CIV E 353 - Geotechnical Engineering I
Shear Strength of Soils (Triaxial Test)

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(To be read in conjunction with the video)

Required reading Das 2006 Sections 11.1 to 11.3, and 11.8 to 11.12 (pages 374 to 378 and 389 to 409).

Introduction - Purpose

This presentation describes the triaxial test and related equipment. The following geotechnical problems illustrate the application of the triaxial test.

Earth dams are used to retain reservoirs of water. The water may be used for the generation of electric power, irrigation, recreation, flood control or municipal water supply. The internal core of an earth dam usually consists of a fine-grained soil such as clay. The core minimises the quantity of water that seeps through the dam. The outer shells of the dam provide stability and usually consist of sand, gravel and rock fill. The upstream and downstream slopes of the dam are determined by stability analyses, which make use of the shear strength of each dam material. The strength characteristics are usually determined with the triaxial test.

There is often the impression that quicksand is a special type of sand. This is untrue. Rather, quicksand is a condition that is caused by the upward flow of water. As water flows upwards, it decreases the forces that act between soil grains. If the upward gradient is large, it can cause a quick condition, or in other words, the effective stresses within the sand mass approach zero and the sand is not capable of supporting any load. This phenomenon is illustrated using the model where a toy truck is seen to sink into the sand when a quick condition occurs. Earthquakes impose cyclic loading. In a saturated loose sand mass, such loading causes a gradual build-up of pore pressure. If this cumulative build-up of pore pressures is large, the effective stresses may approach zero, and a phenomenon known as liquefaction can occur. Liquefaction is similar to a quick condition in that the soil mass provides very little resistance to load. The photo illustrates the destruction caused by the 1964 Alaska earthquake. Contractive behaviour and the consequent pore pressure build up can be studied in the triaxial test.

The photo showing the leaning Tower of Pisa is a successful failure because it has attracted tourists from all over the world. The lean in the tower is caused by large uneven settlements. In the extreme case, failure occurs by bearing capacity. Stress/strain behaviour can be studied in the triaxial test.

These examples show us the importance of understanding the strength and deformation characteristics of soils. The loadings associated with these examples, and the corresponding stress history can be simulated in the triaxial test.

<u>Equipment Description</u>

The major components of the triaxial equipment are the Triaxial Cell, the Universal Testing Machine, and the Pressure Control Panel.

The first major component is the <u>Triaxial Cell</u> that is usually transparent so that the sample can be viewed during the test. The cell has three port connections to the exterior and each port is controlled with a valve.

One port is used to fill the cell with water and to apply an all-round confining pressure to the sample, which is jacketed with a thin rubber membrane. The other two ports are connected to the top and the bottom of the sample; these are used for drainage, backpressure application or pore pressure measurement.

NOTE: Water may go into or out of the sample depending whether the sample tends to dilate or contract. There are situations in nature where no drainage will take place because the rate of loading is much higher than the rate of pore pressure dissipation. To model this case, both top and bottom valves should be kept closed. In this case, pore pressure should be measured to allow calculation of effective stresses. When a sample is allowed to drain, the sample will experience a decrease in volume proportional to the loss of pore water, i.e. an increase in volume gauge readings equates to a decrease in sample volume.

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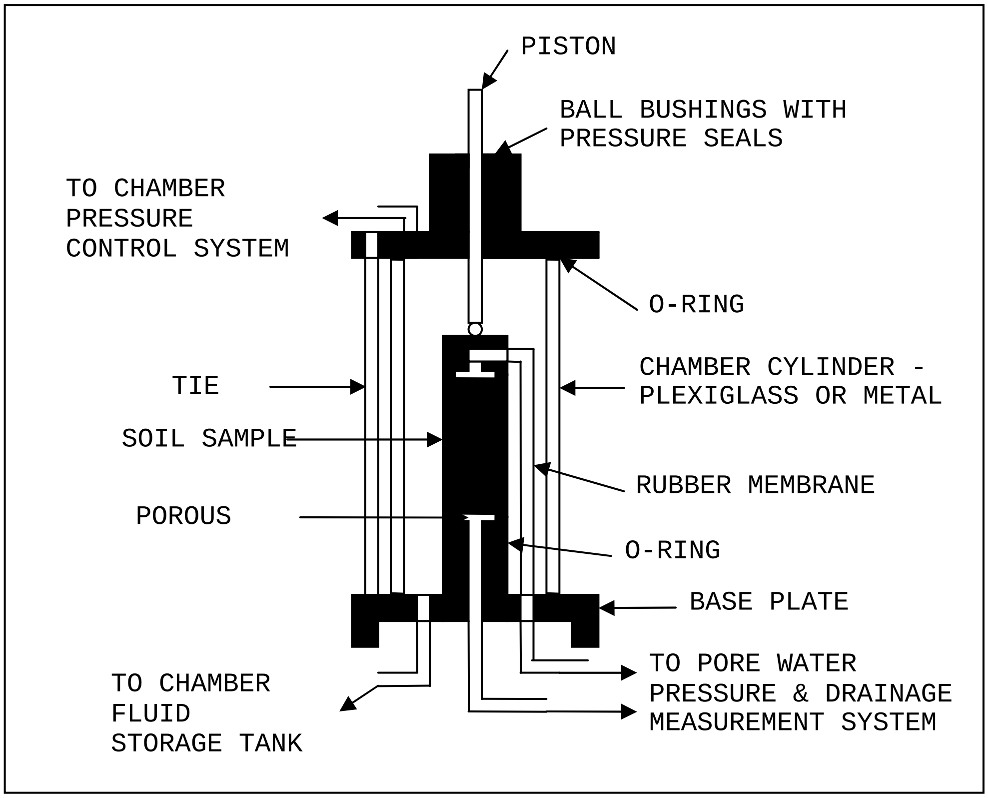

