Refurbishment of Louisiana State University calibration chamber

Ardita Dushi
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REFURBISHMENT OF LOUISIANA STATE UNIVERSITY
CALIBRATION CHAMBER

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science in Civil Engineering

in

The Department of Civil and Environmental Engineering

By
Ardita Dushi
B.S., Bogazici University, Istanbul, Turkey, 2004
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ABSTRACT

This thesis focuses on the refurbishment of Louisiana State University calibration chamber. The testing equipments were checked and connected together to complete the calibration chamber system.

The data acquisition system was upgraded to National Instruments (NI) SCXI system. Therefore, a compatible computer program language in LabVIEW was developed. LabVIEW is a programming language developed by NI that reads the data from the instruments, displays the data in graphical form, calculates the desired parameters, commands the transducer to apply the required pressure to the specimen, and saves the data at the desired frequency.

The Anisotropic Modified Cam Clay Model (AMCCM) following non-associative rule was chosen as the soil model that is going to be used for simulation of piezocone penetration. One-Dimensional consolidation, K₀-loading and unloading, K₀-consolidated undrained compression and extension experiments were conducted to estimate the model parameters. The model was verified by comparing experimental results with the model predictions. The model showed to be in good agreement with the experimental results. The specimens for these tests were a mixture of 50% fine sand and 50% kaolin and were prepared using the slurry consolidation technique.
CHAPTER 1

INTRODUCTION

1.1 General

Cone penetration test (CPT) is a very important in situ test worldwide and especially for the State of Louisiana being a flat and coastal region. Data from the piezocone penetration tests (PCPT or CPTU) and the dissipation tests provide us with many in situ soil properties (Tumay and Acar 1985, Kurup 1993, Voyiadjis et al. 1994, Tumay et al. 1995). Piezocone is a cone penetrometer containing pore pressure sensors. The dissipation test is the measurements of the values of the pore water pressure with time during a pause in pushing the cone while the cone penetrometer is held stationary. Cone penetrometer is referred to as the assembly containing the cone, friction sleeve, any other sensors and measuring systems, as well as the connections to the push rods. Cone resistance, sleeve friction, pore water pressure, a continuous soil profile of subsurface stratigraphy, soil classification from cone tip resistance and friction ratio, and correlations for evaluations of relative density, friction ratio and unconfined compression strength are obtained from CPT soundings.

In situ tests are generally preferred over the laboratory experiments because laboratory tests are usually conducted on small, presumably undisturbed samples. The samples taken from the field have some degree of disturbance, which makes the parameters obtained from such tests not entirely representative of the in situ conditions. Moreover, the piezocone penetration test is simple, fast, reliable, economical, and requires less labor work. Portable systems are also available. For example, the Louisiana Transportation Research Center (LTRC) uses a 20 ton CPT truck for pile
capacity predictions, soil classifications, soil in situ properties, and subsurface settlement predictions. LTRC also uses a minicone truck for soil characterization, in situ shear strength properties, and pavement structures design.

The interpretation of the piezocone penetration tests is very complex and it is influenced by many variables such as the cone design, soil characteristics and the testing procedure (Tumay et al. 1982, Tumay et al. 1998, Kiousis et al. 1988, Voyiadjis et al. 1990, Voyiadjis et al. 1991, Kurup et al. 1994, Kurup and Tumay 1997). Controlled field and laboratory tests are necessary in order to achieve accurate interpretation of the data. Field calibration tests are limited due to the soil stress history and the soil inhomogeneity. Difficulty in controlling these parameters in the field makes the field tests not very accurate for the interpretation of the piezocone penetration tests. Laboratory tests have advantages because homogeneous and reproducible specimens can be prepared in the laboratory under known stress history and controlled boundary conditions (Section 6.5.2 presents a detailed procedure of how to produce homogeneous specimens in the laboratory). The most suitable laboratory test for the interpretation of cone penetration is the calibration chamber test (Chapter 2 and Chapter 3 present detailed information about calibration chamber). Calibration is referred as the generation of correlations between cone penetration resistance and the soil parameters of interest.

1988, Bunting 1990, McManus and Kulhawy 1991, Anderson et al. 1991, de Lima and Tumay 1991, Voyiadjis et al. 1991, Kurup 1993, Voyiadjis et al. 1993). Louisiana State University Calibration Chamber (LSU/CALCHAS) has been used to calibrate electronic cone penetrometers and other in situ testing equipment by simulating the isotropic and $K_o$ consolidation under different boundary conditions. For example, the 1.27 cm$^2$ Fugro-McClelland miniature electric cone penetrometer or known as the “Miniature Quasi-Static Cone Penetrometer” (MQSC) was calibrated by Tumay and de Lima in 1992 in LSU/CALCHAS. Currently, it is used in the design and construction control of roads and highways in the State of Louisiana.

1.2 Objectives of the Research

This project is a collaboration between Louisiana State University (LSU) and University of Wisconsin-Milwaukee (UWM). It consists of four main parts: (1) Refurbishment of the LSU Calibration Chamber (LSU/CALCHAS); (2) Calibration of a soil model to describe the behavior of the clayey soil that will be used in the calibration chamber tests; (3) Numerical simulation of the cone penetration using Finite Element Method (FEM); and (4) Full scale penetration of the cone in the LSU/CALCHAS (Figure 1.1).

The soil model chosen to describe the behavior of the clayey soil is the model proposed by Dafalias et al. (2003). It is called the Anisotropic Modified Cam Clay Model (AMCCM) following non-associative rule which is an extension of the Modified Cam Clay Model (MCCM) developed by Roscoe and Burland (1968). The difference between the AMCCM and the MCCM is that the response is anisotropic followed by non-associate flow rule. The parameters of the AMCCM following non-associative rule are calibrated using the data from the tests conducted at LSU. More information
about the model is presented in Chapter 6. The calibration chamber experiments with full penetration of the cone will be conducted by another researcher at LSU. The time required to perform a full scale penetration of the cone in the LSU/CALCHAS including the clayey specimen preparation and the specimen consolidation in the chamber is at least one month. The limited time restricted the performance of these tests. However, the calibration chamber tests will be conducted in the following months by another student. Meanwhile, the numerical approach using finite element technique (not included in this thesis) is carried by a PhD candidate at University of Wisconsin-Milwaukee (UWM). The finite element approach to interpret the piezocone penetration has many advantages over the bearing capacity theory (Meyerhof 1972), cavity expansion theory (Vesic 1972, Torstensson 1977) and the strain path method (Baligh 1985, Levadoux and Baligh 1986) because: (a) the piezocone geometry can be properly modeled; (b) the equilibrium equations are fully satisfied; and (c) the soil-piezocone interface friction can be addressed (Abu-Farsakh et al. 2003).
My contribution to this research is as follows:

1) Refurbishment of the LSU/CALCHAS by:
   - Upgrading the existing data translation DT-2801A to National Instruments (NI) SCXI system.
   - Changing the existing programming language from Turbo Pascal version 4.0 to LabVIEW 7.1.
   - Developing a computer program in LabVIEW to acquire, analyze and save data.
   - Finding, checking the working condition, adding, modifying and substituting whenever necessary parts of the calibration chamber system.
   - Wiring the sensors/transducers to the system
   - Calibrating the sensors/transducers
   - Connecting a new pile to the data acquisition system

2) Calibration of the soil model which includes:
   - Preparing specimens from the slurry consolidation to be used in the 1-D consolidation tests and the conventional anisotropically consolidated undrained triaxial tests.
   - Conducting 1-D consolidation test to obtain two compressibility parameters.
   - Conducting $K_o$-Consolidated loading and unloading, undrained anisotropically consolidated (conventional) triaxial compression tests ($CK_o$UC) and undrained anisotropically consolidated (conventional) triaxial extension tests ($CK_o$UE) to obtain the other parameters.
   - Checking the performance of the model by comparing its predictions
with the experimental results.

1.3 Thesis Outline

This thesis is organized into seven chapters. Chapter 2 represents a summary of the history of the calibration chambers worldwide and the history of the LSU/CALCHAS.

A full description of the testing equipment is given in Chapter 3. The testing equipment consists of the slurry consolidometer where cohesive soil samples are prepared from high water content slurry; the calibration chamber where the specimen is consolidated and then penetrated by a cone; a panel of control that controls the pressure flows into the chamber; a loading system for the slurry consolidometer; pore pressure transducers connected at the bottom of the specimen to measure the pore pressure at two elevations and at different radial distances; and a hydraulic push jack system used to push the cone into the specimen.

Chapter 4 presents a description of the data acquisition system that consists of the National Instrument NI SCXI system and the power supplies. The NI Measurement and Automation Explorer provide instrument measurements. A scale configuration is given for each sensor connected to the system. LabVIEW is the programming language developed that acquires, analyzes and saves data from the sensors. The end of this chapter presents a description of the configurations, calibrations and functions of the sensors.

A detailed experimental procedure is provided in Chapter 5. Information about soil properties and the experimental stages are presented. The experimental stages consist of slurry sample preparation, consolidation of the slurry into the consolidometer, saturation, anisotropically consolidation of the specimen in the
calibration chamber, and the cone penetration under controlled boundaries.

Description of the constitutive model is presented in Chapter 6. It gives detailed information on the samples preparation including the apparatus used to perform experiments. Consolidation and triaxial tests are conducted and the required parameters are calculated from the data of the tests. The clayey soil behavior is predicted and the predicted results are compared with the experimental results. Chapter 7 draws conclusions about this research and recommendations for future research.
CHAPTER 2

LITERATURE REVIEW

2.1 History of Calibration Chambers

Calibration chambers have been used to obtain empirical correlations between the cone resistance and the properties of soils. Penetration resistance is correlated to the peak friction angle (Houlsby et al. 1988), relative density (Schmertman 1976) and other soil parameters. Considering the lateral boundaries conditions, the calibration chamber can be of rigid-wall or flexible-wall. Large rigid-wall test pits imposing a boundary condition of zero lateral strain have been used in Germany and France by Melzer (1968) and Tcheng (1966) to perform calibration testing. The use of the rigid-wall calibration chamber was limited due to: (a) lateral stresses could not be controlled and (b) large influence on the cone penetration and frictional resistance of a penetrometer because of the large specimen size.

The idea of designing a flexible-wall calibration chamber started from the need to study the performance of the full-size penetrometer in the laboratory where the soil properties, stresses and strains can be measured and/or controlled accurately (Holden 1991). Holden and Lilley designed and built the first flexible-wall calibration chamber in 1969 by the Country Road Board (CRB) in Melbourne, Australia. The original CRB chamber housed specimens of 0.76 m in diameter and 0.91 m in height. The research on CRB chamber started with air-dry sand benefiting from the simplicity of producing uniform specimens by pluvial deposition. The chamber was designed with double wall cylinders leading to a cavity space formed between the two walls. To simulate the field conditions of zero lateral strain the cavity pressure was maintained equal to the
developing lateral sand pressure so that the inner wall of the double wall chamber does not move.

During the tests on the dense sands on the original calibration chamber, it was noticed that a larger calibration chamber was needed to calibrate the penetrometer. In 1971 Holden built the second calibration chamber at the University of Florida known as “Skippy” calibration chamber (Figure 2.1). The chamber housed a specimen of 1.22 m in diameter and 1.22 m in height. Calibration tests were performed to establish mainly engineering properties of Edgar and Ottawa sand and correlations between the penetration resistances of Fugro electrical friction cone penetrometer (de Ruiter 1971) and Dutch mechanical friction cone penetrometer (Begemann 1969).

