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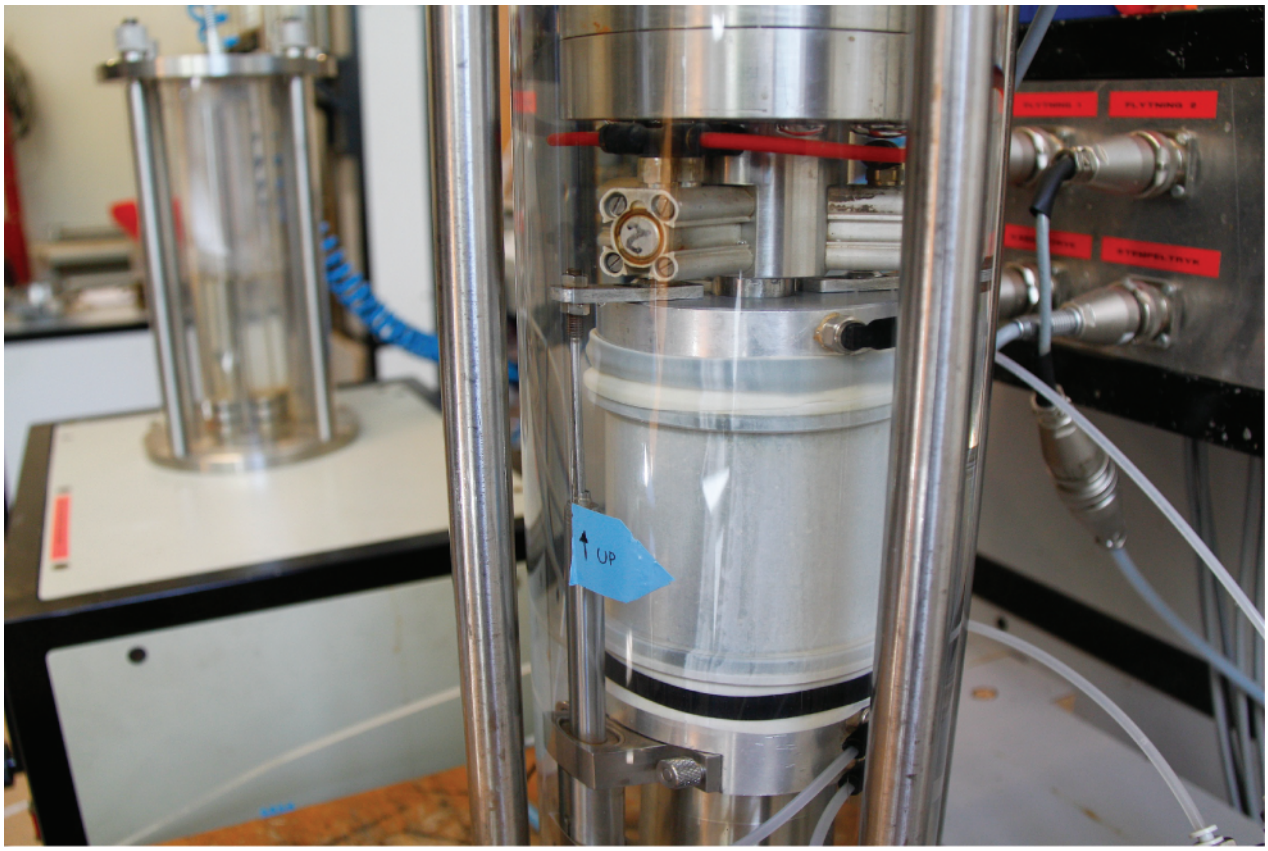

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by

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Contents

PART I

MANUAL

1 Introduction

This manual describes the different steps that is included in the procedure for conducting a cyclic triaxial test at the geotechnical Laboratory at Aalborg University. Furthermore it contains a chapter concerning some of the background theory for the static triaxial tests.

The cyclic/dynamic triaxial cell is overall constructed in the same way as the static triaxial cell at Aalborg University, but with the ability to apply any kind of load sequence to the test sample.

When conducting cyclic triaxial tests, it is recommended that the manual is followed **very** tediously since there are many steps and if they are done improperly or in the wrong order there is a risk of destroying the test sample or obtaining invalid results.

2 Cyclic Triaxial Test Set-up

In this chapter the test set-up and an overall description of how the system works will be described. In Pedersen and Ibsen [2009] a more detailed description of each component can be found.

2.1 Description

The cyclic triaxial apparatus consists of different elements, both electrical and mechanical. Figure 2.1 shows the set-up of the cyclic triaxial test. The *control board*, in Figure 2.1 is only used for sample preparation. It controls the vacuum and the saturation process needed in order to prepare the sample for testing. The purpose of the *backpressure system* is to apply a pressure inside the sample in order to get water out into all the voids and to dissolve any gas. When a CU triaxial test is performed the backpressure system assures that the sample has a constant volume and that no drainage in the sample is allowed. During a CD triaxial test the backpressure system measures the amount of dissipated water and hereby the volumetric changes, which is used when calculating the radial deformations. Furthermore, the backpressure system is used to obtain the desired in-situ effective stresses in the sample.
Notice in Figure 2.1 that the water level in the large outer tube of the backpressure system should be aligned to the middle of the sample height. This is to ensure that there is no geometrical pressure difference added to the backpressure.

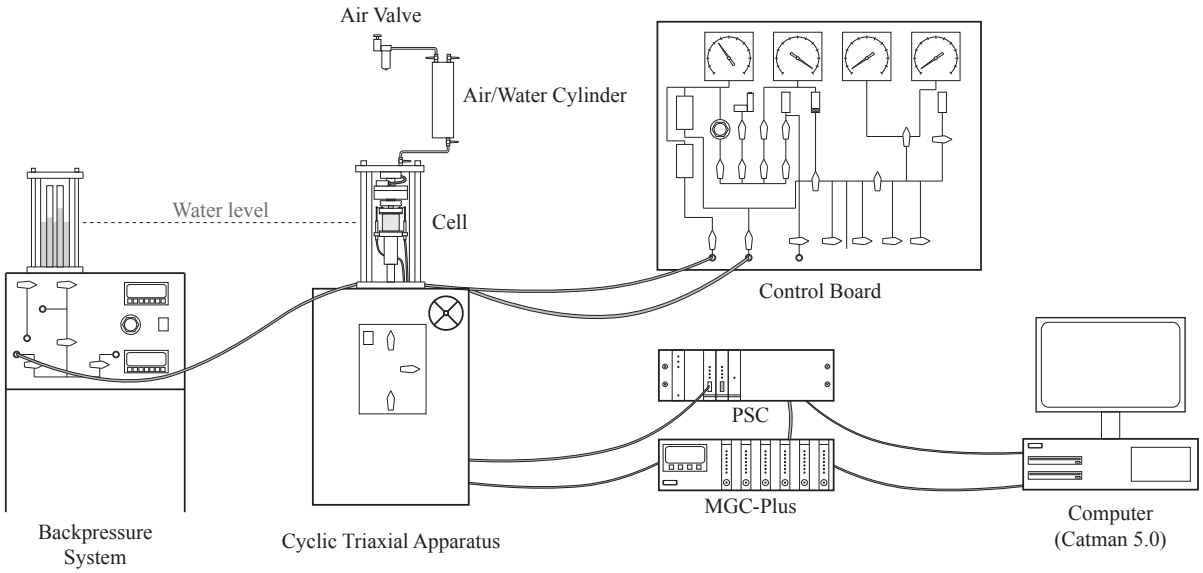

Figure 2.1: Cyclic triaxial test set-up.

The cell is enclosed with a plastic tube, which makes it possible to fill the cell with water. With water in the cell it is possible to increase the cell pressure and thereby the confining pressure on the sample. This is done with the *air valve* and the *air/water cylinder*, which is connected directly to the cell, see Figure 2.1. By opening the air valve, compressed air is let into the air/water cylinder and thereby increasing the pressure in the cell. The air/water cylinder also works as a spring that keeps the cell pressure constant when the piston is moving.

2.2 Cyclic Triaxial Cell

A close-up of the cyclic triaxial cell is shown in Figure 2.2. The cyclic triaxial cell consists of the test specimen and different measuring systems. The measuring systems consists of the *deformation transducers*, the *load cell*, the *pore pressure* and *cell pressure transducers*. The deformation transducers measures the axial deformation of the specimen. The load cell measures the load that the specimen is exposed to. The pore pressure transducer and the cell pressure transducer measures the pore pressure and cell pressure, respectively.

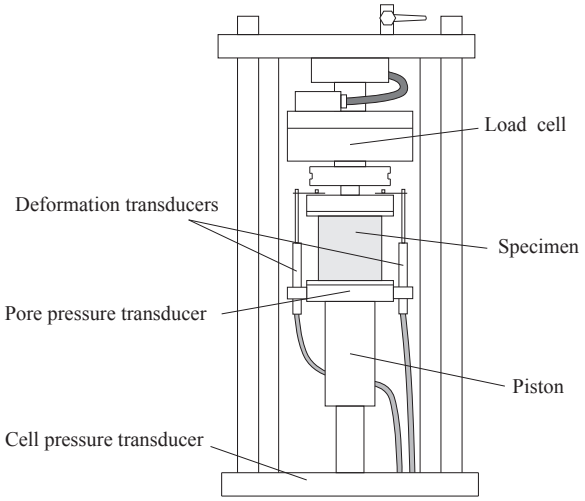

Figure 2.2: *Cyclic triaxial cell.*

When conducting a test a load file is sent from the computer to the *PSC-rack*. The load file consists of a string of numbers which indicate either a value in Newton or a value in millimetres, depending on if the test is conducted as force or deformation[1] controlled. In this way the loading can either be applied static or cyclic dependent on what kind of load path that needs to be simulated.
From the PSC a voltage signal is sent to the piston in the bottom of the cell which then applies a force to the sample. The force is measured in the load cell, which sends a signal to the *MGC-Plus*. From the MGC-Plus a feedback signal is sent to the PSC, and if the feedback signal does not correspond to the signal sent from the computer, adjustments are made automatically so the wanted load is applied.
The measured data is being collected by the MGC-Plus and logged in the computer. Both the MGC-Plus and the PSC are controlled from the computer by the program *Catman 5.0*.

[1] The deformation control does not work properly in the given set-up.

3 Preparing the sample

As mentioned before there are many steps to be executed when conducting a cyclic triaxial test. Overall there are two main points; sample preparation and the actual test execution. The different steps needed in order to prepare the sample for testing are described in the following chapter.

3.1 Boiling the water

Start boiling the water. This is done by filling up the large water container by opening the valves from "TILLØB" up to "VANDBEHANDLING" on the control board, see Figure 3.1. Afterwards vacuum is applied by turning on the vacuum pump on the left side column and opening the valves from "VACUUM PUMPE" up to "VANDBEHANDLING". **Remember to close the valves from "TILLØB" first.** Lastly, the blue button labelled "VANDBEHANDLING" on the left side column is pressed in order to spin the small rod in the bottom of the tube. The water will then start boiling.

