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Mechanical Testing of Soils from the South Range of the Utah Test and Training Range

Derivation of Soil Properties to Support the Earth Entry System Landing for Mars Sample Return

Brandon C. Artis
Applied Research Associates, Inc.
Albuquerque, New Mexico

April 2024

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Applied Research Associates, Inc. (ARA) conducted this soil study under contract to the NASA Langley Research Center (LaRC). The study was conducted to support landing performance analysis of the Earth Entry System (EES) for the Mars Sample Return (MSR) mission. The MSR-EES is a passive entry capsule being developed by NASA to return Mars soil and rock samples to Earth and is planned to land in the South Range of the U.S. Air Force Utah Test and Training Range (UTTR). ARA's soil test results described in this report were used to develop computational soil models to simulate the MSR-EES impact onto UTTR soil. Mr. James M. Corliss, LaRC, provided NASA oversight of this work.

The primary author of this report is Mr. Brandon C. Artis, with technical oversight from Dr. Courtney L. Busch, and contributions from Mr. Anthony "Mark" Wimmer, Mr. Robert Couch, and Mr. Troy Barber. All report contributors are engineers and geologists with ARA. CMT Technical Services of West Valley, Utah provided additional support in the field at UTTR by conducting in-situ geotechnical measurements and collecting some of the soil samples tested by ARA for this study. YeDoma Consultants, LLC of Albuquerque, New Mexico provided services to conduct direct shear tests of UTTR surface crust soil samples. The author also wishes to thank the U.S. Air Force personnel located at the Hill Air Force Base and UTTR Detachment 1 at the U.S. Army Dugway Proving Ground. The support from these personnel was essential to conduct the range operations necessary to collect the soil samples that ARA tested for this study.

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1 Introduction

This report summarizes results from laboratory tests conducted by Applied Research Associates, Inc. (ARA) on soil samples collected from multiple sites within the South Range of the U.S. Air Force Utah Test and Training Range (UTTR). The goal of the laboratory tests was to establish soil constitutive properties and develop computational soil models enabling NASA to simulate impact landings of the Earth Entry System (EES) for the Mars Sample Return (MSR) mission. Test methods and results are presented describing the strength, compressibility, and stiffness of soils in the UTTR South Range including methods to incorporate the measured properties into Ansys LS-DYNA® constitutive material models for EES landing simulations.

1.1 Background

The MSR-EES is an entry capsule being developed by NASA to return Mars soil and rock samples to Earth. After the Mars samples are inserted into the EES, the capsule is returned to Earth on a host spacecraft that releases the EES on an intercept trajectory to enter the Earth's atmosphere and land at UTTR. The EES capsule, shown conceptually in Figure 1-1, uses a blunt-body sphere-cone geometry, 1.2 meters to 1.4 meters in diameter, to pass through the Earth's atmosphere and aerodynamically decelerate to land at UTTR. The EES does not rely on a parachute for additional aerodynamic stability or drag during atmospheric descent or landing, and will therefore impact the ground at UTTR with a velocity as high as 45 m/s (100 mph). The landing impact loads must stay within acceptable limits to prevent damage to the Mars samples and preserve the mission's science objectives. The landing impact loads are dependent on the soil properties in the UTTR landing area. Therefore, the ARA laboratory tests described in this report were conducted to establish the UTTR soil properties and develop Ansys LS-DYNA® material models to simulate the EES ground impact and predict the resulting loads on the EES capsule and the Mars samples.

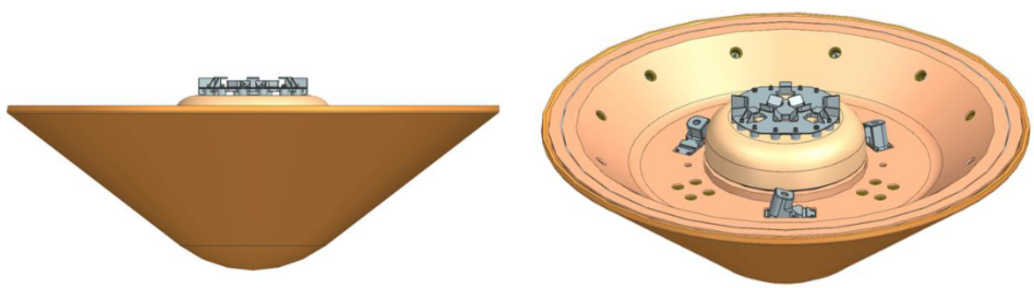
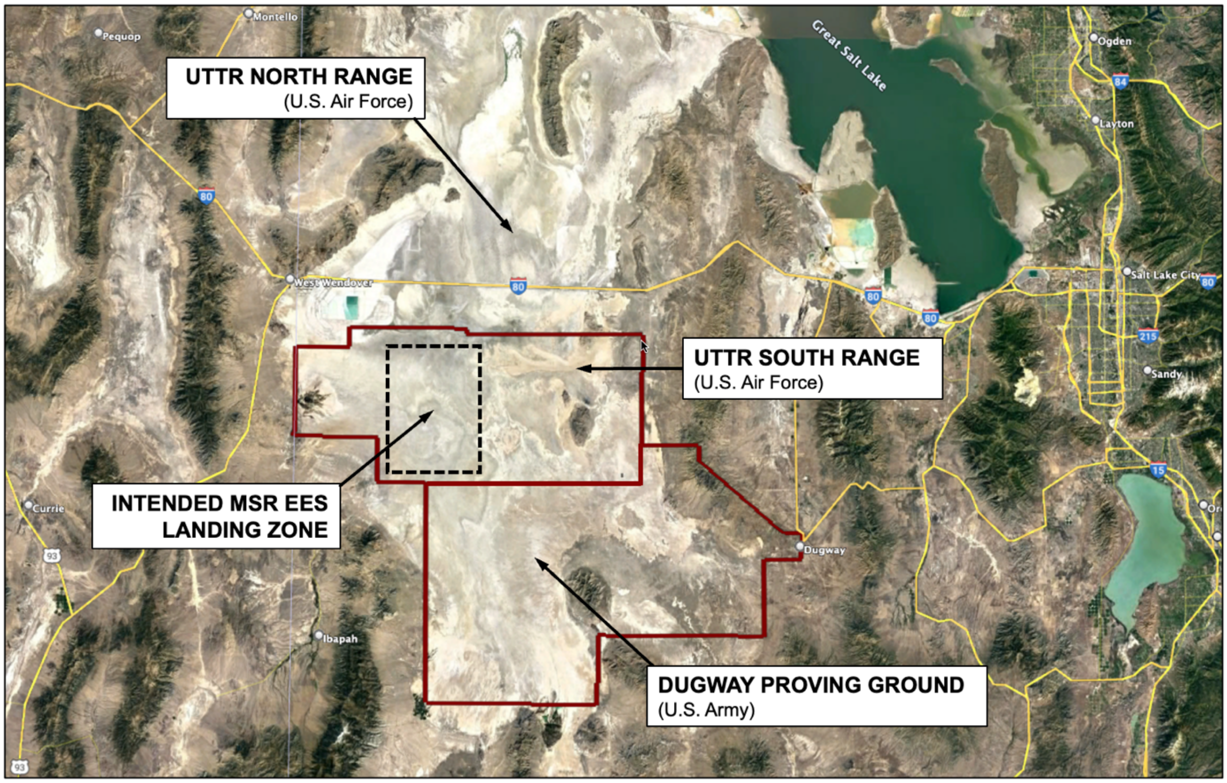


Image Credit: NASA Jet Propulsion Laboratory

Figure 1-1. Mars Sample Return Earth Entry System Concept

1.2 General Site and Soil Description

The UTTR is a U.S. Air Force range located approximately 130 kilometers west of Salt Lake City, Utah and is used extensively for munitions testing and pilot training. UTTR is comprised of a North Range and a South Range depicted in Figure 1-2 1-2, with U.S. Interstate 80 running east-west between the two ranges. The South Range is adjacent to the U.S. Army Dugway Proving Ground located along its southern border. The intended MSR-EES landing zone, shown in Figure 1-2 1-2, is towards the western side of the UTTR South Range where sufficient area exists for the EES to land away from mountainous terrain and man-made infrastructure that could risk damaging the capsule or the Mars samples during the landing.

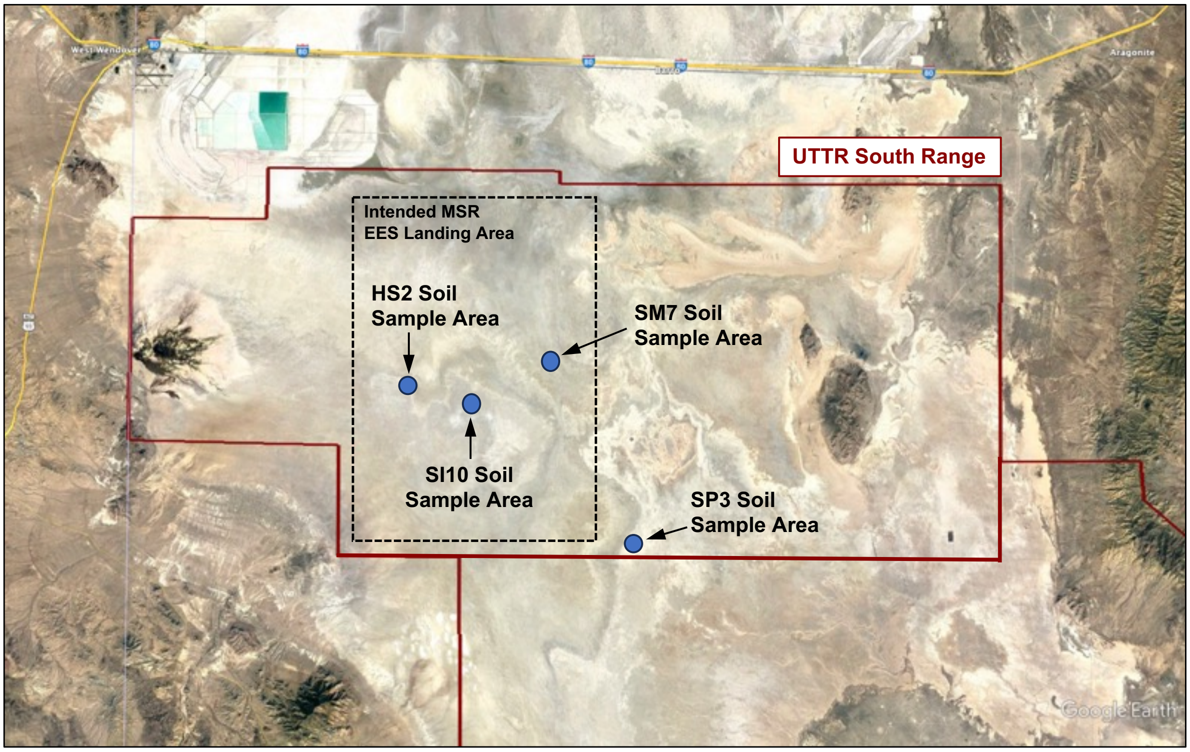


Map Data: Google Earth

Figure 1-2. Intended MSR EES Landing Area at UTTR

The UTTR South Range is located within Utah's Great Salt Lake Desert. The EES landing zone is a flat, barren area situated within an undrained basin routinely flooded by precipitation and snow melt. Playa and Playa-Saltair are the dominant soil types in the landing area with only sparse saltgrass and pickleweed vegetation [Ref. 1]. The saline ground water can be as near as 30.5 cm (12 in) below the surface [Ref. 2] and combines with the silty-clay playa soil to produce moist, low-strength soil conditions that cushion the EES landing and limit the resulting impact loads experienced by the Mars samples to acceptable levels. Extended periods of dry, warm weather will evaporate the moisture from the uppermost layer of soil (i.e., top 5.1 cm or 2 in) and produce a blanket of loose, desiccated silt and clay fines that further cushion the EES landing. However, the high salinity of the ground water is also favorable for warm and dry weather to produce a hard layer of surface crust soil comprised of clay fines and silt cemented together with mineral evaporites. This hard surface crust material will impart higher landing impact loads on the EES than the moist silty-clay playa soil. NASA's soil surveys across the UTTR South Range intermittently found expanses of surface crust material up to 5.1 cm (2 in) thick throughout the EES landing area.

