

# ***Geotechnical Modelling Part 2***

---

*Autumn 24-25*

## **Course Notes**



**University of  
Nottingham**

UK | CHINA | MALAYSIA

# 1 Outline & Plan

In this part of the module you will test the theories learnt in Part 1 — specifically critical state behaviour and the validity of the cam clay yield surface. To test these theories you will plan and undertake a triaxial testing programme in the laboratory. Following this you will analyse the data in such a way as to be able to compare the results to the theoretical framework.

Due to a limitation on the number of students we can have in the laboratory at any one time, we will be splitting you into three groups. This means there will be some timetabled sessions when you do not need to attend class. You should use the slots when you are not attending class to work on coursework components you have access to. The class schedule is provided below. **Please note: the highlighted sessions will not appear in your timetable, but it is a requirement that you attend these sessions.**

Day	Date	Time	Location	Activity
Fri	25/10/2024	12:00	Pope A1	Introduction to Part 2 and Coursework 2 Released
Wed	30/10/2024	09:00	L2-B131	Hands-on introduction to triaxial testing in the lab
Thurs	31/10/2024	11:00	Pope A1	Lecture: data processing
Fri	01/11/2024	12:00	L2-B131	lab: B-Check and Consolidation — Group 1
Wed	06/11/2024	09:00	L2-B131	lab: Begin Shearing — Group 1
Thurs	07/11/2024	09:00	Pope A26	Introduction to numerical modelling with Plaxis
Fri	08/11/2024	12:00	L2-B131	lab: End Shearing, submit CW2a — Group 1
Thurs	14/11/2024	09:00	Pope A26	Setting up Plaxis model of triaxial tests
Fri	15/11/2024	12:00	L2-B131	lab: B-Check and Consolidation — Group 2
Wed	20/11/2024	09:00	L2-B131	lab: Begin Shearing — Group 2
Thurs	21/11/2024	11:00	L2-B131	lab: End Shearing, submit CW2a — Group 2
Fri	22/11/2024	12:00	L2-B131	lab: B-Check and Consolidation — Group 3
Wed	27/11/2024	09:00	L2-B131	lab: Begin Shearing — Group 3
Thurs	28/11/2024	09:00	Pope A26	Numerical modelling and Q&A
Fri	29/11/2024	12:00	L2-B131	lab: End Shearing, submit CW2a — Group 3

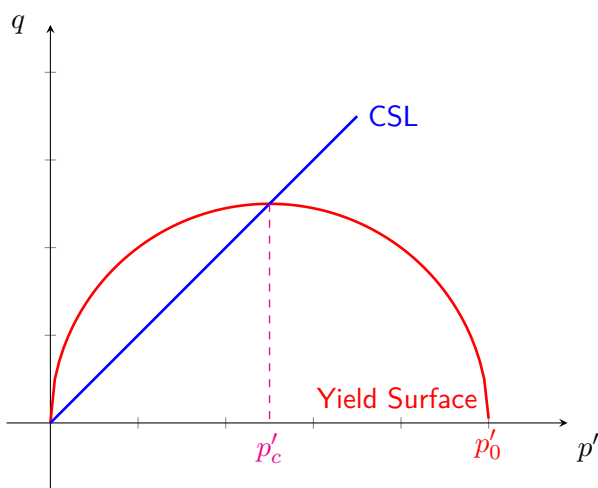
## 2 Introduction

Ultimately we want to test the framework which you learnt in Part 1 of the module. This framework is shown schematically in the figure below.

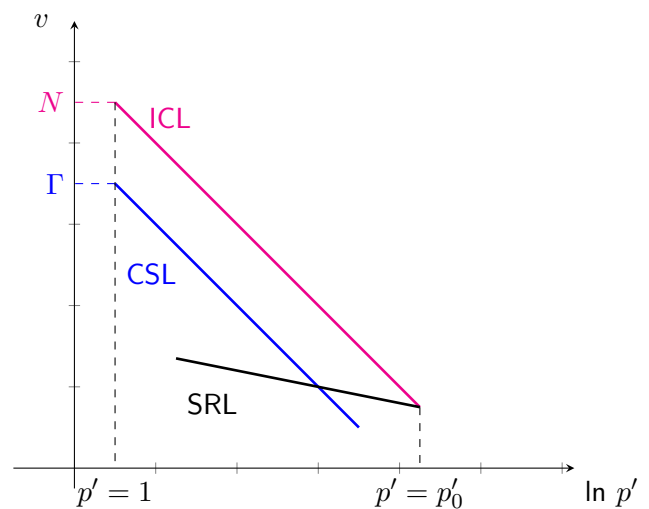
The following are the key parameters which define the lines drawn in the figure and which will need to be extracted from the triaxial test data:

- $\lambda$ : Which is the slope of the normal compression line in  $v$ - $\ln p'$  space, a special case of which is the isotropic compression line (labelled 'ICL' and coloured magenta in the figure). This is also the slope of the critical state line in  $v$ - $\ln p'$  space.
- $\kappa$ : Which is the slope of the swelling and recompression line (labelled 'SRL' and coloured black in the figure)
- $M$ : Which is the slope of the critical state line in  $q$ - $p'$  space (labelled 'CSL' and coloured blue in the figure)
- $N$ : Which is the value of the ICL when  $p' = 1$  kPa
- $\Gamma$ : Which is the value of the CSL when  $p' = 1$  kPa

To obtain the data required to produce  $v$ - $\ln p'$  and  $q$ - $p'$  plots, we will need to first compress our soil while monitoring the change in volume (related to the specific volume,  $v$ ) and the stress state ( $p'$ ). We will then shear our sample, measuring the applied load (related to  $q$ ) and monitoring the stress state of the sample ( $p'$ ).



(a)  $q - p'$  space of Modified Cam Clay



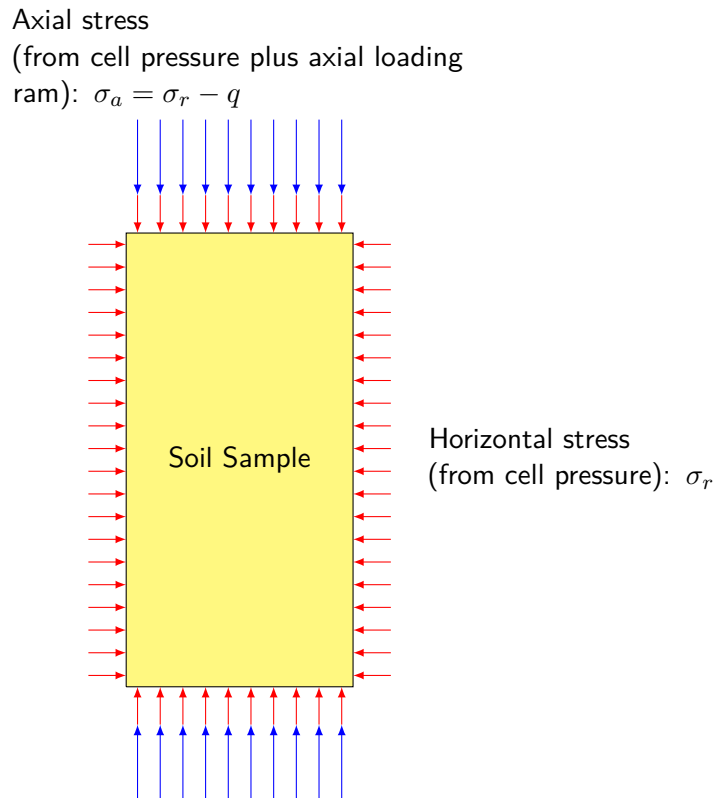
(b)  $v$ - $\ln p'$  space of Modified Cam Clay

### 3 Triaxial Testing Background

In this section we'll cover the basic theory behind triaxial testing, introduce some nomenclature, and then relate the theory to the practical stages of undertaking a triaxial test.

#### 3.1 Theoretical Triaxial Condition

Until now we have mostly dealt with triaxial testing as a theoretical concept idealised most likely by the 2-D cross-sectional schematic shown below and described in the subsequent text.



A cylindrical soil sample, ideally with a height to width ratio of two (i.e. it is twice as tall as it is wide), is subjected to a range of different loading scenarios.

The primary loading which will always be present is an 'all-around' stress – this acts equally to the entire outer surface of the soil sample (as shown with the red arrows in the schematic). This is referred to in triaxial testing as the 'cell pressure' (explained more in the next section). We can control the cell pressure and we will use the cell pressure to isotropically consolidate our samples during our triaxial tests (to allow us to collect the data required for calculating  $\lambda$ ,  $\kappa$ ,  $N$  and  $\Gamma$ ).

