DEVELOPMENT OF COMPUTER-CONTROLLED TRIAXIAL TEST SETUP AND STUDY ON MULTISTAGE TRIAXIAL TEST ON SAND

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

MOSTAFA ALYOUSIF

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
CIVIL ENGINEERING

DECEMBER 2015

Approval of the thesis:

DEVELOPMENT OF TRIAXIAL TEST SETUP AND STUDY ON MULTISTAGE TRIAXIAL TEST ON SAND

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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ABSTRACT

DEVELOPMENT OF COMPUTER-CONTROLLED TRIAXIAL TEST SETUP AND STUDY ON MULTISTAGE TRIAXIAL TEST ON SAND

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December 2015, 88 pages

Triaxial test is one of the most important tests in geotechnical engineering. Yet, it is not commonly conducted due to its complexity and lack of automated devices in the Turkish market and the high price for those manufactured by European and American companies.

This study focuses on developing a fully automated computer-controlled triaxial test for the first time in Turkey and the Middle East. The automation of the new setup is not limited to performing the standard tests, but also includes the advanced and custom tests like Ko consolidation and custom stress paths. Reference conventional triaxial tests are conducted on a well-branded automated device and their results are in agreement with the ones obtained using the developed setup.

The second purpose of this study is to investigate the applicability of multistage triaxial test on sand. Various methods are tested to determine which one yields more accurate results that are closer to those found using the conventional triaxial test with three specimens. Fully removing the deviator stress, as opposed to maintaining it, at the end of every stage of shearing is found to give correct results. Stopping stages at peak deviator stresses is found to estimate a friction angle accurately, as opposed to the lower friction angle obtained by stopping at yielding of the specimen.

Keywords: Triaxial test, automated test, computer control, multistage test, friction angle, yield strength

ÖZ

BİLGİSAYAR KONTROLLÜ ÜÇ EKSENLİ DENEY DÜZENEĞİ GELİŞTİRİLMESİ VE KUMDA ÇOK AŞAMALI ÜÇ EKSENLİ DENEY ÇALIŞMASI

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Aralık 2015, 88 sayfa

Geoteknik mühendisliğindeki en önemli deneylerden biri üç eksenli deneyidir. Ancak deneyin zorluğu, yerli otomatik cihazlar üretilmeyişi ve Avrupa veya Amerika'da üretilen cihazların yüksek fiyatları sebebiyle Türkiye piyasasında yaygın olarak yapılmamaktadır.

Bu çalışma, Türkiye ve Ortadoğu'da ilk kez bir tam otomatik bilgisayar kontrollü üç eksenli deney düzeneğinin geliştirilmesi odaklıdır. Yeni düzeneğin otomasyonu yalnız standart üç eksenli deney türleriyle sınırlı olmayıp, Ko konsolidasyonu ve özel gerilme izleri gibi ileri düzey kullanıcı ve araştırmacılara hitap eden deneyleri de kapsamaktadır. Tanınmış bir markanın ürettiği otomatik düzenekten alınan referans sonuçlar geliştirilen düzenekle elde edilenlerle uyumludur.

Bu çalışmanın ikinci amacı, kumda çok aşamalı üç eksenli deneyinin uygulanabilirliğini araştırmaktır. Bu amaçla çok aşamalı deney için çeşitli yöntemler denenerek, üç ayrı numune üzerinde yapılan geleneksel deney sonuçlarına benzer doğru sonuçlara ulaşılmaya çalışılmıştır. Kesmenin bir aşamasından diğerine geçerken kesme gerilmesini sabit tutmaktansa, kesmeyi sıfırlamanın doğru sonuç verdiği saptanmıştır. Aşamaları numune yenilmeye başladığında sonlandırmanın verdiği düşük sürtünme açısı yerine, deviatör gerilme zirveye ulaşıp sabitlendiğinde aşamayı bitirerek, daha isabetli sürtünme açısı değerleri elde edildiği gözlenmiştir..

Anahtar kelimeler: Üç eksenli deneyi, otomatik deney, bilgisayar kontrolü, çok aşamalı deney, yenilme dayanımı.

To my late beloved father

To my family

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to my supervisor Asst. Prof. Dr. Nabi Kartal Toker for his endless support, guidance, criticism, patience and encouragement throughout this study. I had so many difficult moments in this study, but his presence and motivations kept this work on the track and directed it to a successful end. My appreciation is not only for him being mentor in the academic aspects, but also for treating me as a friend and a brother in the last three years.

Further appreciation goes to ALFA Testing Equipment Company represented by its owners Mr. Kadir Alpay and Mr. Berk Alpay and all its personnel for their sponsorship and limitless guidance during this study. They have been my home away from home, giving their best financial and moral support, taking me as part of the family with their never-ending love.

I would also like to thank to TOKER Laboratory for hosting part of my tests in their premises.

Finally, I want to express my deepest gratitude to my family and my friends who stood by me during this study. Without them this work would not have reached an end.

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LIST OF SYMBOLS AND ABBREVIATIONS

A_0	Initial cross-sectional specimen area
A_m	Membrane area
A_p	Specimen cross-sectional area with parabolic correction
E_m	Membrane modulus of elasticity
K_m	Membrane stiffness
k_0	The coefficient of lateral earth pressure at rest
t_{90}	The time value obtained from the consolidation stage.
$\dot{\varepsilon}$	The strain rate
ε_a	Axial strain
ε_v	Volumetric strain
σ_1'	Effective major principal stress in triaxial test
σ_1	Major principal stress in triaxial test
σ_3	Minor principal stress in triaxial test
σ_3'	Effective minor principal stress in triaxial test
σ'	Effective stress
σ'_{max}	Maximum effective stress
σ_{oct}	Mean normal stress
τ_{oct}	Octahedral shears tress
$\emptyset$	Shear friction angle
BP	Back pressure
CD	Consolidated Drained triaxial test
CIU	Isotrorpically-Consolidated Undrained triaxial test
CP	Cell pressure
CU	Consolidated Undrained triaxial test
DACS	Data acquisition and control system
IDE	Integrated development environment

ISRM	International Society for Rock Mechanics
MCCA	Multistage: Cyclic Loading Method (Passing from max Curvature)
MCSA	Multistage: Cyclic Loading Method (Passing from min Slope)
MCU	Multistage Consolidated Undrained triaxial test
MSCA	Multistage: Sustained Loading Method (Passing from max Curvature)
MSSA	Multistage: Sustained Loading Method (Passing from min Slope)
PVA	Pressure-volume actuator
SA	Single Stage (Verification Test)
SG	Single Stage (Verification Test)
TX-C	Conventional triaxial test
TX-M	Multistage triaxial test
UU	Unconsolidated-Undrained triaxial test

CHAPTER 1

INTRODUCTION

1.1 Motivation

Triaxial testing is one of the most important and reliable geotechnical tests that can be performed on specimens of soil to obtain its shear strength and identify the failure envelope. During the test, the consolidation and shear phases allow examining wide ranges of soil parameters like the angle of shearing resistance and the apparent cohesion.

The negative side about this test is the insufficiency of the know-how and automated test setups due to the complex procedures starting from sample extraction/preparation to the end of the test with the shearing stage. Manufacturers are racing to develop a device that maximizes the automation in performing the test and requires the least know-how from the lab personnel. Few manufacturers in Europe and America managed to build an automated model of the triaxial test but with very high price. The absence of such setups in the Turkish industry, and the difficulties faced in performing the test with the current existing setups are the main reasons for this study. Developing such a setup with the available resources in the local market requires lots of researches, trials and errors, time and efforts in figuring out an algorithm that will be able to handle the triaxial tests on most of the soil types in an automated mode.

1.2 Objective

This study will not only focus on developing automated computer-controlled triaxial tester, but to also investigate some ways on reducing the testing time and the need for more than one sample to perform the test. In common practice, each test permits performing a single consolidation and shearing stage on the specimen and obtain only one stress-strain relationship (one Mohr's circle). To obtain full information which includes calculating the failure envelope, three or more tests should be performed on identical specimens at different stress levels. Performing multiple tests on specimens, assumed to be identical, increases the possibility of errors in preparing the sample, performing the test and gathering the data;

- In case of reconstituted specimens, it is even impossible to obtain duplicate and homogeneous specimens from the exact same soil.
- Intact specimens, on the other hand, usually come from undisturbed samples that may or may not be in quantities sufficient to trim 3 specimens.

In either case, the time required to perform multiple tests is much longer than a single multistage test.

For those reasons, researchers all around the world worked and are still working on finding a method from which the stress-strain relationship along with the failure envelope can be obtained from one sample. This is where the multistage triaxial testing comes into the picture.

1.3 Scope

Multistage triaxial test is performed on a single soil sample with different consolidation pressures. The sample is consolidated to a certain consolidation level and then sheared to a level just before failure, followed by another stage of consolidation to a higher level and then sheared again. Each stage aims to produce a stress-strain relationship that is identical to the early parts of the one obtained from the same sample with conventional (single-stage) test. The results are then combined to identify the failure envelope and other parameters.

One of the main challenges in multistage triaxial tests is to choose where to stop the shearing stage and proceed to the next stress level, a point that represents the correct shear strength but not to exceed the failure level. Another question is to choose whether to take the deviator stress to zero between the stages or keep the specimen loaded while the confinement is increased it to the next consolidation level directly.

In this study, those challenges will be solved and the most practical method to perform a correct and dependable multistage triaxial test will be determined.

During this study, Consolidated Drained Triaxial tests will be performed on Standard Sand. Chapter 2 will contain literature review about the test and the methods used in performing multistage triaxial test. Chapter 3 and 4 will explain in details the triaxial test setup and control software developed in this study. Chapter 5 will show the test procedures followed to conduct the conventional triaxial test. Details about the multistage triaxial test and the methods studied in this thesis will be shown in chapter 6. Finally chapter 7 will include the discussion and conclusion of this study.

CHAPTER 2

LITERATURE REVIEW

The word ***Triaxial*** is derived from the mechanical forces applied to the soil specimen during the test. Basically, the test is performed by applying a load axially on the soil specimen while supporting it laterally against its sides by pressure applied through water, oil, air or other means. One of the earliest devices was invented by Buisman (in 1924) which held many of the current known triaxial test devices' characteristics. But the device that is similar to the modern setups was firstly used by Casagrande (in 1930) in Vienna. Both setups were invented under the recommendations of the father of soil mechanics, Terzagi (Lai 2004).

Triaxial testing of cylindrical soil specimens is common because it allows wide range of mechanical parameters to be examined during consolidation and shear phases (Soranzo 1988). Three or more identical soil samples needs to be tested so as to determine the mechanical parameters of the soil. In order to evade the influence of natural inconsistency faced when trying to prepare several samples from the same soil, multistage tests are used to determine the strength parameters. While trying to do so, it is crucial to pay attention not to alternate the same sample during the long and rather complicated multistage test (Gräsle 2011).

De Beer was the first to introduce multistage triaxial test more than 60 years ago (De Beer 1950). Since that time no standardized procedure is presented and thus no specific steps were followed during the test.

Each triaxial test consists of three main stages; saturation, consolidation and shear.

2.1 Stages of Triaxial Test

2.1.1 Saturation

During saturation, fast application of back-pressure on the sample increases the risk of overconsolidating the sample during the temporary large effective stress. It is proved that the higher the effective stress applied during saturation, the greater the shear strength of the specimen (Brandon, Duncan and Cadden 1990). Figure 1 shows the effective stress distribution in the triaxial specimen during saturation.

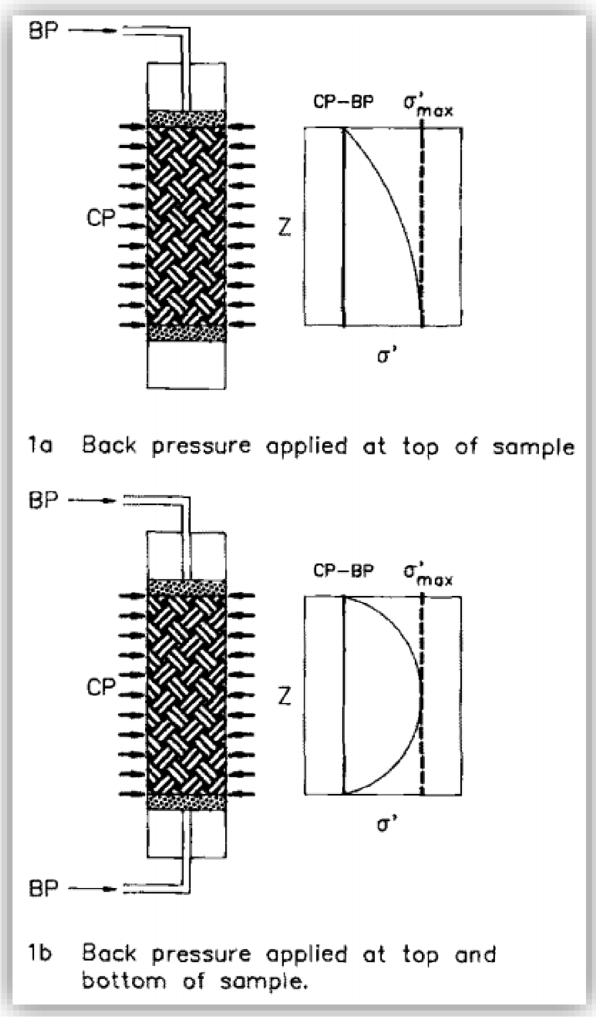


Figure 1: Simplified schematic of effective stress distributions in triaxial specimens during back-pressure saturation (Brandon, Duncan and Cadden 1990)

One of the most common saturation procedures is to set the effective stress not to exceed 35 kPa while pressurizing the sample to a maximum of 700 kPa. Each step consists of increasing the cell and pore pressure with 30 kPa and wait for 30 minutes. This procedure ensures proper saturation without over consolidating the sample but being time-consuming makes it unhelpful in most of the situations (Brandon, Duncan and Cadden 1990). Figure 2 shows the difference in principal stress caused by using different saturation methods.

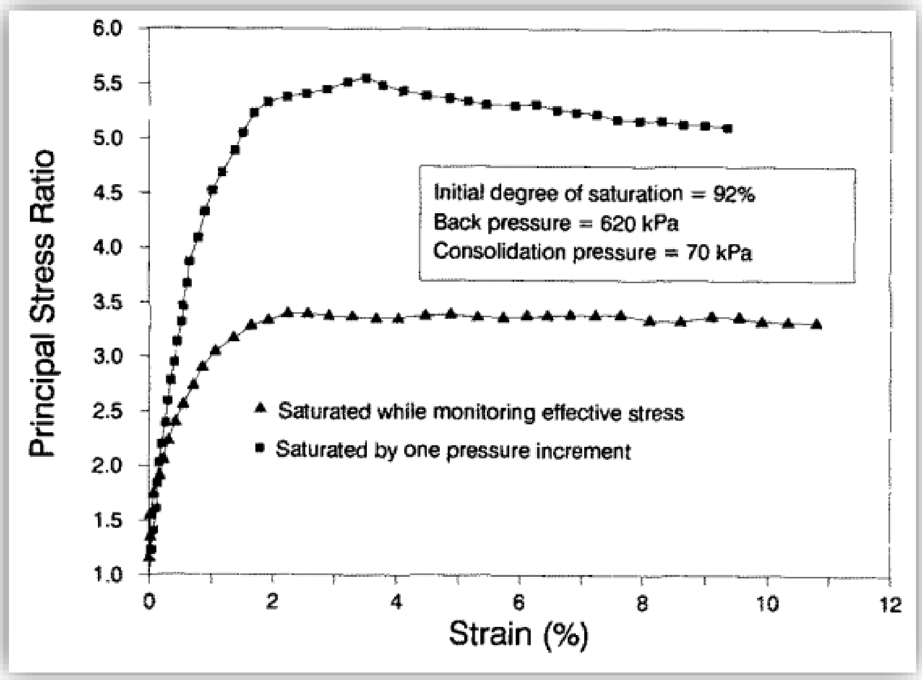


Figure 2: Principal stress ratio versus strain measured for triaxial specimens saturated by different methods (Brandon, Duncan and Cadden 1990)

Using a constant rate while increasing the pressures during saturation is not an effective method of saturation because the behavior of the cell fluid and the sample are not linear, but it experiences an exponential behavior during constant rate. On the other hand, decreasing the rate gradually so as to have linear relationship between pressure and time would be time consuming (Brandon, Duncan and Cadden 1990).

2.1.2 Consolidation

During the consolidation stage, the sample is consolidated to a certain pressure level. Consolidation can be done isotropic, K_0 or any other custom stress path depending on the requirements of the test and the ability of the testing device. At the end of the consolidation stage, coefficient of consolidation (C_v) and K_0 value in case of K_0 consolidation can be obtained. Using the results obtained from the consolidation graph (t_{90} and C_v), the shearing rate can be determined using the following equations (ASTM):

In case with side drain;

$$\dot{\varepsilon} = \frac{4\%}{16 \times t_{90}} \qquad (Eq. 1)$$

In case without side drain;

$$\dot{\varepsilon} = \frac{4\%}{10 \times t_{90}} \qquad (Eq. 2)$$

Where; $\dot{\varepsilon}$ is the strain rate, and

t_{90} is the time value obtained from the consolidation stage.

If the failure is expected to occur at strains other than 4%, the above strain should then be changed to the expected value.

2.1.3 Shear

Shear stage is the last in a triaxial test. During shear, the specimen is loaded axially and the stress-strain relationship is obtained in either drained or undrained mode. Combining the results obtained from a set of at least three samples will provide enough data to determine the Mohr's circles and as a result the shear failure envelope and the shear strength of the soil.

During this stage, the area should be corrected and recalculated at every data point. By assuming that the sample is a rotational body and equating the volume of the sample to the rotational integral of a parabolic body; the maximum area can be calculated at any data point for any type of soil from the following equation (Toker 2007):

$$A_p = \frac{A_o}{16}\left(\sqrt{30 \times \frac{1-\varepsilon_v}{1-\varepsilon_a} - 5} - 1\right)^2 \qquad (Eq. 3)$$

2.1.4 Multistage Shearing

Ho and Fredlund (1982) reported two methods for performing multistage triaxial testing on the sample:

- The first is to apply deviator stress until a peak is recorded, then unload the sample by releasing the deviator stress and then pass to the next consolidation stage, this is called “Cyclic Loading Method”. Figure 3 shows ideal values for this method.

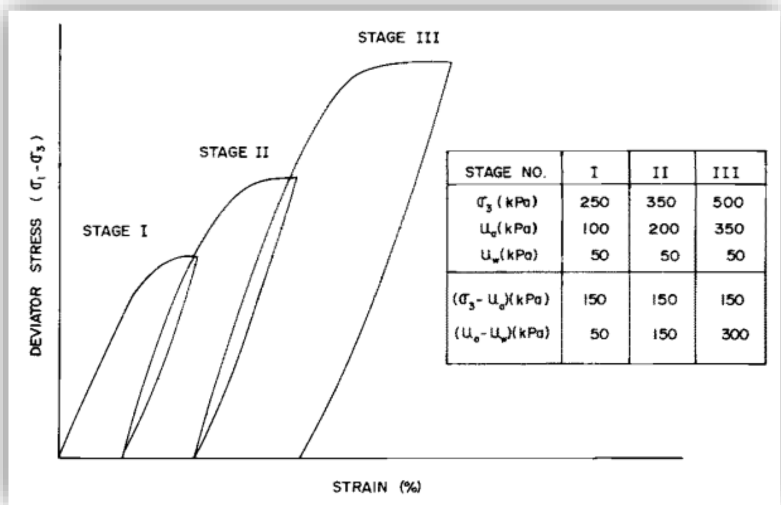


Figure 3: Ideal stress versus strain curves for a multistage test using the cyclic loading procedure (Ho and Fredlund 1982).

- The second method is to shear the sample until a recorded peak, then pass to the next consolidation stage while maintaining the load, which is called “Sustained Loading Method”. The latter is found to be preferred due to the cumulated strain on the sample but keeping the load constant on the sample between the stages might continue to deform the sample due to creep.

For those reasons, “Cyclic Loading Method” is preferred in multistage triaxial tests. Depending on the soil type, the peaks that a certain sample can take while still giving representative data differs. Gräsle (2011) showed that Opalinus Clay from Mont Terri in Switzerland can withstand up-to 4 cycles with a linear Mohr-Circle relationship with regression value of 0.997. If brittle behavior is expected from the sample, development of shear towards failure would destroy the sample and make it unusable for a second stage. Clay is said to be moderate behaving sample. Figure 4 shows the Results of three multistep strength tests displayed in octahedral stress space.

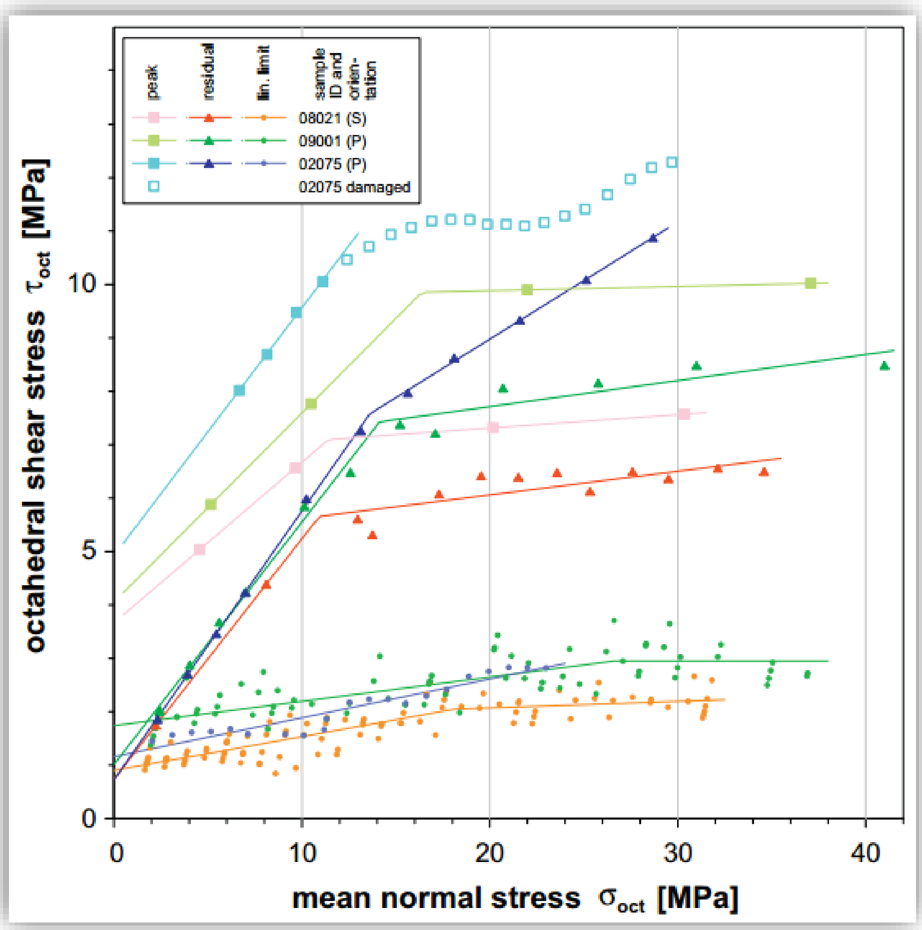


Figure 4: Results of three multistep strength tests displayed in octahedral stress space

It is reported that the brittle soil samples, which are expected to fail at axial strain lower than 5%, will not be suitable for regular multistage triaxial test. Instead, some post-calculations must be done on the samples. For soil samples with medium to low plasticity, that is clayey and silty-clayey samples, that can withstand more than 8% of axial strain, each stage is carried out until a visible peak is reached, then the sample is released from the deviator stress before experiencing the new consolidation pressure. At the beginning of each stage, new dimensions, height and volume, are calculated and allocated to their related equations. Figure 5 shows the results of multistage unconsolidated undrained triaxial test and isotropically consolidated undrained triaxial test on confined specimens. The strain is of the order of 5% for each compression stage in the unconsolidated test and 3% for the consolidated one. In both circumstances, the shear strength peak values are likely to be for strain values greater than 8%, as is the case of various clayey and silty-clayey soils of medium to low plasticity (Soranzo 1988).