In 1973 another modified CRB chamber was designed and built at Monash University in Australia (Chapman 1974). The specimen’s height had increased to 1.82 m. The chamber could obtain a plateau in the sleeve friction resistance under all boundary conditions (Table 2.1) when testing a 10 cm$^2$ electrical penetrometer. More data could be obtained from each sample since automatic recordings of all transducers were also available (Figure 2.2).

Correlations of cone penetration resistance with in situ strength and deformation properties of sand from North Sea were in the interest of the Norwegian Geotechnical Institute (NGI). Taking into consideration the difficulties of a large sample height of the Monash calibration chamber, the NGI decided to build a chamber based on CRB chamber housing a sample of with 1.22 m diameter size and with a height of 1.5 m. NGI adopted the CRB design of electrical friction cone penetrometer for both 5 cm$^2$ and 10 cm$^2$ sizes (Holden 1974). Holden (1976) proposed the idea of allowing the sand to fall freely through a large drop onto two diffusers maintained at a small constant
Figure 2.1 Skippy calibration chamber (Holden 1971)
Figure 2.2 Monash calibration chamber (Chapman 1974)
Table 2.1 Boundary conditions of a flexible wall calibration chamber

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<tr>
<td>BC4</td>
<td>---</td>
<td>0</td>
</tr>
</tbody>
</table>

The fifth calibration chamber was designed in 1978 from the need to correlate the cone penetration resistance with the liquefaction potential of sand deposits under the advice of Holden. Italian Electricity Board (ENEL) designed a modified version of CRB known as CRIS calibration chamber, but with same size as NGI (Figure 2.3). A volume change measurement device and advanced methods for saturating samples (Belloti et al. 1982, Parkin 1982) were included in the design. Calibration tests were performed in dry quartz sand using a 10 cm$^2$ Fugro electrical cone penetrometer (Baldi et al. 1982).

A sixth calibration chamber, ISMES chamber, was built again in Italy in 1981 under the direction of Baldi. The upgraded chamber compared with the ENEL calibration chamber included: (a) production of loose sand under high vacuum; (b) linear variable displacement transducers (LVDT) to measure deformations; (c) a base piston guidance system to prevent it from sticking; and (Parkin 1986).

Several other calibration chambers have been built since then. Calibration chambers to test cohesive soils have been less popular than the ones to test cohesionless soils due to time-consuming and laborious process involved during the preparation of
Figure 2.3 CRIS calibration chamber (Belloti et al. 1982)
the large specimens. Purdue University was the first to develop a calibration chamber to test cohesive soils (Huang 1986). Small specimen size of 0.203 m in diameter and 0.337 m in height could be tested. Clarkson University used the chamber on cohesive specimens of 0.525 m in diameter and 0.812 m in height. Large cohesive specimens of 1.4 m in diameter and 2.1 m high have been prepared at Cornell University to test model drilled shaft foundations (McManus et al. 1991). University of Sheffield also has built a calibration chamber to test self-boring pressuremeters (Anderson et al. 1991). It could test only isotropically consolidated specimens since a single wall was used in the design instead of a double wall where $K_o$ conditions can be simulated. An extensive list of the currently in use calibration chambers around the world is provided by Ghionna and Jamiolkowski (1991) and summarized in Table 2.2.

2.2 Calibration Chambers on Cohesive Soils

The concept of producing large size cohesive soil specimens for use in the calibration chamber tests originated from the “stress-free” reference state. It is the state at which the slurry transforms from a fluid like material (with negligible soil particles) to a material whose behavior is influenced by particle interactions (Monte and Krizek 1976). Specimens from slurry consolidation were prepared using this concept. Slurry consolidation is a process where the dry cohesive soil is mixed with high water content and then consolidated under $K_o$ conditions in the consolidometer under desired vertical stress. Mixing the cohesive soil with a water content of 2 to 2.5 times the liquid limit of the soil is appropriate to produce uniform, homogeneous and repeatable soil samples (Krizek and Sheeran 1970).

Preparation of large specimens to be tested in the calibration chamber requires a two stage process. In the first stage the slurry is prepared and then consolidated inside a
Table 2.2 Calibration chambers in the world (Ghionna et al. 1991)

<table>
<thead>
<tr>
<th>Calibration Chamber</th>
<th>Specimen Diameter (m)</th>
<th>Specimen Height (m)</th>
<th>Boundary Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Owner</td>
<td>Location</td>
<td>Top</td>
<td>Bottom</td>
</tr>
<tr>
<td>Country Roads Board</td>
<td>Melbourne, Australia</td>
<td>0.76</td>
<td>0.91</td>
</tr>
<tr>
<td>University of Florida</td>
<td>Gainesville, U.S.A.</td>
<td>1.22</td>
<td>1.22</td>
</tr>
<tr>
<td>Monash University</td>
<td>Melbourne, Australia</td>
<td>1.22</td>
<td>1.82</td>
</tr>
<tr>
<td>Norwegian Geotechnical Institute</td>
<td>Oslo, Norway</td>
<td>1.22</td>
<td>1.50</td>
</tr>
<tr>
<td>ENEL-CRIS</td>
<td>Milano, Italy</td>
<td>1.22</td>
<td>1.50</td>
</tr>
<tr>
<td>ISMES</td>
<td>Bergamo, Italy</td>
<td>1.22</td>
<td>1.50</td>
</tr>
<tr>
<td>University of California</td>
<td>Berkeley, U.S.A.</td>
<td>0.76</td>
<td>0.80</td>
</tr>
<tr>
<td>University of Texas at Austin</td>
<td>Austin, U.S.A.</td>
<td>Cube 2.1x2.1x2.1</td>
<td>Flexible Flexible Flexible</td>
</tr>
<tr>
<td>University of Houston</td>
<td>Houston, U.S.A.</td>
<td>0.76</td>
<td>2.54</td>
</tr>
<tr>
<td>North Carolina State University</td>
<td>Raleigh, U.S.A.</td>
<td>0.94</td>
<td>1.00</td>
</tr>
<tr>
<td>Louisiana State University</td>
<td>Baton Rouge, U.S.A.</td>
<td>0.55</td>
<td>0.80</td>
</tr>
<tr>
<td>Golder Associates</td>
<td>Calgary, Canada</td>
<td>1.40</td>
<td>1.00</td>
</tr>
<tr>
<td>Virginia Pol. Inst. and State Univ.</td>
<td>Blacksburg, U.S.A.</td>
<td>1.50</td>
<td>1.50</td>
</tr>
<tr>
<td>University of Grenoble</td>
<td>Grenoble, France</td>
<td>1.20</td>
<td>1.50</td>
</tr>
<tr>
<td>Oxford University</td>
<td>Oxford, England</td>
<td>0.90</td>
<td>1.10</td>
</tr>
<tr>
<td>University of Tokyo</td>
<td>Tokyo, Japan</td>
<td>0.90</td>
<td>1.10</td>
</tr>
<tr>
<td>Clarkson University</td>
<td>Postdam, U.S.A.</td>
<td>0.51</td>
<td>0.76</td>
</tr>
<tr>
<td>University of Sheffield</td>
<td>Sheffield, England</td>
<td>0.79</td>
<td>1.00</td>
</tr>
<tr>
<td>Cornell University</td>
<td>Ithaca, U.S.A.</td>
<td>2.10</td>
<td>2.90</td>
</tr>
<tr>
<td>Waterways Experimental Station*</td>
<td>Vicksburg, U.S.A.</td>
<td>0.80 - 3.00</td>
<td>Variable</td>
</tr>
<tr>
<td>National Chiao-Tung University*</td>
<td>Hsinchu, Taiwan, R. O. C</td>
<td>0.51</td>
<td>0.76</td>
</tr>
<tr>
<td>National Chiao-Tung University*</td>
<td>Hsinchu, Taiwan, R. O. C</td>
<td>0.79</td>
<td>1.60</td>
</tr>
</tbody>
</table>

*Hsu and Huang 1999

Slurry rigid wall consolidometer. Large volume changes leads from the use of the rigid wall consolidometer. The second stage involves the removal of the specimen from the slurry consolidometer and transferring it to the calibration chamber where the soil sample is reconsolidated under isotropic or anisotropic conditions (Huang et al. 1988). The main problems during the specimen preparation are the difficulties in mixing, handling, time consuming, requirement of more than two people in the process, instrumentation of the transducers to measure the pore water pressure change.
2.3 LSU Calibration Chamber

Among the calibrations chambers available in the world is also the calibration chamber at the Louisiana State University known as (LSU/CALCHAS). It was designed by Tumay and de Lima (1992) and Kurup (1993). The main purpose for building LSU/CALCHAS was to test cone penetrometers under different boundary conditions which are controlled via the pressure transducers connected to it. Initially the chamber was designed to test compacted specimens (de Lima 1990). The servo-controlled LSU/CALCHAS consisted of: flexible double-wall calibration chamber, a panel of controls, cone penetrometer, hydraulics and chucking system, compactor and compaction mold, penetration depth and measurement system, auxiliary system (Figure 2.4 and 2.5). It can test specimens of 0.525 m in diameter and 0.815 m in height simulating the $K_o$ condition under the four penetration boundary conditions (Table 2.1).

Modifications were done to the LSU/CALCHAS in order to test clay specimens. Kurup (1993) designed slurry consolidometers to prepare cohesive specimens by the same method as described in Section 2.2 (Figures 2.6 and 2.7). A loading system of a reaction frame with a single acting hydraulic cylinder (jack) powered by a hydraulic pump and bolted to the top lid was added to the LSU/CALCHAS. A back pressure system to ensure the saturation of the specimens was included in the design. The use of cohesive soils enabled the instrumentation of the pore pressure transducers at the bottom plate of the specimen. Pore pressure measurements were recorded during both stages of the specimen consolidation.

Penetration tests under different boundary conditions have been performed on the LSU/CALCHAS by Tumay and de Lima (1992) on compacted specimens containing 80% fine sand and 20% kaolinite. Kurup (1993) tested two different clay
Figure 2.4 Louisiana State University Calibration Chamber (LSU/CALCHAS) (Tumay and de Lima 1992)
mixtures: (1) mixture of 50% Edgar fine sand and 50% kaolin; and (2) mixture of 67% fine sand and 33% kaolin. The specimens were prepared from the slurry consolidation. Determination of consolidation characteristics in fine soils were evaluated by Lim (1999) using piezocone tests on isotropically and anisotropically consolidated clay mixtures. Kim (1999) focused on the effect of anisotropy and rate of penetration during cone penetration.
Figure 2.6 Slurry consolidometer system (Kurup 1993)
Figure 2.7 Flexible wall calibration chamber (Kurup 1993)
CHAPTER 3

DESCRIPTION OF THE TESTING EQUIPMENT

3.1 Introduction

LSU/CALCHAS was initially built at the laboratory of the engineering building of LSU (CEBA Building). Later on, the system was transferred to LTRC. Lim and Kim (1999) were the last researchers to perform tests on LSU/CALCHAS (Figure 3.1). The whole system was then moved back to CEBA in 2001 and no work has been done since then. The main problem after the movement to CEBA was that all parts of the system were collected in a place different from the previous one. Besides, they were mixed with the old parts. The first step to put the system in operation was to go through the entire previous dissertations and reports written by earlier researchers to find out how the components of the LSU/CALCHAS system are assembled together for operations. The next step was to check how do these components work and connect them together. Modification and substitution of components was done by the author whenever necessary. Sensors/transducers were wired to the system and calibrated. The existing data translation DT-2801A was upgraded to National Instruments NI SCXI system. The data acquisition was upgraded to a new software system: Measurement and Automation Explorer which acquires the signals and saves the information about each transducer, and LabVIEW code was developed to read the instruments, command transducers to give a desired pressure and display the results in graphical form in real time.