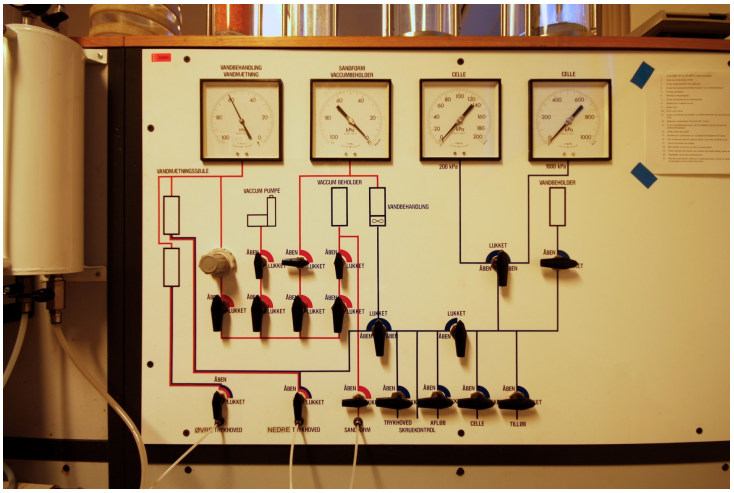

Figure 3.1: Control board for controlling vacuum and saturation of the sample.

3.2 Blowing the cables

All cables from the control board into the triaxial cell are blown with compressed air in order to remove any excess water. Otherwise it will let water into the sample, which foils the saturation process later on. The same operation should be performed on the small valve panel, shown in Figure 3.2, along with the two pressure heads. The compressor must **not** be used on the pressure heads as it applies too much pressure (8 bar). The pore pressure transducer has an upper limit of 7 bar, and may be destroyed when exposed to 8 bar.

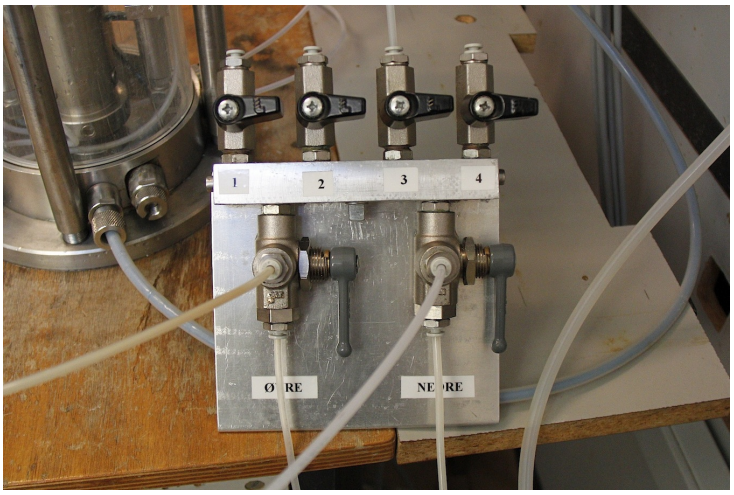

Figure 3.2: Valve panel.

3.3 Cable connection

The cable connections between the control board, the triaxial cell and the backpressure apparatus are as dictated in Table 3.1. It should be noted that the lower pressure head has two valves, the valve nearest the glass plate covering the base of the pressure head is defined as the upper valve. Moreover there is only one cable connection between the cell and the backpressure apparatus when a test is being performed.

Table 3.1: *Cable connections between the control board, the triaxial cell and the backpressure apparatus.*

Cable connection	Controlboard valve	Valve panel valve	Cell valve	Backpressure valve
1	"Øvre trykhoved"	Lower "ØVRE"		
2		Upper "ØVRE"	Upper pressure head	
3	"Nedre trykhoved"	Lower "NEDRE"		
4		Upper "NEDRE"	Lower pressure head lower valve	
5		3	Lower pressure head upper valve	
6		1		Backpressure

3.4 Preparing the pressure heads

Start by mounting the filterstones (Ø 7 mm) into the pressure heads and cut them flush with a knife. Hereafter, rub a decent amount of grease evenly out onto the pressure heads with a finger. Be sure to **not** get any grease on the filterstones. When the grease is evenly distributed over the pressure head it is "dabbed" with a finger in order to make it stick better. Next four rubber membranes are cut into circles with a hole in the center (Ø 8 mm) by using the plastic template. One rubber membrane is placed on top of the greased pressure head. Then a small steel rod is used to squeeze out air bobbles and distributing the grease evenly, see Figure 3.3. Start from the inside near the filterstone and always roll out towards the edge. Then a second coating of grease is applied on top of the first rubber membrane, and lastly the second rubber membrane is applied followed by squeezing out bubbles again. This procedure is done to ensure smooth end plates (see section 8.2) and has to be done on both pressure heads. A finished pressure head can be seen in Figure 3.4.

Figure 3.3: Steel rod squeezes out the air bobbles and distributes the grease evenly.

Figure 3.4: Rubber membrane rings mounted onto the pressure head with grease in between.

3.5 Rubber membrane

A cylindrical rubber membrane is wrapped over the lower pressure head with the two rubber bands mounted to make the fit tight, as shown in Figure 3.5. The membrane should be cut to a length of 15 cm. Next the sand form is mounted onto the lower pressure head. On top of the sand form the small brass ring is mounted and the rubber membrane is pulled over both the ring and the sand form, see Figure 3.6. It should be noted that the rubber membrane should not be stretched to much because this can cause defects in the membrane which foils the saturation process later on. When the rubber membrane is in place the sand form is connected to the control board in order to get vacuum on the sand form by opening the valve "SANDFORM". This ensures that the rubber membrane is smooth and fills out the sand form completely, as shown in Figure 3.7.

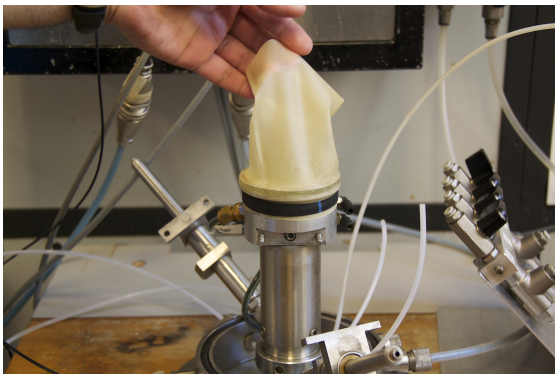

Figure 3.5: Membrane on lower pressure head with the two rubber membranes.

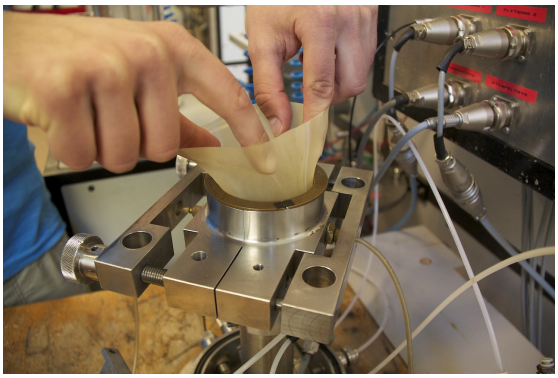

Figure 3.6: Wrapping the membrane over the sand form and brass ring.

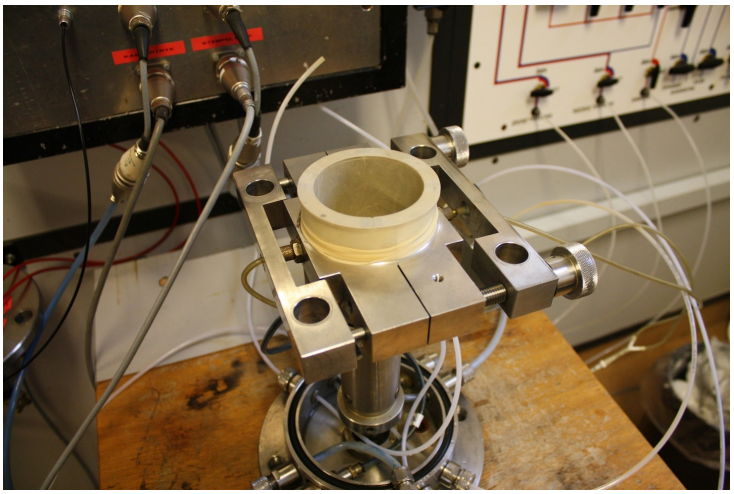

Figure 3.7: Sandform mounted onto the sample with the small brass ring and rubber membrane in place.

3.6 Hydraulic piston

Activate the hydraulic piston by turning the knob to "ON" and pressing the green button on the *circuit breaker panel*, see Figure 3.8. When the piston is turned on it will go all the way to the top position. Therefore MOOG needs to be started so the piston can be moved down (position -900).

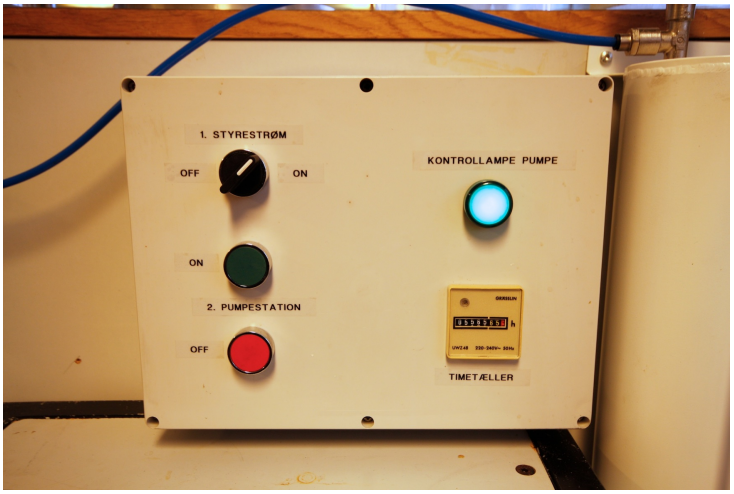

Figure 3.8: Circuit breaker for the hydraulic piston.

3.7 Undercompaction

To get the desired relative density, I_D, of the sample the *sample calculation sheet* is used, which applies the method of undercompaction, see Appendix. This makes it possible to calculate the weight of the individual sand layers needed to get the correct relative density. The sand layers are filled into the sand form one at a time and compacted using the *compaction rod* between each layer, see Figure 3.9. The height and number of blows needed depends on the wanted relative density. However, the number of blows should always be doubled, i.e. 1, 2, 4, 8 or 5, 10, 20, 40 etc.

3.8 Mounting the upper pressure head

When the sand has been compacted the upper pressure head is placed on top of the sand form. Remember to put the small rubber bands loosely onto the pressure head and attach the small tube to the pressure head **before** placing the pressure head on the sand form, see Figure 3.10. Afterwards, suction is applied to the upper pressure head. Then the rubber membrane is wrapped around the upper pressure head and sealed with the two rubber rings. This ensures that there is still vacuum on the specimen. The sand form can now be disassembled along with the small brass ring by closing the valve to "SANDFORM". Remove the sand form first, then remove the small brass ring. Figure 3.11 shows the sample when the sand form has been removed.

