3.1 Introduction

For a better understanding of the behaviour of Singapore Old Alluvium, various kinds of tests are performed. Some of the tests are simple index property tests and some are highly sophisticated stress path or strain path tests. In some tests, new experimental apparatus need to be developed. This chapter introduces the laboratory test setup in this research project, including the experimental apparatus and test procedure. Generally, tests performed in this project can be classified into three groups:

1) Classification Tests
2) Triaxial Tests
3) Oedometer Tests

3.2 Classification Tests

As been said in the previous chapter, Singapore OA is a heterogeneous soil and this heterogeneity was not addressed properly in previous research studies. In this study, the natural heterogeneity of this material has been given special attention. Through literature review and research work, it is recognized that heterogeneity comes from two aspects; one of which is the cementation of the material.
In a sedimentary cycle, a material experiences weathering, erosion, transportation, sedimentation, lithifaction and weathering again. After Old Alluvium was deposited, the process of lithifaction and weathering took place together, leaving both uncemented OA and cemented OA types.

It is also found that the in literature on OA, the term ‘cementing’ is not clearly defined and sometimes the apparent ‘cementation’ is merely due to the very high suction that could develop in tropical soils. The physical meaning of ‘cementing’ in this paper is defined as the ‘glue’, or true cohesion between soil particles, which is different from the apparent cohesion cause by suction of pore water. The true cohesion exists even when the effective confining stress is zero. Clearly, if the soil appears to be strong but breaks easily once in contact with fresh water, the soil is not cemented and the strength is due to suction. Uncemented and cemented OA can be easily distinguished using a simple dispersion test (Shirlaw et al., 2000). As shown in Figure 3-1, two soil samples are placed in two beakers containing clean water. If the soil retains its shape in the water like the left sample in Figure 3-1, the soil is considered cemented. If the soil collapses like the sample on the right hand side, this means the soil does not possess true cohesion and the soil will be deemed as uncemented. The procedure adopted in the present test is the same as the cylinder dispersion test in section 10.8.6, Manual of Soil Laboratory Testing (Head, 1992) except that intact soil samples are used instead of remoulded ones.

The other reason for the OA heterogeneity is the particle size distribution of OA. OA is not a uniform soil and the PSD (Particle Size Distribution) of one sample can be quite different from the other even in the same borehole and a short depth apart. Since the OA soil contains a wide range of particles from pebble to clay, the PSD tests must be
done using wet sieving combined with the sedimentation (hydrometer) test. The soil is first washed on a 63µm sieve. The retained particles are sand and pebbles, and dry sieving is done on them. The fines passing the sieve with water are collected. Dispersion agent is added and hydrometer tests are performed. These are carried out according to the procedures in BS1377: Part 2: 1990: 9.2 and BS1377: Part 2: 1990: 9.5. The PSD curve is plotted combining test results from sieving and sedimentation tests.

After the dispersion and PSD tests, the two aspects of heterogeneity, cementation and PSD, are investigated and the soil can be grouped. In this research project, a classification framework was developed. As shown in Figure 3-2, OA is first divided into two groups: cemented and uncemented by dispersion test. The uncemented OA can be further divided into different subgroups according to its PSD and it is found that a majority of OA is clayey sand, which confirmed the findings of Li and Wong (2001). The main focus of this thesis is on uncemented clayey sand OA, as this is the most abundant.

### 3.3 Triaxial Tests

This research focuses on the engineering properties of uncemented OA and the triaxial equipments are used extensively. Two triaxial systems are available in NUS Geotech Laboratory: One triaxial set is based on the Bishop and Wesley stress path system with a hydraulic cell, GDS digital controller and the data acquisition system. The other one is based on the GDS stress path system.