The main components of LSU/CALCHAS are: slurry consolidometer, calibration chamber, panel of controls, hydraulics and chucking system and auxiliary system.
3.2.1 Slurry Consolidometer

The slurry consolidometer is a rigid-wall system used to prepare homogeneous and repeatable specimens with high water content. The slurry is consolidated under $K_0$ conditions. The slurry consolidometer of LSU/CALCHAS was designed by Kurup (1993). It consists of two green PVC cylinders which are 812 mm high, 15 mm thick and have an inside diameter of 512 mm (Figure 3.2). During the slurry consolidation phase the cylinders are placed on top of each other. They are held together by six steel rods which are bolted to the top lid placed on top of the upper cylinder and a base frame. The final height of the specimen will be at least as the height of a PVC cylinder. Because the initial height of the slurry is large, the top PVC cylinder serves as storage only. The lower tube can be split longitudinally into two halves. The purpose of it is to be able to get the specimen out of the cylinder without using any extruder to avoid disturbance and to make it easier to transfer the sample from the slurry consolidometer.
to the calibration chamber. The two halves are held together by a metal frame which surrounds them. The metal frames are bolted together using the same torque, in order to have a good sealing of the membrane which is 1.59 mm thick. The inside surface of the lower tube is lined with sand paper to help the membrane against slippage which may be caused during the consolidation. The ends of both cylinders are lined with rubber gasket to protect the membrane.

The cylinders are easily moved with the help of a base frame with four rollers. They are placed on top of an aluminum plate which will also be the same plate used in the calibration chamber. The base plate is 525 mm in diameter and 25 mm thick. It consists of holes eight of which are used for pore pressure measurements and the rest are used for drainage and back pressure saturation. The slurry is allowed to drain at top and bottom to consolidate. The load necessary for the consolidation is transferred to the slurry through a piston rod connected to an aluminum piston plate placed on top of the slurry (Figure 3.3). Porous papers are attached to base plate (upper surface) and aluminum piston plate (bottom surface) to prevent the soil from migration and/or clogging the holes on the base plate. The consolidometer is designed to consolidate a specimen up to a maximum vertical stress of 552 kPa (Kurup 1993).

3.2.2 Pore Pressure Transducers

Eight holes in the base plate are used for pore pressure measurements. Each hole is connected to a pore pressure transducer which can measure up to 1380 kPa. Each pressure transducer consists of a stainless adaptor (duct) (Figure 3.4). They are connected at the base plate at different radial distances. To measure the pore water pressure, the transducer is extended from the base plate into the specimen through stainless steel hypodermic tubes at two different elevations. These tubes are 0.23 mm
Figure 3.2 Slurry consolidometer
thick and 1.2 mm inside diameter. To avoid the soil migrate into the tubes, the tips of the tubes were sealed with small porous stones. There is a high possibility that air is entrapped inside the stainless adaptor. To avoid this situation, the ducts with the hypodermic tubes and porous stones attached need to be saturated before starting a test. The rest of the holes of the base plate (mainly the other three) are used for drainage and/or back pressure saturation.

### 3.2.3 Loading System of the Slurry Consolidometer

The slurry consolidation pressure is provided by a single acting hydraulic cylinder (push jack) powered by an air-hydraulic pump (Figure 3.5). It is attached to a metal reaction frame bolted to the top lid. This pressure is transferred to the slurry through a steel piston rod. The piston rod has an aluminum piston plate attached to one end and is placed on top of the slurry. The other end of the piston rod comes out of the
top lid, and is pushed downwards by the hydraulic cylinder piston. The oil pressure of the push jack is increased as the air pressure (which is controlled through a regulator) is applied to the air-hydraulic pump. The pump circles automatically whenever the pressure drops below the desired level. This is a very important feature since the preparation of the sample from the slurry consolidation requires a long time. It is very important that the consolidation pressure is maintained constant through the whole consolidation process. A Linear Variable Displacement Transducer (LVDT) is connected to the piston rod. Care is taken such that the LVDT does not go out of range, because of the high displacement which is a result of relatively large initial slurry.

3.3 Calibration Chamber

LSU/CALCHAS is a double wall flexible chamber. It consists of two sections: the specimen cell and the piston cell. The specimen cell is provided by two cylindrical shells which are made of rolled stainless steel 304 plates. The space between the two
walls is referred as the “outer specimen”. The walls are 6.35 mm thick, 910 mm high and can withstand a maximum pressure of 1440 kN/m² (figure 3.6). The inner diameters of the inner and outer walls are 560 mm and 580 mm, respectively. The walls can house a specimen of 525 mm in diameter and 815 mm high. The space between the inner wall and the soil membrane is referred to as “inner specimen”. The membrane is sealed to the specimen top and bottom plates by 4 O-rings. The specimen top and bottom plates are made of 6061 T-6 aluminum. They have the same diameter of 525 mm and have a height of 38.1 mm 63.5 mm, respectively. The sample bottom plate is the same base plate used in the slurry consolidation. The sample bottom plate stands on a 525 mm in diameter piston made of 6061 T-6 aluminum. The piston is connected to the chamber top lid which is placed on top of specimen top plate via 12 stainless steel rods 12.7 mm
in diameter. The rods are tightened using the same 70 Newton-meter torque. They also serve as reaction frame during consolidation and penetration stage. The chamber top lid is made of 6061 T-6 aluminum and is 635 mm in diameter and 38.1 mm in height. The top lid and top plate allow the specimen to be penetrated in three locations. During specimen reconsolidation in the piston cell, these holes are closed by adaptors. Water lines are connected to both inner and outer specimen cells.

Figure 3.6 Inner wall of the chamber

The piston cell has the same diameter and material as the specimen cell (Figure 3.7). It is a 430 mm high double wall cylinder whose inside cell is kept free for the pore water pressure transducers and the cables. The piston walls have bottom plates attached to them. The bottom piston plate has a hollow piston shaft attached which is 63.5 mm
in diameter and 406 mm long. The chamber bottom plate which is 635 mm in diameter and 38.1 mm high supports the piston inner cell. It also carries a bearing shaft that allows vertical movement of the piston. The chamber bottom plate, the piston cell and the piston cell ring are kept together by 12 stainless steel 304 rods 12.7 mm in diameter. They are tightened using the same 47 Newton-meters torque. The space between the two walls of the piston and some grooves at the bottom of the piston inner cell are filled with deaired water via water lines. The vertical loading is provided by pressurizing the water in the piston cell causing the piston to be raised upward. The vertical deformation of the specimen is measured using an LVDT connected to the piston shaft. The volume change is measured visually by an air-water system connected at the panel of controls (Section 3.4). Another air-water system furbished with a pressure regulator and a pressure gauge is connected directly to an air-line (Figure 3.10). Water lines coming from it are connected to the top and bottom sides of the specimen to provide saturation to the specimen.

![Figure 3.7 Piston Cell](image)

Figure 3.7 Piston Cell
3.4 Panel of Controls

The control panel is a wooden board which measures 122 mm x 196 mm, and attached to it are all the sensors controlling the calibration chamber (Figures 3.9 and 3.10). It consists of five SenSym ST2000 pressure sensors with an output voltage range of 1 to 6 V. They are labeled on the panel as S1, S2, S3, S4 and S5. S1 measures the outer cell pressure, S2 and S3 measure the inner cell pressure, and S4 and S5 measure the vertical pressure. S2/S4 and S3/S5 differ in the capacity ranges. For a pressure less than 30 psi, S2/S4 is used. For a pressure up to 120 psi, S3/S5 is used. The panel has also two Fairchild transducers (F2 and F4) and two Bellofram pressure regulators (F1 and F3). F2 and F4 are electro-pneumatic transducers for independent control of the vertical (F2) and horizontal (F4) pressures. These electro-pneumatic transducers convert the electric signal to a linear pneumatic signal. They are connected to a PC computer through a data acquisition board (NI Instruments). They use an input range of 0 to 10 DC volts. F1 and F3 can be used for manual control of the vertical (F1) and horizontal (F3) pressures. They are mainly used in the $K_o$ consolidation phase. There are four Marsh Gauges (G1, G2, G3, and G5) to visually read the stresses at the
chamber, inner cell, outer cell, and vertical pressure.

The panel includes two Fairchild Model 10 BP Back pressure regulators labeled as BP1 and BP2 (Figure 3.10). Their main function is to provide protection against over pressure in the downstream portion of the pneumatic system. They act as relief valves for inner and outer specimen, and piston cells during penetration phase, where the boundary conditions require keeping a constant pressure in the specimen and piston cells. They vent to atmosphere when the downstream portion pressure exceeds the set pressure. The panel is furnished with two air-water systems. They measure the air pressure, going from the air line to the air-water cylinder and the water pressure.
developed in the space between the specimen and the inner specimen cell. The air-water systems consist of two PVC cylinders, with high pressure caps glued to the top and bottom (Figure 3.10). One of the cylinders placed on the left side of the panel, is connected to the specimen cell. It is 304.8 mm high and 127 mm in diameter. The other cylinder lies on the floor next to the panel with top air line connected to the panel on D1 and bottom water line connected to the panel on D2. The cylinders are filled with 90% water. The rest 10% is filled with air. Oil is inserted in the cylinders while filling them with water, to minimize the air/water absorption. The top line of the cylinders is an air line and the bottom line is a water line. There are two bleed valves on top and bottom of the cylinders to release the air out or fill/drain the cylinder.

All the parts included in the panel are connected to each other via copper tubing, used to minimize the volume changes in the system. Air pressure lines have a diameter of 6.35 mm. Water pressure lines have a larger diameter since they are used not only to pressurize the piston and sample cells, but also to fill them with water at the beginning of the consolidation phase. Three air pressure lines are included on the control board. There are many valves and quick connectors on the panel to control the pressure flow. Referring to Figure 3.10, A1 to A5 are three way valves. They permit the fluid flow to two different directions. Valve A4 is connected to the reservoir which fills the piston cell with water before the start of the test (Figure 3.11). The other valves are on-off valves. The panel is connected to the calibration chamber with copper tubes which pass along the wall. Three valves link the water pressure lines from the left corner of the panel to the chamber connecting the outer specimen cell, inner specimen cell and the piston cell. Some pressure lines also pass from the back of the control panel. They are denoted by dashed lines on the schematic view of the panel of control (Figure 3.10).
Figure 3.10 Schematic of panel of controls

A: 3-Way Ball Valve (A4 is connected to the reservoir)
B, V: On-off Valve
BP: Fairchild Back Pressure Regulator (BP1, 2; Range: 2-150 psi)
D1 & D2: are connected to the 2nd Air-Water System
F: Bellofiam Pressure Regulator (F 1, 3; Range: 0-125 psi)
F: Fairchild E/P Transducer (F 2, 4; Range: 3-120 psi)
G: Marsh Process Pressure Gauge (G 1, 2, 3, 4; Range: 0-100 psi)
S: SenSym Transducer (S 1, 2, 4; Range: 0-30 psi, S 3, 5 Range: 0-100 psi)
3.5 Hydraulic and Push Jack System

The hydraulic and push jack system is used during the cone penetration stage of the testing (Figures 3.12 and 3.13). It allows for the penetration up to a 10 cm$^2$ cross-sectional area. It consists of a dual piston attached to a metal collapsible frame of 2.410 m in its extended height. The system is mounted on top of the top lid of the chamber. When the frame is extended, two long metal pieces are placed on the left and right side of the frame. The cone penetrates the specimen continuously up to a depth of 640 mm on a single stroke. This feature of a single stroke is necessary in saturated cohesive soils. Otherwise, after each stroke, pore pressure dissipation, pile setup or stress relaxation may occur. The hydraulic system is provided with a chucking system that assists in holding the cone during penetration into the soil or extraction from the soil. A
depth decoding system is necessary for the measurement of the penetration depth. It consists of a metal disk, an optical sensor and a light emitting diode. Holes are drilled at equal distances on the circumference of the metal disk. The distance between two consecutive holes represents a penetration of 2 cm. During penetration, the disk is brought close to the cone. As the cone penetrates, the disk rotates generating pulses which are displayed on the computer screen.