We can also apply a normal loading to the top of our sample using a loading ram. This results in a deviatoric stress ( $q$ ) (as shown with the blue arrows on the schematic). Hence the vertical stress on the sample is a combination of the cell pressure and the applied ram loading ( $\sigma_a = \sigma_{cell} + q$ ). Of course the cell pressure is equal to the radial (horizontal stress) on the sample and hence  $\sigma_a = \sigma_r + q$ .

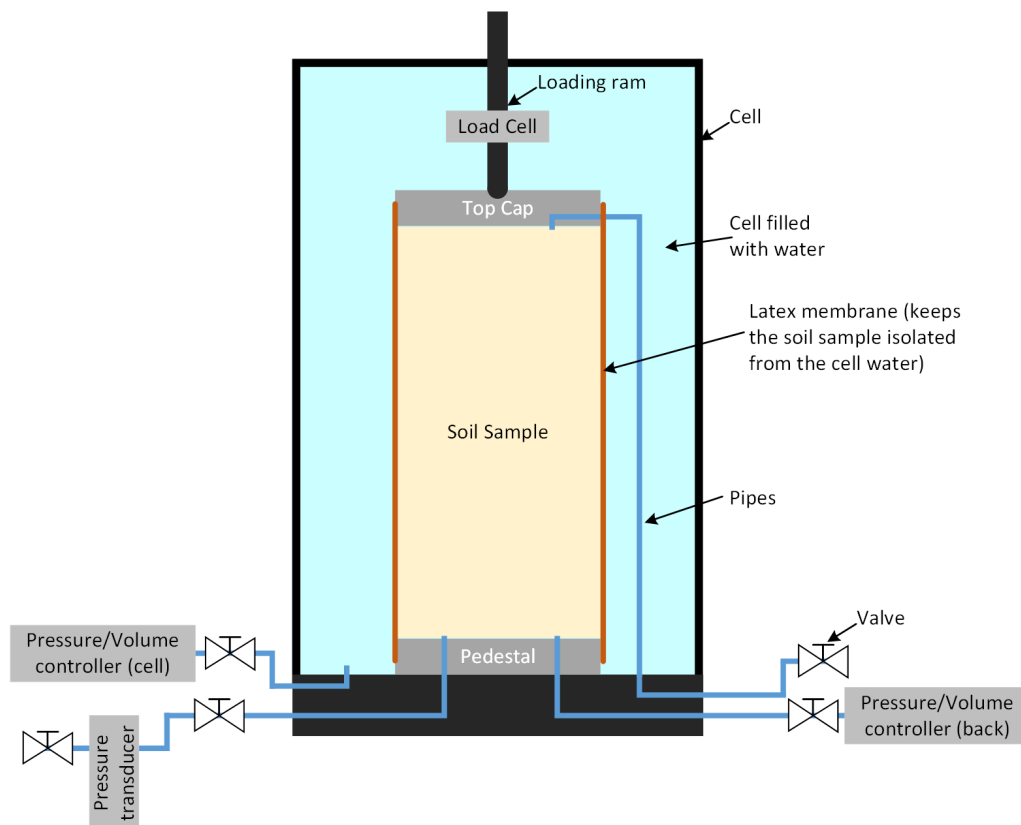
In addition to the parameters shown in the schematic we also measure the pore pressure within the sample, which is important for calculating our effective stress state, and the volume of water which goes into or which leaves our sample during the test. We also measure the overall height of the sample, which is important for calculating axial and radial strain.

If you know all the parameters described above then it is possible to calculate the parameters listed earlier relating to critical state and the Cam-Clay yield surface.

We must however now convert this idealised triaxial sample into a physical test in the laboratory.

### 3.2 Triaxial Apparatus

A picture of a real triaxial apparatus (this one is built by a company called VJ Tech who have provided the machines you will use in the laboratory) is shown in the figure below followed by a labelled schematic to show the parts more clearly. You will become familiar with the equipment during your time in the laboratory. We will discuss the uses for different parts of the apparatus later in these notes and further in-class.



