining stresses causes a **decrease** in void ratio and an **increase** in undrained shear strength as shown in the figure above.

Undrained Shear Strength (Continued..)

- The Atterberg limits (Liquid Limit and Plastic Limit) define the range of undrained shear strengths for a fine-grained plastic soil.



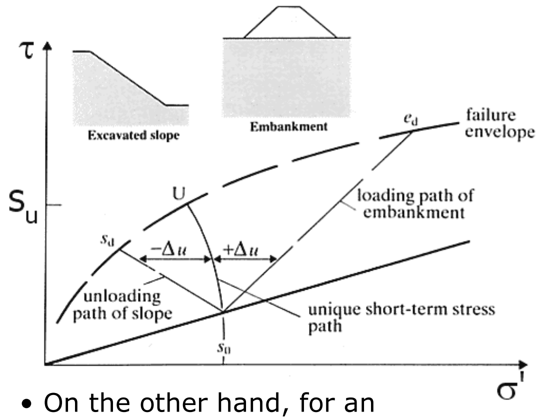
- At its Liquid Limit (i.e. Liquidity Index $I_L = 1$), a clay has s_u approximately equal to 1.5 kPa.
- At its Plastic Limit (i.e. $I_L = 0$), a clay has s_u approximately equal to 150 kPa.
- Therefore, approximate estimate of s_u can be obtained by knowing the water content of the soil.

TSA and ESA

- **TSA** stands for **T**otal **S**tress **A**nalysis.
- A **TSA** uses **undrained shear strength** ($\mathbf{s_u}$) for the analysis of soil strength and soil stability problems.
- **TSA** derives its name from the fact that $\mathbf{s_u}$ value for a fine-grained soil can be obtained using **total stresses** (see description and figure on page 5).
- **ESA** stands for **E**ffective **S**tress **A**nalysis.
- An **ESA** uses **critical state angle of friction** ($\boldsymbol{\phi'_{cs}}$) for the analysis of soil strength and soil stability problems.

Undrained or Drained?

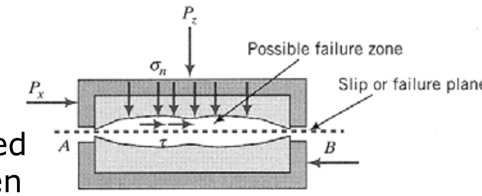
- When designing a geotechnical structure, both undrained and drained conditions must be considered to determine which one is more critical.
- For an excavated slope, the long-term or drained condition is more critical because the drained strength of soil is lower than its undrained strength.

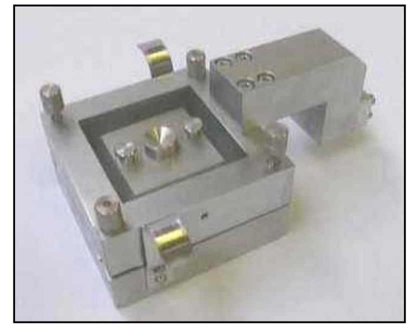


- On the other hand, for an embankment, the short-term or undrained condition is more critical because the undrained strength of soil is lower than its drained strength.

Direct Shear Test

- It involves shearing a soil sample along a horizontal slip plane.
- Vertical force is applied through a metal platen resting on top of the soil sample.
- Horizontal force is applied using a motor for displacement control or by weights through a pulley for load control.



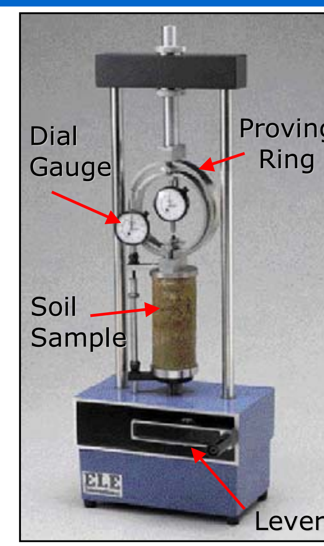


Direct Shear Test (Continued..)

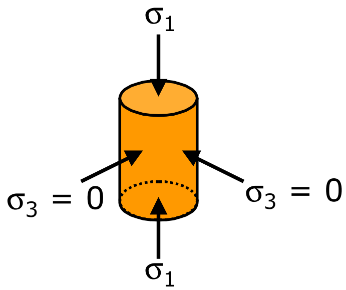
- Most direct shear tests are conducted using displacement control because it facilitates measurement of both the peak and the critical shear stresses.
- When load control is used, it is not possible to obtain data beyond the peak shear stress.
- In a displacement control test, the load is measured using a load cell or a proving ring.
- The horizontal and vertical displacements of the top half of the shear box are recorded using dial gauges to obtain shear and volumetric strains.
- Due to poor drainage control, a direct shear test is not used for obtaining undrained shear strength.