Figure 1: Schematic of a Triaxial Apparatus.

Ports that connect the sample at the top and bottom are useful not only during the performance of the test but also during sample preparation. For example, applying a vacuum to hold sand-samples, or applying a gradient to saturate the soil. This technique allows us to apply pressure to dissolve the air trapped in the void space of the sample, and achieve a full degree of saturation.

The second major component is the Universal Testing Machine that consists of a loading frame and a loading platen. The upper crosshead on the loading frame can be adjusted to accommodate triaxial cells of various sizes. The triaxial cell is placed on a platen which can be moved up or down by either of two hand wheels or by an electric motor. The rate of movement of the platen can be changed and controlled by using different combinations of gears.

As the loading platen is raised, the piston at the top of the cell is forced downwards and this action applies an axial load to the top of the sample. The magnitude of the load is determined by taking dial readings on a calibrated proving ring and the axial deformation of the sample are measured with a second dial gauge.

The third major component is the Pressure Control Panel. The panel is connected to a water supply system and to a pressure system. Each of the three vertical sections on the right hand side of the panel is connected to a port on the triaxial cell. A three-way valve in the upper left corner is used to select a particular port. The pressure to each port is regulated through a regulator that is located at the top of the panel and the pressure is monitored or controlled with a digital display.

Another three-way valve (located immediately below the regulator) allows three options: to open the port to atmospheric pressure, to apply a vacuum or to apply a pressure. A device consisting of an annular pipette is located below the three-way valve. The pipette is used to measure volume changes that occur in the sample during drained tests.

The two-way valve immediately below is used to select large or small volume changes. Along the same serial line of valves that control each of the channels we find another three-way valve which permits incorporating water into the line, or venting it to the atmosphere without going through the volume change measurement system. The last valve permits connecting the line coming from the cell to the panel. The quick-disconnect fitting at the bottom of the panel attaches the tubing to the triaxial cell ports.

The panel is equipped with another three-way valve in each section so that the volume-change measuring device can be bypassed. Connections between the panel and the triaxial cell are made through quick-disconnect fittings, which are located at the base of the panel. Table 1 shows the four main types of triaxial tests that are commonly performed.

Table 1: Variations on the Triaxial Test

	UNCONSOLIDATED UNDRAINED TEST UU	CONSOLIDATED TESTS		
		CONSOLIDATION PHASE	CU	CD
σ_3	HELD CONSTANT	HELD CONSTANT	HELD CONSTANT	HELD CONSTANT
σ_1	GRADUALLY INCREASED FROM σ_3	EQUAL TO σ_3 *	GRADUALLY INCREASED FROM σ_3	VERY GRADUALLY INCREASED FROM σ_3
u	DRAINAGE LINES CLOSED	DRAINAGE LINES OPEN **	NO WATER PERMITTED TO ESCAPE. PORE PRESSURE MEASURED FOR EFFECTIVE STRESS TESTS	DRAINAGE LINES OPEN

* UNLESS ANISOTROPIC CONSOLIDATION IS TO BE EFFECTED
** IN BACK PRESSUREED TESTS, PRESSURE IS SUPPLIED TO PORE LINES, BUT DRAINAGE IS PERMITTED

In summary, there are three main components: the cell with 3 pressure ports and axial plunger; the control panel which permits applying pressure to the sample as well as monitoring pressure and volume changes in each of the three connections from the cell; and finally the loading frame, which provides a constant rate of advance.

Test Procedure

Because unconfined clay samples retain their shape by negative pore pressure, they can be readily handled and trimmed to a particular size, if appropriate. The sample is placed on top of a porous stone and then enclosed in a thin rubber membrane.