### 3.3 Nomenclature & Terminology

There are a range of abbreviations/terminology used which you will need to be familiar with. These include:

- TX: Triaxial.
- CU: Consolidated undrained (refers to a test in which a consolidation stage is followed by an undrained shear stage).
- UU: Unconsolidated undrained (refers to a test in which there is no consolidation stage and shearing is undertaken in an undrained manner).
- CD: Consolidation drained (refers to a test in which a consolidation stage is followed by a drained shear stage).
- PWP: Pore water pressure ( $u$  - measured by the pressure transducer).
- Back: Refers to the control/measurement of the pressure/volume of the water within the sample. Typically the back pressure is equal to the pore water pressure however there are times when the 'back' controller will be closed off from the sample (using a valve) and hence the back pressure and pore pressure may not be equal.
- Cell: Refers to the physical cell that contains the water around the sample but also used in context of the pressure/volume control/measurement of the water within the cell (e.g. 'cell pressure' refers to the pressure of the water around the sample contained within the cell).
- LC: Load cell.
- LVDT: Linear Variable Differential Transformer - this is the displacement transducer.

Test your understanding of the terminology....

*You will be undertaking CU TX tests in which you will first control the cell and back pressures to apply a range of  $p'$  values while measuring the change in back volume. After this you will do a shearing stage in which you prevent any change in back volume and will measure the PWP while maintaining a constant cell pressure and applying load (measured by the LC).*

## 4 Stages of a Triaxial Test

There are several stages to a triaxial test – some of which we have done for you and some of which you will be responsible for in the lab. In this section the stages of a triaxial test are summarised followed by a detailed discussion on each stage.

- Preparation: involves preparing a cylindrical sample of the soil to the correct size, and placing it onto triaxial machine. This has been done for you but you will practice doing this stage so you understand the challenges associated with preparing the sample.
- Saturation: involves ensuring there is no air in the voids or pipes. We have (hopefully) successfully completed this stage for you.
- B-Check: used to check how saturated the sample is. This will be the first thing you do in the laboratory.
- Consolidation: involves changing the cell pressure and measuring the volume of water which enters/leaves sample (while maintain a constant back pressure). You will set up the software to automatically complete a series of consolidation stages.
- Shear: involves applying a load through the loading ram and measuring the response of the sample. This is also a stage you will do with your samples.
- Post-test: certain key measurements must be taken after the end of the test. This is a critical stage you will finish with and cannot be rushed otherwise all your data will be meaningless.

## 4.1 Preparation

We have prepared your samples for you. Your samples are Kaolin clay which was first prepared to a slurry at twice the liquid limit (using de-aired water). The slurry was then carefully placed into a container. A vertical load was then applied to the clay. Water was allowed to drain from the top and bottom of the sample as it consolidated in a one-dimensional manner. The vertical stress was increased in stages over several months until an ultimate vertical stress of  $\sigma_v = 200 \text{ kPa}$  was applied. This final stress was left for a long time until no further settlement occurred (and hence consolidation was assumed to have efficiently finished).

The sample was then unloaded (with the upper and lower water source removed). Hollow tubes (called 'core barrels') were then used to extract 38 mm diameter cylinders of clay. These cylinders were then trimmed to a length of 76 mm (i.e. so the height is twice the diameter).

The trimmed sample is then placed onto the triaxial apparatus. This includes placing a filter paper and porous stone at the top and bottom of the sample. This filter paper and porous stone allows water to enter/leave the top and bottom of the sample while containing the clay particles. A latex membrane is then placed around the sample and sealed (using 'o-rings') to the base pedestal and to the top cap (which sits on top of the sample). Throughout this process exceptional care is taken to ensure no air is trapped within the sample or pipework.

Once the sample is secured on the pedestal, the cell is placed on top and the entire cell lifted onto the triaxial loading frame. At this point connections between the pedestal and the controllers are made, again ensuring no (or minimal) air is trapped.

The back pressure (controlling the pore pressure in the sample) and cell pressure are then applied. As this applies an isotropic stress state but the samples were initially consolidated in a one-dimensional fashion we apply an equivalent isotropic confining stress of  $p' = 135 \text{ kPa}$ . This was calculated assuming a  $K_0 = 0.5$ . For example the initial back pressure may be 20 kPa and initial cell pressure 155 kPa resulting in a  $p' = 135 \text{ kPa}$ .