Figure 3.12 Hydraulic push jack
Figure 3.13 Hydraulic pump and the controlling handle
3.6 Miniature Model Pile

The miniature model pile is designed to measure the friction distribution along the shaft of an instrumented pile segment and pore water pressure at certain locations (Figure 3.14). It is about 2 m long and has a diameter of 25.4 mm and an apex angle of 60°. There are three axial load cells measuring the total load exerted between it and the tip of the pile. Thus, the skin friction is measured at three different segment lengths. Two pore pressure transducers are used to measure the pore water pressure. Fine porous elements are used to resist the lateral soil pressure while allowing the water pressure to be exerted on the pore pressure transducer. Two pressure transducers are located midway between the adjacent load cells. The total lateral pressure which is the sum of the soil pressure and the water pressure is measured using an instrumented load post fitted with a load cap at each end. The load post is allowed to float free restrained only by the pressure exerted on the load cap.

3.7 Auxiliary Materials Used in Testing

Two 150 liter polyethylene containers are available for mixing the cohesive soil with water. An electric mixer assists in mixing the slurry. A funnel and a hose are used to pour the slurry into the consolidometer. The testing area is equipped with a trolley crane system. Two mechanical cranes with a capacity of two ton each are part of the system. They roll over two transverse rail beams and are used for lifting the specimen and placing it properly on top of the chamber piston. A scale of one ton maximum load capacity is placed on the two ton crane and used for measuring the weight of the soil (Figure 3.15).
Figure 3.14 Miniature model pile
Figure 3.15 Auxiliary system
CHAPTER 4

DESCRIPTION OF THE SOFTWARE AND INSTRUMENTATION

4.1 Data Acquisition System

The data acquisition (DAQ) system consists of the National Instruments (NI) SCXI system and the power supplies. The National Instruments SCXI-1000DC is a four-slot chassis that houses the NI SCXI modules. It is powered by 9.5 to 16 VDC, a SCXI-1382 battery pack and SCXI-1383 power supply. Three slots of the SCXI-1000DC chassis have a SCXI-1141 module each and one slot has a SCXI-1180 module (Figure 4.1). The SCXI-1141 module is for Analog Input type measurements and has an 8-channel programmable elliptic low pass filter. The SCXI-1180 module is an accessory with feedthrough panel. Direct-Mount SCXI terminal blocks, where the signals are received, are attached directly to the front of the SCXI modules so that the Input/Output (I/O) signals are connected to the system. The SCXI-1305 terminal connectors are attached to the SCXI-1141 modules and SCXI-1302 terminal connector is attached to the SCXI-1180 module (Figure 4.2). The analog signals are connected from the SCXI to a plug in the DAQCard -6062E. Another power supply connected to the NI is Hewlett Packard 6214B and provides 10 Volts. It provides the required excitation voltage and receives the signal voltages. NI utilizes the NI Measurement and Automation Explorer, and the LabVIEW software.

4.2 Measurement and Automation Explorer

The information about the instruments is entered via the Measurement and Automation Explorer (MAX) version 3.1. MAX interfaces with the SCXI data acquisition system to provide measurements from the instruments. The main components
are: Data Neighborhood, Devices and Interfaces, and Scales (Figure 4.3). The devices are already explained in the previous section.
Figure 4.2 Terminal blocks attached to the modules of the National Instruments system
4.2.1 Data Neighborhood

There are three options to set up the channel configuration in the data neighborhood: Traditional NI-DAQ Virtual Channels where the channels can be set up individually, NI-DAQmx Tasks where the channels can be grouped in similar tasks, and NI-DAQmx Global Channels where global channels can be set up and can be used in any task. For this thesis the NI-DAQmx Tasks is used to group the channels into two tasks. The first one is named “All_Sensors” and includes 22 instruments. The second task is named “Output” and includes 2 instruments. All the instruments in the “All_Sensors” task are set up through SXCI-1141 modules. The two instruments in the “Output” task are set up in DAQCard-6062E.

When creating a new task it is important to select the right measurement type for that task. The “Output” task is created using the Analog Output Voltage measurement. The “All_Sensors” task is created selecting Analog Input Voltage measurement (Figure 4.4). The minimum and maximum input voltage range is set individually for each channel added. The scale for each instrument is also added to the configuration. Each instrument is set up in a certain module and a certain channel (Figure 4.5).

![Figure 4.3 MAX configuration](image)
Figure 4.4 Channel list of the “All_Sensors” task with emphasis on the input voltage range and scale of S1 channel

Figure 4.5 “All_Sensors” task with the channels set up in the modules
4.2.2 Scale Configuration

A linear scale of the form \( y = mx + b \) is used for each instrument, where \( m \) is the slope and \( b \) is the intercept (figure 4.6). The scales for all the instruments are included in Section 4.3. The steps to calibrate an instrument are as follows:

- Choose a channel from the list, say S1. Make sure that the transducer attached to that channel is connected, the proper voltage is set on the power supply, and NI and power supply are turned on.
- Select “Task Timing” and from the generation mode select “Continuous”.
- Click on “Test” (Figure 4.5).
- A window will be displayed where the value from the sensor being tested is displayed in the graph (Figure 4.6a).
- Choose the option where data is displayed as numerical value (Figure 4.6b).
- Take that voltage reading when the pressure is zero.
- Let the water flow in that transducer.
- Make an increment of the pressure manually through the F1 or F3 and observing it from the corresponding gauges.
- Take the reading of the voltage which you read from the computer, and the pressure on the gauge.
- Take the readings for other pressure increments.
- Plot the readings to find the slope and intercept of the line and set the obtained values on the scale configuration (Figure 4.7).

A linear scale of the form \( y = mx + b \) is used for the global channels F2 and F4 also, but the procedure of calibrating the instrument is different from the previous one. This is because the type of the sensor alters. The pressure in this case is controlled by the
Figure 4.6 (a) S1 value displayed on graph (b) S1 value displayed numerically

Figure 4.7 Scale configuration
user via these transducers. The steps to calibrate a F2 and F4 are as follows:

- Choose a channel from the “Output” task, say F2. Make sure that the transducer attached to that channel is connected, the proper voltage is set on the power supply, and NI and power supply are turned on.
- On the panel of control: turn A5 to the right and open B14 and B17 (when testing F4: turn A1 to the right and open B5 and B11).
- Select “Task Timing” and from the generation mode select “1 Specimen” on demand.
- Click on “Test” (Figure 4.8).
- A window with the two channels will be displayed (Figure 4.9).
- Enter a voltage value on the box and press on “Start” button.
- Read the pressure value from G2 (read the pressure from G1 when testing F4). Make sure the pressure has stopped increasing when the reading is taken.
- Set another input value and take readings. Make sure that the maximum voltage value is not exceeded.
- Plot the readings to find the slope and intercept of the line and set the obtained values on the scale configuration as previously.

4.3 Instrumentation

A detailed description of the LSU/CALCHAS instruments is provided in Table 4.1. SenSym sensors are connected with male connecters at the other end and plugged to a bracket with female connectors (Figure 4.10). Tables 4.2 and 4.3 provide information about these sensors.
Figure 4.8 Channel list of “Output” task

Figure 4.9 Voltage input while calibrating F2 channel
Table 4.1 Information about the instrumentation

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Model</th>
<th>Label</th>
<th>Range (psi)</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>SenSym</td>
<td>Transducer</td>
<td>ST 2000</td>
<td>S1</td>
<td>0 - 30</td>
<td>Outer Pressure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>S2</td>
<td>0 - 30</td>
<td>Inner Pressure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>S3</td>
<td>0 – 100</td>
<td>Inner Pressure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>S4</td>
<td>0 - 30</td>
<td>Vertical Pressure</td>
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<td></td>
<td></td>
<td>S5</td>
<td>0 - 100</td>
<td>Vertical Pressure</td>
</tr>
<tr>
<td>Data Instruments</td>
<td>Pressure Transducer</td>
<td></td>
<td>P11</td>
<td>0 - 200</td>
<td>Pore Water Pressure at Elevation 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>P12</td>
<td>0 - 200</td>
<td></td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>P13</td>
<td>0 - 200</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>P14</td>
<td>0 - 200</td>
<td></td>
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<tr>
<td></td>
<td></td>
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<td>P21</td>
<td>0 - 200</td>
<td></td>
</tr>
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<td></td>
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<td>P22</td>
<td>0 - 200</td>
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<td>P23</td>
<td>0 - 200</td>
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<td></td>
<td></td>
<td>P24</td>
<td>0 - 200</td>
<td></td>
</tr>
<tr>
<td>Fairchild E/P</td>
<td>Transducer</td>
<td>T - 5700 - 9</td>
<td>F2</td>
<td>3 - 120</td>
<td>Vertical &amp; Horizontal Pressure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>F4</td>
<td>3 - 120</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2 Physical channels and scale for SenSym sensors and Fairchild transducers

<table>
<thead>
<tr>
<th>Virtual Channel</th>
<th>Symbol on MAX</th>
<th>Module</th>
<th>Channel No.</th>
<th>Scale</th>
<th>Unit</th>
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</thead>
<tbody>
<tr>
<td>SenSym 1</td>
<td>S1</td>
<td>SC1Mod1</td>
<td>1</td>
<td>5.8115</td>
<td>-6.2820</td>
</tr>
<tr>
<td>SenSym 2</td>
<td>S2</td>
<td>SC1Mod1</td>
<td>2</td>
<td>5.7680</td>
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<tr>
<td>SenSym 3</td>
<td>S3</td>
<td>SC1Mod1</td>
<td>3</td>
<td>19.3930</td>
<td>-20.0250</td>
</tr>
<tr>
<td>SenSym 4</td>
<td>S4</td>
<td>SC1Mod1</td>
<td>4</td>
<td>5.8951</td>
<td>-7.7231</td>
</tr>
<tr>
<td>SenSym 5</td>
<td>S5</td>
<td>SC1Mod1</td>
<td>6</td>
<td>19.7610</td>
<td>-27.8040</td>
</tr>
<tr>
<td>Fairchild</td>
<td>F2</td>
<td>Dev2</td>
<td>0</td>
<td>11.2270</td>
<td>4.7066</td>
</tr>
<tr>
<td>Fairchild</td>
<td>F4</td>
<td>Dev2</td>
<td>1</td>
<td>11.6730</td>
<td>8.5240</td>
</tr>
</tbody>
</table>

Table 4.3 Wiring diagram for plug of SenSym and socket of Data Instruments sensors

<table>
<thead>
<tr>
<th>Sensym</th>
<th>Data Instruments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pin Number</td>
<td>Pin Number</td>
</tr>
<tr>
<td>Color</td>
<td>Color</td>
</tr>
<tr>
<td>Wire Function</td>
<td>Wire Function</td>
</tr>
<tr>
<td>---------------</td>
<td>------------------</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>4 Red</td>
<td>3 Black</td>
</tr>
<tr>
<td>5 Black + Ve</td>
<td>4</td>
</tr>
<tr>
<td>Excitation Voltage 10 V</td>
<td>Excitation Voltage 5V</td>
</tr>
<tr>
<td>Output Voltage 5 V</td>
<td>Output Voltage 0 – 100 mV</td>
</tr>
</tbody>
</table>
4.4 LabVIEW Software

LabVIEW version 7.1 is the software used in PC-based data acquisition and instrument control. It is a programming language with a high level functionality designed specifically for measurement and automation applications and is compatible with the National Instruments system. In contrast to other programming languages, LabVIEW uses icons to present the functions and the icons are wired together to determine the flow of data. LabVIEW acquires the data, perform the analysis of the data and presents the data in a chosen format. Virtual Instruments (VI) are the programs in LabVIEW. The LabVIEW program may contain several different VI’s.