The diameter of the membrane is slightly smaller than the diameter of the sample; therefore, a membrane stretcher is used. This membrane is sealed to the base pedestal and the top cap with rubber O-rings. The membrane isolates the sample from the cell fluid and allows the application of an all-round pressure to the sample.

The membrane is slid over the sample and lower platen. Then an O-ring is used to seal the membrane and secure it in place. The membrane stretcher is removed. The top cap is put in place on the sample and the membrane rolled onto the top cap. With a split ring tube, the O-ring is snapped onto the top cap to seal and secure the membrane.

The preparation of samples using granular materials that do not hold together such as sand, involves a slightly different procedure. First the weight of the sand is obtained. Then a split mould is used to form the sample during preparation. The membrane is already located and secured to the lower platen using the O-ring. The split mould is placed around the membrane and a gear clamp is used to hold the three pieces together. Next, the mould is filled with sand that is introduced using a funnel to achieve a very loose condition.

A densely packed sample can be achieved by roding moist sand. The porous stone and top cap are put in place and the membrane is sealed to the top cap.

Finally, the split mould is dismantled while applying a small vacuum holds the sample. This vacuum is maintained until a cell pressure is applied.

For any particular test, the sample weight, diameter and height are measured and recorded. The height should be measured, at two or more diametrically opposed locations. The diameter is measured at several locations with a vernier calliper, averaged, and corrected for membrane thickness.

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Once these initial measurements are completed, the cell is replaced, bolted, and filled with water. Pressure is applied to the water and the vacuum inside the sample is released.

The test must be conducted following the stress path that closely simulates the stress history of the sample in the field. The most common stress path consists of applying the confining pressure (by means of the control panel) followed by the deviatoric stress. The deviatoric stress is defined as (see Figure 2):

$$\text{deviatoric stress} = \frac{P}{A} = (\sigma_1 - \sigma_3)$$

where:
P is vertical force applied to the sample
A is the cross sectional area of the sample;
σ_1 is the major principle stress (vertical in a triaxial test); and
σ_3 is the minor principle stress (confining stress in a triaxial test).

The dial indicators used for monitoring the force and deformation are zeroed. Valves connecting the top and bottom of the sample are kept open for drained tests or closed for undrained conditions.

In the simplest case, only the dial indicator (for the force) and the dial indicator (for the deformations) are read at predetermined increments.

For more elaborate testing, we must also monitor volumetric changes as indicated on the control panel using the pipettes as well as changes in pore pressures if they are allowed. Remember that soil behaviour is primarily determined by the mean state of confining stress, by deviatoric stress and by the void ratio. Therefore, we must continue to monitor these parameters as the test evolves.

Test samples are usually consolidated prior to the application of an axial load. The consolidation is monitored with the volume-change measuring device. After consolidation is complete, the piston is brought into contact with the top of the sample, the dial gauges are zeroed or read, and the drive gears are adjusted to give the desired rate of loading.

The test ends when failure or deformations exceeding 20% is reached. At completion of the test the specimen is unloaded, the confining pressure is reduced to atmospheric, then the cell dismantled and the sample is removed. Final measurements of weight can be made to verify the saturation of the sample.

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Electronic Monitoring

The triaxial system can be enhanced using electronic instrumentation. Force is measured using a force transducer or load cell. This transducer is located inside the cell to cancel the friction effect.

LVDT (linear voltage differential transducers) are used to monitor the deformations.

Three pressure transducers are mounted at the base of the test cell to monitor the confining pressure and the pore pressure in the sample.

The load cell is an electronic device that correlates the deflection of a beam to the force applied to this axis. This transducer incorporates the use of strain gauges to relate deflection to force.

The LVDT replaces the dial indicator used to measure deformations. It is a transformer made up of two external coils and a central core. The change in position of the core relative to the coils produces a variable voltage change calibrated to a deformation measurement.

The pressure transducer uses a strain gage to measure the strain in a metal diaphragm as a result of pressure acting on it.

The volume measurement device makes use of an LVDT to measure the rise or fall of a piston within the volumetric cylinder. This change in movement is calibrated to the volume of water the sample will take in or push out. The volumetric indicator now used by the university was specifically selected to precisely measure very small flow volumes.

All these transducers can be read with a digital voltmeter. Alternatively, an analog to digital converter can be employed to measure the voltages and use the computer to collect the data.
New software was developed for the University of Waterloo soils lab to monitor the triaxial apparatus in May 2000. The new software is based on a National Instruments LabVIEW platform.

The new data output files no longer look like the ones you will work with. The new software performs all necessary calculations and conversions on the fly. However, the triaxial cell is still and will remain manually controlled, even though the LabVIEW software could control the experiment.