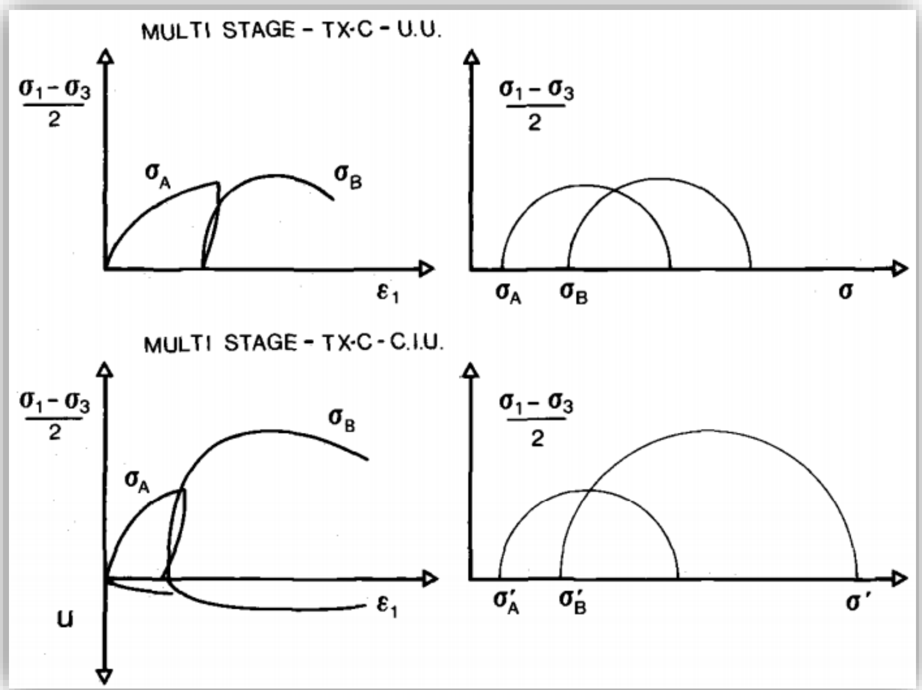


Figure 5: Stress vs Strain and Mohr's Circle plots for UU and CIU multistage triaxial tests on clayey soil with low plasticity

It is recommended by ISRM (International Society for Rock Mechanics) that the axial load between the stages of a multistage Triaxial Test should be kept constant while increasing the confining stress to the next consolidation level (Csuhanics and Debreczeni 2013).

ISRM also reported the modified multistage triaxial test at which the axial load is released before passing to the next consolidation stage (Csuhanics and Debreczeni

2013). Figure 6 shows the deviator stress versus the confining pressure plot obtained using the method suggested by ISRM.

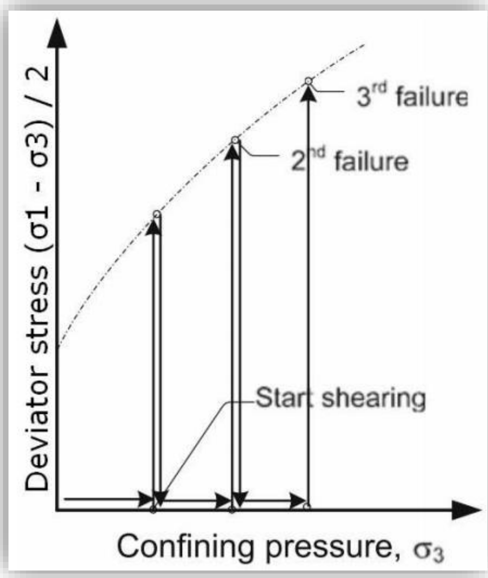


Figure 6: deviator stress versus the confining pressure using the modified method by ISRM

Researchers reported that at each stage, the axial strain should not exceed 3% - 4%. The specimen should be sheared to "near failure" and not to failure (Sridharan and Rao 1972) and then the interpretation suggested by Kondner (Kondner 1963) is to be applied to estimate the failure point and the related deviator stress. The method defined by Kondner states that the stress-strain curves of soils can be approximately calculated by rectangular hyperbolae, at which equations (4) and (5) are used.

$$\frac{\varepsilon_a}{\sigma_1 - \sigma_3} = a + b\varepsilon_a \qquad (Eq. 4)$$

Where ε_a : Axial Strain

$\sigma_1 - \sigma_3$: Deviator Stress

a and b : constants to be experimentally determined

Then plotting $\frac{\varepsilon_a}{\sigma_1 - \sigma_3}$ vs. ε_a will give a straight line. The slope of that line represents the value of the constant b. The intersection of that line with with the vertical axis represents a. By taking the limit of equation 4 for $\varepsilon_a \to \infty$ yields the deviator stress at failure as follows:

$$\lim_{\varepsilon_a \to \infty} = (\sigma_1 - \sigma_3)_f = \frac{1}{b} \qquad (Eq. 5)$$

Kondner's method requires another test with the conventional triaxial test in order to precisely predict the values (Nambair, Rao and Gulhati 1985). Figure 7 shows the applicability of Kondner's equation on kaolinitic clay.

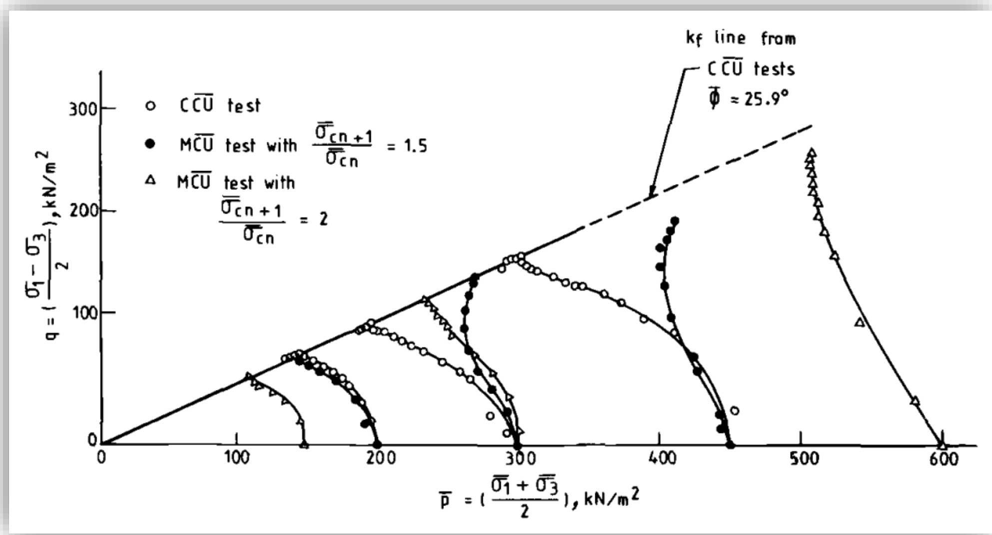


Figure 7: Effective stress paths for kaolinitic clay (CU Triaxial Test)

Nambair et al. (1985) proposed another method based on rational procedure to predict the behavior of the sample during failure before actually failing the sample. Nevertheless, this method also requires at least one test to be carried out using the conventional triaxial test in order to obtain the extrapolation parameters defined by Kondner.

A solution to that problem is suggested by Shahin and Cargeeg (2011) stating that the third, or the last stage, in the multistage triaxial test can be used instead of the conventional triaxial test to predict the related deviator stress for all the stages. This solution consists of shearing the soil at each stage to 3% - 4% axial strain and then pass to the following stage directly. During the last stage, the sample is sheared to 25% axial strain and then the estimation method of Kondner is applied to predict the deviator stress for all the stages from which the data used in plotting the Mohr-Circles are obtained. The results obtained by following these recommendations showed great similarities to those obtained from the conventional triaxial test using three identical samples. With the help of this method, it may be applicable to perform the multistage triaxial test by shearing the sample to near-failure at each stage and then post-calculate the deviator stress for each stage at the end of the last stage. Figures 8-11 show results obtained by Shahin et al using the suggested method by the latest.

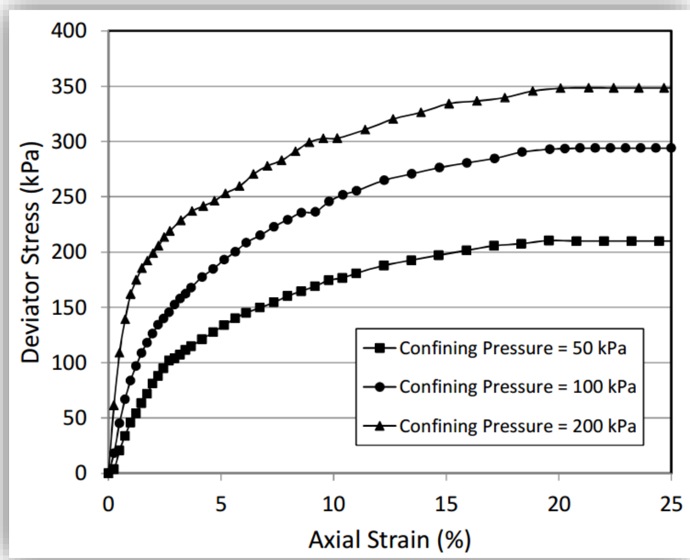


Figure 8: Stress-Strain relationship for the conventional triaxial test (Shahin and Cargeeg 2011)

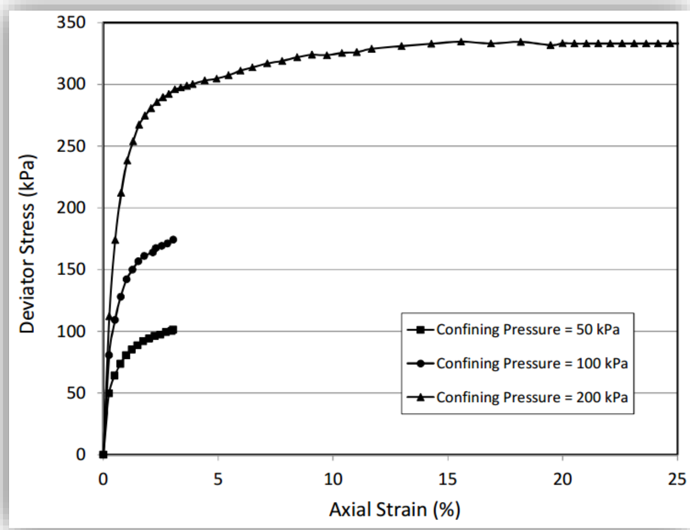


Figure 9: Multistage Triaxial Test Results (Shahin and Cargeeg 2011)

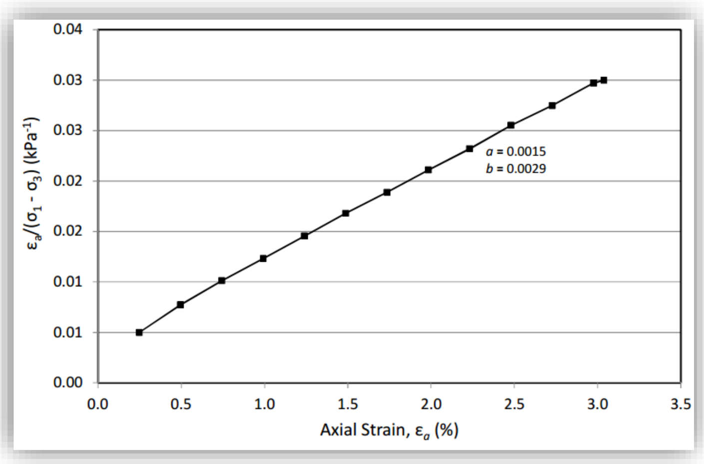
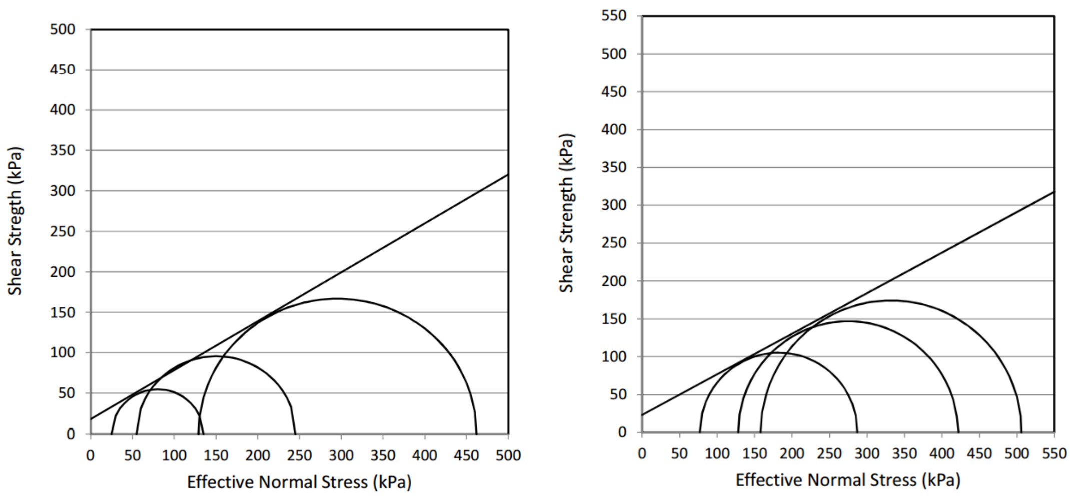


Figure 10: Hyperbolic linearization of the multistage test results (Shahin and Cargeeg 2011)



a b

Figure 11: Mohr's Circle plot from (a) multistage and (b) conventional triaxial tests (Shahin and Cargeeg 2011)

In the case of Cyclic Loading method, it was reported by Schoenemann and Pyles (1988) that the sample experiences axial rebound of around 1% – 3% of its initial height between the stages after taking the deviator stress down. Therefore, it is important to lock the piston in place in order to prevent the rebound from occurring (Refer to figure 12).

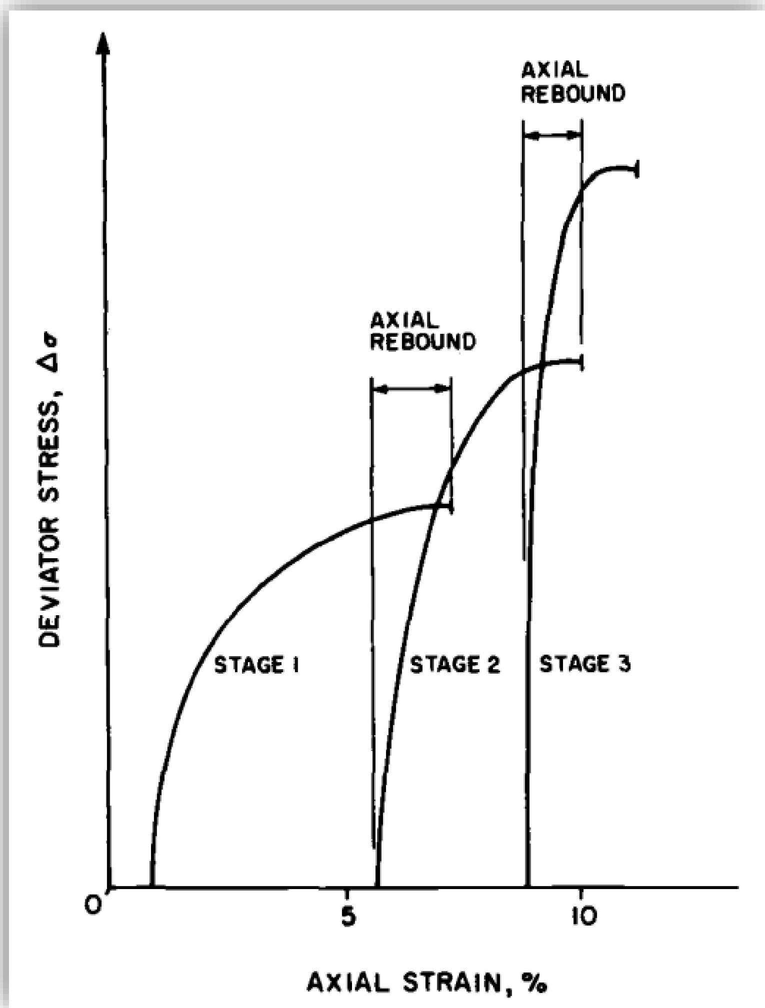


Figure 12: The axial rebound discussed by Schoenemann and Pyles (1988)

Many devices that are available in the market were taken into consideration while developing the test setup in terms of what they can do and what they cannot do (Geocomp, Controls 2015). Bits from everything were taken and combined together to have what is best from the current setups and implement them all into one completely automated computer-controlled setup.

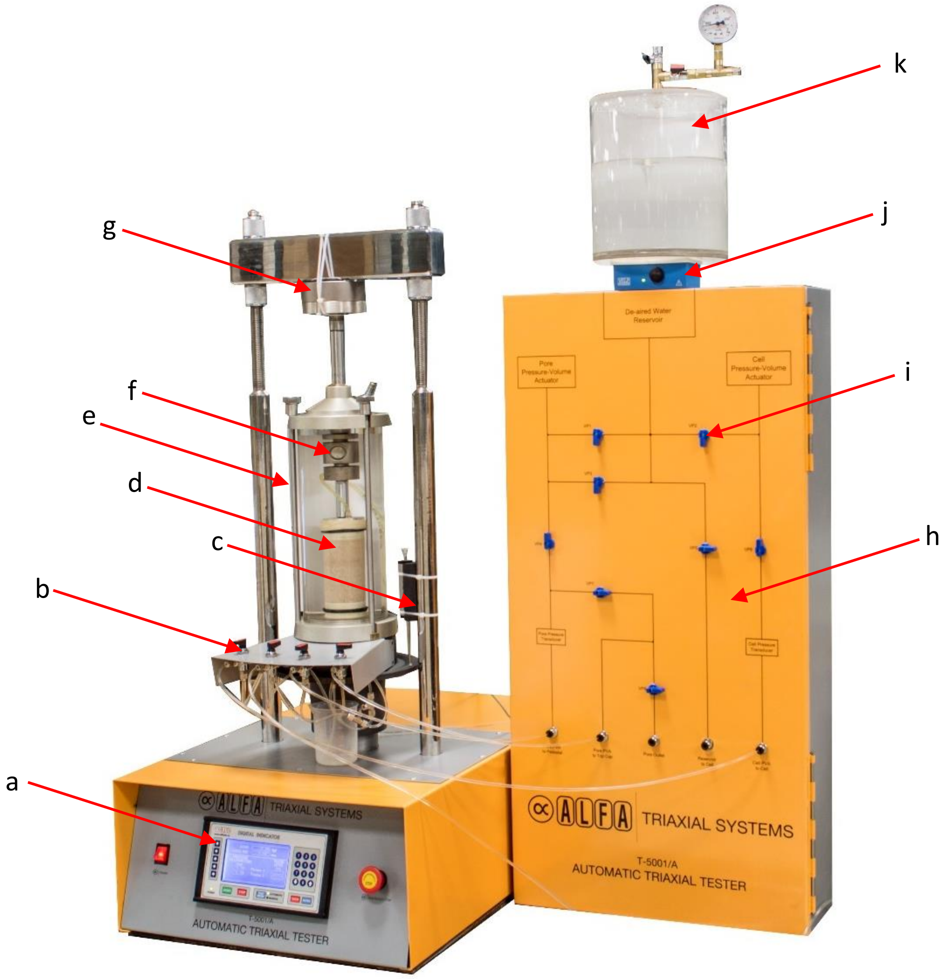
CHAPTER 3

SETUP DEVELOPMENT

3.1 TEST SETUP

The setup used in this study is specially developed for this study by ALFA Testing Equipment in Ankara / Turkey (See Figures 13-15). The main goal while developing was to maximize the automation, decrease the need of know-how and have the device finished by the lowest cost/price tag possible.

The device consists of two main units. The first one contains two pressure-volume actuators (PVA), one connected to the cell and another connected to the sample (explained in detail in 3.1.1). The second unit is the loading frame (explained in detail in 3.1.2). The two units are connected to each other with flexible tubes and valves that allows wide range of triaxial tests to be easily performed. The triaxial cell used in this study is explained in detail in section 3.1.3. A 16-bit data-acquisition system for the PVAs and the loading frame is installed in the main body of the device under the loading frame (explained in detail in 3.1.4).



a	Data Acquisition and Control System	g	External Load Cell *(Backup load cell in case of submersible failure, for development purposes)*
b	Triaxial Cell Valves Panel		
c	Deformation Transducer	h	Pore and Cell PVA System
d	Test specimen	i	PVA Valves Panel
e	Transparent Plexiglas Cell	j	Magnetic Stirrer
f	Submersible Load Cell	k	De-aired Water Tank

Figure 13: ALFA's Triaxial Test Setup

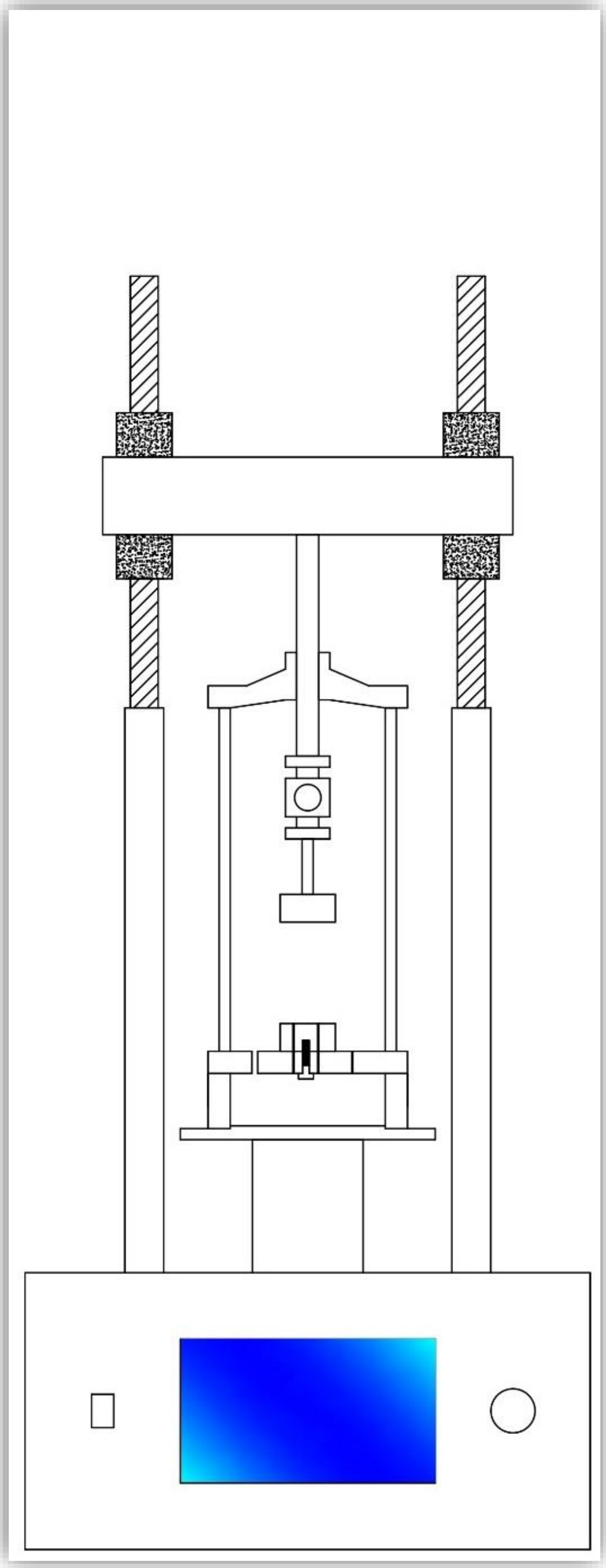


Figure 14: ALFA's Triaxial Tester Loading Frame - Schematic Drawing

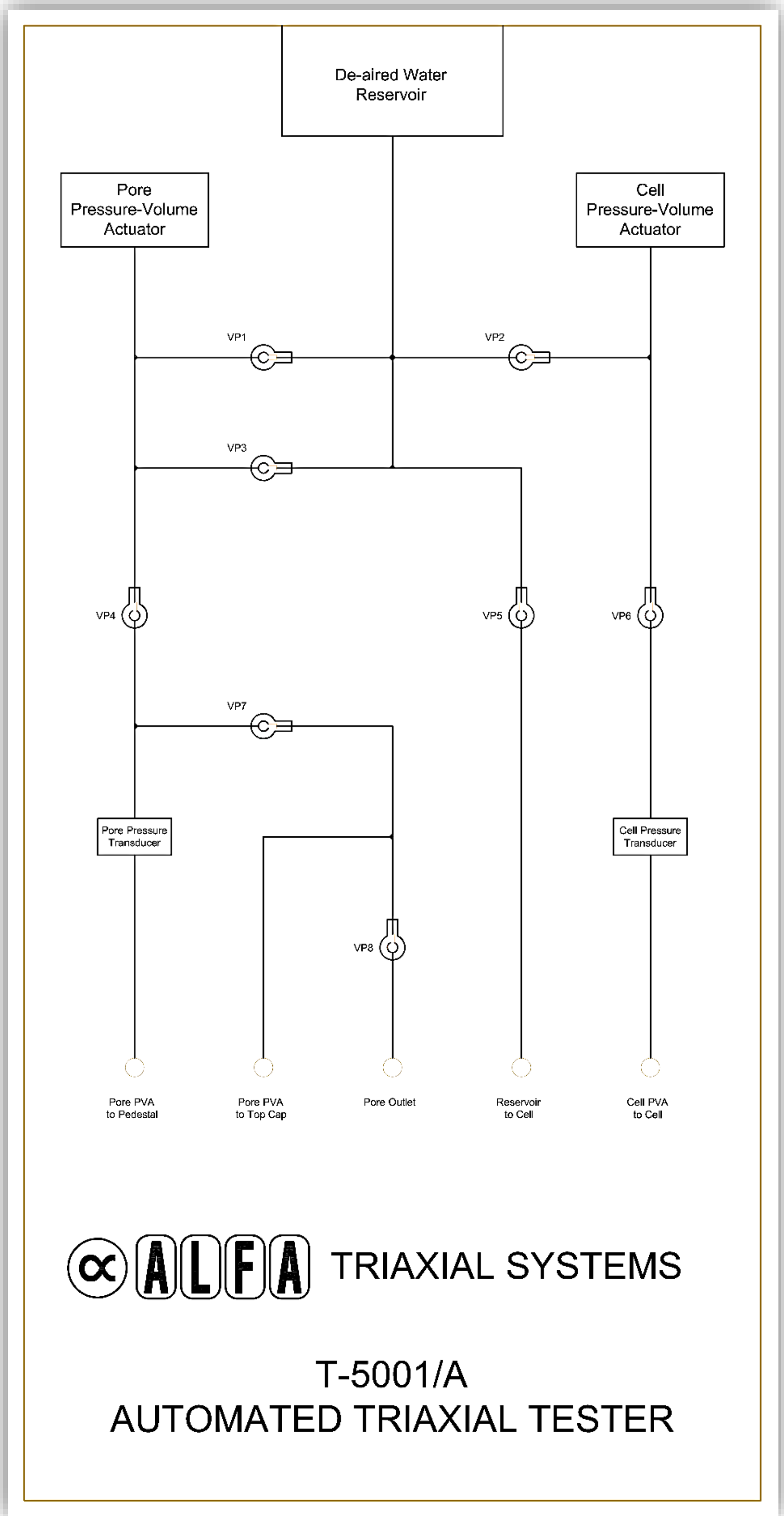


Figure 15: ALFA's Triaxial Tester PVA Cabinet - Schematic Drawing

3.1.1 Pressure-Volume Actuator Unit

The all-in PVA consists of pneumatic piston, Stepper Motor, pressure transducer and a Potentiometric Position Transducer.