The two main components of LabVIEW are the Front Panel and the Block Diagram. The Front Panel is where you measure the data. The Block Diagram is where you wire the VI’s and other functions in a dataflow. The data acquisition includes the automatic configuration, test panels and built-in channel configuration for scaling and naming of the data. The data acquisition (DAQ) Assistant VI configures the measurements in LabVIEW. One can set up Analog Input, Analog Output, Digital I/O, and Counter I/O.
4.4.1 VI’s and Front Panels

The hierarchy of the program is shown in Figure 4.11. There is one main VI named as “Testing” and three other VI’s named as “Slurry Consolidation”, “Ko Consolidation” and “Boundary Condition 1”. There is also a 4th “File Path” VI which is used in saving the data. The “Testing” front panel includes a list of all the instruments connected to the testing system which are under the “All_Sensors” task (Figure 4.12). When running this VI, the program will ask automatically to save the data into a file. Once the file is saved the values from the instruments are displayed numerically and displayed in graphical format in real time. The number of iterations and the time in minutes, hours and days is provided. There are three buttons corresponding to the three phases of the test.

A click on the “Slurry Consolidation” button will launch another front panel which is the one used in the slurry consolidation phase whose data will be automatically saved under the same name as “Testing” file that was saved plus the “Slurry_Consolidation” part added at the end of the file name (Figure 4.13). Ten instruments are connected here from which eight are the transducers that measure pore water pressure and one is the LVDT to measure the deformation. An option to zero the instruments of similar groups or individual sensors is provided. The pore water pressure and the LVDT data are displayed on two graphs. The number of data points included in each graph is controlled by the “Graph Controls” part. The graph can be cleared at any time by pressing the “Clear graph” button. As the test continues the new data begin to be displayed.

The program also gives the option to decide how often the data will be saved. The “Minutes between readings” control button can be increased or decreased according
Figure 4.11 Hierarchy of the “Testing” VI
to which phase the test is in. Every time the “Reading” blinks a new set of data are recorded at that time. This is an important issue since the slurry consolidation phase lasts for at least a month and the data can be recorded less often, in contrast to the penetration phase where the data needs to be recorded at much higher frequency. The use of the old data acquisition system required the use of the oscilloscope for penetration tests to acquire data at very small time intervals. The file can be opened with excel where further calculations can be done. A click on the “Stop” button will take you back to the “Testing” window.

Figure 4.12 Front panel of the “Testing” VI
While the main VI “Testing” is running again the values from the instruments are both displayed numerically and plotted in the same graph. The sensors used in the slurry consolidation will read the same values as they were reading at the end of that stage. The other stage of the testing is $K_0$ consolidation which can be started by clicking the corresponding button. As a sequence another window corresponding to that phase will be opened (Figure 4.14). The other instruments added are the transducers of the panel of control. The values are displayed both numerically and plotted in graphs. As in the slurry consolidation stage, there is the option of zeroing the instruments of similar groups or individually. The chart data points can be changed and the graphs can be cleared at any
time. The interval of the data saved can be changed during testing. The panel of controls has three sensors S1, S2 and S4 that read up to 30 psi and two sensors S3 and S5 that read up to 100 psi. The sensors S2 and S3 are used to measure the horizontal pressure while sensors S4 and S5 are used to measure the vertical pressure. The pressure transducer range is selected from the “Choose Sensor” switch. An important feature of this program is the controlling system through the global channels F2 and F4 which correspond to the electric-pneumatic transducers attached at the panel of controls. The pressure values are not only acquired by the system but are also controlled through LabVIEW such as the desired pressures are applied. F2 is used to control the vertical pressure needed and F4 is used to maintain the pressure in the outer cell the same as in the inner cell. A desired initial vertical pressure can be applied by setting up that value in the “Initial F2 Pressure” and it can be observed by the “Current F2 Pressure”. Before starting the $K_o$ consolidation, the target pressure and the rate of the pressure increase in minutes are set. Clicking on the “F2 Increase” button leads to the start of the $K_o$ consolidation. The only calculated output is the $K_o$ value which is the ratio of the horizontal to the vertical pressure.

The last step of the calibration chamber testing is the penetration. The name of the VI used for penetration is “Boundary Condition 1”. This VI is similar to the “Slurry consolidation” VI. Besides the instruments included during the $K_o$ consolidation, the sensors of the model pile are added (Figure 4.15). Measurements of the pore pressure at two different elevations, the vertical and horizontal pressures, the sample deformation, the depth of the model pile penetrating into the sample, and the load acting on the pile and pore pressures around the pile are displayed numerically and plotted on charts. They are also saved in the same way as the other two stages of the test.
Figure 4.14 Front panel of “K₀ Consolidation” VI
Figure 4.15 Front panel of Penetration VI
4.4.2 Sub-VI’s and Block Diagrams for VI’s

Each of the VI’s contains several sub-VI’s. The common sub-VI’s are the sub-VI’s that create graphs, sub-VI’s that set up the file where the data is saved to, sub-VI’s that zero the instruments, sub-VI’s that transfer the data to excel file with compatibility, and sub-VI’s that produce the time in minutes. Other sub-VI’s used during $K_o$ consolidation are: sub-VI to calculate the $K_o$ value, sub-VI to control the vertical pressure, sub-VI to control the horizontal pressure, and sub-VI to save the data recorded at the end of slurry consolidation. The last mentioned sub-VI is also used in the penetration phase.

While the test is performed, the front panel of the testing program is displayed. The actual program is developed in the block diagram. Each VI and sub-VI has a corresponding block diagram. The main part of the block diagram is the while loop presented in a rectangle. Everything outside the while loop is executed only once either to start or terminate the test and everything inside the while loop is executed continuously throughout the test. The “Testing” block diagram contains a while loop and inside it three other while loops for the three stages of the test as mentioned in the earlier sections (Figure 4.16). The other VI’s have similar block diagram (Figures 4.17, 4.18 and 4.19). Besides of the main while loop have another loop which is used to save the data.
Figure 4.16 Block diagram of “Testing” VI
Figure 4.17 Block diagram of “Slurry Consolidation” VI
Figure 4.18 Block diagram of “Ko Consolidation” VI
Figure 4.19 Block diagram of penetration phase
CHAPTER 5

EXPERIMENTAL PROCEDURE

5.1 Introduction

The tests in the calibration chamber of cohesive soils are performed following four main phases (Figure 5.1). In the first phase the slurry is prepared by mixing the soil with water. The slurry is then consolidated in the slurry consolidometer leading to the preparation of the specimen. In the third stage, the specimen is transferred to the piston cell and is reconsolidated under isotropic or $K_o$ conditions. The last stage requires the miniature model pile penetration under the desired boundary condition. Each of these stages is described in details in the following sections.
5.2 Slurry Sample Preparation

The dry kaolin powder and the dry sand are poured in a large container. Their properties are described in Section 6.5.1. Deaired water content twice the liquid limit of the mixture is poured in another container. Higher water content would require more time to consolidate. The clay-sand mixture is then slowly poured over the water while stirring it using the electric mixer (Figure 5.2). For easier handling, the mixer is hanged on the crane and moved around the container for more uniform mixing. The mixing is continued for 20 minutes to produce a uniform paste of the mix.

Figure 5.2 Mixing the slurry (Kim 1999)

5.3 Slurry Consolidation

Slurry consolidation is the stage where the specimen is prepared. Because of the large scale equipment, it is impossible to obtain an undisturbed specimen from the field. Therefore, the specimen is consolidated in the laboratory. The slurry mix is poured carefully into the consolidometer with the help of a funnel and a hose for minimal air voids entrapment. The desired consolidation stress is applied on top of the slurry while permitting top and bottom drainage. The pore pressure is recorded using the pore
pressure transducers connected at the bottom plate of the consolidometer. At the end of the slurry consolidation where no more change in the pore water pressures occurs, the specimen is transferred to the calibration chamber which is the next phase of the test.

5.3.1 Slurry Consolidometer Setup

- The pore pressure sensors are assembled and the pore pressure ducts are saturated (Section 5.3.3). They are connected at two different elevations and at varying radial distances as shown in Figures 5.3 and 5.4. The other holes are connected to the drainage tubes (Figure 5.5).
- The base frame with four rollers is placed at a convenient location.
- A porous plastic is attached to the chamber bottom plate.
- O-rings are placed on top of the bottom plate.
- The membrane is placed around the bottom plate, and sealed with two O-rings.
- Pore pressure sensors are connected to the bottom plate.
- Chamber bottom plate is placed on top of the base frame.
- Vacuum grease is applied on the surface where the two halves of the lower PVC tubes attach together.
- Place each half of the lower PVC tube of the slurry consolidometer on top of the bottom plate.
- Bolt the two halves together.
- Stretch the membrane out and fold it around the tube.
- Place the other PVC tube on top of it.
- Vacuum is applied on the bottom tube at two opposite sides for sealing of the membrane.
Figure 5.3 Lower tube with membrane and pore water pressure ducts (Kim 1999)

Figure 5.4 Base plate with pore water pressure ducts
5.3.2 Slurry Consolidation

- Pour the slurry through a funnel and a hose into the consolidometer. Make sure that the funnel is long enough such that it reaches the bottom of the consolidometer.
- The piston rod with the aluminum piston plate attached to one end is placed on top of the slurry. The piston plate should have a porous stone attached to it.
- The top lid is put on top of the consolidometer.
- The two PVC tubes are bolted together at the base frame and to the top lid through 6 steel rods applying the same torque.
- The metal reaction frame of the single acting hydraulic cylinder (push jack) powered by an air-hydraulic pump is bolted to the top lid.
The height of the hydraulic cylinder is arranged such that the piston rod of the hydraulic cylinder is in contact with the piston rod of the aluminum plate (Figure 5.6).

An LVDT is attached to the piston rod.

“Testing” VI is open and run continuously.

The file is saved and the readings from the instruments are displayed.

The “Slurry Consolidation” stage is chosen by pressing the corresponding button.

All sensors are set to read zero pressures or displacements.

The desired air pressure is applied to the pump and the handle is pushed down, so that piston of the hydraulic cylinder is moved in downward direction. The vertical stress is chosen such that the specimen can withstand its self weight. For a mixture of 50% clay and 50% fine sand, a 138 kPa vertical stress is sufficient according to Kurup (1993).

Readings of the pore water pressures and displacement with time are taken via pore pressure sensors connected at the bottom plate and the LVDT attached on the piston rod.

