Contents

Quick guide on using this document and the data archive:

- If bulk modulus measurements and locating the data files for "Elastic Moduli Experiment (EM)" are of interest, please go to section 2 of this document. Similarly for shear modulus measurements, please review section 3.

- In order to understand the different notations and parameters used in this document and the triaxial experiment in general, please review the "Triaxial Experiment Dictionary", where definitions and formula are provided for calculating/measuring various quantities.

- If soil shear strength parameters from monotonic shear tests (General 7 Triaxial Experiments (G7)) are of interest, please review section 4 to use the data archive more efficiently.

- Note that the file "Table of Contents, Description, & File Names.pdf", summarizes the constituents of the data archive in a table and provides short descriptions on what each data file contains; in other words, what is being done during each stage of an experiment and how it can be located. It is useful to follow this table to locate desirable data.

1- Device and sample preparation

1.1. Sample preparation

The tests performed were part of a study on the shape of the yield surface and plastic potential surface of a uniformly graded sand called “Orange county Silica sand-mesh 60”. The sand was prepared at its maximum void ratio (e_{max}), in other words at zero relative density (D_r). The samples were prepared by air-pluviation from essentially zero drop height resulting in very low depositional energy.

Before building the sample the following steps were followed:

(a) Top and bottom porous stones were oven dried for 24 hours prior and cooled down before installation
(b) If re-using a membrane, the membrane was washed thoroughly with dishwashing soap and warm water to remove sand grains and possible leftover vacuum grease. After washing the membranes, they were dried using cotton cloths, then baby powder was applied to gain a smooth clean surface similar to an unused membrane. This is in order to remove possible residues and stickiness of the vacuum grease.
(c) The sand was oven-dried for 24 hours and cooled to room temperature prior to sample preparation to assure its dryness.
(d) In order to seal the contact between the top and bottom platens with the membrane, vacuum grease was applied to both platens before installing the membrane.
(e) After placing the membrane on the bottom platen of the apparatus, the membrane is sealed with two O-rings. The O-rings and the vacuum grease, along with a membrane can be seen in Figure 1. The setup of the membrane and O-rings on the bottom platen can be seen in Figure 2 along with the sand used for this study.

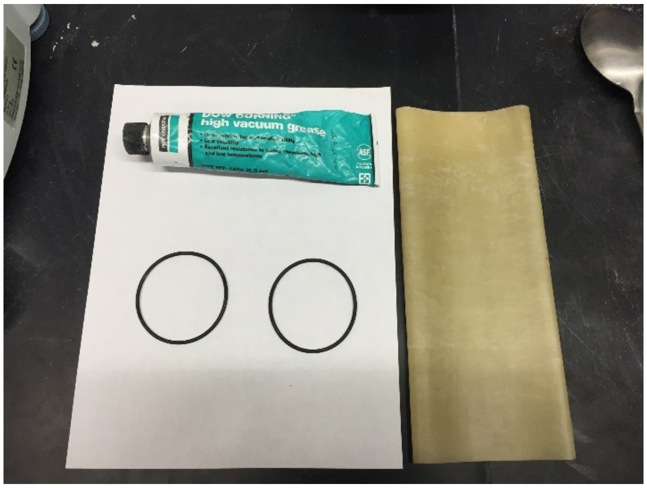
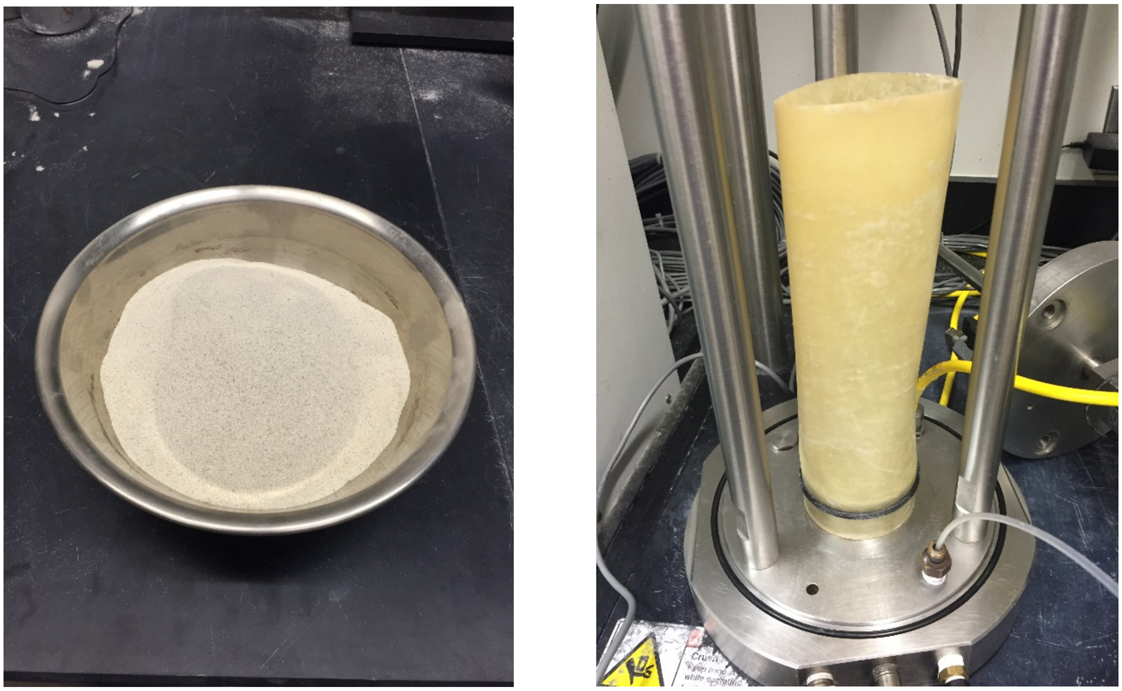