The UTTR soils tested during this study were selected to represent the range of soil conditions the EES could encounter when it lands at UTTR. The soils that were tested are organized into four categories: 1) hard Surface Crust Soils, 2) Silty Clay Soils, 3) clay soils less than 70% saturated, referred to as Partially Saturated Clay Soil, and 4) clay soils greater than 70% saturated, referred to as Saturated Clay Soil. Since these soil conditions are location-dependent and subject to weather conditions, NASA performed multiple surveys in the UTTR South Range from 2019 through 2022 to locate and acquire suitable soil samples for the mechanical tests conducted during this study. Figure 1-3 illustrates the four areas in the UTTR South Range where NASA collected the soil samples for this study.



Map Data: Google Earth

Figure 1-3. UTTR South Range Soil Sample Areas

<u>SP3 Soil Sample Area (40.3480°N, 113.5150°W)</u>:

The SP3 soil sample area, shown in Figure 1-4, has been used regularly by NASA for helicopter drop tests of EES test articles to verify the capsule's aerodynamic performance and to validate LS-DYNA material models of UTTR soils for EES landing simulations. The SP3 area is low-lying and comprised of lean clay soil typically possessing relatively high moisture content due to the area's lower elevation. The majority of mechanical tests conducted during this study to derive properties for "Saturated Clay Soil" used soil samples acquired in the SP3 sample area in late November 2019.

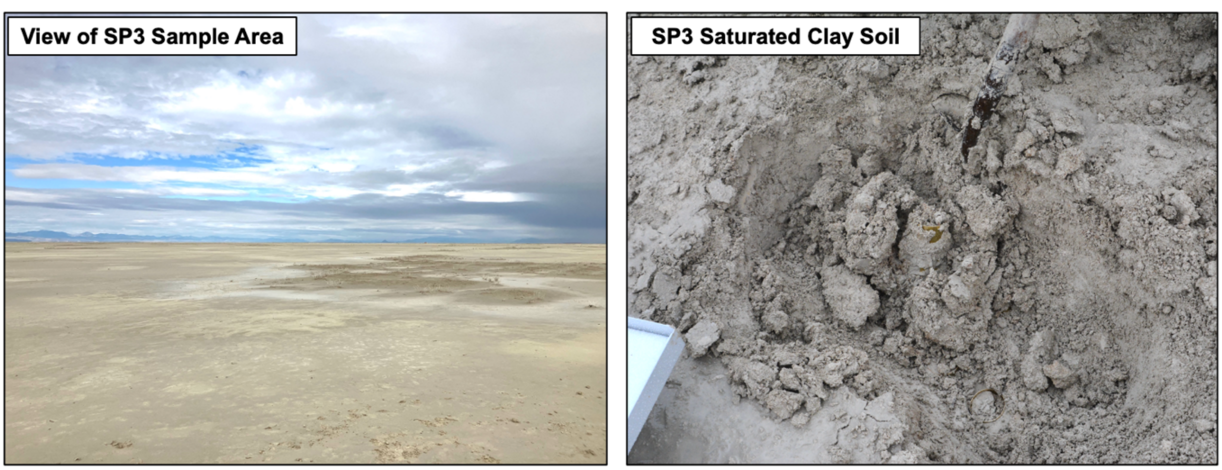


Figure 1-4. SP3 Soil Sample Area – November 2019

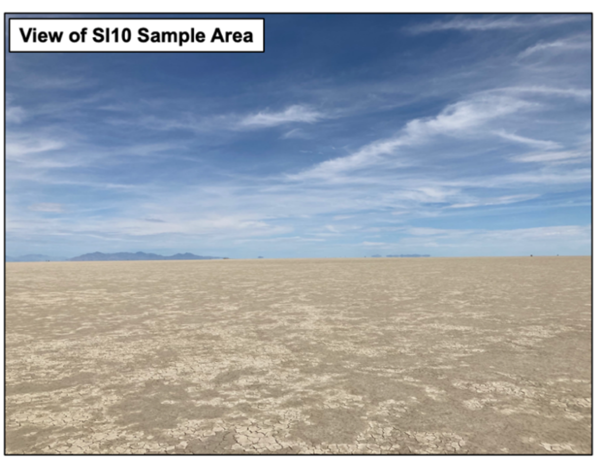
SM7 Sample Area (40.4939°N, 113.6062°W):

The SM7 soil sample area, shown in Figure 1-5, possesses a higher percentage of sand and silt than the other three sample areas. Drop tests of an EES test article were conducted at the SM7 site in September 2021 when 5.1 cm (2 in) of loose, desiccated silt and clay fines blanketed the surface to cushion the test article impact. The SM7 area also possesses high-density, over-consolidated soil beneath the surface that will increase the EES landing loads. The mechanical tests conducted on “Silty Clay Soils” described in this report used soil samples acquired in the SM7 area during the September 2021 EES drop test campaign.

Figure 1-5. SM7 Soil Sample Area – September 2021

SI10 Sample Area (40.4630°N, 113.6840°W):

The SI10 soil sample area, shown in Figure 1-6, is comprised predominantly of lean clay soil. The area was selected for soil sampling because hard surface crust soil, up to 5.1 cm (2 in) thick (see Figure 1-6 inset) was found at the site during an EES helicopter drop test campaign in August 2022. Bulk samples of the surface crust soil at this site were collected during the drop test campaign in August 2022 and used for a subset of the “Surface Crust Soil” mechanical tests described in this report.



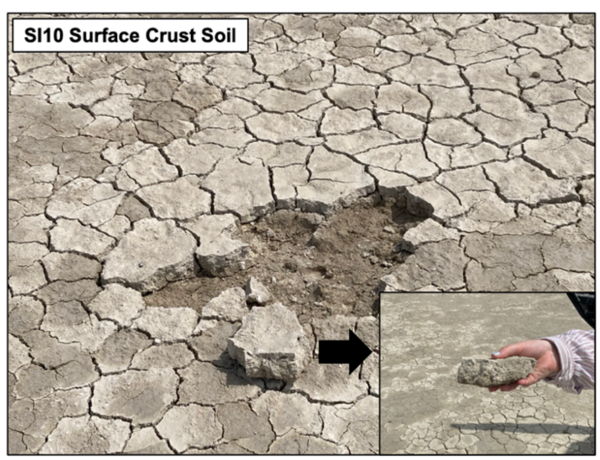


Figure 1-6. SI10 Soil Sample Area – August 2022

HS2 Sample Area (40.4733°N, 113.7536°W):

The HS2 soil sample area provided a range of soil conditions for the mechanical tests conducted during this study. The soil at the HS2 site was classified as lean clay, but with increased concentrations of silt in the upper surface layer in localized areas. The HS2 soil was first sampled In November 2019, shown in Figure 1-7, when the moisture content was relatively high. The soil samples collected in this time frame were tested to derive properties for “Partially Saturated Clay” and “Saturated Clay” soil conditions. The HS2 sample area was surveyed again In September 2022 during an EES helicopter drop test campaign intended to measure EES landing impact loads for surface crust soil conditions. In this time frame, the HS2 area was significantly drier as seen in Figure 1-8, with broad expanses of surface crust soil suitable for the EES drop tests. Bulk samples of surface crust material were collected by NASA during the drop test campaign and used by ARA for a subset of the “Surface Crust Soil” tests conducted during this study.

Figure 1-7. HS2 Soil Sample Area - November 2019

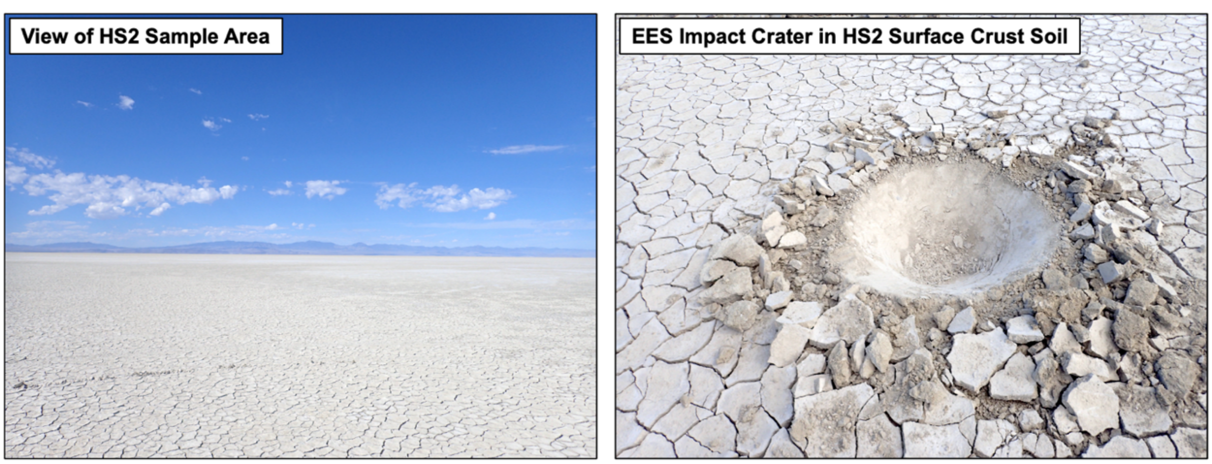


Figure 1-8. HS2 Soil Sample Area - September 2022

In addition to the soil mechanical tests conducted during this study, soil samples from the four sample areas were also tested for grain size distribution, moisture content, grain density, and mass-volume properties, with each sample being classified in accordance with ASTM D2487 criteria [Refs. 3, 4]. Table 1-1, Table 1-2, and Figure 1-9 summarize the results of grain size distribution tests [Ref. 5, 6] and soil classifications conducted on soil samples acquired from the four sample areas. The mass-volume properties and moisture content of individual soil samples for each soil type are presented in later sections with the mechanical test results.