## 4.2 Saturation

The saturation stage essentially consists of two sub-stages: a 'flushing' stage followed by a 'dissolving' stage.

### 4.2.1 Flushing

The flushing stage involves trying to push any air through the sample, out through the top cap and through the pipework. This is achieved by applying a back pressure to the bottom of the sample and opening the valve connected to the top cap of the sample. This means water wants to flow from the higher pressure at the bottom of the sample upwards, through the sample and into the top cap from where it flows through the pipe connected to the top cap. As the water flows, the concept is it 'carries' any air with it – hence essentially flushing the air out of the sample.

To get air out of the pipes it is sometimes necessary to close the top cap valve and allow the pressure to build up before then opening the valve again momentarily – this creates a higher pressure gradient along the pipe and a faster flush of water when the valve is re-opened hence moving the air bubbles along. Otherwise the water moves sufficiently slow that it can move past the air bubble instead of pushing the air bubble along.

It is very important to undertake flushing at a low back pressure. When you open the top cap valve you have essentially zero (gauge) pressure at the top of the sample (i.e.  $u = 0$ ) meaning the effective confining stress will be equal to the cell pressure. Whereas at the bottom of the sample the back pressure will be maintaining a positive (non-zero) pore pressure. There are two dangers with having a high back pressure during the flushing stage. First a high pore pressure at the bottom of the sample and a zero pore pressure at the top of the sample creates a high hydraulic gradient and hence the water tries to flow quickly up the sample – this can result in the sample being 'fractured' by the water (like the fracking process used to extract gas from geological layers). Secondly, you could change the consolidation history of your soil sample. Take our sample, for example, which should maintain an effective  $p' = 135 \text{ kPa}$  during the flushing stage. There are two (a good and bad) example of possible pressures to be used during the flushing stage shown in the table below. In the 'good' example we can see that the effective confining stress at the top of the sample during flushing is  $p' = 155 \text{ (kPa)}$  while at the bottom of the sample it would be  $p' = 135 \text{ (kPa)}$ . Although it is not ideal to have any difference, at least we are keeping

the difference to a minimum. However, if you consider the 'bad' example shown in the table you will see that there is a significant difference between the effective confining stress values at the top and bottom of the sample essentially meaning that when the top-cap valve is subsequently closed (post flushing) and the pore pressures equilibrate to the applied back pressure (i.e.  $p' = 135$  kPa throughout the sample) the top part of the sample will be at an over-consolidation ratio  $OCR=2.1$  while the bottom of the sample will still be normally consolidated ( $OCR=1$ ). Hopefully it is clear why it is important to have patience (it will take longer) and maintain a low back pressure during the flushing stage.

	$\sigma_{cell}$ (kPa)	$\sigma_{back}$ (kPa)	$u$ (kPa)	$p'$ (kPa)
<b>Initial state (good)</b>	155	20	20	135
<b>Flushing (good)</b>	155	20	0 (top of sample) 20 (bottom of sample)	155 (top of sample) 135 (bottom of sample)
<b>Initial state (bad)</b>	285	150	150	135
<b>Flushing (bad)</b>	285	150	0 (top of sample) 150 (bottom of sample)	285 (top of sample) 135 (bottom of sample)

#### 4.2.2 Dissolving

The idea of the dissolving stage is that any air which does remain in the sample after flushing will dissolve into the water around it such that there are no air bubbles left in the sample. You mightn't think of air dissolving into water but that is how fish breath! Dissolving is a slow process however it is expedited by having higher pressures in the sample. Unlike the flushing stage, we can safely increase the pressures during the dissolving stage. As such, after ensuring the top cap valve is closed, we have increase the pressures in your sample such that the back pressure is 250 kPa and the cell pressure is 385 kPa (hence maintaining  $p' = 135$  kPa). The sample is then left under these pressures for several days (or weeks). As air slowly dissolves into the surrounding water the back controller will push more water into the sample to maintain the back pressure.

It is important to note, as it will impact your test plan, that you should never decrease the pore pressure in the sample after the flushing stage as air could come back out of solution and form air bubbles again thus decreasing the saturation level of your sample.