Figure 1. Vacuum grease, O-rings and rubber membrane



(a) **(b)**

Figure 2. (s) Oven dried Orange County Silica sand-mesh 60, (b) membrane and O-ring setup on bottom platen of Triaxial apparatus

(f) In order to pull the membrane and air-pluviate the sand inside the membrane, a custom made mold was used, which after installation, is held firmly by a belt or clamp as shown in Figure 3.

(g) After pulling the membrane to the outside of the mold, it was checked that no torsion was applied to the membrane during pulling its edges around the mold.

(h) A vacuum of about 20 kPa was applied to annular space between the mold and the membrane to stretch the membrane against the mold. In Figure 3, the orange line is connected to the vacuum.

(i) The bottom porous stone was inserted inside the membrane and pushed to the bottom of the membrane, in full contact with the bottom platen.

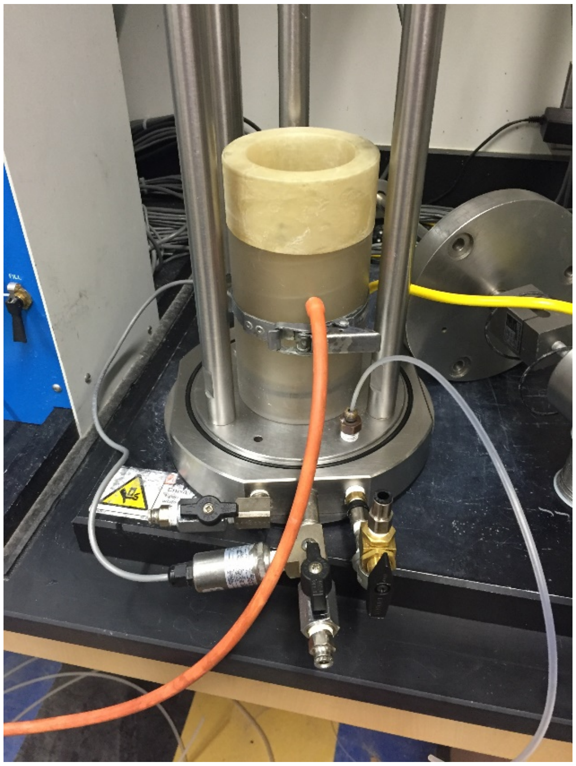


Figure 3. Assembly of the outer mold, clamp and the membrane pulled out of the mold with applied vacuum