Table 1-1. Dry Grain Size Distribution Results

Sample Area	Sample	Soil Classification (ASTM D2487)	Grain Size Distribution (Percent passing sieve size)									
			#200	#100	#80	#50	#40	#30	#16	#10	#8	#4
SP3	SP3-1 Top	Elastic Silt	98.6	99.2		100						
SP3	SP3-2 Top	Lean Clay	99.4	100								
SP3	SP3-3 Top	White Lean Clay	98.1	99.3	99.4	99.6	100					
SP3	SP3A-U	Sandy Lean Clay	78	81	82	84	86	89	97	99	100	100
SP3	SP3A-L	Sandy Lean Clay	95	97	98	98	99	99	100	100	100	100
SP3	SP3-3-L Top	Lean Clay	99.4	100								
SM7	SM7 Surface	White Sandy Lean Clay	97.9	98.1	98.8	99.1	99.5	100				
SM7	SM7 Upper	White Sandy Silt	58.2	94.1	96.7	99.0	99.6	99.6	100			
SM7	SM7 Lower	White Sandy Silt	57.9	94.5	96.9	98.8	99.4	100				
SM7	SM7-1 Top	Silt	51.4	99.0	99.4		100					
SI10	SI-10 Top	Lean Clay	97.3	98.4		99.2	100					
HS2	HS2-4 Top	Silt	98.2	100								
HS2	HS2-3 Top	White Lean Clay	97.8	98.3	99.6	99.8	100					
HS2	DRY-U	Sandy Lean Clay	76	87	89	94	97	98	99	100	100	100
HS2	DRY-L	Sandy Lean Clay	74	83	85	90	92	94	98	99	99	99

Table 1-2. Hydrometer Grain Size Distribution Results

Sample	Soil Classification (ASTM D2487)	Grain Size Distribution (Percent passing opening size, mm)							
	Hydrometer Opening Size (mm)	0.0013	0.0032	0.0056	0.0073	0.0098	0.0186	0.0260	0.0364
SP3-1 Top	Elastic Silt	15.5	25.3	61.3	80.8	89.6	93.5	95.4	97.4
	Hydrometer Opening Size (mm)	0.0013	0.0031	0.0052	0.0069	0.0096	0.0182	0.0256	0.0358
SP3-2 Top	Lean Clay	14.3	31.5	77.5	88.0	91.9	95.7	96.7	98.6
	Hydrometer Opening Size (mm)	0.0013	0.0029	0.0054	0.0074	0.0103	0.0194	0.0272	0.0380
SP3-3 Top	White Lean Clay	21.8	59.6	76.5	93.4	97.4	93.4	95.3	97.3
	Hydrometer Opening Size (mm)	0.0013	0.0030	0.0054	0.0073	0.0099	0.0186	0.0260	0.0364
SP3-3-L Top	Lean Clay	16.9	47.7	72.6	82.6	90.6	95.5	97.5	99.4
	Hydrometer Opening Size (mm)	0.0013	0.0029	0.0056	0.0076	0.0104	0.02	0.028	0.0392
SM7 Surface	White Sandy Lean Clay	45.9	63.9	75.9	85.9	91.9	93.9	95.9	97.9
	Hydrometer Opening Size (mm)	0.0013	0.0031	0.0062	0.0087	0.0123	0.0212	0.0335	
SM7 Upper	White Sandy Silt	35.3	44.4	50.4	51.4	52.5	54.5	54.5	
	Hydrometer Opening Size (mm)	0.0013	0.0031	0.0062	0.0087	0.0123	0.0211	0.0331	
SM7 Lower	White Sandy Silt	31.9	39.9	44.9	46.9	47.9	50.9	52.9	
	Hydrometer Opening Size (mm)	0.0013	0.0033	0.0064	0.0090	0.0128	0.0247	0.0347	0.0486
SM7-1 Top	Silt	23.9	25.9	31.9	33.9	33.9	34.9	36.9	39.9
	Hydrometer Opening Size (mm)	0.0014	0.0034	0.0054	0.0074	0.0104	0.0198	0.0279	0.0392
SI-10 Top	Lean Clay	10.8	21.7	83.0	88.9	90.9	94.8	95.8	96.8
	Hydrometer Opening Size (mm)	0.0013	0.0031	0.0060	0.0081	0.0111	0.0207	0.0285	0.0392
HS2-4 Top	Silt	15.9	39.9	46.9	57.9	65.9	73.9	79.9	85.9
	Hydrometer Opening Size (mm)	0.0013	0.0031	0.0058	0.0079	0.0108	0.0196	0.0272	0.0376
HS2-3 Top	White Lean Clay	25.7	38.5	53.4	62.3	72.2	85.1	89.0	93.0

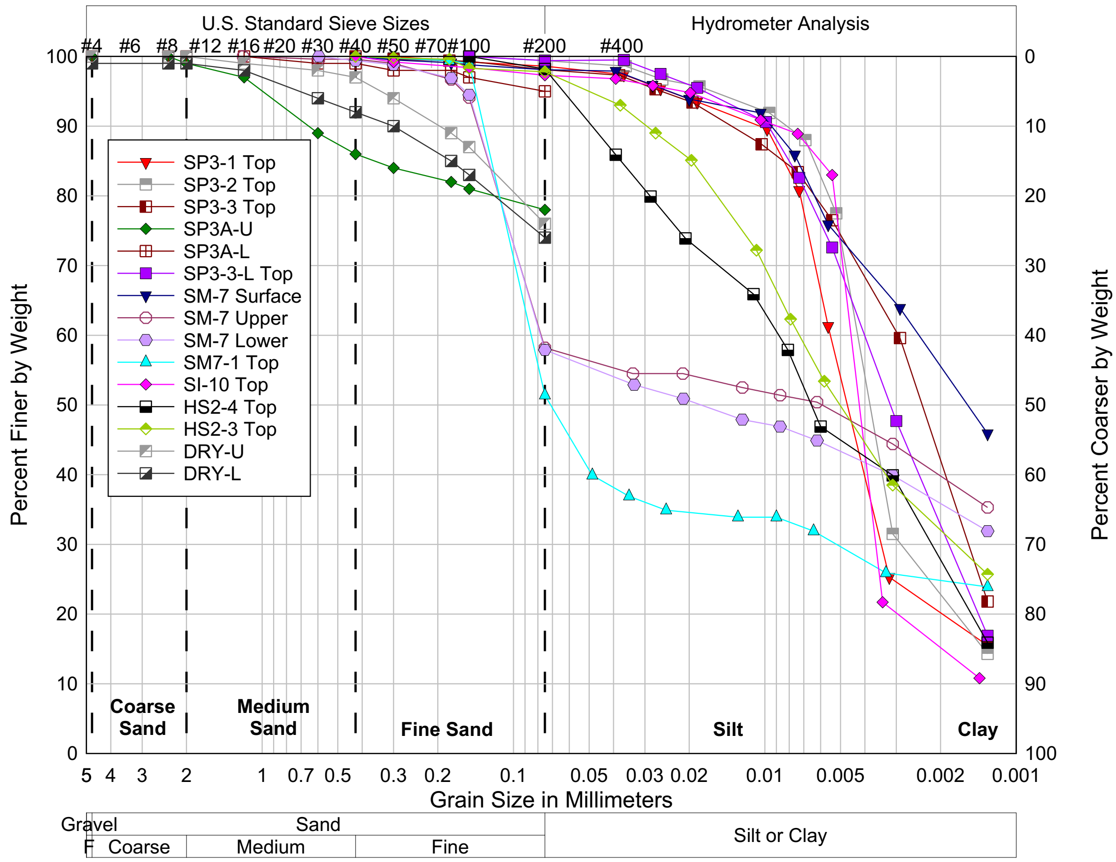


Figure 1-9. UTTR Soil Grain Size Distribution Measurement Results

Soils samples for this study were collected from the surface to a depth of 30.5 cm (12 in). Soil properties are sensitive to sampling disturbance and moisture content [Ref. 7], therefore, the soil samples were collected using techniques to minimize changes to the soil such that the laboratory tests and derived soil properties represented the soil's in-situ condition in the EES landing area at UTTR. Most samples were collected in brass tubes, 5.1 cm (2 in) in diameter and 15.2 cm (6 in) long, that were pressed into the soil at the desired depth at each sample location as shown in Figure 1-10.

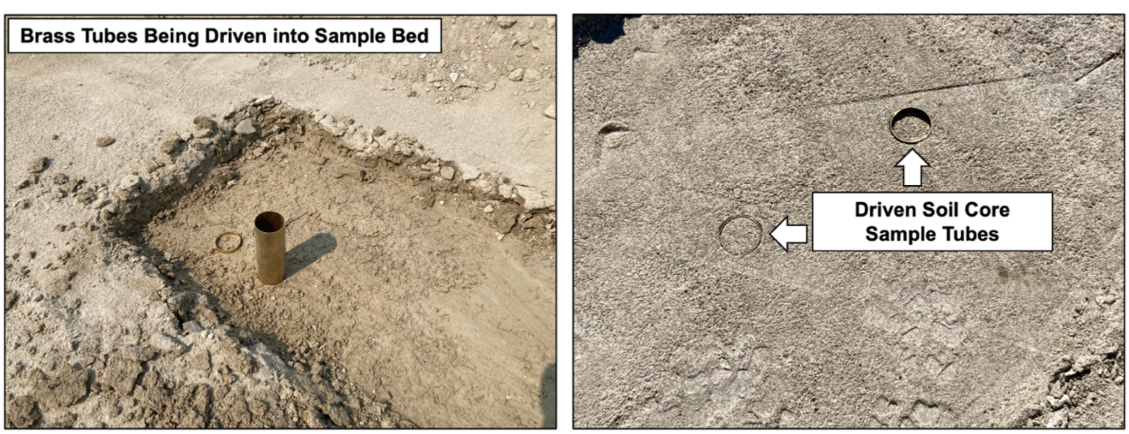


Figure 1-10. Collection of Soil Core Samples

For dry cohesionless soils, such as the loose silt and clay fines found on the surface in the SM7 sample area, the soil was collected in bulk and sealed in heavy duty plastic bags. Surface crust soil, which was brittle and too thin to be sampled as a core specimen, was also collected in bulk and sealed in plastic bags. Care was taken to preserve the moisture content of all samples by sealing core tubes with plastic end caps and tape, and vacuum-bagging surface crust samples as shown in Figure 1-11.

Figure 1-11. Sealed Soil Core and Surface Crust Samples

Soil samples were carefully packaged into heavy duty transport cases to minimize shipping disturbance, and delivered to ARA's testing laboratory located in Randolph, Vermont. Core samples were opened at ARA's laboratory, as shown in Figure 1-12, and then processed and tested to derive the soil characteristics (e.g., density, moisture content, porosity) and mechanical properties for this study.

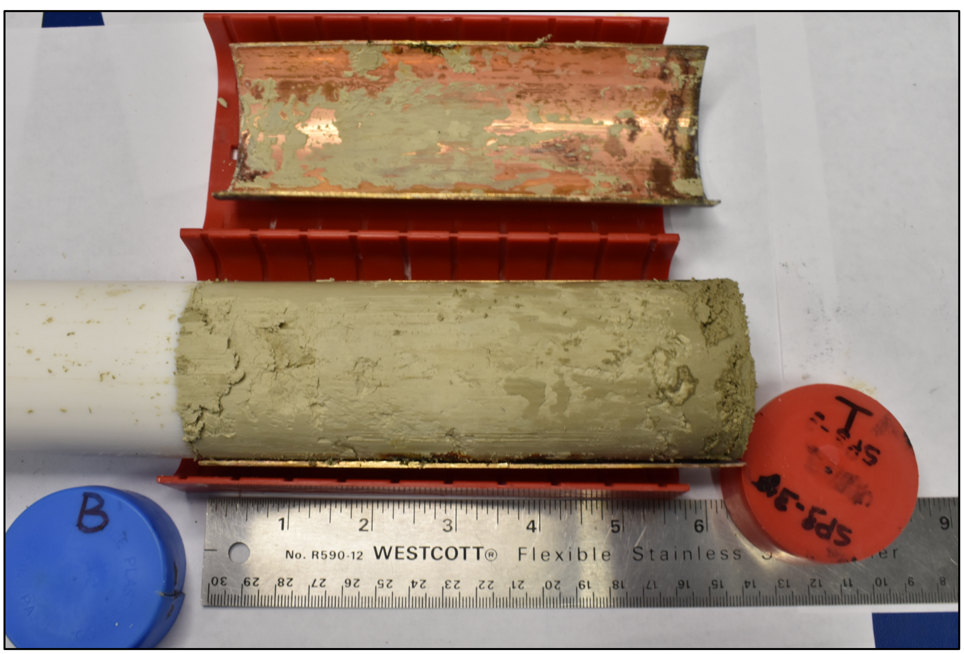


Figure 1-12. Opened Soil Core from the UTTR SP3 Site

1.3 Study Objectives

The technical work for this study was performed in the following four phases.