Whereas electronic systems have advantages, they do not give physical meaning to various procedures and measurements. Therefore, hands-on experience with manual devices is preferred for teaching purposes.

Additional Information

The shear strength of a soil is defined by the Mohr Coulomb failure criterion, which related the apparent cohesion (c'), effective angle of internal friction (ϕ') and the effective stress normal to the plane of failure (σ_n'). The parameters c' and ϕ' can be obtained graphically from a Mohr Coulomb (M-C) plot.

Plotting the principle stresses on the σ_n axis, and connecting them with a circle constructs a Mohr circle. The circle represents all of the possible stress shear (σ_n,τ) combinations measured on any plane through the sample.

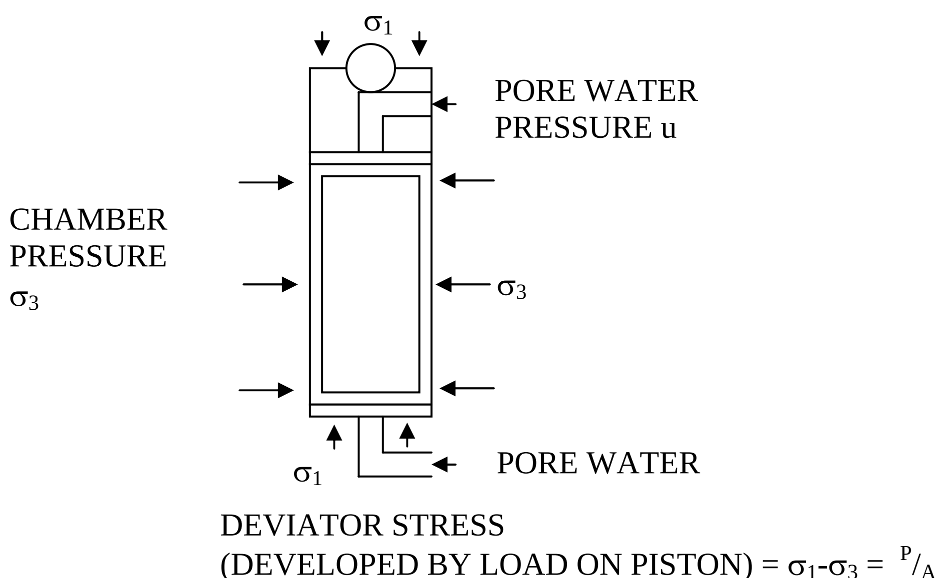

Figure 2: Principle Stress Orientations on a Triaxial Cell

By testing the sample to failure in several stress regimes, several circles can be constructed. The principle stresses are σ_1 (major principle stress), σ_2 (intermediate principle stress), and σ_3 (minor principle stress). The principle plane or no-shear plane is the σ_n axis. In a triaxial test σ_2=σ_3, but this is not always the case so be sure to check. The confining stress in a triaxial cell acts all around the sample so:

$$\sigma_1 = {}^{load}/_{area} + \sigma_3$$

Failure is defined when a stress combination (σ_n, τ) exists above the failure envelope. The failure envelope can be constructed by plotting the failure results from several triaxial tests (σ_f, τ_f). The parameters c' and ϕ' define the envelope. Phi (ϕ) can be determined by calculating the slope of the failure envelope. Phi is the internal angle of friction, or the angle at which grains slide past each other in dilatent behaviour, or break under conditions of grain shearing. Apparent cohesion or c' is the intercept of the failure envelope with the τ axis.

To plot a Mohr circle from triaxial data, obtain σ_1, and σ_3 from the triaxial test and draw a circle connecting the two points centred at $(\sigma_1+\sigma_3)/2$. Repeat for every stress state tested. In a standard triaxial test σ_3 is fixed and σ_1 is gradually increased from σ_3 until failure occurs (a circle intersects the failure envelope). Plotting the results from three or more triaxial tests on the same graph, drawing the circles, and drawing a tangent to the circles constructs the failure envelope. The failure envelope is stress dependent, i.e. if the triaxial tests are performed at significantly different confining stresses the failure envelope will not be a straight line. For analysis a straight line may approximate the failure envelope within a given stress range. For this reason it is important that all triaxial tests be performed in the anticipated field stress range (Figure 5).