3.1.1.1 Pneumatic Piston

The pneumatic piston is used to apply certain pressure on the cell and sample throughout the test. The amount of water inside the piston is back-calculated using the area of the piston with the help of the position indicator (3.1.1.4). The technical properties of the pneumatic piston are shown in Table 1.

Table 1: Technical Specifications of the Pneumatic Piston used in the PVA unit

Model	Pemaks ISO-M 23-250
Country of Origin	Turkey
Standards	ISO 15552
Piston Rod	Stainless Steel (Grade 420)
Thrust Force at 6 bars	482 N
Traction Force at 6 bars	415 N
Effective Diameter	32.00 mm
Effective Area	804.25 mm^2
Effective Length	250.00 mm
Effective Volume	201,061.93 mm^3
Other Specifications	Adjustable Cushioning Magnetic Sensor Running Fat-Free ELOXAL Plated Tubes

3.1.1.2 Stepper Motor

The Stepper Motor is used to move the pneumatic piston in both directions with the help of LEXEM TAIWAN threaded shaft and ball screw. It is controlled by computer through the software. Using Stepper Motor to control the PVA provides an excellent preciseness for the control and feedback algorithm used during the test. The motor is capable of advancing a minimum of 1.8 degrees out of the 360 degrees turn. Each step advances the PVA system 0.02 mm by length, 16.09 mm^3 by volume providing sensitivity 6 times better than the required limit by ASTM standard. The technical specifications of the Stepper Motor are shown in the appendix.

3.1.1.3 Pressure Transducer

The transducer is used to measure the pressure inside the PVA system. The data acquisition system reads data from the transducer four to five times each second allowing the feedback to be responsive for any situation during the test. The measuring-accuracy graph of this sensor is shown in Figure 16. The technical specifications of the pressure transducer are shown in the appendix.

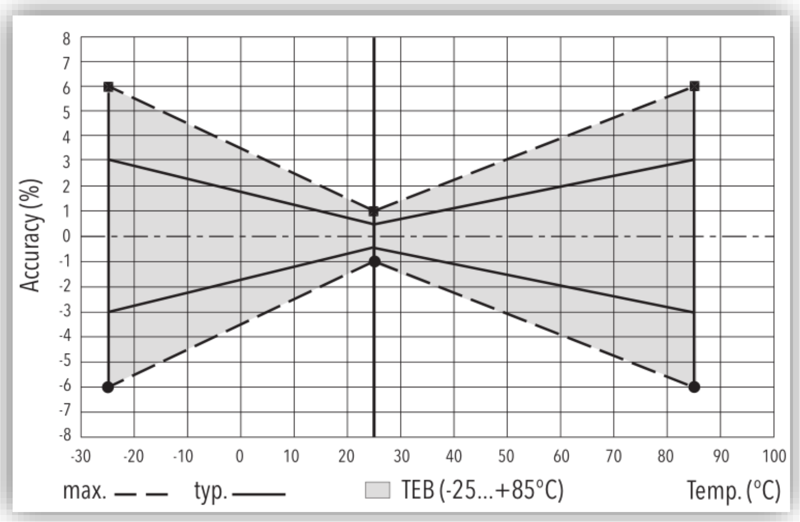


Figure 16: Pressure Transducer Measuring Accuracy vs. Time Graph (Provided by the manufacturer)

3.1.1.4 Potentiometric Position Transducer

The position transducer is used to locate the pneumatic piston and calculate the volume of water going into or out of the sample/cell to determine the volume change. Detailed information about the transducer is shown in the appendix.

3.1.2 Loading Frame

The loading frame has a capacity of more than 10 tons. The height of the cross-beam mounted at the top of the frame can be adjusted using screw nuts. It consists of the following:

3.1.2.1 Loading Platen

The platen is mounted on threaded mill which is connected to the servo-motor. The platen is made of steel, coated with cadmium for extra protection against corrosion and impact. A groove is made around the seating of the triaxial cell to collect all the spilling water before or after the test. The groove is connected to a drainage line to dispose the excess water.

3.1.2.2 Servo-Motor and Driver

The servo-motor is used to move the loading platen upwards or downwards. Having the loading mechanism by a servo-motor gives the ability to precisely control the loading rate of the device. The motor is capable of advancing with a speed as low as 0.00001 mm/min and as fast as 51.00000 mm/min. The positive point about the servo-system is that it sends the actual speed to the data acquisition system, which gives the ability and flexibility for the feedback algorithm to perform perfectly under any circumstance. Technical specifications of the motor and the driver used in this particular study are shown in the appendix.

3.1.2.3 Potentiometric Deformation Transducer

The deformation transducer is installed on the loading frame to report the position of the loading platen and the amount of strain the sample is experiencing before, throughout and after the test. Technical specifications of this item are shown in the appendix.

3.1.3 Triaxial Cell

The cell is manufactured to be able to accommodate triaxial samples up to 70 mm diameter and flexible wall permeability samples up to 90 mm diameter (See figures 17-18).

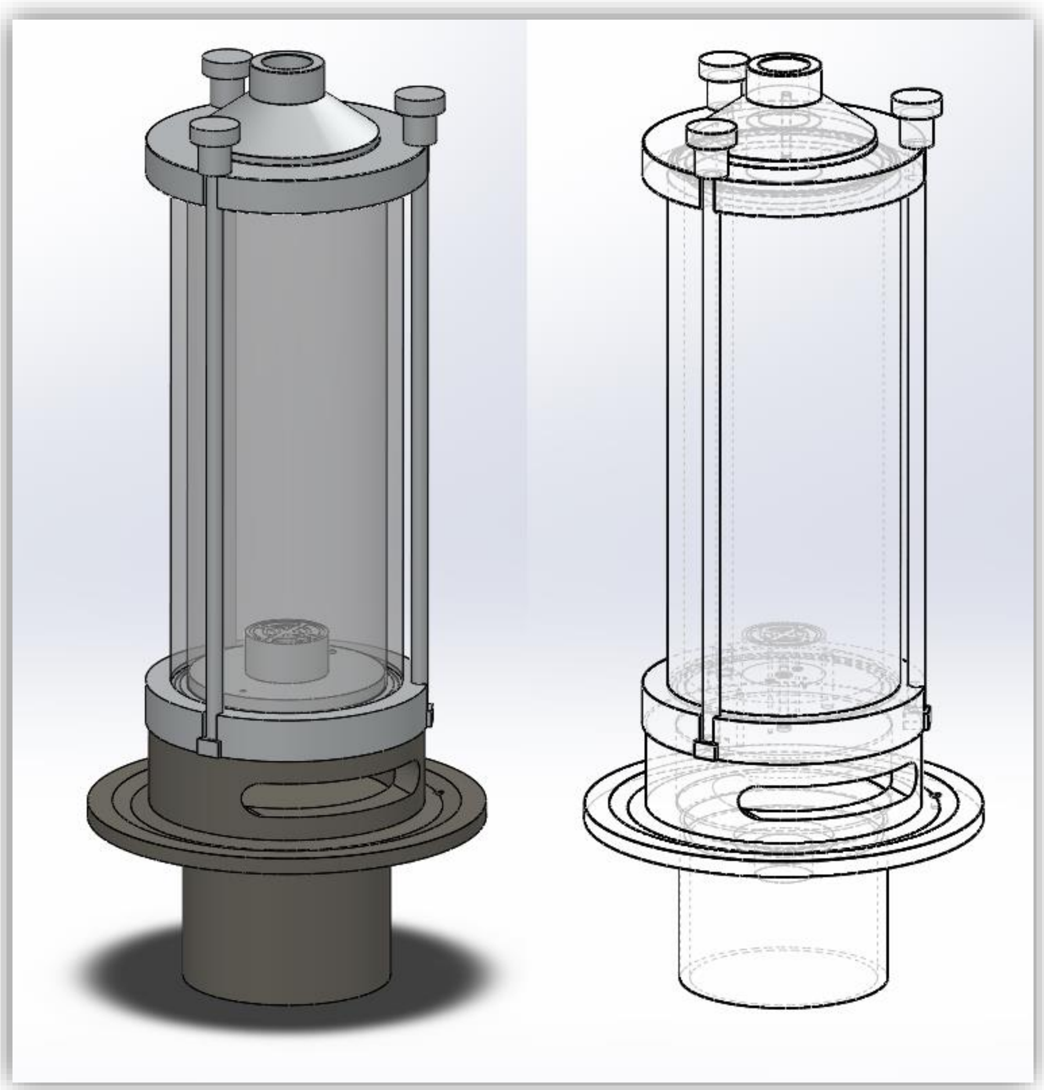


Figure 17: Triaxial Cell Assembly - SolidWorks Design Stage

The cell consists of the following:

3.1.3.1 Base and upper platen

The base and upper plate are made of anodized aluminum to prevent rusting or oxidation (See figures 17-18).

3.1.3.2 Plexiglas Cylinder

The cell wall is made of transparent Plexiglas® with thickness of 10 mm to be able to withstand high pressures without any deformation or risk of creep.

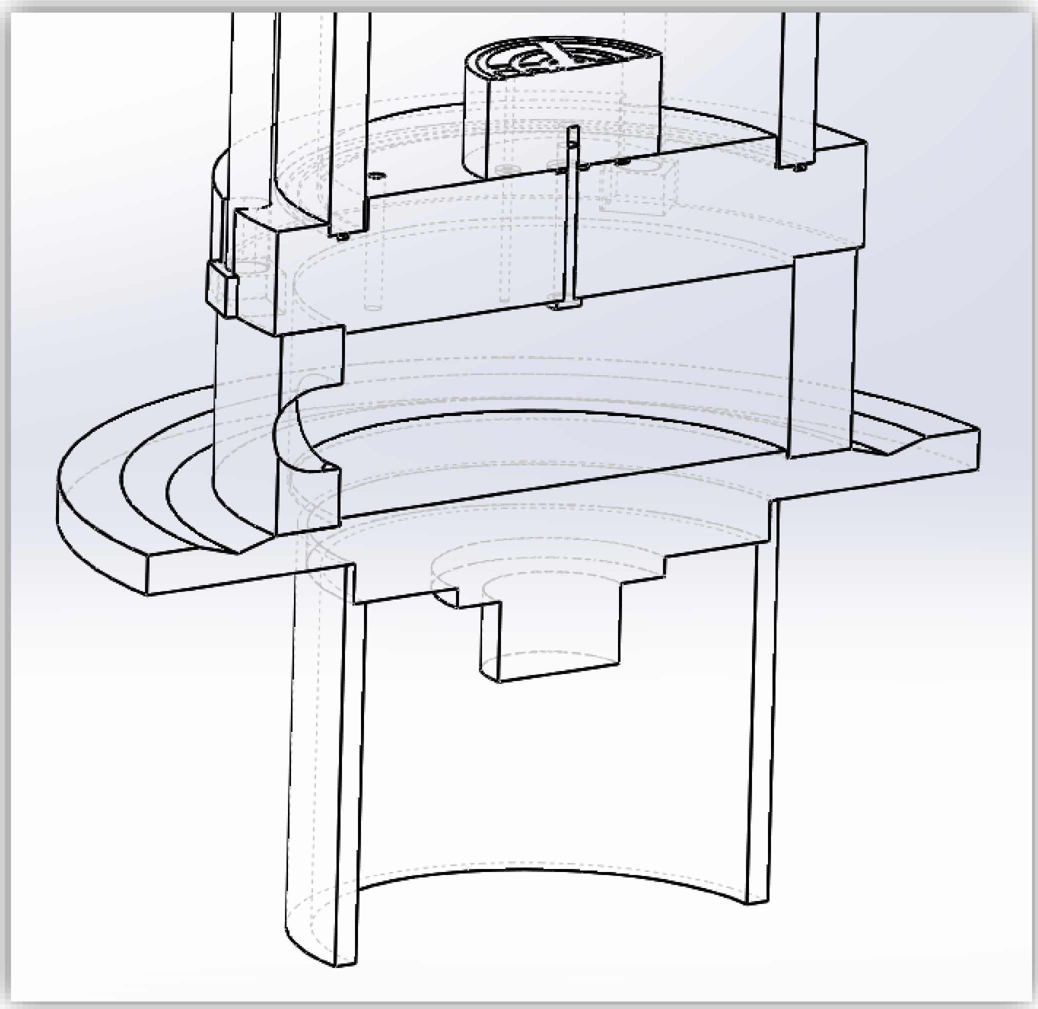


Figure 18: Detailed Sketch for the Base Plate

3.1.3.3 Pedestal and Top Cap

The pedestal and top cap are made of anodized aluminum to prevent rusting or oxidation. The side has a smooth groove for the O-Ring to fit in and hold the membrane in place. The sides touching the sample are grooved to allow water to spread throughout the surface homogeneously towards the porous stone, filter paper and the sample (See figure 19).

The pedestal has two holes that are connected to flexible pipes and to the pipe-network of the device. The top cap has one hole that are connected to flexible pipe through the cell, then down to the base and then to the pipe-network of the device. The upper side of the cap has a rounded seating for the loading piston to fit in and apply the load along the central axis of the cell without exerting lateral forces on the sample.

Both the top cap and the pedestal are changeable to accommodate the desired sample diameter ranging from 35 – 70 mm.

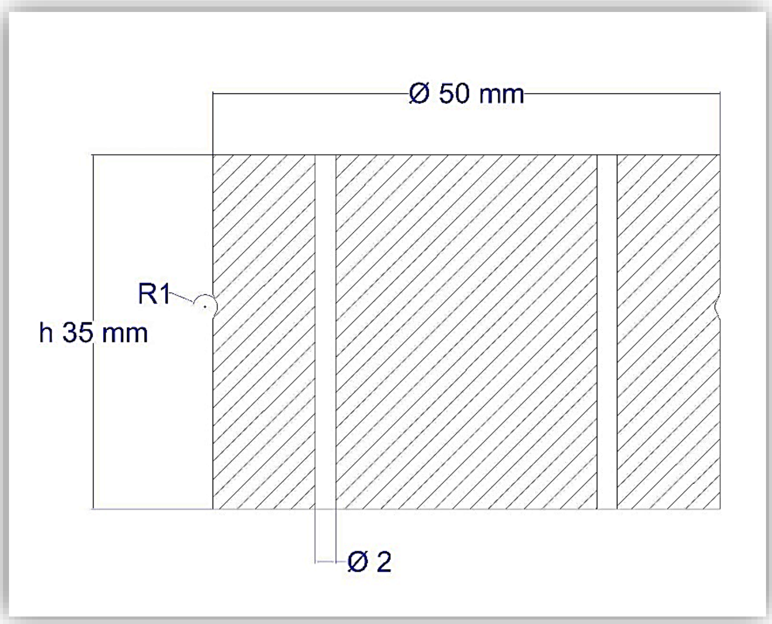


Figure 19: Pedestal Sketch

3.1.3.5 Submersible Water-Proof Load Cell

The setup is equipped with a stainless steel, submersible water-proof load cell. It is specially manufactured for this study and can withstand up to 70 bars of pressure (7000 kPa). The load cell can be submerged in water under 20 bars without having any problems. Having it inside the cell allows more precise reading since it eliminates the piston friction calculations and the up-lifting force of the fluid pressure on the lower surface of the loading piston. The only correction needs to be done on the submersible load cell is taring the force read due to the exerted cell pressure on the load cell surfaces. The cable of the load cell is taken out of the cell through the loading piston, eliminating the need of an extra hole or sealed jack to do this.

3.1.3.6 Loading Piston

The piston is made of stainless steel, having a diameter of 16 mm and length of 200 mm. It is drilled along its length to accommodate the cable of the submerged load cell. The piston is easily detachable from the cross-beam to allow the user to assemble and disassemble the cell in easy and fast way.

3.1.4 Data Acquisition System

The setup is equipped with 16-bit data acquisition and control system (DACS) that can read, control and send the necessary information between the computer and the related components. The DACS is specially manufactured by ALFA Testing Equipment and is being used in most of ALFA's equipment (See figure 20). The DACS is designed such as to accommodate, acquire and control the sensors/motors connected to it. This unique design was implemented for the newly developed Triaxial Setup. Connected to the DACS are the following:

1. Loading Frame:
    a. Servo-Motor through servo-driver
    b. Potentiometric Deformation Transducer
    c. Load Cell through mV Transmitter (Model: PR 2261)
2. Pore PVA
    a. Stepper Motor though the stepper driver
    b. Potentiometric Position Transducer
    c. Pressure Transducer
3. Cell PVA
    a. Stepper Motor though the stepper driver
    b. Potentiometric Position Transducer
    c. Pressure Transducer

Figure 20: Data Acquisition and Control System - LCD Monitor

The DACS sends the readings from all the sensors mentioned above to the computer software which takes them into the control algorithm, performs the necessary calculations and sends the feedback to the DACS. After receiving the feedback, the DACS sends the necessary signals and control commands to the motors to react in accordance to the orders sent by the computer software. The DACS is connected to computer via USB through RS-232 converter.

Table 2 shows a quick comparison between the main requirements of ASTM standard and the capabilities of ALFA's Triaxial System.

Table 2: ASTM vs. ALFA Requirements Comparison

Requirement	**ASTM**	**ALFA**
Load Cell Sensitivity	1% of axial load at failure	0.1 N
Loading Motor Deviation	< 1% from the set value	Servo-System, no deviation
Loading Piston Friction	0.1% of axial load at failure	Submersible Load cell
Volume-Change Measurements	< 94 mm^3 for Ø 50 mm	16 mm^3
Deformation Indicator	0.25% of specimen height	0.01 mm

3.2 ACCESSORIES

In order to perform the test in the easiest and fastest way, some accessories were prepared to prepare the sample and get the device ready for test (See figure 21).

a	Plexiglas Cell	h	Grease
b	Filter Paper	i	Split Compaction Mould
c	O-Ring Stretcher	j	Filter paper for (i)
d	Membrane	k	Compaction Hammer with Adjustable Height
e	Membrane Protector	l	Spatula
f	O-Rings	m	Pipette for Water Content
g	Standard Sand Sample	n	Electronic Balance

Figure 21: Accessories used with ALFA's Triaxial Tester

3.2.1 Split Compaction Mould

The split mould is used to stretch the membrane and also to compact/prepare the reconstituted samples. It consists of two sides, each has a hole connected to flexible pipe to perform sucking and stretch the membrane to its inner walls (See figure 22). Filter paper was installed on its inner wall to ensure distributing the vacuum evenly throughout its surface. The mould is manufactured such as to fit on the pedestal with the O-Ring fitted on it. The effective height of the mould between the upper surface of the pedestal and the lower surface of the top cap is manufactured to be twice the diameter. It can be easily split into two halves for easy removal when the top cap is mounted.

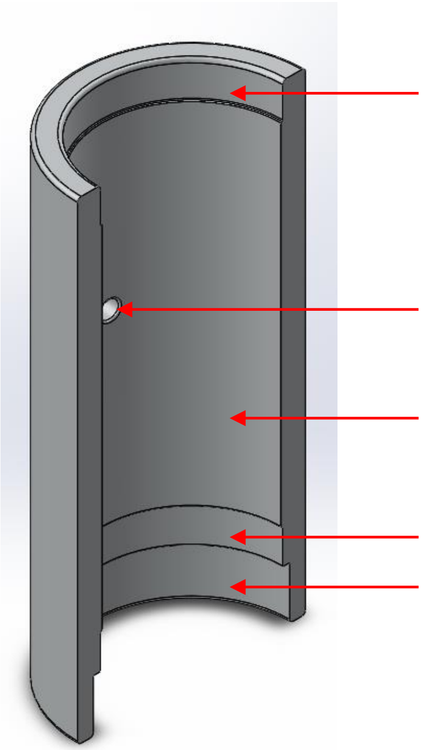


Figure 22: Triaxial Sample Split Mould - SolidWorks Design

<u>3.2.2 Rubber Membrane</u>

A rubber impermeable membrane used in this study is manufactured by Impact Test Equipment in the United Kingdom. The stiffness of the membrane is 6.90 kgf calculated by equation (6).

$$K_m = E_m . A_m \qquad (Eq. 6)$$

The properties of the used membrane are shown in table 3.

Table 3: Membrane Specifications

Country of Origin	United Kingdom
Modulus of Elasticity	14 kgf/cm^2
Perimeter	154 mm
Thickness	0.32 mm
Stiffness	6.90 kgf

The membrane used has a diameter of 49 mm which is 98% of the sample's diameter. ASTM recommends to have the membrane diameter within 95% - 75% of the sample's diameter in order to minimize the membrane effects on the sample.

3.2.3 O-Ring

Many O-rings were used in the setup itself and during the procedure of sample preparation. All the connections and fittings are equipped with O-rings to prevent water leakage and pressure loss. During sample preparation, O-rings are used to hold the membrane in place. The top cap and pedestal have special groove for the O-rings to fit in and stay in place without slipping out. The groove where the Plexiglas fits in has a special channel for the O-Ring to prevent water leakage and ensure perfect seating for the cell.

3.2.4 O-Ring Stretcher

In order to place the O-rings on the membrane while fitting them on the triaxial base; an O-Ring stretcher is used (See figure 23). The stretcher has a cut on one side to allow its extraction from the setup after placing the O-Rings. All the corners and edges of the stretcher are well rounded so as not to have any sharp sides that might cut the O-Rings.

Figure 23: O-Ring Stretcher

3.2.5 Tamping Rod

The tamping rod is used to prepare compacted samples inside the compaction mould. The rod is specially manufactured so as not to give any harm to the membrane while compacting. The tamping rod consists of the following parts (See figure 24):

- Tamping Rod; having diameter half of the sample's diameter
- Mould Seat; to allow proper control on the tamper

- Falling Height Lock; to evenly compact the sample to the desired density without having variations in the compacted layers.