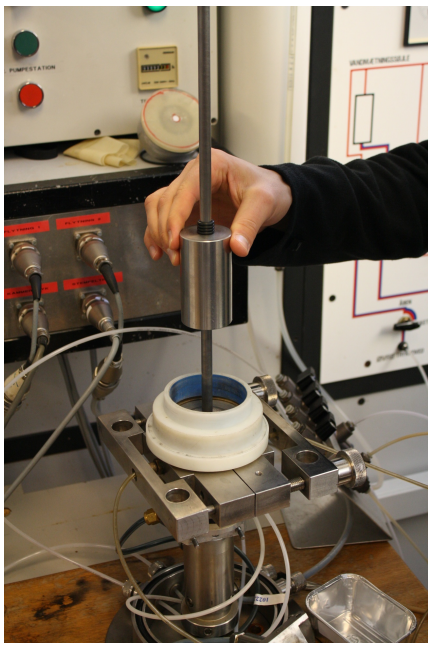

Figure 3.9: Compaction rod used to compact the sand down to the desired relative density, I_D.

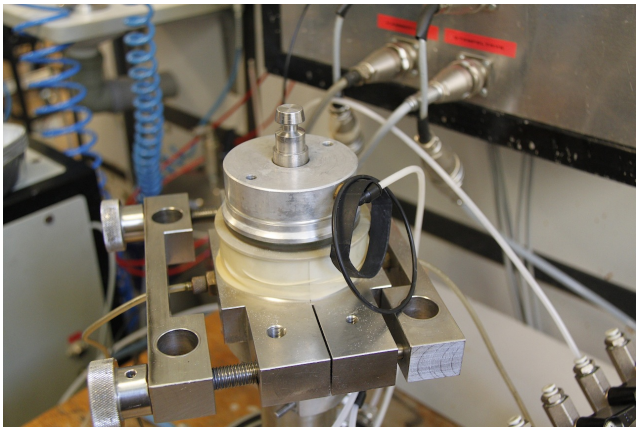

Figure 3.10: Upper pressure head with rubber bands loosely hanging on the side.

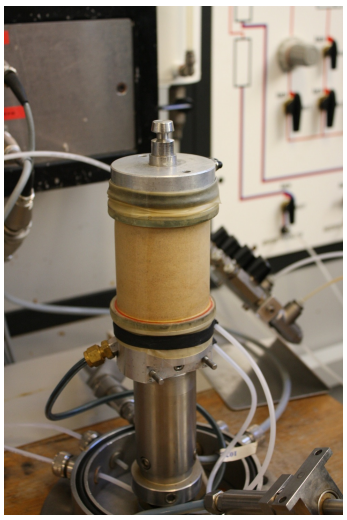

Figure 3.11: Sample when sand form has been removed.

3.9 Mounting the displacement transducers

The displacement transducer are mounted to the sides of the specimen via the small finger screws. On top of the upper pressure head the pins that go into the transducers are mounted via umbraco screws (the short srews) as seen in Figure 3.12. It is a good idea at this point to blow away sand on the table with compressed air. Hereafter the plastic tube is slided onto the entire specimen. Be sure to check that "UP" on the blue sticker is pointing up, see Figure 3.13.

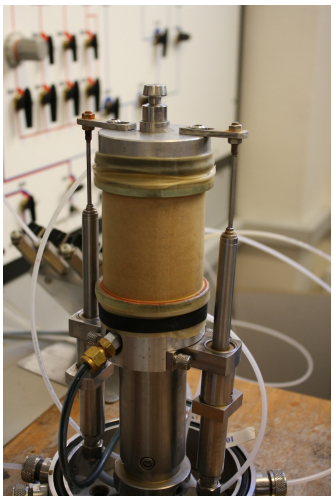

Figure 3.12: Sample with displacement transducers mounted.

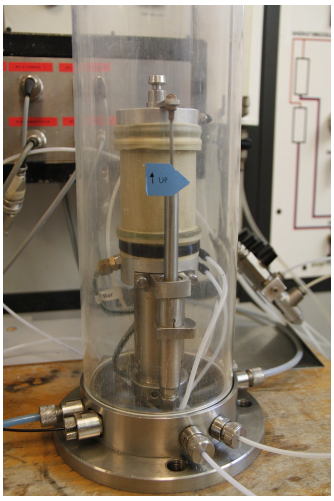

Figure 3.13: Plastic tube mounted with the blue sticker.

3.10 Mounting the load cell

With the piston in the bottom position the load cell is placed on top of the plastic tube. Be sure to align both the plastic tube and the metal ring properly at top and bottom. The locking mechanism in the load cell should be **open**, see Figure 3.14. The locking mechanism consists of three small steel rods that spring into place and holds the sample tight. The mechanism is set to open by opening the valve labelled "Åben" that is connected to the red tubes leading to the load cell. Then the valve below, labelled "Lukket" is closed. Lastly the small brass valve in front of "Lukket" is turned so that the air will escape. Figure 3.15 shows the correct position of the valves.

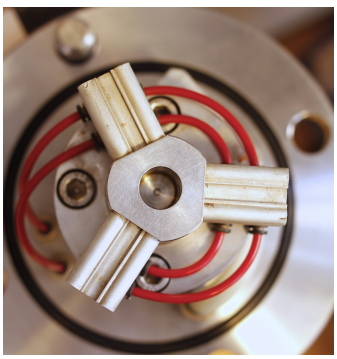

Figure 3.14: Locking mechanism in the load cell set to open.

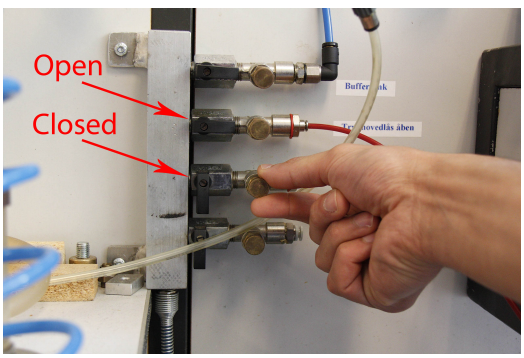

Figure 3.15: Valve position for keeping the locking mechanism open.

Then the steel rods are slided into position and tightened. Remember to "cross-tighten" the rods individually until you cannot even get a finger-nail underneath the rods in the bottom. The final sample is shown in Figure 3.16.

Figure 3.16: Final sample with load cell and plastic tube mounted.

4 Filling the cell with water

When the aforementioned have been conducted, the cell has to be filled with water. Before the filling starts it should be ensured that all cable connections leading to the cell in the bottom are closed and tightened (hard), see Figure 4.1. With over 500 kPa of pressure water will find a way out if they are not tightened hard.

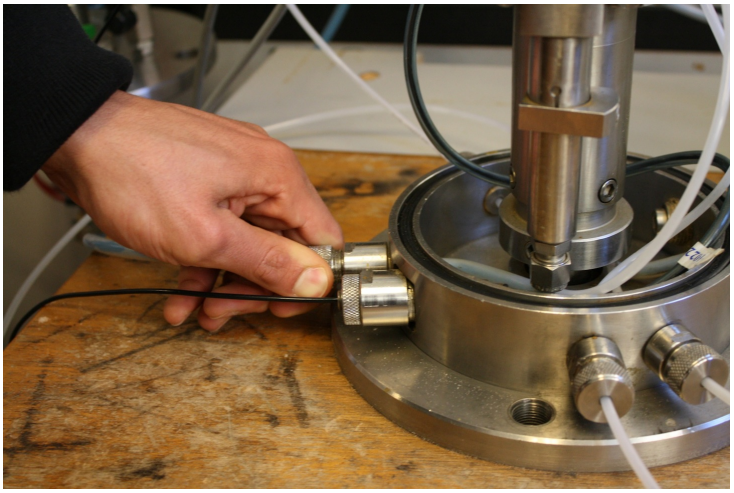

Figure 4.1: Cable connections into the cell. Make sure to tighten them hard.

4.1 Letting water into the cell

Water is let into the cell by turning the valve ”CELLE” on the control board and the valve ”FYLDNING AF CELLE” on the triaxial table control board (see Figure 4.2) to ”ÅBEN”. Be sure to **close the vacuum** for "VAND-BEHANDLING" but still maintaining vacuum for the sample. Also, the black valve on top of the load cell has to be open so the air can get out. The black valve should later be connected to the pressure cylinder.
The cell should be filled half way up (up till the blue sticker) and a reading of the confining pressure should be noted down. This should be the new zero-value for the confining pressure. This is done because the pressure transducer is located in the bottom of the cell and therefore the value it reads is not the same pressure as the sample is subjected to at its higher position.

4.2 Connection of air/water cylinder

Continue filling the cell with water until a few water drops comes out of the black valve on top of the cell. Connect the lower right valve from the air/water cylinder with the black valve on top of the cell and open the lower right valve, see Figure 4.3. Continue the filling of water until the transparent measuring cable on the pressure cylinder is approximately half full. On the air/water cylinder the upper valve should be open during filling the cell with water

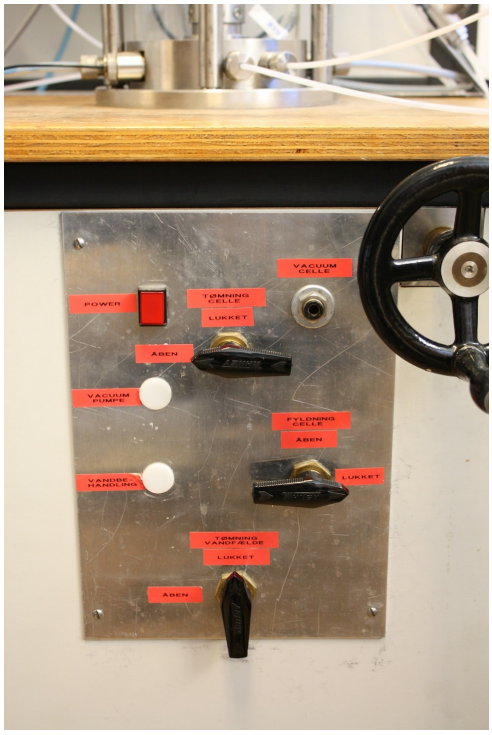

Figure 4.2: Triaxial table control board.

and closed when filling is completed.
The air in the air/water cylinder acts as a spring when the piston is moving, because during movement of the piston the volume of steel inside the cell changes and therefore the amount of water also has to change.

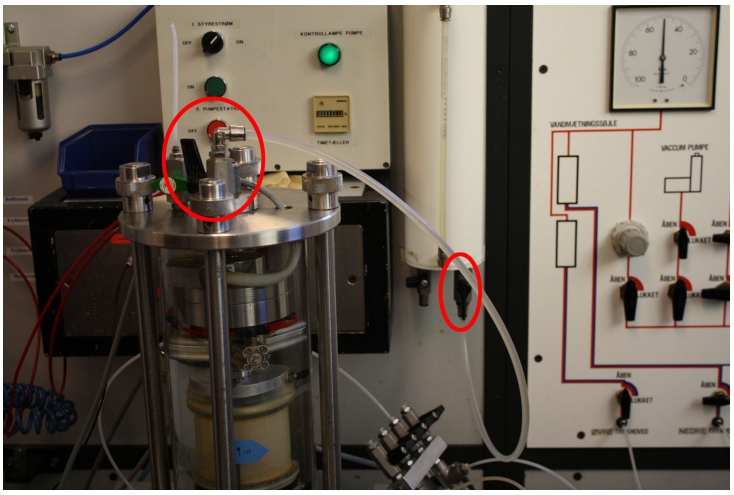

Figure 4.3: Connection between the pressure cylinder and cell marked with red circles.