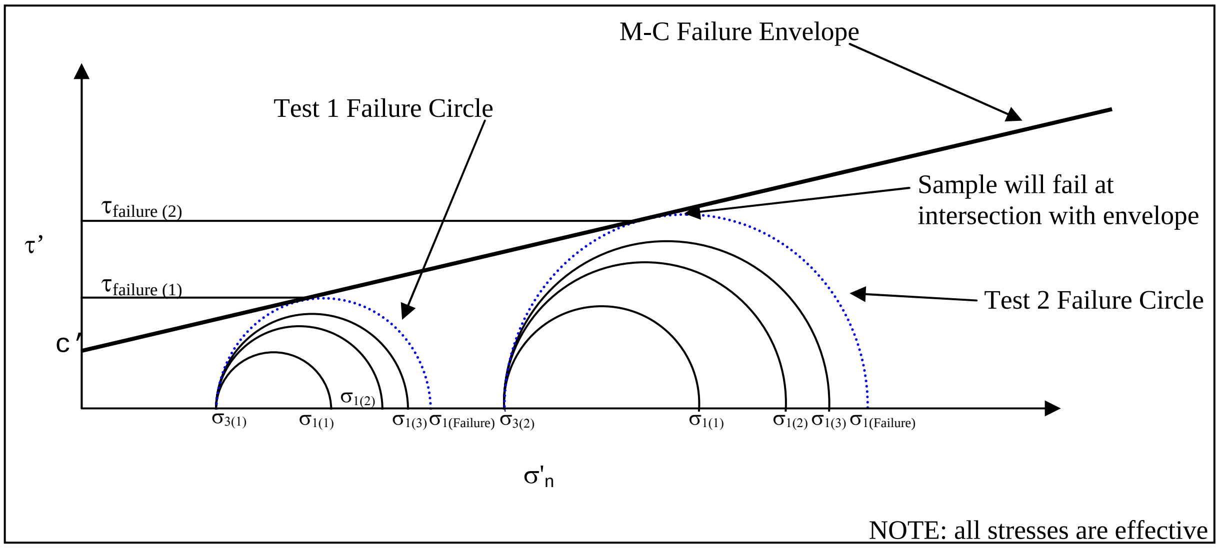

Figure 3: Mohr Circle Construction

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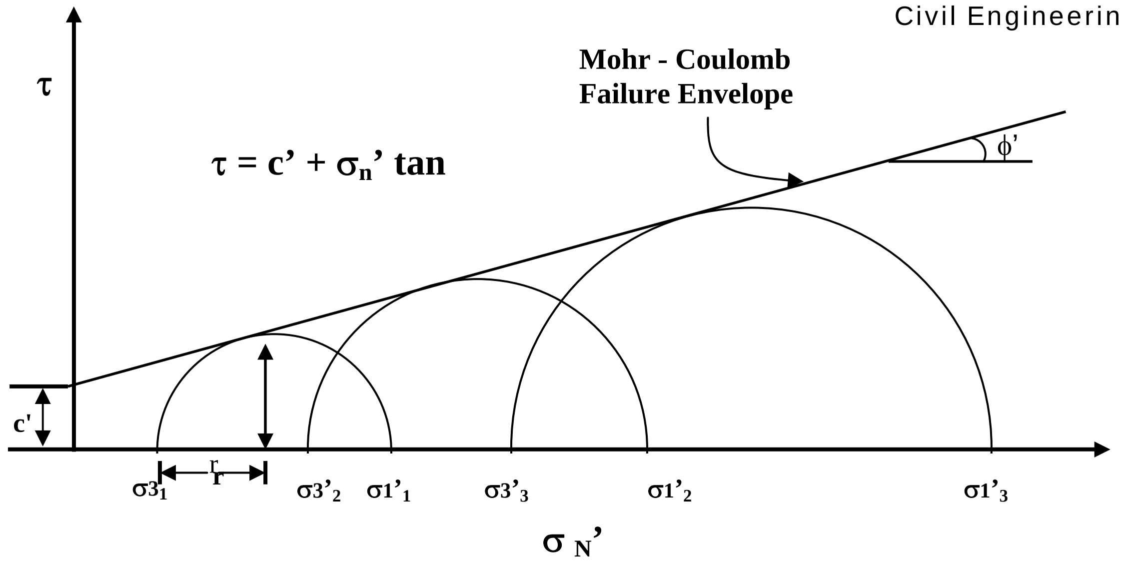