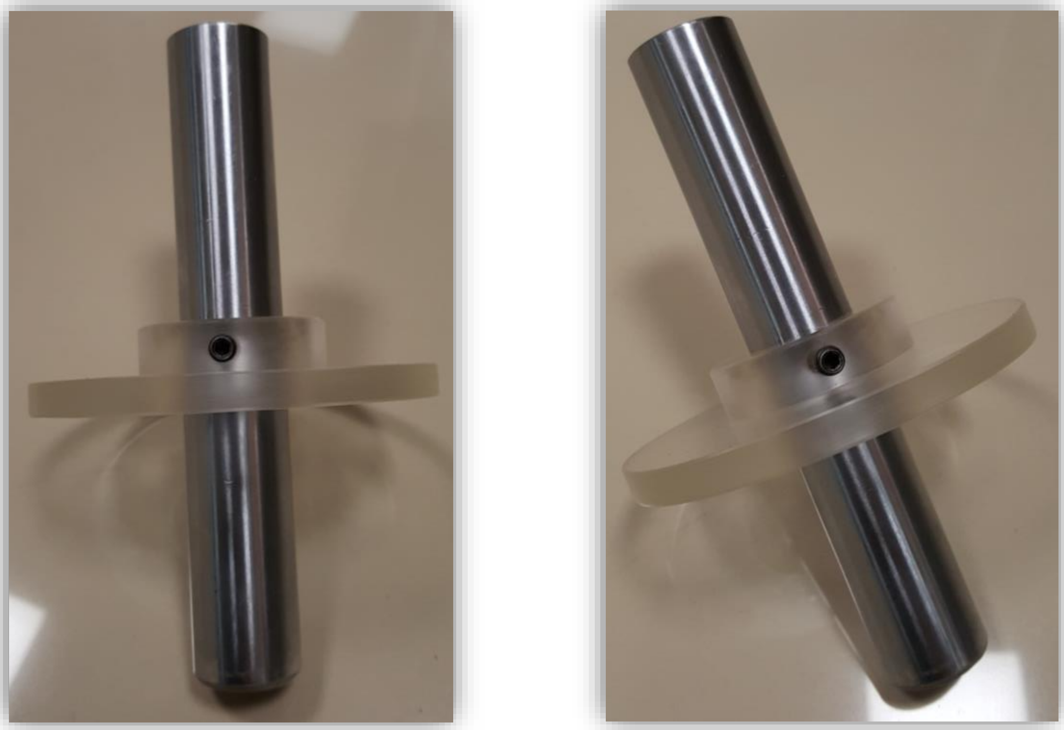


Figure 24: Tamping Rod

3.2.6 De-Airing Water Tank

The de-airing water tank consists of Plexiglas tank, closed at both ends with thick Plexiglas plate (See figure 25). Each plate has a hole that is connected to a valve. The upper plate is connected to the vacuum pump. The lower plate is connected to the network so as to feed the PVA pistons and the cell with water when desired. Right under the Plexiglas tank, a magnetic stirrer is installed to mix and stir the water inside the tank with the help of magnetic motor rotating a coated magnet inside the tank. This helps de-airing the water faster than using just the vacuum pump. The technical specifications for the Magnetic Stirrer are shown in the appendix

Figure 25: De-Airing Water Tank

CHAPTER 4

TRIAXIAL CONTROL SOFTWARE

4.1 Programming

The Triaxial Control Software (currently at its 1.2.5.0 stable version) is programmed by the author using Visual Studio 2015 in Visual Basic.Net language.

Visual studio is an integrated development environment (IDE) from Microsoft. It is used to program, develop and debug computer software using different programming languages. The program used in this study to prepare the Triaxial Software is Visual Basic with embedded dotNet framework 4.6.1. Several libraries, which were used as references within the program, are shown in table 4.

Table 4: Libraries used as references in the software

Library Name	**Library Type**	**Version**
TeeChart Pro	ActiveX	8
OLE Automation	ActiveX	2.0.0.0
Microsoft Report Viewer Common	DLL Assembly	12.0.0.0
Microsoft Report Viewer WinForms	DLL Assembly	12.0.0.0
Microsoft Visual Basic Power Packs	DLL Assembly	9.0.0.0
System Core	DLL Assembly	4.0.0.0
System Data	DLL Assembly	4.0.0.0
System Data Dataset Extensions	DLL Assembly	4.0.0.0
System Deployment	DLL Assembly	4.0.0.0

System Design	DLL Assembly	4.0.0.0
System Drawing	DLL Assembly	4.0.0.0
System IO Compression Filesystem	DLL Assembly	4.0.0.0
System Web Services	DLL Assembly	4.0.0.0
System Windows Forms	DLL Assembly	4.0.0.0
System Xml	DLL Assembly	4.0.0.0
System Xml LINQ	DLL Assembly	4.0.0.0

With code exceeding 17,000 lines, the program is developed by the author especially for this study. Many other devices, research and testing procedures found in the literature and websites of other manufacturers were taken into consideration while programming and developing the software, in order to come with the most flexible and user friendly software (See figures 26 and 27). The program runs at the minimum requirements specified in Table 5.

Table 5: Triaxial Control Software - Computer's Minimum Requirements

Feature	**Minimum Requirements**
Operating System	Microsoft Windows 7 or later
Processor	1 gigahertz (GHz) or faster 32-bit (x86) or 64-bit (x64)
RAM	1 gigabyte (GB) RAM (32-bit) or 2 GB RAM (64-bit)
Hard Disk	128 MB
Screen Resolution	1280 x 768 pixels

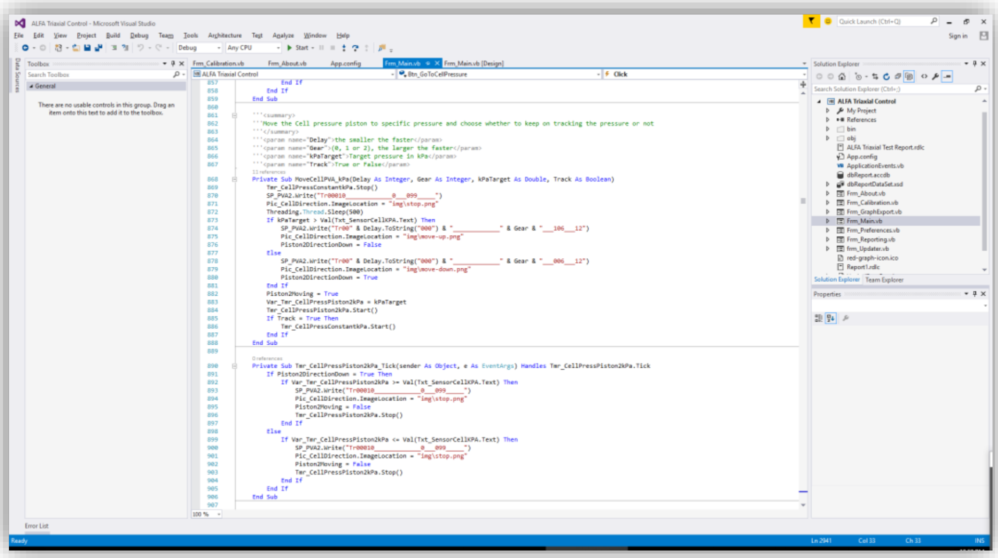


Figure 26: Screenshot from Visual Studio, programming Triaxial Control

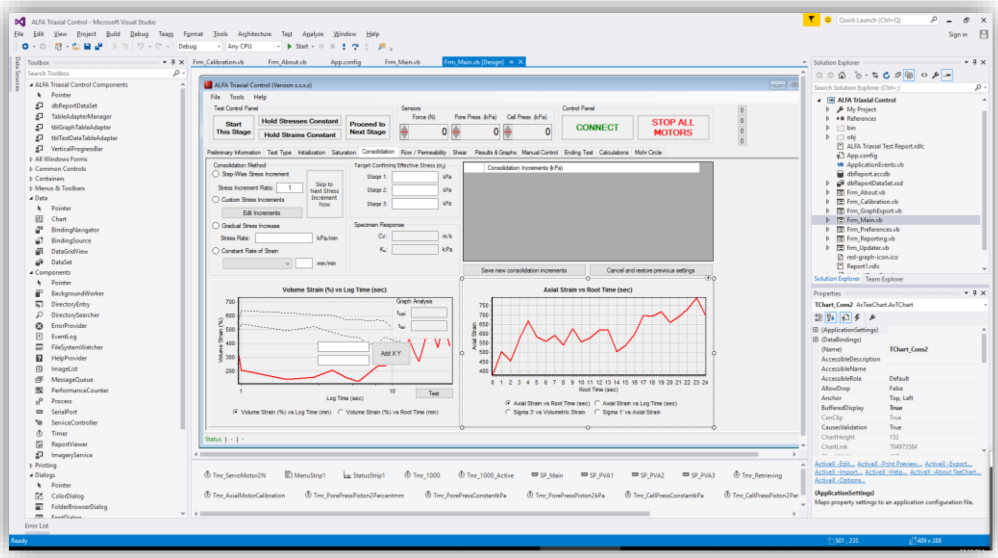


Figure 27: Triaxial Control interface through Visual Studio

4.2 Software Interface

In this section, the software interface will be briefly explained. Each tab/section of the software will be viewed and commented on briefly to give general information about the software and its capabilities (See figure 28).

The software provides full control on ALFA's Triaxial Tester (T-5001/A). It consists of different tabs with self-explanatory notes and guides taken from the international standards and based on the findings of reliable researchers and universities around the world.

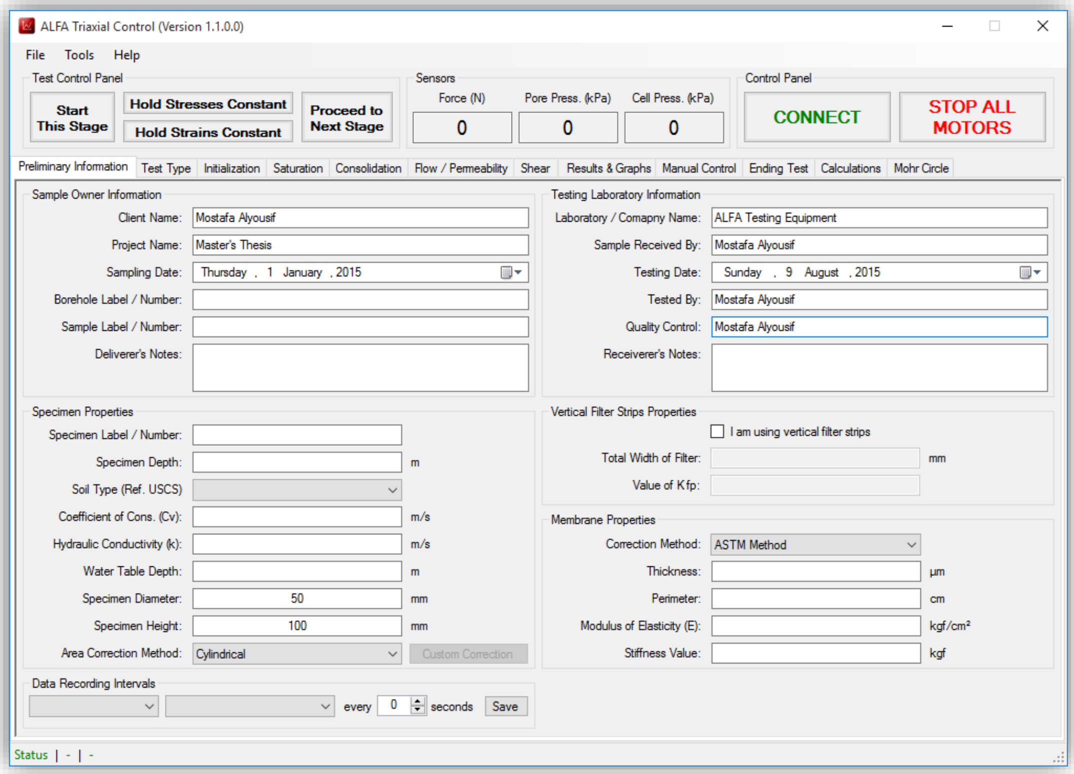


Figure 28: Triaxial Control Software - User Interface

Each tab guides the user to what should be done in very simple step-by-step progress. The top part of the software is fixed, with some buttons that provide quick access to some important control functions on the software and the machine, such as proceeding to next stage, changing the data recording method for the report, emergency stop for the machine … etc.

4.2.1 Preliminary Information Tab

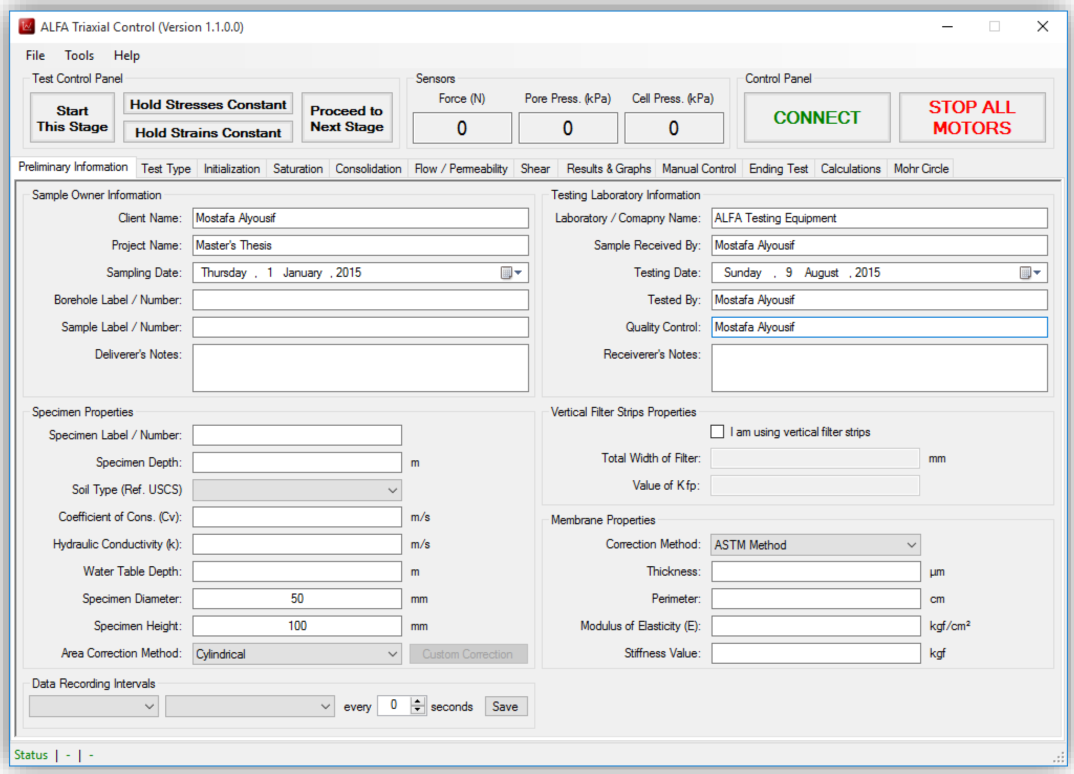


Figure 29: Triaxial Control Software - Preliminary Information Tab

- Sample Owner Information: To be filled with the sample owner's information. This information appears in the final report.
- Testing Laboratory Information: To be filled with the testing laboratory or institute's information. This information appears in the final report.
- Specimen Properties: Specimen number, depth, coefficient of consolidation, water table, soil type, diameter, height, area correction method … etc. are all selected and specified from this section. These entries are crucial and some are used in further calculations and to decide the behavior of the equipment based on the sample properties.
- Vertical Strips: Specifying whether the vertical strips are used or not, with their properties.
- Membrane Properties: Specify the correction method for the membrane and specify its properties.

4.2.2 Test Type Tab

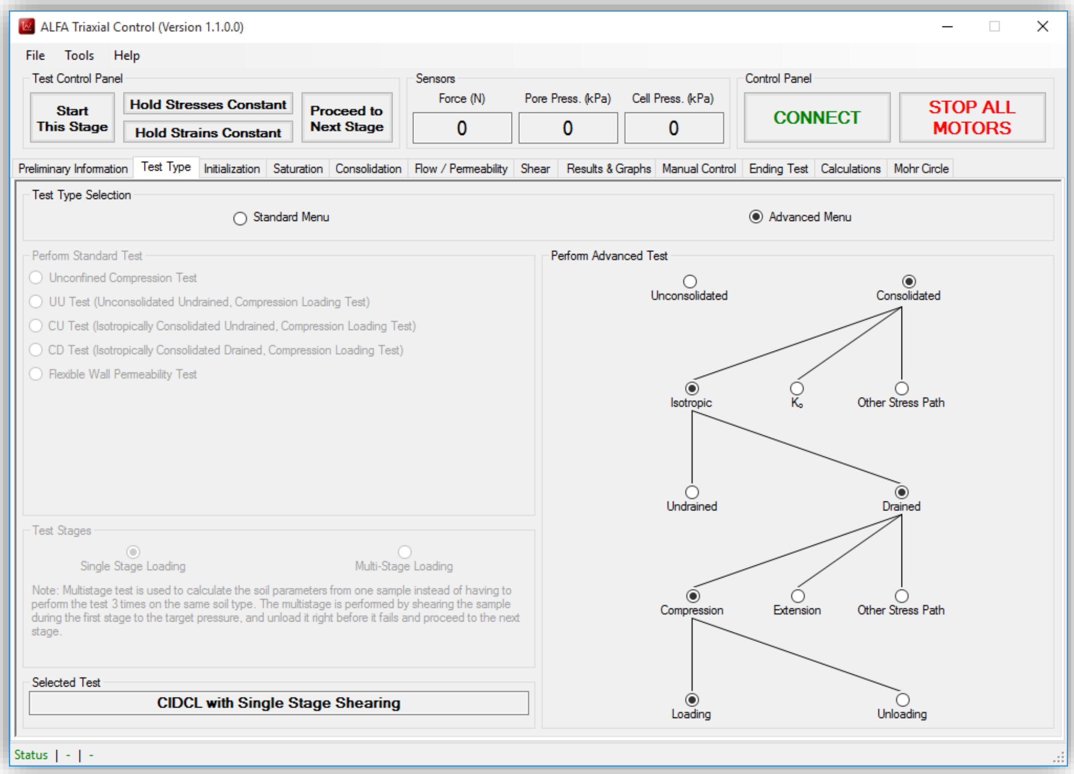


Figure 30: Triaxial Control Software - Test Type Tab

- Test Type Selection: Select whether to have simplified menu (for standard tests) or advanced menu (for custom tests).
- Perform Standard Test: Choose the test type from simplified selections.
- Perform Advanced Test: Choose the test from stage-by-stage selection. This option gives the ability to perform any custom test on the sample from very wide range of functions.
- Test Stages: Select between single-stage or multistage tests. This option gives the ability to obtain 3 Mohr's circles and determine the strength parameters from a single triaxial soil sample.
- Selected Test: Displays the chosen test type.

4.2.3 Initialization Tab:

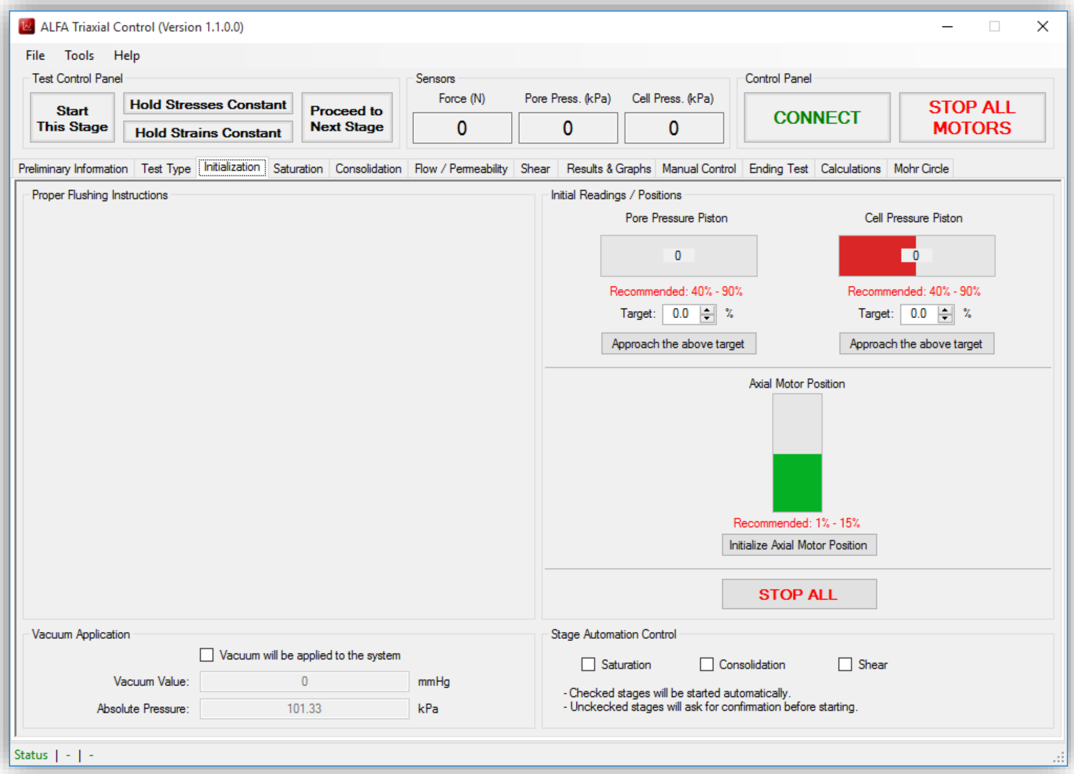


Figure 31: Triaxial Control Software - Initialization Tab

- Proper Flushing Instructions: Some instructions to perform proper flushing for the setup to avoid having air bubbles left over.
- Initial Readings / Positions: Shows and controls the initial positions of each piston/motor to avoid over-travelling or running out of water during the test.
- Vacuum Application: Gives the ability to include the vacuum calculations to the software if applied (used for sand samples).
- Stage Automation Control: Gives the option to select which stage to start automatically.

4.2.4 Saturation Tab

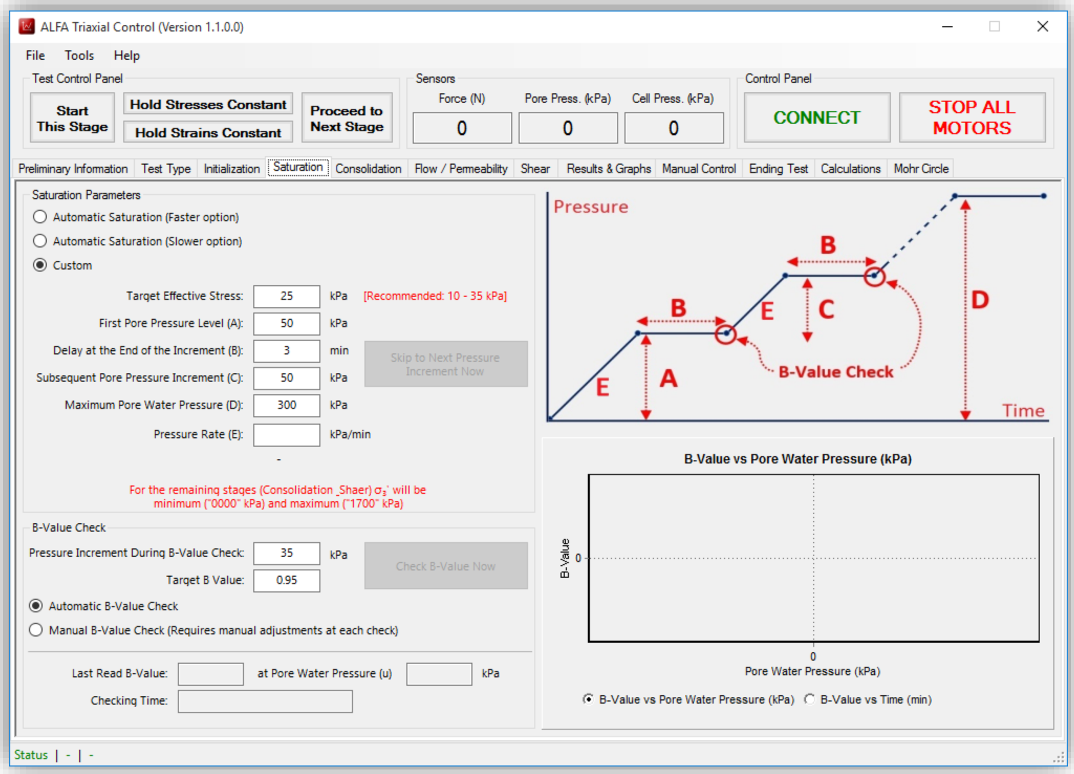


Figure 32: Triaxial Control Software - Saturation Tab

- Saturation Parameters: Provides full control on the saturation steps, the initial pore pressure level, increments, subsequence and the maximum desired pore water pressure. It increases the cell and pore pressure together to avoid increasing the effective stress unintentionally.
- B-Value Check: To specify the desired B-Value and to control the B-Value check after each increment or at any desired moment. (Does not require valve adjustments with automatic mode).
- Graphs: Top graph shows simplified sketch for the saturation parameters and bottom graph shows the B-Value versus the Pore Pressure.