At this stage, the sample was pluviated. In order to achieve zero drop height, a plastic pipe with outer diameter slightly smaller than the inner diameter of the specimen mold was inserted inside the membrane. The plastic pipe was equipped with a mesh at the bottom that regulated the rate at which the sand grains passed through. The sand was poured into the pipe, and the mold was brought up very slowly to ensure that the drop height of the sand grains remain practically zero. Care was taken to prevent the pluviation device only moved upward, and never downward, as any downward movement could densify the sand.

After pulling the inner mold thoroughly outside of the outer mold, the excess sand was removed while creating a flat surface for the top of the sample. The removed excess sand was weighed and subtracted from the initial weight of the oven-dried sand. This is necessary to measure the sample mass at the beginning of the test.

The top porous stone was inserted on top of the sand carefully in a way not to disturb the sand. The top cap of the apparatus is attached to the loading piston, and the top plate was secured with the piston holding the top cap slightly above the porous stone. At this time, the internal load cell was set to zero through the CATS advanced software. After this stage, the top cap was carefully lowered until making contact with the top porous stone, and the membrane was pulled on to the top platen. Once more, two O-rings assure the seal between the membrane and the top platen, where vacuum grease is also applied to the platen.

The vacuum applied to the mold was removed, and 20 kPa vacuum was applied to the specimen through the valve of the bottom platen. This is done to maintain effective stress on the specimen until the cell is assembled so that the mold may be disassembled and removed from around the sample. In order to maintain vacuum the top platen tube was inserted to the top cap and to the red fitting which can be seen in Figure 4, and the top platen valve was closed.