- **Phase 1** consisted of testing soil samples from the HS2 and SP3 sample areas at their *in-situ*, near-saturated conditions at the time of sample collection. Samples in the SP3 area were collected at two locations identified as SP3A and SP3B.
- **Phase 2** consisted of additional testing of three remaining SP3 samples from Phase 1 in their *in-situ* condition. Phase 2 also included testing of four HS2 samples in a drier condition (not the in-situ condition). These samples were air-dried until they reached a gravimetric moisture content of roughly 15%. A full suite of tests was then completed on these remaining HS2 samples at the reduced moisture content and saturation.
- **Phase 3** consisted of testing soil samples from the SM7 sample area. These tests included samples of dry, loose silt and clay fines, as well as partially saturated silty-clay soil cores collected from the SM7 area.
- **Phase 4** consisted of testing surface crust (desiccated clay) samples from the SI10 and HS2 sample areas. This testing included direct shear tests to determine strength properties and hydrostatic compression and oedometer tests to determine compressibility properties.

The laboratory tests conducted in this study were designed to produce the required constitutive model properties for LS-DYNA's Material Model 16: Pseudo Tensor, which is the model used by NASA for modeling the interaction between the MSR-EES and the soil located in the landing area at UTTR. The constitutive models are valid for a mean stress up to 5 MPa, which is the maximum soil mean stress predicted by NASA's LS-DYNA landing simulations. Material properties for computations above 5 MPa mean stress should be revaluated to account for differences in soil response at the higher stress levels.

2 LS-DYNA Material Model Description

LS-DYNA Material Model 16 (MAT016) was selected by NASA for modeling the UTTR soils. The constitutive properties derived in this report are tailored for constructing this type of model for a maximum mean stress level of 5 MPa. This section describes the physical meaning of the MAT016 model inputs. Section 3 discusses how the model inputs are obtained from the soil mechanical tests conducted during this study.

Since soil strength is pressure dependent, a pressure dependent material model is necessary for constitutive modeling. The Material Model 16: Pseudo Tensor is a pressure-dependent strength model available in LS-DYNA. While the model can run in more complex modes, the most straightforward is Mode I, which invokes a simplified, pressure-dependent shear failure surface defined as a curve of stress difference (σ_1- σ_3) versus mean stress. The benefit of this model is that it allows the user to define the material failure envelope by a series of discrete points, as opposed to relying on the parabolic curve fit required by other models, such as LS-DYNA Material Model 5: Soil and Foam.

The material's compressibility response is described through the Tabulated Compaction Equation of State (EOS8), which requires tabulated values of mean stress versus the natural logarithm of the true volumetric strain. A bulk unloading modulus, K_n, must also be defined to describe the unloading path of the material. Table 2-1 describes the inputs required for Mode I of the Pseudo Tensor model. The *LS-DYNA Theoretical Manual* [Ref. 8] and the *LS-DYNA Keyword User's Manual* [Ref. 9] describe the MAT016 and EOS8 models in more detail.

Table 2-1. LS-DYNA Material Model 16 Inputs (Mode I Response).

Input	Data Method	Description
MID	N/A	LS-DYNA's material identification number. A unique number identifying an input set of material properties. A number must be assigned.
RO	Mass-volume lab tests	Mass density. Obtained from dividing weight density (mass/unit volume) by gravity.
G	Uniaxial strain	Elastic shear modulus. The slope of the shear stress vs. shear strain curve. Can be computed from the constrained modulus and Poisson's ratio from a uniaxial test.
PR	Uniaxial strain	Poisson's ratio
SIGF	Triaxial Compression	Tensile cutoff. Maximum tension stress allowed, representing tensile fracture. It is the mean stress intercept of the shear failure envelope. Note: when a0 is negative, SIGF is assumed to be the unconfined concrete compressive strength.
a0, a1, a2	Triaxial Compression	Quadratic fit coefficients. Set to zero to invoke Mode I model response.
a0f, a1f	N/A	Quadratic fit coefficients for damaged material. Set to zero to invoke Mode I model response.
b1	N/A	Damage scaling factor. Set to zero to invoke Mode I model response.
x_n	Triaxial Compression	Mean stress values of the shear failure surface, where *n* number of points (16 max) can be used to define the curve in Mode I.
YS_n	Triaxial Compression	Yield stress values of the shear failure surface, where *n* number of points (16 max) can be used to define the curve in Mode I.
***EOS_TABULATED_COMPACTION (EOS 8)**		
EOSID	N/A	LS-DYNA's equation of state identification number. A unique number identifying an input set of EOS properties. A number must be assigned.
GAMA	N/A	Gamma parameter. Set to zero so that c_n is equal to pressure on the loading curve.
E0	N/A	Initial internal energy. Set to zero in this study.
V0	N/A	Unit initial volume.
ev_n, c_n	Uniaxial strain	Volumetric strain and mean stress points from the pressure volume curve, where *n* number of points (2 min, 10 max) can be used to define the curve. At zero loading, there is zero volume change. ev_i is the natural logarithmic volume strain = ln (1 – ε_{volume}), where ε_{volume} = (initial volume – current volume)/initial volume. Volumetric strain values should be input as negative in compression and in descending order. Pressure is positive in compression.
k_1, K_2...K_n	Hydrostatic compression	Unloading bulk modulus, which should be defined for each *n* number of points (2 min, 10 max) used in the pressure volume curve. The slope of the mean stress vs. strain curve when the pressure is reduced (unloaded) from a higher-pressure load. Can also be obtained from uniaxial strain unloading.

3 Methodology for Obtaining Constitutive Soil Properties

This section describes the methodology for deriving soil constitutive properties for LS-DYNA Material Model 16 inputs from laboratory test data. ARA operates a specialized geotechnical laboratory in Randolph, Vermont where the soil samples collected at UTTR were shipped for testing. The types of tests conducted for this study are listed below and explained in the following subsections.

Soil Characterization Tests
- Grain density
- Moisture content

Soil Strength Tests
- Triaxial compression tests
- Unconfined compression tests
- Direct shear tests (for surface crust samples)

Soil Compressibility Tests
- Hydrostatic compression tests
- Uniaxial strain tests
- Oedometer type tests (for surface crust samples)

3.1 Grain Density

A given volume of soil is comprised of solid particles and void space. The grain density of a soil is the density of the solid particles. The grain density is a basic piece of information in characterizing a soil and is needed to perform accurate saturation and void volume calculations. Soils typically have a grain density of approximately 2.7 ± 0.1 Mg/m^3.

The grain density is measured in accordance with the procedures defined by ASTM D854 [Ref. 10]. This test is performed using a pycnometer, a special-purpose glass flask with a drilled ground glass stopper that allows it to be filled with a consistent volume of water with density, ρ_w. First, the weight of a 100-ml pycnometer is determined. Next, the pycnometer is filled with distilled, de-aired water to its fill point and re-weighed, (m_a). Then, the water is discarded, and the oven dried soil sample is placed in the dried pycnometer and weighed to determine the mass of the oven-dried sample, (m_0). Distilled, de-aired water is added to the pycnometer again to slightly above the soil sample. The air entrapped in the sample is removed by vacuum. More de-aired, distilled water is added to the pycnometer until reaching the same fill point, and the mass of the pycnometer, soil, and water (m_b) is recorded. Finally, the grain density of the soil (ρ_g) is computed, including temperature corrections, which are not shown, by Equation 3-1.

Equation 3-1. Equation for Determining Grain Density

$$\rho_g = \frac{\rho_w m_0}{m_0 + (m_a - m_b)}$$

The UTTR clay soils contained both pore water and adsorbed (molecular) water within each sample. The mechanical response of the soils during an impact event will be controlled by the pore water, and the laboratory testing was performed to quantify the pore water response while still maintaining a total mass that included adsorbed water. To achieve this goal, all samples were oven-dried at a low temperature (35°C), and grain density tests were performed with methyl-alcohol to avoid interaction with adsorbed water.

3.2 Moisture Content

The moisture content of a soil is another key property and is tested using method ASTM D2216 [Ref. 11]. Soil moisture content may be specified in terms of either *volumetric* or *gravimetric* moisture content. Moisture content values in this report are reported as *gravimetric* values.

The moisture content is the gravimetric ratio of water to dry soil material. Soils have an optimum moisture content at which soil strength is maximized. Any moisture content above or below this optimum value will reduce the soil strength. At lower values, removing water also removes some cohesive strength. At higher values, the extra water causes pore water pressures to build up in the soil, reducing its effective strength. Approximate moisture content can be obtained through field testing with a nuclear density gage and verified through laboratory testing.

Laboratory testing to obtain gravimetric moisture content (w) is performed by first weighing a set of soil samples. Then the samples are oven dried and weighed again (m_s) to measure the difference in weight caused by the loss of water (m_w). The formula for calculating the resulting gravimetric water content is shown below in Equation 3-2.

Equation 3-2. Equation for Determining Gravimetric Moisture Content

$$w = \frac{m_w}{m_s}$$

Although not a direct input to LS-DYNA's Material Model 16, the moisture content plays an important role in the soil strength. Knowing the moisture content in conjunction with grain density allows one to compute porosity, saturation, and air void content in the soil. Equation 3-3 through Equation 3-5 present the relationships for determining porosity, saturation, and air void content, respectively.

Equation 3-3. Equation for Determining Porosity

$$n = 1 - \frac{\rho_d}{\rho_g}$$

where: $\rho_d = dry\ bulk\ density$
$\rho_g = grain\ density$

Equation 3-4. Equation for Determining Degree of Saturation

$$S = \frac{w\rho_g(1-n)}{n}$$

Equation 3-5. Equation for Determining Air Void Content

$$A = n(1-S)$$

3.3 Triaxial Compression

The results of triaxial compression tests are used to define the strength envelope, or yield surface as it is referred to in LS-DYNA, of the soil. The following discussion describes the triaxial testing machine, how the soil sample is tested, and how the shear failure surfaces are derived from the laboratory test data.

The triaxial compression test apparatus is illustrated in Figure 3-1. For each test, a cylindrical specimen of soil is first prepared inside a fluid-tight membrane to prevent infiltration of the confining fluid. In the test apparatus, it is possible to apply two independently controlled components of load to the test specimen, as appropriate to each individual test. Pressurized fluid in the vessel is used to impose a hydrostatic stress, simulating the effect of confining pressure imposed by adjacent soil *in-situ*. The other component of load is derived from a piston, which extends through a seal in the top of the pressure vessel, loading the cylindrical specimen in the axial direction. Electronic instrumentation is used to measure both the applied loads and the resulting deformation of the soil specimen.