4.2.5 Consolidation Tab

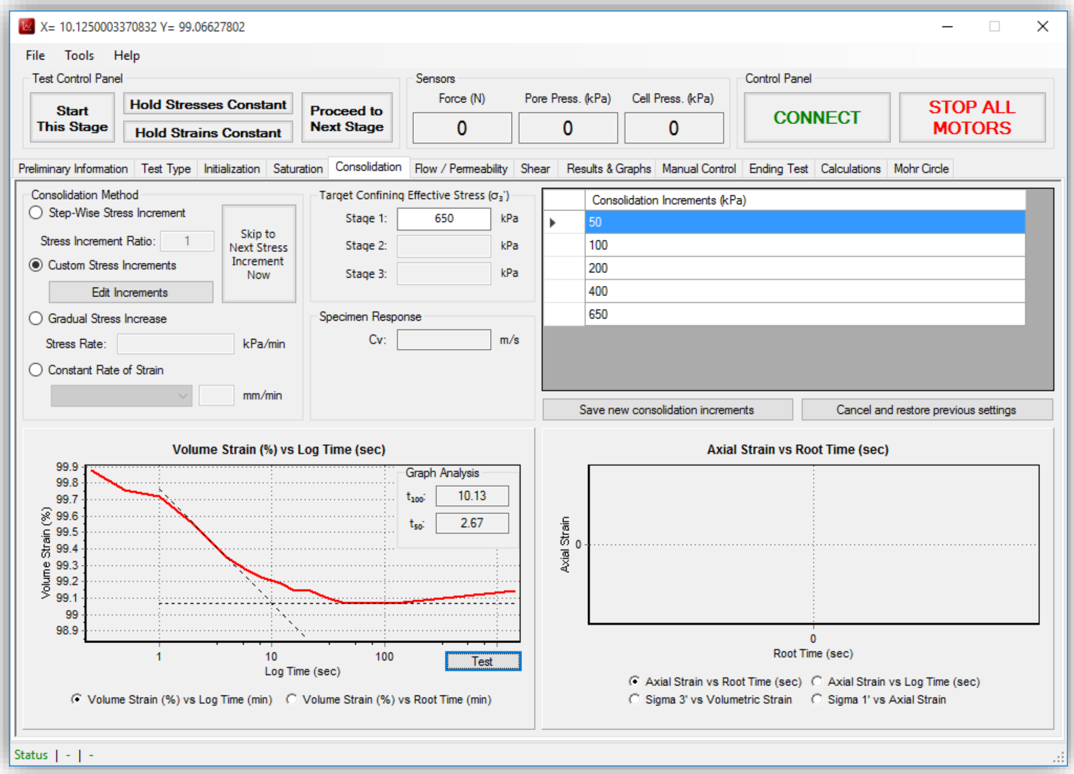


Figure 33: Triaxial Control Software - Consolidation Tab

- Consolidation Method: Gives the ability to select which method to follow in order to consolidate the sample.
- Target Pressures: Gives the option to target 3 consolidation pressures in multistage mode to obtain the strength parameters from single sample.
- Specimen Response: Shows the consolidation coefficient and, if K_0 consolidation is selected, the K_0 value.
- Graphs (Shows in real time):
  - Axial Strain vs. time (log / root)
  - σ_3 vs. volumetric strain
  - σ_1 vs. Axial strain
  - Volumetric strain vs. time (log / root) (for t_{50}, t_{90} and t_{100} calculations)

4.2.6 Shear Tab

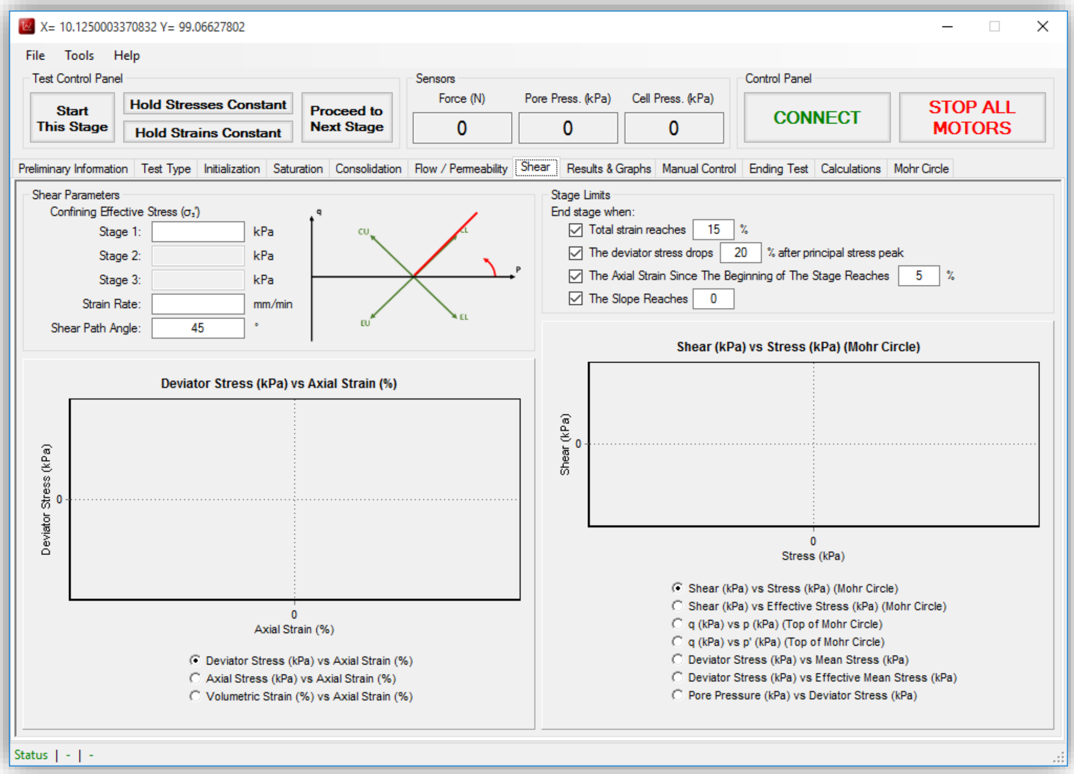


Figure 34: Triaxial Control Software - Shear Tab

- Shear Parameters: Displays the target pressure for each stage and gives the ability to draw any custom path for the sample. The strain rate is also specified in this section.
- Stage Limits: Gives the option to set conditions to end the test with any desired limitations.
- Graphs (Shows in real time):
  - Deviator Stress vs. Axial Strain
  - Axial / Volumetric Stress vs. Axial Strain
  - Shear vs. Stress (Mohr Circle)
  - Shear vs. Effective Stress (Mohr Circle)
  - q vs. p / q vs. p'
  - Deviator Stress vs. Mean Stress
  - Deviator Stress vs. Effective Mean Stress
  - Pore Pressure vs. Deviator Stress

4.2.7 Results and Graphs Tab

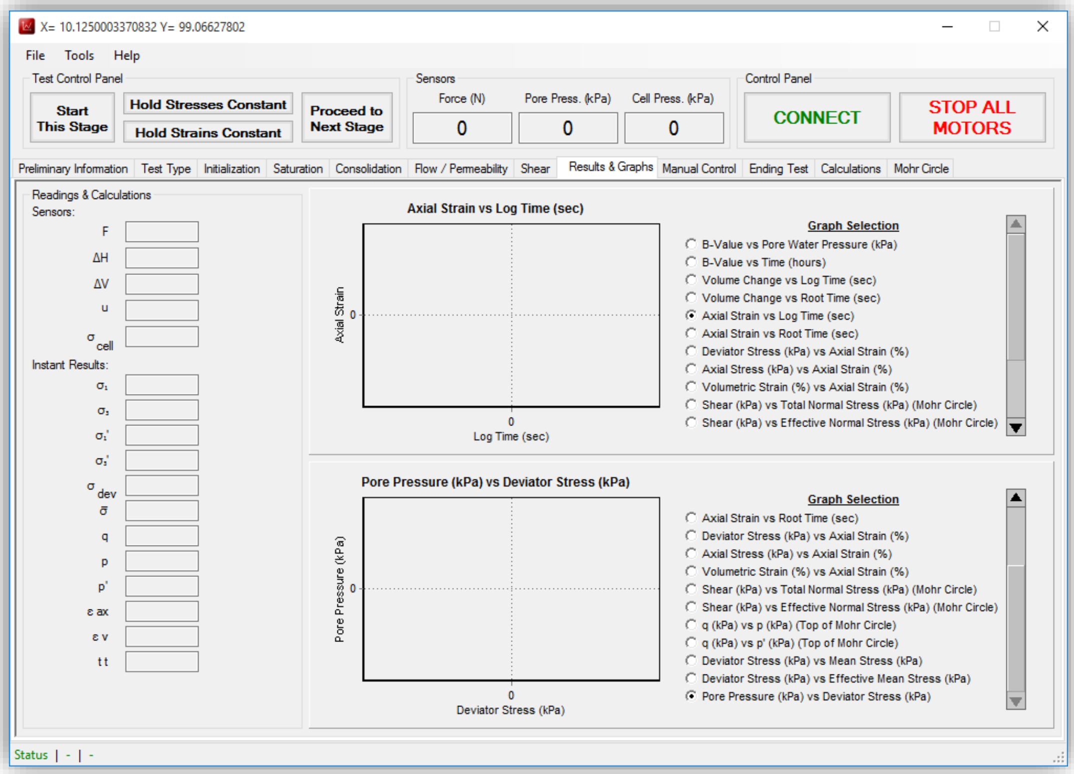


Figure 35: Triaxial Control Software - Results and Graphs Tab

- Readings and Calculations: Shows the readings from all the sensors and all the calculated values simultaneously.
- Graphs (Shows in real time):
  - B-Value vs. Pore Water Pressure (kPa)
  - B-Value vs. Time (hours)
  - Volume Change vs. Log Time (sec)
  - Volume Change vs. Root Time (sec)
  - Axial Strain vs. Log Time (sec)
  - Axial Strain vs. Root Time (sec)
  - Deviator Stress (kPa) vs. Axial Strain
  - Axial Stress (kPa) vs. Axial Strain
  - Volumetric Strain vs. Axial Strain
  - Shear (kPa) vs. Total Normal Stress (kPa) (Mohr Circle)
  - Shear (kPa) vs. Effective Normal Stress (kPa) (Mohr Circle)

- q (kPa) vs. p (kPa) (Top of Mohr Circle)
- q (kPa) vs. p' (kPa) (Top of Mohr Circle)
- Deviator Stress (kPa) vs. Mean Stress (kPa)
- Deviator Stress (kPa) vs. Effective Mean Stress (kPa)
- Pore Pressure (kPa) vs. Deviator Stress (kPa)

4.2.8 Manual Control Tab

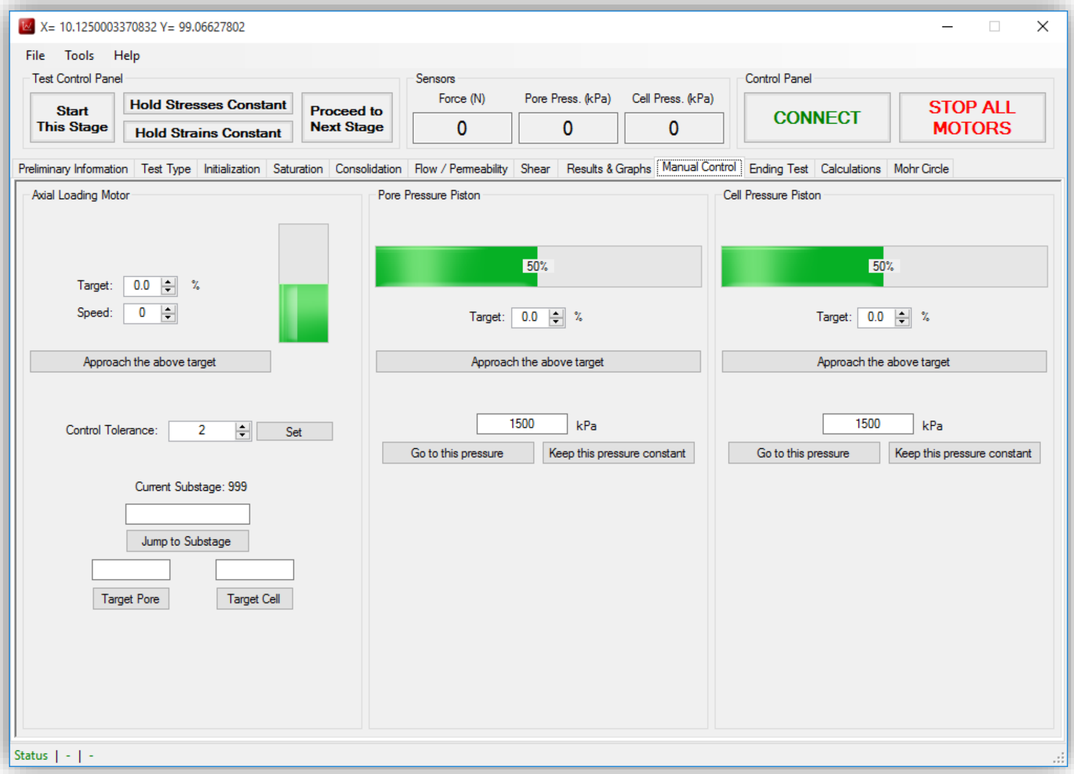


Figure 36: Triaxial Control Software - Manual Control Tab

- Provides manual control on each motor/PVA and on the sub-stages of the test at any second during the test.

4.2.9 Ending Test Tab

- Gives instructions on how to end the test properly and empty the cell water.

4.2.10 Calculations Tab

- Shows all the performed calculations for each stage separately and the raw readings from all the sensors.

4.2.11 Mohr's Circle Tab

- Shows the graphical plot of Mohr's Circles of either three (single-stage) conventional tests or one multistage test (with three stages). It draws the Mohr's circles using the top points obtained from the deviator stress versus axial strain graph, and then calculates the best fit line for the top of Mohr's circles from which the best fit tangent line is calculated.

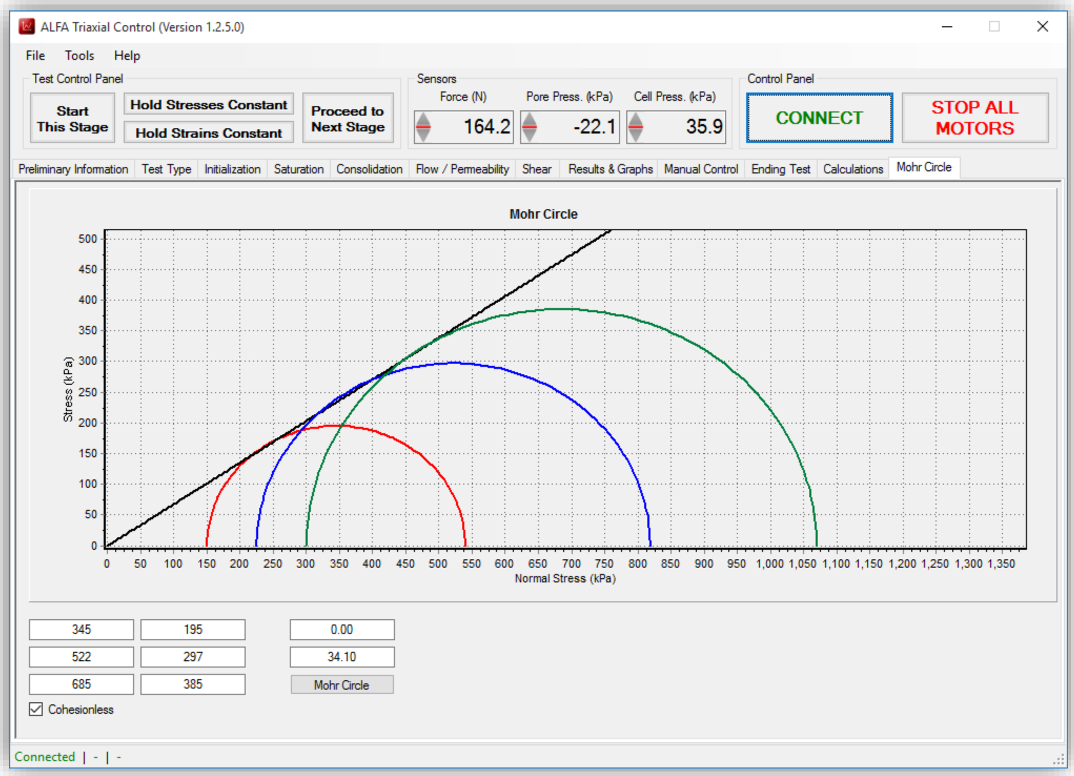


Figure 37: Triaxial Control Software - Mohr's Circle Tab

CHAPTER 5

CONVENTIONAL TRIAXIAL TEST PROCEDURES

This chapter deals with providing all the necessary information to perform proper and fault-less tests, and to minimize the risk of disturbing the sample or spoiling the test results.

5.1 Maintenance

Before starting the tests; it is very important to keep all the setup parts and accessories under frequent and continuous maintenance to reduce risk of losing the sample and to allow the test to run smoothly without any fault. Doing frequent and continuous maintenance on the Triaxial setup and the accessories ensure flawless tests and provide more precise test results. Maintenance includes, but not limited to, the followings:

5.1.1 Flexible Tubes Maintenance

The tubes should be always watched closely before each test to ensure that there is none that was accidently cut or defected.

5.1.2 O-rings Maintenance

All the O-Rings, especially the ones used to seal the cell, should be always under maintenance. All O-rings must be free of any twist, hair pieces, soil particles, irregularities in shape or any other visual defects. The O-rings must be greased before each test to ensure having the best sealing.

5.1.3 Triaxial Base

The base is so sensitive to any dirt or sand particles as it may ruin the seal of the Plexiglas or the sample. Or even worse, those particles might go through the pipes and into the PVA systems or the pressure transducers and cause serious damage to the setup. Therefore, it is highly recommended to watch for any dirt or soil particles that spilled accidently on the base and try to remove them in such way to prevent them from entering the tube holes or the seals.

5.1.4 De-Airing Water Tank Maintenance

The maintenance on the water tank is necessary from time to time. It is important to always have clean water inside the tank to allow proper test. This was done by following those steps:

a) Empty and refill the tank from time to time.
b) Ensure having the coated magnetic for the stirrer in the middle of the tank for stirring purposes if it is accidently drifted to the side of the tank.
c) Control and check the connected valves at the top and bottom of the tank
d) Visually inspect the tank for any cracks or defects as it is under continuous creep action due to vacuuming.

5.1.5 PVA Maintenance

The maintenance on the Pressure-Volume Actuators is necessary from time to time. It is important to always have clean water inside the PVA to allow proper test:

a) Empty and refill the PVA from time to time.
b) Control and check the connected tube on the PVA.
c) Visually inspect the PVA and the position transducer for any defects or pipes/wire knobs that might restrict the movement of the PVA pistons.

5.1.6 Cell Plexiglas Maintenance

Visually inspect the cell for any cracks or deformations as it is always under creep action due to pressurizing / depressurizing in each test and between the tests.

5.2 Preparation for Test

a) Ensure that all the parts and accessories are clean, ready to be used and close to where the sample is going to be prepared.

b) Fill the water tank with water up to the marked limit and start the de-airing process by turning on the magnetic stirrer and the vacuum pump after properly connecting the tubes.

5.3 Proper Flushing Instructions

a) Fill the Cell PVA piston to 70% - 90% so that enough water would be available at any time during the test without having to stop, refill and continue the test.
b) Fill the Pore PVA piston to 60% - 80% so that enough water would be available at any time during the test. At the same time, enough room would be available if for any reason excess pore water leaves the sample.
c) Bring the loading motor down to its initial position.
d) Flush all the tubes with water, ensure that no air-bubbles are trapped within.
e) Flush the valves near the triaxial base by allowing water to spill out of the holes and the open-ends.
f) Flush the porous stones and the filter paper with water.
g) Ensure that there is no visible leakage or damaged section on the tubes and the valves.

5.4 Reconstituted Sand Sample Preparation

a) Put the triaxial base on the working bench
b) Place the membrane at the pedestal, ensure no wrinkle is present
c) Grease the O-rings and the O-Ring stretcher
d) Place the O-Ring on the stretcher
e) Bring the stretcher on the pedestal, and shoot the membrane in place carefully
f) Adjust the membrane so as to fit on the groove.
g) Install the split compaction mould on. Pay attention not to damage the membrane while locking the mould in place.
h) Connect the vacuum pump to the flexible tubes of the split mould, and apply vacuum of around 400 – 500 mmHg (more vacuum might be required when using thick membrane).
i) Adjust the membrane so as not to have any wrinkle or irregular shape, add the protective membrane if required (Refer to figure 38).
j) Place the porous stone and the filter paper on the pedestal respectively.

k) Measure the effective length of the sample from the top surface of the filter paper up to the inner edge of the split mould where the sample is supposed to end. Use this information in calculating the amount of sample to be prepared for each layer by multiplying the density with the volume of the sample and dividing by the number of layers.

l) This figure is then multiplied by the target water content (4%).

Figure 38: Sample Preparation - Split mould with membrane installed on the base

m) Adjust the tamping rod falling height so as to allow 20 mm layer to be compacted on the pedestal. Take into account the extra height on the compaction mould which will contain the top cap (This height is 10 mm in the used mould).

n) Evenly distribute the soil using the spatula, be careful not to harm or cut the membrane.

o) Place the adjusted tamping rod on the split mould and start compacting in a circular pattern.

p) Scarify the top surface of each layer before placing the next one to ensure better bounding between the layers.

q) After finishing all the layers' compaction, place the filter paper and the top porous stones respectively over the sample.
r) Put the O-rings that are going to be placed on the top cap on the O-Ring stretcher and pass it through the top cap.
s) Carefully place the top cap on top of the porous stone.
t) Unfold the membrane from the mould into the cap.
u) Bring the O-Ring stretcher in position and shoot the O-Ring carefully so as to have it on the groove.
v) Remove the O-Ring stretcher by passing the top cap drainage pipe through the slot made on the stretcher.
w) Apply vacuum through the top cap on the sample. Wait for 1-2 minutes for the vacuum to be applied.
x) Slowly remove the vacuum from the split mould.
y) Disassemble the split mould carefully, make sure not to hit, vibrate or damage the sample.
z) Visually inspect the membrane, the O-rings and the sample for any weird or unusual state. Make sure to have the membrane and the O-rings without any wrinkle.

5.5 Setup Initialization

a) Grease then place the O-rings on the base and the top platen where the triaxial cell will rest.
b) Place the Plexiglas on its groove on the base, ensure proper seating.
c) Fix the top platen and lock all the three columns enough (slightly tight by no more than the force of your fingers not to harm the cell).
d) Visually inspect the loading piston, the load cell and the cable for proper placing.
e) Lock the piston to the cross-beam.
f) Open the ventilation valve at the top of the cell, then open the line that connects the cell to the de-aired tank until the cell is filled up to half-the-sample height.
g) When the water surface is at half-the-height of the sample, take zero reading for the cell pressure transducer from the software.
h) Continue filling the cell till the water spills out of the ventilation line.
i) Close the ventilation line.

j) Apply initial cell pressure (around 30 kPa in this study).
k) Release the vacuum pump from the sample.

5.6 Saturation

a) Allow the water to flow by gravity through the pedestal towards the specimen by opening the line that connects the pedestal to the de-aired water tank.
b) Open the valve that connects the top cap to the atmosphere and wait for the water to start spilling out of the open-end.
c) Close the line that connects the sample to the water tank, then close the line that connects the top cap to the atmosphere.
d) Apply pore pressure so as to maintain the desired effective stress.
e) Increase the cell pressure and the pore pressure simultaneously to the first desired pressure level (referred to as "A" in ALFA Triaxial Control).
f) After reaching the targets, wait for some time for the pressure to reach equilibrium and distribute throughout the specimen (referred to as B in ALFA Triaxial Control).
g) Perform Skempton's B-Value check (Skempton 1954). ALFA Triaxial Control gives the option to automatically perform B-Value check without having to mechanically adjust the valves, and thus does not require any personnel to be present at the time of B-Value check. The check is performed as follows:
    - Release the pore piston from tracking the pressure.
    - Take the pore pressure reading.
    - Increase the cell pressure by the desired amount of pressure (35 kPa in this study) rapidly.
    - Wait for 120 seconds for the pressure to reach equilibrium state.
    - Measure the pore pressure and calculate the B-Value.
    - ASTM standards (D4767 and D7181) consider the sample to be saturated if the B-Value is above 0.95.
    - If the B-Value reaches the range 0.80 to 0.95 and then drop, this is said to be indication of saturation. The stage can be considered completed and the sample ready for consolidation.
    - If, for any reason, the B-Value turned out to be above 1.00, it indicates that there is a leakage between the sample and the cell through the membrane,

the O-Ring seals, the pipe connections or any other leakage reason. If so, stop the test, disassemble the sample, and attempt to prepare another sample for the test.

h) Wait for the B-Value result, check if it is satisfying the requirements. If yes, proceed to the next phase (Consolidation or Shear). If no, continue the saturation phase.
i) If the B-Value did not satisfy the limit, continue with the following saturation increments on both the cell and the specimen simultaneously (referred to as C in ALFA Triaxial Control). Make sure not to pass the pre-set maximum pore pressure (referred to as D in ALFA Triaxial Control).
j) Re-follow the instructions written in g – j.

5.7 Consolidation (Isotropic)

Skip this section if consolidation is not required.

a) Take readings of all the sensors and initiate the volume change calculations from the pore PVA.
b) Make sure that the piston is touching the top cap.
c) Increase the cell pressure to the desired effective consolidation target pressure.
d) Since the sample type is sand, consolidation does not take long time. Wait for several minutes before passing to the next stage.

5.8 Shear

a) Calculate the shearing rate either from the consolidation graph or by estimating the shearing time up-to 15% axial deformation. 0.50 mm/min loading rate is used in this study.
b) Correct the area using equation (3) mentioned in section 2.1.3 at each data point against the parabolic behavior of the specimen (Toker 2007).
c) Record all the sensors throughout the shearing stage, end the test if any of the followings occur:
    a. If the total strain reaches 15%.
    b. If the deviator stress drops 20% after principal stress peak.
    c. If the axial strain from the beginning of the test reaches 5%.