4.3 Reducing vacuum

The next step is to reduce the vacuum inside the sample while increasing the cell pressure. This is done with an interval of 10 kPa. First negative pore pressure is increased 10 kPa (e.g. from -30 kPa to -20 kPa) and afterwards the cell pressure is increased by 10 kPa. The cell pressure is applied by turning the knob connected to the air/water cylinder. Before opening the black valve labelled "Buffertank" for the pressure cylinder placed to the left, it should be made sure, that the knob is loose so that a large cell pressure will not be added instantly, thereby destroying the sample, see Figure 4.4.

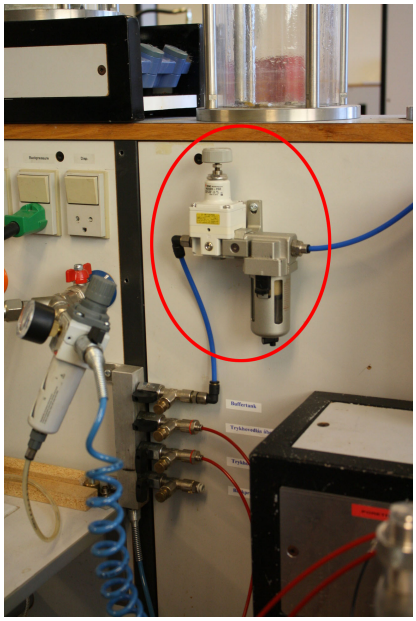

Figure 4.4: Valve for the buffertank along with the knob that adjusts the pressure.

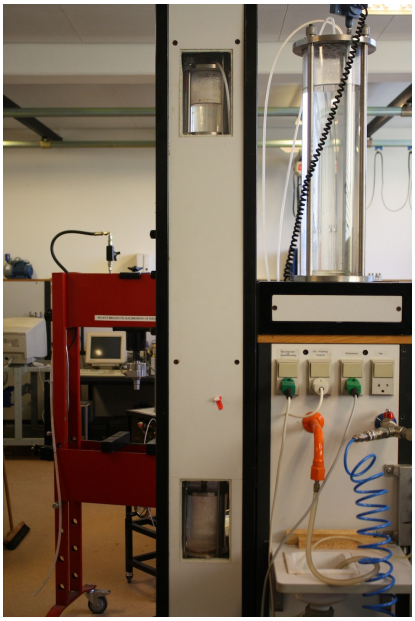

Figure 4.5: Small water containers used when saturating the sample.

4.4 Saturation column

It should be insured that the upper water container in the left column (saturation column) is filled with water which is used later on to saturate the sample. This container is filled with water from "VANDBEHANDLING". This is done by making vacuum in the upper water container while making sure that there is no vacuum in the "VAND-BEHANDLING" container.
The lower water container in the left column should be emptied every time before conducting a test. Otherwise it will let unwanted water into the sample. The two water containers in the left column are shown in Figure 4.5.

5 Saturation of the sample

After the cell is filled with water, the test specimen has to be fully saturated. Before the sample is saturated with water it first needs to be saturated with carbon dioxide (CO_2) because this is easier dissolved than air. CO_2 is heavier than atmospheric air, and when let into the soil from the lower pressure head the atmospheric air will be driven out. CO_2 is let in via the lower pressure head through the sample and up into the upper pressure head, where it is lead out into a plastic bag. The pressure from the CO_2 tank should be low enough to still maintain a decent amount of effective stresses. Proceed with the saturation process until the plastic bag is filled with CO_2. Remember to also fill the valve panel with CO_2.

5.1 Saturation of the sample

Next the soil sample has to be saturated with water. This is done by letting water from the small water container (top in the left column) through the lower pressure head. The water has to pass through the sample and out through the upper pressure head over into the small water container (bottom of the left column). This process takes approximately 30 min. If there is no water left in the small water container in the top after the sample is saturated, it needs to be filled again for later use. This is done in the same way as before, by making vacuum and opening the valves to "VANDBEHANDLING".

5.2 Saturation of the valve panel

Now the valve panel needs to be fully saturated. This is done by making sure that the left grey valve is in the upward position while the right grey valve is in the downward position, as shown in Figure 5.1. Meanwhile all the black valves needs to be open. Now water can be let from the small water container in the top via the lower pressure head and out through the valve panel, thereby assuring that the entire valve panel is saturated.

5.3 Saturation of backpressure system

After the saturation of the valve panel is complete, it is time to saturate the tube connecting the valve panel with the backpressure system, see Figure 5.2. First close black valve numbers 2 and 4. Secondly, close the valve on the back of the backpressure system and disconnect the blue tube, as shown in Figure 5.3. Now water can be let through in the same way as before (via the small water container in the top) and over into the backpressure system. Be sure to set the valves up to "MÅLERØR" to "ÅBEN". The tube labeled 85 cm3 needs to be approximately half full.

Next, level the backpressure system with the sample. Make sure that the water-level in the largest cylinder (the surrounding cylinder) in the backpressure system is at the same height as the middle of the sample (blue sticker marks the spot). Afterwards the blue tube on the back is reconnected and the valve is opened again.

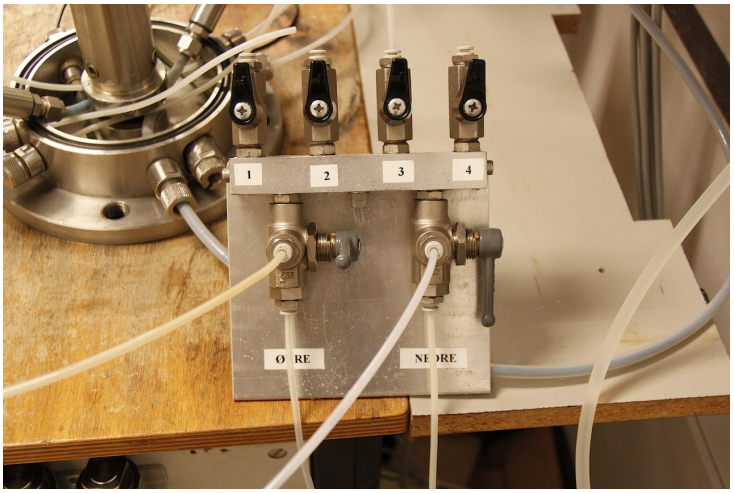

Figure 5.1: Position of grey valves on valve panel for saturating the valve panel.

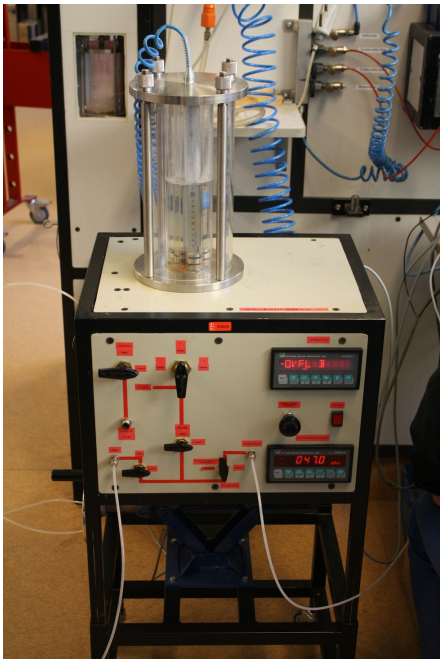

Figure 5.2: Backpressure apparatus.

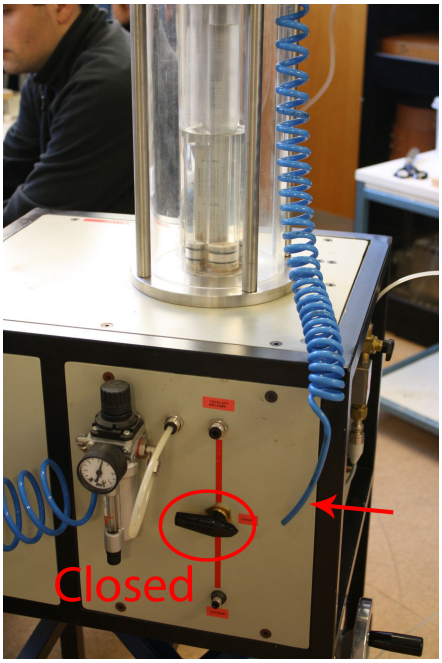

Figure 5.3: Blue tube on the back of the back pressure system.

5.4 Activation of backpressure system

When saturation of both the sample and the tubes to the backpressure system are complete, both grey valves on the valve panel are turned upwards so the backpressure system is activated and the control board is deactivated. The position of the valves can be seen in Figure 5.4.

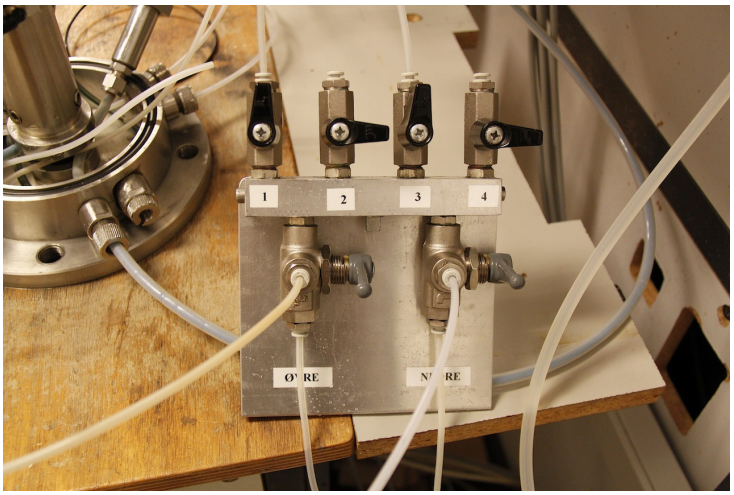

Figure 5.4: Valve panel with the backpressure system activated.

The system is now ready for the backpressure to be applied. On the front of the backpressure system the lower right valve is turned to "BACKPRESSURE". The lower left valve should be set to "LUKKET" and the lower middle valve should be set to "ÅBEN". The next phase is to apply the same amount of cell pressure as backpressure. Firstly the backpressure is increased by e.g. 10 kPa, and at the same time the cell pressure is increased by the same amount. In order to apply the backpressure the lower left valve is set to "ÅBEN" in a few seconds so the pressure can stabilise, and then turned to "LUKKET" again.

6 Skempton's constant B

The cyclic triaxial apparatus is used for investigating the effects that cyclic loading will have on a soil sample. These effects will primarily have an impact on pore pressure. It is therefore important that all test samples that are used in the cyclic triaxial apparatus are completely saturated. The criterion for saturation of the test is given by the Skempton's constant, B, which is 1 for a fully saturated specimen. A completely saturated sample is difficult to obtain in the cyclic triaxial apparatus. Therefore a lower boundary is established which is dependent on the relative density, I_D, of the sample.