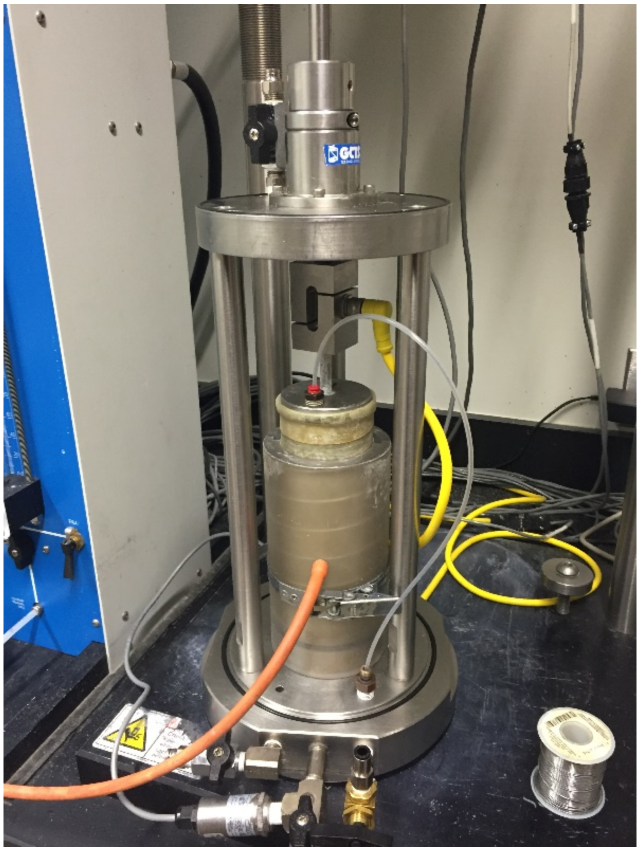
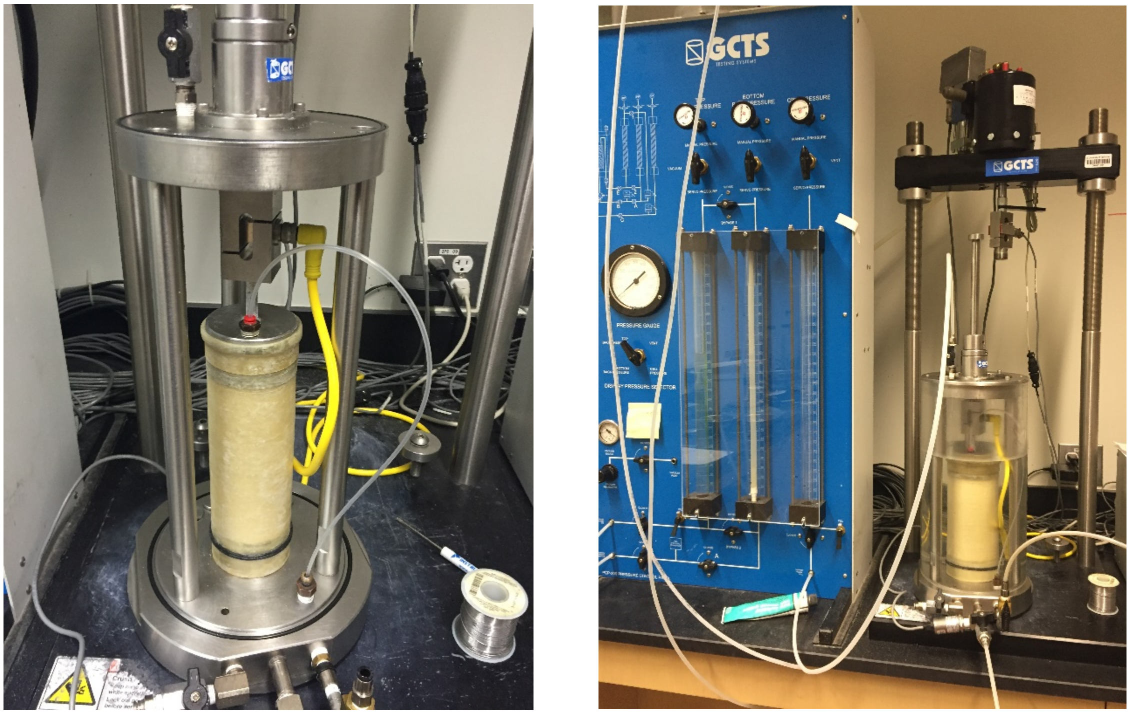


Figure 4. Setup of specimen with vacuum applied through the bottom platen and the top platen put in place

Removing the mold and the clamp, the sample under vacuum is now ready. This can be seen in Figure 5 (a). After this step, the cell is assembled by installing the acrylic chamber. Following this, the cell is filled with water to just above the red fitting on the top cap, as shown in Figure 5 (b). Filling the cell with water prevents diffusion of air directly through the membrane.

At this stage, the vacuum is slowly reduced while the cell pressure is slowly increased simultaneously to keep an effective confining pressure of 20 kPa on the specimen. The sample is ready for the saturation stage.



(a) (b)

Figure 5. (a) Built sample under vacuum, (b) built sample and cell filled with water

1.2. Saturation

To facilitate volume change measurements during drained loading and/or undrained loading conditions, the specimen must first be thoroughly saturated. The adequacy of saturation was assessed by measuring Skempton's B-value ($B = \Delta u/\Delta\sigma_3$). The samples after being prepared were saturated to a B-value of 95% and above. The steps of saturating the samples are described in the following. Note that the saturation stage is performed manually during these tests.

After the sample is prepared, carbon dioxide (CO_2) was slowly percolated through the specimen for 20 minutes. The purpose of flushing the specimen with CO_2 is that it is much more soluble in water than air, therefore enabling easier saturation of the specimen. Note that CO_2 is also denser than air, therefore the air slowly escapes from the top of the specimen as the CO_2 percolates into the sand. The rate of flow of CO_2 is regulated to ensure laminar flow to avoid disturbing the sand grains.

De-aired water was then slowly percolated through the specimen from the bottom cap. The water was percolated for at least 30 minutes to ensure minimal air bubbles inside the specimen or through the lines. After this stage, both the bottom and top platen valves are closed to stop the flow of water through the specimen.

