



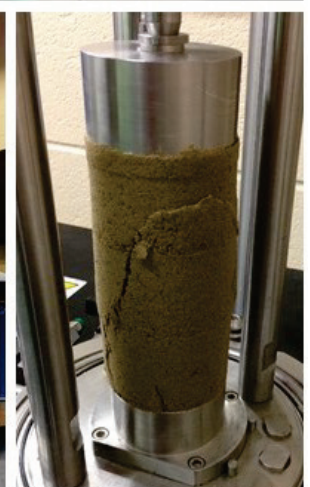
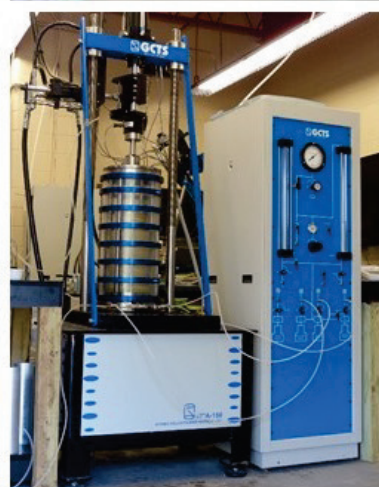
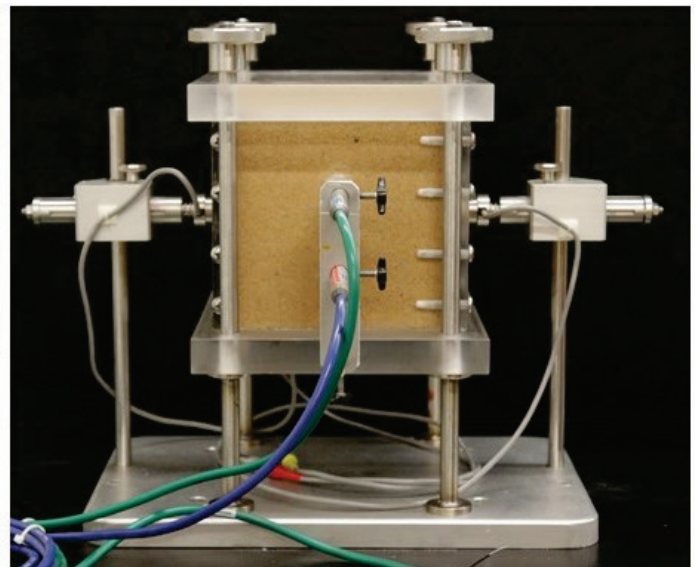
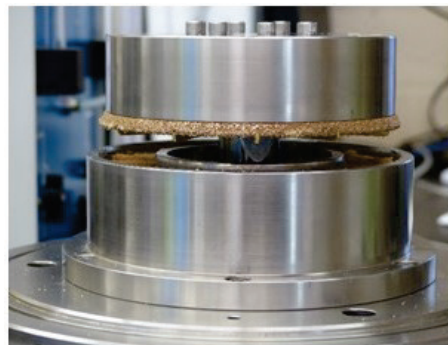
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## Near Surface Laboratory Testing Protocol Development

Woodman W. Berry, Amy L. Cunningham, Katherine E. Winters,  
Oliver-Denzil S. Taylor, Wesley R. Rowland, and Mark D. Antwine

July 2018



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# **Near Surface Laboratory Testing Protocol Development**

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## Abstract

Geotechnical laboratory testing focuses on the behavior of soils subjected to confining pressures in excess of those experienced within the near-surface environment (the upper 1 m of the soil profile). Such standardized protocols have set-up stresses, e.g., seating loads and stabilization vacuum pressures, in excess of the failure strength observed at low confinement. Therefore, effective stress principles are often used to infer low confinement behavior within a laboratory setting. Neither the standardized protocols nor the use of effective stress principles encapsulate the near-surface environment or the true behavior. The purpose of this technical report is to provide laboratory-testing protocols for physical experimentation within the near-surface environment. For standardized testing equipment, e.g., triaxial and simple shear devices, existing protocols have been modified. New testing protocols have been designed for experimental equipment, e.g., the Ultrasonic Near-Surface Inundation Testing device (UNIT) or for unconfined drained self-supporting testing (UD). The protocols presented herein are for commercial and prototype equipment used in the ERDC Geotechnical and Structures Laboratory (GSL) and are readily adaptable to other equipment manufacturers' devices.

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## Preface

This study was conducted for the U.S. Army Corps of Engineers under the Assistant Secretary of the Army, Acquisition Logistics and Technology (ASAALT) AT40 “Integrated Force Protection against Advanced Threats Program.” The Program Manager was Dr. Bradley Foust.

The work was performed by the Structural Engineering Branch (GSS) of the Geosciences and Structures Division (GS), U.S. Army Engineer Research and Development Center, Geotechnical and Structures Laboratory (ERDC-GSL). At the time of publication, Mr. Charles W. Ertle was Chief, CEERD-GSS; and Mr. James Davis was Chief, CEERD-GS. The Deputy Director of ERDC-GSL was Dr. William P. Grogan, and Mr. Bartley P. Durst was the Director.

COL Bryan S. Green was the Commander of ERDC, and Dr. David W. Pittman was the Director.

## Unit Conversion Factors

| English - Multiply           | By             | To Obtain - Metric        |
|------------------------------|----------------|---------------------------|
| cubic feet                   | 0.02831685     | cubic meters              |
| cubic inches                 | 1.6387064 E-05 | cubic meters              |
| cubic yards                  | 0.7645549      | cubic meters              |
| feet                         | 0.3048         | meters                    |
| pounds (force) per foot      | 14.59390       | newtons per meter         |
| pounds (force) per inch      | 175.1268       | newtons per meter         |
| pounds (mass)                | 0.45359237     | kilograms                 |
| pounds (mass) per cubic foot | 16.01846       | kilograms per cubic meter |
| pounds (mass) per cubic inch | 2.757990 E+04  | kilograms per cubic meter |
| yards                        | 0.9144         | meters                    |

# 1 Introduction

This technical report is a follow-on to the Taylor et al. (2016) technical report entitled “Protocol for Cohesionless Sample Preparation for Physical Experimentation.” The focus of the Taylor et al. (2016) report was to develop a standardized protocol for specimen preparation for cohesionless materials that produces consistent, highly repeatable test samples. Centered around this precise sample preparation method, the research was presented to show two similar materials can obtain comparable continuum behavior in laboratory settings using a normalization approach to sample preparation, thereby reducing the reliance on soil specific sampling and testing. Laboratory testing results were presented and used to compare the strength of cohesionless sands utilizing this normalization approach.

The focus of this technical report is neither the sample preparation, nor the results from laboratory testing, but rather a detailed outline of the test procedures and equipment/software settings for each laboratory testing equipment for which results have already been presented.

This technical report is intended to be a checklist to detail for the user how to create and execute low confinement laboratory tests using Geotechnical Consulting and Testing Systems (GCTS) software: Monotonic Triaxial (axial loading), Monotonic Simple Shear (shear strength), Ring Shear (anisotropic strength), and Hollow Core (isotropic strength). Software screen captures are generic examples of the display at any given step and are intended to clarify the location of buttons and windows inside the software; they are not intended to show specific values. The specific guidance and procedural steps outlined herein are altered from the manufacturer’s manuals and protocols (GCTS 2011, GCTS 2014a, b, c). Greater care in testing sensitivity was employed to test in this sensitive regime, thereby necessitating this report so that future efforts can reproduce past and current data.

The setup procedures provided in the sections titled, *Initializing System for Test*, are color-coded for clarity. When initializing the system, the user will need to make adjustments to the software, the cell, and the cabinet. When a step is directing the user to the software, it will be denoted in blue. Green symbolizes a step focused on adjustments to the cabinet, and red signifies changes made to the cell.

## 1.1 Overview

Understanding the true behavior of cohesionless soils immediately impacts the fields of internal erosion prediction, surficial sloughing of dams and levees, wave propagation, geo-sensor coupling, and geo-environmental contamination and remediation designs. Extensive testing has concluded that specimen preparation and loading rates have a significant impact on soil specimen test results for a variety of test conditions. Research over the past four decades has illustrated that the manner in which a laboratory test specimen is reconstituted can greatly influence the behavior of the material (Cho et al. 2006, Ladd 1974, Ladd 1977, Mulilis et al. 1977). The impacts of the combination of preparation and loading rates form the basis of typical laboratory testing protocols. Taylor et al. (2016) addresses the sample preparation issue and presents a standardized means for preparing cohesionless samples irrespective of loading manner. The purpose of this technical report is to provide laboratory testing protocols, i.e., test conditions post-sample preparation, for physical experimentation within the near-surface environment.

Geotechnical laboratory testing focuses on the behavior of soils subjected to confining pressures in excess of those experienced within the near-surface environment (the upper 1 m of the soil profile). Such standardized protocols have set-up stresses, e.g., seating loads and stabilization vacuum pressures, in excess of the failure strength observed at low confinement. Therefore, effective stress principles are often used to infer low confinement behavior within a laboratory setting (Fannin et al. 2005, Huang et al. 2015, Lancelot et al. 2006). Neither the standardized protocols nor the use of effective stress principles encapsulate the near-surface environment or the true behavior. For standardized testing equipment, e.g., triaxial and simple shear devices, existing protocols have been modified. New testing protocols have been designed for experimental equipment, e.g., the Ultrasonic Near-Surface Inundation Testing device (UNIT) or for unconfined drained self-supporting testing (UD). The protocols presented herein are for commercial and prototype equipment used in the ERDC Geotechnical and Structures Laboratory (GSL) and are readily adaptable to other equipment manufacturers' devices.

## 1.2 Triaxial compression test

Chapter 2 describes the protocols for conducting consolidated drained triaxial compression ( $CD_{TX}$ ) tests for evaluating behavior of near-surface

materials. The procedures outlined were developed using Geotechnical Consulting & Testing System's (GCTS) USTX-2000 Unsaturated Soil Triaxial Testing System. The protocols for this test follow closely the ASTM Standard Test Method for Consolidated Drained Triaxial Compression Test for Soils (D7181-11 2011). The procedures that differ from D7181-11 are detailed in Chapter 2.

### **1.3 Torsional ring shear test**

Chapter 3 describes the protocols for conducting monotonic, cyclic, unsaturated, and saturated torsional ring shear ( $RS_{MU}$ ,  $RS_{MS}$ ,  $RS_{CYU}$ , and  $RS_{CYS}$ ) tests for evaluating critical state behavior of near-surface materials. The procedures outlined were developed using GCTS SRS-150 Residual Ring Shear Testing System. The basic protocols for this test follow the ASTM Standard Test Method for Torsional Ring Shear Test to Determine Drained Residual Shear Strength of Cohesive Soils (D6467-13 2013) with some additional requirement as detailed in Chapter 3.

### **1.4 Hollow cylinder test**

Chapter 4 describes the protocols for conducting isotropic monotonic torsional shear hollow cylinder ( $HC_{MTS}$ ) testing for near-surface material. Applications were developed based on research conducted at the Engineering Research and Development Center, Geotechnical and Structures Laboratory. The ASTM International Standards does not provide a standard testing protocol for  $HC_{MTS}$  testing. The procedures outlined were developed using GCTS' HCA-150 Dynamic Hollow Cylinder Testing System.

### **1.5 Simple shear test**

Chapter 5 describes the protocols for conducting isotropic consolidated drained simple shear ( $CD_{SS}$ ) tests for evaluating behavior of near-surface materials. This methodology for simple shear testing was developed specifically for near-surface material applications, but could be applied for any cohesionless material. There is no ASTM standard for simple shear testing. The procedures outlined were developed using GCTS SSH-100 Simple Shear Testing System.

### **1.6 Unconfined self-supporting test**

Chapter 6 describes the protocols for conducting unconfined drained (UD) self-supporting tests for evaluating behavior of near-surface materials. The

procedures for preparing the “free standing” specimen follow the steps outlined in the August 2015 technical report entitled, “Protocol for Cohesionless Sample Preparation for Physical Experimentation.” The methodology used for loading these specimen are detailed in Chapter 6.

## **1.7 Ultrasonic Near-surface Inundation Test (UNIT)**

The UNIT is an ERDC-designed testing apparatus to look at the effect of water on the top meter of the near-surface soil. The understanding that signal propagation and attenuation of sensors placed in the top meter of the subsurface in-situ can be affected by meteorological variability and that there are no known laboratory or in-situ experiments that explore the effects of active inundation on seismic wave properties in the near surface, lead to the development of the UNIT (Martin et al 2014).

## 2 Triaxial Compression Test

### 2.1 Apparatus

GCTS' USTX-2000 Unsaturated Soil Triaxial Testing System, Figure 2.1, was used to develop the procedures outlined herein for studying near-surface soil behavior through isotropic consolidated drained triaxial compression (ICD<sub>TX</sub>) testing. The order of operations may be slightly different when using other manufacturers' equipment.

Figure 2.1. GCTS USTX-2000 unsaturated soil triaxial testing system.



The USTX-2000 is an electro-pneumatic system with closed-loop digital servo control. This system is developed for performing fully automated static and dynamic triaxial tests on saturated or unsaturated soil specimens. The system's Windows-based software provides over 20 parameters, such as stresses, strains, suction, etc., for real time display and/or control and also enables fully automated testing and direct measurement of volume and pressure change. Pore water pressures from -100 kPa to 2,000 kPa and lateral confining pressures up to 2,000 kPa can be applied with the pressure/volume controller. Pore air pressure can be computer controlled up to 2,000 kPa.

This system has a stainless steel loading piston that applies the load axially to the specimen, and its rigid loading connection enables stress reversal with a low-friction (under 10 N) graphite seal. It can accommodate samples with a diameter up to 75 mm and a length of 2.0 to 2.5 times the diameter.

Also available with the USTX-2000 are combination platens for unsaturated soil testing with embedded ultrasonic sensors, bender elements, to measure P and S wave velocities. The system is capable of applying cyclic wave forms at up to 5 Hertz.

## **2.2 Specimen and equipment setup**

The protocols outlined herein for isotropic consolidated drained triaxial compression testing (ICD<sub>TX</sub>) for near-surface material applications follow closely the ASTM Standard Test Method for Consolidated Drained Triaxial Compression Test for Soils (D7181-11 2011). The procedures that differ from D7181-11 (2011) are detailed in the following sections.

### **2.2.1 Test specimen preparation**

#### *2.2.1.1 Specimen size*

The specimen shape and size should meet all the requirements detailed in section 6.1 of D7181-11 (2011); specifically, a minimum diameter of 33 mm and a height-to-diameter ratio between 2 and 2.5. Cylindrical specimens with a height and diameter of 145 and 72 mm, respectively, were used for developing the procedures outlined herein.

#### *2.2.1.2 Tamping method*

All specimens for this study were reconstituted using a modified moist tamping method similar to Bradshaw and Baxter (2007). The focus of this approach for sample reconstitution is maintaining a uniform compactive effort throughout the sample. The procedures outlined herein for near-surface lab testing were developed using cohesionless materials, and the reconstitution method used is detailed in ERDC/GSL TR-16-11 *Protocol for Cohesionless Sample Preparation for Physical Experimentation* (2016). This report describes, in part, the method for determining an appropriate reconstituted saturation and the specifics of how to create a reconstituted soil fabric that is consistent throughout, and that results in a specimen that meets a specific density requirement by carefully controlling the water content and applied energy.

Based on the specific requirements outlined in ERDC/GSL TR-16-11 (2016), a pre-determined amount of oven-dried material and water is thoroughly mixed to produce a target water content. The material is stored in a covered container for 10 to 15 minutes prior to compaction. This wait time is substantially shorter than the 16-hour waiting period required by the ASTM Standard D7181-11 (2011), since the exact water content is such a critical component in the methodology followed herein in ERDC/GSL TR-16-11 (2016). The whole premise of preparing repeatable cohesionless specimen outlined in ERDC/GSL TR-16-11 (2016) is based around controlling the water-to-material ratio and the applied energy. For that reason, the material mixed with water cannot sit a long period of time and still meet the tight tolerances for water content.

When mixing the material, ensure additional material is accounted for in excess of what is required for the specimen. After the material is mixed and has been covered for the appropriate time, three samples from the mixture should be removed for determining the water content in accordance with ASTM Test Method D2216 (2010). This moisture content is to verify the material is at the specified water content just prior to the specimen reconstitution. If the average moisture content error is greater than  $\pm 2\%$ , i.e., the water content is not between 5.292-5.508% for a target moisture content of 5.40%, the test specimen should be discarded.

The combination of number of layers, number of tamps per layer, force per tamp (rammer weight), rammer drop height, and diameter of the tamper base directly affect the energy being applied to the specimen. Each of these variables must be carefully considered to create the optimal combination of each that results in the desired energy. These are also detailed specifically in ERDC/GSL TR-16-11 (2016). The top of each compacted layer should be scarified before affixing each additional layer; the top of the specimen should not be scarified.

#### *2.2.1.3 Verifying specimen dimensions*

After the specimen has been formed, measurements from the top of the mold down to the top of the specimen should be taken from the center of the specimen and at least four other points over the top of the specimen. Based upon the average measured height of the specimen, if the volume is not within  $\pm 2\%$  of the target volume, i.e., for a 145 mm tall specimen no more than  $\pm 4.35$  mm in height differential, the specimen should be discarded.

### 2.2.2 Mounting specimen

With the mold still around the specimen, the top cap is placed carefully on top of the specimen, and the membrane is pulled up over the edges of the top cap. To seal the specimen, two rubber bands are placed snugly over the top cap, around the membrane. Rubber bands are preferred to O-rings due to tighter seal generation and decreased sample disturbance during apparatus assembly. Two additional rubber bands secure the membrane to the bottom cap and are attached before the specimen is built.

For ICD<sub>TX</sub> tests in excess of 20 kPa confining pressure, a vacuum is applied to the specimen through the top cap by placing an airline from the top cap valve to the connection on the top side of the base plate corresponding to Valve B in Figure 2.2. The vacuum line is connected to the sample through Valve B, Figure 2.2. A vacuum of approximately 5 in. Hg (17 kPa) (not to exceed the test confining pressure) is applied to the specimen. After giving the vacuum a couple of minutes to equilibrate throughout the specimen, the mold is then removed from the specimen. This step must be skipped for tests below 20 kPa testing confinement so not to over-stress the material in advance of load application.

The latex membrane should be carefully inspected for holes and/or leaks before proceeding. If tears are found in the membrane, the specimen should be discarded.

### 2.2.3 Preparing triaxial chamber

#### 2.2.3.1 Assemble triaxial chamber

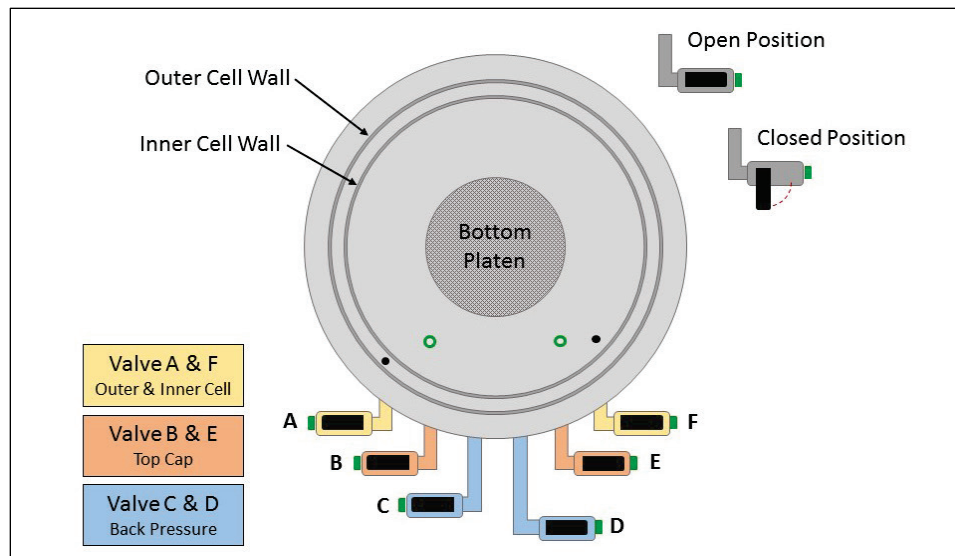
As the triaxial chamber is assembled, a thin coating of silicon grease is applied to each O-ring to aid in creating a tight seal inside the chamber in order to properly maintain testing pressures throughout testing. When the axial load piston is inserted into the chamber, the piston should be aligned with the specimen's top cap but not allowed to rest on top cap. To install the chamber's top plate, instead of moving in a clockwise or counterclockwise direction tightening adjacent screws, a move in a crisscross pattern will ensure a uniform seating of the plate with the O-ring. When the chamber is fully assembled, it should be carefully slid beneath the load cell until the top of the load cell arm is centered under the load cell connector. If necessary, the load cell can be moved up to allow the piston room to slide beneath the load cell. Tiny adjustments to the position of the chamber may be required

until the load cell and piston are vertically aligned. The piston should never be attached to the load cell when making adjustments to the position of the chamber. Once the piston is attached to the load cell, the clamps on the bottom plate should be tightened to secure the chamber to the platform.

#### 2.2.3.2 Fill chamber with distilled, de-aired water

The inner and outer cells of the triaxial chamber should be filled with distilled de-aired water using a gravity feed of minimal head to prevent over-stressing the sample prior to testing. To do this, a line should be connected to Valve A and F (Figure 2.2) to fill the outer and inner cells, respectively. As the cells fill, any excess air is bled out through the bleed holes on the top plate of the triaxial chamber. Once both cells are full, ensure Valves A and F are closed and remove the fill lines.

Figure 2.2. Triaxial cell chamber valve system.

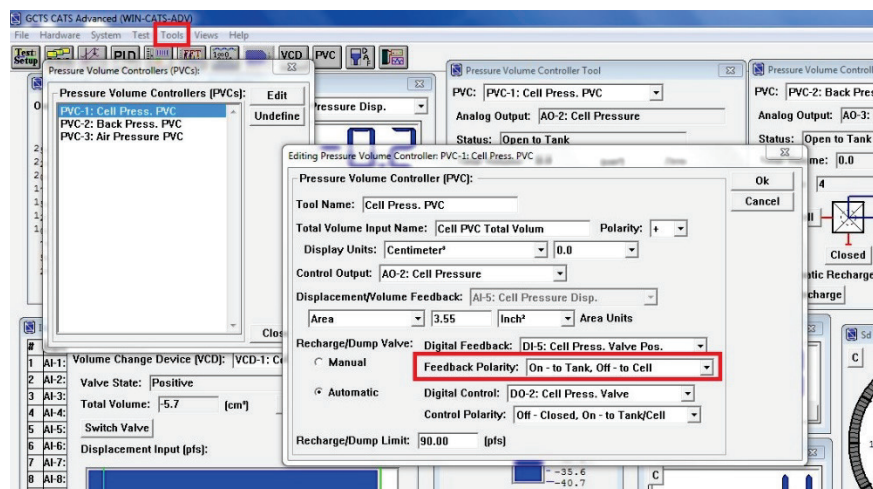


#### 2.2.4 Initializing system for test

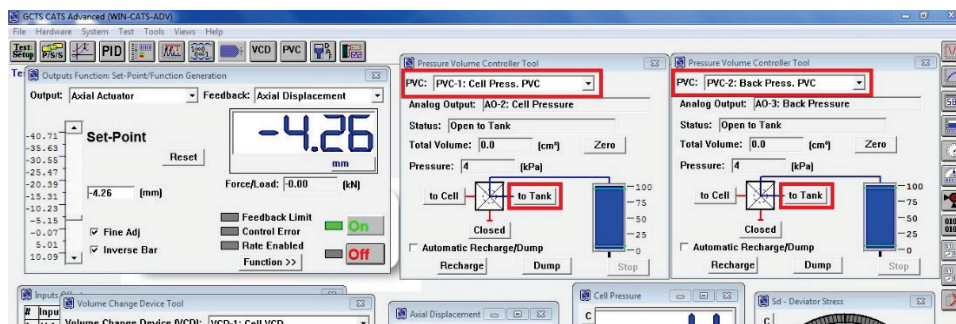
With the specimen under a 5 in. Hg (17 kPa) vacuum and the chamber filled with de-aired distilled water, performing the following operations will prepare the system for testing:

1. Ensure pressure in cabinet is set to 0 kPa.
2. Turn on SCON.
3. Boot up system computer.
4. Open *GCTS CATS Advanced* Software.

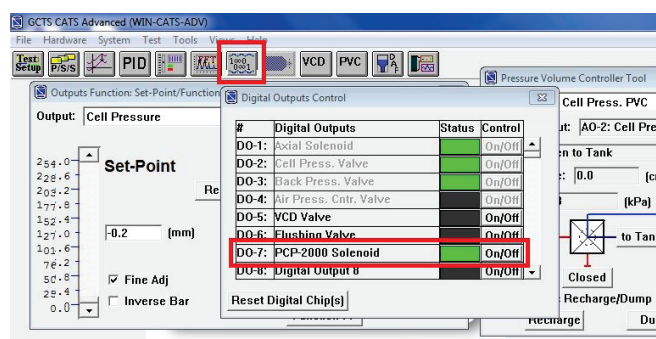
5. **Software:** Check polarity of PVCs by opening *Tools – PVC tools – Setup*, then double click a PVC name in the *Pressure Volume Controller* window to open the corresponding PVC settings window. Verify the selection next to *Feedback Polarity* is “On to tank – off to cell.”



6. **Software:** Using the toolbar at the top of the software window, open the *Outputs Function* window and two instances of the *Pressure Volume Controller Tool*. In one of the *Pressure Volume Controller Tool* windows select “Cell Pres, PVC” and in the other select “Back Press, PVC.”
7. **Software:** From the *Pressure Volume Controller Tool* windows point the back pressure and cell pressure PVCs “to Tank.”



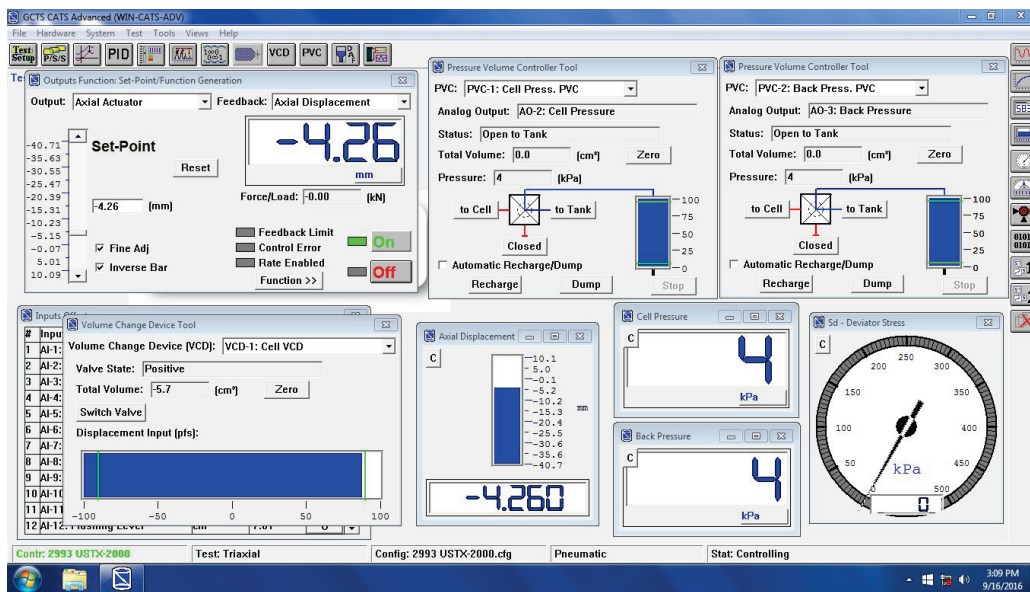
8. **Software:** Open the *Digital Outputs Control* window by clicking the Digital Outputs button on the toolbar at the top of the software window. From this window, turn on PCP-2000 Solenoid by clicking the On/Off button on the right side. The status block will be green when the PCP-2000 Solenoid is on.