The reason we go to such great lengths to ensure our sample is fully saturated is because: a) unsaturated soil can develop significant negative pore pressures due to the interaction of the water and air – we wouldn't capture this with our transducers and even if we could capture it, unsaturated soil mechanics is very complicated and we want to avoid it (in this module) and; b) during our consolidation stages we want to measure accurately the volume change of our sample (so we can plot a  $v-\ln p'$ ) – we will achieve this by measuring the volume of water which leaves/enters the sample and hence we need to ensure air is not dissolving into the water during our consolidation stage as this would affect our results.

#### 4.3 B-check

The B-check stage allows us to check how well saturated our sample is but it is not a perfect check and the results require some interpretation and judgement. The 'B' part of the B-check refers to the parameter calculated which ascertains the saturation level of the sample.

In brief, the B-check stage involves increasing the cell pressure by a known amount while monitoring the increase in pore pressure in the sample. The 'B-value' is the ratio of increase in pore pressure to increase in cell pressure, i.e.:

$$B = \frac{\Delta u}{\Delta \sigma_{cell}}$$

Let us consider why this works by thinking about a balloon (yes, a normal balloon). Read through and think about the following permutations using our balloon:



1. Imagine the balloon is full of water (no air at all) and the initial pressure in the water within the balloon is 10 kPa. Now let's squeeze the balloon (isotropically) with a stress of 30 kPa. What happens to the pressure of the water inside of the balloon?

Well we know equilibrium must apply and we're applying a load onto the balloon and the only thing that could react against that load is the water. Hence the water pressure must increase by the same amount as the pressure we've applied (i.e. the water pressure is now 40 kPa).

If we calculated the B-value for the balloon it would be:  $B = \frac{40 - 10}{30} = 1$ . Therefore a value of  $B=1$  means something is perfectly saturated ( $S_r = 100\%$ ).

2. However, we don't have just water in our 'balloon', we also have some soil. It is easier conceptually (I find) to imagine this as sand instead of clay for now. Let's place two tiny particles of sand into our balloon – so it is mostly water with just a couple of sand particles floating around.

We now do the same test as before – applying an isotropic pressure of 30 kPa to the outside of our balloon. What happens to the pressure of the water inside of the balloon?

Well we still must have equilibrium but what is reacting against our applied stress this time? The sand particles can't be doing anything – they are just floating around. Hence the applied pressure must be taken again by the water and once again we would get a B value of 1.

3. Let us now think about the opposite problem – we take all the water out of our balloon and fill it with sand (and air in the voids, no water). We once again squeeze the balloon isotropically from the outside with a stress of 30 kPa. We can't ask what is happening to the water pressure now, as we have no water. So instead ask yourself, what is reacting against our applied stress?

The only thing that could be providing resistance against our applied load is the sand. We squeeze on the balloon and the sand particles mobilise force chains to react against us.

However, a subtle but important point is raised here – '**mobilise** force chains'. In order for the sand to generate the effective stress required to react against us, deformation (volume change) needs to occur. Another way to think about this is with the  $v-\ln p'$  plot – you know it is impossible to have a change in effective stress without a corresponding change in volume (assuming pore pressures remain constant and that you are not at yield).

You may be wondering about the air in the voids during this example - air is very compressible meaning it would take a very large volume change to mobilise the required stress to react against our applied isotropic stress. Comparatively the sand particles mobilise the required load a lot quicker and hence any increase in air pressure is negligible by the time equilibrium is reached.

4. One thing to note about water is that it has a very high stiffness (bulk modulus) such that when you squeeze it, load is generated very quickly without much volume change (completely the opposite to air as discussed above). In fact, we (geotechnics people) consider the water to be infinitely stiff such that it is capable of reacting against load without any volume change (theoretically impossible but a good enough assumption for now). This means in examples numbers 1 and 2 above, the balloon did not change volume when we squeezed it.

Let's return to our sand filled balloon but with the voids completely full of water (no air). We once again squeeze our balloon isotropically – what happens?

Well we know equilibrium is maintained and hence 'something' is reacting against our applied stress. This time it could be the sand, or the water, or both - so which is it?

Think now about two important points we have raised previously: 1) water can develop a reaction force without any change in volume and 2) the sand particles cannot develop a reaction force without a change in volume.