All data are displayed in graphs for a better visualization.

Stop button is pressed when the consolidation is finished. The program will return back to the “Testing” front panel.

### 5.3.3 Saturation of the Pore Pressure Ducts

For more accurate results and for a faster pore pressure response during the testing phase, the pore pressure sensors are saturated using a dual stage technique (Kurup 1993) before the start of a test. In the first stage of the saturation, the duct is
connected on one side to the plastic adaptor and the other side to the hypodermic tube and the porous stone is placed at its tip. It is then submerged into deaired water (Figure 5.7). The sensor is also submerged into deaired water in the same tub, and connected to the duct through the plastic adaptor. The second stage is done to ensure the saturation. The tips of the ducts are submerged into deaired water and then subjected to vacuum in the Nold DeAerator (Figure 5.8). The pore pressures sensors should respond quickly and they should read initially the same pressure as the vertical pressure applied.
Figure 5.7 Pore pressure transducer, ducts and adaptors assembled together are submerged in deaired water

Figure 5.8 Saturation of the duct under vacuum in the Nold DeArerator
5.4 $K_o$ Consolidation

After the specimen is consolidated in the consolidometer, it is transferred to the chamber, saturated and reconsolidated under zero lateral strains. Transferring the specimen requires a lot of care, so that the specimen is transferred safe to the chamber, otherwise more than a month will be wasted.

5.4.1 Transfer of the Specimen

The chamber is prepared before transferring the specimen to the piston cell. The piston of the calibration chamber is filled with water. Water coming from reservoir flows through the copper tubes on the panel of control to the piston cell (the lower tube line on the panel). To achieve this, the valve A4 is opened and B15 is closed (Figure 3.10). The upper valve (V3) of the piston is kept open and both the water line (A4) and V3 valve are closed when water start to come out of V3 valve. Then:

- The loading system is removed from the top of the consolidometer.
- The six steel rods are unbolted, the top lid, and upper tube of the consolidometer are removed.
- The excessive soil is trimmed such that it becomes on the same level as the bottom tube of the consolidometer (Figure 5.9).
- The top plate of the chamber is placed on top of the specimen.
- The membrane is unfolded and two o-rings are slipped around it and fitted on the groove of the plate.
- The bottom tube of the consolidometer, with the specimen inside it, is attached through chains to the crane and lifted (Figure 5.10).
- The combined weight of the sample is determined by weighing the whole unit.
- The specimen is transferred to the piston of the calibration chamber. Care is
taken that the pore pressure sensor wires and the drainage tubes are allowed to pass through the inside cell space of the piston before the specimen is fully set above the piston (Figure 5.11).

- Vacuum is applied on top and bottom sides of the specimen so that the specimen will not bulge.
- The lower tube is unbolted, split and moved away.
- The membrane is checked if damage has occurred. If so, the membrane is cured with strong water proof glue.
- The inner cell wall is grabbed from the top and placed around the specimen (Figure 5.12).
- The outer cell wall is grabbed from the sides and placed carefully around the inner cell wall. Top lid is placed on top of them (Figure 5.13).
- The top lid and the piston are connected together via twelve equal rods and tightened using the same torque.
- The tube connected to the vacuum is passed over the top lid. It will be later used to saturate the specimen.
- The holes of the top lid are sealed with adaptors (Figure 5.14).
- Specimen inner and outer cells are filled with deaired water. This is done by opening A4 to the left side, B7 and B8. The air bubbles are removed by keeping the valves V1 and V2 open at the top of the chamber top plate.
- Close A4 when the cells are completely filled.
- The LVDT is installed on the piston shaft.
Figure 5.9 Specimen after the slurry consolidation (Kim 1999)

Figure 5.10 Transfer of the specimen into the calibration chamber (Kim 1999)
Figure 5.11 Specimen in the lower tube of consolidometer and above the piston cell (Kim 1999)

Figure 5.12 Placing chamber inner wall over the specimen (Lim 1999)
Figure 5.13 Specimen in inner and outer walls (Kim 1999)

Figure 5.14 Final assembly of the specimen (Lim 1999)
5.4.2 Reconsolidation in the Chamber

Depending on the stress conditions, the specimen can be consolidated isotropically or anisotropically. Before isotropic consolidation starts, the specimen is saturated under a back pressure of the same level as it was consolidated in the slurry consolidometer. The back pressure is provided through an air-water system (not connected on the panel of control) whose lines are connected at the top and bottom of the specimen. The specimen pressure is provided via the panel of controls. Applications of stress increments are used to ensure saturation. The B-value is recorded after each stress increment as follows (Figure 3.10):

- Close the back pressure valve of the air-water system.
- Turn A5 to the left side. Close the valve that allows water to flow on the piston cell. Open B16, B15 and B21. Open B9 and B14 for visual check of the pressures. Turn A2 to the right to observe the sample pressure (Figure 3.9).
- Open and run “Testing” VI. Press the “K₀ Consolidation” button.
- Make an increment to the specimen pressure via rotating the screw on F1.
- Wait for equalization of the pressures and record the B-value.
- Open the back pressure valve and increase the back pressure, via the pressure regulator attached to the air-water system, to a value less than the sample pressure and let the sample saturate. Observe the back pressure via the gauge attached to the air-water system.
- Repeat the stress increments until saturation is ensured and the desired effective isotropic stress is reached. Effective stress is the specimen pressure minus the back pressure. The back pressure is increased up to the effective slurry consolidation pressure.
- Open the back pressure valves and let the water expel from the specimen.
- The consolidation has started.
- Stop the consolidation when there is no more specimen deformation.

The procedure for the $K_o$ consolidation is different when compared to the isotropic consolidation. Since the loading occurs from the bottom of the specimen, a vertical equilibrium pressure is applied to the inner piston cell water. It is the pressure that needs to equilibrate the pressure generated by the combined weight of the inner piston cell, specimen, specimen bottom plate and specimen membrane. The consolidation can start only when the applied vertical pressure exceeds the equilibrium pressure which is calculated by dividing the combined total weight by the area of the bottom plate of the inner piston cell. The equilibrium pressure is reached by adjusting the control panel as follows:

- Direct the compressed air flow from the air filter to F1 by turning A5 to the left. Open B13, B14 and B16.
- Open F1 slowly up to the equilibrium pressure and control the vertical pressure via BP2. The pressure can be also observed from G2.
- Close B3 (the valve on piston water line), B13 and B16 when the equilibrium pressure is reached and the specimen touches the top plate.

The $K_o$ consolidation is provided by compressing the specimen in vertical direction under zero lateral strain. When the specimen is loaded, the water pressure increases in the inner cell. The same pressure is applied to the specimen outer cell via the computer software. The specimen inner wall can not move since the pressures on both sides of the wall are the same. During $K_o$ consolidation, the vertical and horizontal stresses, the vertical deformation and the pore water pressure can be recorded,
displayed in graphic form and saved in a file. The $K_o$ value is displayed during the test. The $K_o$ consolidation can either be performed manually using the Bellofram pressure regulators F1 and F3 or automatically using the Fairchild electric-pneumatic transducers F2 and F4.

For manual operation of the $K_o$ consolidation, the following procedure is applied (Figure 3.10):

- Launch the “Ko Consolidation” VI run.
- Open valve B15.
- Decide which pair of Sensym transducers are going to be used. If S2 and S4 are chosen, then turn A2 and A3 valves to the left side. If S3 and S5 are chosen, then turn A2 and A3 valves to the right side.
- Open valves B5, B9 and B14 which control the water flow into G1, G3 and G2 gauges, respectively and needed for visual check of the pressure.
- Open valves B4, B7, B20 and B15.
- Turn A1 and A5 to the left sides and open B10 and B16.
- The system is ready for load application.
- Make a very small vertical pressure increment by increasing the pressure slowly via F1 and observing via S4/S5. Meanwhile, observe the pressure in the inner sample via S2/S3 and apply that pressure to the outer sample via F3 and observe it via S1.
- Wait for equalization of the pressures and make another increment in the same way until the effective consolidation pressure is reached.
- The change in volume of the sample is observed on the air-water system 1.
For automatic operation of the $K_o$ consolidation, the panel of controls is prepared in the same way as before except that A1 and A5 are opened to the right side. Also, B11 and B17 valves are open instead of B10 and B16. The procedure follows as:

- While the “Testing” VI is running, press the “$K_o$ Consolidation” button.
- The “$K_o$ consolidation” front panel will open.
- An initial vertical pressure can be set up via the “Initial F2 Pressure” control unless this pressure was applied before.
- Observe the pressure from “Current F2 Pressure” and also from the G2 gauge.
- Set the target pressure which is the maximum effective pressure that needs to be applied.
- Set the F2 pressure rate increase in minutes.
- Press on the “F2 Increase” button.
- The $K_o$ consolidation has started.
- The data are displayed numerically and they are plotted on the graphs.

5.5 Penetration Phase and Boundary Conditions

The penetration phase involves the application of four boundary conditions (Table 2.1). LabView program is the same for all four conditions. The boundaries are applied by making some changes in the panel of control (Tumay et al. 1992). Referring to Figure 3.10, the boundaries are applied as follows:

Boundary condition 1 (BC1) requires the constant maintenance of vertical and horizontal pressure via the back pressure regulators BP1 and BP2. Any increase in pressures will be vented out of the system since these regulators work like pressure relief valves for the inner specimen cell (BP1) and the piston (BP2).

o Set BP2 to the vertical stress and BP1 to the horizontal stress achieved at the end of the \( K_0 \) consolidation by adjusting the screw at the top of the pressure regulators.

o Observe the pressure on BP1 and BP2 via G4 and G5 gauges.

o Check that G1 reads the horizontal pressure and that G2 reads the vertical pressure at the end of consolidation.

o Close valves B7, B10/B11 and B16/B17 and open B8, B6, and B13.

o The system is ready for penetration stage.

Boundary condition 2 (BC2) does not permit any vertical or horizontal strains. To maintain zero lateral strain, a procedure similar to the \( K_0 \) consolidation is applied. Close valves B8, B6, B13, and B15.

For boundary condition 3 (BC3), the specimen is kept under constant vertical stress and zero lateral strain. Therefore, any increase in the vertical pressure is vented out of the system via BP1 and the pressure in the inner and outer sample cells are kept the same.

o Close valve B13.

o Set BP2 to the vertical stress achieved at the end of the \( K_0 \) consolidation.

o Observe BP2 via G5 gauge.

o Close B16/B17 and open B13.

o Maintain valves B8 and B6 closed.

The last boundary condition 4 (BC4) implies zero vertical strain and constant lateral stress. The pressure generated during penetration should be released via BP1 as explained in BC1 and the vertical strain is maintained at zero level as explained in BC2. Make sure that valves B7, B11 and B15 are closed before the penetration starts.
Figure 5.15 Hydraulic system mounted on the calibration chamber (Kim 1999)

Figure 5.16 Hydraulic push jack for penetration stage (Kim 1999)
Figure 5.17 Depth decoding system (Kim 1999)
CHAPTER 6

SOIL CONSTITUTIVE MODEL DESCRIPTION AND CALIBRATION OF ITS PARAMETERS

6.1 Introduction

This chapter describes the soil model that will be used for the simulation of piezocone penetration. Many efforts have been made in the last two decades for the development of soil constitutive models. The common objective of these models is to predict the behavior of the soil. One such model is called the Modified Cam Clay Model (MCCM) which was developed by Roscoe and Burland (1968) assuming that the soil behavior is isotropic and it obeys the associative flow rule which means that the yield surface is the same as the plastic potential. However, this is not always the case in reality. Anisotropy influences the stress-strain behavior of the soil (Wroth and Houlsby 1985, Ladd 1965, Banerjee et al. 1984). Moreover, the coefficient of consolidation is overestimated by 20-30% if anisotropy is not taken into account in piezocone penetration tests (Levadoux and Baligh 1980).