9. *Software*: From the same *Digital Outputs Control* window, click the button at the bottom of the window to “Reset Digital Chips.” Now close the *Digital Outputs Control* window.
10. *Software*: Synchronize the system by selecting *System- Configuration- Synchronize* from the menu bar at the top of the software window.
11. *Software*: From the *Pressure Volume Controller* tool, verify the Cell Pressure PVC is pointed to the tank, then press the Dump button to empty the PVC into the tank. Once the dumping process is complete, dump the Back Pressure PVC into the tank. With both PVCs emptied, Press the Recharge button to re-fill the Cell Pressure PVC. Once complete, recharge the Back Pressure.
12. *Cabinet*: Increase the pressure in the cabinet to 700 kPa.
13. *Software*: Point the Cell Pressure PVC “to cell.”
14. *Software*: From the *Outputs Function: Set-Point/Function Generation* window, select **Cell Pressure** for the output mode, and select **Displacement** for the Feedback mode.
15. *Cabinet*: Insert a hose into the connector on the cabinet labeled “Cell”. This hose should have a T-connection on the opposite end of the line to connect to both the Cell and the Volume Control Device.
16. *Software*: Using the *Outputs Function* window, advance the Set-point (in Cell Pressure – displacement mode) to push water through the hose until all the air in the hose has been displaced.
17. *Cell*: Insert one side of the hose split by a T-connection into Valve F, Figure 2.2, on the cell chamber.
18. *Software*: Using the *Outputs Function* window, advance the Set-point (in Cell Pressure – displacement mode) to push water through the hose until water has filled the other side of the T-connection.
19. *Cell*: Insert the other side of the hose split by a T-connection into the Volume Control Device (VCD). Connect a second hose into the opposite side of the VCD.

20. *Software*: Using the *Outputs Function* window, continue to advance the Set-point slowly (in Cell Pressure – displacement mode) to push water through the VCD and fill the second hose with water. Once all the air in the line has been displaced, open the Inputs Offsets window. Holding the hose next to Valve A, Figure 2.2, (without inserting it yet) zero the Cell Pressure from the Inputs Offsets window.
21. *Cell*: Insert the hose into Valve A, Figure 2.2, on the cell chamber.
22. *Software*: From the *Outputs Function: Set-Point/Function Generation* window, with **Cell Pressure** still selected for the output mode, select **Cell Pressure** for the Feedback mode.
23. *Software*: Using the Set Point function in the *Outputs Function: Set-Point/Function Generation* window, set the **Cell Pressure** to 10-15 kPa.
24. *Software*: Point the Back Pressure PVC “to cell.”
25. *Software*: From the *Outputs Function: Set-Point/Function Generation* window, select **Back Pressure** for the output mode, and select **Displacement** for the Feedback mode.
26. *Cabinet*: Insert a hose into the cabinet’s connector labeled “Pore Water.”
27. *Software*: Using the *Outputs Function* window, advance the Set-point (in Back Pressure – displacement mode) to push water through the hose until all the air in the hose has been displaced. Once all the air in the line has been displaced, open the Inputs Offsets window. Holding the hose next to Valve C on the cell chamber (without inserting it yet) zero the back pressure from the Inputs Offsets window.
28. *Cell*: Insert the hose into Valve C, Figure 2.2, on the cell chamber.
29. *Software*: Leave the Back Pressure Feedback in **Displacement** mode in the *Outputs Function: Set-Point/Function Generation* window.
30. *Cell*: Shut off the vacuum line going to the sample by rotating Valve B, Figure 2.2, on the cell chamber to the closed position.
31. *Cabinet*: Close the vacuum lever on the cabinet and reduce the vacuum pressure to zero.
32. *Cell*: Rotate Valves A and F, Figure 2.2, to the open position. The Cell Pressure in the inner and outer cell chambers will equalize to the pressure set in the Outputs Function window.
33. *Cell*: Once the cell pressure has stabilized to the set point, release the vacuum from the sample by opening Valve D, Figure 2.2. This valve should remain open throughout the remainder of the test.
34. *Cell*: Open the back pressure valve to the cell, Valve C, Figure 2.2,
35. *Software*: Verify from the *Pressure Volume Controller Tool* window, that the back pressure reading went to zero once Valve C, Figure 2.2, was opened.

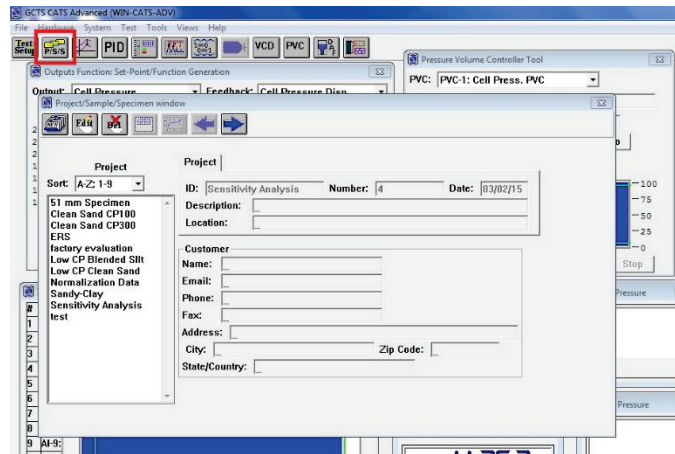
36. *Software*: From the *Outputs Function: Set-Point/Function Generation* window, select **Axial Actuator** for the output mode, and select **Sa – Deviator Stress** for the Feedback mode. Using the Set Point function, apply a 5 kPa seating load. The piston should lower until in contact with the specimen.
37. *Software*: The following window setup is suggested for verifying and monitoring the system during setup and testing:



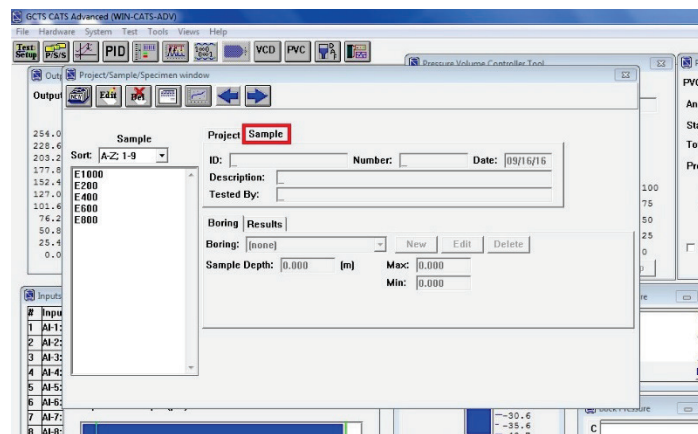
### 2.2.5 Executing test (software)

With the specimen under a 10-15 kPa confining pressure, a 5 kPa seating load, and the back pressure open to atmosphere, perform the following operations to begin the isotropic consolidated drained triaxial compression test, (ICD<sub>TX</sub>):

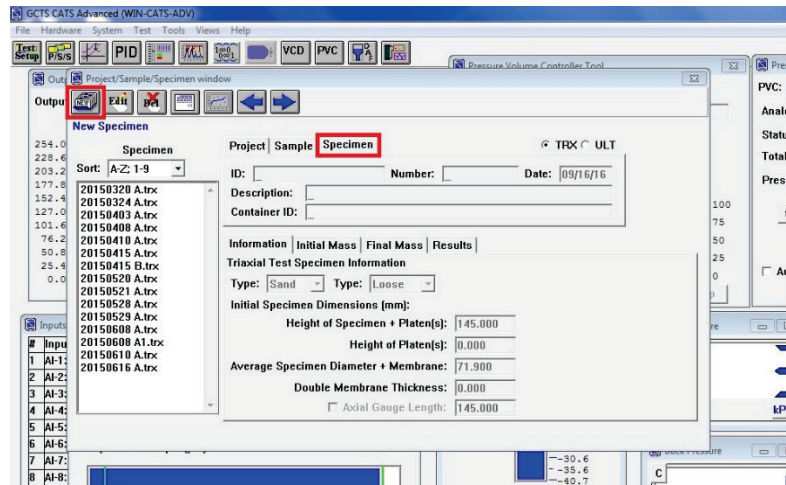
1. Click on the **PSS** button from the toolbar at the top of the software window to open the *Project/Sample/Specimen* window.



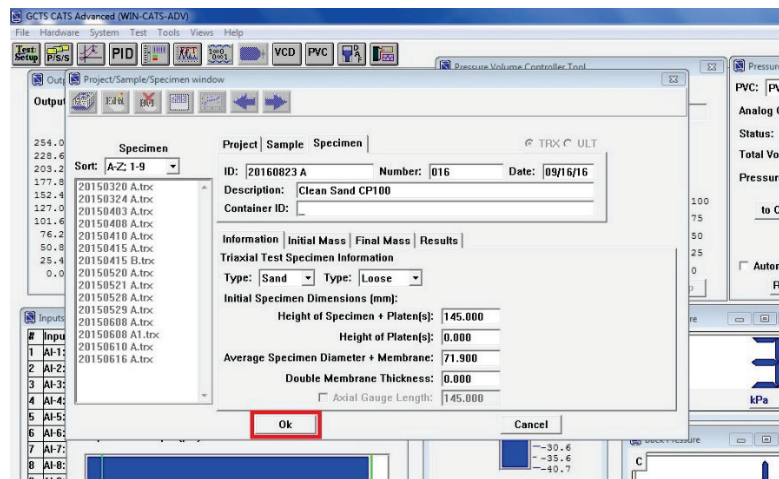
2. From the PSS window, a Project is selected by one of two ways:
  - a. Create a new project by clicking the **New** button from the toolbar, or
  - b. An existing project can be selected by double-clicking a title from the project list on the left side of the window.
3. Once a project is selected, a second tab, *Sample*, appears in the PSS window. Tests (or Specimen) are organized into “Sample” groups. Inside each “Sample,” numerous tests can be stored. A single project can have one or several “Samples.” Similar to the previous step, a Sample must either be created or an existing one selected.



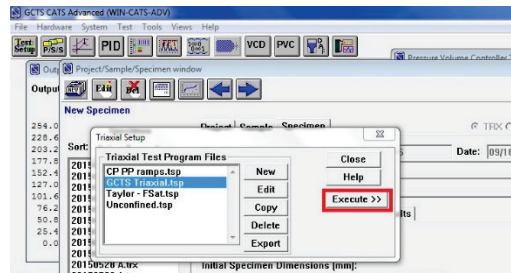
4. Once a sample is selected, a third tab, *Specimen*, appears in the PSS window. Each “specimen” is a single test file for each individual test run on the system. To run a new test, a new specimen must be created by clicking the **New** button from the toolbar.



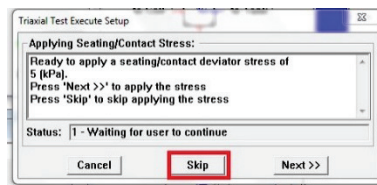
- After pressing the **New** button from the toolbar, the fields in the form will become active. A unique test name must be entered into the “ID” field. The height of the specimen must also be entered in the appropriate space near the center of the window. After the specimen data has been entered, press **OK** to continue.



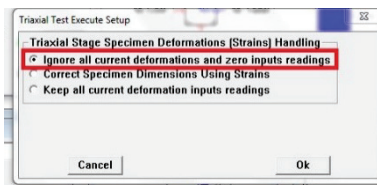
- The next window that appears is the Triaxial Setup window. From this window, the Triaxial Test program is selected. Ensure the desired test is highlighted by clicking the title of the test program, and then click the **Execute** button.



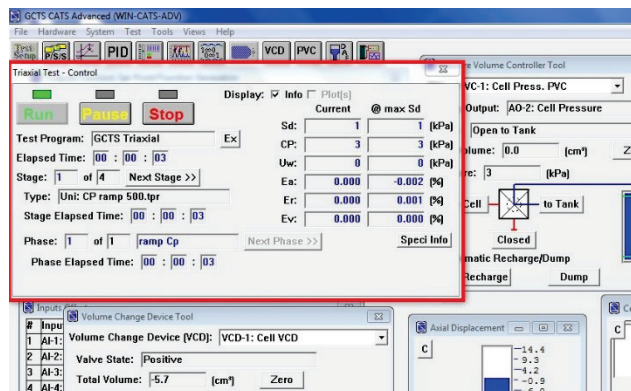
7. From the next window that appears, select the **Skip** option because the seating load has already been applied.



8. Next, select the option to “Ignore all current deformations and zero inputs readings.”



9. The Test Control window will appear when the test begins.



## 2.3 Triaxial Compression Test, Isotropic Consolidated Drained (ICD<sub>TX</sub>)

The ICD<sub>TX</sub> test is designed to ramp up the cell pressure to a desired confining pressure and hold that confining pressure throughout the duration of the test, while the Axial Strain is continually increased at a rate of 0.25% per minute.

### 2.3.1 ICD<sub>TX</sub> Stage 1: Ramp up

During the first stage of the test, the cell pressures are increased at a slow and constant rate until the cell pressure reaches the test confining pressure. The duration allowed for this stage depends on the test confining pressure. The cell pressure should increase at a steady rate between 30-40 kPa per minute. For example, for a test confining pressure of 100 kPa, this stage would be set to last three minutes. The deviator stress remains constant at 5 kPa throughout Stage 1. The example test program below shows Stage 1 for a test set to ramp to a confining pressure of 100 kPa:

```

===== STAGE 1: Uni: CP ramp 100.tpr =====
*****
~~~~~ Universal Program ~~~~~
ID: CP ramp 100
Description: ramp up Cp
Stages: 1
*****
~~~~~ Stage: 1 - ramp Cp ~~~~~
Duration:
    Timed: 3 (Minute(s))
    Input Limit: NS
    Until Output Completes: NS
Data Acquisition
    Timed Increments: 5 (Seconds)
    Level Crossing: NS
    Peak/Valley: NS
Cycle Recording
    Every Cycle
Data Saving
Data Buffer: Continuous
Defined Analog & Temperature Outputs:
===== AO-1: Axial Actuator =====
FeedbackTI-7: Sd - Deviator Stress
Waveform: Constant
    Constant Control Value Type: Relative/Current
===== AO-2: Cell Pressure =====
FeedbackAI-4: Cell Pressure
Waveform: Ramp
    Initial Control Value Type: Relative/Current
    Target End Value: 100 (kPa)
    Rate: 33 (kPa)/(Minute(s))
    Duration: 3 (Minute(s))
===== AO-3: Back Pressure =====

```

```

FeedbackAI-7: Back Pressure Disp.
Waveform: Constant
      Constant Control Value Type: Relative/Current
=====
=====
Master Output: AO-1: Axial Actuator

Digital Outputs Control: (none)
*****

Times to Repeat Stage(s) above: 0
*****

Beginning of Stage - Handling Strains:
      Zero Deformations

```

### 2.3.2 ICD<sub>TX</sub> Stage 2: Hold

Stage 2 of the ICD<sub>TX</sub> test is the “hold” stage. At this stage, the cell pressure has reached the test confining pressure and remains constant for the duration of the stage. The deviator stress also remains constant at 5 kPa throughout Stage 2. For cohesionless material, Stage 2 is set to hold for three minutes. Below is Stage 2 of the example test program:

```

===== STAGE 2: Uni: hold pressures.tpr =====
*****

~~~~~ Universal Program ~~~~~

ID: hold pressures
Description: _
Stages: 1
*****

~~~~~ Stage: 1 - hold pressures ~~~~~

Duration:
      Timed: 3 (Minute(s))
      Input Limit: NS
      Until Output Completes: NS

Data Acquisition
      Timed Increments: 5 (Seconds)
      Level Crossing: NS
      Peak/Valley: NS

Cycle Recording
      Every Cycle

Data Saving
Data Buffer: Continuous
Defined Analog & Temperature Outputs:
===== AO-1: Axial Actuator =====

```

```

FeedbackTI-7: Sd - Deviator Stress
Waveform: Constant
    Constant Control Value Type: Relative/Current
===== AO-2: Cell Pressure =====
FeedbackAI-4: Cell Pressure
Waveform: Constant
    Constant Control Value Type: Relative/Current
===== AO-3: Back Pressure =====
FeedbackAI-7: Back Pressure Disp.
Waveform: Constant
    Constant Control Value Type: Relative/Current
=====
=====
Master Output: AO-1: Axial Actuator
Digital Outputs Control: (none)
*****

Times to Repeat Stage(s) above: 0
*****

Beginning of Stage - Handling Strains:
    Update Specimen Dimensions
    Zero Deformations

```

### 2.3.3 ICD<sub>TX</sub> Stage 3: Triaxial test

The triaxial test begins at Stage 3. During Stage 3, both the cell pressure and back pressure remain constant, while the Axial Strain ramps at a constant rate of 0.25% per minute, the recommended strain rate as per ASTM D7181-11 (2011). The Axial Strain will continue to ramp until the value set in the test program is reached. For the example shown here, the axial strain is set to increase until it reaches 16% strain. When setting this value in the test program, it is important to consider the material and the peak strain it is expected to reach. Failure is often taken to correspond to either the maximum deviator stress attained or the deviator stress at 15% axial strain (D7181-11 2011). If a final axial strain value is set too low, and the specimen's deviator stress does not peak within the axial strain limits set for the test, the testing time cannot be extended during the test to capture additional data. It may be necessary to set the final strain value for this stage to a higher value than expected to ensure the peak is captured in the dataset. The user has the option to continue to the next stage of the test if a sufficient dataset for the specimen has been captured prior to the set end value. Below is Stage 3 of the example test program:

```

===== STAGE 3: SL: Triaxial test =====
===== AO-1: Axial Actuator =====
Control Feedback: TI-1: Ea - Axial Strain
Mode: Ramp
      Initial Value: Relative/Current
      Ramp Rate: 0.25 (%) / (Minute(s))
      Final Value: 16 (%)
===== AO-2: Cell Pressure =====
Control Feedback: AI-4: Cell Pressure
Mode: Constant
      Constant Value: Relative/Current
===== AO-3: Back Pressure =====
Control Feedback: AI-7: Back Pressure Disp.
Mode: Constant
      Constant Value: Relative/Current
===== Air Pore Pressure =====
Control Feedback: None - Control Undefined
*****
Stage End
      Maximum Axial Strain: 16.000 (%)
      Maximum Time for Static Loading Stage: NS
      Input Limit: NS
      Peak Reversal: NS
Data Acquisition
      Timed Increments: 0.5 (Seconds)
      Level Crossing: NS
Type: Undrained:  $E_v = 0$ 
Beginning of Stage - Handling Strains:
      Update Specimen Dimensions
      Zero Deformations

```

#### 2.3.4 ICD<sub>TX</sub> stage 4: Ramp down

The final stage of the triaxial test decreases the cell pressure until it reaches a target end value of 15 kPa. Once this stage is complete, the system can be safely disassembled. The test data are automatically saved to the system once this stage is complete. A window will appear on the screen when the data has been saved successfully. Below is stage 4 of the example test program:

===== STAGE 4: Uni: ramp down Pressures.tpr =====

\*\*\*\*\*

~~~~~ Universal Program ~~~~~

ID: ramp down Pressures

Description: \_

Stages: 1

\*\*\*\*\*

~~~~~ Stage: 1 - ramp down pressures ~~~~~

Duration:

Timed: 3 (Minute(s))

Input Limit: NS

Until Output Completes: NS

Data Acquisition

Timed Increments: 5 (Seconds)

Level Crossing: NS

Peak/Valley: NS

Cycle Recording

Every Cycle

Data Saving

Data Buffer: Continuous

Defined Analog & Temperature Outputs:

===== AO-1: Axial Actuator =====

FeedbackAI-2: Axial Displacement

Waveform: Constant

Constant Control Value Type: Relative/Current

===== AO-2: Cell Pressure =====

FeedbackAI-4: Cell Pressure

Waveform: Ramp

Initial Control Value Type: Relative/Current

Target End Value: 15 (kPa)

Rate: ?? (kPa)/(Minute(s))

Duration: 3 (Minute(s))

===== AO-3: Back Pressure =====

FeedbackAI-7: Back Pressure Disp.

Waveform: Constant

Constant Control Value Type: Relative/Current

=====

=

Master Output: AO-1: Axial Actuator

Digital Outputs Control: (none)

```

*****

Times to Repeat Stage(s) above: 0
*****

Beginning of Stage - Handling Strains:
    Update Specimen Dimensions
    Zero Deformations
*****