This means, when we apply a load to our fully saturated balloon it is the water which reacts against us as it develops the required reaction force before any volume change has occurred and hence no effective stress (from the sand) can be mobilised. In fact this concept is not new to you - you should be comfortable with the fact that the pore pressure increases while the effective stress remains unchanged during undrained loading. Our balloon is simply an undrained loaded block of soil.

5. Our final consideration is when there is a tiny amount of air inside of balloon - so it is mostly sand and water but there is some air. This time when we squeeze the balloon the air will be squeezed and reduce in volume, this means that there is a volume change and hence effective stress can be mobilised (in the sand). Depending on the amount of air in the balloon, our applied isotropic stress will be balanced by a combination of an increase in the water pressure as well as effective stress coming from the sand particles. Calculating how much will be balanced by the water and how much by the sand is not easy and will depend on the stiffness of the sand body (i.e. if the sand was really dense it would be stiffer and hence would mobilise effective stress more quickly when the volume changes). This means the increase in water pressure is a function of the soil matrix stiffness and the saturation level.

So what does this mean for our triaxial sample. Our triaxial sample is essentially a balloon filled with soil and water, and hopefully very little air. During a B-check, we increase the cell pressure by a known amount (which is like squeezing the balloon) and then measure the change in pore pressure. The closer the change in pore pressure is to the change in cell pressure, the more saturated the sample. However, this will depend on the stiffness of the soil body as previously discussed. In reality no sample will ever be perfectly saturated and hence a B-value of 1 is very unlikely (normally only occurs if there is some error in our reading of cell or pore pressure).

The values presented in the table below relate a qualitative stiffness to expected B-values for different levels of saturation. It is remarkable how low a B-value would be expected for a very stiff sample and how high a B-value would be required for a soft sample for the same level of saturation. Deciding how 'stiff' the sample is isn't easy, meaning the B-value tends to be more indicative as opposed to absolute.

Soil category	Degree of saturation		
	100%	99.5%	99.0%
soft	0.9998	0.992	0.986
medium	0.9988	0.963	0.930
stiff	0.9877	0.69	0.51
very stiff	0.913	0.2	0.10

If the B-value is considered to indicate a degree of saturation lower than what is required, then it is necessary to repeat steps from the saturation stage described previously and then repeat the B-check until a satisfactory B-value is achieved. In practice, due to time restraints, you will have to accept whatever B-value you obtain and move on with your consolidation stages. However, a low B-value may feature in your report discussion related to any irregularities in your results.

## 4.4 Consolidation

This is the first stage which produces the data you require to compare against the theoretical framework learnt in Part 1 of the module. Consolidation stages are quite straightforward, following these steps:

1. Turn off the valve to the back controller (or stop the back controller)
2. Ensure data is being recorded
3. Increase the cell pressure to the required level

#### 4. Turn on the value to the back controller (or re-enable pressure control)

The reason for disconnecting the back controller during the cell pressure increment is because you ideally want to ‘instantaneously’ increase cell pressure such that no drainage occurs until the new cell pressure is achieved. This then allows the initial rate of drainage to be captured – the data of which will feed into your shear rate calculations for the next stage of the test. As it is not possible to increase the cell pressure instantly, we instead prevent drainage by turning off the back controller or turning off the value which connects the back controller to the sample until the cell pressure has reached its new value.

It is important to note that the back pressure controller only controls the pressure at the bottom (or top and bottom if we’re using double drainage – we’ll talk more about this in the laboratory) of the sample – it cannot control the water pressure at the centre of the sample, for example. When we increase the cell pressure, the water pressure in the entire sample will increase by (almost) the same value as we have increased the cell pressure (this is essentially like doing another B-check). When we then reconnect the back controller, the water pressure at the points where the back controller connects to the sample will instantly drop to the same as the set back pressure value. However it will take time for the excess pore pressure in the remainder of the sample to dissipate back to the same value as the back pressure (this dissipation involves water seeping out of the soil and being collected in the back pressure controller). During this consolidation (excess pore pressure dissipation) process we do not know the pore pressure everywhere in our sample or even the average pore pressure for our sample and hence cannot calculate a  $p'$  value. In fact we only know our  $p'$  prior to the start of the consolidation stage and at the very end of the consolidation stage (once all excess pore pressures have dissipated). This means each consolidation stage only provides a single point on our  $v-\ln p'$  plot, meaning we must do multiple consolidation stages to get a  $\lambda$  and  $\kappa$  line (the end of one consolidation stage being the start of the next). We will discuss this more when we look at how to plan our triaxial test.