In order to dissolve remaining air bubble through the specimen, a stage of back pressure saturation is also performed where the back pressure is connected to the bottom platen. At this time, in order to keep the initial effective stress constant on the specimen, the cell pressure and back pressure are simultaneously increased through the specimen. Usually, the back pressure was increased from 0 to 100 kPa, where the cell pressure was increased by the same amount from 20 to 120 kPa.

After a period of 10 minutes, the B-value measurement can be made. For this purpose, the back pressure valve was closed, then the cell pressure was increased by a certain amount, usually 10 kPa. Measuring the pore water pressure difference and having the difference in the change of the cell pressure, the B-value can be calculated.

The tests were continued to consolidation and shear stages, if a B-value of 95% or more was achieved.

2. Bulk Modulus Measurement

To measure the bulk modulus of loose sand samples, the "Elastic Moduli Experiment (EM)" was considered. This testing was performed on a loose sand sample (made at zero relative density) in the triaxial compression device under drained conditions (i.e., with the drainage taps open) to measure the shear modulus and bulk modulus of the soil skeleton at various mean effective confining stresses. To measure bulk modulus, *K*, the soil is consolidated to a desired pressure, then the mean effective confining stress is cyclically increased and decreased while the volume change is measured. The deviator stress is zero during this phase of testing.

These tests are imposed in seven stages, where stages 1, 2, 3 and 4 involve tests where the soil is being consolidated to higher effective stresses whereas stages 5, 6 and 7 involve the soil being isotropically unloaded to lower effective confining pressures. The output data for this section (bulk modulus measurements) of the EM test are available in the "Event: Elastic Moduli Experiment (EM)" folder and stages EM1 through EM7 under "2- Bulk Modulus" MS Excel spreadsheets. For more information please review "Table of Contents, Description, & File Names.pdf", where specifics are provided about what the data files contain and how to locate them through the data archive.

The bulk modulus can be found from the ratio of change in mean effective confining pressure (Cambridge Mohr effective stress parameter, or p') over change in volumetric strain (from initial to final). This would be a measurement of the bulk modulus at an *average* mean effective confining pressure. Note that definitions of parameters are given in more details in a separate file labeled as "Triaxial Experiment Dictionary" in the archive.

Note that you may find the Matlab code "PlotModuli.m" useful for plotting the data and making elastic moduli measurements. For this purpose you would need to download the data files and place them in the same folder as the Matlab script to run the code. You may find the data noisy which is due to the noise of the load cell measuring shear, and the LVDT which measures axial deformations.

A sample output of the plots generated by running the Matlab code is provided in Figure 6. Note that the Matlab code generates three plots (see Figure 6); consolidation (ε_v vs. p′) which presents volumetric behavior of the soil as the sample was consolidated to either a higher or lower effective confining stress, a p′ vs. volumetric strain (ε_v) for bulk modulus measurement, and a plot of deviator stress (q) vs. axial strain for secant Young's modulus and shear modulus measurements (which are described in section 3 of this document).

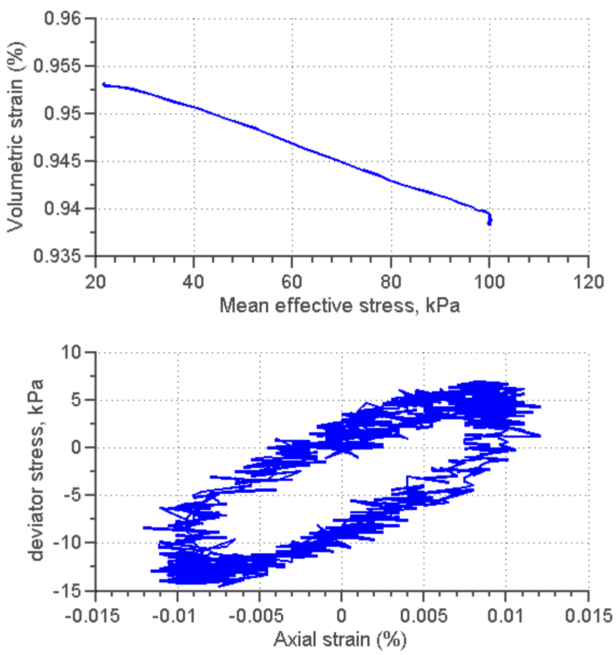


Figure 6. Example plots generated from Matlab code "PlotModuli" from Elastic Moduli Experiment (EM) data

3. Shear Modulus Measurement

The Shear modulus can be found indirectly from bulk modulus (described in section 2 above) and secant shear modulus measurements which is described here in more details.