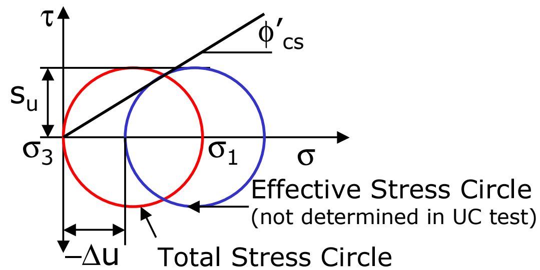
Unconfined Compression Test

- This test subjects the soil to an axial compressive load between two platens as shown in the picture.
- There is no confinement of the sample in the radial direction.
- The load is recorded using a proving ring or a load cell and the axial deformation of the soil sample is recorded using a dial gauge.
- Loading is applied manually by turning a lever.



Unconfined Compression Test (Continued..)



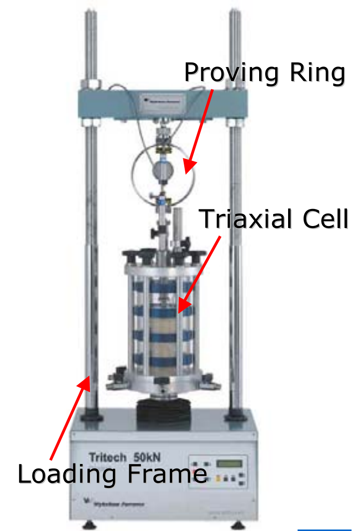


- Since there is no arrangement to control drainage, the soil sample is sheared at a fast rate to ensure undrained condition.
- Undrained shear strength of the soil sample is given by:

$$s_u = \frac{1}{2}\sigma_1$$

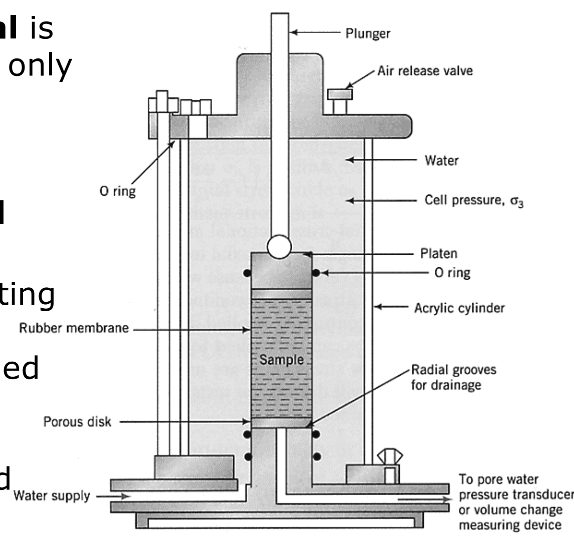
Conventional Triaxial Test

- A conventional triaxial test is widely used for obtaining shear strength parameters for a variety of soil types.
- A typical triaxial apparatus is shown in the picture.
- The essential components are:
  - A Reaction Loading Frame
  - A Triaxial Cell for the application of confining pressure
  - A load measurement device (e.g. a proving ring)
  - Deformation measurement devices



Conventional Triaxial Test (Continued..)

- The name **Triaxial** is a misnomer since only **two**, not three, **stresses** can be controlled – **axial stress** and **radial stress**.
- It involves subjecting a cylindrical soil sample to controlled increases in axial stresses or axial displacements and radial stresses.



Conventional Triaxial Test (Continued..)

- The soil sample is laterally confined by a membrane and radial stresses are applied by pressurizing water in the triaxial cell.
- The axial stresses are applied by loading a plunger.
- If axial stress (σ_1) is **greater than** radial stress (σ_3), the sample is compressed vertically and the test is called a **Triaxial Compression Test**.
- If axial stress (σ_1) is **less than** radial stress (σ_3), the sample is compressed radially and the test is called a **Triaxial Extension Test**.
- The flow of water in and out of the soil sample can be controlled accurately and therefore, it is possible to do both undrained and drained tests.