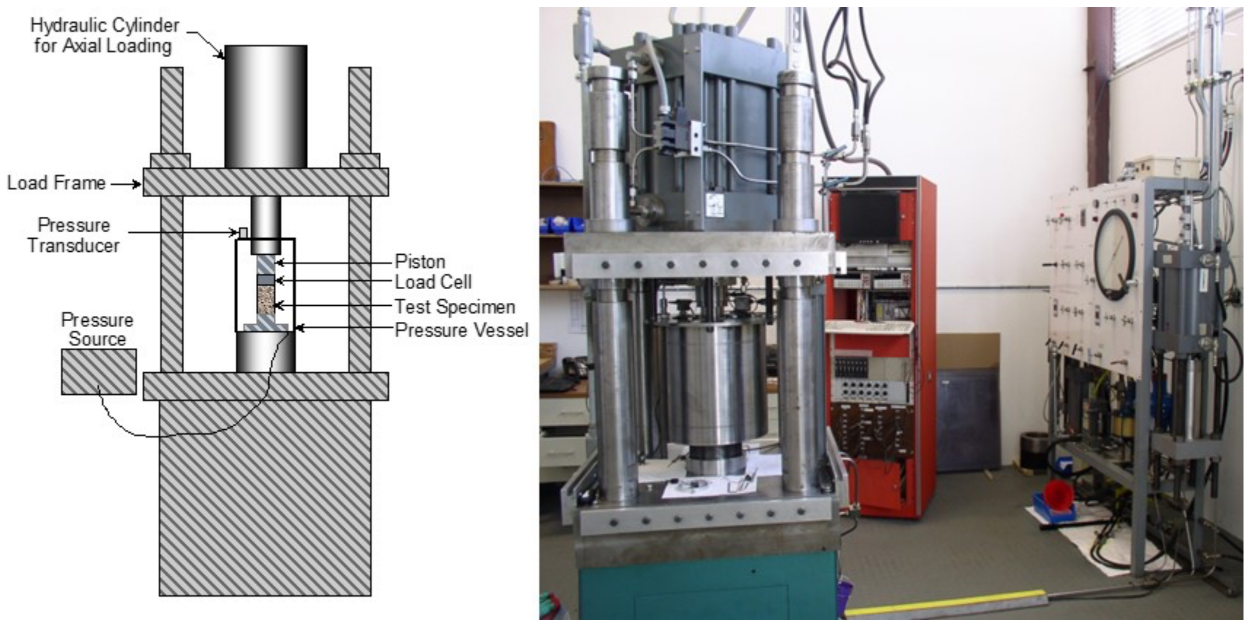


Figure 3-1. Schematic and Photograph of the ARA Triaxial Compression Apparatus

The first step in the test process is to place the soil sample inside the latex rubber membrane that separates the specimen material from the confining fluid. Once the sample is placed in the membrane, the top cap is installed in the same manner as the bottom cap, and final measurements of the specimen dimensions and mass are conducted. The sample is then placed in the triaxial compression apparatus. Figure 3-2 illustrates how the membranes are sealed on each end to the hardened steel endcaps through which the axial load is applied. The membrane is then sealed to the top and bottom caps using sealant and O-rings.

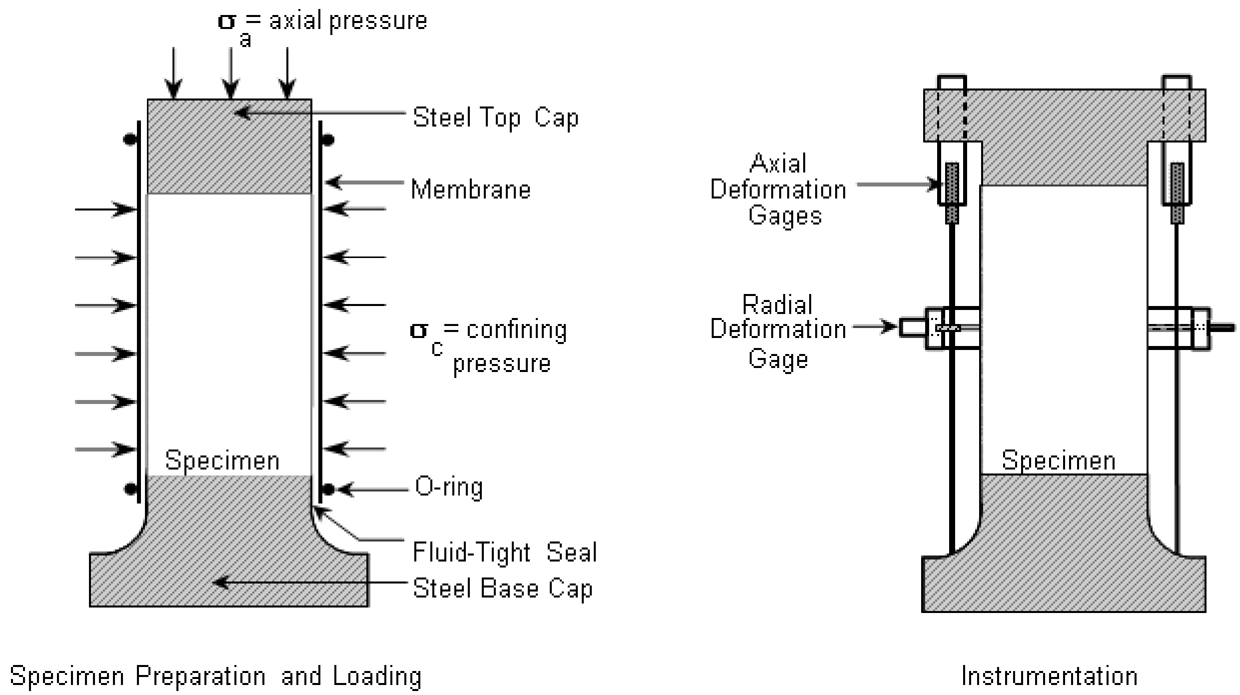


Figure 3-2. Schematic of an Instrumented Soil Specimen for Triaxial Compression Test

Electronic instruments are used to monitor the applied loads and specimen responses during all tests. Four linear variable differential transformer (LVDT) type displacement transducers were installed as illustrated in Figure 3-2 to provide measurements of specimen deformations under load. A pressure transducer was used to monitor the confining pressure, which is equal to the radial stress on the specimen, and a load cell measured the axial load. The load cell was located inside the pressure vessel to eliminate errors that would result from seal friction if it were instead located outside the vessel. The necessary corrections were made to eliminate the effects of confining pressure on the load cell output. All the instruments were calibrated against standards required by the National Institute of Standards Technology (NIST) and adjusted to provide the necessary measurement resolution over the expected range of each test. A microcomputer-based digital data acquisition system was used to record the transducer output at equally spaced discrete intervals in time.

In the triaxial compression test, the specimen is loaded hydrostatically to a pre-selected confining pressure. The confining pressure is then held constant while a compressive axial strain is imposed. The imposed axial strain induces an increment of axial stress above the confining pressure level, and that stress difference results in shear stresses on all planes except the principal directions parallel and perpendicular to the specimen axis. The shear strength of earth materials is strongly dependent on the normal stress level. By performing strength tests at a range of confining pressure levels, the strength envelope (yield surface) of the material can be defined. The measured specimen deformations provide additional information on the material's volumetric response to shear loading. For this study, confining pressures ranged from 0 MPa to 5 MPa. Each test corresponds to a point on the strength envelope, and the maximum shear stresses achieved at these pressures define the strength of the materials over the stress range of interest. The lower confining pressures simulate the near-surface soil conditions.

Two components of load are measured in the triaxial compression test. The measured confining pressure is equal in all directions on the specimen. Force is also measured in the axial direction, from which the axial stress is determined. The strength data in this report are presented in terms of true axial stress (σ_a). True axial stress is computed at each evenly spaced time interval. It is defined as the total axial load divided by the current cross-sectional area of the specimen as derived from the radial deformation measurement. True stress difference, (σ_Δ), is the difference between the true axial stress and the confining pressure. Because the confining pressure is always applied to the current area, it is naturally a measure of true stress in all directions (σ_c).

For presentation of strength results, and to relate the triaxial compression test data to LS-DYNA Material Model 16, the true stress difference ($\boldsymbol{\sigma_\Delta}$) is plotted against true mean stress ($\bar{\boldsymbol{\sigma}}$), which is the average of the stresses in the three perpendicular directions. True mean stress is equal to effective pressure (X_n) and true stress difference is equal to yield stress (YS_n) in the LS-DYNA MAT016 material model (Table 2-1 in Section 2). An example of the MAT016 Mohr-Coulomb shear failure surface is shown in Figure 3-3. In this figure, the X-axis represents the pressure, and the Y-axis represents the stress difference. The triaxial test outputs are defined in Equation 3-6 and Equation 3-7.

Equation 3-6. Equation Defining True Stress Difference

$$\sigma_\Delta = \sigma_a - \sigma_c$$

Equation 3-7. Equation Defining True Mean Stress

$$\bar{\sigma} = \frac{\sigma_a + 2\sigma_c}{3}$$

where: $\sigma_a = true\ axial\ stress$
$\sigma_c = true\ radial\ stress = confining\ pressure$
$\bar{\sigma} = p = pressure$

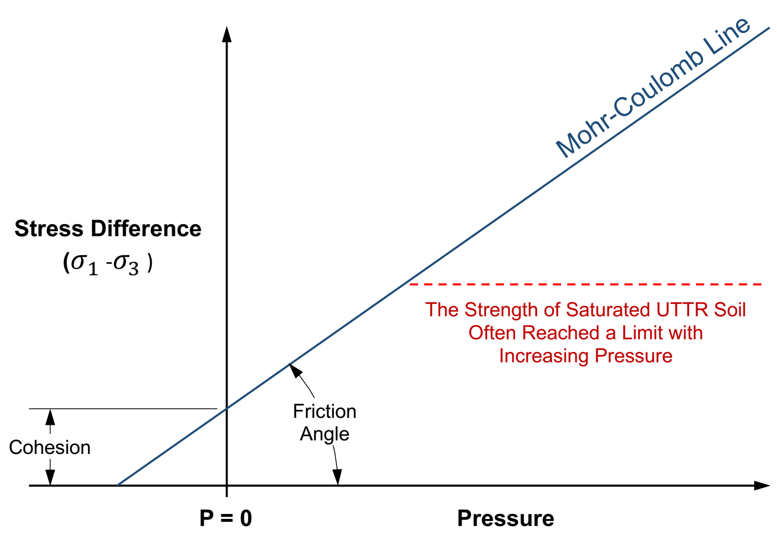


Figure 3-3. MAT016 Mohr-Coulomb Shear Failure Surface

3.4 Direct Shear

Phase 4 of this study involved measuring the strength and compressibility of the desiccated surface crust soil samples collected from the SI10 and HS2 areas at UTTR. These surface crust samples were thin, only 2.5 cm to 5.1 cm (1 in to 2 in) which required the strength testing to be conducted using direct shear methods instead of triaxial compression tests, for which samples with a 2-to-1 aspect ratio are needed.

Direct shear testing is another method for determining the shear strength of soil materials and is considered to be one of the most common and simplest tests to derive the soil strength. For this study, direct shear tests were conducted in accordance with ASTM D3080-03 [Ref. 12]. In a direct shear test, a sample is placed into a shear box that is split horizontally into halves and loaded to produce a specified normal compressive stress. The sample is then sheared in the horizontal direction perpendicular to the normal stress causing shear failure in the soil sample. Figure 3-4 shows a general diagram of a direct shear box.