When testing Skempton's constant B a reading of the cell pressure and the pore pressure is made. Next the cell pressure is raised by 10 kPa and new readings are made. From this the Skempton's constant B is calculated from (6.1)

$$B = \frac{\Delta u}{\Delta \sigma_3} \tag{6.1}$$

If the criterion is not fulfilled then both the backpressure and cell pressure is raised e.g. 100 kPa so the effective stresses are still kept constant. Then the procedure is repeated until Skempton's constant B satisfies the lower boundary value for a given index density.

When a specimen is 100 % saturated and the cell pressure, σ_3, is increased in an undrained test, the pore pressure, u, will theoretically increase exactly the same amount. In practice a saturation of 100 % is not possible and therefore the tests have to be conducted on specimens with a lower saturation. For soils with a saturation lower than 100 % the value of Skemptons B is highly dependent on the stiffness of the soil skeleton.
When conducting triaxial tests on dense sand this is important to consider because a fully saturated sample will only give relative small values of Skemptons B. In Holtz et al. [2011] an example of a very dense sand is given, which is shown in Table 6.1.

Soil Type	S = 100 %	S = 99 %
Soft, normally consolidated clays	0.9998	0.986
Compacted silts and clays; lightly overconsolidated clays	0.9988	0.930
Overconsolidated stiff clays; sands at most densities	0.9877	0.51
Very dense sands	0.9130	0.10

Table 6.1: *Skemptons B as a function of degree of saturation, S. Holtz et al. [2011]*

In order to take this into account when preparing samples, a minimum value of B must be calculated for each soil, i.e. the relative density and grain size distribution. This can be done from equation (6.2), which take into account the saturation and the relative stiffness of the soil compared to water.

$$B(u) = \frac{1}{1 + \frac{n\,S\,K_s}{K_w} + \frac{n\,K_s}{u+p_{atm}}\,(1-S)} \tag{6.2}$$

where

n	Porosity [-]
S	Degree of saturation [-]
K_s	Bulk Modulus of soil sketelon [Pa]
K_w	Bulk Modulus of water [Pa]
u	Pore pressure [Pa]
p_{atm}	Atmospheric pressure [Pa]

From a consolidation test the Bulk Modulus of the soil skeleton, K_s, is calculated to approximately 108 MPa. Note that this is for the sand deposit from Frederikshavn. If another sand is being used then new consolidation tests has to be conducted in order to calculate the correct bulk modulus. An overview of the used parameters can be seen in Table 6.2.

Parameter	Symbol	Value	Unit
Porosity	n	0.42	-
Degree of saturation	S	0.9-1.0	-
Bulk Modulus of soil sketelon	K_s	$108{\cdot}10^6$	Pa
Bulk Modulus of water	K_w	$2000{\cdot}10^6$	Pa
Atmospheric pressure	p_{atm}	101325	Pa

Table 6.2: *Parameters used in calculating the necessary value of Skemptons B to gain a given degree of saturation.*

A degree of saturation of 99 % will be considered as sufficient, and the dependency of Skemptons B as a function of pore pressure is given in Figure 6.1.

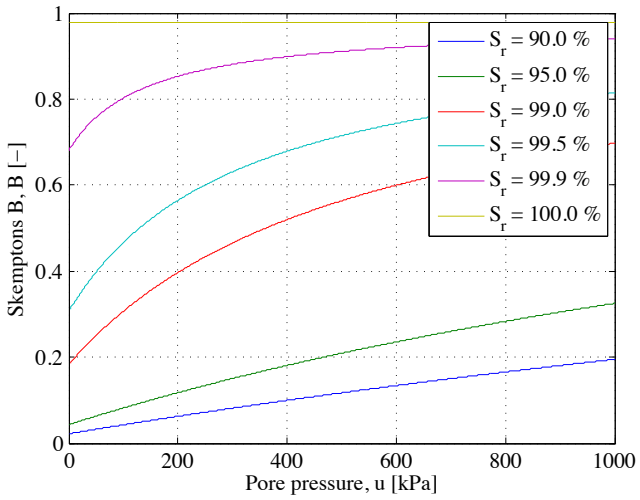

Figure 6.1: *Skemptons B as a function of pore pressure.*

7 Conducting a test

When the cell pressure and backpressure is high enough to fulfil the lower value of Skempton's B, the piston should be force controlled up into the right position in the load cell in order to lock the load cell onto the sample. To do this open MOOG on the computer. Write "*upar1*" and press enter. Press F2 and write "*dyntriax.log*" and press enter. When it is done loading press shift+F1 and shortly after press F2. This should bring up the *Engineering User Interface* as seen in Figure 7.1.

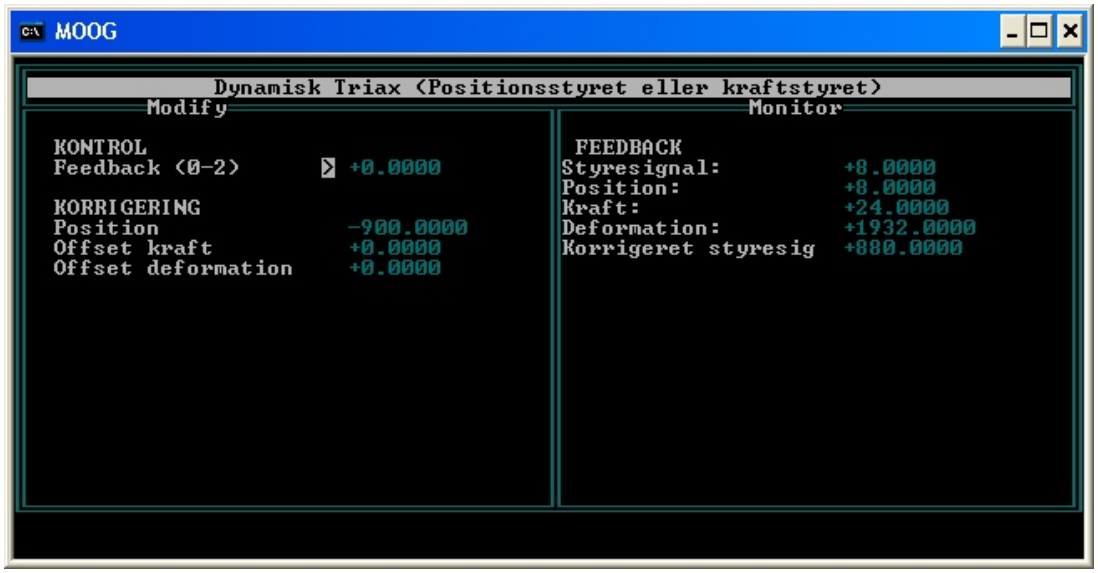

Figure 7.1: Engineering User Interface. This program controls the piston.

At the Engineering User Interface screen "KONTROL" should be set to "1". This makes the piston force controlled. Under "KORRIGERING" the value of "Offset kraft" (Offset force) is changed in order to get the piston to move up to the correct position. To find the right value of offset force for the piston to start moving takes some practice, but do note that a negative value will make the piston go up and a positive value will make it go down.

With the piston in the right position the load cell needs to be locked to the sample. This is done by closing the valve labelled "Åben" that is connected to the red tubes leading to the load cell. Then the valve below, labelled "Lukket" is opened. Lastly the small brass valve in front of "Åben" is turned so that the air will escape and then it's closed again (see Figure 7.3).

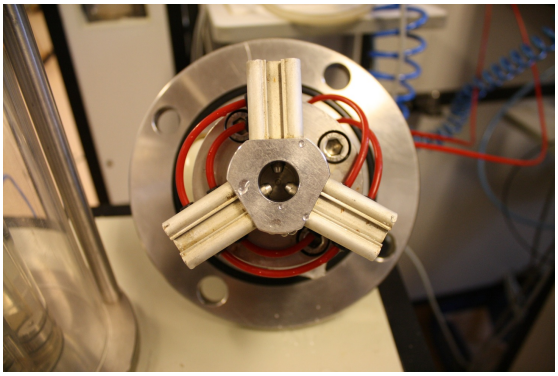

Figure 7.2: The locking mechanism consists of three steel rods that spring into place.

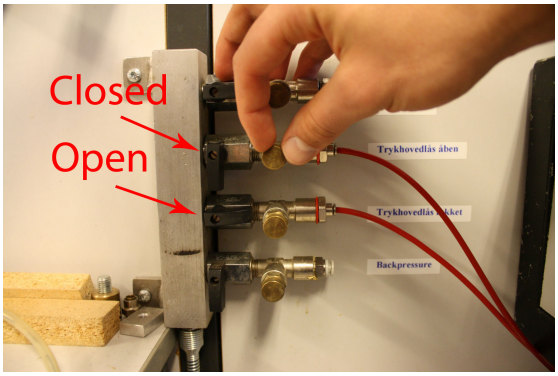

Figure 7.3: Valve position for locking the load cell.

When the sample has been locked into place, MOOG needs to be closed down. This is done by pressing escape, then type "q", press enter, lastly type "n" and press enter.

7.1 Uploading the load file

In order to apply the desired load to the sample, an input file (.inp) is created by using the matlab script *CyclicLoad-Generator.m* from Pedersen and Ibsen [2009]. When the file is created it needs to be uploaded to the PSC-rack. This is done by opening the *Online page* found on the desktop. A screenshot can be seen in Figure 7.4.

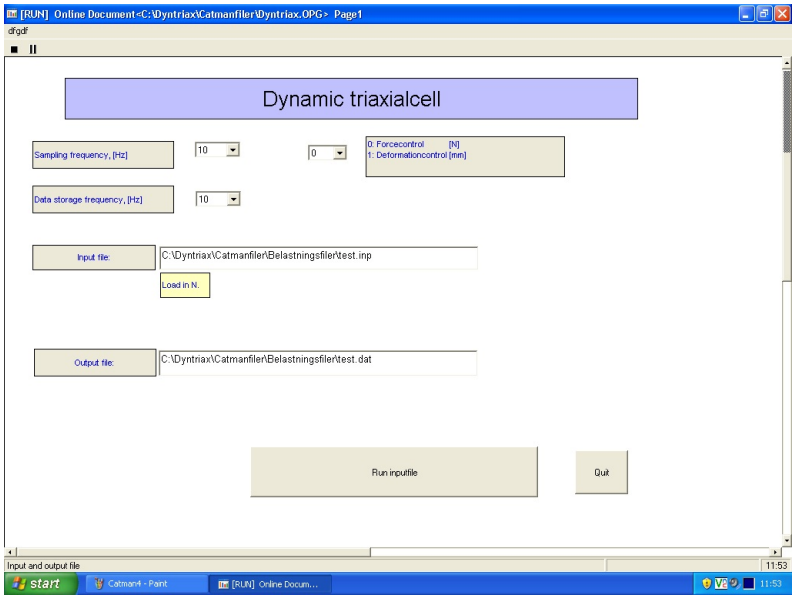

Figure 7.4: Online page where the load file is uploaded to the PSC-rack.