The data you are interested in from the consolidation stages are: the back volume (tells you about how much water has drained from your sample and hence the change in volume of the sample), the cell pressure, and the pore/back pressure.

### 4.5 Shear

When shearing the sample (i.e. changing the stress state of the soil by varying the deviatoric stress) we have two options:

1. Shear the sample in a ‘drained’ fashion. During a drained test the back controller is used to control the water pressure within the sample at a constant value. As the back controller can only control the pressures at the bottom and/or top of the sample, it is important to shear slowly to allow any excess pore pressures which develop at the centre of the sample to dissipate towards the boundaries. During a drained test we record the volume change of the sample by measuring the volume of water which enters/leaves the back controller.
2. Shear the sample in an ‘undrained’ fashion. During an undrained test the back controller is disconnected from the sample such that no water can enter/leave the sample. Therefore excess positive or negative pore pressures can (mostly likely will) develop in the sample which are then measured by the pressure transducer. Although it is generally assumed an undrained test can be sheared quicker than a drained test, as excess pore pressures do not need to dissipate, it is important that the pore pressure throughout the sample is constant so that the pressure transducer reading is representative of the overall sample. As such it is important not to shear too quickly. We (the geotechnical academics in the department) have recently been discussing what ‘not too quickly’ means, and it is not a straightforward question. Although there are codes and guidelines, think for yourself what it could mean for the sample if even a small area developed a higher excess pore pressure, for example, even temporarily.

For your testing you will shear the sample in an undrained manner. This means you will close the valve between the sample and the back controller before starting to apply deviatoric load through the loading ram. During this stage you will measure the axial displacement, load in the loading ram and pore pressure while maintaining the cell pressure at a constant value. We will talk more about the shearing stage and some of the intricacies related to it in the laboratory.

## 4.6 Post-test

After the test we need to remove the sample from the machine. This is a more delicate process than it may initially sound. During our test so far we have collected a lot of data, some of the most important of which was the volume change of the sample (measured using the back controller) during the consolidation stages. We are going to use that volume change to plot a  $v\text{-}\ln p'$  plot, however the back controller doesn't measure a change in specific volume, instead it measures the volume of water entering/leaving the sample. As such we need to convert from our volume measurements to specific volume. In order to do this, we need to know the specific volume at the end of the test. We will discuss the calculation steps in more detail in a separate lecture however for now let's consider how we obtain the specific volume of a sample of soil.

We know that  $v = 1 + e = 1 + \frac{V_v}{V_s}$ , so how would we measure  $V_v$  and  $V_s$ ?

The voids, we hope, are fully saturated with water, hence if we measured the volume of water in our sample that would provide us with  $V_v$ . We therefore take our sample and measure its mass, place it in an oven to fully dry it, and then measure its mass again. The difference in mass tells us the mass of water which was in the sample which, using the density of water, allows us to calculate the volume of water and hence  $V_v$ .

The volume of solids ( $V_s$ ) can be obtained using the same measurements. After drying the sample the only thing contributing to the mass of the sample is the solids. Hence if we know the density of the solids we can calculate the volume of solids from the mass of the dry sample.

As such the above equation for specific volume can be expanded as follows:

$$v = 1 + e = 1 + \frac{V_v}{V_s} = 1 + \frac{M_w/\rho_w}{M_s/\rho_s} = 1 + \frac{M_w/\rho_w}{M_s/(G_s \cdot \rho_w)} = 1 + \frac{M_w \cdot G_s}{M_s}$$

Where  $G_s$  is the standard geotechnical parameter of 'specific density of solids':  $G_s = \frac{\rho_s}{\rho_w}$ , which is provided for Kaolin clay in the Geotechnical Data Book.

Therefore, in order to make use of any of the consolidation data, it is critically important to get the mass of the sample at the end of the test. This means, once shearing has finished we need to take care not to add or remove water until we have obtained the mass measurement – the process by which we do this will be explained in the laboratory.

## 5 Overview

These notes are intended as a brief high-level introduction to the stages of a triaxial test so hopefully things make a little more sense when you get into the laboratory. We will be exploring the concepts, and required calculations in more detail in the laboratory and also in class.