To measure Young's modulus, *E*, within the "Elastic Moduli Experiment (EM)" at each effective confining stress (same as in section 2), the cell pressure is kept constant while the soil is cyclically sheared at the smallest amplitude that the triaxial device can reliably impose. Secant Young's modulus can be found by plotting deviator stress versus axial strain as shown in the q vs. ε_a plot in Figure 6 and measuring the secant slope. The data for this section can be found from the “3-Shear Modulus” MS Excel spreadsheets in the “Event: Elastic Moduli Experiment (EM)” folder through stages EM1 to EM7.

4. Monotonic Shear

Seven triaxial compression tests were performed on loose samples of sand. The samples are made at zero relative density for each experiment, then consolidated to different values of mean effective confining stresses ranging from 100 to 400 kPa and at 50 kPa intervals. The initial void ratios that the seven samples were made can be found in a separate MS Excel spreadsheet “Initial Void Ratios”.

After sample preparation, each sample is isotropically consolidated to a desirable consolidation stress, then through a second stage the specimens are sheared in stress-controlled conditions. The shear stage is under drained conditions while p′ is held constant, and at intervals the experiment is switched to undrained loading by closing the drainage valve. The purpose of imposing such stress paths is to find yield surfaces and plastic potentials for the sand which is beyond the scope of this document. However, strength parameters of the sand can be found using these monotonic shear experiments, as well as stress paths and volumetric behavior of the soil can be observed.

The data for these tests can be found in the “Event: General 7 Triaxial Experiments (G7)” folder. For each test there are two subfolders in the “General 7 Triaxial Tests” folder; the “MSC#” subfolders contain the consolidation stage data of each experiment, and the “MS#” subfolders contain the data during the shear stage. For more information please review “Table of Contents, Description, & File Names.pdf”, where specifics are provided about what the data files contain and how to locate them through the data archive. You may find Matlab scripts “PlotConsol” and “PlotShear” useful for observing the data.

5. Test Configuration with CATS Advanced Software

After the samples are made and saturated, before continuing with the consolidation and shear steps, the test should be configured through the CATS advanced software. Test configuration basically means to plan and define the different stages/steps of the test since the device is fully automatic and computer controlled.

Consolidation

The first stage is the consolidation stage. The consolidation stage is defined as a stress controlled universal stage, where the deviator stress is kept constant at an absolute value of zero. This is in order to ensure isotropic consolidation on the sample, and that no shear is applied to the specimen during the consolidation stage.

As the deviator stress is kept constant, so is the back pressure since it will not change during this stage. The cell pressure however, needs to be increased and/or decreased during the consolidation process and therefore, it can either be programmed to ramp up or down with time by a given rate, or can be manually increased or decreased by the pressure valve by the user. Either way, the software is recording the changes during the consolidation phase of the test. Screenshots of the consolidation test setup can be seen in Figure 7.