From the online page it is possible to select the desired input file, and where to place the output file (.dat). If deformation-controlled is selected[1] the data from the input file should be in *mm*, and if force controlled is selected

[1] Deformation control does not work properly at present time

it should be in *N*. Furthermore, it is possible to select the sampling frequency[2] and the data storage frequency. When everything is set-up, press "Run inputfile". This will bring up the second online page, shown in Figure 7.5.

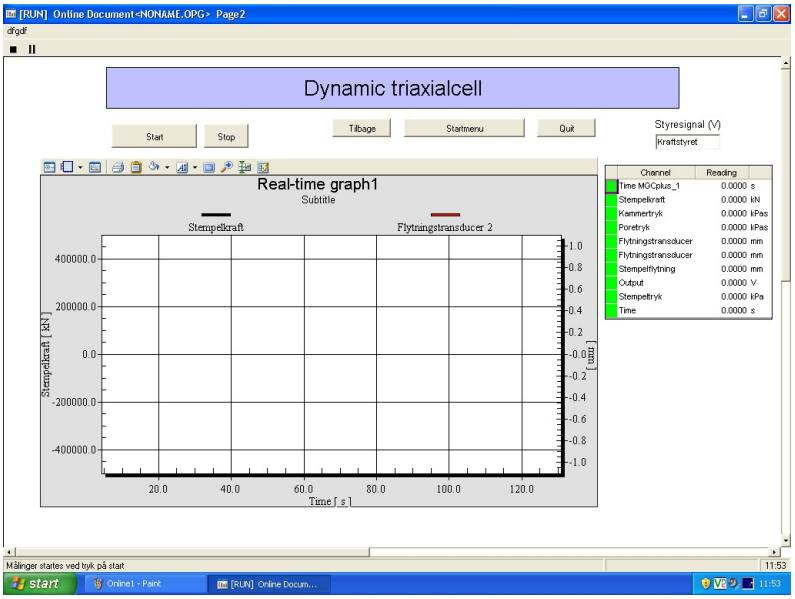

Figure 7.5: Online page where the data storage can be monitored.

The test will not start yet, but the input file is being uploaded to the PSC-rack. This can take some time depending on the size of the input file. Figure 7.6 shows how long it takes for a certain file size to upload. After the file is finished uploading the test is started by pressing "Start".

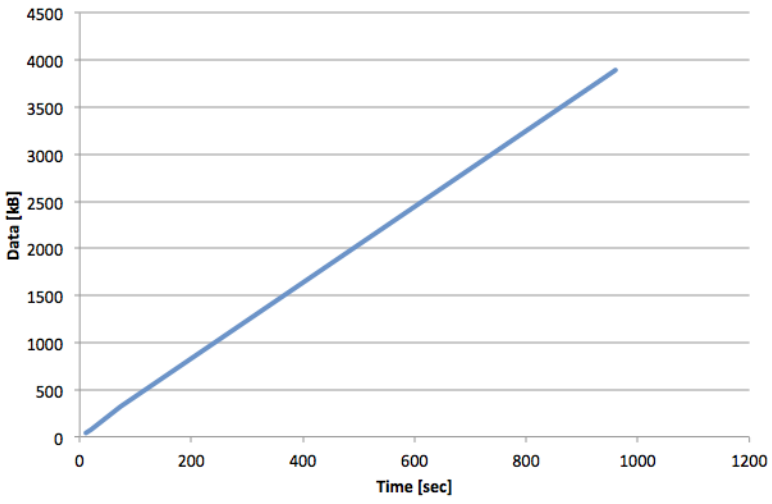

Figure 7.6: Time it takes to load an input file into the PSC-rack.

[2] 50 Hz and 25 Hz seems to be too high. It is therefore recommended not to go above 10 Hz.

PART II

THEORY

8 Theory

When conducting triaxial tests it is necessary to construct different types of diagrams in order characterise the soil. The following chapters treats basic triaxial test theory and different aspects regarding the analysis of triaxial test data.

8.1 Output from Triaxial apparatus

The output data obtained when performing a cyclic triaxial test (cTxT) at Aalborg University is described in Chapter 2, and an overview is given in Table 8.1.

Table 8.1: *Output data from cyclic triaxial test apparatus.*

Measurement		Unit
Piston force	F_{pist}	[kN]
Confining pressure	σ_{conf}	[kPa]
Pore pressure	u	[kPa]
Axial def. transducer 1	d_1	[mm]
Axial def. transducer 2	d_2	[mm]
Piston position	d_3	[mm]
Differential pressure	ζ	[g]
Elapsed time	t	[s]

From the output data, stresses and strains are calculated in order to construct the necessary geotechnical diagrams, which are applied when analysing soil behaviour in order to characterise soil parameters. The equations in Table 8.2 are used in order to calculate stresses and strains.

Table 8.2: *Equations used for calculating stresses and strains.*

Deformations	Strains	Stresses
$\Delta H = \frac{(d_1+d_2)}{2}$	$\varepsilon_1 = \frac{\Delta H}{H_0}$	$\sigma_3 = \sigma_{conf}$
$\Delta V = \frac{\zeta}{\rho_w}$	$\varepsilon_2 = \frac{\Delta D}{D_0}$	$\sigma_1 = \frac{F_{pist}}{A} + \sigma_3$
$\Delta D = \sqrt{\frac{\Delta V + V_0}{\Delta H + H_0}\frac{4}{\pi}} - D_0$	$\varepsilon_3 = \varepsilon_2$	$\sigma_3^{'} = \sigma_{conf} - u$
$A = \frac{V_0 - \Delta V}{H_0 - \Delta H}$	$\gamma = \varepsilon_1 - \varepsilon_3$	$\sigma_1^{'} = \frac{F_{pist}}{A} - u + \sigma_3^{'}$
	$\varepsilon_v = \frac{\Delta V}{V_0}$	$p^{'} = \frac{\sigma_1^{'} + 2 \cdot \sigma_2^{'}}{3}$
		$q = \sigma_1 - \sigma_3$

8.2 Homogeneous and uniform conditions

A prerequisite for the above equations to be applicable is homogeneous and uniform stress and strain conditions. Ibsen and Lade [1998] proved that for a sample with a height/diameter (H/D) ratio larger than one failure will occur in a localised narrow rupture zone (shear band) where two solid bodies will slide with respect to one another

along a failure line, see illustration (a) in Figure 8.1. If this is the case shear deformations and volume changes will take place in the rupture zone and not uniformly throughout the entire test specimen. However, the height of this localized failure zone is unknown and inconsistent along the shear band. Even though, strains and stresses are calculated from the full specimen height giving rise to misleading soil behaviour and a shortening of the stress-strain curve, which may only be correct at the very beginning of test, see Figure 8.2.

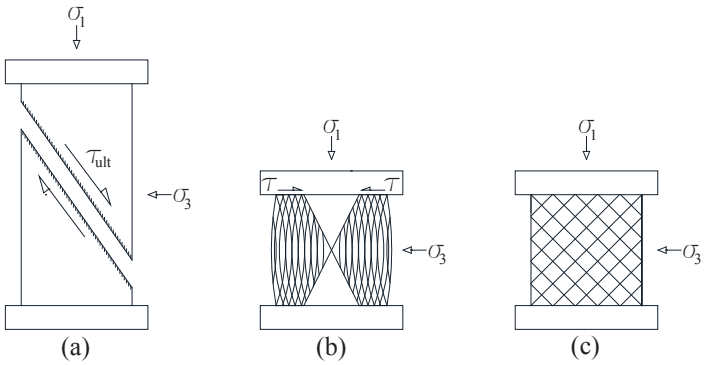

Figure 8.1: *Failure mechanism for triaxial specimen. (a) H=2D with a shear band. (b) H=D with rough end plates causing inhomogeneous conditions because of shear forces at end plates. (c) H=D with smooth end plates which entails uniform conditions.*

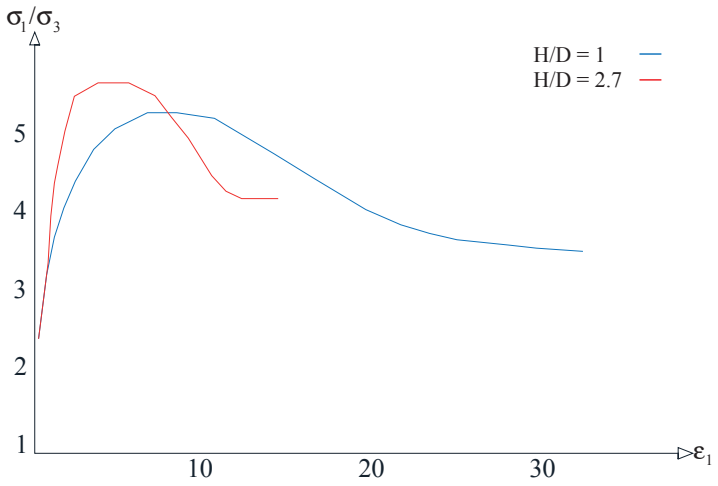

Figure 8.2: *Axial strain as a function of longitudinal and transversal stress ratio for Santa Monica Beach sand with $D_R = 90\%$. Red graph shows the path of a specimen with H/D=2.7 and blue graph is for H/D=1 [Ibsen and Lade, 1998].*

According to Ibsen and Lade [1998], when undrained triaxial tests are conducted on specimens with a H/D ratio larger than one, both compaction and dilation occurs at the same time throughout the shear band. This results in zero volumetric strain since water will flow from contracting areas to zones that dilate. Therefore the test is not truly undrained although the overall volumetric strains are zero.

Homogeneous an uniform stress and strain conditions are obtained if the test specimen have a H/D ratio equal to one with smooth end plates, see illustration (c) in Figure 8.1. If the end plates are rough shear forces will develop at the pressure heads causing a drum shaped specimen where strain and stresses are no longer homogeneous, see illustration (b) in Figure 8.1.

8.3 Data analysis

When the stresses and strains are calculated from the measured data, different diagrams are constructed in order to characterise soil behaviour and soil parameters. The response and parameters of the soil is different depending on if it is a drained or undrained triaxial test. The different diagrams are listed in Table 8.3.

Table 8.3: *Necessary diagrams for the analysis of triaxial test.*

Diagram		Drainage state
Deviatoric stress as a function of effective mean stresses	$p^{'} - q$	Drained/undrained
Deviatoric stress as a function of axial strain	$\varepsilon_1 - q$	Drained/undrained
Volumetric strain as a function of axial strain	$\varepsilon_1 - \varepsilon_v$	Drained
pore pressure as a function of axial strain	$\varepsilon_1 - \Delta u$	Undrained
Shear stress as a function of effective stresses	$\sigma^{'} - \tau$	Drained/undrained

8.3.1 Drained vs. Undrained

When conducting a drained triaxial test the soil behaviour can be characterised by plotting volumetric strain, ε_v, as a function of axial strain, ε_1. If it is a loose sample the test specimen will compact and positive volumetric strains will develop. If the sample is dense it will initially compact and then shift to dilation, which leads to expansion of the specimen and negative volumetric strain will develop, see illustration (a) in Figure 8.3.
When performing an undrained triaxial test the soil behaviour can be characterised by plotting change in pore pressure, Δu, as a function of axial strain, ε_1. This is due to the fact that when conducting an undrained test the volumetric strains are zero and therefore the overburden pressure is carried by the pore water. This means that positive change in pore pressure indicates compactive behaviour and negative pore pressure change indicates dilative behaviour, see illustration (b) in Figure 8.3.