~~~~~ Save Objects ~~~~~

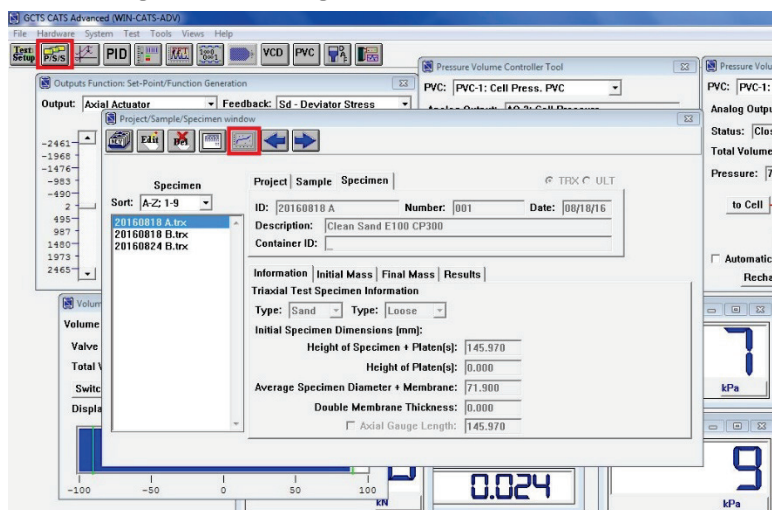
Save @ each Recording:
    Time
    Cycles
    Inputs: 14
        AI-1: External Axial Load
        AI-2: Axial Displacement
        AI-4: Cell Pressure
        AI-5: Cell Pressure Disp.
        AI-6: Back Pressure
        AI-8: Pore Pressure
        AI-9: Air Pressure
        AI-11: VCD Displacement
        VCD-1: Cell VCD Total Volum
        PVC-2: Back PVC Total Volum
        TI-1: Ea - Axial Strain
        TI-2: Er - Radial Strain
        TI-3: Ev - Volumetric Strain
        TI-7: Sd - Deviator Stress
    Analog Outputs: 0
    Ultrasonics
        P wave: NS
        S wave: NS
*****

```

## 2.4 ICD<sub>TX</sub> test output

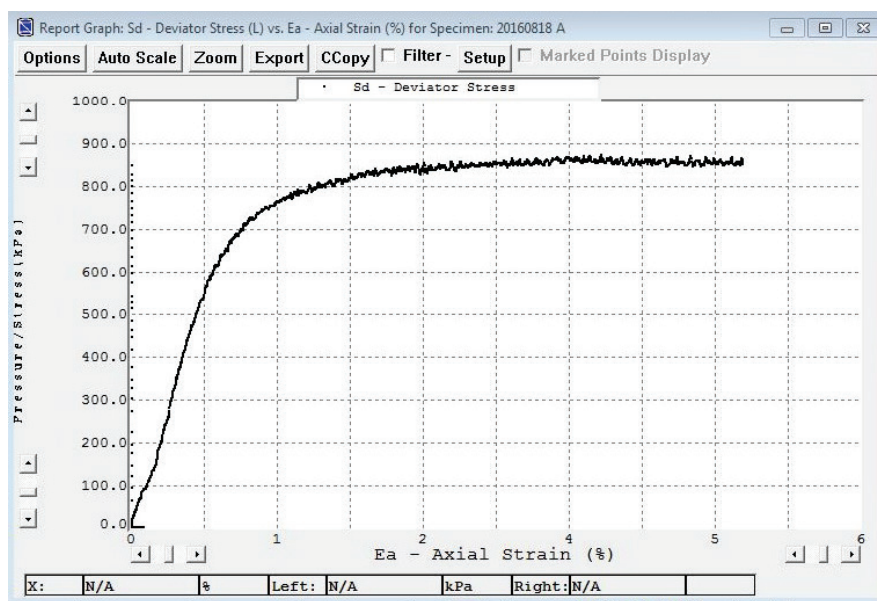
A plot of the test output can easily be generated within the *GCTS CATS Advanced* software by first clicking the PSS button from the toolbar at the top of the software window. On the left side of the *Project/Sample/Specimen* window that opens, the filename of the completed test should be highlighted, then the *Report Graph* button from the toolbar at the top of the PSS window is clicked to generate the graph for the for the selected test, Figure 2.3.

Figure 2.3. Plotting test data from GCTS software.



An example of a typical ICD<sub>TX</sub> test plot, Axial Strain ( $E_a$ ) versus Deviator Stress ( $S_d$ ), is shown in Figure 2.4.

Figure 2.4. Typical data output from triaxial test, axial strain versus deviator stress.

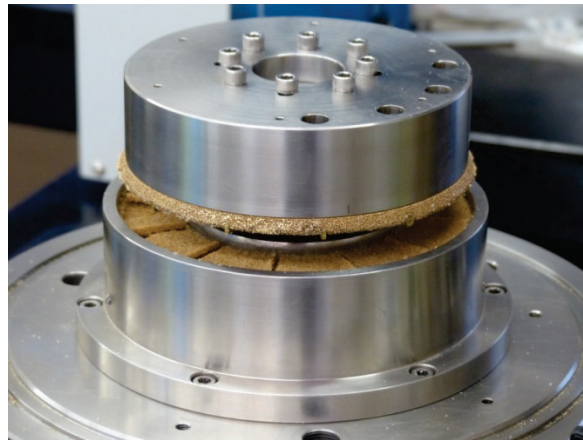


### 3 Torsional Ring Shear Test

#### 3.1 Apparatus

GCTS' SRS-150 Residual Ring Shear Testing System, Figure 3.1, was used to develop the procedures outlined herein for studying near-surface soil behavior through monotonic unsaturated ring shear testing (RSMU), cyclic unsaturated ring shear testing (RSCYU), monotonic saturated ring shear testing (RSMs), and cyclic saturated ring shear testing (RSCYS). The order of operations may be slightly different when using other manufacturers' equipment.

Figure 3.1. GCTS SRS-150 residual ring shear system.



The SRS-150 is a fully automatic electro-pneumatic and servo-controlled testing system used for determining the drained residual strength of continuously sheared soils. Its shearing actuator allows for a large range of shearing rates, from 0.001 to 360 degrees per minute continuously without backlash for replication of true in situ strain rates during failure. Its axial load capacity and torque capacity is 10 kN and 300 N-m, respectively. Normal stress loads can reach up to 1,000 kPa while the shear stress load can reach up to 1,300 kPa. This system also has the capability to collect ultrasonic data during testing; however, a test setup with this function is not described here.

#### 3.2 Specimen setup

The protocols outlined herein for monotonic saturated ring shear testing (RSMs) for near-surface material applications follow closely the ASTM Standard Test Method for Torsional Ring Shear Test to Determine Drained

Residual Shear Strength of Cohesive Soils (D7181-11 2011). However, the application in our study was for cohesionless soils. The other ring shear test protocols outlined herein for the cyclic and unsaturated ring shear testing (RS<sub>MU</sub>, RS<sub>CYS</sub>, and RS<sub>CYU</sub>) have identical specimen preparation procedures, differing only in the apparatus setup and actual test procedures. Each of the four ring shear tests are described in detail in the following sections.

Although ASTM D6467-13 (2013) was written for cohesive material, cohesionless material was used to develop the protocols outlined herein. All material tested with these protocol passed the No. 4 sieve, with no material having a diameter greater than 0.85 mm.

### **3.2.1 Test specimen preparation**

#### **3.2.1.1 Specimen size**

The SRS-150 device accepts 150 mm (6 in.) outside diameter and 100 mm (4 in.) inside diameter annular specimens for testing granular materials. These dimensions are within the guidelines outlined in Section 6.2 of ASTM Standard D6467-13 (2013) that state the inside diameter of the specimen container be no less than 50 mm (2 in.) and the inside-to-outside diameter ratio not be less than 0.6. According to D6467-13 (2013), the only height requirement for the specimen is that the initial specimen depth before consolidation and pre-shearing is not less than 5 mm (0.2 in.). All ring shear specimen for the testing protocols described herein are reconstituted with a target height of 25 mm.

#### **3.2.1.2 Specimen reconstitution**

Each ring shear specimen is reconstituted in an identical manner regardless of the type of ring shear test to be conducted, i.e., RS<sub>MS</sub>, RS<sub>MU</sub>, RS<sub>CYS</sub>, or RS<sub>CYU</sub>. All specimens should be reconstituted using a modified moist tamping method detailed in ERDC/GSL TR-16-11 *Protocol for Cohesionless Sample Preparation for Physical Experimentation* (2016). The focus of this approach for sample reconstitution is maintaining a uniform compactive effort throughout the sample. TR-16-11 (2016) describes, in part, the details of the rammer that should be used and the method for determining an appropriate reconstituted saturation. Carefully controlling the water content and applied energy to the specimen are critical to the methodology for creating a reconstituted soil fabric that is consistent throughout and results in a specimen that meets a specific density requirement.

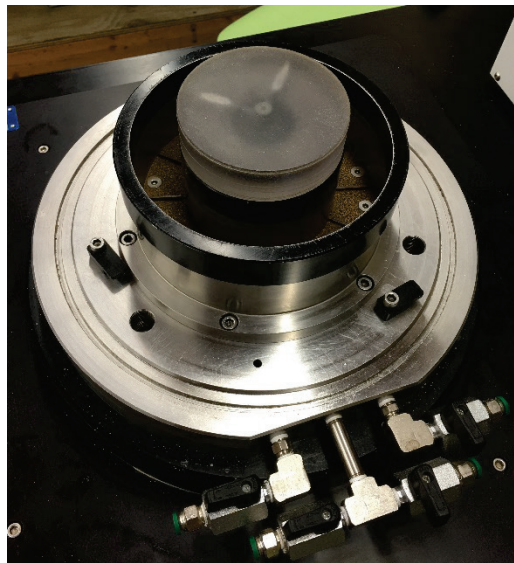
Following the requirements outlined in TR-16-11 (2016), a specific amount of oven-dried material and water is thoroughly mixed to produce a target water content. The material is stored in a covered container for 10 to 15 minutes prior to compaction. This wait time is substantially shorter than was detailed in D6467-13 (2013), since the exact water content is such a critical component in the methodology followed herein in ERDC/GSL TR-16-11 (2016). The whole premise of preparing repeatable cohesionless specimen outlined in ERDC/GSL TR-16-11 (2016) is based around controlling the water-to-material ratio and the applied energy. For that reason, the material mixed with water cannot sit a long period of time and still meet the tight tolerances for water content.

When mixing the material, ensure additional material is accounted for in excess of what is required for the specimen. After the material is mixed and has been covered for no longer than 15 minutes, three samples from the mixture should be removed for determining the water content in accordance with Test Method D2216 (2010). This moisture content is to verify the material is at the specified water content just prior to the specimen reconstitution. If the average moisture content error is greater than  $\pm 2\%$ , i.e., the water content is not between 5.292-5.508% for a target moisture content of 5.40%, the test specimen should be discarded.

The specimen container should be assembled and attached to the ring shear base plate before sample reconstitution. A bronze porous disc is placed in the bottom of the specimen container to allow drainage from the soil specimen along the bottom boundary. The porous disc is secured with 12 screws. Two O-rings are placed on the underside of the specimen container with a thin coating of silicon grease to each O-ring to aid in creating a tight seal between the bottom platen and the base plate. The bottom platen is secured to the base plate with 6 screws.

Before the prepared material is placed into the specimen container, rings are placed on the top edges of the container, one on the outer wall and one on the inner wall, to prevent the specimen material from over-spilling the edges before the material is tamped (Figure 3.2.) As the loose material is placed inside the container, it is important to distribute the material evenly around the ring. Uneven distribution of the material will create an uneven top surface of the final reconstituted specimen. It is critical for the specimen to have a level top surface, so that during testing the shear load is applied to the entire surface and not just to the tallest sections of the specimen.

Figure 3.2. Ring shear specimen container assembled.



The combination of number of tamps, force per tamp (rammer weight), and rammer drop height directly affect the energy being applied to the ring shear specimen. Each of these variables must be carefully considered to create the optimal combination of each that results in the desired energy. The process for determining the proper combination of these variables are detailed specifically in ERDC/GSL TR-16-11 (2016). Figure 3.3 shows the material in the specimen container before being tamped, after being tamped, and once the top rings are removed.

Figure 3.3. Ring shear specimen.



### 3.2.1.3 Verifying specimen dimensions

After the reconstituted specimen has been formed, measurements from the top of the specimen container to the top of the specimen should be taken at eight points around the specimen, choosing four from the outside edge and

four from the inside edge, spacing the locations out evenly across the sample in order to obtain a representative average height of the specimen. Based on the average measured height of the specimen, if the volume is not within  $\pm 2\%$  of the target volume, i.e., for a 145 mm tall specimen no more than  $\pm 4.35$  mm in height differential, the specimen should be discarded.

### 3.2.2 Seating the specimen

#### 3.2.2.1 Calibrating axial displacement

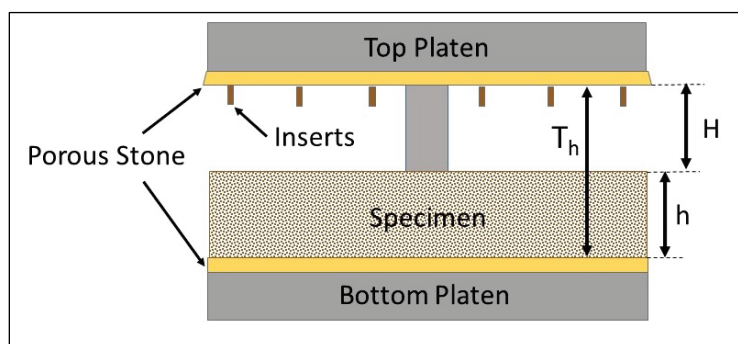
When applying the seating load to the specimen, great care should be taken to ensure the load being registered by the system is not just from the contact of the inserts with the specimen, but is instead the load applied by the entire top porous stone being in full contact with the top of the specimen. As the top platen is lowered and the inserts rest on the top surface of the specimen, a small load will be registered by the system. The calibration process described here provides a method to determine the proper distance to drop the top platen to ensure the inserts are sufficiently embedded into the specimen and an accurate seating load is established.

Before the specimen is placed into the ring shear container, the total height from the bottom porous disc to the top porous disk, with the top platen raised to its highest point,  $T_h$ , must be determined. Note, this is not a measurement to the bottom of the inserts, but from porous disk to porous disk, Figure 3.4. The height of the specimen,  $h$ , used for this calculation should be the tallest of the eight height measurements described in section 3.2.1.3, not the average. The height the top platen should be lowered, starting from its highest position is then calculated by:

$$H = T_h - h \quad (1)$$

where,  $H$  is the calibrated axial displacement drop height.

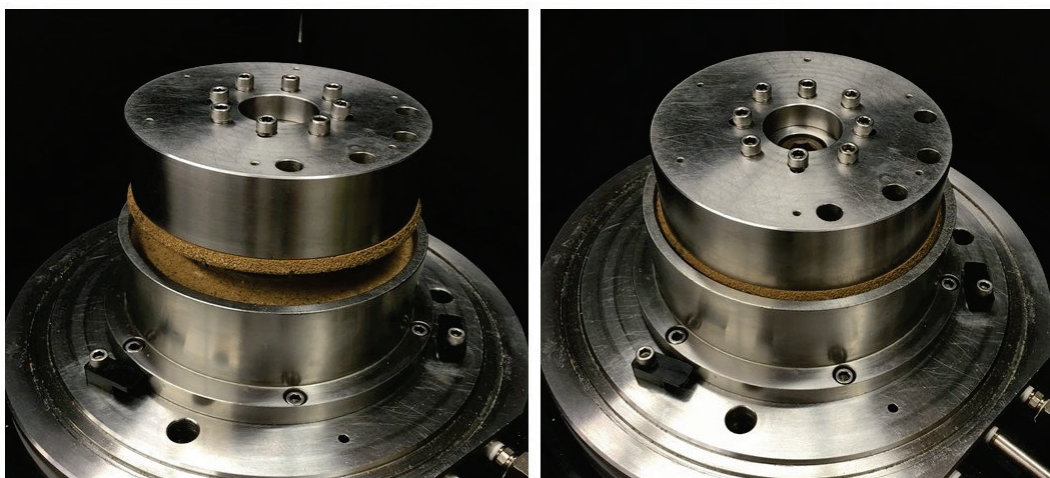
Figure 3.4. Axial displacement calibration measurements.



### 3.2.2.2 Applying the seating load

Once the specimen container has been securely attached to the ring shear base plate, the loading arm should be raised to its highest point and the top platen attached with the porous disc, Figure 3.4. With the top platen secure, zero the axial load, axial displacement, torque, and angular displacement. The top platen can now be lowered the distance,  $H$ , calculated from Equation 1. As it nears the surface of the specimen, special care should be taken to ensure the specimen is not loaded too quickly; the surface should be given time to adjust, making slow adjustments to the axial displacement until the top platen has been lowered the full distance,  $H$ . With the platen now in full contact with the specimen, the axial load and axial displacement should be zeroed again. At this point, the 5 kPa seating load can be applied to the specimen, as in Figure 3.5. Note, a 5 kPa seating load should only be applied to specimen that will be tested with a confining pressure of 10 kPa or greater. The seating load should never be greater than the confining pressure.

Figure 3.5. (A) Top platen attached to ring shear loading arm (B) Seating load applied to ring shear specimen.

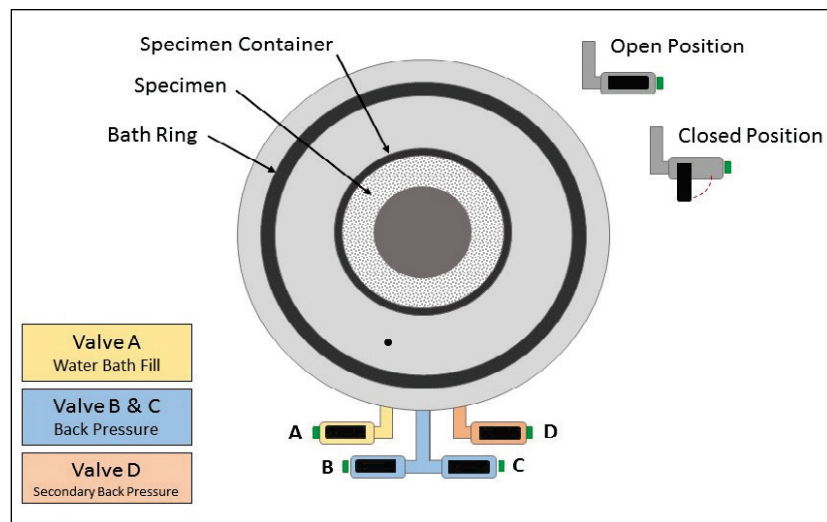


## 3.3 Saturating the ring shear specimen

If preparing a specimen to conduct an unsaturated ring shear test, the steps outlined in this section should be skipped. After completing the steps outlined in *Section 3.2 Specimen Setup*, skip to section 3.4 or 3.5 for the monotonic unsaturated (RS<sub>MU</sub>) or the cyclic unsaturated (RS<sub>CYU</sub>) test procedures, respectively. For saturated ring shear testing, continue with the following procedures.

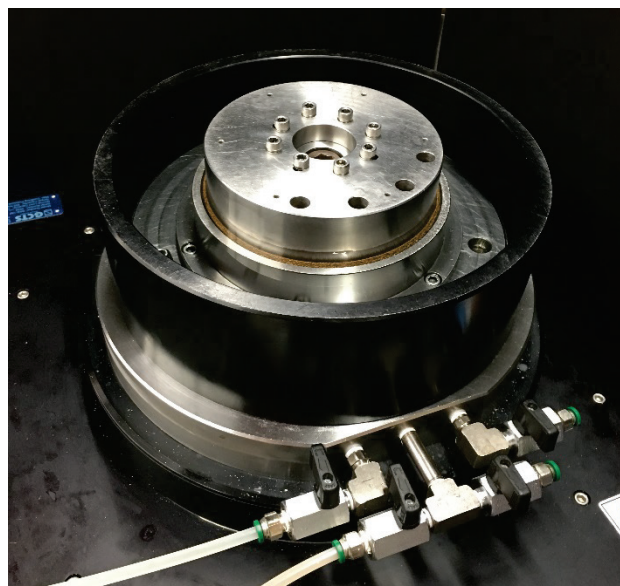
With the specimen confined under the seating load, the outer ring should be attached to the ring shear base plate. Valve B should be opened, Figure 3.6, and a drain line connected to Valve B to allow the water to run through the sample and out the drain line.

Figure 3.6. Ring shear valve system.



From Valve A, the water bath should be filled with distilled de-aired water using a gravity feed of minimal head to prevent water from inundating the specimen too quickly. Continue to fill until the water level is above the specimen, watching closely to ensure the water level does not rise above the water bath ring, Figure 3.7.

Figure 3.7. Ring shear water bath.



The rate in which the water flows into the water bath may need to be adjusted to ensure the water level stays above the top of the specimen, while not overflowing the wall of the water bath. The water level should be maintained at the same level as the specimen is being saturated. Shortly after the water begins to inundate the specimen, water will begin draining through the drain line. Continue to allow the water to drain until the water exiting from the drain line is clear and free of bubbles. The length of time this takes will depend on the type of material.

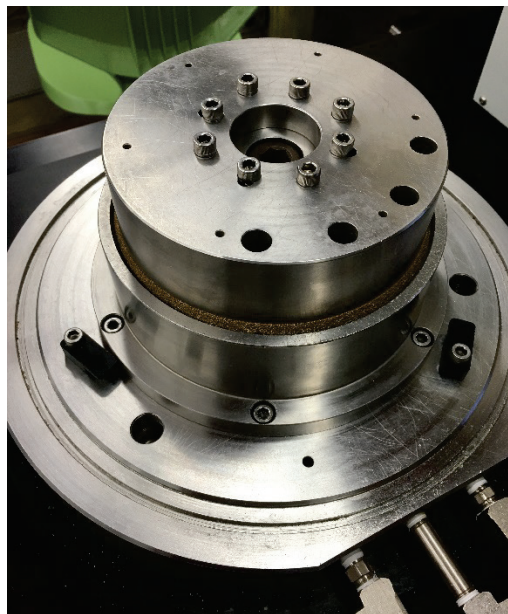
### 3.4 Monotonic ring shear testing

Ring shear tests are designed to investigate large strains and critical state mechanics across a pre-defined failure plane. In the case of monotonic loading, the ring shear applies a constant strain in one torsional direction until both failure and a critical state is achieved. The monotonic unsaturated ring shear test ( $RS_{MU}$ ) and the monotonic saturated ring shear test ( $RS_{MS}$ ) protocols are detailed below.

#### 3.4.1 Monotonic Unsaturated Ring Shear test ( $RS_{MU}$ )

Since an unsaturated ring shear test does not require a water bath for the specimen, after completing the steps outlined in *Section 3.2 Specimen Setup*, a monotonic unsaturated ring shear test ( $RS_{MU}$ ) is ready to be executed. Figure 3.8 shows an unsaturated ring shear setup ready for testing. The  $RS_{MU}$  test is designed in three stages: consolidation, hold, and shear.

Figure 3.8 Unsaturated ring shear setup.



### 3.4.1.1 $RS_{MU}$ Stage 1 - consolidation

During Stage 1, the confining pressure, or normal stress, is increased at a slow and constant rate until the confining pressure reaches the test confining pressure. This stage is set for a duration of three minutes for confining pressures of 60 kPa or less. Tests with higher confining pressures should adjust the duration of the consolidation stage, so that the normal stress is applied to the specimen at a rate not to exceed 20 kPa per minute. The example test program below shows Stage 1 for a testing confining pressure of 50 kPa:

```
===== Stage: 1 - Cons: Consolidation =====
Consolidation Normal Stress: 50 (kPa)
Time to Apply Consolidation Stress: 180 (sec)
Maximum Time for Consolidation Stage: 3 (Minute(s))
Data Acquisition
    Timed Increments: 0.5 (Seconds)
    Level Crossing: NS
    Peak/Valley: NS
Shear Deformation for Area Correction: None - No area correction
```

### 3.4.1.2 $RS_{MU}$ Stage 2 – hold

Stage 2 is a hold period. The length of this stage for an unsaturated specimen is much shorter than for a saturated specimen. For the unsaturated specimen, this stage takes three minutes.

```
~~~~~ Stage: 2 - hold ~~~~~
Duration:
    Timed: 3 (Minute(s))
    Input Limit: NS
    Until Output Completes: NS
Data Acquisition
    Timed Increments: 5 (Seconds)
    Level Crossing: NS
    Peak/Valley: NS
Cycle Recording
    Every Cycle
Data Saving
Data Buffer: Continuous
Defined Analog & Temperature Outputs:
===== AO-1: Axial Actuator =====

Feedback: TI-2: Sn - Normal Stress
Waveform: Constant
    Constant Control Value Type: Relative/Current
===== AO-2: Shear Actuator =====

Feedback: UFI-1: Angular Displacement
Waveform: Constant
    Constant Control Value Type: Relative/Current
=====
```

Master Output: AO-1: Axial Actuator

Digital Outputs Control: (none)

\*\*\*\*\*

### 3.4.1.3 $RS_{MU}$ Stage 3 – monotonic shear

The final stage is the shearing stage. Ensure the back pressure valve, Valve B (Figure 3.4) is left in the open position during the test to prevent the back pressure from building inside the specimen as it is being sheared. During this stage, the normal stress remains constant while the specimen is sheared for two minutes at a rate of 0.074 revolutions per minute.

==== Stage: 3 - Uni: Shear.tpr =====

\*\*\*\*\*

~~~~~ Universal Program ~~~~~

ID: Shear

Description: \_

Stages: 1

\*\*\*\*\*

~~~~~ Stage: 1 - Shear ~~~~~

Duration:

Timed: 2 (Minute(s))

Input Limit: NS

Until Output Completes: AO-2: Shear Actuator

Data Acquisition

Timed Increments: 0.5 (Seconds)

Level Crossing: NS

Peak/Valley: NS

Cycle Recording

Every Cycle

Data Saving

Data Buffer: Continuous

Defined Analog & Temperature Outputs:

==== AO-1: Axial Actuator =====

Feedback: TI-2:  $S_n$  - Normal Stress

Waveform: Constant

Constant Control Value Type: Relative/Current

==== AO-2: Shear Actuator =====

Feedback: CI-1: Angular Revolution

Waveform: Ramp

Initial Control Value Type: Relative/Current

Target End Value: ?? (rev)

Rate: -0.074 (rev)/(Minute(s))

Duration: 2 (Minute(s))

=====

Master Output: AO-1: Axial Actuator

Digital Outputs Control: (none)

\*\*\*\*\*

Times to Repeat Stage(s) above: 0

\*\*\*\*\*

Shear Deformation for Area Correction: None - No area correction

\*\*\*\*\*

~~~~~ Save Objects ~~~~~

Save @ each Recording:

Time

Inputs: 6

AI-1: Axial Load

AI-2: Axial Displacement

AI-3: Torque

CI-1: Angular Revolution

TI-1: T - Shear Stress

TI-2: Sn - Normal Stress

Analog Outputs: 0

Ultrasonics

P wave: NS

S wave: NS

\*\*\*\*\*

### 3.4.2 Monotonic Saturated Ring Shear test (RS<sub>MS</sub>)

Once the specimen is saturated, as detailed in *Section 3.3 Saturating the Ring Shear Specimen*, and the water draining through the specimen is clear and free of bubbles, the RS<sub>MS</sub> test is ready to be executed.

#### 3.4.2.1 RS<sub>MS</sub> Stage 1 – consolidation

The water should be allowed to continue draining throughout Stage 1 of the RS<sub>MS</sub> test. When the test begins, the confining pressure (normal stress) is increased at a slow and constant rate until the final confining pressure is reached. This stage is set for a duration of three minutes for confining pressures of 60 kPa or less. Tests with higher confining pressures should adjust the duration of the consolidation stage, so that the normal stress is applied to the specimen at a rate not to exceed 20 kPa per minute. The example test program below shows Stage 1 for a confining pressure of 50 kPa:

===== Stage: 1 - Cons: Consolidation =====

Consolidation Normal Stress: 50 (kPa)

Time to Apply Consolidation Stress: 120 (sec)

Maximum Time for Consolidation Stage: 3 (Minute(s))

Data Acquisition

Timed Increments: 0.5 (Seconds)

Level Crossing: NS

Peak/Valley: NS

Shear Deformation for Area Correction: None - No area correction

### 3.4.2.2 $RS_{MS}$ Stage 2 - hold

Once Stage 2 of the  $RS_{MS}$  test begins, both Valves A and B (Figure 3.4) should be closed to stop the water bath from continuing to fill and to stop the water from draining out of the specimen. For this stage of the test, the specimen will be held at the confining pressure for 30 minutes. This hold period allows for pore pressures to reach a state of static equilibrium. There is no angular displacement during this stage. Below is Stage 2 of the example test program:

```
~~~~~ Stage: 2 - hold ~~~~~
Duration:
    Timed: 30 (Minute(s))
    Input Limit: NS
    Until Output Completes: NS
Data Acquisition
    Timed Increments: 5 (Seconds)
    Level Crossing: NS
    Peak/Valley: NS
Cycle Recording
    Every Cycle
Data Saving
    Data Buffer: Continuous
Defined Analog & Temperature Outputs:
===== AO-1: Axial Actuator =====

Feedback: TI-2: Sn - Normal Stress
Waveform: Constant
    Constant Control Value Type: Relative/Current
===== AO-2: Shear Actuator =====

Feedback: UFI-1: Angular Displacement
Waveform: Constant
    Constant Control Value Type: Relative/Current
=====
Master Output: AO-1: Axial Actuator

Digital Outputs Control: (none)

*****
```

### 3.4.2.3 $RS_{MS}$ Stage 3 – monotonic shear

Shearing of the specimen begins in Stage 3 of the  $RS_{MS}$  test. Just before stage three begins, re-open the water source line and back pressure valve, Valves A and B, respectively (Figure 3.4), to allow water to flow through the specimen throughout the remainder of the test. This will prevent the back pressure from building inside the specimen as it is sheared. For this stage of the test, the normal stress remains constant as the specimen is sheared for two minutes at a rate of 0.074 revolutions per minute.

Once this stage is complete, the water is drained from the water bath and the specimen is removed from the ring shear base. A water content sample should be taken from the saturated specimen to be recorded with the test data. Below is Stage 3 of the example test program:

==== Stage: 3 - Uni: Shear.tpr =====

\*\*\*\*\*

~~~~~ Universal Program ~~~~~

ID: Shear  
Description: \_  
Stages: 1

\*\*\*\*\*

~~~~~ Stage: 1 - Shear ~~~~~

Duration:

Timed: 2 (Minute(s))

Input Limit: NS

Until Output Completes: AO-2: Shear Actuator

Data Acquisition

Timed Increments: 0.5 (Seconds)

Level Crossing: NS

Peak/Valley: NS

Cycle Recording

Every Cycle

Data Saving

Data Buffer: Continuous

Defined Analog & Temperature Outputs:

==== AO-1: Axial Actuator =====

Feedback: TI-2: Sn - Normal Stress

Waveform: Constant

Constant Control Value Type: Relative/Current

==== AO-2: Shear Actuator =====

Feedback: CI-1: Angular Revolution

Waveform: Ramp

Initial Control Value Type: Relative/Current

Target End Value: ?? (rev)

Rate: -0.074 (rev)/(Minute(s))

Duration: 2 (Minute(s))

=====

Master Output: AO-1: Axial Actuator

Digital Outputs Control: (none)

\*\*\*\*\*

Times to Repeat Stage(s) above: 0

\*\*\*\*\*

Shear Deformation for Area Correction: None - No area correction

\*\*\*\*\*

~~~~~ Save Objects ~~~~~

Save @ each Recording:

Time

Inputs: 6

AI-1: Axial Load

AI-2: Axial Displacement

AI-3: Torque  
 CI-1: Angular Revolution  
 TI-1: T - Shear Stress  
 TI-2: Sn - Normal Stress  
 Analog Outputs: 0  
 Ultrasonics  
     P wave: NS  
     S wave: NS

\*\*\*\*\*

### 3.5 Cyclic ring shear testing

Ring shear tests are designed to investigate large strains and critical state mechanics across a pre-defined failure plane. In the case of cyclic loading, the ring shear applies an accumulative cyclic strain until both failure and a critical state is achieved. The cyclic unsaturated ring shear test (RS<sub>CYU</sub>) and the cyclic saturated ring shear test (RS<sub>CYS</sub>) protocols are detailed below.

#### 3.5.1 Cyclic Unsaturated Ring Shear test (RS<sub>CYU</sub>)

After preparing the specimen as described in *Section 3.2 Specimen Setup*, a cyclic unsaturated ring shear test (RS<sub>CYU</sub>) is ready to be executed. The RS<sub>CYU</sub> test is designed in three stages: consolidation, hold, and shear.

##### 3.5.1.1 RS<sub>CYU</sub> Stage 1 – consolidation

During Stage 1, the confining pressure, or normal stress, is increased at a slow and constant rate until the confining pressure reaches the test confining pressure. This stage is set for a duration of three minutes for confining pressures of 60 kPa or less. Tests with higher confining pressures should adjust the duration of the consolidation stage, so that the normal stress is applied to the specimen at a rate not to exceed 20 kPa per minute. The example test program below shows Stage 1 for a testing confining pressure of 25 kPa:

~~~~~ Stage: 1 - Consolidation ~~~~~

Duration:  
     Timed: 3 (Minute(s))  
     Input Limit: NS  
     Until Output Completes: NS  
 Data Acquisition  
     Timed Increments: 5 (Seconds)  
     Level Crossing: NS  
     Peak/Valley: NS  
 Cycle Recording  
     Every Cycle  
 Data Saving  
 Data Buffer: Continuous

Defined Analog & Temperature Outputs:

===== AO-1: Axial Actuator =====

Feedback: TI-2: Sn - Normal Stress

Waveform: Ramp

Initial Control Value Type: Relative/Current

Target End Value: 25 (kPa)

Rate: 8 (kPa)/(Minute(s))

Duration: 3 (Minute(s))

===== AO-2: Shear Actuator =====

Feedback: UFI-1: Angular Displacement

Waveform: Constant

Constant Control Value Type: Relative/Current

=====

Master Output: AO-1: Axial Actuator

Digital Outputs Control: (none)

\*\*\*\*\*

### 3.5.1.2 $RS_{CYU}$ Stage 2 - hold

Stage 2 is a hold period. The length of this stage for an unsaturated specimen is much shorter than for a saturated specimen. For the unsaturated specimen, this stage is three minutes.

~~~~~ Stage: 2 - hold ~~~~~

Duration:

Timed: 3 (Minute(s))

Input Limit: NS

Until Output Completes: NS

Data Acquisition

Timed Increments: 5 (Seconds)

Level Crossing: NS

Peak/Valley: NS

Cycle Recording

Every Cycle

Data Saving

Data Buffer: Continuous

Defined Analog & Temperature Outputs:

===== AO-1: Axial Actuator =====

Feedback: TI-2: Sn - Normal Stress

Waveform: Constant

Constant Control Value Type: Relative/Current

===== AO-2: Shear Actuator =====

Feedback: UFI-1: Angular Displacement

Waveform: Constant

Constant Control Value Type: Relative/Current

=====

Master Output: AO-1: Axial Actuator

Digital Outputs Control: (none)

\*\*\*\*\*

### 3.5.1.3 $RS_{CYU}$ Stage 3 – cyclic shear

Shearing of the specimen begins in Stage 3 of the  $RS_{CYU}$  test. Ensure the back pressure valve, Valve B (Figure 3.4) is left in the open position during the test to prevent the back pressure from building inside the specimen as it is being sheared. During Stage 3, the normal stress remains constant and the shear actuator shears the specimen using a Sine waveform set to an amplitude of 2.5 mm and a frequency of 0.5 for a duration of 10 cycles. During this stage, data is collected every 0.1 seconds. Below is Stage 3 of the example test program:

~~~~~ Stage: 3 - Cyclic Shear ~~~~~

Duration:

Timed: NS

Input Limit: NS

Until Output Completes: AO-2: Shear Actuator

Data Acquisition

Timed Increments: 0.1 (Seconds)

Level Crossing: NS

Peak/Valley: NS

Cycle Recording

Every Cycle

Data Saving

Data Buffer: Continuous

Defined Analog & Temperature Outputs:

===== AO-1: Axial Actuator =====

Feedback: TI-2:  $S_n$  - Normal Stress

Waveform: Constant

Constant Control Value Type: Relative/Current

===== AO-2: Shear Actuator =====

Feedback: UFI-1: Angular Displacement

Waveform: Sine

Delay: 0 (sec)

Stage Shift: 0 (deg)

Mean Control Value Type: Relative/Current

End Control Value: Last value

Amplitude: 2.5 (mm)

Frequency: 0.5 (Hz)

Compensations:

Peak & Valley Compensation: NS

Duration: 10 (Cycles)

=====

Master Output: AO-2: Shear Actuator

Digital Outputs Control: (none)

\*\*\*\*\*

Times to Repeat Stage(s) above: 0

\*\*\*\*\*

Shear Deformation for Area Correction: None - No area correction

\*\*\*\*\*

~~~~~ Save Objects ~~~~~

Save @ each Recording:

Time

Cycles  
 Inputs: 6  
     AI-2: Axial Displacement  
     AI-3: Torque  
     CI-1: Angular Revolution  
     UCI-1: Corrected Axial Load  
     TI-1: T - Shear Stress  
     TI-2: Sn - Normal Stress  
 Analog Outputs: 0  
 Ultrasonics  
     P wave: NS  
     S wave: NS

### 3.5.2 Cyclic Saturated Ring Shear test (RScys)

Once the specimen is saturated and the water draining through the specimen is clear and free of bubbles, the cyclic saturated ring shear test, RScys, is ready to begin. The RScys test is divided into three stages: Consolidation, Hold, and Cyclic Shear.

#### 3.5.2.1 RScys Stage 1 – consolidation

The water should be allowed to continue draining throughout Stage 1 of the RScys test. When the test begins, the confining pressure (normal stress) is increased at a slow and constant rate until the final confining pressure is reached. This stage is set for a duration of three minutes for confining pressures of 60 kPa or less. Tests with higher confining pressures should adjust the duration of the consolidation stage, so that the normal stress is applied to the specimen at a rate not to exceed 20 kPa per minute. The example test program below shows Stage 1 for a testing confining pressure of 25 kPa:

~~~~~ Stage: 1 - Consolidation ~~~~~

Duration:  
     Timed: 3 (Minute(s))  
     Input Limit: NS  
     Until Output Completes: NS  
 Data Acquisition  
     Timed Increments: 5 (Seconds)  
     Level Crossing: NS  
     Peak/Valley: NS  
 Cycle Recording  
     Every Cycle  
 Data Saving  
 Data Buffer: Continuous  
 Defined Analog & Temperature Outputs:

===== AO-1: Axial Actuator =====

Feedback: TI-2: Sn - Normal Stress  
 Waveform: Ramp  
     Initial Control Value Type: Relative/Current

```

Target End Value: 25 (kPa)
Rate: 8 (kPa)/(Minute(s))
Duration: 3 (Minute(s))
===== AO-2: Shear Actuator =====

Feedback: UFI-1: Angular Displacement
Waveform: Constant
Constant Control Value Type: Relative/Current
=====
Master Output: AO-1: Axial Actuator

Digital Outputs Control: (none)

*****

```

### 3.5.2.2 $RS_{CYS}$ Stage 2 – hold

Once Stage 2 of the  $RS_{CYS}$  test begins, both Valves A and B (Figure 3.4) should be closed to stop the water bath from continuing to fill and to stop the water from draining out of the specimen. For this stage of the test, the specimen will be held at the confining pressure for 30 minutes. This hold period allows for pore pressures to reach a state of static equilibrium. There is no angular displacement during this stage. Below is Stage 2 of the example test program:

```

~~~~~ Stage: 2 - hold ~~~~~

Duration:
    Timed: 30 (Minute(s))
    Input Limit: NS
    Until Output Completes: NS
Data Acquisition
    Timed Increments: 5 (Seconds)
    Level Crossing: NS
    Peak/Valley: NS
Cycle Recording
    Every Cycle
Data Saving
Data Buffer: Continuous
Defined Analog & Temperature Outputs:
===== AO-1: Axial Actuator =====

Feedback: TI-2: Sn - Normal Stress
Waveform: Constant
Constant Control Value Type: Relative/Current
===== AO-2: Shear Actuator =====

Feedback: UFI-1: Angular Displacement
Waveform: Constant
Constant Control Value Type: Relative/Current
=====
Master Output: AO-1: Axial Actuator

Digital Outputs Control: (none)

*****

```

### 3.5.2.3 *RS<sub>CYS</sub> Stage 3 – cyclic shear*

Shearing of the specimen begins in Stage 3 of the RS<sub>CYS</sub> test. Just before stage three begins, the back pressure valve, Valve B, should be re-opened along with the water source line, Valve A, to allow water to flow through the specimen throughout the remainder of the test. This will prevent the back pressure from building inside the specimen as it is being sheared. During Stage 3, the normal stress remains constant and the shear actuator shears the specimen using a Sine waveform set to an amplitude of 2.5 mm and a frequency of 0.5 for a duration of 10 cycles. During this stage, data is collected every 0.1 seconds. Once this stage is complete, the water is drained from the water bath and the specimen is removed from the ring shear base. A water content sample should be taken from the saturated specimen to be recorded with the test data. Below is Stage 3 of the example test program:

~~~~~ Stage: 3 - Cyclic Shear ~~~~~

Duration:

Timed: NS

Input Limit: NS

Until Output Completes: AO-2: Shear Actuator

Data Acquisition

Timed Increments: 0.1 (Seconds)

Level Crossing: NS

Peak/Valley: NS

Cycle Recording

Every Cycle

Data Saving

Data Buffer: Continuous

Defined Analog & Temperature Outputs:

===== AO-1: Axial Actuator =====

Feedback: TI-2: S<sub>n</sub> - Normal Stress

Waveform: Constant

Constant Control Value Type: Relative/Current

===== AO-2: Shear Actuator =====

Feedback: UFI-1: Angular Displacement

Waveform: Sine

Delay: 0 (sec)

Stage Shift: 0 (deg)

Mean Control Value Type: Relative/Current

End Control Value: Last value

Amplitude: 2.5 (mm)

Frequency: 0.5 (Hz)

Compensations:

Peak & Valley Compensation: NS

Duration: 10 (Cycles)

=====

Master Output: AO-2: Shear Actuator

Digital Outputs Control: (none)

\*\*\*\*\*

Times to Repeat Stage(s) above: 0

\*\*\*\*\*

Shear Deformation for Area Correction: None - No area correction

\*\*\*\*\*

~~~~~ Save Objects ~~~~~

Save @ each Recording:

Time

Cycles

Inputs: 6

AI-2: Axial Displacement

AI-3: Torque

CI-1: Angular Revolution

UCI-1: Corrected Axial Load

TI-1: T - Shear Stress

TI-2: Sn - Normal Stress

Analog Outputs: 0

Ultrasonics

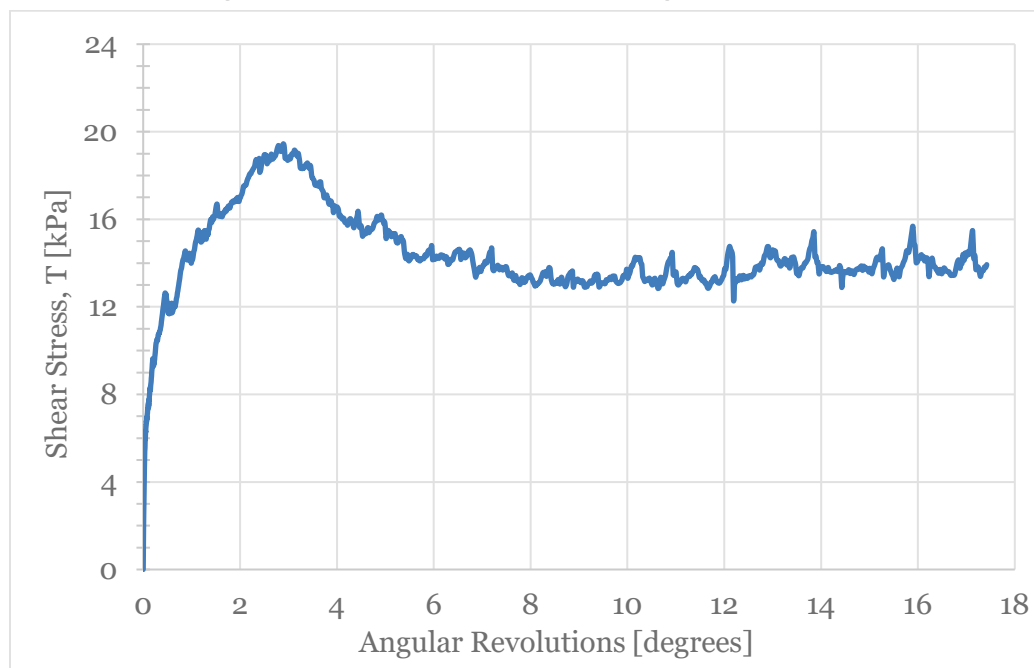
P wave: NS

S wave: NS

### 3.6 Monotonic ring shear test output

Monotonic ring shear test data is plotted as shear stress versus angular revolutions, with angular revolutions and strain being equivalent. The failure is taken as the peak shear stress from the plot, shown in the example in Figure 3.9 as approximately 19 kPa.

Figure 3.9 Typical shear stress versus angular revolutions.



### 3.7 Cyclic ring shear test output

For a cyclic ring shear test, shear stress can be plotted versus time or angular revolutions. The failure point is the cycle when no change to shear stress is seen over additional cycles, i.e. equilibrium. From the example in Figure 3.10, the failure cycle was determined to be the fourth cycle. Critical state is when the hysteresis loop stays constant with each additional cycle, as determined from Figure 3.11.

Figure 3.10. Typical shear stress versus time.

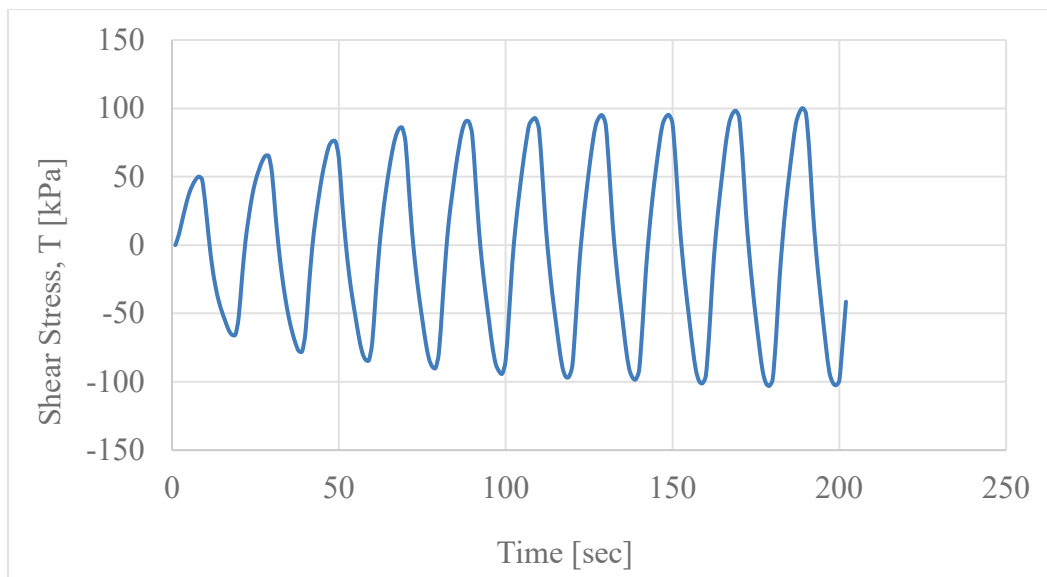
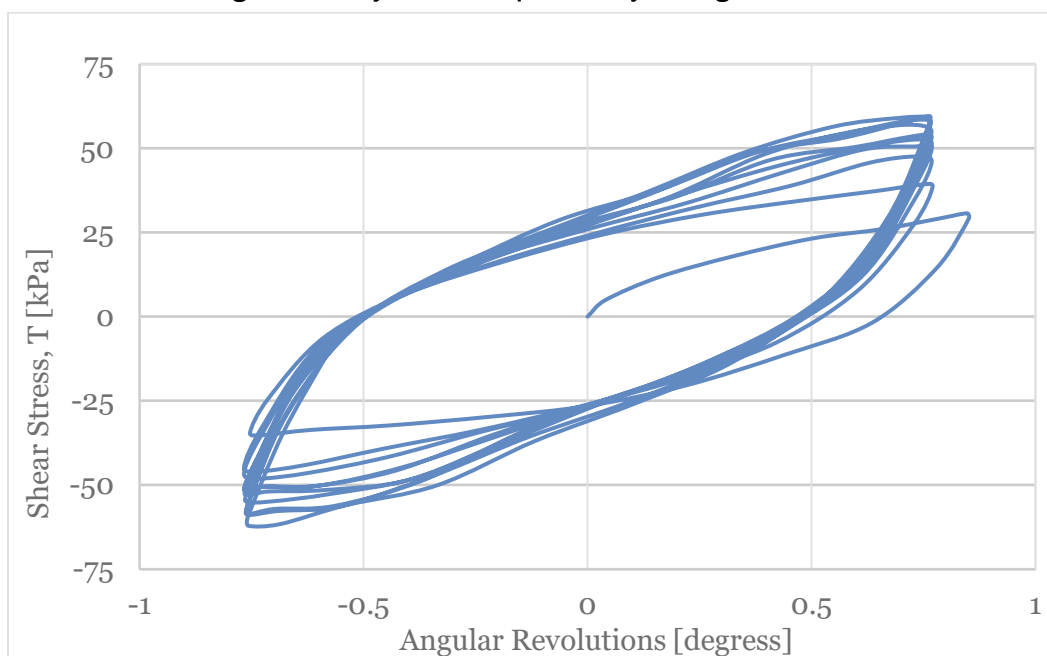


Figure 3.11. Hysteresis output from cyclic ring shear test.

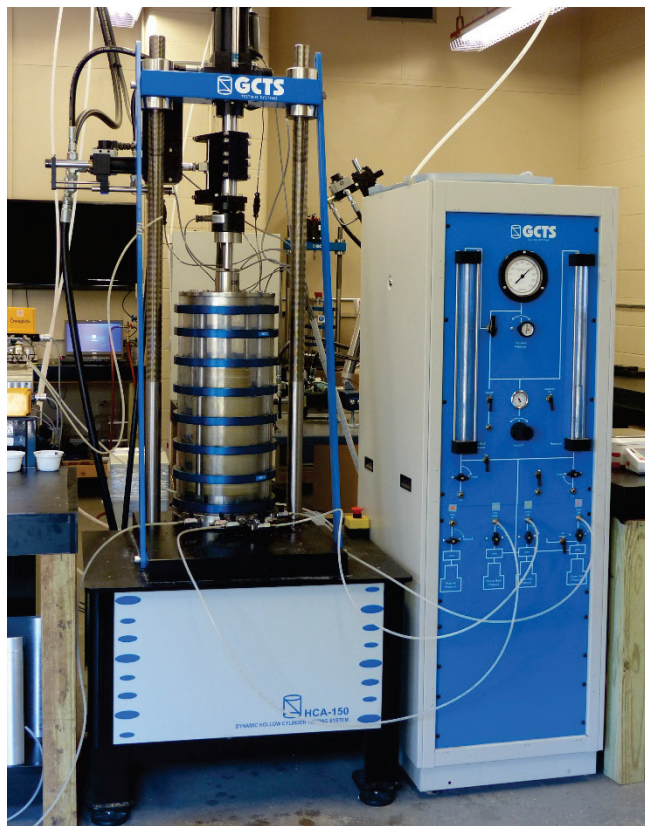


## 4 Hollow Cylinder Test

### 4.1 Apparatus

GCTS' HCA-150 Dynamic Hollow Cylinder Testing System, Figure 4.1, was used to develop the procedures outlined herein for studying near-surface soil behavior through isotropic monotonic torsional shear hollow cylinder (HC<sub>MTS</sub>) testing. The order of operations may be slightly different when using other manufacturers' equipment.

Figure 4.1. GCTS hollow cylinder.



The HCA-150 is a pneumatic system with closed-loop digital servo control. This system is developed for performing fully automated static and dynamic hollow cylinder tests on saturated or unsaturated soil specimens. This system also has optional ultrasonic platens for shear modulus testing with bender elements. Other possible tests include: measurement of dynamic shear strength and deformation, liquefaction potential, shear modulus and damping ratio. The system's Windows-based software automatically calculates up to 28 HCA test parameters in real-time that can be used as control feedback during testing.

This system has a 25 kN axial load capacity, 225 N-m torsional load capacity, 25 Hz maximum frequency, 25° maximum rotation, and is capable of applying back/pore water pressures up to 1000 kPa. The HCA-150 can accommodate specimens up to 150 mm in diameter.

## **4.2 Specimen and equipment setup**

The protocols outlined herein for isotropic monotonic torsional shear hollow cylinder (HC<sub>MTS</sub>) testing for near-surface material applications were developed based on research conducted at the Engineer Research and Development Center, Geotechnical and Structures Laboratory. The ASTM International Standards does not provide a standard testing protocol for HC<sub>MTS</sub> testing. A protocol for isotropic monotonic torsional shear hollow cylinder (HC<sub>MTS</sub>) testing is outlined herein.

### **4.2.1 Test specimen preparation**

#### *4.2.1.1 Specimen size*

The hollow cylinder testing protocol described herein is based on a specimen with an outside and inside diameter of 150 and 75 mm, respectively. The height of the specimen is 300 mm.

#### *4.2.1.2 Tamping method*

All specimens for this study were reconstituted using a modified moist tamping method similar to Bradshaw and Baxter (2007). The focus of this approach for sample reconstitution is maintaining a uniform compactive effort throughout the sample. The procedures outlined herein for near-surface lab testing were developed using cohesionless materials, and the reconstitution method used is detailed in ERDC/GSL TR-16-11 (2016). This report describes, in part, the method for determining an appropriate reconstituted saturation and the process of how to create a reconstituted soil fabric that is consistent throughout, which results in a specimen that meets a target density requirement by carefully controlling the water content and applied energy.

Based on the specific requirements outlined in ERDC/GSL TR-16-11 (2016), a pre-determined amount of oven-dried material and water is thoroughly mixed to produce a target water content. The material is stored in a covered container for 10 to 15 minutes prior to compaction. This wait time is substantially shorter than the 16-hour waiting period required by

the ASTM Standard D7181-11 (2011) since the exact water content is such a critical component in the methodology followed herein in ERDC/GSL TR-16-11 (2016). The whole premise of preparing repeatable cohesionless specimen outlined in ERDC/GSL TR-16-11 (2016) is based upon controlling the water-to-material ratio and the applied energy. For that reason, the material mixed with water cannot sit a long period of time and still meet the tight tolerances for water content.

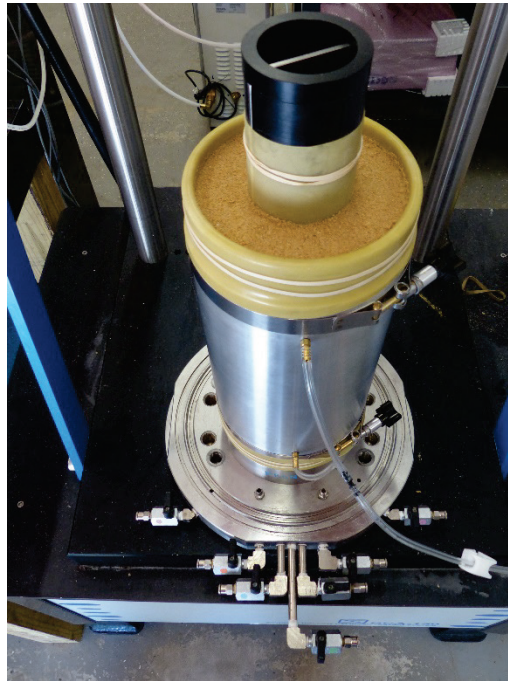
When mixing the material, ensure additional material is accounted for in excess of what is required for the specimen. After the material is mixed and has been covered for the appropriate time, three samples from the mixture should be removed for determining the water content in accordance with Test Method D2216 (2010). This moisture content is to verify the material is at the specified water content just prior to the specimen reconstitution. If the average moisture content error is greater than  $\pm 2\%$ , i.e., the water content is not between 5.292-5.508% for a target moisture content of 5.40%, the test specimen should be discarded.

The combination of number of layers, number of tamps per layer, force per tamp (rammer weight), rammer drop height and diameter of the tamper base directly affect the energy being applied to the specimen. Each of these variables must be carefully considered to create the optimal combination of each that results in the desired energy. These are also detailed in ERDC/GSL TR-16-11 (2016). Figure 4.2 shows a completed hollow cylinder specimen before the top cap has been placed and the mold removed.

#### 4.2.1.3 *Verifying specimen dimensions*

After the reconstituted specimen has been formed, measurements from the top of the specimen mold to the top of the specimen should be taken at eight points around the specimen, choosing four from the outside edge and four from the inside edge, spacing the locations out evenly across the sample in order to obtain a representative average height of the specimen. Based on the average measured height of the specimen, if the volume is not within  $\pm 2\%$  of the target volume, i.e., for a 300 mm tall specimen no more than  $\pm 6$  mm in height differential, the specimen should be discarded.

Figure 4.2. Reconstituted hollow cylinder specimen.

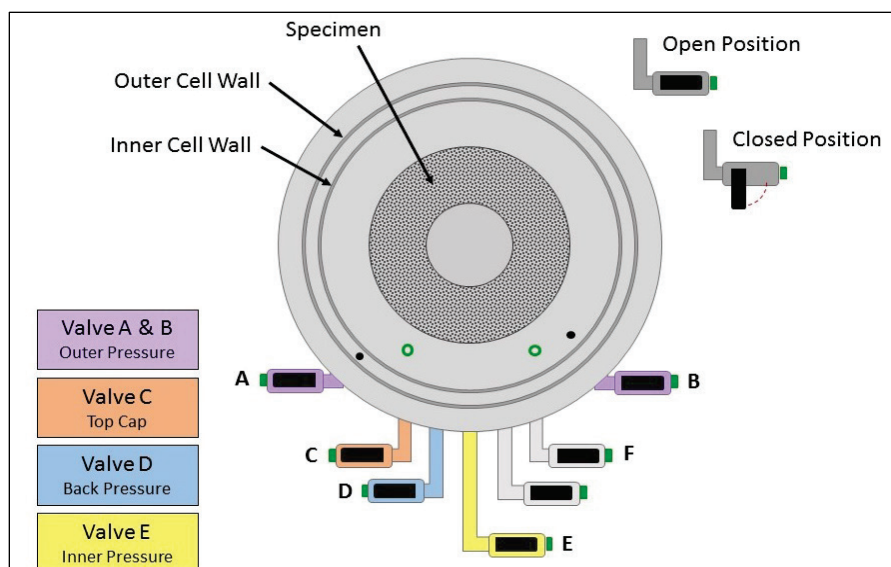


#### 4.2.2 Mounting specimen

Once the volume of the specimen has been verified, the top cap is placed carefully on top of the specimen, and the inner membrane is secured to the top cap with a rubber band. The center chamber of the specimen is then filled with distilled de-aired water. Once the center chamber is full of water, the inside mold can be removed. The outer membrane is then pulled up over the edges of the top cap and sealed with two rubber bands. Two additional rubber bands secure the outer membrane to the bottom cap and are attached before the specimen is built.

Before the outside mold is removed from the specimen, a vacuum must be applied to the specimen through the top cap by placing an air line from the top cap valve to the connection on the top side of the base plate corresponding to Valve C in Figure 4.3.

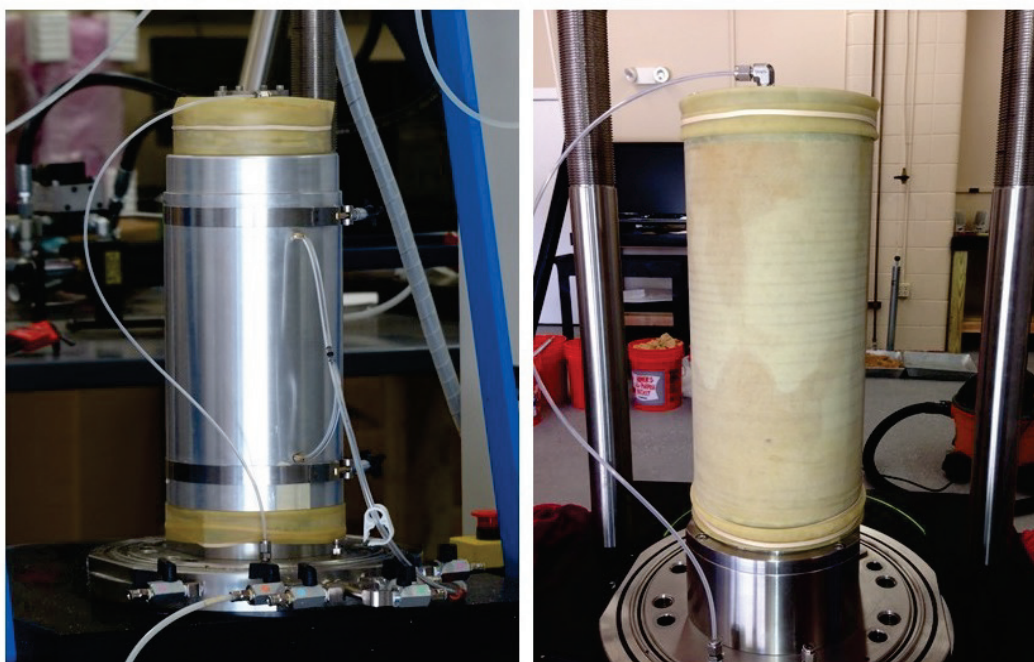
Figure 4.3. Hollow cylinder valve system.



A vacuum of approximately 5 in. Hg (17 kPa) (not to exceed the test confining pressure) is applied to the specimen. After giving the vacuum 5-10 minutes to equilibrate throughout the specimen, the outer mold can be removed from the specimen.

Carefully inspect the latex membrane for holes and/or leaks before proceeding. If any tears are found in the membrane, the specimen should be discarded.

Figure 4.4. Applying a vacuum to the hollow cylinder specimen.



### **4.2.3 Preparing hollow cylinder chamber**

#### *4.2.3.1 Boot up system*

The HCA-150 computer system should be turned on and allowed to warm up for approximately 15 minutes prior to testing. Once the specimen is under vacuum, it is a convenient time to turn on the system to warm up while the final assembly of the chamber is continued. Boot up the system, and turn on the pump, axial actuator, and torsional actuator. Synchronize the system. This may need to be done several times. The system should warm up for at least 15 minutes.

As the system is warming up, and before the piston is attached to the specimen, the piston should be loosely attached to the load cell and the Axial Load and Torque set to zero. This will ensure the weight of the piston is accounted for when applying the load to the specimen later.

#### *4.2.3.2 Assemble chamber*

As the hollow cylinder chamber is assembled, a thin coating of silicon grease should be applied to each O-ring to aid in creating a tight seal inside the chamber in order to properly maintain test pressures throughout testing. To install the chamber's top plate, instead of moving in a clockwise or counterclockwise direction tightening adjacent screws, moving in a crisscross pattern will ensure a uniform seating of the plate with the O-ring.

When the chamber is fully assembled, it should be carefully slid beneath the load cell to align the four bolt connections that attach the loading arm to the load cell. Placing the Torsional Actuator in Torque mode will allow adjustment of the rotation of the load cell to align the bolt holes. The piston should never be attached to the load cell when making adjustments to the position of the chamber. Once all four bolts are aligned and secured in the holes (but not tightened), the Torsional Actuator should be changed back to Displacement mode to keep the load cell from rotating. Tightening the clamps on the bottom plate will secure the chamber to the platform.

Using the locking screws located near where the piston enters the top platen will prevent the piston from moving up or down. A 5 kPa Stress Difference should be applied to force the load cell down onto the locked piston. Zeroing the Axial Displacement and tightening the bolts will hold the piston to the load cell. Finally, the Torsional Displacement and Angular

Displacement should be zeroed and the collar on the piston tightened to prevent the piston from rotating.

#### 4.2.3.3 *Fill chamber with distilled de-aired water*

While continuing to leave the specimen under a vacuum, the inner and outer cells of the hollow cylinder chamber should be filled with distilled de-aired water using a gravity feed of minimal head to prevent over-stressing the sample prior to testing. To do this, connect a line to Valve A and B (Figure 4.4) to fill the outer cells. Valve F, Figure 4.4, may also be used to fill the chamber to speed up the filling process. As the cells fill, any excess air is bled out through the bleed holes on the top plate of the hollow cylinder chamber. Once both cells are full, Valves A and B are to be closed and the fill lines removed.

#### 4.2.4 **Initializing system for test**

With the specimen under a 5 in. Hg (17 kPa) vacuum and the chamber filled with de-aired distilled water, perform the following operations to prepare the system for testing:

1. Point all PVCs TO TANK.
2. Make sure all OP, IP and BP PVCs are in Displacement Feedback.
3. Turn on Outer Pressure, Inner Pressure, and Back Pressure PVCs.
4. Open PVC Setup windows for each PVC to ensure polarity is correct.
5. Point PVCs to CELL.
6. Bleed Outer and Inner PVC lines, zero lines and connect them to sample.
7. Put OP and IP PVCs in Pressure Feedback, set to Zero, and open OP and IP valves.
8. Apply 15 kPa Inner Pressure then Outer Pressure.
9. Release Vacuum, leave orange valve open throughout test.
10. Loosen screw on collar.
11. Bleed Back Pressure PVC, zero and connect to sample. **Leave in Displacement mode – do not set the Back Pressure using the Pressure feedback.**
12. Open Back Pressure valve to sample.
13. Execute test.

### 4.3 Hollow cylinder test, Isotropic Monotonic Torsional Shear (HC<sub>MTS</sub>)

The HC<sub>MTS</sub> test is set up in four different stages. The first stage ramps up the outer pressure and inner pressure simultaneously until it reaches the test confining pressure. The second stage holds the confining pressures steady for short rest period before the test begins in Stage 3. The final stage brings the confining pressures back down so that the chamber can be safely disassembled. Below is an example HC<sub>MTS</sub> test file:

#### 4.3.1 HC<sub>MTS</sub> Stage 1 – Ramp OP IP

During the first stage of the HC<sub>MTS</sub> test, the outer pressure and inner pressure are increased simultaneously at a slow and constant rate until both the outer and inner cell pressures reach the test confining pressure. The duration allowed for this stage depends on the test confining pressure. The cell pressure should increase at a steady rate between 25-30 kPa per minute. For example, for a test confining pressure of 100 kPa, the ramp stage would be set for a duration of four minutes. Throughout this stage, the axial stress difference remains constant at the defined seating load and the torsional displacement remains static. The example test program below shows Stage 1 for a HC<sub>MTS</sub> test set to ramp to a confining pressure of 100 kPa:

```
*****
~~~~~ Stage: 1 - ramp up OP_IP ~~~~~
Duration:
    Timed: 4 (Minute(s))
    Input Limit: NS
    Until Output Completes: NS
Data Acquisition
    Timed Increments: 5 (Seconds)
    Level Crossing: NS
    Peak/Valley: NS
Cycle Recording
    Every Cycle
Data Saving
Data Buffer: Continuous
Defined Analog Outputs:

===== AO-1: Axial Actuator =====
FeedbackTI-11: Sd - Axial Stress Difference
Waveform: Constant
    Constant Control Value Type: Relative/Current

===== AO-2: Torsional Actuator =====
FeedbackAI-14: Torsional Displacement
Waveform: Constant
    Constant Control Value Type: Relative/Current

===== AO-3: Outer Pressure =====
FeedbackAI-5: Outer Pressure
```

```

Waveform: Ramp
    Initial Control Value Type: Relative/Current
    Target End Value: 100 (kPa)
    Rate: ?? (kPa)/(Minute(s))
    Duration: 4 (Minute(s))

===== AO-4: Inner Pressure =====
FeedbackAI-15: Inner Pressure
Waveform: Ramp
    Initial Control Value Type: Relative/Current
    Target End Value: 100 (kPa)
    Rate: ?? (kPa)/(Minute(s))
    Duration: 4 (Minute(s))

=====
Master Output: AO-1: Axial Actuator
Digital Outputs Control: (none)
*****
Times to Repeat Stage(s) above: 0
*****
Beginning of Stage - Handling Strains:
    Zero Deformations
===== 2: Universal: hold OP_IP.tpr =====
*****

```

#### 4.3.2 HC<sub>MTS</sub> Stage 2 – hold

Stage 2 of the HC<sub>MTS</sub> test is the “hold” period. At this stage, the cell pressures have reached the defined test confining pressure and remains constant for the duration of the stage. The axial stress difference continues to remain constant at the defined seating load and the torsional displacement remains static. For cohesionless material, the duration of the hold stage for the HC<sub>MTS</sub> test is set for five minutes. Below is Stage 2 of the example test program:

```

*****
~~~~ Stage: 2 - hold OP_IP ~~~~~

Duration:
    Timed: 5 (Minute(s))
    Input Limit: NS
    Until Output Completes: NS
Data Acquisition
    Timed Increments: 5 (Seconds)
    Level Crossing: NS
    Peak/Valley: NS
Cycle Recording
    Every Cycle
Data Saving
Data Buffer: Continuous
Defined Analog Outputs:
===== AO-1: Axial Actuator =====

FeedbackTI-11: Sd - Axial Stress Difference
Waveform: Constant
    Constant Control Value Type: Relative/Current

```

```

===== AO-2: Torsional Actuator =====

FeedbackAI-14: Torsional Displacement
Waveform: Constant
      Constant Control Value Type: Relative/Current
===== AO-3: Outer Pressure =====

FeedbackAI-5: Outer Pressure
Waveform: Constant
      Constant Control Value Type: Relative/Current
===== AO-4: Inner Pressure =====

FeedbackAI-15: Inner Pressure
Waveform: Constant
      Constant Control Value Type: Relative/Current
=====
Master Output: AO-1: Axial Actuator

Digital Outputs Control: (none)
*****
Times to Repeat Stage(s) above: 0
*****

```

### 4.3.3 HC<sub>MTS</sub> Stage 3 – shear strain

The shear/strain portion of the test begins in Stage 3. During this stage, the axial stress difference stays constant while the shear strain increases at a rate of 0.25% per minute. The shear strain continues to increase until it reaches 7.5%. Throughout the shear strain stage, the outer and inner pressures remain equal and constant at the set testing pressure.

When setting the maximum shear strain value for the stage end, it is important to consider the material and the peak shear strain that is expected. Failure is often taken to correspond to either a peak in shear stress or 10% strain. If the final shear strain value is set too low and the specimen does not fail within the shear strain range set for the test, the testing time cannot be extended during the test to capture additional data. It may be necessary to set the final shear strain value for this stage to a higher value than expected to ensure the peak is captured in the dataset. The user has the option to continue to the next stage of the test if a sufficient dataset for the specimen has been captured prior to the set end value. Below is Stage 3 of the example test program:

```

===== Stage 3: Static: HCA test =====

--- Axial Actuator -----

Control Feedback: TI-11: Sd - Axial Stress Difference
Mode: Constant
      Constant Value: Relative/Current

```

```

--- Torsional Actuator -----
Control Feedback: TI-4: Es - Shear Strain
Mode: Ramp
      Initial Value: Relative/Current
      Ramp Rate: 0.25 (%)/(Minute(s))
      Final Value: 7.5 (%)

--- Outer (Cell) Pressure -----
Control Feedback: AI-5: Outer Pressure
Mode: Constant
      Constant Value: Relative/Current

--- Inner Pressure -----
Control Feedback: AI-15: Inner Pressure
Mode: Constant
      Constant Value: Relative/Current

--- Back Pressure -----
Control Feedback: AI-8: Back PVC Disp.
Mode: Constant
      Constant Value: Relative/Current

--- Air Pore Pressure -----
Control Feedback: None - Control Undefined

Stage End
      Maximum Shear Strain 7.500 (%)
      Maximum Time for Static Loading Stage: NS
      Input Limit: NS
      Peak Reversal: NS
Data Acquisition
      Timed Increments: 0.5 (Seconds)
      Level Crossing: NS
Type: Undrained:  $E_v = 0$ 
Beginning of Stage - Handling Strains:
      Update Specimen Dimensions
      Zero Deformations

```

#### 4.3.4 HC<sub>MTS</sub> Stage 4 – ramp down OP IP

The final stage of the HC<sub>MTS</sub> test decreases the outer and inner pressures at a uniform rate until the pressures reach a target end value of 15 kPa. Once this stage is complete, the system can be safely disassembled. The test data is automatically saved to the system once this stage is complete. A window will appear on the screen when the data has been saved successfully. Below is Stage 4 of the example test program:

```

~~~~~ Stage: 4 - Ramp Down OP_IP ~~~~~

Duration:
      Timed: 3 (Minute(s))
      Input Limit: NS
      Until Output Completes: NS
Data Acquisition

```

```

        Timed Increments: 5 (Seconds)
        Level Crossing: NS
        Peak/Valley: NS
Cycle Recording
    Every Cycle
Data Saving
Data Buffer: Continuous
Defined Analog Outputs:

===== AO-1: Axial Actuator =====

FeedbackAI-2: Axial Displacement
Waveform: Constant
    Constant Control Value Type: Relative/Current
===== AO-2: Torsional Actuator =====

FeedbackAI-14: Torsional Displacement
Waveform: Constant
    Constant Control Value Type: Relative/Current
===== AO-3: Outer Pressure =====
FeedbackAI-5: Outer Pressure
Waveform: Ramp
    Initial Control Value Type: Relative/Current
    Target End Value: 15 (kPa)
    Rate: ?? (kPa)/(Minute(s))
    Duration: 3 (Minute(s))

===== AO-4: Inner Pressure =====
FeedbackAI-15: Inner Pressure
Waveform: Ramp
    Initial Control Value Type: Relative/Current
    Target End Value: 15 (kPa)
    Rate: ?? (kPa)/(Minute(s))
    Duration: 3 (Minute(s))

===== AO-5: Back Pressure =====
FeedbackAI-8: Back PVC Disp.
Waveform: Constant
    Constant Control Value Type: Relative/Current
=====
Master Output: AO-1: Axial Actuator

Digital Outputs Control: (none)
*****

Times to Repeat Stage(s) above: 0
*****

Beginning of Stage - Handling Strains:
    Update Specimen Dimensions
    Zero Deformations

*****

~~~~~ Save Objects ~~~~~
Save @ each Recording:
    Time
    Inputs: 18
        AI-1: Axial Load
        AI-2: Axial Displacement
        AI-5: Outer Pressure
        AI-7: Back/Pore Pressure
        AI-11: VCD Displacement
        AI-13: Torque
        AI-14: Torsional Displacement
        AI-15: Inner Pressure

```

AI-19: Circumferential Def.  
 UFI-1: Gauge Axial Def.  
 VCD-1: Cell VCD Total Volum  
 PVC-1: Outer PVC Total Volu  
 PVC-2: Inner Pressure PVC T  
 PVC-3: Back PVC Total Volum  
 TI-1: Ea - Axial Strain  
 TI-2: Er - Radial Strain  
 TI-3: Et - Tangential Strain  
 TI-4: Es - Shear Strain

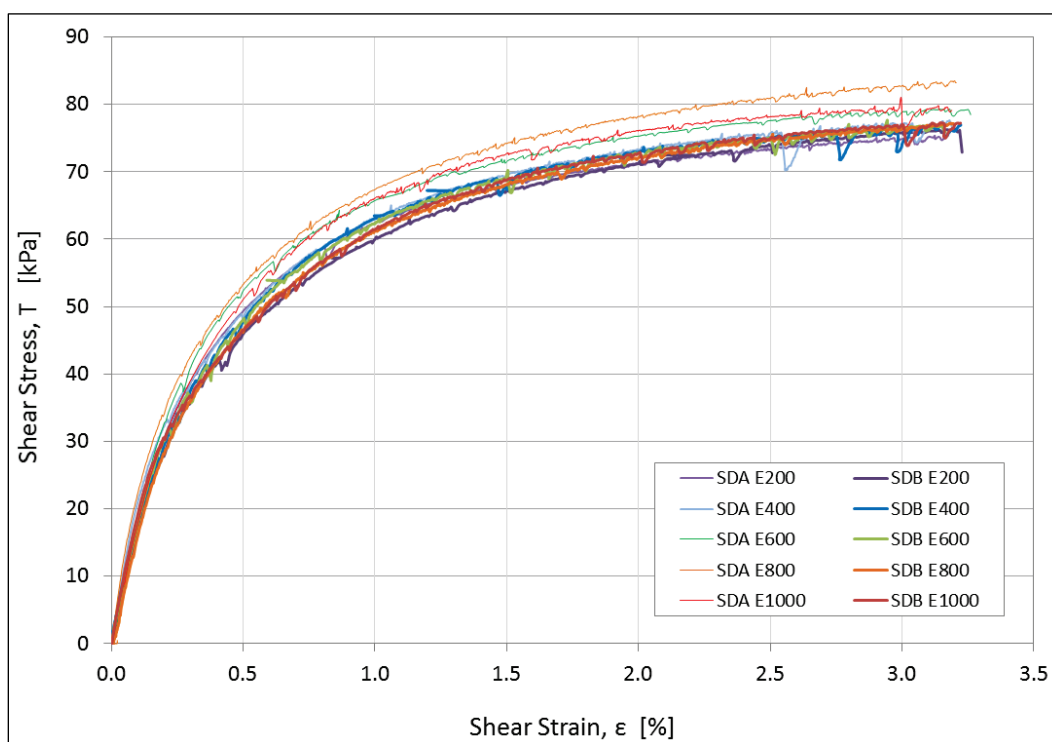
Analog Outputs:

\*\*\*\*\*

#### 4.4 HC<sub>MTS</sub> test output

Typical output from a hollow cylinder test is a plot of shear stress versus shear strain. Figure 4.5 is a plot of a series of hollow cylinder tests showing the repeatability of test results when using the sample reconstitution method detailed in ERDC/GSL TR-16-11 (2016).

Figure 4.5. Typical hollow cylinder test output.

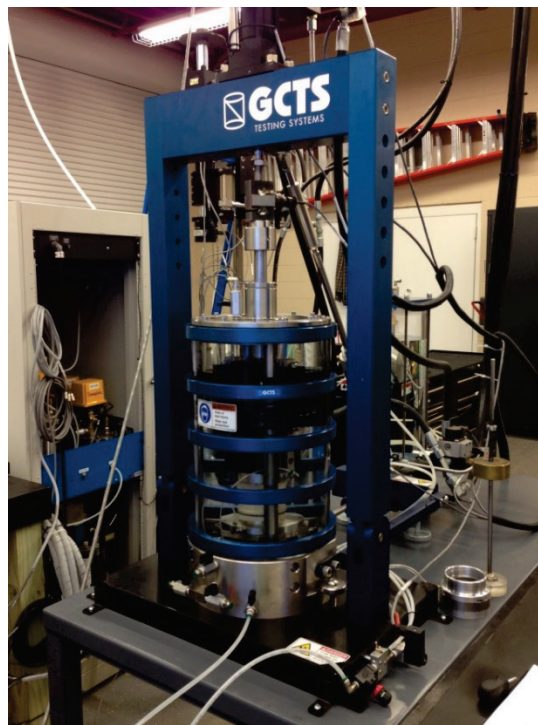


## 5 Simple Shear Test

### 5.1 Apparatus

GCTS Simple Shear System SSH-100, Figure 5.1, was used to develop the procedures and protocols outlined herein for studying near-surface soil behavior through isotropic consolidated drained simple shear testing (CD<sub>ss</sub>). The order of operations may be slightly different when using other manufacturers' equipment.

Figure 5.1. GCTS direct simple shear.



The SSH-100 testing system is a dynamic and static apparatus capable of applying cyclic loads at up to 20 Hz. It is also capable of performing isotropic and anisotropic consolidation; UU, CD, and CU tests with volume change or pore pressure measurements. It can also be used for cyclic loading tests including cyclic stress path; dynamic shear strength and deformation, liquefaction potential, shear modulus and damping ratio, and has the capability of servo controlling the shear load actuator, the normal load actuator, and the cell and back pressure.

Its normal (vertical) load frame has a 50-mm (2-in.) stroke,  $\pm 25$  kN static load capacity,  $\pm 20$  kN dynamic load capacity, 50 Hz maximum frequency

and 200 mm/sec maximum velocity. This system can reach up to 1,000 kPa lateral confining pressures and includes lines for top and bottom specimen drainage.

## **5.2 Specimen and equipment setup**

The protocols outlined herein for isotropic consolidated drained simple shear testing (CD<sub>ss</sub>) for near-surface material applications were developed based on research conducted at the Engineer Research and Development Center, Geotechnical and Structures Laboratory. The ASTM International Standards does not provide a standard testing protocol for CD<sub>ss</sub> testing. The protocol for CD<sub>ss</sub> testing developed through this research is outlined herein.

### **5.2.1 Test specimen preparation**

#### *5.2.1.1 Specimen size*

Standard cylindrical specimens with a height and diameter of 32 and 72.9 mm, respectively, were used for developing the procedures outlined herein.

#### *5.2.1.2 Tamping method*

All specimens for this study were reconstituted using a modified moist tamping method similar to Bradshaw and Baxter (2007). The focus of this approach for sample reconstitution is maintaining a uniform compactive effort throughout the sample. The procedures outlined herein for near-surface lab testing were developed using cohesionless materials and the reconstitution method used is detailed in ERDC/GSL TR-16-11 (2016). This report describes, in part, the method for determining an appropriate reconstituted saturation and the process of how to create a reconstituted soil fabric that is consistent throughout and that results in specimen that meets a target density requirement by carefully controlling the water content and applied energy.

Based on the requirements outlined in ERDC/GSL TR-16-11 (2016), a specific amount of oven-dried material and water is thoroughly mixed to produce a desired water content. The material is stored in a covered container for 10 to 15 minutes prior to compaction. This wait time is substantially shorter than the 16 hour waiting period required by the ASTM Standard D7181-11 (2011) since the exact water content is such a critical component in the methodology followed herein in ERDC/GSL TR-16-11

(2016). The whole premise of preparing repeatable cohesionless specimen outlined in ERDC/GSL TR-16-11 (2016) is based on controlling the water-to-material ratio and the applied energy. For that reason, the material mixed with water cannot sit a long period of time and still meet the tight tolerances for water content.

When mixing the material, ensure additional material is accounted for in excess of what is required for the specimen. After the material is mixed and has been covered for the appropriate time, three samples from the mixture should be removed for determining the water content. This moisture content is to verify the material is at the specified water content just prior to the specimen reconstitution. If the average moisture content error is greater than  $\pm 2\%$ , i.e., the water content is not between 5.292-5.508% for a target moisture content of 5.40%, the test specimen should be discarded.

The combination of number of tamps, force per tamp (rammer weight), rammer drop height and diameter of the tamper base directly affect the energy being applied to the specimen. Each of these variables must be carefully considered to create the optimal combination of each that results in the desired energy. These are also detailed specifically in ERDC/GSL TR-16-11 (2016).

#### *5.2.1.3 Verifying specimen dimensions*

After the specimen has been formed, measurements from the top of the mold down to the top of the specimen should be taken from the center of the specimen and at least four other points over the top of the specimen. Based off the average measured height of the specimen, if the volume is not within  $\pm 2\%$  of the target volume, i.e. for a 32 mm tall specimen no more than  $\pm 0.64$  mm in height differential, the specimen should be discarded.

### **5.2.2 Mounting specimen**

With the mold still around the specimen, the normal actuator is lowered to carefully position the top platen in contact with the top of the specimen and the membrane is pulled up over the edges of the top platen. To seal the specimen, two rubber bands are placed snugly over the top platen, around the membrane. Rubber bands are preferred to O-rings due to tighter seal generation and decreased sample disturbance during apparatus assembly. Two additional rubber bands secure the membrane to the bottom platen and are attached before the specimen is built.

For SS<sub>CD</sub> tests in excess of 20 kPa confining pressure, a vacuum is applied to the specimen through the top platen by placing an air line from the top platen valve to the vacuum valve on the apparatus base. Another air line is connected from the bottom platen to the drain valve of the apparatus base, and this valve is closed to enable the vacuum. A vacuum of approximately 5 in. Hg (17 kPa) (not to exceed the test confining pressure) is applied to the specimen. After giving the vacuum 5-10 minutes to equilibrate throughout the specimen, the mold is then removed from the specimen. This step must be skipped for tests below 20 kPa confinement so not to over-stress the material in advance of load application.

The latex membrane should be carefully inspected for holes and/or leaks before proceeding. If tears are found in the membrane, the specimen should be discarded.

After locking the normal actuator in place and disconnecting it from the load cell, the loading arm should be lowered to prepare for placing the chamber.

### **5.2.3 Preparing simple shear chamber**

#### *5.2.3.1 Assemble simple shear chamber*

As the simple shear chamber is assembled, a thin coating of silicon grease is applied to each O-ring to aid in creating a tight seal inside the chamber in order to properly maintain test pressures throughout testing. To install the chamber's top plate, instead of moving in a clockwise or counterclockwise direction tightening adjacent screws, moving in a crisscross pattern will ensure a uniform seating of the plate with the O-ring. Once the chamber and top plate are in place, the loading arm should be raised and the normal actuator reconnected to the load cell and unlocked.

#### *5.2.3.2 Fill chamber with distilled, de-aired water*

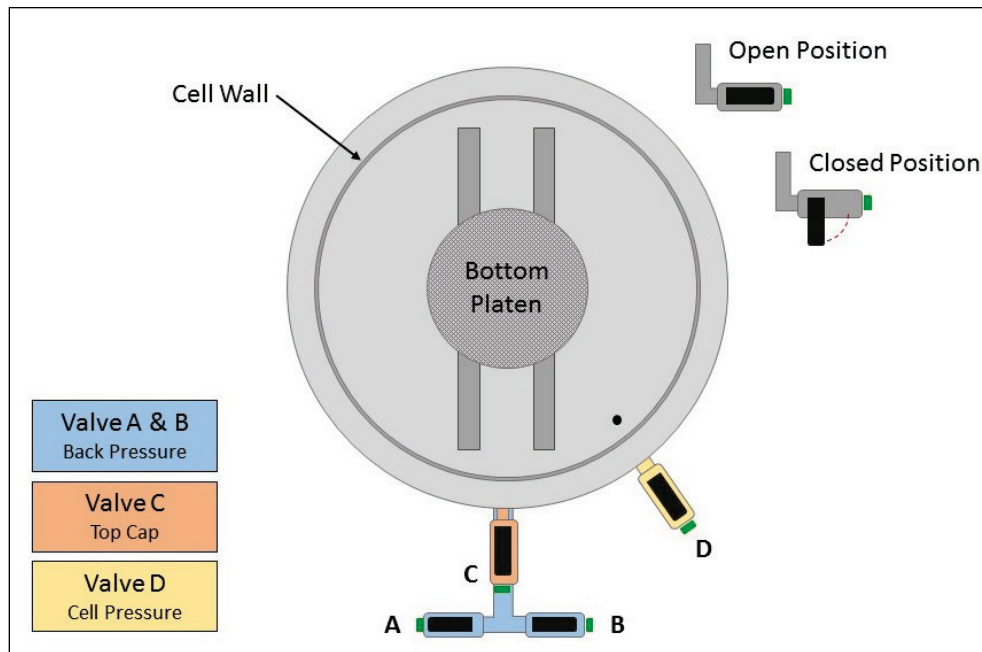
The cell of the simple shear chamber should be filled with distilled de-aired water using a gravity feed of minimal head to prevent over-stressing the sample prior to testing. The top valve should be left open until the cell is nearly full. Once the cell is full, any excess air should be bled out through the bleed holes on the top plate of the chamber, then all valves should be closed.

### 5.2.4 Initializing system for test

With the specimen under a 5 in. Hg (17 kPa) vacuum and the chamber filled with de-aired water, perform the following operations to prepare the system for testing:

1. *Software*: Point the Cell Pressure PVC “to cell.”
2. *Software*: From the *Outputs Function: Set-Point/Function Generation* window, select **Cell Pressure** for the output mode, and select **Displacement** for the Feedback mode.
3. *Cabinet*: Insert a hose into the connector on the cabinet labeled “Cell.”
4. *Software*: Using the *Outputs Function* window, advance the Set-point (in Cell Pressure – displacement mode) to push water through the hose until all the air in the hose has been displaced. Holding the hose next to Valve A, Figure 5.2, (without inserting it yet) zero the Cell Pressure from the Inputs Offsets window.

Figure 5.2. Simple shear valve system.



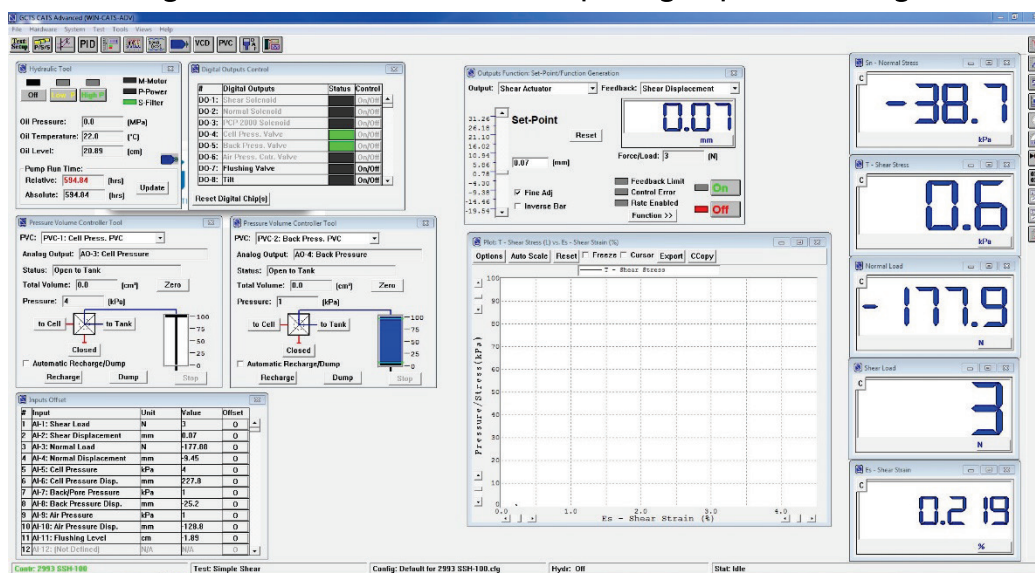
5. *Cell*: Insert the hose into the cell Valve D, Figure 5.2.
6. *Software*: From the *Outputs Function: Set-Point/Function Generation* window, with **Cell Pressure** still selected for the output mode, select **Cell Pressure** for the Feedback mode.
7. *Software*: Using the Set Point function in the *Outputs Function: Set-Point/Function Generation* window, set the **Cell Pressure** to 10-15 kPa.

8. **Cell:** Shut off the vacuum line going to the sample by rotating Valve C, Figure 5.2, on the cell chamber to the closed position.
9. **Cabinet:** Close the vacuum lever on the cabinet and reduce the vacuum pressure to zero.
10. **Cell:** Once the cell pressure has stabilized to the set point, release the vacuum from the sample by opening Valve C, Figure 5.2. This valve should remain open throughout the remainder of the test.
11. **Software:** Using the Set Point function in the *Outputs Function: Set-Point/Function Generation* window, set the **Cell pressure** to the test cell pressure.
12. **Software:** From the *Outputs Function: Set-Point/Function Generation* window, select **Normal Actuator** for the output mode, and select **S<sub>a</sub> – Axial Stress Difference** for the Feedback mode. Using the Set Point function, apply a 5 kPa seating load. The piston should lower until in contact with the specimen.

## 5.2.5 Execute test

With the specimen under the test confining pressure, a 5 kPa seating load, and the specimen open to atmosphere, the consolidated drained simple shear test (CDss) can begin. Figure 5.3 shows a recommended screen setup for monitoring the system during a test.

Figure 5.3. Recommended screen setup during simple shear testing.



### 5.3 Isotropic Consolidated Drained Simple Shear test (CD<sub>ss</sub>)

The CD<sub>ss</sub> test protocol detailed below shears the specimen at a strain rate of 0.25% per minute. Failure strength is determined at 3.5% shear strain. The value for the cell pressure is set for each individual test as desired.

#### 5.3.1 CD<sub>ss</sub> Stage 1: set cell pressure

The first stage of the CD<sub>ss</sub> test is to set the confining pressures. This is done manually by using the set point controls inside the GCTS software to gradually increase the cell pressure until the desired confining pressure is reached. The rate at which the cell pressure is increased should be no greater than 25 kPa per minute. The deviator stress/seating load remains constant at 5 kPa as the cell pressure is increased.

#### 5.3.2 CD<sub>ss</sub> Stage 2: shear strain

The CD<sub>ss</sub> test program is designed to shear the specimen at a constant rate of 0.25% per minute until the shear strain value reaches 10%. As the specimen is being sheared, the cell pressure and axial stress difference is held constant at the set testing values. Below is an example CD<sub>ss</sub> test program for a specimen sheared with testing confining pressure of 100 kPa:

```
===== Shear Strain =====
--- Shear Actuator -----
Control Feedback: TI-1: Es - Shear Strain
Mode: Ramp
      Initial Value: Relative/Current
      Ramp Rate: 0.25 (%)/(Minute(s))
      Final Value: 10 (%)

--- Normal Actuator -----
Control Feedback: TI-7: Sd - Axial Stress Difference
Mode: Constant
      Constant Value: Relative/Current

--- Cell Pressure -----
Control Feedback: AI-5: Cell Pressure
Mode: Constant
      Constant Value: Absolute/Change to: 100 kPa

--- Back Pressure -----
Control Feedback: None - Control Undefined
Stage End
      Maximum Shear Strain 10.000 (%)
      Maximum Time for Static Loading Stage: NS
      Input Limit: NS
      Peak Reversal: NS
Data Acquisition: Automatic
Type: Drained
Beginning of Stage - Handling Strains:
      Update Specimen Dimensions
```

## Zero Deformations

```

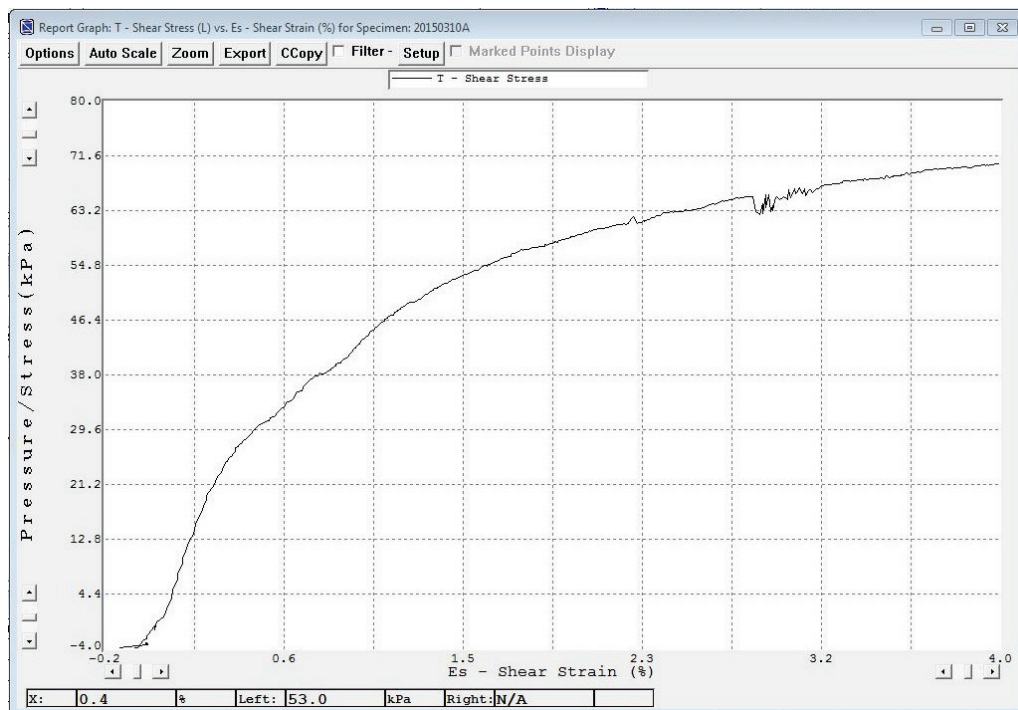
*****
~~~~~ Save Objects ~~~~~
Save @ each Recording:
    Time
    Inputs: 7
        AI-1: Shear Load
        AI-2: Shear Displacement
        AI-3: Normal Load
        AI-4: Normal Displacement
        AI-5: Cell Pressure
        AI-7: Back/Pore Pressure
        PVC-1: Cell PVC Total Volum
    Analog Outputs: 0
*****

```

## 5.4 CD<sub>ss</sub> test output

A plot of the test output can easily be generated within the *GCTS CATS Advanced* software by clicking the PSS button from the toolbar at the top of the software window. From the PSS window that opens, the specimen filename for a completed test should be highlighted on the left side before clicking the *Report Graph* button from the toolbar at the top of the PSS window. An example of a typical CD<sub>ss</sub> test plot, Shear Strain ( $\epsilon_a$ ) versus Shear Stress (T), is shown in Figure 5.4.

Figure 5.4. Typical data output from CD<sub>ss</sub> test, shear strain versus shear stress.



## 6 Unconfined Drained Self-Supporting Test

### 6.1 Apparatus

The unconfined self-supporting specimens are built on a tabletop using a split mold with a bottom platen. The bottom platen contains a porous stone, Figure 6.1, to allow free drainage through the bottom of the specimen. Instead of a latex membrane around the specimen, the mold is lined with wax paper for easy removal from the specimen, reducing the potential for disturbance of the reconstituted specimen. The load is applied to the specimen using loose, cylindrical precision weights, shown in Figure 6.1, that have the same diameter of the specimen to ensure even distribution of the weight across the specimen. A range of different weights, from 50 to 1,000 grams, are used as the load is applied to the specimen. The heavier weights are brass while the lighter weights are made out of aluminum.

Figure 6.1. Unconfined self-supporting test mold, platen, weights and wax paper.



### 6.2 Test specimen preparation

The protocols outlined herein for unconfined self-supporting tests for near-surface material applications were developed through research by the Engineer Research and Development Center's Geotechnical and Structures Laboratory.

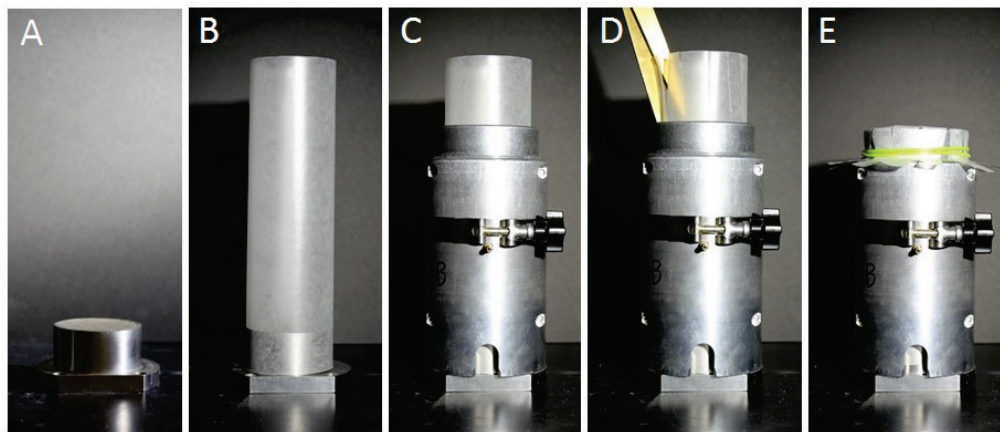
### 6.2.1 Specimen size

The protocol developed for unconfined self-supporting testing uses a reconstituted specimen with a height and diameter of 145 and 72 mm, respectively.

### 6.2.2 Preparing mold

The first step in preparing the mold for unconfined self-supporting tests is to attach wax paper to the bottom platen, Figure 6.2B. The wax paper should fit around the outside diameter of the platen and overlap a 1/2-inch to 1-inch. If the wax paper does not overlap, the soil could stick to the mold as the mold is being removed; however, too much overlap in the wax paper could create a bulk in the paper during sample reconstitution and create cavities in the side of the specimen. The wax paper should be taped so that the paper fits snugly around the platen, creating a cylindrical shape around the platen, being careful that the diameter at the top of the wax paper is the same as the diameter near the platen. If the wax paper diameter is smaller at the top, the wax paper will not lay smoothly inside the mold as the specimen material is added during reconstitution and will cause cavities on the edges of the specimen.

Figure 6.2. Preparing mold for unconfined self-supporting specimen test.



With the wax paper attached to the platen, the mold should be placed around the wax paper. At least two inches of wax paper should be visible above the top edge of the mold, Figure 6.2C. Scissors should be used to cut vertical slits in the wax paper 1/2 to 3/4 inches wide down to the top edge of the mold, Figure 6.2D. This allows the wax paper to be folded over the top edge of the mold and remain smooth on the inside of the mold. The wax

paper slits are to be secured to the outside edge of the mold using rubber bands, Figure 6.2E.

### 6.2.3 Sample reconstitution

Specimens are reconstituted using a modified moist tamping method similar to Bradshaw and Baxter (2007). The focus of this approach for sample reconstitution is maintaining a uniform compactive effort throughout the sample. The procedures outlined herein for near-surface lab testing were developed using cohesionless materials and the reconstitution method used is detailed in ERDC/GSL TR-16-11 (2016). This report describes, in part, the method for determining an appropriate reconstituted saturation and the specifics of how to create a reconstituted soil fabric that is consistent throughout which results in a specimen that meets a specific density requirement by carefully controlling the water content and applied energy.

Based on the requirements outlined in ERDC/GSL TR-16-11 (2016), a pre-determined amount of oven-dried material and water is thoroughly mixed to produce a target water content. The material is stored in a covered container for 10 to 15 minutes prior to compaction. This wait time is substantially shorter than the 16-hour wait period required by the ASTM Standard D7181-11 (2011) since the exact water content is such a critical component in the methodology followed herein in ERDC/GSL TR-16-11 (2016). The whole premise of preparing repeatable cohesionless specimen outlined in ERDC/GSL TR-16-11 (2016) is based on controlling the water-to-material ratio and the applied energy. For that reason, the material mixed with water cannot sit a long period of time and still meet the tight tolerances for water content.

When mixing the material, ensure additional material is accounted for in excess of what is required for the specimen. After the material is mixed and has been covered for the appropriate time, three samples from the mixture should be removed for determining the water content in accordance with ASTM Standard Test Method D2216 (2010). This moisture content is to verify the material is at the specified water content just prior to the specimen reconstitution. If the average moisture content error is greater than  $\pm 2\%$ , i.e., the water content is not between 5.292-5.508% for a target moisture content of 5.40%, the test specimen should be discarded.

The combination of number of layers, number of tamps per layer, force per tamp (rammer weight), rammer drop height and diameter of the tamper

base directly affect the energy being applied to the specimen. Each of these variables must be carefully considered to create the optimal combination of each that results in the desired energy. These are also detailed specifically in ERDC/GSL TR-16-11 (2016). The top of each compacted layer should be scarified before adding each additional layer. The top of the specimen should not be scarified.

#### **6.2.4 Verifying specimen dimensions**

After the specimen has been formed, measurements from the top of the mold down to the top of the specimen should be taken from the center of the specimen and at least 4 other points over the top of the specimen. Based off the average measured height of the specimen, if the volume is not within  $\pm 2\%$  of the target volume, i.e., for a 145 mm tall specimen no more than  $\pm 4.35$  mm in height differential, the specimen should be discarded.

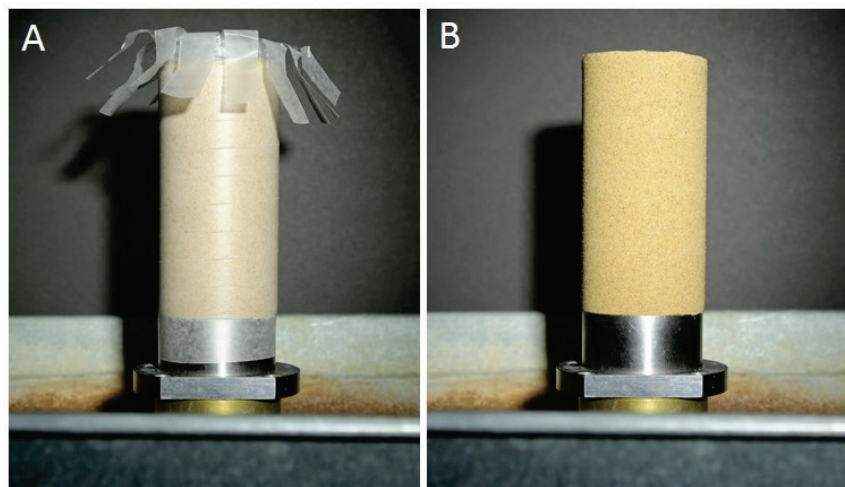
#### **6.2.5 Removing mold from specimen**

Before the mold is removed from the specimen, the specimen can be carefully moved to a pan or clean surface so that the material can be contained during testing and failure of the specimen. For these examples, the specimen was also placed on a raised disk for better image capturing while inside a pan. Once the mold is removed, the specimen should not be disturbed.

As the split mold is separated for removal, care should be taken that a suction between the wax paper and the mold does not cause disturbance of the specimen. Figure 6.3A shows the specimen after the mold has been removed. Next, the wax paper is carefully peeled away from the specimen, Figure 6.3B.

Once the wax paper is removed, the specimen should be inspected for imperfections. Should any cracks or cavities be found, the specimen should be discarded.

Figure 6.3. Removing wax paper from unconfined self-supporting specimen.



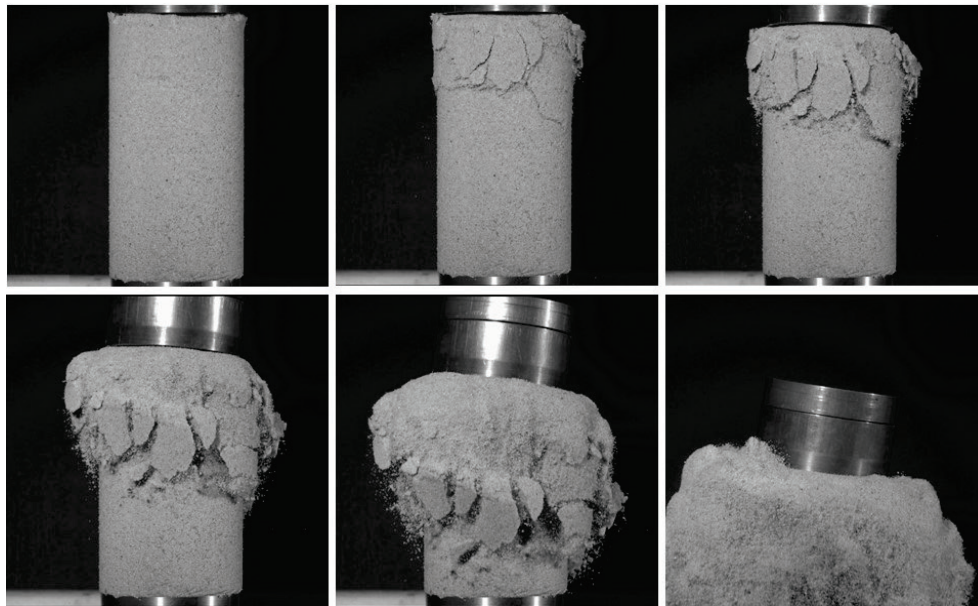
### 6.3 Unconfined drained tests

The protocol for conducting unconfined self-supporting tests, as it applies to studying near-surface soil behavior and failure mechanics of a cohesionless sand, for both saturated and unsaturated, is detailed in the following sections. Four unique tests, Unconfined Drained Dry ( $UD_K$ ), Unconfined Drained Unsaturated ( $UD_P$ ), Unconfined Drained Saturated ( $UD_S$ ) and Unconfined Drained High Stress ( $UD_{HS}$ ) are described. Each test method starts with an identical specimen, reconstituted at a given saturation, as described in section 6.2.3.

#### 6.3.1 Unconfined drained dry ( $UD_K$ )

The  $UD_K$  tests are allowed to air-dry in a controlled temperature environment until no detectable moisture remains. For this research, the specimens were air-dried for 48 hours, and produced immeasurable water contents comparable to that of oven-dried material. The air-dried specimen is then carefully loaded with precision weights, waiting 20 seconds between each load application. Weight continues to be added until failure. The amount of weight held before failure and the amount of weight at failure is recorded. After failure, moisture content samples are taken in accordance with ASTM Standard Test Method D2216 (2010). If the water content of the failed specimen is greater than 0.02%, the test should be discarded. Figure 6.4 shows a typical failure for an  $UD_K$  test specimen.

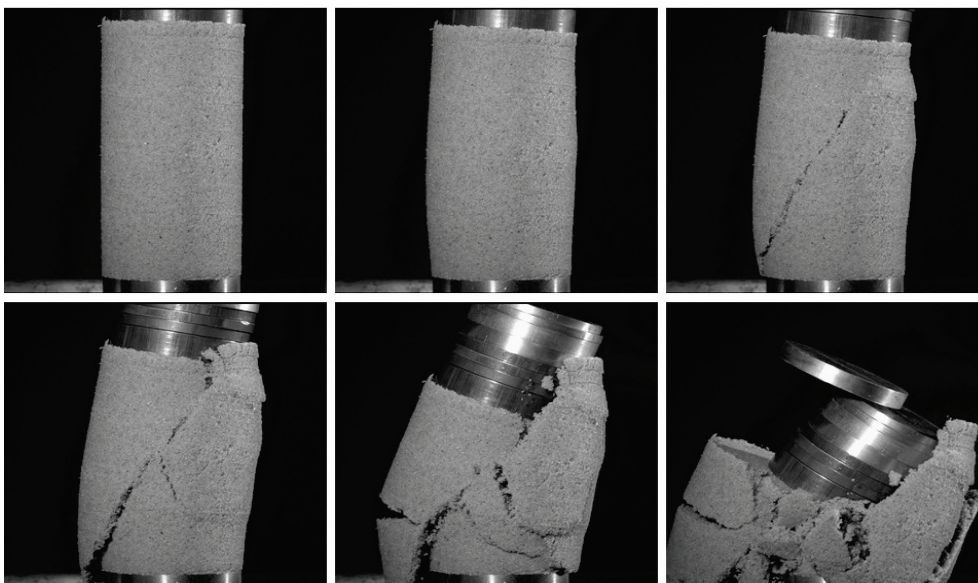
Figure 6.4. Unconfined drained (UD<sub>K</sub>) test failure.



### 6.3.2 Unconfined drained unsaturated (UD<sub>P</sub>)

The UD<sub>P</sub> test is conducted immediately after specimen reconstitution. The specimen is carefully loaded with precision weights, waiting 20 seconds between each load application. Weight continues to be added until failure. The amount of weight held before failure and the amount of weight at failure is recorded. After failure, moisture content samples are taken in accordance with ASTM Standard Test Method D2216 (2010). Figure 6.5 shows a typical failure for an UD<sub>P</sub> test specimen.

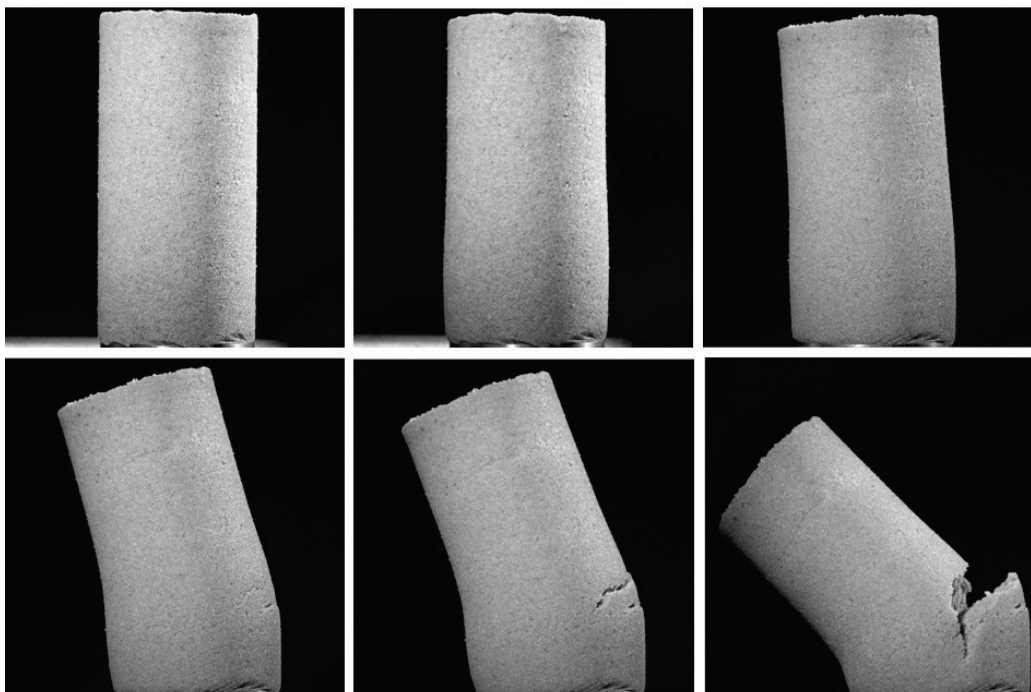
Figure 6.5. Unconfined drained unsaturated (UD<sub>P</sub>) test failure.



### 6.3.3 Unconfined drained saturated (UDs)

The UD<sub>s</sub> test is conducted immediately after specimen reconstitution. A small container filled with de-aired distilled water and a dropper are needed for this test. The total weight of the container, de-aired distilled water, and dropper are recorded. The top of the specimen should be uniformly saturated with the de-aired water using the dropper in 3 mL increments (and waiting 20 sec between each application). At the onset of failure, saturation should be suspended. If complete failure does not occur within 20 seconds, the saturation process is continued until failure begins. After failure, the final total weight of the container, de-aired water, and dropper are recorded. The amount of weight held before failure and the amount of weight at failure is recorded. Moisture content samples should be collected in accordance with ASTM Standard Test Method D2216 (2010) from the failed specimen. The saturation of the failed specimen is then calculated based on the final water content at failure. Figure 6.6 shows a typical failure for an UD<sub>s</sub> test specimen.

Figure 6.6. Unconfined drained saturated (UD<sub>s</sub>) test failure.

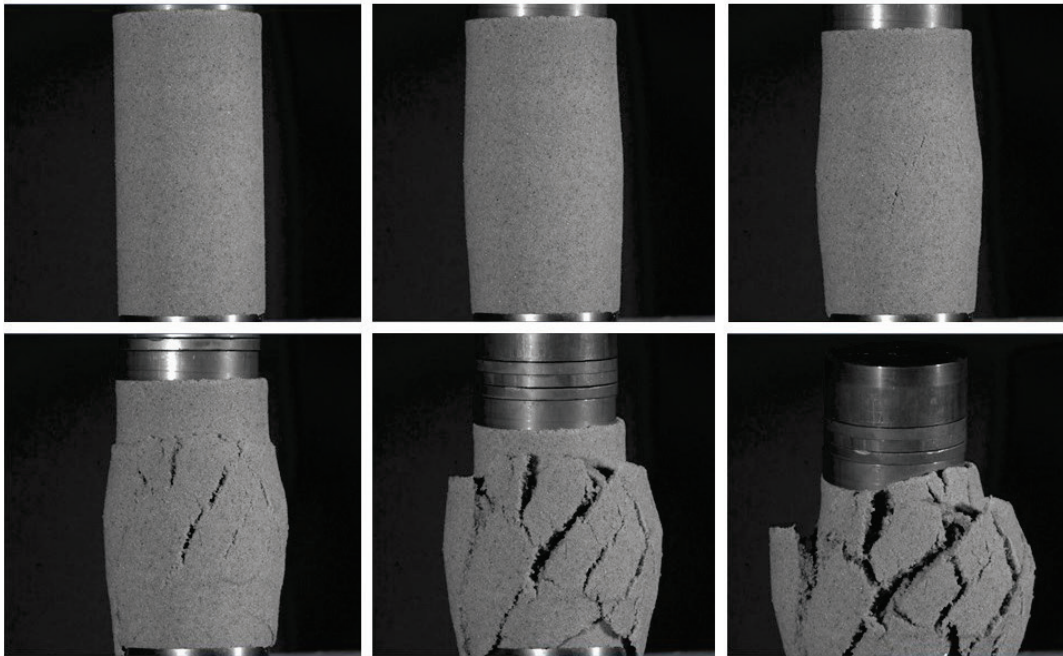


### 6.3.4 Unconfined drained high stress (UD<sub>HS</sub>).

The UD<sub>HS</sub> test is conducted immediately after specimen reconstitution. The specimen is carefully loaded with precision weights, waiting 20 seconds between each load application as to not exceed 90% of the UD<sub>P</sub> strength

when adding weight to the specimen. At 90%  $UD_P$  strength, a final load increment in excess of the  $UD_k$  strength should be applied. After failure, a recording of the last load before failure and the load at failure should be taken. Collect moisture content samples in accordance with ASTM Standard Test Method D2216 (2010). Figure 6.7 shows a typical failure for an  $UD_{HS}$  test specimen.

Figure 6.7. Unconfined drained high stress ( $UD_{HS}$ ) test failure.



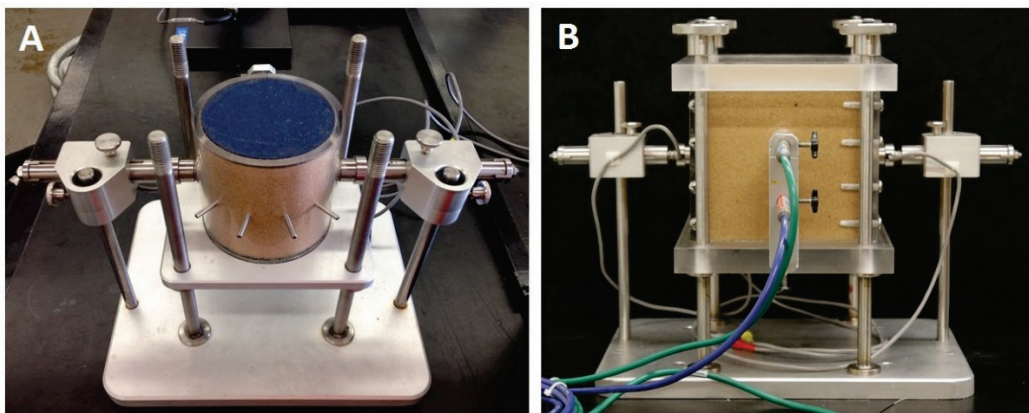
## 7 Ultrasonic Near-Surface Inundation (UNIT) Test

The Ultrasonic Near-Surface Inundation Testing (UNIT) device is a state-of-art system designed and patented by the U.S. Army Engineer Research and Development Center's Geotechnical and Structures Laboratory to investigate the phenomena related to moisture effects within near-surface environments. The UNIT soil cell allows researchers to propagate shear waves through the medium both perpendicular and parallel to the direction of fluid flow while maintaining an elastic free soil-air surface boundary under atmospheric conditions.