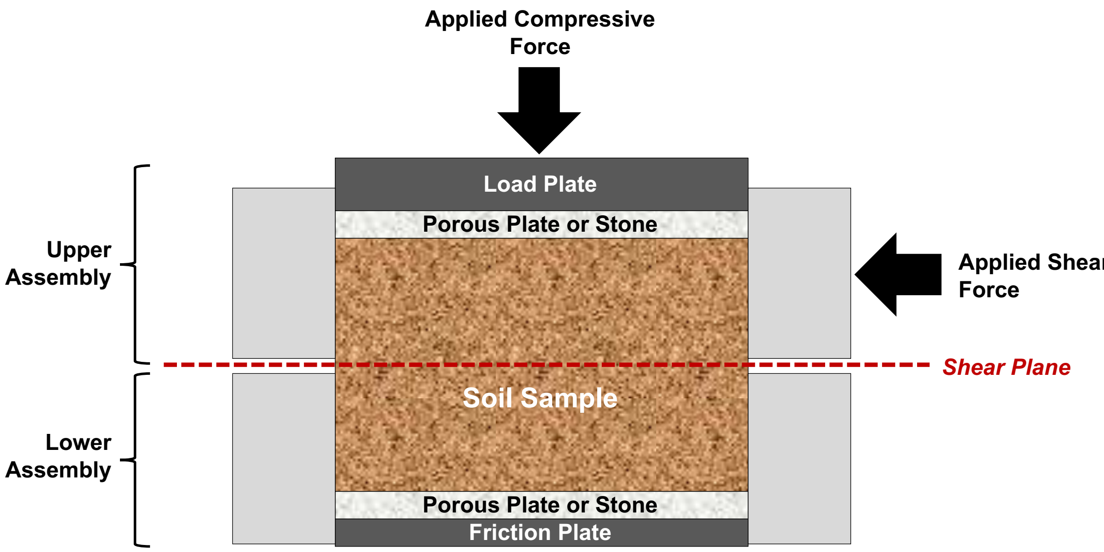


Figure 3-4. Diagram of a Direct Shear Box

Equation 3-8 presents the definition of the Mohr-Coulomb failure criterion. The direct shear testing directly provides the shear strength and the normal stress. Typically, three sets of direct shear tests are conducted on a single soil type and a curve is fit to all three data points to define the cohesion and the friction angle. These data can then be translated to stress difference versus mean stress space to compare to triaxial compression results and to use as an input to the LS-DYNA MAT016 properties.

Equation 3-8. Equation Defining Mohr-Coulomb Failure Criterion

$$\tau = c + \sigma_n tan\phi$$

where: $\tau = shear\ strength$
$c = cohesion\ (inherent\ shear\ strength)$
$\sigma_n = normal\ stress$
$\phi = friction\ angle$

3.5 Hydrostatic Compression

Hydrostatic compression tests are also conducted using the triaxial compression test apparatus. In the hydrostatic compression test, the cylindrical soil specimen is loaded only by fluid pressure with no piston loading. The stresses on the specimen are the same in all directions and there is no shear stress on any plane. This is referred to as the hydrostatic state of compression. Material Model 16's pressure (*p*) is equal to the hydrostatic fluid pressure. The results of these tests are used to define the volumetric deformation behavior of the material for modeling. The stress state is completely defined by the confining pressure. When confining pressure is reduced, the soil expands with a different stiffness than during compression. This expanding behavior of the soil yields the bulk unloading modulus (k_n, see Table 2-1).

In the laboratory, LVDT measurements are used to define axial and radial deformations which, in turn, are used to compute the current volume of the specimen at each time step. The volumetric strain (ε_v) can be computed using Equation 3-9.

Equation 3-9. Equation defining volumetric strain.

$$\varepsilon_v = \frac{V_0 - V_d}{V_0}$$

where: $V_d = current\ (deformed)\ volume\ of\ the\ specimen$
$V_0 = initial\ specimen\ volume\ (including\ grains\ and\ void\ space)$

The axial and radial specimen strains are recorded as the fluid pressure (P) increases inside the triaxial vessel. The data form a pressure versus volumetric strain curve analogous to that used in the EOS8 model represented by Figure 3-5. The curve's initial loading slope, shown in Figure 3-5, defines the material's bulk modulus. At selected pressure intervals during the test the specimen is unloaded. The slopes of these unloading portions define the material's bulk unloading modulus, shown in Figure 3-5, at corresponding levels of compacted volumetric strain. Figure 3-6 shows an expanded view of the unload region for an example hydrostatic test performed on a UTTR soil sample. In this case, the unloading behavior is non-linear, and geotechnical expertise was used to approximate the curve with a single line. The resulting slope of the line defines the bulk unloading modulus, which was K_u = 6.0 GPa for this example.

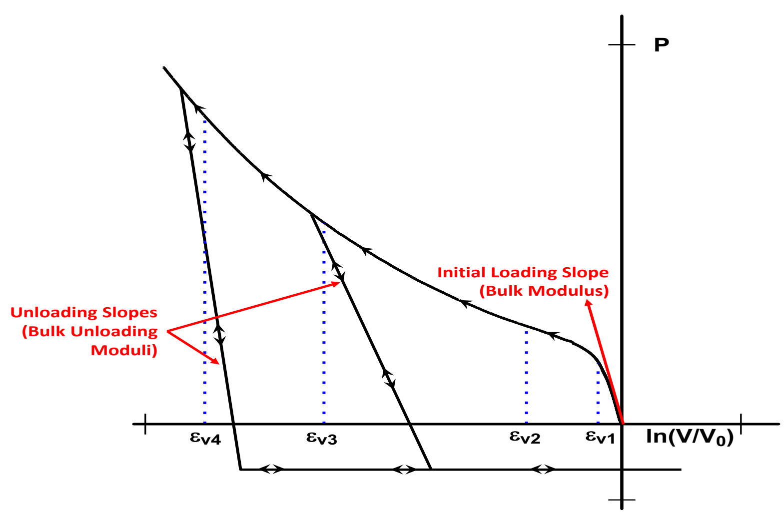


Figure 3-5. Compressibility Curve for EOS8 - Tabulated Compaction

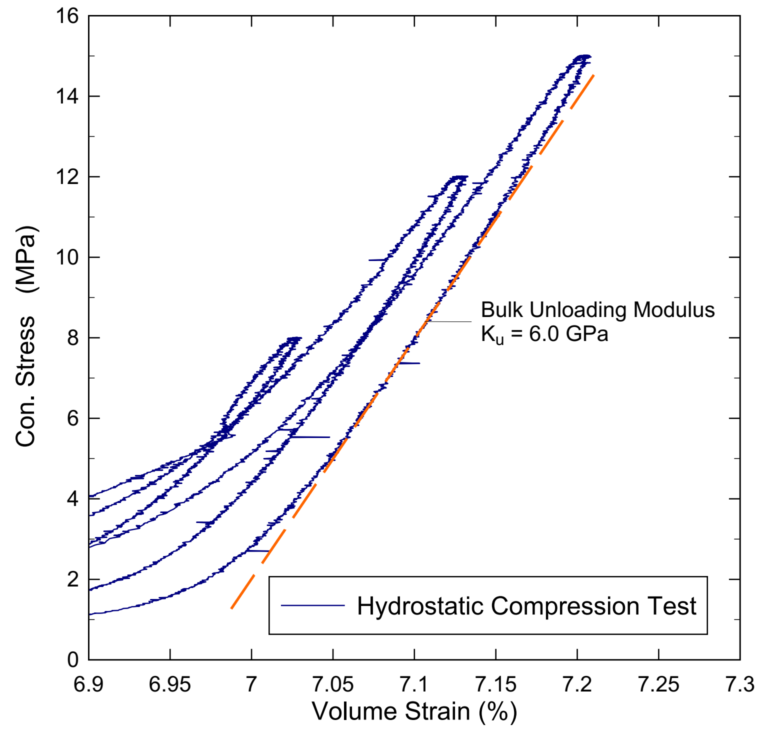


Figure 3-6. Unloading Region of a UTTR Soil Hydrostatic Compression Test

3.6 Uniaxial Strain

The uniaxial strain test also utilizes the triaxial compression apparatus, albeit differently. In a uniaxial strain test, the axial stress and confining pressure are applied in such a way that the specimen undergoes compressive axial strain with no strain in the radial direction. The uniaxial strain loading is accomplished with an automated loading control system using the radial deformation measurement as feedback in the control loop. If the radial strain increases slightly, the confining pressure is increased to return the radial strain to zero. Because no radial strain is allowed in a uniaxial strain test, the axial strain is equal to the volumetric strain in the specimen. There is a difference between axial and radial stress, and hence shear stresses exist in the specimen. However, the uniaxial strain constraint typically prevents the stress state from reaching the strength envelope, and failure of the specimen does not occur. The Material Model 16 shear modulus (G) and the EOS8 pressure-volume curve can be derived from uniaxial strain data, as explained in the following discussion.

The elastic constants to calculate shear modulus (G) are derived from a uniaxial strain test. First, Poisson's ratio can be obtained from an axial stress versus confining pressure plot, which is an output from the uniaxial strain test. Two independent components of loading are applied, confining pressure and axial load. Other linear combinations of these two independent components can yield other properties. For example, the mean stress and stress difference are invariants of the stress tensor and deviatoric stress tensor, respectively.

The elastic Poisson's ratio can be derived from the initial portion of the axial stress versus confining pressure curve. A fitted line is drawn over the initial curve portion. The inverse slope of the fitted line is commonly called lateral earth pressure (k_0). Poisson's ratio (v) is related to (k_0) as defined in Equation 3-10.

Equation 3-10. Relationship Between Poisson's Ratio, v and Lateral Earth Pressure, k_0

$$\nu = \frac{k_0}{1 + k_0}$$

Figure 3-7 shows the application of the method to obtain Poisson's Ratio (*v*) from uniaxial strain test data of a UTTR soil sample. The plot on the left shows the full set of test data, while the plot on the right shows a close-up of the curve fit. Commonly, there is a very small region at the beginning of the test where the data are somewhat incoherent when the loading piston is initially contacting the specimen. Usually, uniaxial strain control cannot be maintained in this region because of sample "seating," when the loading piston closes the tiny gaps between test hardware contact points. Because this occurs at very low stress only, it is generally ignored for the analysis. However, this must be carefully evaluated for the soft UTTR soils tested in this study, as the initial linear response occurs at very low stress values. By fitting a line to the initial linear portion of this example test, we find it has a slope of 1.6. Therefore, (k_0) = 1/1.6 = 0.63 and from Equation 3-10 (*v*) = 0.39.

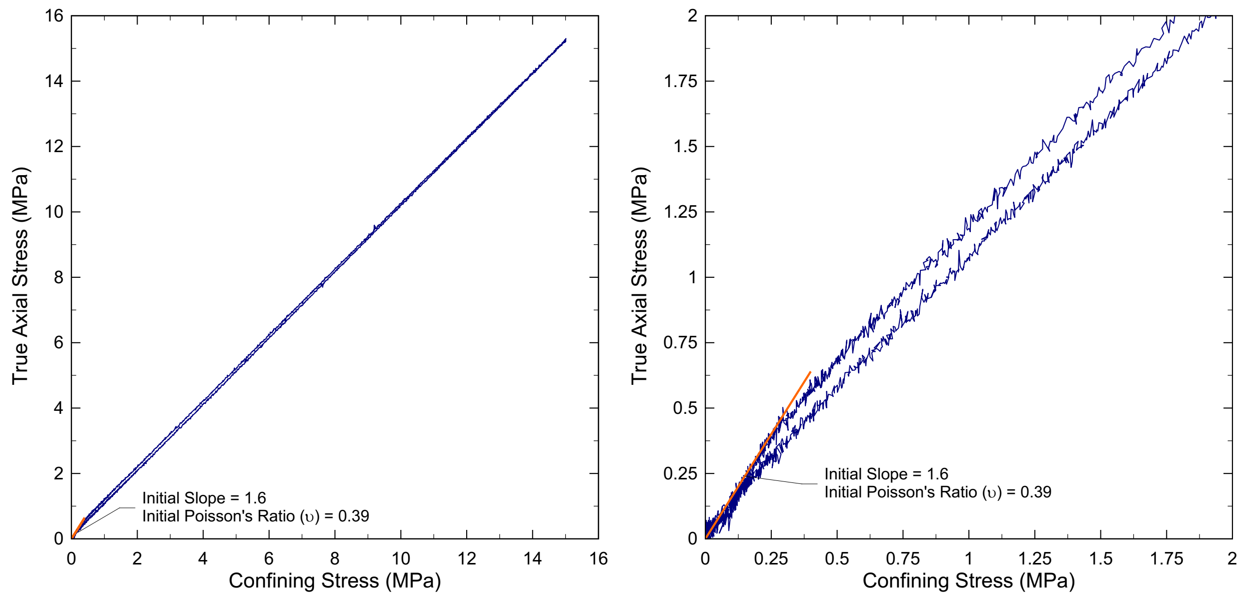


Figure 3-7. Example of UTTR Uniaxial Strain Test Data and Poisson's Ratio Derivation

After deriving the Poisson's ratio, it is necessary to define another constant to establish a complete set of elastic properties. In a uniaxial strain test, the radial strain in the specimen is constrained to be zero, and the axial strain is equal to the volumetric strain. In Figure 3-8, axial strain is plotted against both axial stress and mean stress. As with the definition of Poisson's ratio, for the purpose of defining elastic constants, attention is given to the initial linear regions of the curves. First, consider the axial stress curve in Figure 3-8. The initial slope of the axial stress curve is the constrained modulus (*M*) of the soil. It is defined as the ratio of axial stress to axial (volumetric) strain under uniaxial strain conditions. From Figure 3-8, it is seen that (*M*) = 0.017 GPa.