Besides normal triaxial compression tests, many sophisticated triaxial tests were also performed in this research project and these tests may have specific requirements for the equipment. For example, $K_o$ consolidation tests with volume calculation need the
volume to be measured very accurately and an automated consolidation program, which is only available on the new GDS stress path system. Sometimes the triaxial system needs to be upgraded to cater for the test requirements. For example, the extension cap and local submersible LVDTs were added to the Bishop and Wesley stress path cell by the author, which enabled the setup to measure small strain stiffness and impose extension axial strain to the soil sample. After these modifications, the system can be used to conduct $K_o$ Consolidation with lateral strain measurement and also to simulated ‘ideal tube sampling’ tests. Various types of triaxial tests and the equipment used in this research project are summarized in Table 3-1 and the triaxial systems will be described further in details.

**Table 3-1 Triaxial test types and equipment used**

<table>
<thead>
<tr>
<th>Group</th>
<th>Test Type</th>
<th>Equipment Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shearing Tests</td>
<td>Triaxial Compression</td>
<td>Bishop and Wesley Stress Path Cell System; GDS Stress Path Cell System</td>
</tr>
<tr>
<td></td>
<td>Triaxial Extension</td>
<td>Bishop and Wesley Stress Path Cell System with Extension Cap</td>
</tr>
<tr>
<td></td>
<td>Small Strain Stiffness Measurement</td>
<td>Bishop and Wesley Stress Path Cell System with Extension Cap and Local LVDT</td>
</tr>
<tr>
<td>Stress Path Tests</td>
<td>‘Perfect Sampling’</td>
<td>Bishop and Wesley Stress Path Cell System; GDS Stress Path Cell System</td>
</tr>
<tr>
<td></td>
<td>$K_o$ Consolidation with Lateral Strain Measurement</td>
<td>Bishop and Wesley Stress Path Cell System with Local LVDT</td>
</tr>
<tr>
<td></td>
<td>$K_o$ Consolidation with Volume Calculation</td>
<td>GDS Stress Path Cell System</td>
</tr>
<tr>
<td>Strain Path Tests</td>
<td>Ideal Tube Sampling</td>
<td>Bishop and Wesley Stress Path Cell System with Extension Cap</td>
</tr>
</tbody>
</table>
3.3.1 Bishop and Wesley Hydraulic Cell

Bishop and Wesley (1975) developed a simple and versatile hydraulic triaxial stress path cell, which is called the Bishop and Wesley cell.

As shown in Figure 3-3, the vertical load in the stress path cell is applied by the hydraulic pressure inside the lower pressure-chamber. The cell chamber (upper) and the lower pressure-chamber are all sealed with belloframs and the loading ram is placed between these two chambers. Considering the equilibrium of the loading ram:

\[ \sigma_a A + \sigma_r (a - A) + W = p_c a \]  

(3.1)

in which

- \( \sigma_a \): axial stress on the sample
- \( \sigma_r \): radial stress on the sample, the cell pressure
- \( A \): sample area
- \( a \): bellofram area
- \( W \): weight of the loading ram and the sample
- \( p_c \): lower pressure-chamber pressure

With any given \( \sigma_r \), the desired \( \sigma_a \) can be achieved by adjusting the \( p_c \). Generally, since OA is a strong material, the pressure needed in the lower pressure-chamber is relatively high and the air pressure provided by the laboratory air compression line is not enough. A GDS digital controller capable of applying 3000kPa was used and details are given below.

3.3.2 GDS Digital Controller

The GDS digital controller is a microprocessor controlled hydraulic actuator. It generates,
measures and logs both liquid pressure and volume change (Figure 3-4). De-aerated water in a cylinder is pressurized and displaced by a piston moving in the cylinder. Since pressure and volume ramps and cycles can be performed, once the cylinder is linked to the lower pressure chamber of the stress path machine, it allows the stress path cell to perform strain controlled or stress controlled loading and unloading. When the pressure in the lower chamber cell is lower than the pressure in the upper cell and with the help of the extension cap, conditions of $\sigma_a < \sigma_r$ can be achieved.