Figure 4: Final Mohr Coulomb Plot

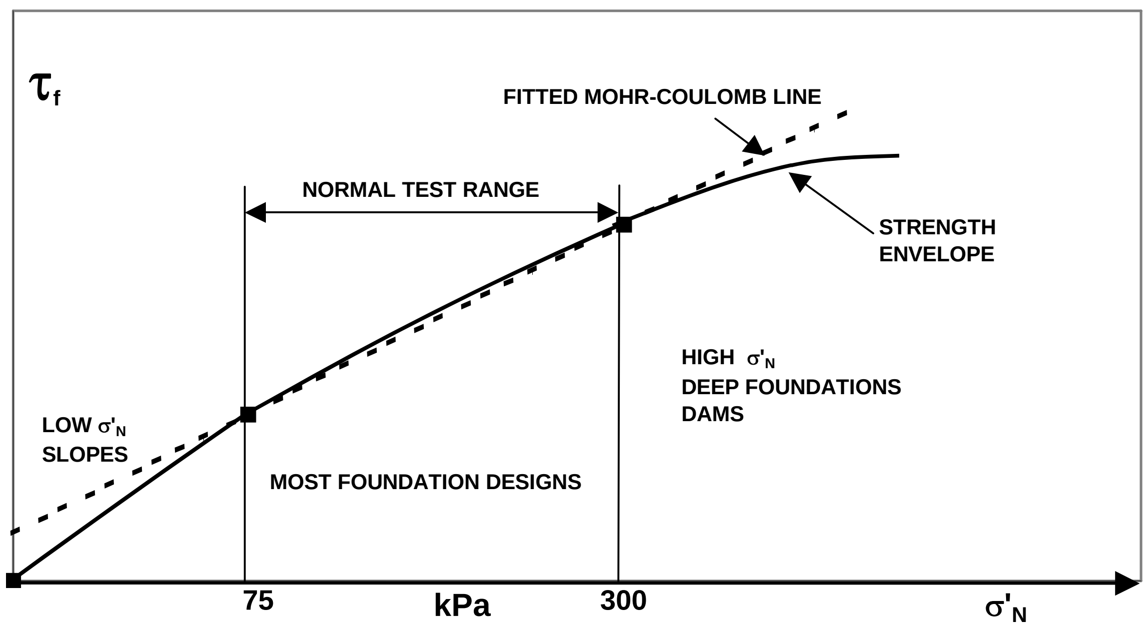

Figure 5: Changes in Strength Envelope with Changes in Stress State

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There are other methods for construction of a failure envelope. A t-s (or p-q depending on the reference) plot can also be developed using the centre and radius of the Mohr circles. The t-s relations can be transformed to convention M-C relations through the equations presented on Figure 6. Traditionally, t-s plots are used to track the stress path of a sample, when conventional M-C plots would be too cluttered. A stress path is a line that connects a series of points, each of which represent a successive stress state experienced by a soil specimen during the progress of a triaxial test.

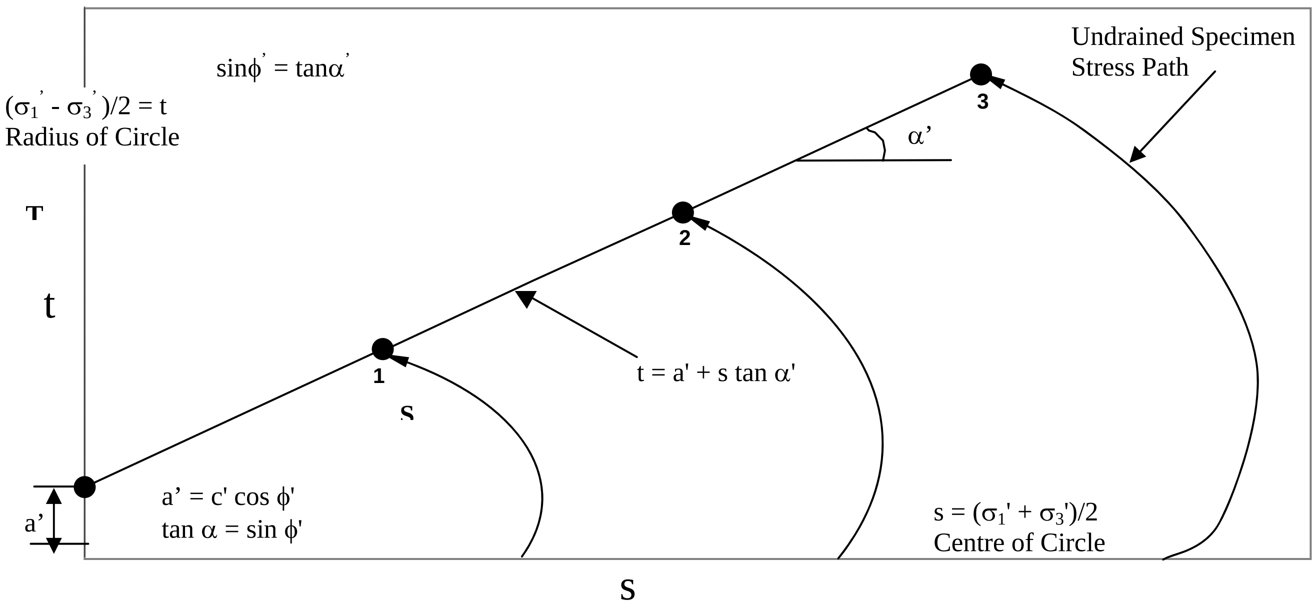

Figure 6: t-s Plot with Stress Paths

Other Parameters

There are two other pore water parameters of interest in a triaxial test, Skempton's *A* and *B* pore water coefficients.