5.9 Ending test and recovering the sample

a) Remove the pressure from the sample and close all the valves connecting the sample to the PVA.
b) Apply vacuum through water trap to the sample to preserve its shape for post-investigations.
c) Remove the pressure from the cell, open the ventilation valve and empty the cell.
d) Demount the cell top plate, loading piston and cell Plexiglas.
e) Investigate the sample, take the required measurements and then remove the sample from the pedestal.
f) Take part of the sample for moisture content if required.

CHAPTER 6

TEST PROGRAM

This chapter will show the results of all the tests that were carried out in this study. Since the equipment used in this study is developed totally from scratch; the results obtained from the reference tests using Geocomp Triaxial Tester (Origin: USA) has to be compared with the results obtained from ALFA Triaxial Tester (Origin: Turkey). Table 6 shows a list of the conducted tests.

Table 6: Carried CD Triaxial Tests Summary on Sand

Test Type	Specimen Diameter	Equipment Brand	Test Code
Single Stage (Verification Test)	38 mm	Geocomp USA	SG
Single Stage (Verification Test)	50 mm	ALFA TURKEY	SA
Multistage: Cyclic Loading Method (Passing from minimum Slope)	50 mm	ALFA TURKEY	MCSA
Multistage: Cyclic Loading Method (Passing from maximum Curvature)	50 mm	ALFA TURKEY	MCCA
Multistage: Sustained Loading Method (Passing from minimum Slope)	50 mm	ALFA TURKEY	MSSA
Multistage: Sustained Loading Method (Passing from maximum Curvature)	50 mm	ALFA TURKEY	MSCA

6.1 General Soil Characteristics

The soil used in this study is standard sand (aka. CEN Standard Sand) produced by LIMAK company in Turkey in accordance to EN 196-1. CEN Standard sand (ISO standard sand) is a natural sand, which is siliceous particularly its finest fractions. It is clean, the particles are generally isometric and rounded in shape with 2.65 specific gravity. Figures 39-40 shows the sample and its particle size distribution along with the upper and lower limit for the standard sand specified by EN 196-1:1994 and ISO 679:2009.

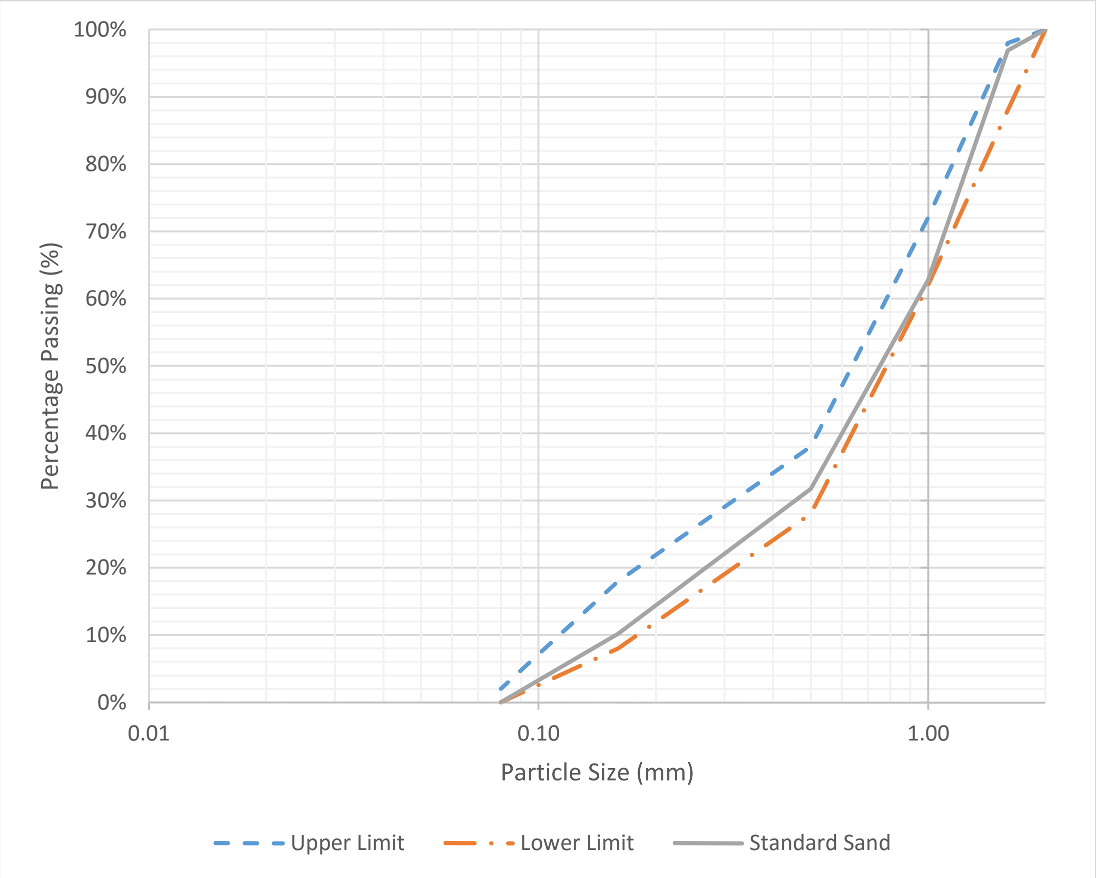


Figure 39: Standard Sand Particle Size Distribution

Figure 40: Limak's CEN Standard Sand

The sand had a specific gravity of 2.65, maximum dry density of 1.76 g/cm^3 and minimum dry density of 1.52 g/cm^3.

The sand sample used in this study is compacted to a dry density of 1.70 g/cm^3. It is prepared in split mould that doubles as membrane stretcher via the vacuum hose attached to it. The sample is compacted in 5 layers, each with 20 mm height. Through the density relationship, using the known volume of the sample; the mass of each layer was determined to be 66.76 g plus 4% water content for the tests performed on ALFA's setup with diameter of 50 mm.

6.2 Verification Tests

Two types of verifications tests were conducted; the first is to verify whether the developed setup is performing well and within the standard method. For this reason, a set of three conventional CD triaxial test were performed using a reference setup, and another set of tests were performed using the developed setup. The second verification is to compare the results obtained from the conventional set of three tests with the ones obtained from multistage tests method.

6.2.1 Reference Setup

The reference setup for this study was the fully automated triaxial stress path test system by Geocomp Corporation, USA. The tests were carried by the author in Toker Laboratory in Ankara / Turkey (Figures 41 and 42 shows both GeoComp and ALFA's setups). The specimen was 38 mm in diameter, and 80 mm in height compacted at 4 equal layers.

Figure 41: Geocomp’s Triaxial Test Setup at Toker Laboratory (Private Laboratory)

Figure 42: ALFA's Triaxial Test Setup at ALFA Research and Development Department

6.2.2 Comparison between ALFA's and Geocomp's Test Setups

- Loading Frame

The difference between the two loading frames is that ALFA uses submersible load cell, which does not require piston friction calculations to be included within the algorithm. Unlike Geocomp's, which uses a regular external load cell that needs piston friction correction to be applied (See figures 41 and 42).

- Pressure-Volume Actuators

The PVAs are almost the same in both setups. ALFA installed both PVAs into one cabinet, while Geocomp manufactures them as separate units.
ALFA's PVA system is equipped with water de-airing system which doubles as water reservoir for the PVA pistons and the cell before and during the test. Geocomp does not have such system, and water should be fed to the system from external tank.

- Valves and Pipes

Geocomp system does not have physical valves in the PVA system. Instead, electronic valves are installed in the PVAs that opens and closes either from the micro-controller on the PVA units or from computer. However, the cell has mechanical valves. Keeping in mind that the pipes should be connected/disconnected before, during and after the test when necessary.
On the other hand, ALFA's setup does not have electronic valves, all of them are mechanical. Those valves are used for filling the pistons, cell with water before the test or for maintenance purposes. None of those valves need to be opened or closed during any test nor any pipe to be connected/disconnected at any time during any type of test.

- Software

The main difference between the two setups is the controlling software. Geocomp's software requires lots of know-how. Regular lab technician with basic knowledge about triaxial test will not be able to run the test (See figure 43). The lack of graphical sketches and instructions are some main problems faced while performing the tests on it.

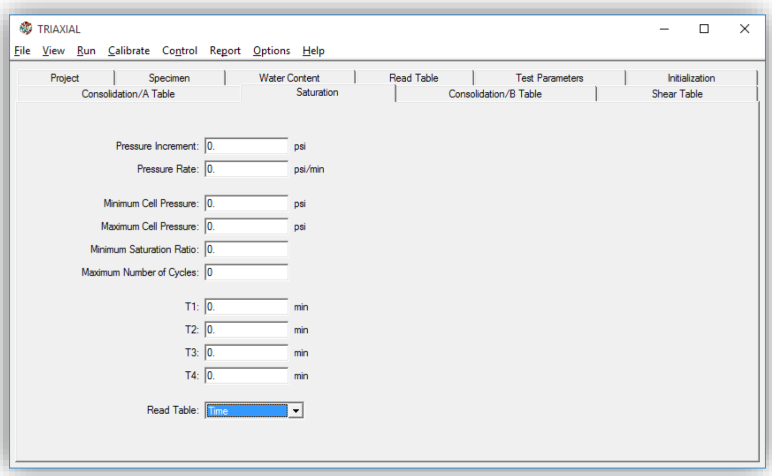


Figure 43: Geocomp Triaxial Software User Interface at saturation stage

On the other hand, ALFA's controlling software is user-friendly, designed to require the least know-how from the user. All the parameters come filled automatically with the default values depending on the soil type, at the same time, the user has the chance to change any when required. Notes from ASTM standards and the studies reviewed in chapter 2 are embedded into the software to guide the user without having to return to the user manual or the test procedure instructions (See figure 44).

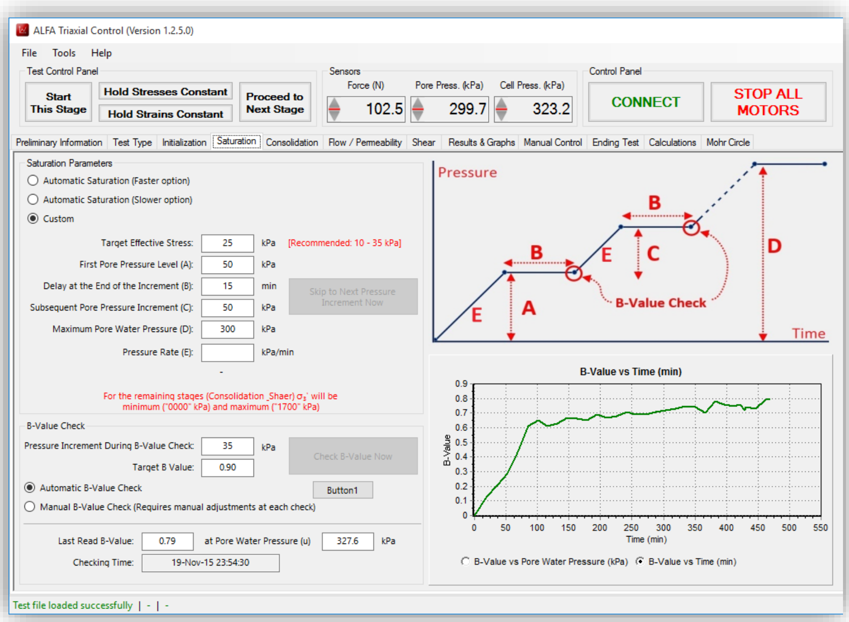


Figure 44: ALFA Triaxial Software User Interface at saturation stage

6.2.3 SG Test Results

Three single-stage CD triaxial tests were conducted using Geocomp Automated Triaxial Tester as reference tests for the equipment developed during this study. Figure 23 shows the test setup and the sample mounted in it. The results obtained are shown in figures 45-47.

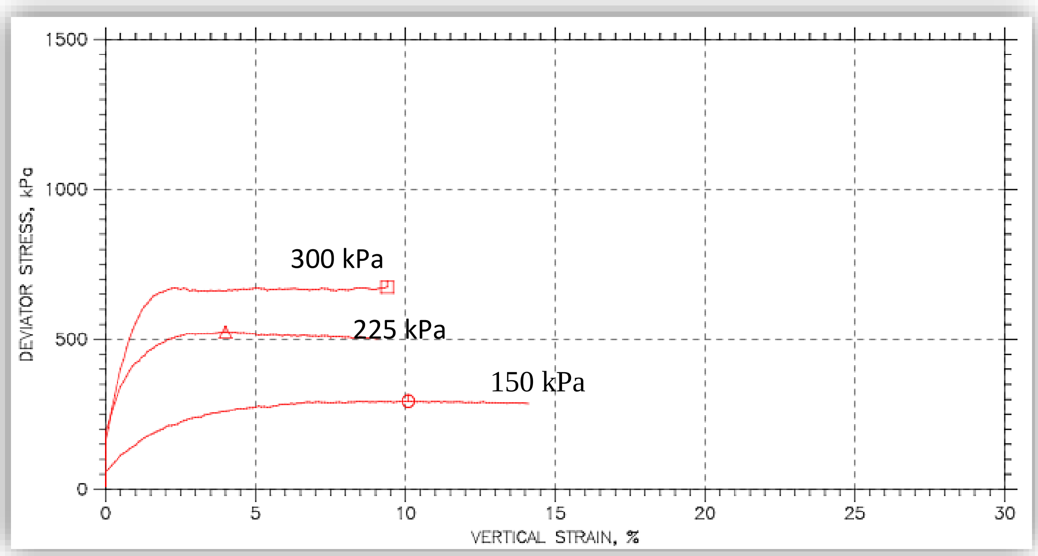


Figure 45: Deviator Stress vs. Vertical Strain - GeoComp (SSG)

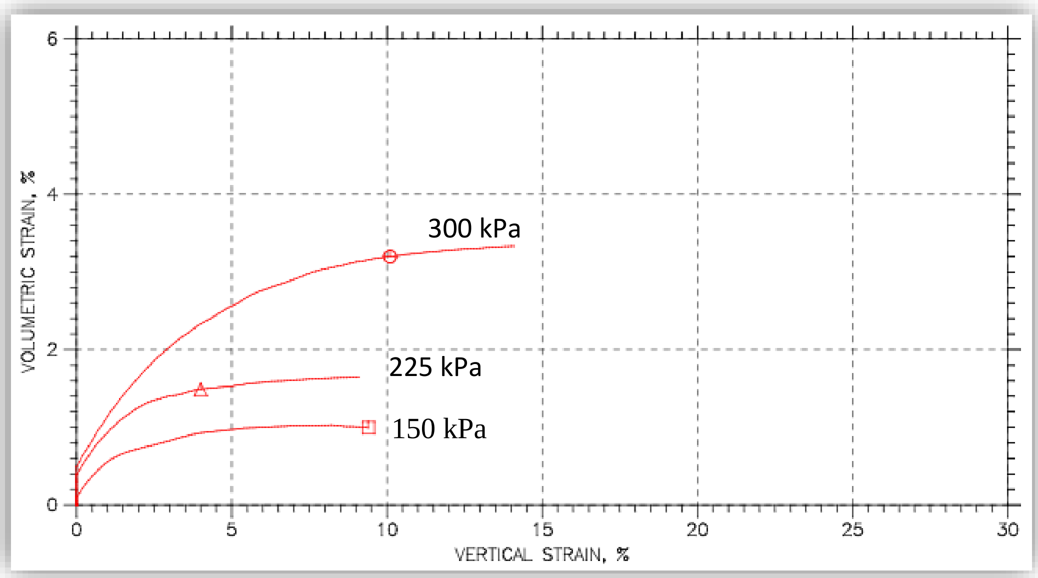


Figure 46: Volumetric Strain vs. Axial Strain - GeoComp (SG)

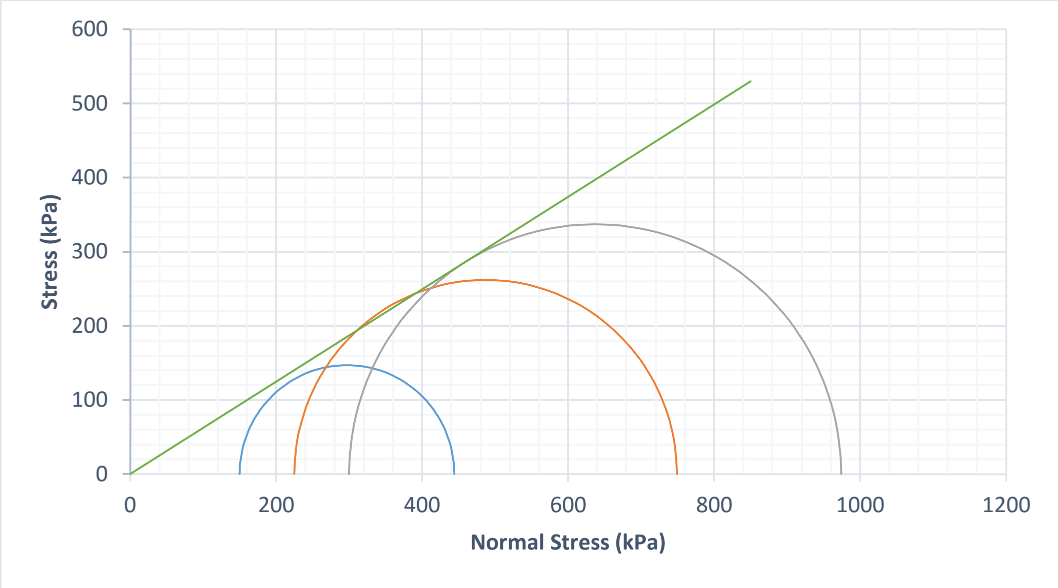


Figure 47: Failure Envelope - GeoComp (SG)

After examining the figures, the apparent cohesion is found zero and the friction angle is 32°.

6.2.4 SA Test Results

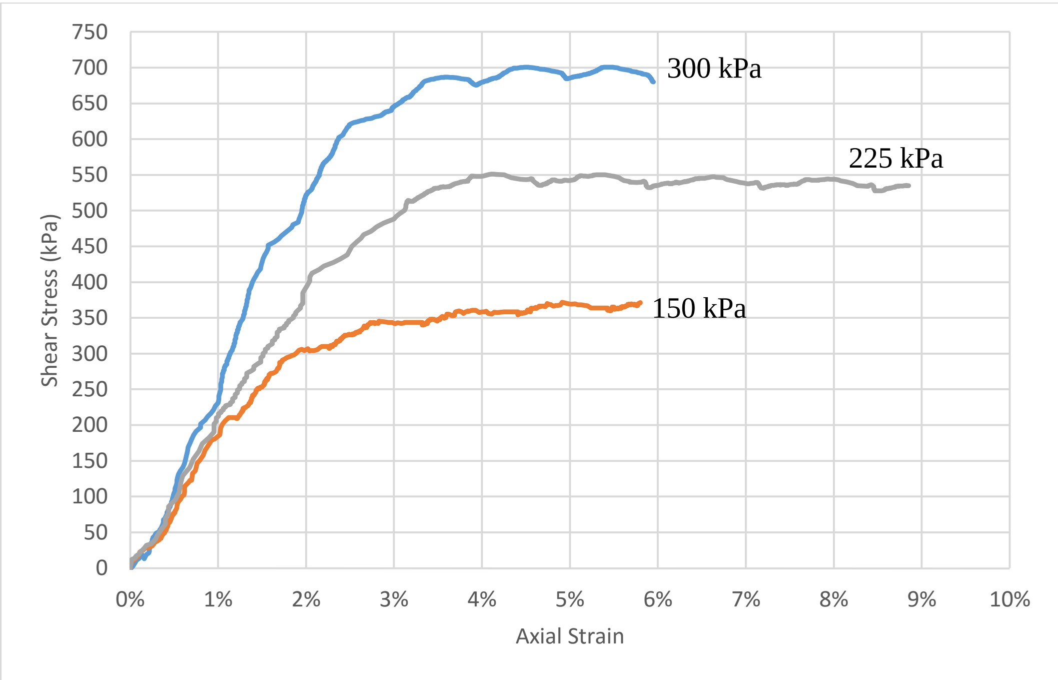


Figure 48: Deviator Stress vs. Axial Strain - ALFA (SA)

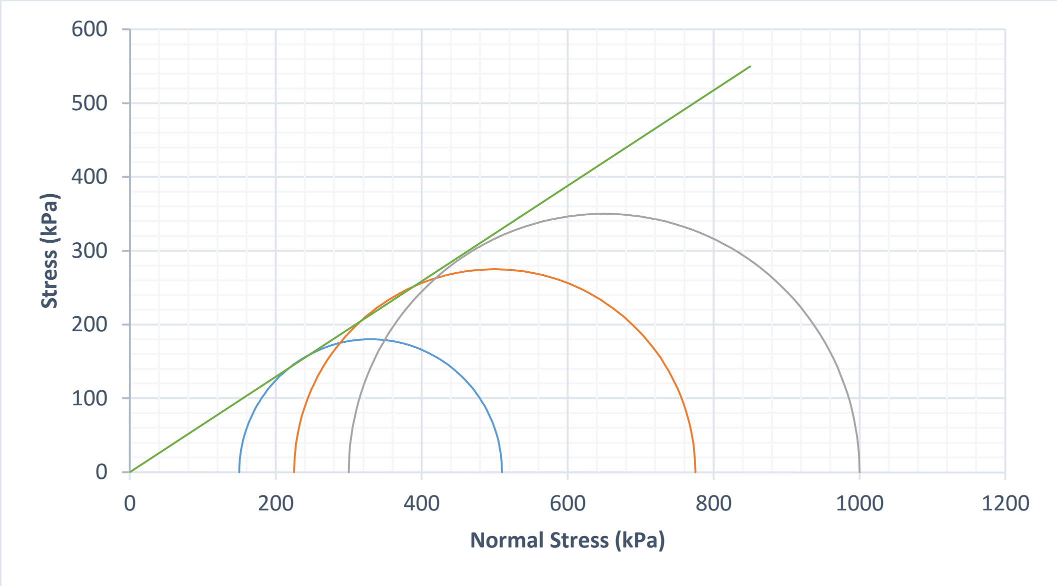


Figure 49: Failure Envelope - ALFA (SA)

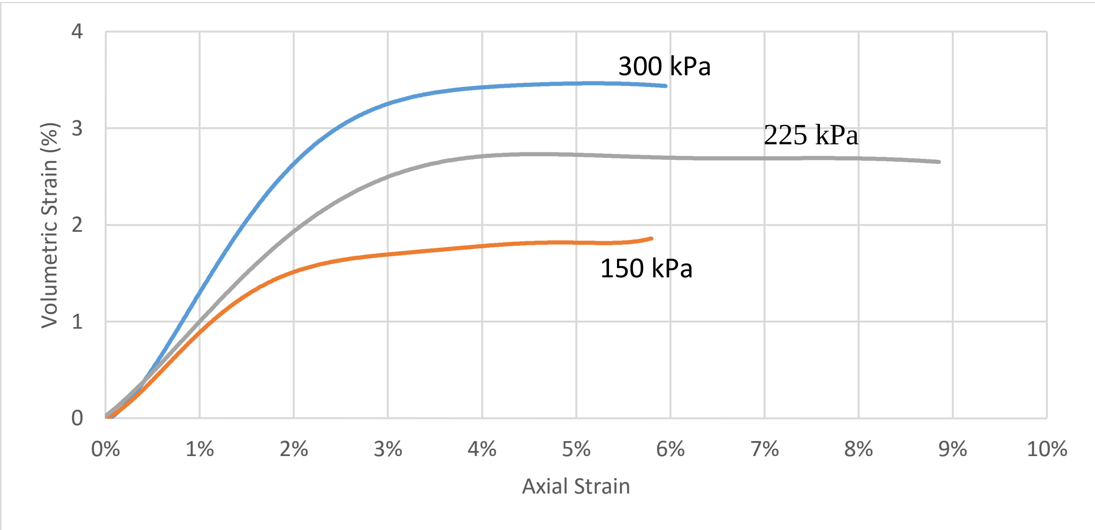


Figure 50: Volumetric Strain vs Axial Strain - ALFA (SA)

After examining the figures 48-50, the apparent cohesion is found zero and the friction angle is 33°.

Figure 51 shows the failure envelope of the conventional tests (SA) drawn from the maximum curvature on the stress-strain graph.