### 3.3.3 Extension Cap

An extension cap functions as a coupling which transfers the tension between the sample top cap and the load cell. As reviewed by Baldi et al. (1988) and shown in Figure 3-5, there are various designs of the extension cap. The suction cap connection was chosen for the present study since it minimizes subjecting the sample to torsion and allows easy sample preparation.

Once installed in the Bishop and Wesley hydraulic cell, the air inside the suction cap is always linked to the outside atmosphere by the tube, which means the air pressure is zero. Consider the vertical equilibrium of the suction cap:

$$\sigma_a A = \sigma_r (A - a')$$

in which

$a'$: suction cap seal area

which means that though $\sigma_a$ can be smaller than $\sigma_r$, it should satisfy

$$\sigma_a > \sigma_r (1 - a'/A)$$

(3.3)

to ensure the contact between suction cap and the load cell.
With the help of the suction cap, extension tests and ideal tube sampling tests can be done in the Bishop and Wesley hydraulic cell.

3.3.4 Local LVDTs

Traditionally, in a triaxial test, the strain is measured from the dial gauge or displacement transducer which is outside the cell. As reviewed by Baldi et al. (1988) and shown in Figure 3-6, some errors are caused by the external measurement of displacement including:

1) seating errors
2) alignment errors
3) bedding errors
4) system compliance
5) nonuniform strains along the specimen height resulting from end restraint.

The errors can only be eliminated when the strains are measured inside the cell, locally on the sample. Thus, the importance of using internal transducers to measure local strain is highlighted.

Tatsuoka et al. (1994) pointed out that to obtain accurate and continuous results for a strain range from about 0.0001 % to 1 % from static triaxial tests, at least the following requirements should be satisfied:

1) The load cell should be sensitive enough to measure very small loads and it should be placed inside the triaxial cell to be free from the effect of piston friction.
2) The axial displacement transducer should be sensitive enough to measure very small displacements and it should be free from the effects of both system compliance and bedding errors.

3) The time lag between measured stress and strain should be acceptably small.

4) To evaluate Poisson’s ratios and shear moduli, radial strains should be measured as accurately as axial strains.

Various internal strain measuring devices have been developed and the most commonly used are LDT (Local Deformation transducer), Hall effect transducer and submersible LVDT (Linear Variable Differential Transformer). Presti et al. (1994) compared the performance of these three types of devices. In his calibration experiments, the LVDT displayed the best stability while the Hall effect transducer was severely affected by electric noise. In tests performed on sand specimens, LVDT and LDT readings agreed. The two Hall effect transducers’ readings didn’t agree well with each other.

Scholey et al. (1995) also reviewed several types of transducers, among which the LVDT seemed to be the most promising. Compared to Hall effect transducers, LVDTs have the advantage of linear calibration. Inclinometers respond not only to axial strain but also rigid body rotation, thus making the readings unreliable. Other equipments are cumbersome to use.

As reported by Cuccovillo & Coop (1997), by using 2 RDP model D5/200 submersible LVDTs, satisfactory test results were obtained. The data showed that the LVDTs allow strains to be accurately measured around $10^{-5}$ mm, giving good agreement between the two transducers. The agreement between internal and external readings also
agreed well. The error induced if the transducers are not perfectly vertical is small; it would have to be inclined at an angle of 8° to give a 1 % error. At small strains, the electrical noise is the most important factor.

A local LVDT system similar to that of Cuccovillo & Coop has been developed and used in this research. Two axial local LVDTs (RDP model D5/200) shown in Figure 3-7, and one radial local LVDT (RDP model D5/100) shown in Figure 3-8 were used. A separate stable power supply was linked to the LVDTs, to reduce the noise caused by the fluctuations in laboratory power supply. The data logger samples the LVDTs at a higher frequency than other transducers and averaging the data over 50 points, which successfully reduced the electrical noise to $10^{-4}$ mm. Therefore, the local LVDTs became accurate enough to measure in the small strain range (0.001 % to 0.1 %) of a 100mm high soil sample.