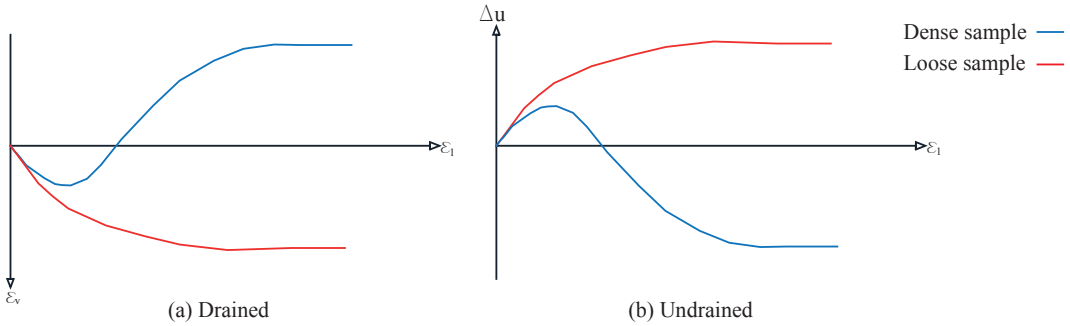

Figure 8.3: *(a) Volumetric strain as a function of axial strain. (b) Pore pressure as a function of axial strain.*

8.3.2 Deviatoric Stress

The same behaviour characteristics can be established by plotting deviatoric stress, q, as a function of the axial strain, ε_1. When a dense specimen is sheared the deviatoric stress reaches a maximum value after which the curve softens and goes towards a constant ultimate value (critical state), see Figure 8.4. When a loose specimen is sheared the deviatoric stress increases with no distinct peak towards an ultimate value, see Figure 8.4. The deviatoric stress

for a loose specimen will have approximately the same ultimate value as the dense specimen.[Holtz et al., 2011]

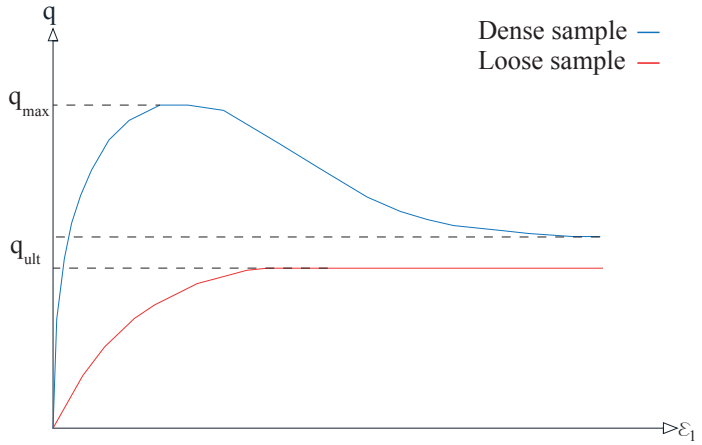

Figure 8.4: *Deviatoric stress as a function of axial strain.*

8.3.3 Void ratio

When a sample is sheared the void ratio, e, evolves in such a manner that it will move towards a critical void ratio, e_{crit}, see Figure 8.5. When a soil has reached the critical void ratio the volumetric strains and the deviatoric stress will be constant for continuous longitudinal and transversal strains. At this critical state a rearranging of the soil particles is possible but the relative density will remain constant hence the constant volume. The value of the critical void ratio depends on the isotropic stress level, particle shape and grain size distribution.
The critical void ratio for the loose and dense sample are not coinciding in Figure 8.5. In theory the value of the void ratio at failure should be the same for the loose and dense specimen but due to the absence of precise measurements of ultimate void ratio as well as non uniform stress and strain distribution a small deviation will be observed. Similarly the ultimate value at critical state of the deviatoric stress should be the same for the two tests.

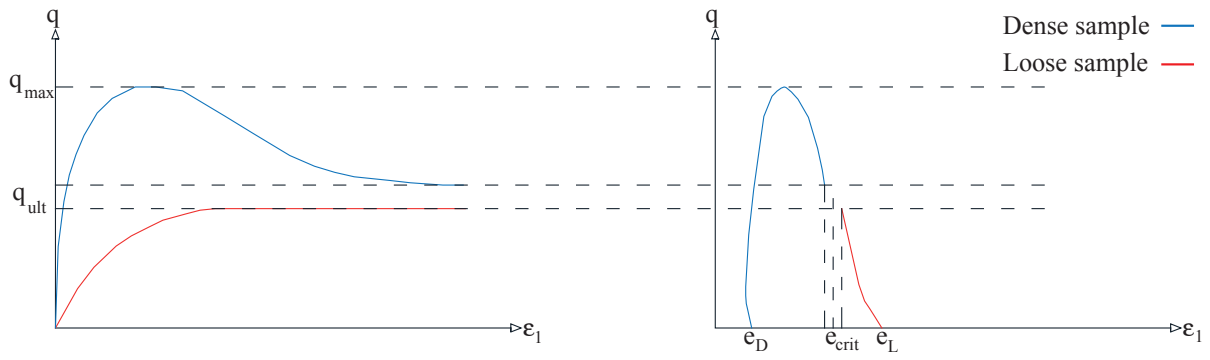

Figure 8.5: *Triaxial test on loose and dense specimens of a typical sand. The blue graph indicates the path of the dense sample whereas the red indicates the loose sample.*

8.3.4 Mohr's Circle Diagram

Once the maximum deviatoric stress value is obtained for different confining pressures, e.g. by a $\varepsilon_1 - q$ or $e - q$ diagram, σ_{conf}, Mohr's circle diagram can be constructed. Hereby the the angle of internal friction, φ, can be determined and thereby the ultimate shear strength of a given soil, see illustration (a) in Figure 8.6. The failure envelope in Figure 8.6 has its origion in origo because the sand is cohesionless. The angle of internal friction is determined by equation (8.1), where the numerator is the radius of a circle and the denominator is the center position of a circle.
If a dense specimen is sheared, dilative behaviour can be observed except at high confining pressures because crushing of the particles takes place. This will entail that Mohr's failure envelope is no longer linear but curved instead, see illustration (b) in Figure 8.6.

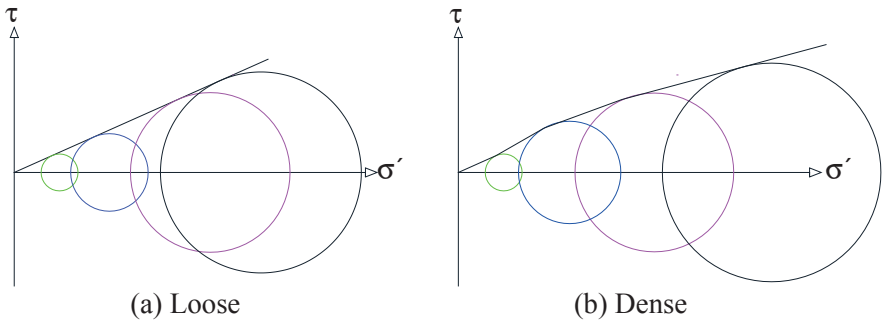

Figure 8.6: Illustration of Mohr's circle diagram. Applied in order to determine the angle of internal friction.

$$sin(\varphi) = \frac{1/2\left(\sigma'_{1f} - \sigma'_{3f}\right)}{1/2\left(\sigma'_{1f} + \sigma'_{3f}\right) + c\ cot(\varphi)} = \frac{\left(\sigma'_{1f} - \sigma'_{3f}\right)}{\left(\sigma'_{1f} + \sigma'_{3f}\right)} \tag{8.1}$$

The amount of dilative behaviour is determined by the dilation angle, ν, which is defined as the slope of the gradient in a $\varepsilon_1 - \varepsilon_v$ diagram, see Figure 8.7.

Progression of the circles in Mohr's circle diagram in the undrained and drained case can be seen in Figure 8.8. The reason for the progression in different directions is caused by the change in stresses due to excess pore pressure. In the undrained case the overburden pressure is carried entirely by the excess pore pressure as listed in Table 8.4. From the tabular it is seen that the effective axial stress is constant during an undrained test and that the effective transversal stress is constant when performing a drained test.
It should be noted that in a laboratory test it is difficult to achieve a 100 % porepressure response, this is due to the fact that it is hard to obatin a fully saturated sample. In consequence of this the effective axial stress in the undrained case will not be completely constant.

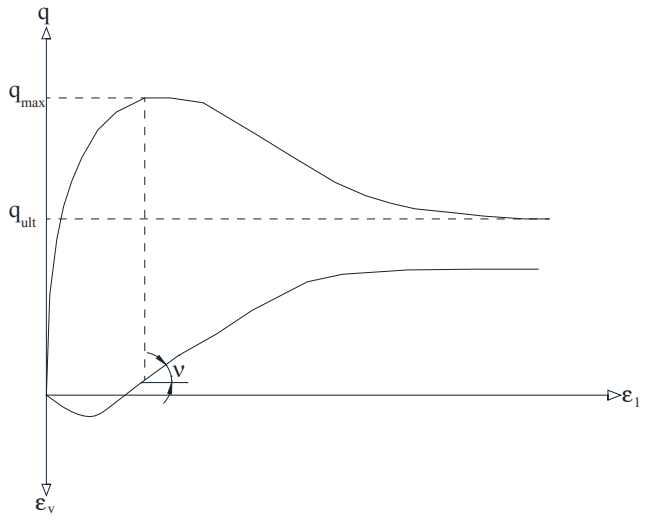

Figure 8.7: *Illustration of dilation angle,* ν.

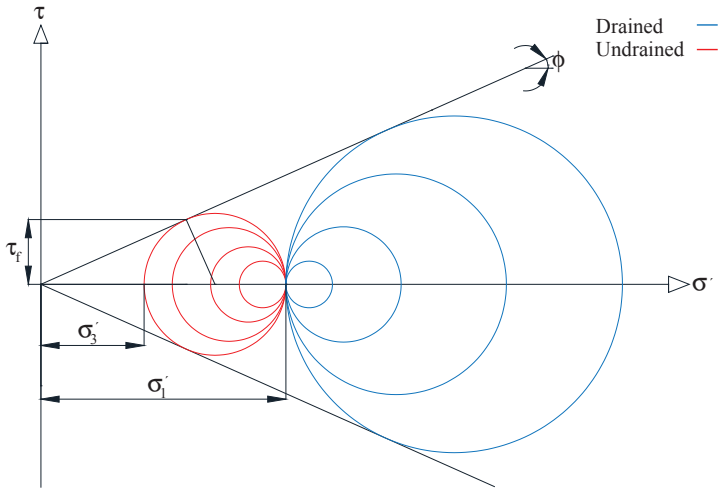

Figure 8.8: *Circle development in Mohr's circle diagram. Circles evolving to the left are showing stress conditions in a undrained triaxial test and circle evolving to the right is the drained case. It should be noted that the major and minor principle stress is different for the drained case*

Table 8.4: *Stresses during drained and undrained triaxial test.*

Undrained triaxial test	Drained triaxial test
$\sigma_3 = \sigma_{conf}$	$\sigma_3 = \sigma_{conf}$
$\sigma_3' = \sigma_{conf} - u$	$\sigma_3' = \sigma_3$
$\sigma_1 = \sigma_3 + p$	$\sigma_1 = \sigma_3 + p$
$\sigma_1' = \sigma_3 + p - u = \sigma_3'$	$\sigma_1' = \sigma_1$

8.3.5 *p - q* Diagram

It is impractical to use Mohr's circles in a σ - τ diagram when analysing soil behaviour during cyclic triaxial testing. This is due to the fact that it contains many informations since changes in stress conditions will appear as different circles changing both in size and position. Therefore it is more convenient to picture stress conditions as deviatoric stress, q, as function of effective mean stresses, p', see Figure 8.9.
When the coefficient of lateral earth pressure, K, is less than one it corresponds to a condition where the vertical stresses are larger than the lateral (axial compression) and vice versa. The failure envelope in this diagram is indicated by the coefficient of lateral earth pressure at failure, K_f. The slope of this line, ψ in relation to Mohr's failure envelope is established through (8.2).