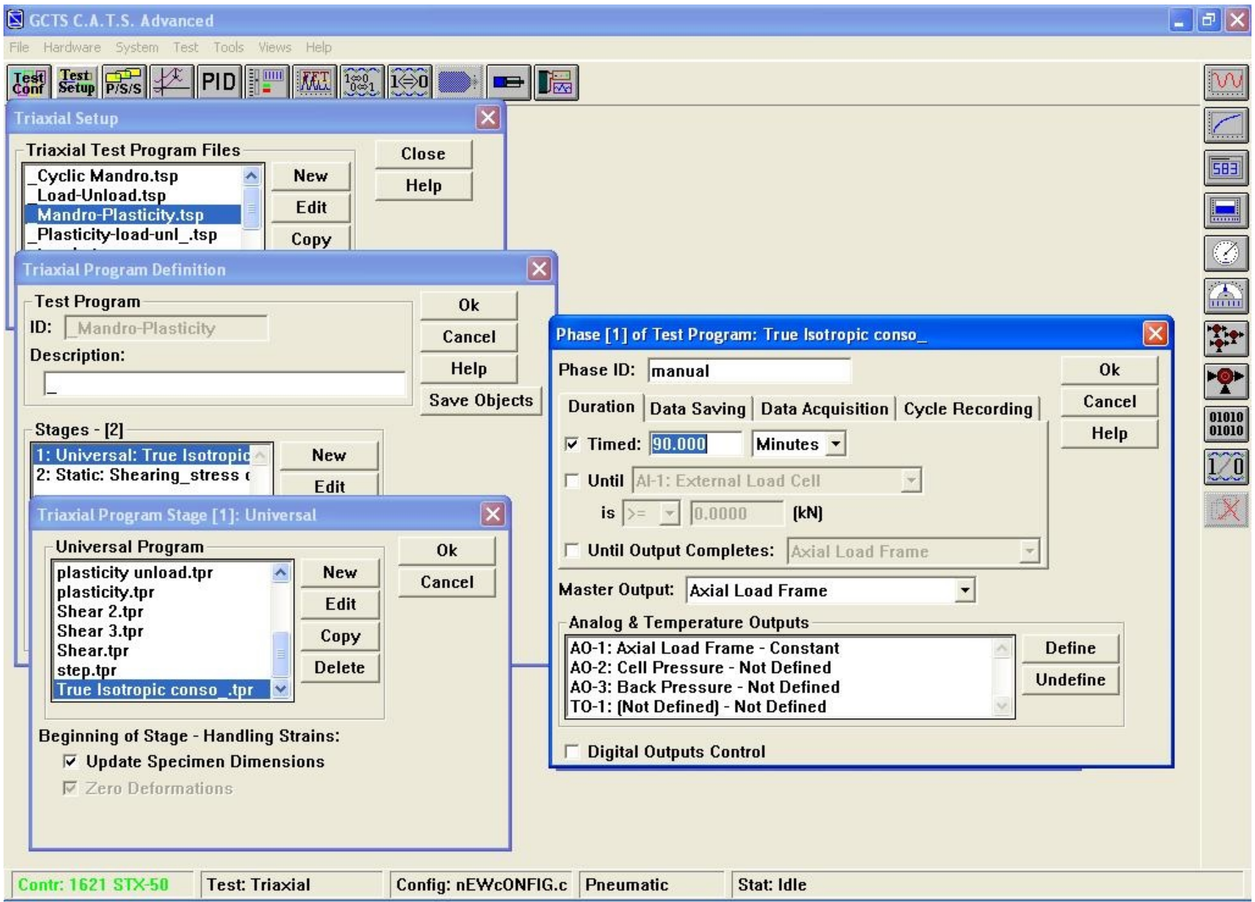


Figure 7. Example of test configuration for consolidation stage

Shear

After consolidating the sample to the desired effective confining pressures, the sample is ready for shear. The tests ran for this study are performed in a stress controlled manner and therefore, the computer will need to control the deviator stress being applied to the specimen.

Note that for the purposes of this study, the tests are done in a way that the effective stress path needs to remain vertical (i.e. constant *p'*) during shear. For this purpose, the mean effective stress shall be decreased by one third of the increase in the deviator stress applied to the specimen. For instance, if the rate of deviator stress is a constant value of *dq*, then the rate of the cell pressure should be *–dq/3*.

The back pressure is controlled by the computer and kept constant at the initial value after consolidation, which is usually 100 kPa. Note that shear is started under drained loading conditions where the drainage valve is kept open, at intervals during the shear process, the specimen is sheared under undrained conditions where the drainage valve is manually closed and then re-opened. Screenshots of the shear stage test setup can be seen in Figure 8.