Figure 3-9 shows the axial strain measured by local and outside LVDTs in the small strain range and the discrepancy between the outside LVDT and the two local LVDTs is clear. The outside LVDTs were measuring the axial strain of the loading machine and overestimated the axial strain of the sample by around 25%. The readings of the outside LVDT show much more fluctuation, though the trend line is a linear line, showing the triaxial machine is compressing at a constant strain. The two local LVDTs showed little fluctuation and agreed well, however, the trendlines are not straight, showing the sample was not deforming at a constant strain. Such difference clearly demonstrated the sources of error in Baldi’s analysis and the satisfying agreement of the two local LVDTs ensured the reliability of measuring small strain stiffness using submersible local LVDTs.
3.3.5 Data Acquisition and Control System

Water pressures (the cell pressure, the back pressure and the pore pressure) are measured using WF (Wykeham Farrance) 17060 pressure transducers with range from 0~1000 kPa. All three pressure transducers are calibrated by the GDS controller. A WF 17043 automatic volume change apparatus was fixed to the back pressure line to measure the water flow in or out the sample to compute change in volume. The axial load is measured inside the cell using a submersible WF 3kN load cell. An outside 25mm LVDT is also used to record the axial strain.

The three local LVDTs are connected to the computer via in-line amplifiers, RDP S7AC. All other transducers are linked to the computer via an 8-channel amplifier. The CIO-DAS1402/16 high speed 16 bit analog input board allows the computer to receive the signals from the transducers.

The control system allows the cell pressure, the back pressure and the pore pressure to be controlled by electro-pneumatic (EP) regulators, which are shown in Figure 3-10. The CIO-DAC 08/16 analog output board enables the computer to send out analogs to control the EP regulators.

All the input and output signals within the Bishop and Wesley stress path system are controlled by the software named Labtech Notebook-Pro (version 9.0). During a test, the results are shown on screen in various ways (digital or waveform) and at the same time, recorded on the hard disk.

3.3.6 GDS Stress Path Triaxial System

The above sections from 3.3.1 to 3.3.5 illustrate the Bishop and Wesley stress path triaxal
system in NUS Geotech laboratory. A new GDS stress path system is also used, which is shown in Figure 3-11 and Figure 3-12. This system is different in several aspects.

The loading ram in the triaxial cell is not driven by hydraulic pressure, but a loading machine connected to the computer. Thus, either load or displacement of the loading ram can be controlled. The cell pressure and back pressure are all controlled by GDS digital controller, which can be controlled by the computer. This feature makes the cell very versatile in performing stress path tests. There are also automated control modules in the controlling software GDSLAB including \( K_o \) consolidation using volume and displacement calculation. This GDS stress path triaxial system is mainly used to perform triaxial \( K_o \) consolidation tests.

### 3.3.7 Procedures of Triaxial \( K_o \) Test

Unlike oedometer tests, in which the \( K_o \) condition is imposed by the rigid boundaries, in triaxial \( K_o \) consolidation, the \( K_o \) condition is maintained by monitoring the relationship between axial displacement and volume change and using a feedback loop to maintain approximately a condition of zero lateral displacement. The soil sample is consolidated in such a way that

\[
\Delta V = A_o \Delta H
\]

in which

- \( \Delta V \): the volume change
- \( A_o \): the section area of soil sample
- \( \Delta H \): the change in sample height
In this Equation 3.4, $\Delta V$ is measured by back pressure GDS controller and $\Delta H$ measured by LVDT. As shown in Figure 3-13, in the loading stage, $\sigma'_a$ is increased first. The sample will deform and there will be a change in volume, $\Delta V_1$ and a change in sample height, $\Delta H_1$. Since $\sigma'_r$ is not increased accordingly, the sample will be somewhat actively sheared and the soil expand laterally so $\Delta V_1 < A_o \Delta H_1$. Then $\sigma'_r$ is increased and the sample elongated, which cause a new change in volume $\Delta V_2$, and a new change in sample height, $\Delta H_2$. $\sigma'_r$ is increased until

$$\Delta V = \Delta V_1 + \Delta V_2 = A_o \Delta H = A_o (\Delta H_1 + \Delta H_2)$$

(3.5)

is satisfied. The other way is to increase $\sigma'_r$ first and adjust $\sigma'_o$ accordingly to meet Equation 3.4.