Skempton's A criterion is used to quantify changes in pore pressure resulting from changes in σ_1. The stress on the sample resulting from the change in vertical stress is transferred from the soil skeleton to the pore fluid. When the sample fails the *A* parameter is called the Skempton's pore water coefficient at failure or A_f.

$$A_f = \frac{\Delta \mu_f}{\Delta \sigma_{1(f)}}$$

Note: the value of *A* will usually increase to A_f when loading is increased. Figure 7 shows the relationship of A_f to the over consolidation ratio (OCR) of the soil.

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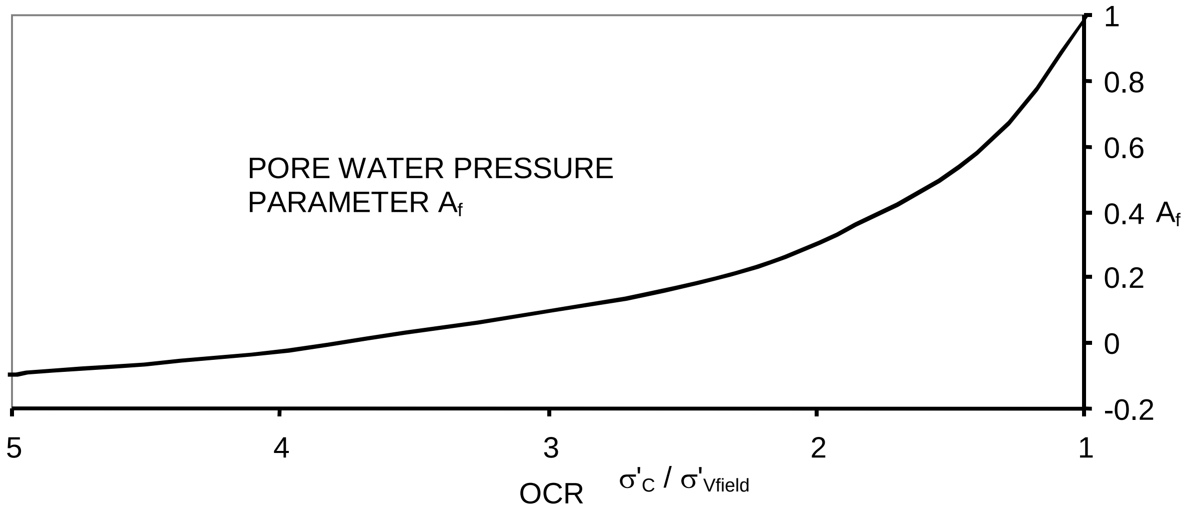

Figure 7: Relation Between A_f and OCR

The Skempton's *B* criterion indicates the degree of sample water saturation. If a sample is 100% saturated and no pore water drainage is allowed to occur an increase in the confining stress (σ_3) on the sample should result in an equivalent change in pore pressure (u). The B pore water coefficient can be expressed in the non-dimensional form:

$$B = \frac{\Delta\mu}{\Delta\sigma_3}$$

For saturated soft soils B is approximately 1. For saturated stiff soils *B* may be less than 1. A triaxial test specimen with a *B* value of 0.95 or greater is usually considered saturated.

Conclusion

The triaxial test is essential to understand soil behaviour. We can measure strength and stiffness, monitor the internal response of the particulate medium, monitor pore pressures as they build, and watch volume changes taking place during the test.

Proper understanding of material behaviour followed by the proper assessment of its characteristics allows the Engineer to improve designs and to reduce the risk of failures.

Selected References

ASTM, D2850 -82.

Bishop, A.W., and Henkel, D.J., 1962, The Measurements of Soil Properties in the Triaxial Test, Edward Arnold Ltd.

Craig, R.F., 1997, Soil Mechanics, Chapman and Hall.

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Triaxial Test

Instructions for Laboratory Report

The consolidated-drained CD triaxial test is a popular test in geotechnical design. Engineers and consultants use parameters derived from this test in the design of foundations, retaining systems, slope stability analyses, etc. Deformation parameters at different levels of strain and confinement are determined from stress-strain plots (σ-ε), and the Coulomb failure envelope is obtained from Mohr circles or from a t-s plot (p-q).

The data set is from four CD (Consolidated Drained) triaxial tests on Winnipeg clay.