Similarly, the slope of the mean stress-volume strain curve is defined as the bulk loading modulus (K). In reality, bulk modulus is defined as the ratio of pressure to volumetric strain under hydrostatic loading, but as long as the material behaves elastically, this definition is equivalent. From Figure 3-8, (K) = 0.013 GPa. It is of interest to know how these values relate to other elastic constants. Recall that Young's modulus (E) is the ratio of axial stress to axial strain under unconfined compression (or tensile) loading. The relations between (E) and the constrained and bulk moduli are expressed in Equation 3-11 and Equation 3-12, respectively. From these two equations, it is straightforward to find the relationship between (M) and (K) which is defined in Equation 3-13.

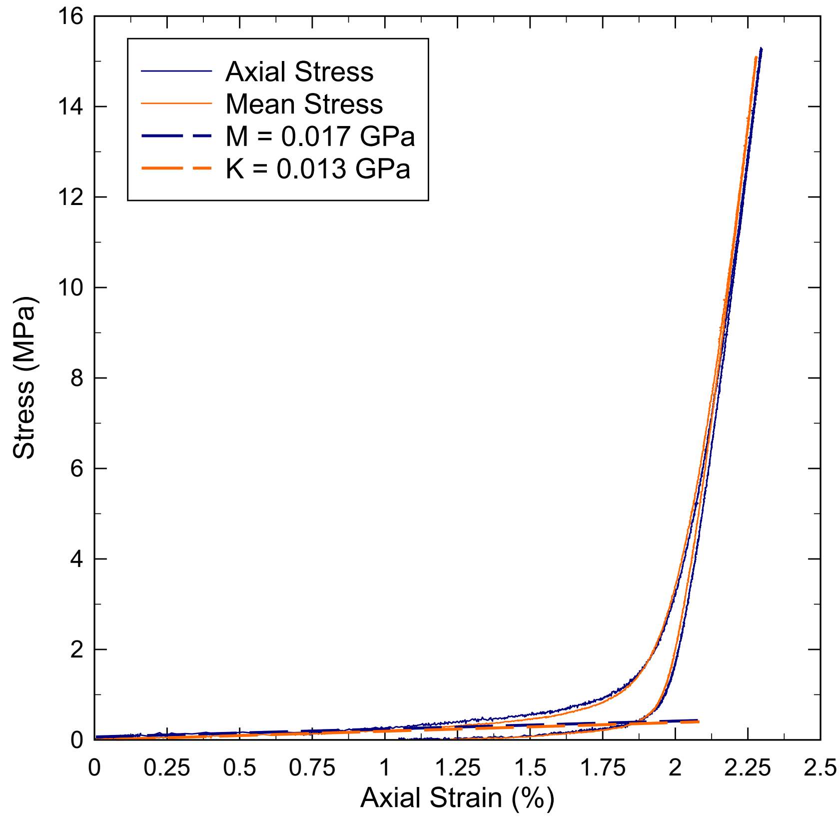


Figure 3-8. Example of Deriving Bulk and Constrained Moduli from UTTR Uniaxial Strain Test Data

Equation 3-11. Relationship Between Poisson's Ratio and Constrained Modulus, M

$$M = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)}$$

Equation 3-12. Relationship Between Poisson's Ratio and Bulk Modulus, K

$$K = \frac{E}{3(1-2\nu)}$$

Equation 3-13. Relationship Between Constrained Modulus, M and Bulk Modulus, K

$$\frac{M}{K} = \frac{3(1-\nu)}{(1+\nu)}$$

If the left-hand side of Equation 3-13 is computed from the values of (M) and (K) determined above, and the right-hand side is computed using (v) = 0.39 previously derived for this specimen, it is found that both sides are equal to 1.3, thus producing a consistent set of elastic constants. During constitutive modeling derivation, slight fit adjustments for constrained and bulk moduli were made to ensure consistency in Equation 3-13. The final elastic constant of interest for Material Model 16 is the shear modulus (G) which is related to (E) and (v) by Equation 3-14. The complete set of elastic constants, for the initial loading phase of this example UTTR soil specimen, is summarized in Table 3-1.

Equation 3-14. Relationship Between G, E, and v

$$G = \frac{E}{2(1+\nu)}$$

Table 3-1. Example Set of Elastic Constants from Uniaxial Strain Testing

Elastic Constant	Value
Constrained Modulus, M	0.017 GPa
Poisson's Ratio, v	0.39
Young's Modulus, E	0.009 GPa
Bulk Loading Modulus, K	0.013 GPa
Shear Modulus, G	0.003 GPa

Uniaxial strain tests are also used to develop the compressibility curve for Material Model 16 and the Tabulated Compaction Equation of State. The LS-DYNA manuals [Ref. 8, 9] state that the compressibility curve used for MAT016 and ESO8 is defined in terms of logarithmic strain, which is defined in Equation 3-15.

Equation 3-15. Definition of Logarithmic Strain Compressibility for MAT016 and EOS8

$$\varepsilon_{log} = ln\left(\frac{V}{V_0}\right)$$

where: $V = current\ volume$
$V_0 = initial\ specimen\ volume$

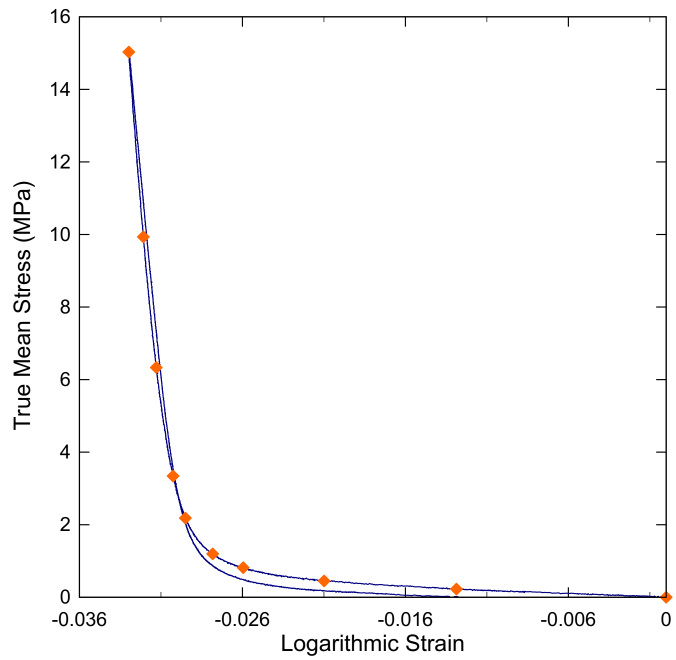
Because there is no radial strain in the uniaxial strain test, the cross-sectional area remains constant, and the logarithmic strain can be computed from the initial length and change in length of the specimen as defined by Equation 3-16.

Equation 3-16. Definition of Compressibility from Uniaxial Strain Test Length Measurements

$$\varepsilon_{log} = ln\left(\frac{L_0 - \Delta L}{L_0}\right)$$

where: $L_0 = initial\ specimen\ length$
$\Delta L = change\ in\ length\ (positive\ in\ compression)$

The logarithmic strain is negative in compression. The pressure-logarithmic strain curve from the example uniaxial strain test is presented in Figure 3-9 with the ten-point idealization for input to the LS-DYNA EOS8 model. The ten points are chosen to best characterize the shape of the compressibility curve.



Example Pressure-Volume Points from Uniaxial Strain Test

Mean Stress (GPa)	Logarithmic Strain
0.00e+00	0.00e+00
2.25e-04	-1.29e-02
4.50e-04	-2.10e-02
8.17e-04	-2.60e-02
1.20e-03	-2.78e-02
2.18e-03	-2.95e-02
3.34e-03	-3.03e-02
6.33e-03	-3.13e-02
9.93e-03	-3.21e-02
1.50e-02	-3.30e-02

Figure 3-9. Example Compressibility Curve from UTTR Soil Uniaxial Strain Test

3.7 Oedometer Testing

Due to the limited thickness of the UTTR surface crust samples tested during Phase 4 of this study, typical uniaxial strain testing could not be conducted on these samples. Uniaxial strain testing requires a minimum length-to-diameter ratio of 1.5-to-1, which could not be achieved with the surface crust samples. To help characterize the compressibility of the UTTR surface crust, ARA developed a test apparatus to emulate a typical oedometer test setup.

Oedometer tests are designed to simulate one-dimensional soil compressibility under a static load while restricting radial deformation. The oedometer tests are performed by applying axial loads to a soil sample and measuring the axial deformation response. In this test, the soil sample is trimmed to match the inner diameter of the confining ring, which prevents deformation in the radial direction (similar to uniaxial strain tests). Dead weights are then placed onto the loading beam, which allows for a constant axial load to be maintained indefinitely. Deformations of the loading frame (deflections) must be measured during this test to later be subtracted from the total measured deformation to compute the deformation experienced by just the soil.

Figure 3-10 shows the oedometer setup that was developed in ARA's soil and rock laboratory to test the UTTR surface crust soil samples. This set up was implemented to utilize the existing digital data acquisition capabilities of the laboratory. The concept of using this setup is the same as the standard oedometer setup. The soil sample is trimmed and placed into the confining ring, constructed of hardened steel, which restricts any radial deformation. A load cell is installed in line with the hydraulic ram to measure the exact load applied to the specimen. Two axial LVDTs were used to accurately measure the axial deformation. In this case, two were used in case of any differential axial straining of the sample during testing.

Using this instrumentation setup, ARA was able to measure the axial load applied to the specimen and the axial strain resulting from that load, which is equal to the volumetric strain since no radial deformation is permitted. As with the uniaxial strain testing, applying a least-squares fit to the test data provides the constrained modulus (M).