### 3.4 $K_o$ Test in Oedometer Cell

#### 3.4.1 Oedometer Cell

Normal oedometer cells naturally impose the $K_o$ condition on the soil samples but lack the ability to measure the lateral stress. To investigate the $K_o$ values of soil, a special oedometer cell was made with slots on the sidewalls to install earth stress cells. The cell is made of four pieces of stainless steel assembled using bolts to ensure no lateral expansion. In Figure 3-14, one side of the cell is disassembled to show the slots and grooves on the sidewall. Earth stress cells can be embedded in these slots and wires in grooves to measure horizontal stresses during 1-D consolidation. In Figure 3-14, the stress cells are embedded in a panel which is placed at the bottom and this is for
calibration of the earth stress cells. The inner area of the cell is 150mmx150mm, with a height of 200mm.

There main problem associated with using a rectangle cell is that the walls are liable to deflecting and thus violating the $K_0$ condition. A cylindrical cell would not have such a problem, but then it is difficult to make sure the stress cells flush with the cylindrical inner wall. For practical reasons, the rectangle cell is selected and the deformation of the side wall is calculated as following. The side wall can be seen as a plate simply supported at two sides, which is under a distributed load. The maximum deflection at the center of the plate is:

$$\delta_{\text{max}} = \frac{5wl^4}{384EI}$$  \hspace{1cm} (3.6)

In which

- $w$: the distributed load
- $L$: the span (0.15m)
- $E$: Young’s modulus of the stainless steel (200x10$^6$ kPa)
- $I$: modulus of inertial of the plate section, $I=\frac{1}{12}bh^3$ (b=0.2m, h=0.016m)

The maximum vertical stress is around 2000kPa, which resulted in a horizontal stress of around 1000kPa. At that time the height of the soil is about 0.06m. So the distributed load is: $w=1000\text{kPa} \times 0.06\text{m}=6\times10^4 \text{ N/m}$. The calculated maximum deflection is 0.029mm. This corresponds to deformation to around 0.02% lateral strain in loading to 2000kPa axial pressure. Since the movement is small, the $K_0$ condition is believed to be maintained.
3.4.2 Behaviour of Earth Stress Cells in Soil

The stress cells used in the present project were SSK-P310S-10, which belong to the flexible diaphragm stress cell group. As shown in Figure 3-15, the cell is made of a stiff metal cylinder outer casing with a black, thin diaphragm attached to one side. The diameter of the cell is 8mm and the height is 4mm. According to the factory calibration chart, this type of cell is able to measure stress level up to 1000kPa.

It is important to understand the way earth stress cells work. The factory calibration chart is usually derived from the performance of earth stress cells in pressured water, as shown in Figure 3-16 (a). The cell is subjected to isotropic stress with $\sigma_1 = \sigma_2$, and the pressure distribution on the diaphragm is truly uniform. However, when the earth stress cell is embedded in soil, as shown in Figure 3-16 (b), the condition is different. The cell is now subjected to anisotropic loading with $\sigma_1 \neq \sigma_2$ and due to soil arching, the pressure distribution on the diaphragm is far from uniform. Thus, even at the same normal stress $\sigma_1$, the voltage output of the earth stress cell in Figure 3-16 (b) does not agree with that in the factory calibration condition. The ratio of the voltage output in soil to that measured in fluid is defined as registration ratio $R$ (Weiler and Kulhawy, 1982). Registration ratio $R$ is affected by many factors like stress cell properties and geometry, properties of soil, and environment.