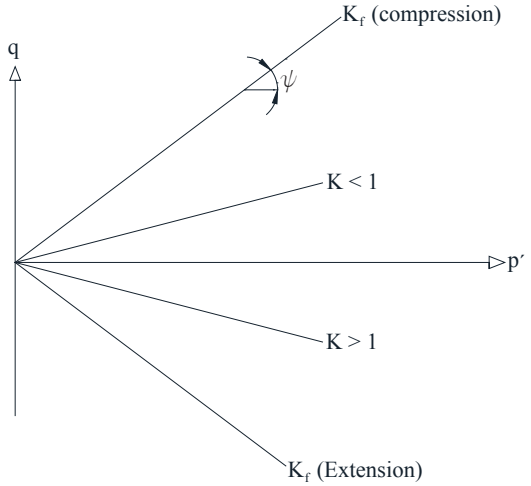

Figure 8.9: *p'-q diagram applied in the analysis of triaxial testing.*

$$sin\ \varphi = tan\ \psi \tag{8.2}$$

The initial stress condition is given by the coefficient of lateral earth pressure at rest, K_0, and can be depicted in a $p' - q$ diagram. This is point A in Figure 8.10 where K is less than one (axial compression). When a specimen is sheared from this configuration both the effective stress path, ESP, as well as the total stress path, TSP, can be outlined in the diagram. For drained cases theses two stress paths will be identical because no excess pore pressure is generated when the specimen is sheared. During undrained shearing the TSP is not coinciding with the ESP because excess pore pressure develops, which thereby has an effect on the effective stresses.

A loose specimen will try to contract when sheared, and therefore positive excess pore pressure, Δu, is generated in the undrained case. This entails that the mean effective stresses will be reduced and the ESP is lower than the TSP. The excess pore pressure can be read off as the horizontal distance between the TSP and the ESP as illustrated in Figure 8.10. In situations where a static ground water table exists there is a initial pore water pressure (hydrostatic) which implies that in reality there are three stress paths; effective stress path ESP, total stress path TSP and total stress path corrected for hydrostatic pore water $TSP - u_0$ see Figure 8.10.

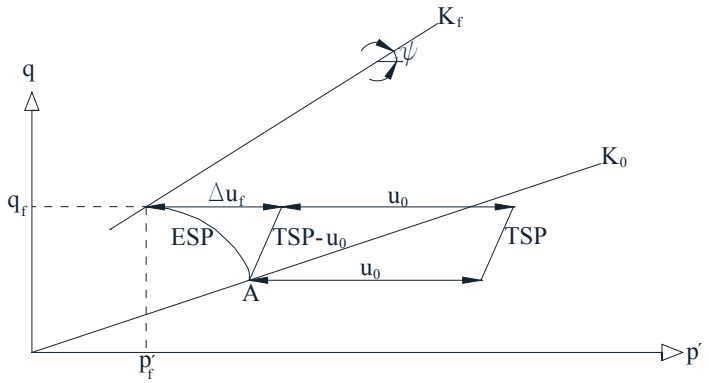

Figure 8.10: *Different stress paths for a given initial condition with coefficient of earth pressure at rest less than one.*

A dense specimen will initially generate a positive excess pore pressure due to contraction, and thereafter a negative excess pore pressure due to dilation, during undrained shearing. The evolution of the ESP will therefore initially be lower than TSP and eventually become higher than TSP, as seen in Figure 8.11.

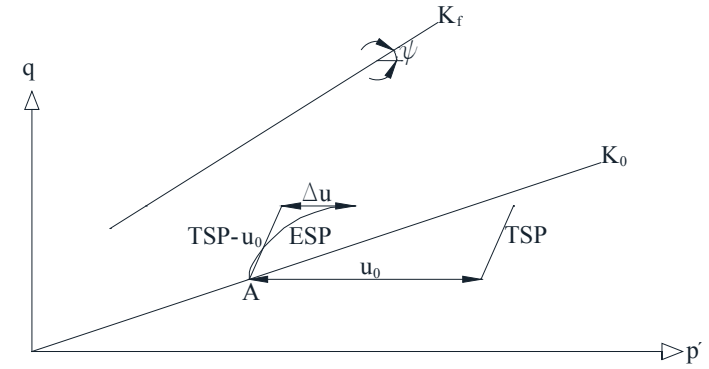

Figure 8.11: *Stress path for dense specimen. Negative excess pore pressure is generated therefore the ESP is to the right of the TSP.*

When failure takes place there will be no further development of the stress paths, in $p' - q$ diagram, since failure is defined as constant volume and constant principle stress difference for strains going towards infinity.

PART III

APPENDIX

Vann. $\Delta W_w - \Delta W_i - \Delta W_s =$ ____

Materiale: ____ *)

Dybde: ____ *) m, P_o': ____ *) kPa

γ_s = ____ *) kN/m³

Vi må regnes to ganger

Type forsök: ____ *)

Rutineundersøkelse ved innbygging: ____ *)

H_i = ____ mm, D_i = ____ mm

V_i = ____ cm³, w_i = ____ % (w_i = 0 hvis problemer med våt)

Fin silt:	w_i = 5-10	Fin sand:	w_i = 2-5 %
Mid. "	w_i = —"—	Mid. "	w_i = —"—
Grov "	w_i = —"—	Grov "	w_i = —"—

γ_{dmax} = ____ *) kN/m³ (g=9.81 m/s²);

γ_{dmin} = ____ *) kN/m³, D_{ri} = ____ % (J lab. økes med +2 hvis w_i = 0 ellers økes med +2,5)

$$\gamma_{di} = \frac{\gamma_{dmax} \cdot \gamma_{dmin}}{\gamma_{dmax} - D_{ri}(\gamma_{dmax} - \gamma_{dmin})} = \text{____ kN/m}^3$$

$$\left(\text{Kontr. } D_{ri} = \frac{\gamma_{dmax} \cdot (\gamma_{di} - \gamma_{dmin})}{\gamma_{di} \cdot (\gamma_{dmax} - \gamma_{dmin})} = \text{____}\right)$$

$$W_i = \frac{\gamma_{di}}{g} \cdot (1+w_i) \cdot V_i = \text{____ g}$$

Kontroller ↓

$W_s = W_i/(1+w_i)$ = ____ g, $\gamma_{di} = \frac{W_s \cdot 9.81}{V_i}$ = ____

$W_w = W_i - W_s$ = ____ g, $w_i = \frac{W_w}{W_s}$ = ____

Lag nr. 1

Total vekt: $\Delta W_{i1} = \frac{W_i}{n_{tot}}(1-U_1)$ = ____ g

Vekt sand: $\Delta W_{s1} = \frac{\Delta W_{i1}}{1+w_i}$ = ____ g

Vekt vann: $\Delta W_{w1} = \Delta W_{i1} - \Delta W_{s1}$ = ____ g

Alle andre lag

$$\Delta W_i = \frac{W_i}{n_{tot}}\left[2 - \left(U_1 \frac{n_{tot}-2}{n_{tot}-1}\right)\right] - \Delta W_{i1}$$

= ____ g

Sand: $\Delta W_s = \frac{\Delta W_i}{1+w_i}$ = ____ g

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Tidsfrist for ferdige tegninger: *

Kontroller

1) $\Delta W_{i1} + \sum \Delta W_i = W_i$? ____

2) $\Delta W_{s1} + \sum \Delta W_s = W_s$? ____

(n_{tot} er vanligvis lik 6.)

For D_r = 40%	velges	U_1 = 0.03	
" " = 50%	"	= 0.04	
" " = 60%	"	= 0.05	
" " = 70%	"	= 0.03	
" " = 80%	"	= 0.01	
" " = 90%	"	= 0.005	
" " = 100%	"	= 0	

Valgt verdi av U_1 = ____

Sug: ____ kp/cm²

Glatte endeplater? ____ Antall gum.lag? ____

Spyling med CO_2? ____ Nold-vann? ____

Saltinnhold i vann som spyles gj. prøve? ____

" " " filtere? ____

Topp st. ____ Tilt { >0.6/30, 0.5/25 ? ____ ; = " ? ____ ; = 0 (ingen tilt) ? ____ }

Cellevæske: ____ Type celle: ____

Konsolidering:

σ'_{acmax} = ____ *) kPa = ____ kp/cm²

σ'_{rcmax} = ____ *) kPa = ____ kp/cm²

σ'_{acmin} = ____ *) kPa = ____ kp/cm²

σ'_{rcmin} = ____ *) kPa = ____ kp/cm²

σ'_{ac} = ____ *) kPa = ____ kp/cm²

σ'_{rc} = ____ *) kPa = ____ kp/cm²

Mottrykk: ____ kp/cm² B-verdi: ____ %

Skal prøven sykles? ____ *) Bruk tilleggsskjema for eventuell syklisk del.

Statisk skjæring:

Maks tenkelige verdi av skjærstyrke:

S = ____ *) kPa $\dot{\varepsilon}_a$ = ____ % pr. time

eller V = ____ min/mm Max def.: ____ *)

Viktig å ta ut moduler fra forsöket? ____ *

Utbygging: Foto før splitting? ____ *

Skal c-verdi måles? ____ etter splitting? ____

Skal prøven { kastes □ ; Lagres i 3 vann □ ; " " □ (*) }

Rutineundersökelser ved utbygging: (på förket prøve) +

Sign lab.:

Sign. prosjektleder ____ *

SPESIFIKASJONSSKJEMA FOR TREAKSIALFORSØK MED UNDERKOMPRIMERING (stampet prøve)

PROSJEKTETS NAVN (MAKS 38 KARAKTERER) *)

Leiested	Job. no *)	Boring *)	Tube *)	Part *)	Test *)
	Maks.: 6 siffer	Maks.: 10 karakterer	Tall: 1-99 (+16 dks)	Maks.: 2 store bok.	Maks.: 1 siffer (1-9)

← Undernr. på tegning *)

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