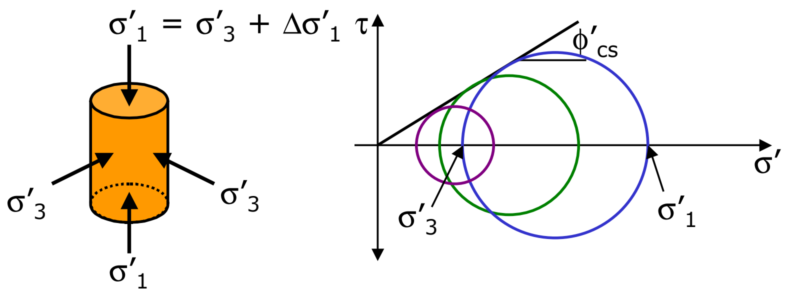
Conventional Triaxial Test (Continued..)

- It is also possible to measure the pore water pressure in the soil sample due to an increase in axial or radial stresses.
- Therefore, it is possible to calculate the effective stresses in the soil sample.
- Depending on the drainage conditions, a triaxial compression test can be of two types:
  - Consolidated Drained (CD) Test
  - Consolidated Undrained (CU) Test
- Both the **CD** and the **CU** tests subject the soil sample to initial **consolidation** to bring the effective stresses within the soil sample close to the field value.

Consolidated Drained (CD) Test

- The purpose of a CD test is to obtain drained shear strength parameter (ϕ'_{cs}) for the analysis of long-term or drained loading of a soil mass.
- The effective Young's modulus **E'** and shear modulus **G** can also be obtained from a CD test.
- Since the soil is **drained** for the entire duration of the test, there is **no change** in the pore pressure value.
- Therefore, according to the **Effective Stress Principle**, the change in **total** stress is **equal to** change in **effective** stress.
- Hence, the analysis of CD test results is done on the basis of **effective** stresses.

Consolidated Drained Test (Continued..)



- Usually, three or more soil samples are tested at different values of effective confining stress σ'_3.
- Mohr's circle of stress can be drawn for each of these tests – the **larger** the value of σ'_3, the **larger** the diameter of the circle.
- The **common tangent** to all the circles **passing through origin** is the Coulomb's failure line and its inclination with respect to σ'-axis is the critical state angle of friction ϕ'_{cs} for soil

CD Triaxial Test – An Example

- The results of three CD triaxial tests on a soil at failure are given in the table below. Estimate the ϕ'_{cs} value for the soil.

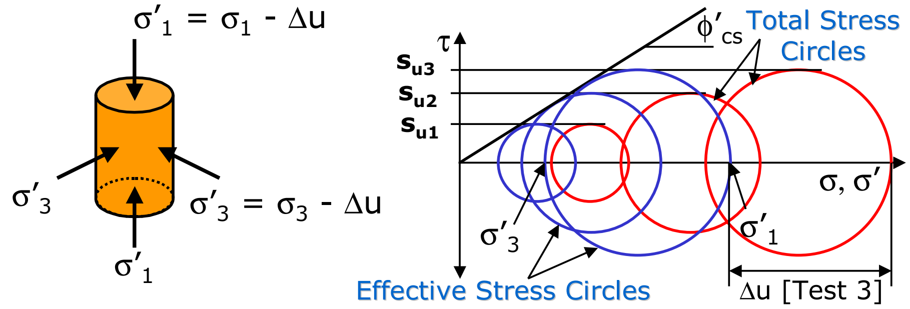
Test No.	σ'_3 (kPa)	σ'_1 at failure (kPa)
1	100	305
2	150	442
3	200	593

[This example will be solved in the class.]

Consolidated Undrained Test

- Both **undrained** (**s_u**) and **drained** (**ϕ'_{cs}**) parameters can be obtained from a consolidated undrained (CU) test.
- A CU test is conducted in a similar manner as a CD test except that at the end of initial consolidation, the axial load or displacement is increased under undrained condition and the excess pore water pressure is measured.
- Plotting of Mohr's circle of stress can be done using **total stresses** if only **s_u** values are required.
- If **ϕ'_{cs}** value for the soil is required in addition to **s_u** values, the Mohr's circle of stress must be plotted using **effective stresses**.

Consolidated Undrained Test (Continued..)



- Mohr's circle of stress in terms of effective stresses can only be plotted if pore water pressure is measured during a test.
- The excess pore water pressure is the horizontal offset between Mohr's circles of effective stress and total stress.

CU Triaxial Test – An Example

- A CU triaxial test was conducted on a saturated soil by isotropically consolidating the soil sample using a cell pressure of **150 kPa** and then incrementally applying load on the plunger while keeping the cell pressure constant. Failure was observed when the stress exerted by the plunger was **160 kPa** and the pore water pressure recorded was **54 kPa**. Determine (a) **s_u** and (b) **ϕ'_{cs}** of the soil by plotting Mohr's circles for total and effective stresses.

[This example will be solved in the class.]