According to Dunnicliff (1988), total stress measurement in soil falls into two basic categories: measurement within a soil mass (embedding earth pressure cells) and measurement at the face of a structural element (contact earth pressure cells). In these two types, embedding earth pressure cells are plagued by errors resulting from poor conformance. If a stress cell is embedded in the soil body, as shown in Figure 3-16 (b),
due to the fact that the stiffness of the cell is much greater than the soil around, it will change the stress field around it, making the situation very complicated. The performance of total stress cells in soft clays were studied in detail by Lee et al. (2002) and Juneja (2002). It is found that the registration ratio \( R \) varies with different soil type, backing plate and the presence of pore water pressure.

On the other hand, many researchers (Hvorslev, 1976; Brown, 1977; Weiler and Kulhawy, 1978, 1982; Boyce, 1983; Dunnicliff, 1988; Clayton and Bica, 1993) agreed that if the total stress cell is placed at the boundary of structure and soil mass (contact earth pressure cells) to measure the normal pressure, as shown in Figure 3-16 (c), many of the errors related with embedment earth pressure cells can be avoided and the normal stress can be measured with greater accuracy. In this case, since the cell is embedded in the structure and not in the soil body, it does not cause changes to the surrounding stress distribution. This is the reason why in the present study, the earth stress cells are embedded in the steel sidewalls to measure the lateral stress.

Dunnicliff (1988) listed several factors affecting measurement of contact earth pressure cells. The first is the number of cells, the more cells the better. In this project, 4 total stress cells were used and the readings taken are the average values of the four, thus reducing the scatter. The second factor is the temperature effects on cell and thermal sensitivity of total stress cells were also reported by Juneja (2002). In this project, since all the cells were used in a constant-temperature laboratory, the thermal sensitivity is not a problem. The third factor is the stiffness of cell: errors will be caused by excessive diaphragm displacement. The outer casing of SSK stress cells are made of steel and satisfy the requirement. The fourth factor is the irregularity of structure surface. Such
irregularity does not exist in the present project because the stress cells are embedded in flat and smooth steel panels and the diaphragms are flush with the surface.

Besides those mentioned above, another important factor affecting the measurement of stress is the laboratory calibrations, which will be explained in detail in the next section.

### 3.4.3 Earth Stress Cell Calibration

As can be seen from Figure 3-16 (c), though contact earth pressure cells avoids many problems associated with embedment earth pressure cells, the stress condition differs with Figure 3-16 (a) in fluid and soil arching on the diaphragm still exist. Therefore, registration ratio $R=1$ can not be achieved. Under such circumstances, according to Selig (1980), a direct calibration of the cell in the same soil in which it is subsequently to be placed is needed. Following the instruction, calibration is performed in each type of soil used (clean sand and sand with various percentage of clay) in $K_o$ consolidation.

During calibration, sand is first mixed with clay to form a slurry. Then the slurry is scooped into the cell. Stress cells are embedded in the plate as shown in Figure 3-14, but in this case the plate is on top of the soil with the stress cells facing down, as shown in Figure 3-17 (a). A seating dead load is applied for one day to ensure the contact between stress cells and soil. Thus a full contact between stress cells and soil is ensured. The loading begins using a loading machine and the pressure is calculated using the readings from the loading ring and the section area of the oedometer cell. The soil is
loaded continuously for two days to around 1000kPa, which is the maximum capacity of the stress cells, then unloaded.

Calibration results of these 4 cells are shown in Figure 3-18 to Figure 3-21. It can be seen that all these cells show essentially linear behaviour in both loading and unloading. Output voltage is compared with the factory calibration charts and registration ratios are shown in Table 3-2. As shown in the table, registration ratios in dry sand are considerately smaller than in saturated clayey sand. For a given stress cell, clay content from 20% to 40% does not affect registration ratio very much.