Dafalias (1986) proposed a simple anisotropic model for clays as an extension to the MCCM considering a rotated and distorted ellipse for the yield surface (Figure 6.1). The model known as Anisotropic Modified Cam Clay Model (AMCCM) has proven to describe reasonably well the clay response during and after anisotropic $K_o$ consolidation (Dafalias 1986). However, the softening response for some clays cannot be simulated during undrained triaxial compression loading after $K_o$ consolidation because of the associative flow rule assumption (Dafalias et al. 2002). A solution to this issue was to modify the rotational hardening rule (Wheeler et al. 1999) and/or introduce non-associative plasticity (Newson and Davies 1996). Dafalias et al. (2003) introduced
another simple model where the plastic potential has the same form as the yield surface but with a different internal rotational variable and/or critical state ratio in q-p space. It is called AMCCM following non-associative rule. The associative flow rule ellipse of the MCCM model is obtained by setting $f = g$ and $\alpha = 0$.

Figure 6.1 Anisotropic yield surface in p - q space (Dafalias 1986)

6.2 Theoretical Formulation of the Soil Model

The AMCCM was developed based on the dissipation of the anisotropic energy. It predicts the undrained shear strength of a soil after anisotropic consolidation where the yield surface consists of a distorted and rotated ellipse and is different from the plastic potential (Papadimitriu et al. 2005). The equations of the yield surface ($f$) and the plastic potential ($g$) are described by Equations 6.1 and 6.2.
\[ f = (q - p\beta)^2 - (N^2 - \beta^2) p(p_o - p) = 0 \]  \hspace{1cm} (6.1)
\[ g = (q - p\alpha)^2 - (M^2 - \alpha^2) p(p_a - p) = 0 \]  \hspace{1cm} (6.2)

where,

\[ p = (1/3)(\sigma_1 + 2\sigma_3) \] = mean stress where \( \sigma_i \) are the principal stress components

\[ q = \sigma_1 - \sigma_3 \] = deviatoric stress

\( \beta \) = rotational hardening variable

\( N \) = model parameter

\( \eta = q/p \)

\( p_o \) = isotropic hardening variable = \( p \) when \( \eta = \beta \)

\( M \) = critical stress ratio

\( \alpha \) = stress anisotropic parameter

\( p_a \) = \( p \) value when \( \eta = \alpha \)

Both surfaces have the same functional form, where \( M, \alpha \) and \( p_a \) in the plastic potential surface substitute \( N, \beta \) and \( p_o \) in the yield surface (Figure 6.2). \( p_o \) and \( p_a \) govern the size, \( \alpha \) and \( \beta \) govern the rotation angle of the yield surface and plastic potential surface, respectively. A detailed equation derivation of the model is found in Papadimitriu et al. (2005).

6.3 Parameters of Soil Model

The constitutive equations of the model have parameters that can be estimated based on the experimental results. As a result, the model has to be calibrated. The data needed in the calibration are typically obtained from standard laboratory tests. Table 6.1 describes the model parameters. Parameters \( \lambda \) and \( \kappa \) present the slopes of normal compression and swelling lines in the e-lnp space. A one-dimensional consolidation test to stresses larger than the preconsolidation pressure is required to obtain the values of \( \lambda \) and \( \kappa \).
Figure 6.2 Yield surface and plastic potential surface for AMCCM (Papadimitriu et al. 2005)

Poisson’s ratio (\(\nu\)) and the value of x are calculated from data obtained during one dimensional (\(K_o\)) compression and swelling reaching stresses larger than the preconsolidation pressure and using a computer controlled triaxial device. Undrained triaxial compression (\(CK_oUC\)) and undrained triaxial extension (\(CK_oUE\)) tests on normally \(K_o\)-consolidated clay are performed to determine \(M_c\), \(M_e\) and \(N\) parameters where subscript c denotes compression and subscript e denotes extension.
### Table 6.1 Parameters of AMCCM following non-associative rule

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>Slope of critical state line (CSL)</td>
</tr>
<tr>
<td>κ</td>
<td>Slope of swelling line</td>
</tr>
<tr>
<td>λ</td>
<td>Slope of normally consolidation line (NCL)</td>
</tr>
<tr>
<td>ν</td>
<td>Poisson's ratio</td>
</tr>
<tr>
<td>N</td>
<td>Shape of the yield surface</td>
</tr>
<tr>
<td>x</td>
<td>Saturation limit of anisotropy (under paths with $\eta = q/p$ constant)</td>
</tr>
<tr>
<td>c</td>
<td>Rate of evolution of anisotropy</td>
</tr>
</tbody>
</table>

### 6.4 Calibration of the AMCCM following Non-Associative Rule

Once the experiments are performed, the parameters can be estimated accordingly. Given the slopes of compressibility index ($C_c$) and swelling index ($C_s$) in the $e$ - $\log\sigma_a$ space, the values of $\lambda$ and $\kappa$, are calculated as:

\[
\lambda = \frac{C_c}{\ln 10} \tag{6.3}
\]

\[
\kappa = \frac{C_s}{\ln 10} \tag{6.4}
\]

$M_c$ and $M_e$ depend on the friction angle which is calculated from the CK_oUC and CK_oUE tests. If CK_oUE test is not available, the relation $M_{e,\text{min}} \leq M_e \leq M_c$, where $M_{e,\text{min}}$ is the value of $M_e$ corresponding to $\phi_e = \phi_c$, should be taken into consideration.

\[
M_c = \frac{6 \sin \phi_c}{3 - \sin \phi_c} \quad \text{and} \quad M_e = \frac{6 \sin \phi_c}{3 + \sin \phi_c} \tag{6.5}
\]

Assuming that the clay behavior is elastic during unloading from $K_o$ condition, the yield surface lies along the $K_o$-loading line. Thus, when $\beta = \eta_{ko}$ no more rotation and distortion of the yield surface occurs. The stress path during $K_o$ unloading lies
within the yield surface and the elastic Poisson’s ratio (ν) is calculated from the slope of the initial part of K₀-unloading as:

\[
\frac{\Delta q}{\Delta p} = \frac{3(1-2\nu)}{1+\nu}
\]  

(6.6)

Parameter x controls the degree of anisotropy. It depends on the K₀ value and is an increasing function of K₀. The value of x is estimated during constant η = q/p drained loading (K₀ consolidation) for which α = β = constant. x and α are estimated using the following equations:

\[
x = \frac{2\varepsilon \eta_k (1 - \frac{K}{\lambda})}{B\varepsilon \eta_k^3 + \eta_k^2 + [2(1 - \frac{K}{\lambda}) - BM \varepsilon^2] \varepsilon \eta_k - M \varepsilon^2}
\]

(6.7)

\[
\alpha_k = \frac{\eta_k}{x}
\]

(6.8)

where, K₀ is the coefficient of earth pressure at rest, ε = 3/2 for most K₀ loading paths, subscript k represents K₀ consolidation, \( \eta_k = \frac{3(1 - K_0)}{1 + 2K_0} \) and \( B = \frac{2(1 + \nu) \kappa}{9(1 - 2\nu) \lambda} \).

The undrained loading requires that there is no change in the volumetric strain. Thus, \( \Delta \varepsilon^e + \Delta \varepsilon^p = 0 \), where \( \Delta \varepsilon^e \) and \( \Delta \varepsilon^p \) are the elastic and plastic volumetric strain rates, respectively. Taking into consideration that f = 0 and β is constant, the undrained effective stress path equation is formulated as:

\[
\frac{p}{p_{in}} = \left( \frac{\eta_{in}^2 - 2\beta \eta_{in} + N^2}{\eta^2 - 2\beta \eta + N^2} \right)^{1-\frac{\kappa}{\lambda}}
\]

(6.9)

where \( \eta_{in} \) and \( p_{in} \) are the initial values of \( \eta \) and \( p \). To calculate N, the undrained effective stress path equation is modified as:
\[
\frac{p_f}{p_{ko}} = \left( \frac{N^2 - \eta_{ko}^2}{N^2 - 2\eta_{ko}M_c + M_c^2} \right)^{\frac{1-c}{2}}
\]  
(6.10)

where \( \eta_{in} = \beta = \eta_{ko} = 3(1-K_o)/(1+2K_o) \) = constant under the assumption that the yield surface is not rotating, \( p_{in} = p_{ko} \) = the value of \( p \) at the end of \( K_o \)-consolidation, \( p_r \) is the value of \( p \) when the critical state is reached. Softening occurs in the effective stress path of \( CK_oUC \) for \( N < \eta < M_c \). The value of \( N \) is suggested to be greater than \( M_c \) for the use in Eq. 6.10.

Parameter \( c \) can be estimated after estimating the other constants and requires the accomplishment of trial runs. A \( CK_oUE \) test is more appropriate than a \( CK_oUC \) test because it yields more significant surface rotation. The predicted undrained strength is greater for higher values of \( c \) in triaxial extension (Papadimitriu et al. 2005).

### 6.5 Experimental Work

#### 6.5.1 Introduction

One-dimensional consolidation and triaxial experiments were carried out to determine the parameters of the clay model described in the previous sections. The experiments that will be performed in the LSU/CALCHAS require the preparation of the specimens from the slurry consolidation. To be consistent, the specimens used in the consolidation and triaxial tests were prepared from slurry consolidation. In addition, since this clay model will be used for the simulation of the piezocone penetration, the conditions of the experiments are according to the conditions of the model pile penetration test. The specimens were a mixture of 50% fine sand and 50% clay (kaolin) by weight. The soil properties are given in Table 6.2 and the particle size distribution for sand is shown in Figure 6.3.
Table 6.2 Properties of sand, clay and their mixture

<table>
<thead>
<tr>
<th>Type of soil</th>
<th>Kaolin</th>
<th>Fine Sand</th>
<th>50% Kaolin and 50% Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Limit, %</td>
<td>53</td>
<td>---</td>
<td>28</td>
</tr>
<tr>
<td>Plastic Limit, %</td>
<td>30</td>
<td>---</td>
<td>17.5</td>
</tr>
<tr>
<td>Plasticity Index, %</td>
<td>23</td>
<td>---</td>
<td>10.5</td>
</tr>
<tr>
<td>Specific Gravity, Gs</td>
<td>2.66</td>
<td>2.67</td>
<td>---</td>
</tr>
</tbody>
</table>
6.5.2 Specimen Preparation

The slurry was prepared by thoroughly mixing clay and fine sand with distilled water of twice the liquid limit of the clay-sand mixture (Figure 6.4). It was then poured into a cylindrical aluminium mold via a funnel and hose attached to it in order to minimize air-entrapment during placement process. The inside surface walls of the aluminium mold were coated with a lubricant to decrease the friction between the soil surface and the inside surface of cylindrical aluminium mold. Porous stones and filter papers are placed on the bottom and top platens to allow vertical drainage and to prevent clogging of the porous stones. The cylindrical aluminium mold was placed in the slurry consolidometer and a consolidation load of 138 kPa is applied (Figure 6.5). Higher consolidation loads and lower water contents provide shorter time for consolidation. A consolidation load is applied slowly such that a load of twice the previous one is added after every 24 hours, until the desired final load is reached.