### 7.1 Apparatus

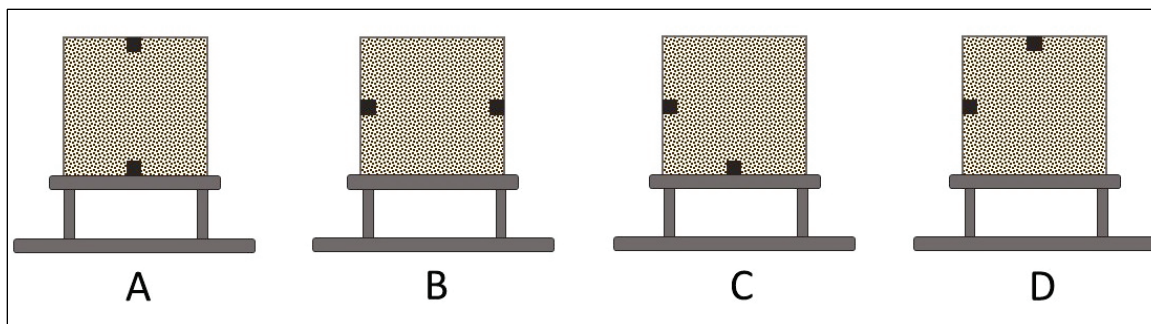
The initial design on the UNIT had a cylindrical specimen container and was later redesigned with a cube-shaped specimen container to reduce the reflectance of the bender element signal, Figure 7.1. Also, the addition of moisture sensors within each sample eliminated the need for weighing the sample numerous times. Piezometers were also added to determine the pressure within the sample. The cylinder UNIT measures 11.5 cm in height and has a diameter of 10 cm. The dimension of the cube UNIT is 15 cm x 15 cm.

Figure 7.1. (A) Cylindrical UNIT apparatus (B) Cube UNIT apparatus.



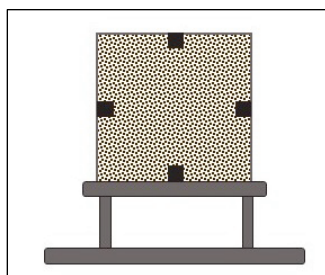
The UNIT design incorporates the use of bender elements to evaluate the S-wave propagation in soil specimens as water is added to the specimen. The UNIT test can incorporate one or two pair of bender elements arranged using one of several configurations. For a setup with one pair of bender elements the configuration options are, Figure 7.2: (A) Horizontal, (B) Vertical, (C) 90 degrees – bottom and side, or (D) 90 degrees – top and side.

Figure 7.2. Bender element configurations – one pair.



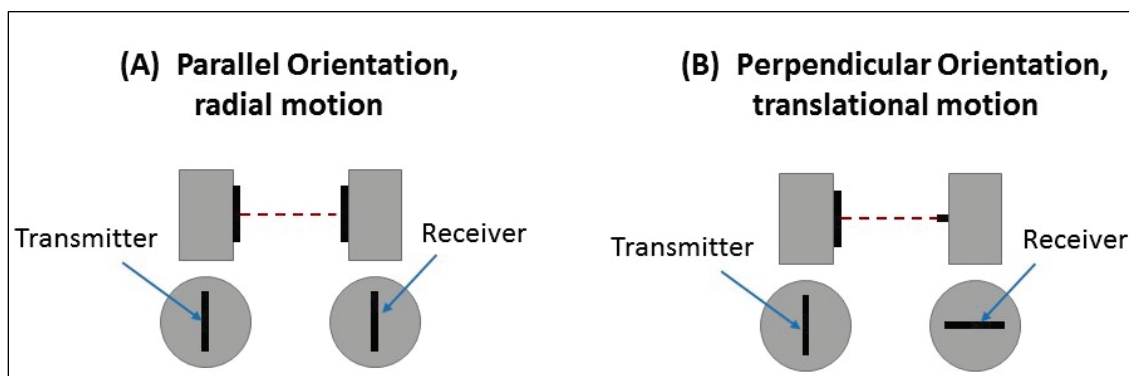
When using two pair of bender elements, one pair is configured on the top and bottom of the specimen, and the second pair is configured on the sides of the specimen, Figure 7.3.

Figure 7.3 Bender element configurations – two pair.



In addition to the configuration, or placement of the bender elements, the orientation of the bender elements can also be set up differently. Each pair of bender elements is oriented either parallel or perpendicular to one another, Figure 7.4.

Figure 7.4. Bender element orientation.



## 7.2 Specimen reconstitution

Specimens are reconstituted using a modified moist tamping method (Bradshaw and Baxter 2007, Taylor 2011, Taylor et al. 2016). The focus of this approach for sample reconstitution is maintaining a uniform compactive effort throughout the sample. The procedures outlined herein for near-surface lab testing were developed using cohesionless materials, and the reconstitution method used is detailed in ERDC/GSL TR-16-11 (2016). This report describes, in part, the method for determining an appropriate reconstituted saturation and the specifics of how to create a reconstituted soil fabric that is consistent throughout, which results in a specimen that meets a target density requirement by carefully controlling the water content and applied energy.

Based on the requirements outlined in ERDC/GSL TR-16-11 (2016), a pre-determined amount of oven-dried material and water is thoroughly mixed to produce a target water content. The material is stored in a covered container for 10 to 15 minutes prior to compaction. This wait time is substantially shorter than the 16-hour waiting period required by the ASTM Standard D7181-11 (2011), since the exact water content is such a critical component in the methodology followed herein in ERDC/GSL TR-16-11 (2016). The whole premise of preparing repeatable cohesionless specimen outlined in ERDC/GSL TR-16-11 (2016) is based around controlling the water-to-material ratio and the applied energy. For that reason, the material mixed with water cannot sit a long period of time and still meet the tight tolerances for water content.

The reconstituted specimens for the cylindrical device are built in four layers and the cube specimen is built in five layers. For the cylindrical UNIT, the target height of the reconstituted specimen is 100 mm. The target height used for the cube UNIT device is 145 mm.

## 7.3 Specimen saturation

The specimen is saturated using two different methods: static or dynamic. The static method adds a measured amount of water to the specimen, then waits a specified length of time before taking a reading. The measured amount of water and the wait time between each iteration is the same throughout a single test. There are four different water/time combinations that have been used for a single static test: 15 mL/10 minutes, 20 mL/12.5 minutes, 40 mL/15 minutes, and 50 mL/20 minutes. The water is added to

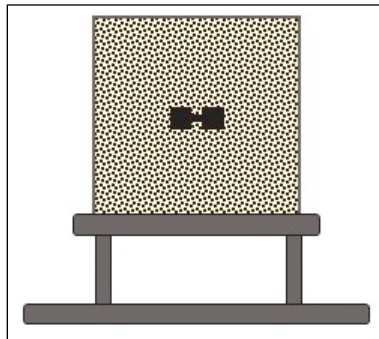
the specimen, using a pipette or dropper, through an opening in the top of the specimen container. This process is continued until the sample is saturated, i.e. the specimen does not absorb any more water. The dynamic method of saturating the specimen allows water to continually flow through the specimen. For both the static and dynamic tests, readings are taken at specified time intervals as the specimen saturates. Once the specimen is fully saturated, the specimen is then allowed to dry while continuing readings intermittently as the specimen dries. Drying of the specimen can be done naturally by allowing the specimen to air dry or by placing a small electric heater near the specimen to speed the drying process.

## 7.4 Static source test

The source test is used as a base line to determine how the bender elements' signal performs during wetting and drying cycles without a substance between them. The source test creates a base line for the signal. The protocol for conducting a static source test uses the cylindrical UNIT device, but the base-line data obtained from the source test is applicable to any static test, whether done with the cylindrical or cube device.

For the static source test, the bender elements are placed with the transmitter and receiver parallel, Figure 7.4-A, and in contact with each other in the center of the specimen, Figure 7.5. The step-by-step procedure for completing the static source test is detailed below.

Figure 7.5 Static source test bender element placement.



1. Cover the holes in the bottom of the specimen container, the drain hole, and element opening with tape.
2. Place a solid porous stone on the bottom of the specimen container.

3. Apply a thin coating of silicon grease on the bottom edge of the cylinder to ensure a tight seal between the cylinder and the bottom of the specimen container. It is important that no silicon grease gets inside the cylinder.
4. Place the cylinder over the porous stone, with the metal pegs facing forward, and press securely into place.
5. Place rubber plugs into the element openings in the side of the cylinder to prevent the soil from spilling out as the specimen is prepared. If needed, use tape to hold the rubber plugs in place.
6. Prepare the first two layers of the reconstituted specimen.
7. Insert the moisture sensor into the sample.
8. Weigh and record weight of bender elements.
9. Place the bender elements in the center of the sample on top of the second layer of soil. Place the elements where they are close enough to touch. Ensure the bender elements' transmitter and receiver are parallel to each other, placing them as straight as possible. If the bender elements are misaligned, the signal readings will be inaccurate. Once the bender elements have been aligned properly, secure with tape to maintain proper position throughout the test.
10. Prepare the third layer of soil. This layer should be equal in weight to the first layer, but less the weight of the bender elements.
11. Prepare the final layer of the reconstituted specimen.
12. Secure the top of the specimen container with screws.
13. Connect the bender elements to the GDS Bender Element Master Signal Conditioning Unit and Slave Box (if using a slave box) and turn them on.
14. Start the GDS software.
15. Take initial S-wave, P-wave, pressure, and moisture measurements.
16. Add the specified amount of water for the test.
17. Wait the specified amount of time for the test.
18. Take measurements for the S-wave, P-wave, pressure, and moisture after each wait time.
19. Repeat saturation process until the sample is fully saturated.
20. After the last measurements are taken, close the GDS software, and unplug the bender elements from the GDS Bender Element Master Signal Conditioning Unit and Slave Box and turn them off.

## 7.5 Static testing

Static tests can be conducted using either the cylindrical or cube UNIT device. A single test can use one of many configurations for the bender elements. The setup procedures for each configuration are detailed below.

### 7.5.1 Static - horizontal elements

1. Cover the holes in the bottom of the specimen container, the drainhole, and element opening with tape.
2. Place a solid porous stone on the bottom of the specimen container.
3. Apply a thin coating of silicon grease on the bottom edge of the cylinder to ensure a tight seal between the cylinder and the bottom of the specimen container. It is important that no silicon grease gets inside the cylinder.
4. Place the cylinder over the porous stone, with the metal pegs facing forward, and press securely into place.
5. Place rubber plugs into the element openings in the side of the cylinder to prevent the soil from spilling out when the sample is built; if needed use tape to hold them in place.
6. Build the soil sample (four layers for the cylindrical UNIT or five layers for the cube UNIT). Ensure each layer is measured out and hammered to desired energy.
7. Take the rubber plugs out of the side of the cylinder; coat the outside of the bender elements with vacuum grease and attach the elements to the poles on each side of the specimen container.
8. Secure the top of the specimen container with screws.
9. Place the bender elements into the openings on the side of the cylinder, Figure 7.2-B. Ensure the bender elements are level and straight before inserting them into the openings. If the bender elements are misaligned, the signal readings will be inaccurate.
  - a. **For Horizontal Parallel Elements:** Orient the bender elements' transmitter and receiver parallel to one another, Figure 7.4-A.
  - b. **For Horizontal Perpendicular Elements:** Orient the bender elements' transmitter and receiver perpendicular to one another as shown in Figure 7.4-B.
10. Connect the bender elements to the GDS Bender Element Master Signal Conditioning Unit and Slave Box (if using a slave box) and turn them on.
11. Insert the moisture and the pressure sensors into the sample.
12. Start the GDS software.
13. Take initial S-wave, P-wave (if taking P-wave), pressure, and moisture measurements.
14. Add the specified amount of water for the test.
15. Wait the specified amount of time for the test.
16. Take measurements for the S-wave, P-wave (if taking P-wave), pressure, and moisture after each wait time.
17. Repeat saturation process until the sample is fully saturated.

18. After the last measurements are taken, close the GDS software and unplug the bender elements from the GDS Bender Element Master Signal Conditioning Unit and Slave Box and turn them off.

### 7.5.2 Static - vertical elements

1. Cover the bottom drain hole in the specimen container with tape.
2. Place a porous stone with an opening in the middle on the bottom of the specimen container.
3. Put a rubber plug into the opening in the bottom of the specimen container and stone; use tape to hold it in place.
4. Apply a thin coating of silicon grease on the bottom edge of the cylinder to ensure a tight seal between the cylinder and the bottom of the specimen container. It is important that no silicon grease gets inside the cylinder.
5. Put the cylinder over the porous stone, with the metal pegs facing forward, and press securely into place.
6. Place rubber plugs into the element openings in the side of the cylinder to prevent the soil from spilling out when the sample is built; if needed use tape to hold them in place.
7. Build the soil sample (four layers for the cylindrical UNIT or five layers for the cube UNIT). Ensure each layer is measured out and hammered to desired energy.
8. Take the rubber plug out of the bottom of the cylinder carefully; place a large bead of vacuum grease around the outside of the bender element and place the element into the opening in the bottom of the specimen container, Figure 7.2-A. Place tape on the bottom edges of the bender element to secure it to the specimen container.
9. Place the top on the specimen container and screw it down.
10. Place a small bead of silicone grease around the outside of another bender element, Figure 7.2-A. Place the element through the opening in the top of the specimen container and porous stone. Ensure the bender elements are level and straight before inserting them into the openings. If the bender elements are misaligned, the signal readings will be inaccurate.
  - a. **For Vertical Parallel Elements:** Orient the bender elements' transmitter and receiver parallel to one another, Figure 7.4-A.
  - b. **For Vertical Perpendicular Elements:** Orient the bender elements' transmitter and receiver perpendicular to one another, Figure 7.4-B.
11. Connect the bender elements to the GDS Bender Element Master Signal Conditioning Unit and Slave Box (if using a slave box) and turn them on.
12. Insert the moisture and the pressure sensors into the sample.

13. Start the GDS software.
14. Take initial S-wave, P-wave (if taking P-wave), pressure, and moisture measurements.
15. Add the specified amount of water for the test.
16. Wait the specified amount of time for the test.
17. Take measurements for the S-wave, P-wave (if taking P-wave), pressure, and moisture after each wait time.
18. Repeat saturation process until the sample is fully saturated.
19. After the last measurements are taken, close the GDS software and unplug the bender elements from the GDS Bender Element Master Signal Conditioning Unit and Slave Box and turn them off.

### **7.5.3 Static - 90 degree elements (bottom and side elements)**

1. Cover the bottom drain hole in the specimen container with tape.
2. Place a porous stone with an opening in the middle on the bottom of the specimen container.
3. Put a rubber plug into the opening in the bottom of the specimen container and stone; use tape to hold it in place.
4. Apply a thin coating of silicon grease on the bottom edge of the cylinder to ensure a tight seal between the cylinder and the bottom of the specimen container. It is important that no silicon grease gets inside the cylinder.
5. Put the cylinder over the porous stone, with the metal pegs facing forward, and press securely into place.
6. Place rubber plugs into the element openings in the side of the cylinder to prevent the soil from spilling out when the sample is built; if needed use tape to hold them in place.
7. Build the soil sample (four layers for the cylindrical UNIT or five layers for the cube UNIT). Ensure each layer is measured out and hammered to desired energy.
8. Take the rubber plug out of the bottom of the cylinder carefully; place a large bead of vacuum grease around the outside of the bender element and place the element into the opening in the bottom of the specimen container. Orientation of the transmitter and receiver (parallel or perpendicular) is not important for this configuration. Place tape on the bottom edges of the bender element to secure it to the specimen container.
9. Take one of the rubber plugs out of the side of the cylinder (whichever side desired); coat the outside of the bender elements with vacuum grease and attach the element to the pole on the side of the specimen container, Figure 7.2-C
10. Place the top on the specimen container and screw it down.

11. Place the bender element into one of the openings on the side, Figure 7.2-C.
12. Connect the bender elements to the GDS Bender Element Master Signal Conditioning Unit and Slave Box (if using a slave box) and turn them on.
13. Insert the moisture and the pressure sensors into the sample.
14. Start the GDS software.
15. Take initial S-wave, P-wave (if taking P-wave), pressure, and moisture measurements.
16. Add the specified amount of water for the test.
17. Wait the specified amount of time for the test.
18. Take measurements for the S-wave, P-wave (if taking P-wave), pressure, and moisture after each wait time.
19. Repeat saturation process until the sample is fully saturated.
20. After the last measurements are taken, close the GDS software and unplug the bender elements from the GDS Bender Element Master Signal Conditioning Unit and Slave Box and turn them off.

#### **7.5.4 Static - 90 degree elements (top and side elements)**

1. Cover the bottom holes (the drain hole and the element opening) in the specimen container with tape.
2. Place a solid porous stone on the bottom of the specimen container.
3. Apply a thin coating of silicon grease on the bottom edge of the cylinder to ensure a tight seal between the cylinder and the bottom of the specimen container. It is important that no silicon grease gets inside the cylinder.
4. Put the cylinder over the porous stone, with the metal pegs facing forward, and press securely into place.
5. Place rubber plugs into the element openings in the side of the cylinder to prevent the soil from spilling out when the sample is built; if needed use tape to hold them in place.
6. Build the soil sample (four layers for the cylindrical UNIT or five layers for the cube UNIT). Ensure each layer is measured out and hammered to desired energy.
7. Take one of the rubber plugs out of the side of the cylinder (whichever side desired); coat the outside of the bender elements with vacuum grease and attach the element to the pole on the side of the specimen container.
8. Place the top on the specimen container and screw it down.
9. Place a small bead of vacuum grease around the outside of another bender element. Place the element through the opening in the top of the specimen container and porous stone, Figure 7.2-D. Orientation of the transmitter and receiver (parallel or perpendicular) is not important for this configuration.

10. Place the bender element into the side opening, Figure 7.2-D.
11. Connect the bender elements to the GDS Bender Element Master Signal Conditioning Unit and Slave Box (if using a slave box) and turn them on.
12. Insert the moisture and the pressure sensors into the sample.
13. Start the GDS software.
14. Take initial S-wave, P-wave (if taking P-wave), pressure, and moisture measurements.
15. Add the specified amount of water for the test.
16. Wait the specified amount of time for the test.
17. Take measurements for the S-wave, P-wave (if taking P-wave), pressure, and moisture after each wait time.
18. Repeat saturation process until the sample is fully saturated.
19. After the last measurements are taken, close the GDS software and unplug the bender elements from the GDS Bender Element Master Signal Conditioning Unit and Slave Box and turn them off.

#### **7.5.5 Static - four elements perpendicular**

1. Cover the bottom drain hole in the specimen container with tape.
2. Place a porous stone with an opening in the middle on the bottom of the specimen container.
3. Put a rubber plug into the opening in the bottom of the specimen container and stone; use electrical tape to hold it in place.
4. Apply a thin coating of silicon grease on the bottom edge of the cylinder to ensure a tight seal between the cylinder and the bottom of the specimen container. It is important that no silicon grease gets inside the cylinder.
5. Put the cylinder over the porous stone, with the metal pegs facing forward, and press securely into place.
6. Place rubber plugs into the element openings in the side of the cylinder to prevent the soil from spilling out when the sample is built; if needed use tape to hold them in place.
7. Build the soil sample (four layers for the cylindrical UNIT or five layers for the cube UNIT). Ensure each layer is measured out and hammered to desired energy.
8. Take the rubber plug out of the bottom of the cylinder carefully; place a large bead of vacuum grease around the outside of the bender element and place the element into the opening in the bottom of the specimen container. Place tape on the bottom edges of the bender element to secure it to the specimen container.
9. Place the top on the specimen container and screw it down.

10. Place a small bead of vacuum grease around the outside of another bender element. Place the element through the opening in the top of the specimen container and porous stone, Figure 7.3. Make sure the top and bottom elements are perpendicular to each other before inserting them into the openings, Figure 7.4-B. Also, try and make them as straight as possible; if they are at an angle to each other, different readings will be obtained.
11. Take the rubber plugs out of the side of the cylinder; coat the outside of the bender elements with vacuum grease and attach the elements to the poles on each side of the specimen container.
12. Place the bender elements into the openings on the side, Figure 7.3. Make sure the elements are perpendicular to each other before inserting them into the openings, Figure 7.4-B. Also, try and make them as straight as possible; if they are at an angle to each other, one will get different readings.
13. Connect the bender elements to the GDS Bender Element Master Signal Conditioning Unit and Slave Box (if using a slave box) and turn them on.
14. Insert the moisture and the pressure sensors into the sample.
15. Start the GDS software.
16. Take initial S-wave, P-wave (if taking P-wave), pressure, and moisture measurements.
17. Add the specified amount of water for the test.
18. Wait the specified amount of time for the test.
19. Take measurements for the S-wave, P-wave (if taking P-wave), pressure, and moisture after each wait time.
20. Repeat saturation process until the sample is fully saturated.
21. After the last measurements are taken, close the GDS software and unplug the bender elements from the GDS Bender Element Master Signal Conditioning Unit and Slave Box and turn them off.

#### **7.5.6 Static - four elements parallel**

1. Cover the bottom drain hole in the specimen container with tape.
2. Place a porous stone with an opening in the middle on the bottom of the specimen container.
3. Put a rubber plug into the opening in the bottom of the specimen container and stone; use electrical tape to hold it in place.
4. Apply a thin coating of silicon grease on the bottom edge of the cylinder to ensure a tight seal between the cylinder and the bottom of the specimen container. It is important that no silicon grease gets inside the cylinder.
5. Put the cylinder over the porous stone, with the metal pegs facing forward, and press securely into place.

6. Place rubber plugs into the element openings in the side of the cylinder to prevent the soil from spilling out when the sample is built; if needed use tape to hold them in place.
7. Build the soil sample (four layers for the cylindrical UNIT or five layers for the cube UNIT). Ensure each layer is measured out and hammered to desired energy.
8. Take the rubber plug out of the bottom of the cylinder carefully; place a large bead of vacuum grease around the outside of the bender element and place the element into the opening in the bottom of the specimen container. Place tape on the bottom edges of the bender element to secure it to the specimen container.
9. Place the top on the specimen container and screw it down.
10. Place a small bead of vacuum grease around the outside of another bender element. Place the element through the opening in the top of the specimen container and porous stone, Figure 7.3. Make sure the top and bottom elements are parallel to each other, Figure 7.4-A, before inserting them into the openings. Also, try and make them as straight as possible; if they are at an angle to each other, different readings will be obtained.
11. Take the rubber plugs out of the side of the cylinder; coat the outside of the bender elements with vacuum grease and attach the elements to the poles on each side of the specimen container.
12. Place the bender elements into the openings on the side, Figure 7.3. Make sure the elements are parallel to each other, Figure 7.4-A, before inserting them into the openings. Again, ensure they are positioned as straight as possible; if they are at an angle to each other, different readings will be obtained.
13. Connect the bender elements to the GDS Bender Element Master Signal Conditioning Unit and Slave Box (if using a slave box) and turn them on.
14. Insert the moisture and the pressure sensors into the sample.
15. Start the GDS software.
16. Take initial S-wave, P-wave (if taking P-wave), pressure, and moisture measurements.
17. Add the specified amount of water for the test.
18. Wait the specified amount of time for the test.
19. Take measurements for the S-wave, P-wave (if taking P-wave), pressure, and moisture after each wait time.
20. Repeat saturation process until the sample is fully saturated.
21. After the last measurements are taken, close the GDS software and unplug the bender elements from the GDS Bender Element Master Signal Conditioning Unit and Slave Box and turn them off.

## 7.6 Water additions to the static UNIT specimen

The procedure for water addition for the Cube UNIT and the source test UNIT samples included the addition of different amounts of water associated to a specified waiting time (15 mL/10 minutes, 20 mL/12.5 minutes, 40 mL/15 minutes, and 50 mL/20 minutes). The amount of water needed to keep the samples constant for every test was deduced by determining the porosity at a specified compaction energy level and the air volume of the sample. The air volume then relates to the water volume of the sample at saturation.

Readings were taken for the cylinder specimen container over a 72-hour time period. The results showed that up to 4 hours after the water addition, the signal stabilized (Figure 7.6). After the fifth hour, the signal started to vary. It was concluded that the optimum time to take a reading was 1 hour after the water was added to the sample.

Readings were taken for the cube specimen container over a 48-hour time period. The results showed that the signal stabilized after the water addition during hours 4 through 7 (Figure 7.7). Before the fourth hour and after the eighth hour, the signal varied. It was concluded that the optimum time to take a reading was four hours after the water was added to the sample.

The top stone was left off when doing the static source test in the cylinder specimen container to provide a free surface for the specimen.

Figure 7.6. Seventy-two-hr graph of 15 ml water addition to cylinder UNIT sample.

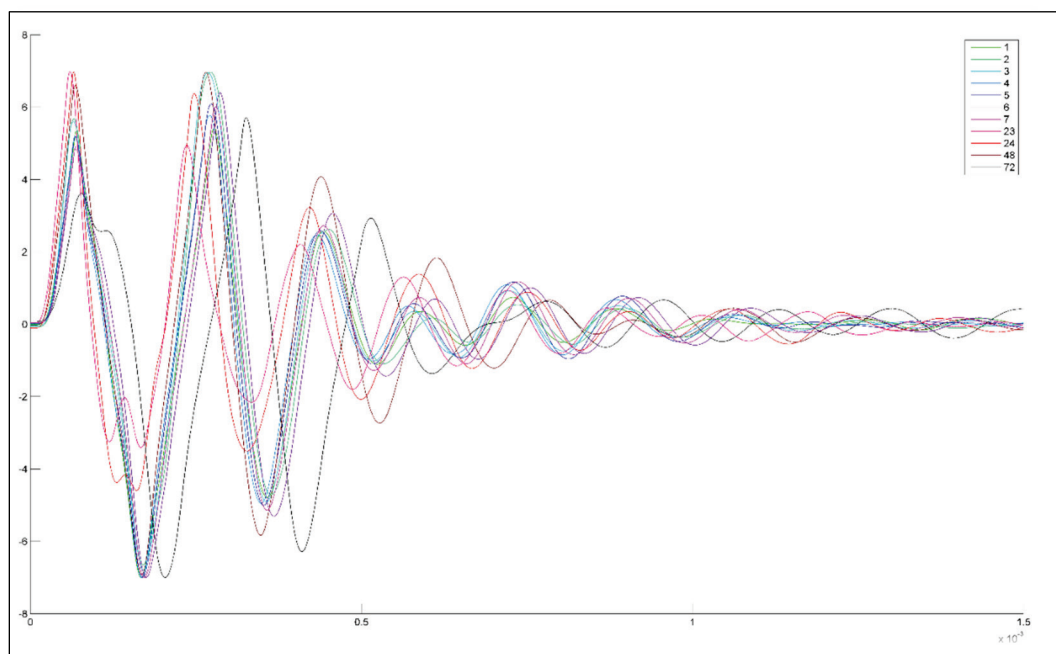
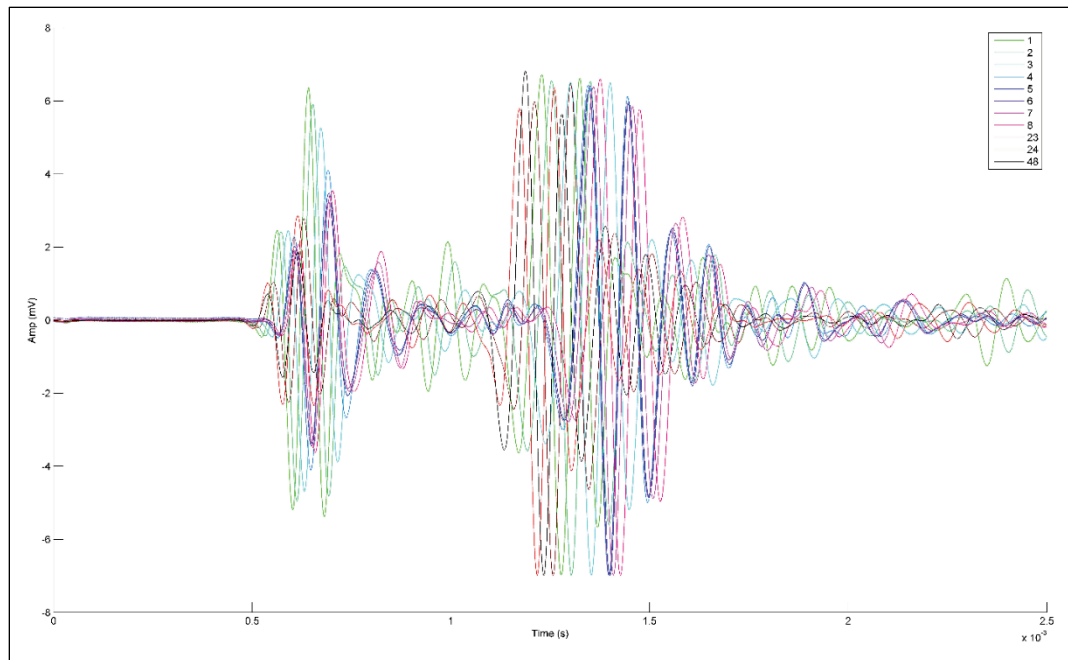


Figure 7.7. Forty-eight-hr graph of 70 ml water addition to cube UNIT sample.