Cell 1 and cell 2 are older cells and have lower registration ratios compared with new cell 3 and cell 4. Before testing, a thin layer of silica glue was applied to these stress cells to prevent leaking. Since cell 3 and 4 have been used before, there was some silica glue remnant sticking to the cell. A new layer of silica glue was applied to cell 3 and 4, which resulted in a thicker silica layer around the cell. This may reduced the stiffness of the cell and resulted in a lower registration ratio.

In Table 3-2, registration ratios are referred as the ratio of the output voltage in the tests to the factory calibration voltage output, which was done in fluid. Since the fluid-calibration coefficient of a stress cell can drift due to different ambient temperature, strictly speaking, the fluid-calibration coefficient of a cell must also be re-determined. However, this is not necessary in this research. The factory calibration voltage output is only used as a reference to obtain ‘registration ratios’ of stress cells in different kinds of soils. Table 3-2 showed that it is important to calibrate the stress cell in each type of soils used. As long as the ‘registration ratio’ of a particular soil is applied to both effective vertical and horizontal stresses, the $K_o$ value obtained in that soil is still correct.
There are also clear signs of grain size effect of the ‘registration ratio’ measured in Table 3-2, as the R increases with the increase of clay content. When the soil grain size (which can be characterized by \( D_{50} \)) is big compared to the diameter of the cell (d), there is ‘point load’ effect, which resulted in non-uniform distribution of load on the diaphragm. Weiler and Kulhawy (1982) recommended a \( d/D_{50} \) value of 10 or greater for diaphragm type stress cell in order for such ‘point loads’ to yield the same result as if a uniform load is acting on the diaphragm cell. In this test, for clean sand the \( D_{50} \) is 1mm, so \( d/D_{50} \) is 8. When clay is added to the sand, \( D_{50} \) decreases so the ratio \( d/D_{50} \) increases to around 12 for 40% clay. Therefore, the grain size effect is shown in Table 3-2. However, as stated before, this does not affect the \( K_o \) values measured because the ‘registration ratio’ is applied to both effective vertical and horizontal stresses measured.

<table>
<thead>
<tr>
<th>Table 3-2</th>
<th>Registration ratios of earth stress cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean sand</td>
<td></td>
</tr>
<tr>
<td>Sand with 20% clay</td>
<td></td>
</tr>
<tr>
<td>Sand with 30% clay</td>
<td></td>
</tr>
<tr>
<td>Sand with 40% clay</td>
<td></td>
</tr>
<tr>
<td>Cell 1</td>
<td>0.523</td>
</tr>
<tr>
<td>Cell 2</td>
<td>0.538</td>
</tr>
<tr>
<td>Cell 3</td>
<td>0.634</td>
</tr>
<tr>
<td>Cell 4</td>
<td>0.616</td>
</tr>
</tbody>
</table>

3.4.4 Side Wall Friction

If stress cells are attached to the panel and the panel is placed down the soil, as shown in Figure 3-18 (b), the stress cell behaviour would be quite different. As shown in Figure 3-22 and Figure 3-23, stress cells show lower registration ratio in loading and hysteresis
behaviour during unloading. The reason for such a behaviour is suspected to be due to the side wall friction. Though grease is applied to the stainless steel sidewall, it can’t remove completely the friction. Thus, in loading, some of the load is carried by the oedometer cell, not the soil alone. Therefore, the vertical pressure at the bottom is less than the pressure applied on top of the soil. During unloading, the friction makes the soil difficult to swell, therefore may have added stress to the pressure at the bottom.