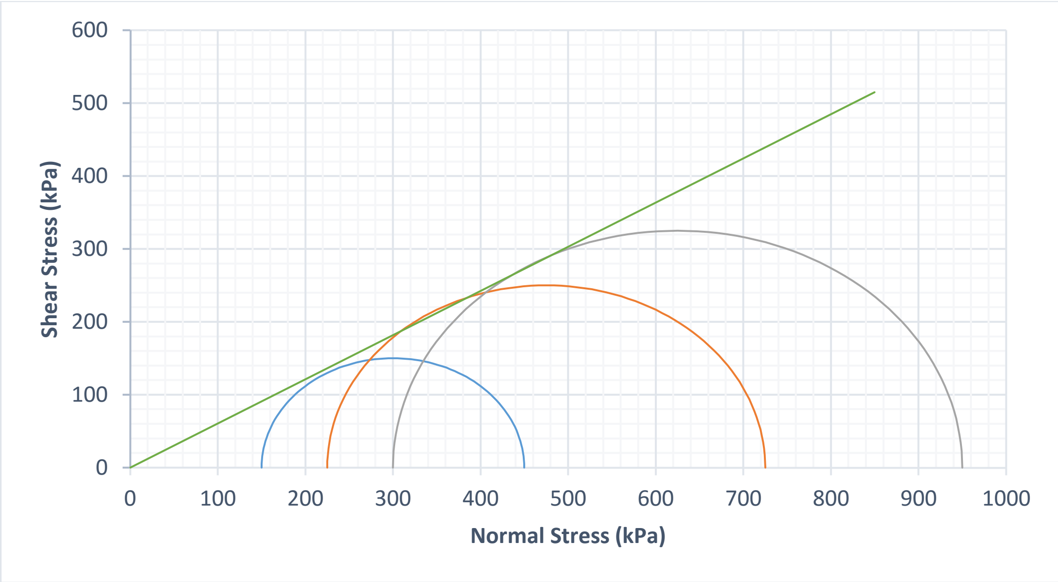


Figure 51: Failure Envelope for the Conventional Tests drawn from the max. curvature (C = 0 kPa, Ø = 31°)

6.2.5 Comparing SG and SA

The results obtained from the conventional triaxial tests performed on identical reconstituted sample using Geocomp's and ALFA's Triaxial System respectively showed great similarities in the obtained results. Both samples were reconstituted and compacted to the same density and flushed with carbon dioxide to accelerate the saturation stage.

By examining the deviator stress versus axial strain graph, it can be seen that both graphs are highly similar to each other in terms of behavior, deformation and yielding.

Both set of tests had the cohesion intercept at 0 kPa and the friction angle around 33° – 34°.

6.3 Multistage Triaxial Tests

6.3.1 Multistage Triaxial Test Procedures

In this study, more than one procedures for multistage are examined. The best procedure for sand specimens will be determined depending on the comparison between the results obtained from one set of conventional CD triaxial tests and the results obtained from one specimen using one of the multistage triaxial test methods.

In multistage triaxial tests, the saturation phase and the first stage of consolidation phase are carried out normally by following the test procedure mentioned in Chapter 5. The difference starts at the first stage of the shear phase. Basically, the idea is to shear the specimen up to near-failure point and then pass to the next consolidation pressure and shear again. The number of stages a specimen can withstand depends on the soil type, but generally three stages are supposed to be applicable on almost all types of soils. Some soil types like Opalinus Clay can withstand up to four stages and still report correct results (Gräsle 2011). The rest of the section deals with the details of each multistage testing method during consolidation and shear stages.

6.3.2 Multistage Triaxial Test Methods

In multistage triaxial test, the effective consolidation pressure is raised to the first consolidation stage. Afterwards, the sample is sheared until a maximum curvature or a stress drop that follows is noticed on the Deviator Stress vs. Axial Strain graph (See 6.3.3).

- Method 1: Sustained Loading Method

In this method, after performing the first shearing stage to near-failure, the effective consolidation pressure is increased to the second stage while maintaining the deviator load on the specimen. Followed by another stage of shear.

- Method 2: Cyclic Loading Method

In this method, after performing the first shearing stage to near-failure, the deviator load is released from the specimen; then the effective consolidation pressure is increased to the second stage. After that, the sample is sheared again to near failure.

6.3.3 When to finish the shearing stage

It is important to decide when and where to start the new stage of the multistage triaxial test. In this study, two sub-methods will be followed;

a. The first sub-method is to pass to the next stage at the maximum curvature on the Deviator Stress vs. Axial Strain graph;
b. The second is to pass to the next stage after experiencing maximum curvature followed by a drop in the deviator stress.

Multistage cycles/stages should be repeated at least three times in order to get correct and representative Mohr's circles and strength parameters.

6.3.4 MCSA Test Results

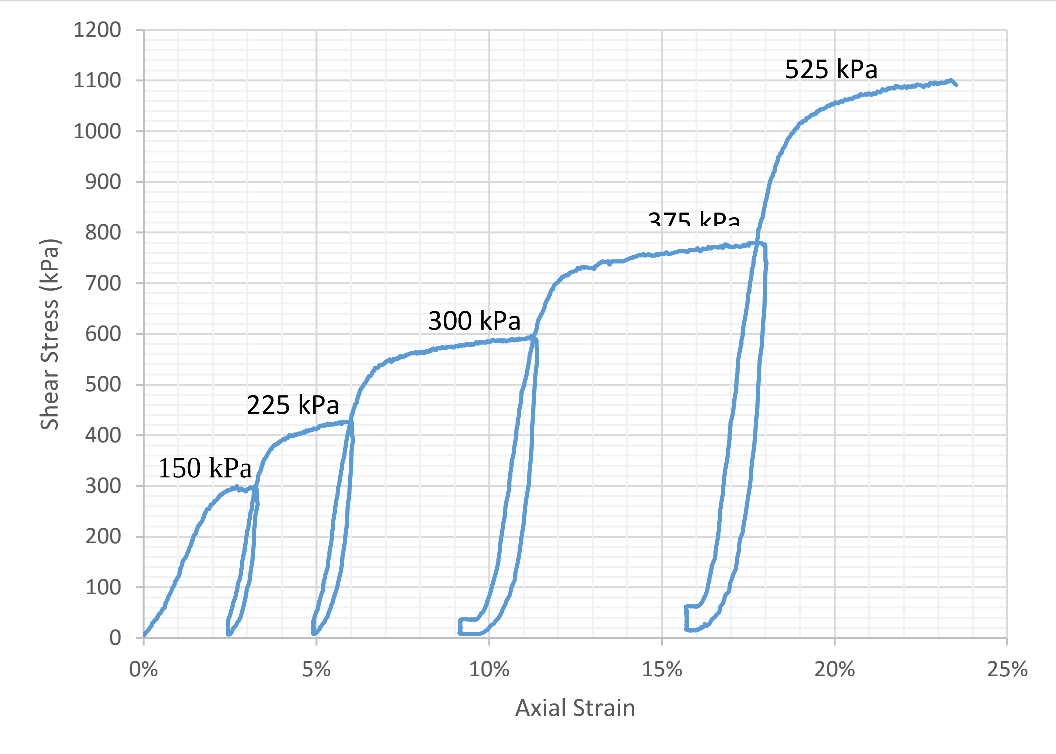


Figure 52: Deviator Stress vs. Axial Strain - ALFA (MCSA)

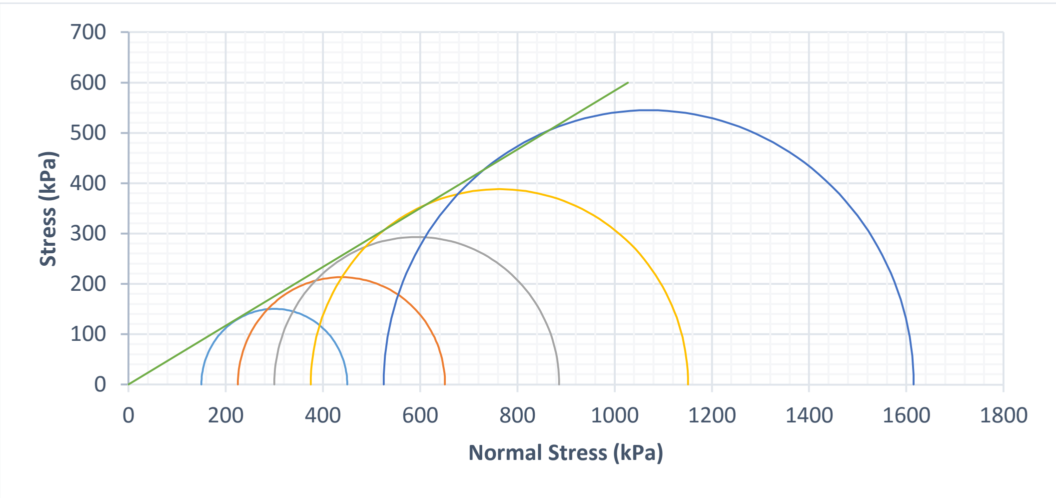


Figure 53: Failure Envelope - ALFA (MCSA)

After examining the figures 52 and 53, the apparent cohesion is found zero and the friction angle is 32°.

6.3.5 MCCA Test Results

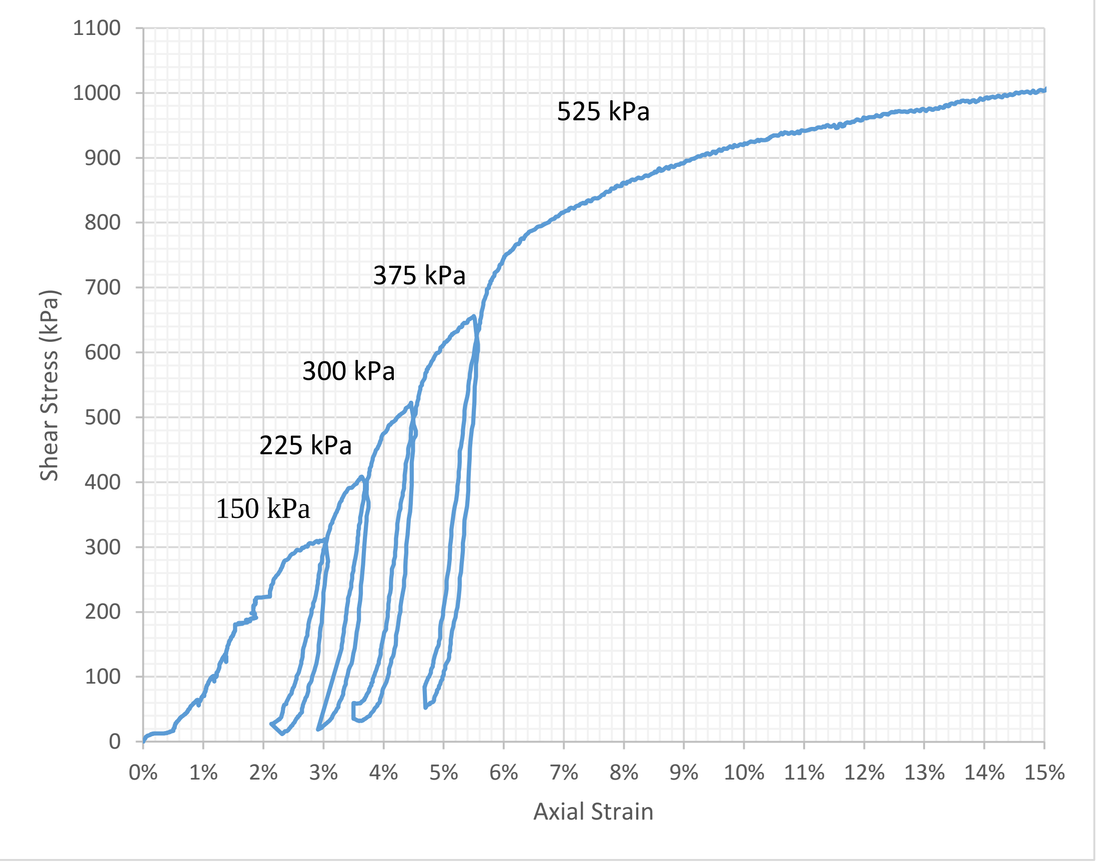


Figure 54: Deviator Stress vs. Axial Strain - ALFA (MCCA)

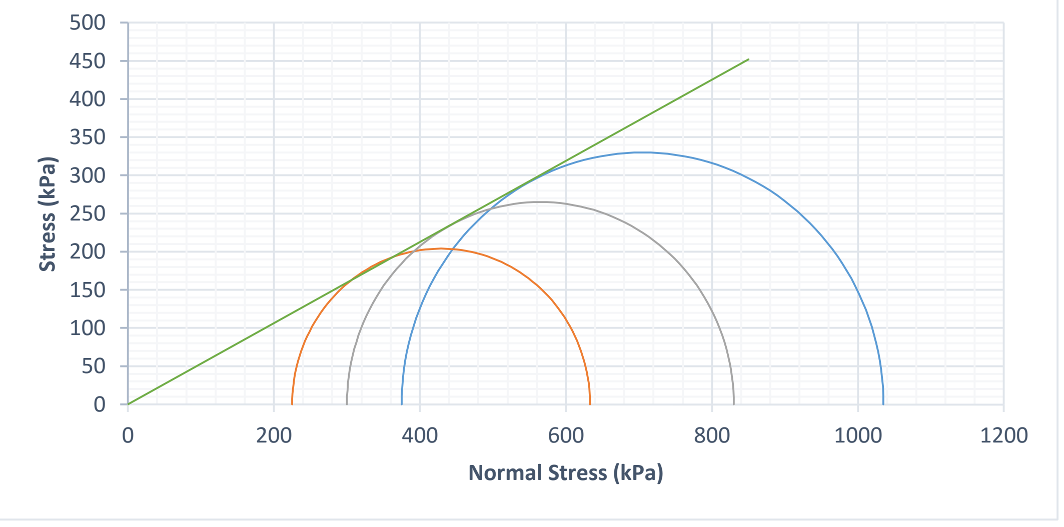


Figure 55: Failure Envelope - ALFA (MCCA)

After examining the figures 54 and 55, the apparent cohesion is found zero and the friction angle is 28°.

6.3.6 MSSA Test Results

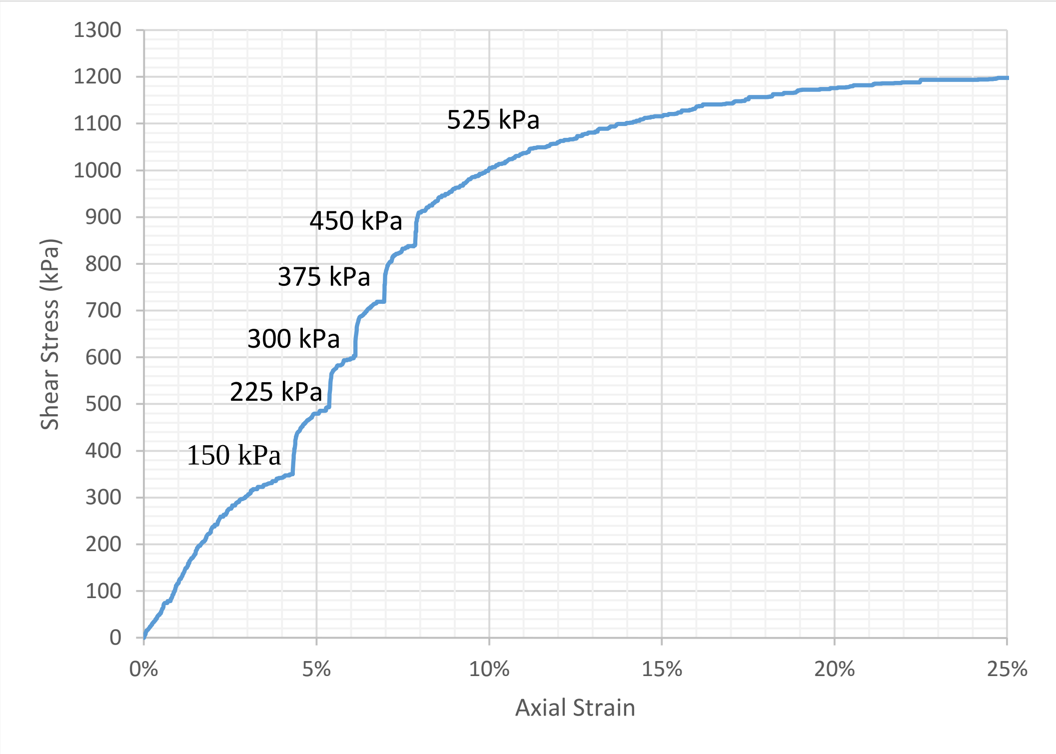


Figure 56: Deviator Stress vs. Axial Strain - ALFA (MSSA)

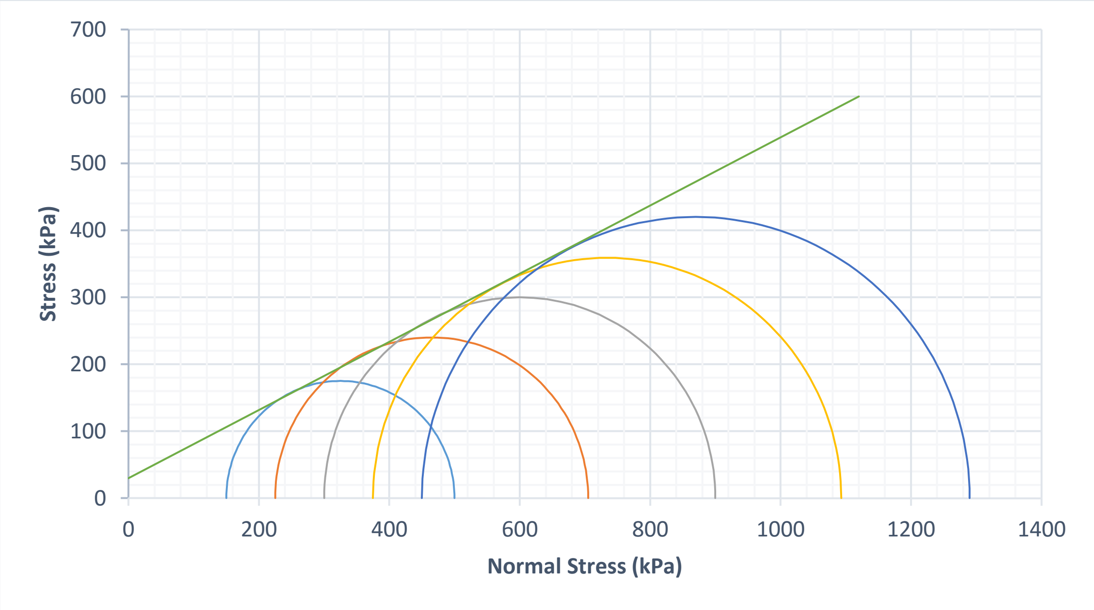


Figure 57: Failure Envelope - ALFA (MSSA)

After examining the figures 56 and 57, the apparent cohesion is found 30 kPa and the friction angle is 28°.

6.3.7 MSCA Test Results

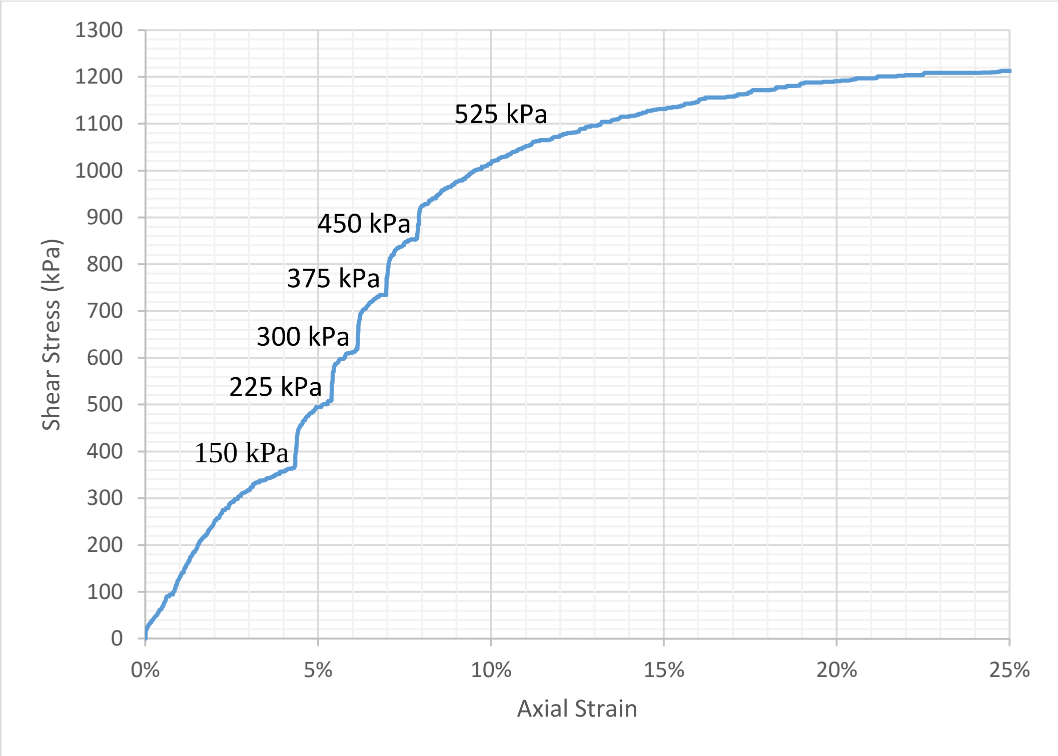


Figure 58: Deviator Stress vs. Axial Strain - ALFA (MSCA)

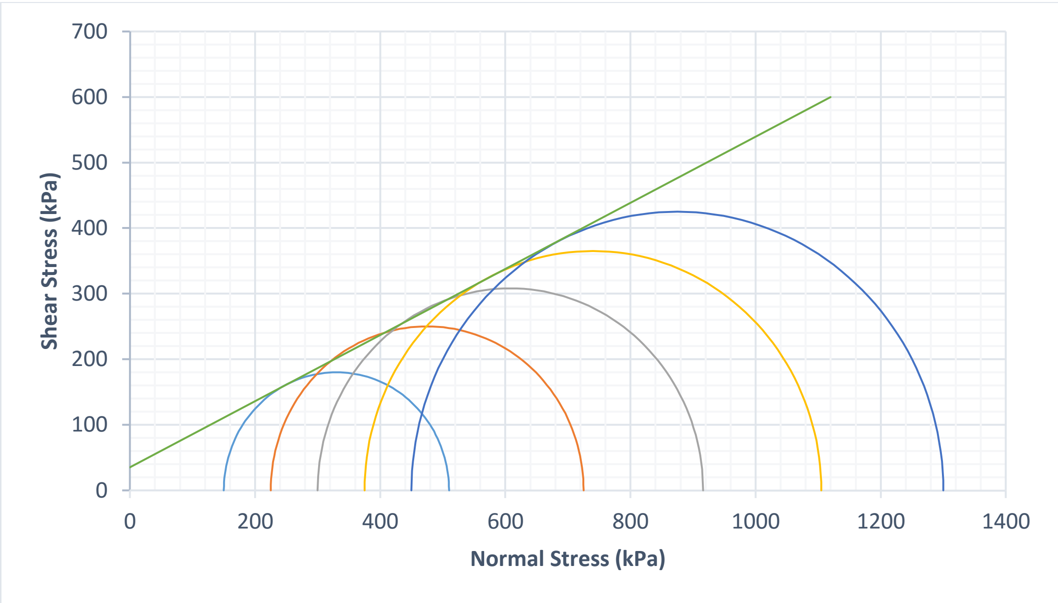


Figure 59: Failure Envelope - ALFA (MSCA)

After examining the figures 58 and 59, the apparent cohesion is found 35 kPa and the friction angle is 27°.

6.3.7 Comparing the results obtained using the multistage methods

The results obtained from various methods of multistage triaxial test showed that some of those methods are not applicable on reconstituted sand specimen. Some of them resulted in cohesion intercept higher than zero. In general, it can be said that the cyclic loading method is more applicable and results in parameters similar to those obtained using the conventional triaxial test. The point at which the stage is assumed finished and the specimen is ready to take another shear stage should not be the yielding point on the deviator stress versus axial strain relationship, instead it should be somewhere close to the peak, or when the slope is below 8% while fixing the axis ratio so as 60 kPa is at the same length of 1% axial deformation.

As a summary; the soil parameters found from the conducted tests (single-stage and multistage tests) are shown in table 7.

Table 7: Soil Parameters - Summary Results

Test Code	Number of reported tests	Test Type	Apparent Cohesion (c) kPa	Friction Angle (Ø) degrees
SG	3	Geocomp USA	0	32
SA	3	ALFA TURKEY	0	33
MCSA	1	ALFA TURKEY	0	32
MCCA	1	ALFA TURKEY	0	28
MSSA	1	ALFA TURKEY	30	28
MSCA	1	ALFA TURKEY	35	27

CHAPTER 7

DISCUSSION AND CONCLUSION

7.1 Triaxial Setup Development

In this study, fully automated computer-controlled triaxial testing system was developed. The main reason for this study was the lack of such system in the Turkish industry and the high price provided by the other manufacturers in America and Europe for this system.

The developed setup is able to perform the basic and standard triaxial tests in fully automated manner. Nevertheless, advanced tests like K_0 and custom stress paths can also be conducted either in fully automated mode or fully manual to give the user the choice to adjust, try and investigate different approaches in this test.

The software of this setup is developed such as not much of know-how is required to perform the test. Each single tab is filled with comments and notes to guide the user without even having to return to the instructions manual. Not mentioning the ability to easily customize the desired test report and have it compiled at an eye blink.