Figure 6.4 Slurry mixing process
A different mold was used for consolidation and triaxial tests. The consolidation cell used for the preparation of the specimen for one-dimensional consolidation tests was 63.5 mm in diameter and 108 mm in height (Figure 6.6a). On the other hand, the consolidation cell used for the preparation of the specimen for triaxial tests was 70 mm in diameter and 381 mm in height and had the feature of a cylindrical split whose halves are held together by tightening the screws on the sides (Figure 6.6b).

Consolidation of the slurry is recorded with time during the slurry consolidation. Once the consolidation has finished, which means that no more deformation occurs and no more water comes out, the consolidation cell is taken out (Figure 6.7). The specimens are ready for experiments.
To ensure that the specimen has a uniform water content distribution throughout the entire height, one specimen was cut into slices and the water content for each slice was measured. The results are shown in Figure 6.8 where the maximum difference in the water content is about 1%. This indicates a fairly uniform moisture distribution throughout the specimen.

6.5.3 One-Dimensional Consolidation Experiment

The experiment was performed using a fully automated testing system known as the “Sigma-1 ICON” manufactured by Geotechnical Test Acquisition & Control (GEOTAC) Company (Figure 6.9). The sample used in 1-D consolidation test was 63.5 mm (2.5 in.) in diameter and 25.4 mm (1 in.) in height. The consolidation cell used is the one shown in figure 6.6a. The specific volume (v) is calculated as \( v = e + 1 \), where \( e \) is the void ratio, and it is plotted versus vertical effective stress to obtain the compression index \( (C_c) \) and the swelling index \( (C_s) \) (Figure 6.10). \( C_c \) and \( C_s \) are found
Figure 6.7 Specimen prepared from slurry consolidation for triaxial test

Figure 6.8 Water distribution of the prepared specimen
to be 0.199 and 0.017, respectively, which leads to the two model parameter values being as $\lambda = 0.087$ and $\kappa = 0.01$.

Figure 6.9 Consolidation testing system

Figure 6.10 Specific volume versus consolidation pressure
6.5.4 $K_o$-Consolidated Triaxial Experiments

One $K_o$-loading and unloading, three $CK_o$UC and two $CK_o$UE tests were carried out. $K_o$-loading and unloading was carried out to obtain the Poisson’s ratio from the initial slope of $K_o$-unloading path in $q – p’$ plane. The difference between $CK_o$UC and $CK_o$UE is that the former is compressed and the later is extended during shearing phases. Triaxial experiments were carried out using a fully automated triaxial testing system and the TruePath software manufactured by Trautwein Soil Testing Equipment Company (Figure 6.11). The cell and pore pressure is controlled by two digital flow pumps: one for the cell pressure and the other one for the pore pressure (Figure 6.12). The pistons of the pumps exert an upward/downward movement pressurizing/releasing the water. The software provides seating (of the load cell), saturation, isotropic/$K_o$ consolidation, and undrained/drained and compression/extension shearing phases.

The specimens prepared from the slurry consolidation were placed in the triaxial cell. They were 70 mm in diameter and 139 mm in height. A rubber membrane was placed around the specimens via a membrane stretcher and it was sealed via two O-rings around the end platens. The specimens were saturated by applying increments of back pressure and cell pressure accordingly to maintain the same effective stress. The effective stress was kept 7 kPa and the maximum back pressure applied was 138 kPa. A B-value check was done before each stress increment to check the degree of saturation. A B-value of 95-97% was obtained for all experiments.

The specimens were $K_o$ consolidated after the saturation phase was finished. $K_o$ consolidation requires a condition of zero lateral strain as the specimen is loaded vertically. For such condition, the cross area of the specimen remains constant and the axial strain is maintained equal to the volumetric strain. The fully automated triaxial
system adjusts the cell stress ($\sigma_3$) accordingly as the axial stress ($\sigma_1$) is increased. The specimens were $K_o$ consolidated under a stress greater than the slurry consolidation stress. An axial stress of 207 kPa and a rate of strain of 0.2%/hour were applied during this phase. Top and bottom drainage were permitted during $K_o$ consolidation.

Figure 6.11 True Path software used for the triaxial tests

Figure 6.12 Triaxial system
The specimens were sheared in compression and extension at constant rate of strain of 0.5%/hour. Such rate is slow enough to permit equalization of the excess pore water pressure within the specimen (Blight 1963). The compression/extension was provided by increasing/decreasing the axial stress and keeping the lateral stress constant. The drainage valves were closed to provide undrained loading.

**6.5.5 $K_o$-Consolidated Triaxial Experiments Results**

The coefficient of earth pressure at rest ($K_o$) depends mainly on the soil itself and its stress history (Brooker 1965). It is the ratio of effective lateral stress to the effective axial stress and it was measured during $K_o$ consolidation. $K_o$ value is unity at the beginning of the consolidation phase (since vertical and lateral stresses are equal) and decreased as consolidation occurred. Its value stabilized after the vertical pressure exceeded 70 kPa. $K_o$ value versus effective vertical stress is presented in Figure 6.13. The stress paths of the experiments during $K_o$ consolidation and shearing phase are presented in Figure 6.14, where CU denotes the undrained compression and EU denotes the undrained extension. It was observed that shear stress and effective mean stress increased at constant ratio $\eta=q/p'$ during $K_o$-loading.

Referring to Figure 6.15, one can notice that the three compression experiments showed very similar results during loading under undrained condition. The peak deviator stress occurred at small strains in contrast to the deviator stress at the critical state which occurred at relatively larger strains. Unlike the isotropic behavior, undrained loading caused the deviator stress increase at very small strains and after that the deviator stress decreased allowing softening to occur. Same behavior of $K_o$ consolidated clay was observed from Skempton and Sowa (1963), Ladd (1965), Vaid and Campanella (1974), Alshibli and Akbas (2006). Two specimens were extended.
during the shearing phase which means that the load was applied in the upward direction in contrast with the compression tests where the load was applied in the downward direction. The axial stress was decreased during unloading until the axial stress became equal to the lateral stress (zero shear stress). No area correction of shearing phase was done for extension tests, in contrast to the compression tests which were corrected for the cross-sectional area increase. CK₀UC experiments showed a higher change in the excess pore water pressure when compared to the CK₀UE experiments as a result of loading.

### 6.6 Model Predictions

Once the parameters of the model were determined, the model was verified by comparing the experimental with the model prediction. A summary of the experiments results at the critical state and the peak state are given in Table 6.3 where CU and EU denote the undrained compression and extension experiments, respectively. The
Figure 6.14 Stress paths during $K_o$ consolidation and shearing phase in $q - p'$ plane.

Figure 6.15 Clay behavior during shearing phase.
calibrated parameters for CU_1 are listed in Table 6.4. The model prediction is obtained by using incremental equations. Comparison of the experimental with the predicted results for CU_1 and EU_1 are shown in Figures 6.16 and 6.17 where the experimental results compared well with the model predictions.

Table 6.3 Summary of the experiments

<table>
<thead>
<tr>
<th>EXPERIMENTS</th>
<th>CU_1</th>
<th>CU_2</th>
<th>CU_3</th>
<th>EU_1</th>
<th>EU_2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension (mm)</td>
<td>D=70, L=140</td>
<td>D=70, L=139</td>
<td>D=70, L=139</td>
<td>D=70, L=139</td>
<td>D=70, L=139</td>
</tr>
<tr>
<td></td>
<td>Peak State</td>
<td>Critical State</td>
<td>Peak State</td>
<td>Critical State</td>
<td>Peak State</td>
</tr>
<tr>
<td>K_0</td>
<td>0.44</td>
<td>0.44</td>
<td>0.48</td>
<td>0.48</td>
<td>0.47</td>
</tr>
<tr>
<td>σ'_{3r}</td>
<td>71</td>
<td>40</td>
<td>74.7</td>
<td>33</td>
<td>80.3</td>
</tr>
<tr>
<td>σ'_{1f}</td>
<td>214.3</td>
<td>161</td>
<td>211.2</td>
<td>151.3</td>
<td>201.3</td>
</tr>
<tr>
<td>q_f</td>
<td>143.3</td>
<td>121.2</td>
<td>136.5</td>
<td>118.3</td>
<td>121</td>
</tr>
<tr>
<td>ε_f</td>
<td>0.08</td>
<td>6.33</td>
<td>0.16</td>
<td>5.88</td>
<td>0.1</td>
</tr>
<tr>
<td>Φ_i</td>
<td>30.1</td>
<td>37.1</td>
<td>28.5</td>
<td>39.9</td>
<td>25.4</td>
</tr>
<tr>
<td>M</td>
<td>1.21</td>
<td>1.53</td>
<td>1.14</td>
<td>1.63</td>
<td>1.00</td>
</tr>
<tr>
<td>s_u</td>
<td>71.7</td>
<td>60.6</td>
<td>68.2</td>
<td>59.1</td>
<td>60.5</td>
</tr>
</tbody>
</table>

1Effective confining pressure at the end of K_0 consolidation phase
2Major effective stress at the end of shearing phase
3Shear stress at the end of shearing phase
4Axial strain at the end of shearing phase
5Effective friction angle at the end of shearing phase
6Undrained shear strength

Table 6.4 Calibrated parameters for CU_1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>λ</th>
<th>κ</th>
<th>v</th>
<th>M_c</th>
<th>M_e</th>
<th>N</th>
<th>x</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>0.087</td>
<td>0.007</td>
<td>0.21</td>
<td>1.53</td>
<td>0.06</td>
<td>1.147</td>
<td>2.5</td>
<td>1</td>
</tr>
</tbody>
</table>
Figure 6.16 Comparison of experimental results with model predictions in q - p’ plane

Figure 6.17 Deviator stress vs. axial strain for experiments and model predictions
CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Accomplishments and Conclusions

1) The data acquisition system of LSU/CALCHAS was upgraded to National Instruments (NI) SCXI system.

2) A special computer program was developed using LabVIEW software to acquire the data from the transducers, display the data numerically and plot in graphical form, calculate the desired parameters, and save the data at the desired frequency.

3) The sensors/transducers were connected to the new data acquisition system and were calibrated.

4) A detailed procedure of each phase of the testing was updated based on previous studies on LSU calibration chamber.

5) The equipment of LSU/CALCHAS was combined together so that the system works again. The working conditions of the parts of calibration chamber system were checked, modified and substituted whenever it was necessary.

6) The specimens prepared from the slurry consolidometer showed a fairly uniform moisture distribution throughout the specimen which indicates that this technique is effective in preparing repetitive and undisturbed cohesive specimens with known stress history.

7) One 1-D consolidation, one $K_0$-loading and unloading, three $K_0$-consolidated undrained compression ($CK_0$UC) and two $K_0$-consolidated undrained extension ($CK_0$UE) experiments were performed using the fully automated consolidation and triaxial testing systems. Two ($CK_0$UC) and one ($CK_0$UE) were replications.
to check the reliability of the experiments where both types of tests proved to give very similar behavior.

8) Model parameter values were calculated from the data obtained from the laboratory experiments.

9) The experimental results were compared with the model predictions for verification of the model. The model showed a good agreement with the experimental results.

7.2 Recommendations

A full experiment (including all phases of testing) is recommended to be run using the LSU/CALCHAS. Even though the equipments were connected and the computer program was developed, the whole system needs to be checked as one unit. The reason that a full cone penetration test was not conducted was the lack of the time and the laborious work needed.
REFERENCES


VITA

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