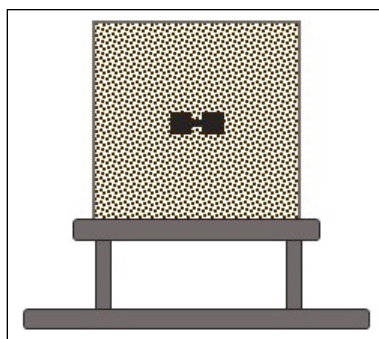


## 7.7 Dynamic source test

The source test is used as a base line to determine how the bender elements' signal performs during wetting and drying cycles without a substance between them. The source test creates a base line for the signal. The protocol for conducting a dynamic source test uses the cylindrical UNIT device, but the base-line data obtained from the source test is applicable to any dynamic test, whether done with the cylindrical or cube device.

For the dynamic source test, the bender elements are placed with the transmitter and receiver parallel, Figure 7.4-A, and in contact with each other in the center of the specimen, Figure 7.8. The step-by-step procedure for completing the dynamic source test is detailed below.

Figure 7.8 Dynamic source test bender element placement.



1. Connect the drain spout to the drain hole in the bottom of the specimen container.
2. Place a solid porous stone on the bottom of the specimen container.
3. Apply a thin coating of silicon grease on the bottom edge of the cylinder to ensure a tight seal between the cylinder and the bottom of the specimen container. It is important that no silicon grease gets inside the cylinder.
4. Put the cylinder over the porous stone, with the metal pegs facing forward, and press securely into place.
5. Place rubber plugs into the element openings in the side of the cylinder to prevent the soil from spilling out when the sample is built; if needed use tape to hold them in place.
6. Build two layers of the soil. Ensure each layer is measured out and hammered to desired energy.
7. Insert the moisture sensor into the sample.
8. Place the bender elements in the center of the sample on top of the second layer of soil. Place the elements where they are close enough to touch, the same as the static source test shown in Figure 7.5. Be sure the elements are parallel to each other, Figure 7.4-A. Make them as straight as possible; if they are at an angle to each other, different readings will be obtained. Tape the elements in place when finished positioning them.
9. Measure out the next layer of soil (the same amount as the first two but less the weight of the elements). Hammer this layer into place.
10. Add the final layer to the specimen.
11. Place the top, with porous stone, on the specimen container and screw it down.
12. Place a bead of vacuum grease around the edge of the small reservoir and place it onto the top of the specimen container.
13. Connect the bender elements to the GDS Bender Element Master Signal Conditioning Unit and Slave Box (if using a slave box) and turn them on.
14. Connect a hose from the water pump (which is in a bucket of water) to the large reservoir that is located on the wall above the sample. Also, connect a hose from the overflow port in the large reservoir to the water bucket.
15. Connect a hose from the bottom of the large reservoir to the small reservoir on top of the sample. Also, connect a hose from the overflow in the small reservoir to the water bucket.
16. Connect a hose from the drain port at the bottom of the sample to the water bucket.
17. Start the GDS software.
18. Take initial S-wave, P-wave (if taking P-wave), pressure, and moisture measurements.

19. Turn on the water pump and begin the water flow through the sample.
20. Take measurements for the S-wave, P-wave (if taking P-wave), pressure, and moisture at a pre-determined interval.
21. Repeat the measurements until the sample is saturated and has flowed for 30 minutes after saturation.
22. After the last measurements are taken, close the GDS software and unplug the bender elements from the GDS Bender Element Master Signal Conditioning Unit and Slave Box and turn them off.
23. Disconnect all the hoses from the sample.
24. Dump the top layers into a pan to dry.
25. Take out the bender elements and clean off the sand and vacuum grease.
26. Dump the remaining soil into a pan for drying and clean the cylinder and the specimen container of soil and vacuum grease.

## **7.8 Dynamic testing**

Dynamic tests can be conducted using either the cylindrical or cube UNIT device. A single test can use one of many configurations for the bender elements. The setup procedures for each configuration are detailed below.

### **7.8.1 Dynamic - horizontal elements**

1. Connect the drain spout to the drain hole in the bottom of the specimen container.
2. Place a solid porous stone on the bottom of the specimen container.
3. Apply a thin coating of silicon grease on the bottom edge of the cylinder to ensure a tight seal between the cylinder and the bottom of the specimen container. It is important that no silicon grease gets inside the cylinder.
4. Put the cylinder over the porous stone, with the metal pegs facing forward, and press securely into place.
5. Place rubber plugs into the element openings in the side of the cylinder to prevent the soil from spilling out when the sample is built; if needed use tape to hold them in place.
6. Build the soil sample (four layers for the cylindrical UNIT or five layers for the cube UNIT). Ensure each layer is measured out and hammered to desired energy.
7. Take the rubber plugs out of the side of the cylinder; coat the outside of the bender elements with vacuum grease and attach the elements to the poles on each side of the specimen container.
8. Place the top, with porous stone, on the specimen container and screw it down.

9. When using cylindrical UNIT device, place a bead of vacuum grease around the edge of the small reservoir and place it onto the top of the specimen container. For the cube device this step is not needed because the reservoir is built into the top plate of the design.
10. Place the bender elements into the openings on the side of the cylinder, Figure 7.2-B. Ensure the bender elements are level and straight before inserting them into the openings. If the bender elements are misaligned, the signal readings will be inaccurate.
  - a. **For Horizontal Parallel Elements:** Orient the bender elements' transmitter and receiver parallel to one another, Figure 7.4-A.
  - b. **For Horizontal Perpendicular Elements:** Orient the bender elements' transmitter and receiver perpendicular to one another as shown in Figure 7.4-B.
11. Connect the bender elements to the GDS Bender Element Master Signal Conditioning Unit and Slave Box (if using a slave box) and turn them on.
12. Insert the moisture and the pressure sensors into the sample.
13. Connect a hose from the water pump (which is in a bucket of water) to the large reservoir that is located on the wall above the sample. Also, connect a hose from the overflow port in the large reservoir to the water bucket.
14. Connect a hose from the bottom of the large reservoir to the small reservoir on top of the sample. Also, connect a hose from the overflow in the small reservoir to the water bucket.
15. Connect a hose from the drain port at the bottom of the sample to the water bucket.
16. Start the GDS software.
17. Take initial S-wave, P-wave (if taking P-wave), pressure, and moisture measurements.
18. Turn the water pump on and begin water flow through the sample.
19. Take measurements for the S-wave, P-wave (if taking P-wave), pressure, and moisture at a pre-determined interval.
20. Repeat the measurements until the sample is saturated and has flowed for 30 minutes after saturation.
21. After the last measurements are taken, close the GDS software and unplug the bender elements from the GDS Bender Element Master Signal Conditioning Unit and Slave Box and turn them off.

### 7.8.2 Dynamic - vertical elements

1. Connect the drain spout to the drain hole in the bottom of the specimen container.

2. Place a porous stone with an opening in the middle on the bottom of the specimen container.
3. Put a rubber plug into the opening in the bottom of the specimen container and stone; use tape to hold it in place.
4. Apply a thin coating of silicon grease on the bottom edge of the cylinder to ensure a tight seal between the cylinder and the bottom of the specimen container. It is important that no silicon grease gets inside the cylinder.
5. Put the cylinder over the porous stone, with the metal pegs facing forward, and press securely into place.
6. Place rubber plugs into the element openings in the side of the cylinder to prevent the soil from spilling out when the sample is built; if needed use tape to hold them in place.
7. Build the soil sample (four layers for the cylindrical UNIT or five layers for the cube UNIT). Ensure each layer is measured out and hammered to desired energy.
8. Take the rubber plug out of the bottom of the cylinder carefully; place a large bead of vacuum grease around the outside of the bender element and place the element into the opening in the bottom of the specimen container, Figure 7.2-A. Place tape on the bottom edges of the bender element to secure it to the specimen container.
9. Place the top, with porous stone, on the specimen container and screw it down.
10. Place a bead of vacuum grease around the edge of the small reservoir and place it onto the top of the specimen container.
11. Place a small bead of vacuum grease around the outside of another bender element.
12. Place the element through the opening in the top of the specimen container and porous stone, Figure 7.2-A. Ensure the bender elements are level and straight before inserting them into the openings. If the bender elements are misaligned, the signal readings will be inaccurate.
  - a. **For Horizontal Parallel Elements:** Orient the bender elements' transmitter and receiver parallel to one another, Figure 7.4-A.
  - b. **For Horizontal Perpendicular Elements:** Orient the bender elements' transmitter and receiver perpendicular to one another as shown in Figure 7.4-B
13. Connect the bender elements to the GDS Bender Element Master Signal Conditioning Unit and Slave Box (if using a slave box) and turn them on.
14. Insert the moisture and the pressure sensors into the sample.

15. Connect a hose from the water pump (which is in a bucket of water) to the large reservoir that is located on the wall above the sample. Also, connect a hose from the overflow port in the large reservoir to the water bucket.
16. Connect a hose from the bottom of the large reservoir to the small reservoir on top of the sample. Also, connect a hose from the overflow in the small reservoir to the water bucket.
17. Connect a hose from the drain port at the bottom of the sample to the water bucket.
18. Start the GDS software.
19. Take initial S-wave, P-wave (if taking P-wave), pressure, and moisture measurements.
20. Turn on the water pump and begin the water flow through the sample.
21. Take measurements for the S-wave, P-wave (if taking P-wave), pressure, and moisture at a pre-determined interval.
22. Repeat the measurements until the sample is saturated and has flowed for 30 minutes after saturation.
23. After the last measurements are taken, close the GDS software and unplug the bender elements from the GDS Bender Element Master Signal Conditioning Unit and Slave Box and turn them off.

### **7.8.3 Dynamic - 90 degree elements (bottom and side elements)**

1. Connect the drain spout to the drain hole in the bottom of the specimen container.
2. Place a porous stone with an opening in the middle on the bottom of the specimen container.
3. Put a rubber plug into the opening in the bottom of the specimen container and stone; use tape to hold it in place.
4. Apply a thin coating of silicon grease on the bottom edge of the cylinder to ensure a tight seal between the cylinder and the bottom of the specimen container. It is important that no silicon grease gets inside the cylinder.
5. Put the cylinder over the porous stone, with the metal pegs facing forward, and press securely into place.
6. Place rubber plugs into the element openings in the side of the cylinder to prevent the soil from spilling out when the sample is built; if needed use tape to hold them in place.
7. Build the soil sample (four layers for the cylindrical UNIT or five layers for the cube UNIT). Ensure each layer is measured out and hammered to desired energy.
8. Take the rubber plug out of the bottom of the cylinder carefully; place a large bead of vacuum grease around the outside of the bender element and

- place the element into the opening in the bottom of the specimen container, Figure 7.2-C. Place tape on the bottom edges of the bender element to secure it to the specimen container.
9. Take one of the rubber plugs out of the side of the cylinder (whichever side desired); coat the outside of the bender elements with vacuum grease and attach the element to the pole on the side of the specimen container, Figure 7.2-C.
  10. Place the top, with porous stone, on the specimen container and screw it down.
  11. When using cylindrical UNIT device, place a bead of vacuum grease around the edge of the small reservoir and place it onto the top of the specimen container. For the cube device this step is not needed because the reservoir is built into the top plate of the design.
  12. Place the bender element into one of the openings on the side.
  13. Connect the bender elements to the GDS Bender Element Master Signal Conditioning Unit and Slave Box (if using a slave box) and turn them on.
  14. Insert the moisture and the pressure sensors into the sample.
  15. Connect a hose from the water pump (which is in a bucket of water) to the large reservoir that is located on the wall above the sample. Also, connect a hose from the overflow port in the large reservoir to the water bucket.
  16. Connect a hose from the bottom of the large reservoir to the small reservoir on top of the sample. Also, connect a hose from the overflow in the small reservoir to the water bucket.
  17. Connect a hose from the drain port at the bottom of the sample to the water bucket.
  18. Start the GDS software.
  19. Take initial S-wave, P-wave (if taking P-wave), pressure, and moisture measurements.
  20. Turn on the water pump and begin the water flow through the sample.
  21. Take measurements for the S-wave, P-wave (if taking P-wave), pressure, and moisture at a pre-determined interval.
  22. Repeat the measurements until the sample is saturated and has flowed for 30 minutes after saturation.
  23. After the last measurements are taken, close the GDS software and unplug the bender elements from the GDS Bender Element Master Signal Conditioning Unit and Slave Box and turn them off.

#### **7.8.4 Dynamic - 90 degree elements (top and side elements)**

1. Connect the drain spout to the drain hole in the bottom of the specimen container.

2. Place a solid porous stone on the bottom of the specimen container.
3. Apply a thin coating of silicon grease on the bottom edge of the cylinder to ensure a tight seal between the cylinder and the bottom of the specimen container. It is important that no silicon grease gets inside the cylinder.
4. Put the cylinder over the porous stone, with the metal pegs facing forward, and press securely into place.
5. Place rubber plugs into the element openings in the side of the cylinder to prevent the soil from spilling out when the sample is built; if needed use tape to hold them in place.
6. Build the soil sample (four layers for the cylindrical UNIT or five layers for the cube UNIT). Ensure each layer is measured out and hammered to desired energy.
7. Take one of the rubber plugs out of the side of the cylinder (whichever side desired); coat the outside of the bender elements with vacuum grease and attach the element to the pole on the side of the specimen container, Figure 7.2-D.
8. Place the top, with porous stone, on the specimen container and screw it down.
9. When using cylindrical UNIT device, place a bead of vacuum grease around the edge of the small reservoir and place it onto the top of the specimen container. For the cube device this step is not needed because the reservoir is built into the top plate of the design.
10. Place a small bead of vacuum grease around the outside of another bender element. Place the element through the opening in the top of the specimen container and porous stone, Figure 7.2-D.
11. Place the bender element into the opening on the side.
12. Connect the bender elements to the GDS Bender Element Master Signal Conditioning Unit and Slave Box (if using a slave box) and turn them on.
13. Insert the moisture and the pressure sensors into the sample.
14. Connect a hose from the water pump (which is in a bucket of water) to the large reservoir that is located on the wall above the sample. Also, connect a hose from the overflow port in the large reservoir to the water bucket.
15. Connect a hose from the bottom of the large reservoir to the small reservoir on top of the sample. Also, connect a hose from the overflow in the small reservoir to the water bucket.
16. Connect a hose from the drain port at the bottom of the sample to the water bucket.
17. Start the GDS software.
18. Take initial S-wave, P-wave (if taking P-wave), pressure, and moisture measurements.

19. Turn on the water pump and begin the water flow through the sample.
20. Take measurements for the S-wave, P-wave (if taking P-wave), pressure, and moisture at a pre-determined interval.
21. Repeat the measurements until the sample is saturated and has flowed for 30 minutes after saturation.
22. After the last measurements are taken, close the GDS software and unplug the bender elements from the GDS Bender Element Master Signal Conditioning Unit and Slave Box and turn them off.

#### **7.8.5 Dynamic - four elements perpendicular**

1. Connect the drain spout to the drain hole in the bottom of the specimen container.
2. Place a porous stone with an opening in the middle on the bottom of the specimen container.
3. Put a rubber plug into the opening in the bottom of the specimen container and stone; use tape to hold it in place.
4. Apply a thin coating of silicon grease on the bottom edge of the cylinder to ensure a tight seal between the cylinder and the bottom of the specimen container. It is important that no silicon grease gets inside the cylinder.
5. Put the cylinder over the porous stone, with the metal pegs facing forward, and press securely into place.
6. Place rubber plugs into the element openings in the side of the cylinder to prevent the soil from spilling out when the sample is built; if needed use tape to hold them in place.
7. Build the soil sample (four layers for the cylindrical UNIT or five layers for the cube UNIT). Ensure each layer is measured out and hammered to desired energy.
8. Take the rubber plug out of the bottom of the cylinder carefully; place a large bead of vacuum grease around the outside of the bender element and place the element into the opening in the bottom of the specimen container, Figure 7.3. Place tape on the bottom edges of the bender element to secure it to the specimen container.
9. Place the top, with porous stone, on the specimen container and screw it down.
10. When using cylindrical UNIT device, place a bead of vacuum grease around the edge of the small reservoir and place it onto the top of the specimen container. For the cube device this step is not needed because the reservoir is built into the top plate of the design.
11. Place a small bead of vacuum grease around the outside of another bender element. Place the element through the opening in the top of the specimen

- container and porous stone, Figure 7.3. Make sure the top and bottom elements are perpendicular to each other, Figure 7.4-B, before inserting them into the openings. Also, try and make them as straight as possible; if they are at an angle to each other, different readings will be obtained.
12. Take the rubber plugs out of the side of the cylinder; coat the outside of the bender elements with vacuum grease and attach the elements to the poles on each side of the specimen container, Figure 7.3.
  13. Place the bender elements into the openings on the side, Figure 7.3. Make sure the elements are perpendicular to each other before inserting them into the openings, Figure 7.4-B. Also, try and make them as straight as possible; if they are at an angle to each other different readings will be obtained.
  14. Connect the bender elements to the GDS Bender Element Master Signal Conditioning Unit and Slave Box (if using a slave box) and turn them on.
  15. Insert the moisture and the pressure sensors into the sample.
  16. Connect a hose from the water pump (which is in a bucket of water) to the large reservoir that is located on the wall above the sample. Also, connect a hose from the overflow port in the large reservoir to the water bucket.
  17. Connect a hose from the bottom of the large reservoir to the small reservoir on top of the sample. Also, connect a hose from the overflow in the small reservoir to the water bucket.
  18. Connect a hose from the drain port at the bottom of the sample to the water bucket.
  19. Start the GDS software.
  20. Take initial S-wave, P-wave (if taking P-wave), pressure, and moisture measurements.
  21. Turn on the water pump and begin the water flow through the sample.
  22. Take measurements for the S-wave, P-wave (if taking P-wave), pressure, and moisture at a pre-determined interval.
  23. Repeat the measurements until the sample is saturated and has flowed for 30 minutes after saturation.
  24. After the last measurements are taken, close the GDS software and unplug the bender elements from the GDS Bender Element Master Signal Conditioning Unit and Slave Box and turn them off.

#### **7.8.6 Dynamic - four elements parallel**

1. Connect the drain spout to the drain hole in the bottom of the specimen container.
2. Place a porous stone with an opening in the middle on the bottom of the specimen container.

3. Put a rubber plug into the opening in the bottom of the specimen container and stone; use tape to hold it in place.
4. Apply a thin coating of silicon grease on the bottom edge of the cylinder to ensure a tight seal between the cylinder and the bottom of the specimen container. It is important that no silicon grease gets inside the cylinder.
5. Put the cylinder over the porous stone, with the metal pegs facing forward, and press securely into place.
6. Place rubber plugs into the element openings in the side of the cylinder to prevent the soil from spilling out when the sample is built; if needed use tape to hold them in place.
7. Build the soil sample (four layers for the cylindrical UNIT or five layers for the cube UNIT). Ensure each layer is measured out and hammered to desired energy.
8. Take the rubber plug out of the bottom of the cylinder carefully; place a large bead of vacuum grease around the outside of the bender element and place the element into the opening in the bottom of the specimen container, Figure 7.3. Place tape on the bottom edges of the bender element to secure it to the specimen container.
9. Place the top, with porous stone, on the specimen container and screw it down.
10. When using cylindrical UNIT device, place a bead of vacuum grease around the edge of the small reservoir and place it onto the top of the specimen container. For the cube device this step is not needed because the reservoir is built into the top plate of the design.
11. Place a small bead of vacuum grease around the outside of another bender element. Place the element through the opening in the top of the specimen container and porous stone, Figure 7.3. Make sure the top and bottom elements are parallel to each other, Figure 7.4-A, before inserting them into the openings. Also, try and make them as straight as possible; if they are at an angle to each other, different readings will be obtained.
12. Take the rubber plugs out of the side of the cylinder; coat the outside of the bender elements with vacuum grease and attach the elements to the poles on each side of the specimen container, Figure 7.3.
13. Place the bender elements into the openings on the side, Figure 7.3. Make sure the elements are parallel to each other, Figure 7.4-A, before inserting them into the openings. Also, try and make them as straight as possible; if they are at an angle to each other, different readings will be obtained.
14. Connect the bender elements to the GDS Bender Element Master Signal Conditioning Unit and Slave Box (if using a slave box) and turn them on.
15. Insert the moisture and the pressure sensors into the sample.

16. Connect a hose from the water pump (which is in a bucket of water) to the large reservoir that is located on the wall above the sample. Also, connect a hose from the overflow port in the large reservoir to the water bucket.
17. Connect a hose from the bottom of the large reservoir to the small reservoir on top of the sample. Also, connect a hose from the overflow in the small reservoir to the water bucket.
18. Connect a hose from the drain port at the bottom of the sample to the water bucket.
19. Start the GDS software.
20. Take initial S-wave, P-wave (if taking P-wave), pressure, and moisture measurements.
21. Turn on the water pump to begin the water flow through the sample.
22. Take measurements for the S-wave, P-wave (if taking P-wave), pressure, and moisture at a pre-determined interval.
23. Repeat the measurements until the sample is saturated and has flowed for 30 minutes after saturation.

After the last measurements are taken, close the GDS software and unplug the bender elements from the GDS Bender Element Master Signal Conditioning Unit and Slave Box and turn them off.

## References

- ASTM D2216-10. 2010. *Standard test method for laboratory determination of water (moisture) content of soil and rock by mass*. Annual Book of ASTM Standards. West Conshohocken, PA: ASTM International.
- ASTM D6467-13. 2013. *Standard test method for torsional ring shear test to determine drained residual shear strength of cohesive soils*. Annual Book of ASTM Standards. West Conshohocken, PA: ASTM International.
- ASTM D7181-11. 2011. *Standard test method for consolidated drained triaxial compression test for soils*. Annual Book of ASTM Standards. West Conshohocken, PA: ASTM International.
- Bradshaw, A., and C. Baxter. 2007. Sample preparation of silts for liquefaction testing. *Geotechnical Testing Journal*. 30:324-332.
- Cho, G.-C., J. Dodds, and J. C. Santamarina. 2006. Particle shape effects on packing density, stiffness, and strength: Natural and crushed sands. *Journal of Geotechnical and Geoenvironmental Engineering* 132(5):591-602.
- Fannin, R. J., A. Eliadorani, and J. M. T. Wilkinson. 2005. Shear strength of cohesionless soils at low stress. *Geotechnique* 55(6):467-478.
- GCTS. 2011. *Dynamic hollow cylinder testing system manual*. Project #2274. Tempe, AR: GCTS Testing Systems.
- GCTS. 2014a. *Unsaturated soil triaxial test system manual*. Project #2993. Tempe, AR: GCTS Testing Systems.
- GCTS. 2014b. *Simple shear test system manual*. Project #2993. Tempe, AR: GCTS Testing Systems.
- GCTS. 2014c. *Soil ring shear test system manual*. Project #2822. Tempe, AR: GCTS Testing Systems.
- Huang, Y., H. L. Cheng, T. Osada, A. Hosoya, and A. Zhang. 2015. Mechanical behavior of clean sand at low confining pressure: Verification with element and model tests. *Journal of Geotechnical and Geoenvironmental Engineering* 141.
- Ladd, R. S. 1974. Specimen preparation and liquefaction of sands. *Journal of the Geotechnical Engineering Division* 100:1180-1184.
- Ladd, R. S. 1977. Specimen preparation and cyclic stability of sands. *Journal of the Geotechnical Engineering Division* 103:535-547.
- Lancelot, L., I. Shahrour, and M. A. Mahmoud. 2006. Failure and dilatancy properties of sand at relatively low stresses. *Journal of Engineering Mechanics* 132:1396-1399.

- Martin, K. E., O.-D. S. Taylor, W. W. Berry, and W. R. Rowland. 2014. *Near surface seismic signal response due to active fluid infiltration in partially saturated soil: Laboratory analysis of observational phenomenon*. (U) 2014 Joint Meeting of the Military Sensing Symposia (MSS) Specialty Groups. Washington, DC.
- Mulilis, J. P., H. B. Seed, and C. K. Chan. 1977. Effects of sample preparation on sand liquefaction. *Journal of the Geotechnical Engineering Division* 103:91-108.
- Taylor, O.-D. S. 2011. Use of an energy-based liquefaction approach to predicting deformation in silts due to pile driving. PhD thesis, University of Rhode Island, Kingston.
- Taylor, O.-D. S., W. W. Berry, K. E. Winters, W. R. Rowland, M. D. Antwine, and A. L. Cunningham. 2016. *Protocol for cohesionless sample preparation for physical experimentation*. ERDC/GSL TR-16-11. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

| REPORT DOCUMENTATION PAGE                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                             |                                                                                                             |                            | Form Approved<br>OMB No. 0704-0188                                  |                                           |
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| 14. ABSTRACT<br>Geotechnical laboratory testing focuses on the behavior of soils subjected to confining pressures in excess of those experienced within the near-surface environment (the upper 1 m of the soil profile). Such standardized protocols have set-up stresses, e.g., seating loads and stabilization vacuum pressures, in excess of the failure strength observed at low confinement. Therefore, effective stress principles are often used to infer low confinement behavior within a laboratory setting. Neither the standardized protocols nor the use of effective stress principles encapsulate the near-surface environment or the true behavior. The purpose of this technical report is to provide laboratory-testing protocols for physical experimentation within the near-surface environment. For standardized testing equipment, e.g., triaxial and simple shear devices, existing protocols have been modified. New testing protocols have been designed for experimental equipment, e.g., the Ultrasonic Near-Surface Inundation Testing device (UNIT) or for unconfined drained self-supporting testing (UD). The protocols presented herein are for commercial and prototype equipment used in the ERDC Geotechnical and Structures Laboratory (GSL) and are readily adaptable to other equipment manufacturers' devices. |                             |                                                                                                             |                            |                                                                     |                                           |
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