In order to verify the developed equipment, two sets of conventional CD triaxial tests were carried out. One was conducted using a reference testing equipment (Geocomp's Triaxial System, USA) and another using the one developed in this study (ALFA's Triaxial System, Turkey). The results obtained from those sets were similar, which verifies the usability of the newly developed system.

7.2 Multistage Testing of Sand

The other goal of this study was to examine the behavior of sand under multistage triaxial tests using different methods and to determine which method provides more accurate results that are close to those obtained with the conventional tests. The main challenge was to determine when and how to finish the shearing stage and pass to the next stage. In determining this, the methods followed were ***Cyclic Loading Method*** and ***Sustained Loading Method***. For each method, two options were examined, the first is to finish the shearing stage when the stress-strain relationship reaches down to 8% slope or lower; and the other is after passing the maximum curvature on that graph.

7.3 Findings

After examining the results obtained from the conducted tests; it is proved that the Cyclic Loading Method is more accurate and close to the conventional tests when applied on sand. The shear stage can be assumed finished when the stress-strain curve is at 8% or lower slope. If with this method, the transaction between the stages was based on the maximum curvature, then the test will result in lower friction angle. For both, the cohesion intercept came out correct (zero for sand).

The second method, Sustained Loading Method, was not applicable on this specific sample. Both the slope and the maximum curvature approaches tend to give cohesion intercept higher than zero (which is not applicable on sand samples) and low friction angle (around 20% lower than the conventional "single-stage" test and multistage test with cyclic loading).

It has been also proved in this study that the method suggested by Kondner (1963) is not applicable on sand samples.

7.4 Recommendations for Future Studies

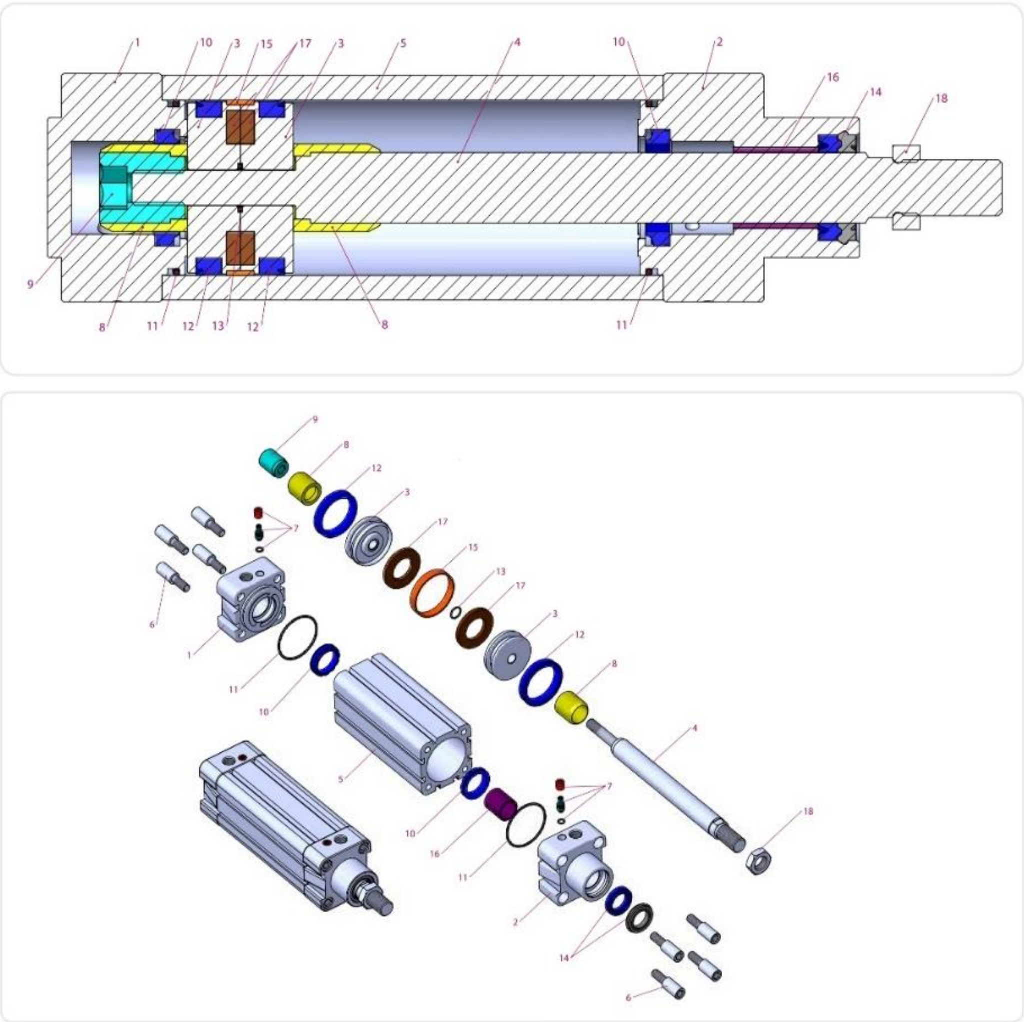
a) Install a third PVA to the system and perform flexible wall permeability in automatic mode.
b) Install a camera sensor to the setup that analyze the sample in real time and embed the results to the area correction calculations.
c) Using the same setup, multistage applicability other soil types can be tested (i.e., clay, silt or mix of soil) with both cyclic and sustained loading methods.
d) Automate Kondner’s hyperbolic approach and further study its applicability on different soil types.

APPENDIX

DETAILED TECHNICAL SPECIFICATIONS

Table 8: Technical Specifications of the Stepper Motor used in the PVA unit

Model	MCM-Motor 57MC20
Country of Origin	United States of America
Holding Torque	2.00 Nm
Detent Torque	0.06 Nm
Current	3 A
Resistance	1.0 Ω/Ø
Inductance	3.5 mH/Ø
Rotor Inertia	440 $g.cm^2$
Lead Wire	4 pin
Step Angle	1.8°
Step Angle Accuracy	± 5% (full step, no load)
Resistance Accuracy	± 10%
Inductance Accuracy	± 20%
Temperature Rise	80°C max. (rated current, 2 phase on)
Ambient Temperature	-20°C ~ +50°C
Insulation Resistance	100 MΩ min, 500 VDC
Dielectric Strength	500 VAC for one minute
Shaft Radial Play	0.02 max (450 g-load)
Shaft Axial Play	0.08 max (450 g-load)
Max Radial Force	75 N (20 mm from the flange)
Max Axial Force	15 N



No	MATERIAL NAME	CHARACTERISTIC	PC.
1	Rear Head	Aluminium	1
2	Front Head	Aluminium	1
3	Middle Piston	Aluminium	2
4	Piston Rod	X20 Cr13 Hard Chrome Plated	1
5	Tube	Al Mg Si 0,5 + Eloxal Plated	1
6	Bolt	Galvanized Steel	8
7	Cushioning Screw	Brass+AISI 303 NBR	2
8	Cushioning Plastic	Polyacetal	2
9	Cushioning Fem. Thread	Galvanized Steel	1
10	Cushioning Seal	PU	2
11	Head O-ring	NBR	2

No	MATERIAL NAME	CHARACTERISTIC	PC.
12	Piston Seal	PU	2
13	Middle Piston O-ring	NBR	1
14	Rod Seal	HYTREL + PU	1
15	Guiding Band	Polyacetal	1
16	Guiding Bush	CSB-40	1
17	Magnet		2
18	Nut	Galvanized Steel	1

Note:
Dia 32: Instead of Cushioning Plastic is used Cushioning yellow and instead of Cushioning Plastic Female Thread is used Cushioning yellow Female Thread. (Material:Brass)

Dia 125:Instead of Cushioning Plastic is used Cushioning Aluminium and instead of Cushioning Plastic Female Thread is used Cushioning Aluminium Female Thread. (Material: Anodized Aluminium)

Figure 60: Pneumatic Piston - Schematic Diagram

Table 9: Technical Specifications of the Stepper Motor used in the PVA unit

Model	Trafag ECT 8472
Country of Origin	Germany
Capacity	25 bars
Measuring Principle	Thick film on ceramic
Measuring Range	0 – 25 bars
Measuring Accuracy	0.5 %
Over Pressure	50 bars
Burst Pressure	75 bars
Accuracy at 25°C	± 0.5%
Media Temperature	-25°C ~ +125°C
Ambient Temperature	-25°C ~ +85°C
Output	4 ... 20 mA
Load Resistance	9 V / 20 mA
U Supply	9 – 30 VCD
Electrical Connection	Male Electrical Plug EN 175301-803-A, Mat. PA
Sensor	Ceramic (Al_2O_3) 96%
Housing / Pressure Connections	Titanium Grade 5
Sealing	FKM 70 Sh, CR, EPDM
Mounting Torque	15 … 20 Nm

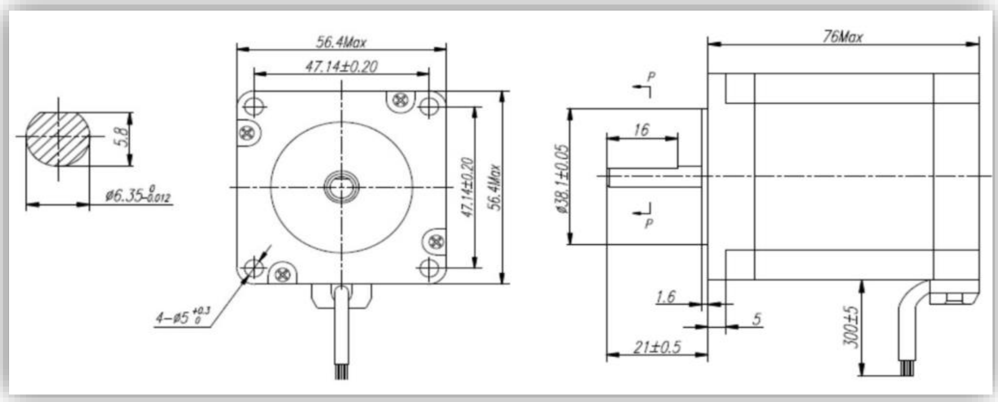


Figure 61: Stepper Motor - Schematic Diagram

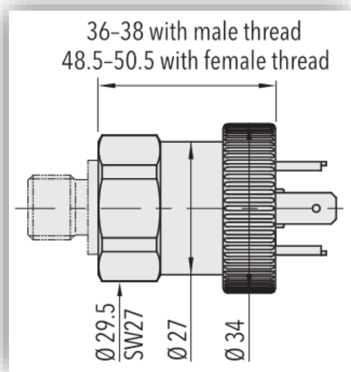


Figure 62: Pressure Transducer Electrical Connection

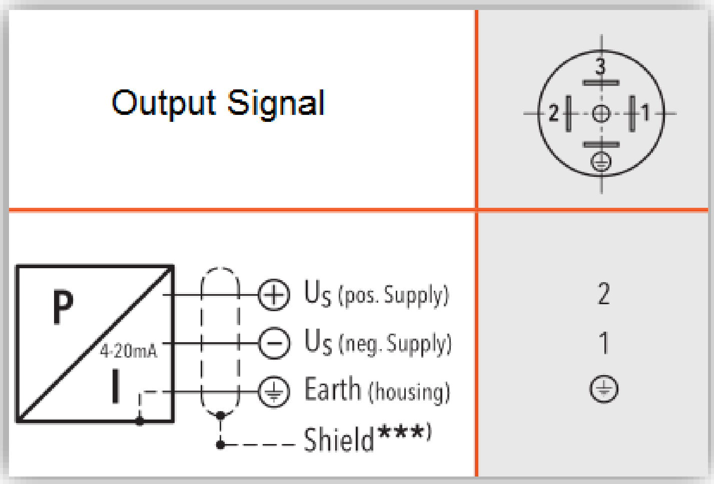


Figure 63: Pressure Transducer Output Signal Connection

Table 10: Technical Specifications of the Potentiometric Position Transducer used in the PVA unit

Model	Novotechnik LWH-0250
Country of Origin	Germany
Housing	Anodized Aluminum
Mounting	Adjustable Clamps, snap in on all sides
Actuator	Stainless steel (1.4305), rotatable, external thread M6
Resistance element	Conductive plastic
Wiper Assembly	Precious metal multi-finger wiper, elastomer-damped

Electrical Connection	4-pin plug socket to DIN 43650
Defined Electrical Range	250 mm
Electrical Stroke	254 mm
Nominal Resistance	5 kΩ
Resistance Tolerance	±20 %
Independent Linearity	± 0.07%
Repeatability	0.01 mm
Recommended Operating Wiper Current	≤ 1 μ
Maximum Permissible Wiper Current	10 mA
Maximum Permissible Applied Voltage	42 V
Effective Temperature Coefficient of the Output-to-Applied Voltage Ratio	Typical 5 ppm/K
Insulation Resistance (500 VDC)	≥ 10 MΩ
Dielectric Strength (500 VAC, 50 Hz)	≤ 100 μA
Body Length (A)	324 mm (± 2mm)
Mechanical Stroke (B)	262 mm (± 2mm)
Operating Force	≤ 10 N
Temperature Range	-30°C ~ +100°C
Vibration	5 … 2000 Hz Amax = 0.75 mm amax = 20 g
Shock	50 g 11 ms
Life	> 100 x 10^6 movem.
Operating Speed	10 m/s max
Operational Acceleration	200 (20 g) m/s^2 max
Protection Class	IP55 (DIN EN 60529)

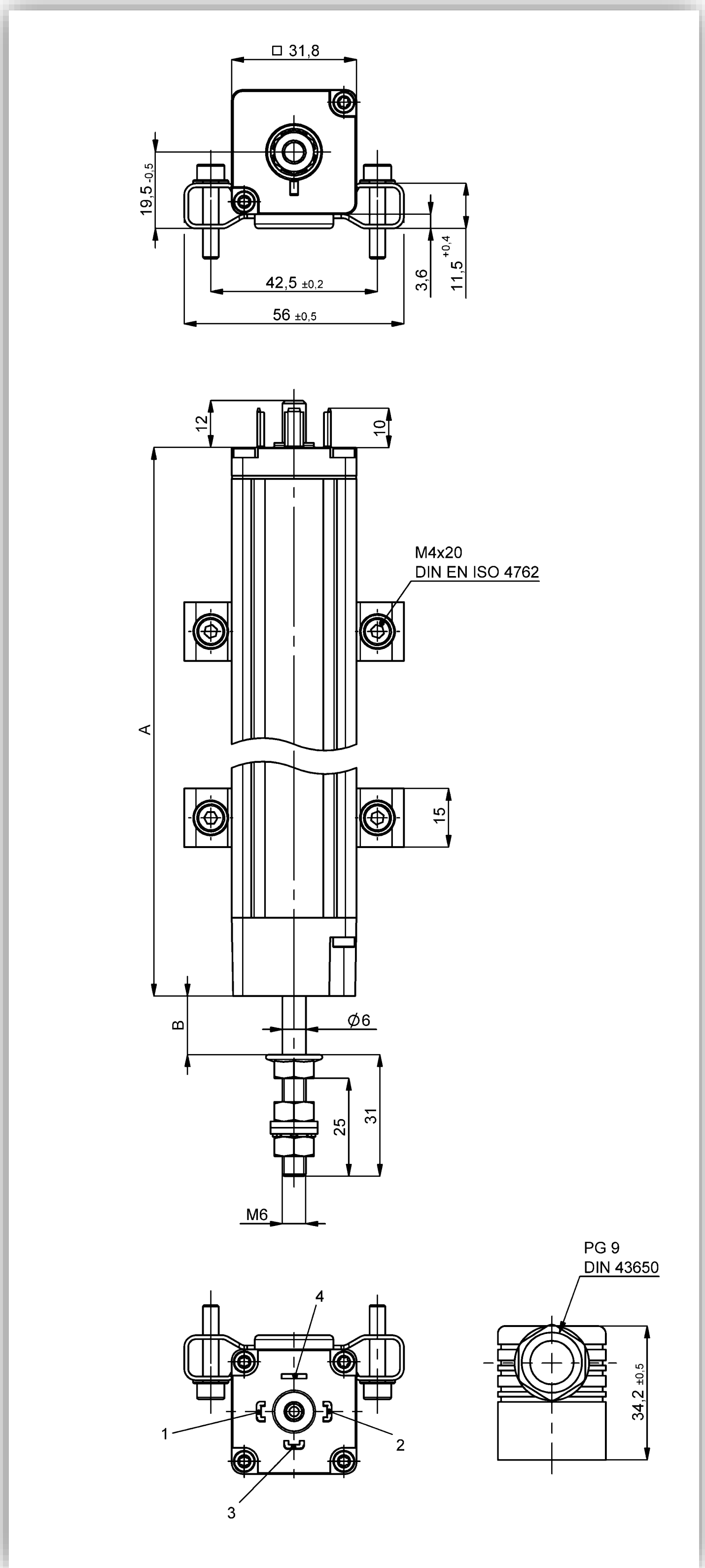


Figure 64: PVA Potentiometric Position Transducer - Schematic Diagram

Table 11: Technical Specifications of the Servo-System used in the loading frame

Model	Delta ASDA-B2
Country of Origin	Japan
Phase	Single
Voltage	220 V / 50 – 60 Hz
Continuous Output Current	5.1 Arms
Cooling System	Natural Air Circulation
Encoder/Feedback Resolution	17-bit (160,000 p/rev)
Control of Main Circuit	SVPWM Control
Tuning Mode	Auto / Manual
Dynamic Brake	Built-in
Max Input Pulse Frequency	500 Kpps (Line Driver / Low Speed) 4 Mpps (Line Receiver / High Speed) 200 Kpps (Open Controller)
Pulse Type	Pulse + Direction (A Phase + B Phase : CCW Pulse + CW Pulse)
Command Source	External Pulse Train / Internal Parameters
Speed Control Range	0:5000 Hz

Figure 65: Servo-Driver Part Names and Functions

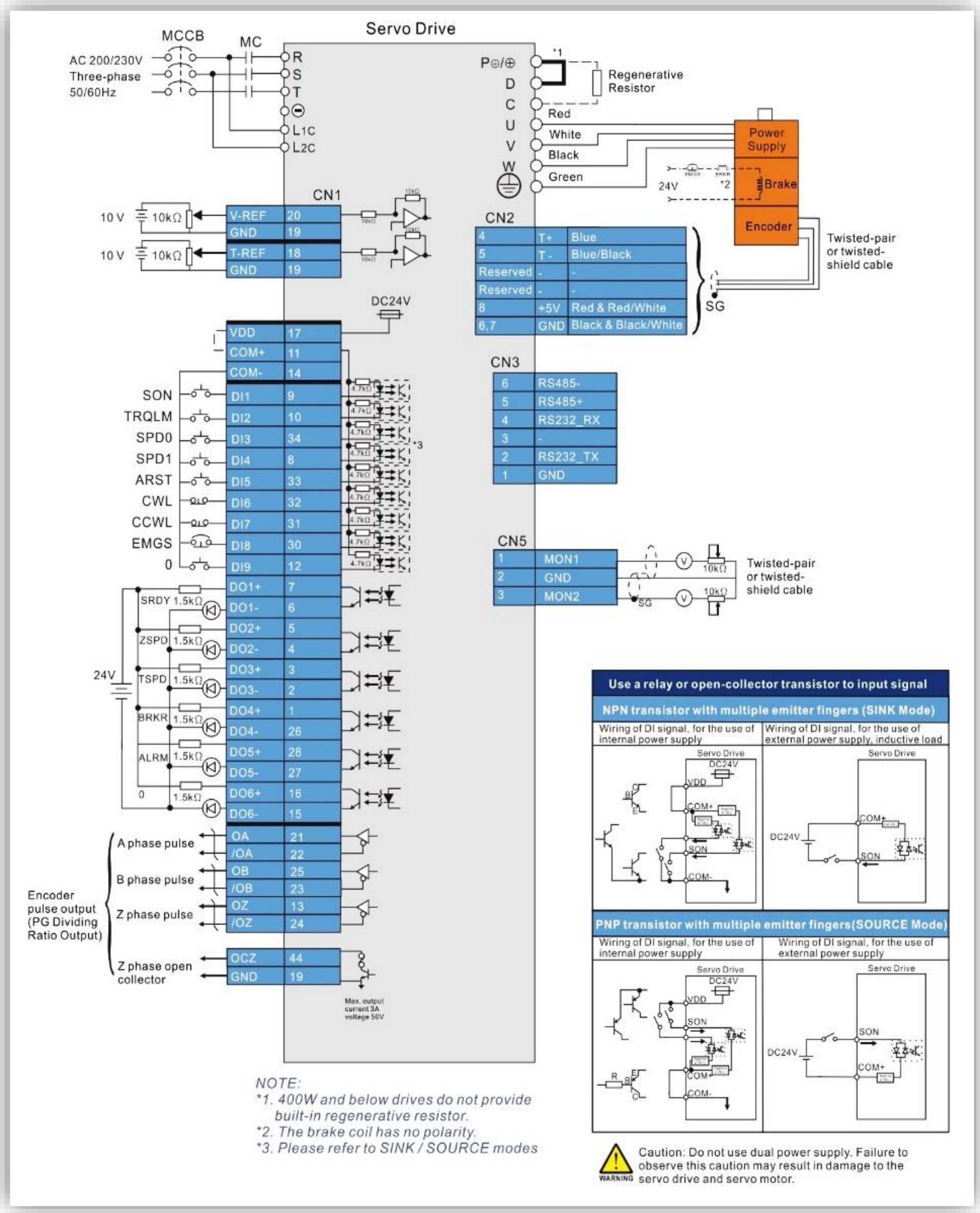


Figure 66: Servo-System Speed Control Connection Schema

Table 12: Technical Specifications of Potentiometric Deformation Transducer

Model	Novotechnik TR-0050
Country of Origin	Germany
Defined Electrical Range	50 mm
Electrical Stroke	52 mm
Repeatability	0.002 mm
Operating Speed	10 m/s max
Protection Class	IP40 (DIN EN 60529)

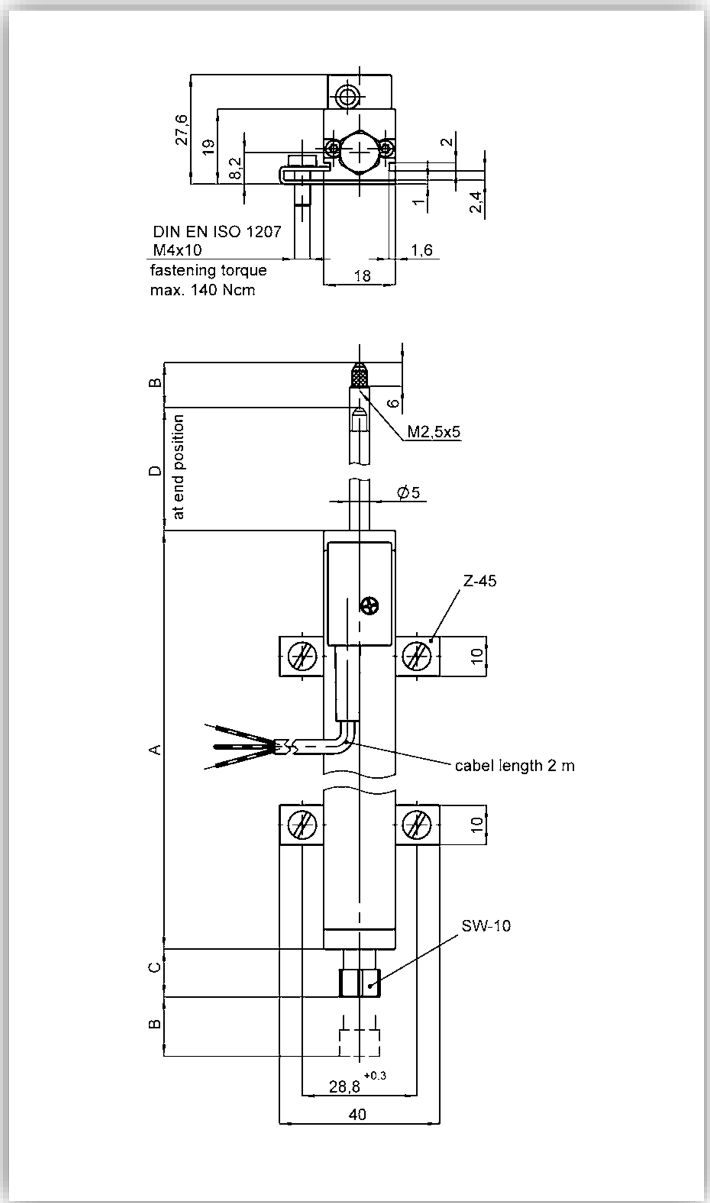


Figure 67: Potentiometric Deformation Transducer - Schematic Diagram

Table 13: Magnetic Stirrer - Technical Specifications

Construction material	Techno-Polymer
Power	0.6 W
Electronic speed regulation	up to 1100 rpm
Stirring volume (H_2O)	up to 5 liters
Speed control	Available even at low revolutions

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