Comparing Figure 3-22 with Figure 3-18 and Figure 3-23 with Figure 3-21, the magnitude of sidewall friction can be calculated. The relationship of sidewall friction and vertical pressure is shown in Figure 3-23. It is proposed that in loading,

\[ F = 0.0002\sigma_v^2 + 0.00186\sigma_v \]  \hspace{1cm} (3.7)

In which

- \( F \): sidewall friction (in kPa)
- \( \sigma_v \): vertical pressure at the top of soil (in kPa)

and in unloading

\[ F = 0.0009\sigma_v^2 - 0.7052\sigma_v \]  \hspace{1cm} (3.8)

From the above discussion it can be seen that due to sidewall friction, the vertical pressure at the top is not equal to the vertical pressure at the bottom. When doing \( K_o \) consolidation with lateral stress measurement, the stress cells are attached to the sidewall as shown in Figure 3-17 (c) and the horizontal stress measured. When calculating vertical pressure at the place of stress cells, sidewall friction need to be corrected.

### 3.5 Summary

In this chapter test equipments and some test procedures were introduced. As can be seen,
in this research project, OA samples were first grouped using the classification tests and the framework shown in Figure 3-2. Then various tests were performed on these samples.

The next chapter, Chapter 4, will discuss the effect on the true behaviour of OA during the sampling process. Tests performed in Chapter 4 are mainly triaxial tests, including ‘perfect sampling’ stress path tests, ideal tube sampling strain path tests, and undrained triaxial compression tests. Chapter 5 focuses on $K_o$ of OA. Tests include triaxial $K_o$ tests and oedometer $K_o$ tests. In-situ pressuremeter tests are also carried out, which will be introduced in that chapter. Chapter 6 explores the undrained shear strength and stiffness of OA. Tests performed are mainly PSD tests and undrained triaxial shearing tests. Triaxial compression and extension with small strain stiffness measurement are also included.
(a) before immersion

(b) 1 minute after immersion
Figure 3-1 Dispersion test: (a) before immersion; (b) 1 minute after immersion; (c) 30 minutes after immersion; (d) 1 hour after immersion
Figure 3-2 Old Alluvium classification framework

Figure 3-3 Bishop and Wesley triaxial stress path cell (1975)
Figure 3-4  GDS digital controller

Figure 3-5  Possible connections for extension tests (after Baldi et al., 1988)
Figure 3-6  Sources of errors in external axial deformation measurement (after Baldi et al., 1988)

Figure 3-7  Submersible local LVDTs, Axial
Figure 3-8  Submersible local LVDTs, Radial
Figure 3-9  Axial Strain measured by Local and Outside LVDTs, in the Small Strain Range

Figure 3-10  Electro-pneumatic (EP) regulators
Figure 3-11  GDS stress path system, cell

Figure 3-12  GDS stress path system, data acquisition and control
Figure 3-13  Procedures of doing $K_0$ consolidation in triaxial cell, method i)

![Diagram showing procedures for doing $K_0$ consolidation](image)

Increase $\sigma'_a$, no change in $\sigma'_r$; lateral expansion change in volume, $\Delta V_1$

increase $\sigma'_r$, sample elongation change in volume, $\Delta V_2$

until $\Delta V = \Delta V_1 + \Delta V_2 = A_o \Delta H$

Figure 3-14  Equipment setup of the oedometer cell with horizontal stress measurement

![Equipment setup of oedometer cell](image)
Figure 3-15  Picture and section of flexible diaphragm stress cell

Figure 3-16  Stress conditions of earth stress cells (a) in fluid (b) embedment earth pressure cells (c) contact earth pressure cells
Figure 3-17  Placement of Stress Cells in the oedometer (a) stress cells embedded in top plate (b) stress cells embedded in bottom plate (c) stress cells embedded in side walls

Figure 3-18  Stress cell calibration in dry clean sand
Figure 3-19 Stress cell calibration in saturated sand with 20% clay

Figure 3-20 Stress cell calibration in saturated sand with 30% clay
Figure 3-21  Stress cell calibration in saturated sand with 40% clay

Figure 3-22  Stress cell behaviour at the bottom of dry clean sand
Figure 3-23  Stress cell behaviour at the bottom of saturated sand with 40% clay

Figure 3-24  Sidewall friction versus vertical stress