Include in your report:

Using the test data available (Civ 353 triaxial test data.xls) in the public directory.

- Plots of σ_1-σ_3 vs. ε_a and $\Delta V/V$ vs. ε_a.
- Plot Mohr Circles at maximum σ_1-σ_3 and compute c′ and ϕ'.
- Plot the t vs s graph (or p-q) and determine a' and α'. (include the stress path)
  - Using a' and α' compute c' and ϕ'
- Compare the values of c′ and ϕ' obtained from the Mohr Circles with the values of c′ and ϕ' obtained from a' and α'. Are these values reasonable?
- Comment on the post-peak behaviour of the Winnipeg clay tested.
- What is the physical meaning of parameters c' and ϕ'?

Note:

$$\varepsilon_v = \frac{V_0 - V_1}{\mathrm{V}_0}$$

where V is the specimen volume and subscripts 0 and 1 represents initial and final specimen volumes respectively. It should be noted that triaxial testing is usually performed in compression ($V_0 > V_1$).

$$\varepsilon_a = \frac{H_0 - H_1}{\mathrm{H}_0}$$

where H is the specimen height and subscripts 0 and 1 represents initial and final specimen height respectively. It should be noted that triaxial testing is usually performed in compression ($H_0 > H_1$).

Triaxial Test Data for Consolidated Drained Compression Tests on Winnipeg Clay

		SAMPLE 1			SAMPLE 2			SAMPLE 3			SAMPLE 4		
σ_3	kg/cm^2		0.25			0.77			1.40			3.00	
Vo	cm^3		80.68			81.15			80.70			77.70	
Ho	cm		8.04			8.01			7.99			7.92	
Ao	cm^2		10.03			10.12			10.10			9.81	
		Load kg.	Axial Deform. mm	Volume Gauge cc	Load kg.	Axial Deform. mm	Volume Gauge cc	Load kg.	Axial Deform. mm	Volume Gauge cc	Load kg.	Axial Deform. mm	Volume Gauge cc
		0	0	2	0	0	2	0	0	2	0	0	2
		1.11	0.037	2.02	0.9	0.01	2.18	0.99	0.04	2.1	1.65	0.079	2.02
		1.57	0.08	2.09	1.79	0.181	2.2	1.68	0.083	2.15	27.2	1.745	3.1
		4.51	0.318	2.19	2.42	0.232	2.29	2.83	0.154	2.13	29.3	1.982	3.11
		5.36	0.369	2.24	5.2	0.475	2.49	7.07	0.485	2.29	33.2	2.602	3.3
		5.52	0.402	2.28	6.01	0.56	2.5	8.35	0.602	2.4	34.9	3.183	3.45
		5.99	0.448	2.29	6.5	0.608	2.57	9.06	0.685	2.5	35	3.68	3.47
		8.27	0.698	2.34	8.04	0.802	2.66	12.53	1.038	2.68	26.4	4.303	3.42
		9.11	0.788	2.37	8.65	0.861	2.69	13.68	1.162	2.72	25.6	4.508	3.4
		9.54	0.838	2.4	8.94	0.906	2.7	14.27	1.248	2.79	22.4	5.242	3.3
		11.38	1.092	2.39	10.56	1.11	2.79	16.82	1.622	2.9	22.1	5.334	3.47
		11.66	1.118	2.4	11.12	1.178	2.82	17.53	1.75	2.98	22.8	5.383	3.57
		11.97	1.16	2.4	11.49	1.228	2.89	17.59	1.763	2.9			
		12.1	1.179	2.4	11.6	2.282	3	17.69	1.781	2.9			
		12.32	1.219	2.41	12.12	2.552	2.99	17.77	1.798	2.93			
		12.34	1.242	2.41	10.34	2.86	2.8	17.92	1.833	2.97			
		12.57	1.521	2.29	9.8	3.032	2.72	19.23	2.217	2.96			
		12.03	1.6	2.23	9.09	3.338	2.62	19.3	2.267	2.97			
		11.33	1.705	2.17	9.06	3.481	2.63	19.34	2.288	2.97			
		5.56	2.959	1.27				19.34	2.302	2.98			
		5.55	2.978	1.26				19.34	2.338	2.9			
								19.33	2.382	2.92			
								19.33	2.448	2.99			
								12.83	4.232	2.68			
								12.78	4.342	2.68			
								12.73	4.437	2.7			

Note: kg/cm^2 *98.07 = kPa

An increase in volume gauge reading means a **DECREASE** in sample volume.

$$A_{corr} = A_O \left[\frac{1 + \frac{\Delta V}{V_O}}{1 + \frac{\Delta H}{H_O}} \right]$$

Caution: Use the correct sign in the Δ!!! + **or -?**