Note that the Shear stage can be configured either by a universal testing stage such as for the consolidation stage, or it can be defined by a static loading stage, which is in the case shown in Figure 8.

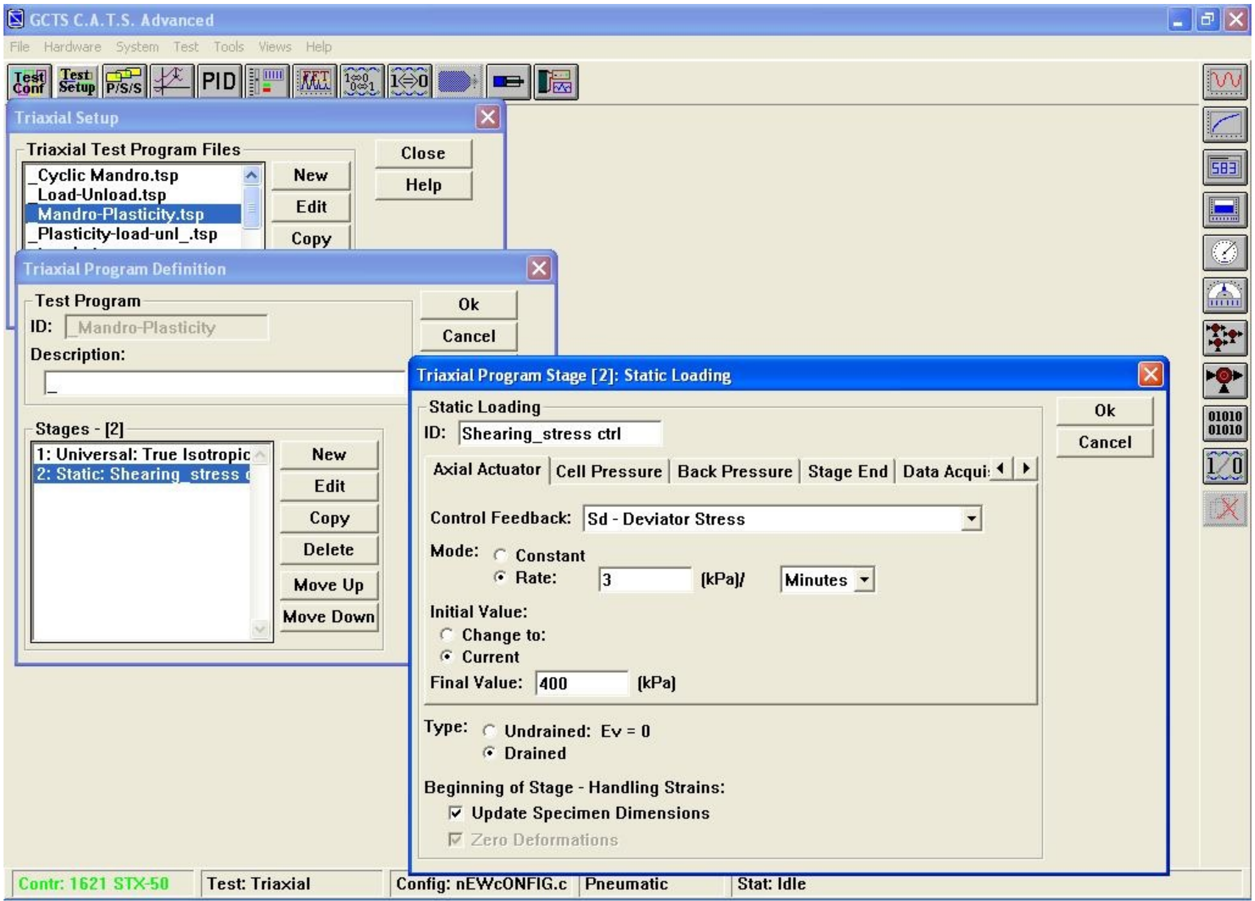


Figure 8. Example of test configuration for shear stage