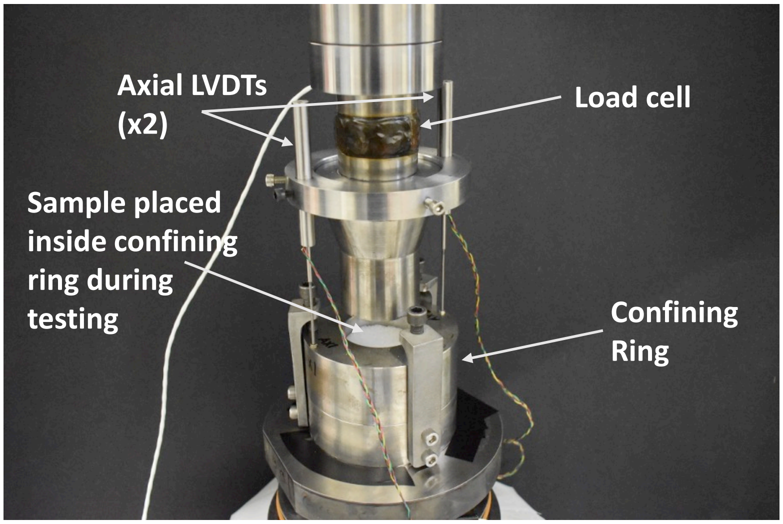


Figure 3-10. ARA's Developed "Oedometer" Apparatus to Test UTTR Surface Crust

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4 UTTR Soil Strength Testing Results

The following subsections summarize the results of the mechanical tests conducted to determine the strength properties of the UTTR soils evaluated in this study. Strength tests included triaxial compression tests performed at varying confining stresses, unconfined compression tests, and direct shear tests performed at varying normal stresses.

The strength testing results are organized by soil type, and detailed results plots from the individual strength tests are presented in Appendix A through Appendix D.

4.1 Surface Crust Soils

Direct shear tests were conducted on the surface crust soils from the UTTR SI10 and HS2 sites. The UTTR surface crust soil, shown in Figure 4-1 at the HS2 site, is brittle and too thin to be tested using the tri-axial compression apparatus as previously discussed (Section 3.4). The strength of the surface crust soils was, therefore, measured using direct shearing methods (Section 3.4). After the direct shear test of each specimen was completed, moisture content tests were performed on a portion of the sample to produce its mass-volume properties, the results of which are presented in Table 4-1.

Figure 4-1. UTTR Surface Crust at HS2 Site

Table 4-1. Mass-Volume Properties of Tested UTTR Surface Crust Soils

Lab Sample ID	Group	Test Type	Target Normal Stress (MPa)	Moisture Content	Dry Bulk Density (Mg/m^3)	Grain Density (Mg/m^3)	Porosity	Saturation
SI10-1	1a	DS	1.79	8.2%	1.345	2.719	50.5%	21.9%
SI10-2	1b		3.76	10.0%	1.396	2.719	48.6%	28.8%
SI10-1	1c		5.65	9.6%	1.636	2.719	39.8%	39.4%
SI10-5	2a		1.79	7.6%	1.621	2.719	40.4%	30.4%
SI10-2	2b		3.76	14.8%	1.580	2.719	41.9%	55.8%
SI10-3	2c		5.65	7.4%	1.749	2.719	35.7%	36.5%
SI10	3a		1.79	9.7%	1.425	2.719	47.6%	29.0%
SI10-4	3b		3.76	10.9%	1.594	2.719	41.4%	42.2%
SI10-3	3c		5.65	6.3%	1.574	2.719	42.1%	23.4%
SI10-5	4a		1.79	8.7%	1.599	2.719	41.2%	33.8%
SI10-1	4b		3.76	8.3%	1.593	2.719	41.4%	31.8%
SI10-3	4c		5.65	9.3%	1.677	2.719	38.3%	40.7%
			SI10 Average	**9.2%**	**1.566**	**2.719**	**42.4%**	**34.5%**
HS2-1-5	1a	DS	0.10	8.7%	1.490	2.729	45.4%	28.5%
HS2-1-5	1b		0.38	9.1%	1.474	2.729	46.0%	29.2%
HS2-1-5	1c		0.79	11.1%	1.437	2.729	47.3%	33.7%
HS2-1-4	2a		1.79	9.5%	1.356	2.729	50.3%	25.5%
HS2-1	2b		3.76	10.0%	1.514	2.729	44.5%	34.0%
HS2-1-3	2c		5.65	10.6%	1.420	2.729	48.0%	31.4%
HS2-1-4	3a		1.79	9.7%	1.391	2.729	49.0%	27.5%
HS2-2-5	3b		2.34	10.0%	1.559	2.729	42.9%	36.4%
HS2-1	3c		3.76	8.6%	1.542	2.729	43.5%	30.6%
HS2-1-3	3d		5.65	10.3%	1.502	2.729	45.0%	34.5%
HS2-2-5	4a		1.55	10.9%	1.428	2.729	47.7%	32.7%
HS2-1-4	4b		1.79	8.5%	1.404	2.729	48.5%	24.6%
HS2-1	4c		3.76	9.4%	1.607	2.729	41.1%	36.8%
			HS2 Average	**9.7%**	**1.471**	**2.729**	**46.1%**	**31.2%**

Notes:
DS = Direct Shear

The surface crust soil samples from each site were organized into four groups, and three or four direct shear tests were conducted within each group at varying normal stresses to define their Mohr-Coulomb failure envelopes. Direct shear tests with higher normal stresses define the soil's friction angle, while tests with lower normal stresses define the cohesion of the soil. The majority of surface crust shear tests were performed at normal stresses between 1.5 MPa and 6.0 MPa. For the HS2 surface crust samples, a group of tests (Group 1) was conducted at lower normal stresses less than 1.0 MPa to provide an estimate of the soil's cohesion.

Figure 4-2 illustrates the results of a UTTR surface crust direct shear test. The surface crust sample is prepared into a cylindrical test specimen to fit the direct shear box (see Section 3.4), a normal force is applied, and the sample is sheared laterally into two halves. The shear force and displacement are continually measured during the test producing the curve shown in Figure 4-2, from which the soil's shear strength is derived for the given applied normal stress.

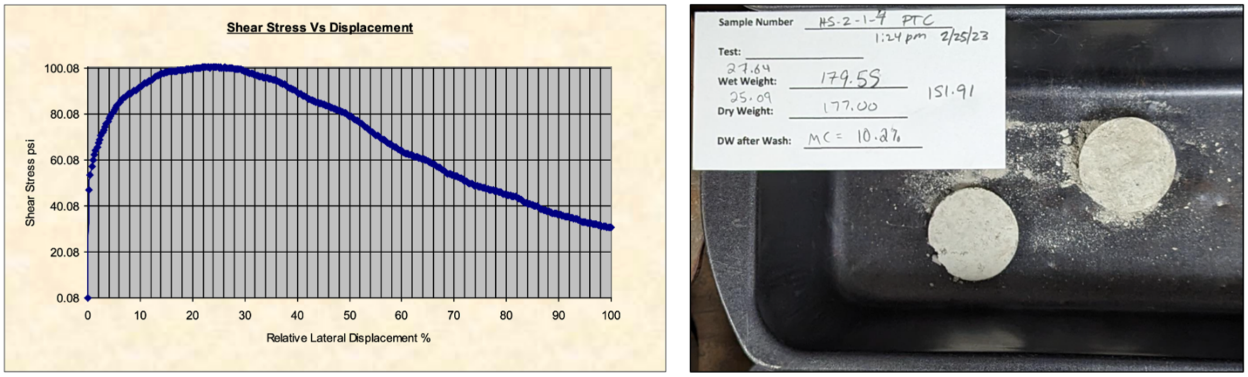

Figure 4-2. Example of a UTTR Surface Crust Direct Shear Test

Figure 4-3 and Figure 4-4 present the results in terms of Mohr's circles from the SI10 and HS2 direct shear tests respectively, along with the recommended strength envelopes for each site considering all tests from that location. The HS2 tests conducted at normal stresses less than 1.0 MPa enabled fitting a strength envelope defining a cohesion of 0.259 MPa.

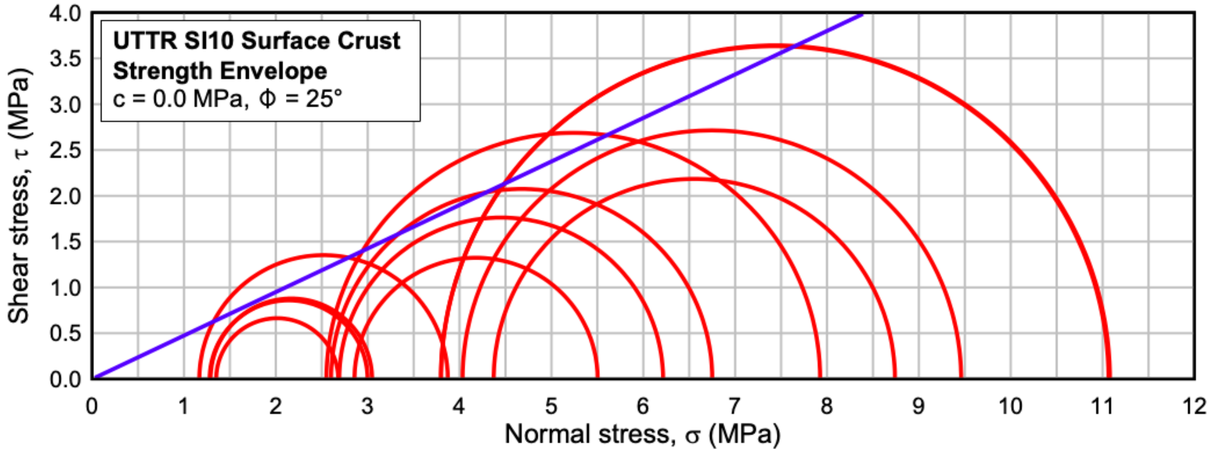

Figure 4-3. SI10 Direct Shear Mohr's Circles and Recommended Strength Envelope

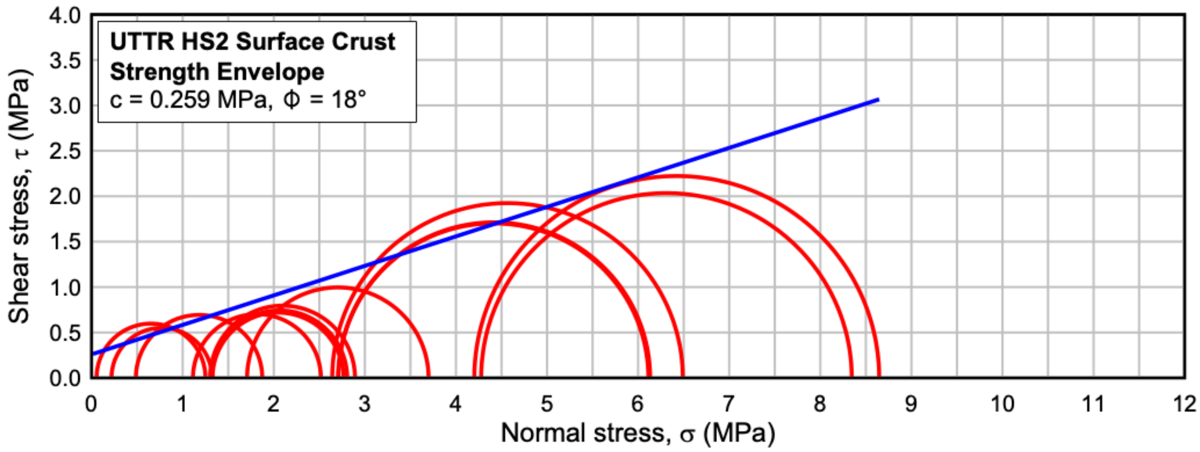

Figure 4-4. HS2 Direct Shear Mohr's Circles and Recommended Strength Envelope

Table 4-2 presents the detailed results for the surface crust direct shear tests including recommended strength envelopes for each group of tests from the SI10 and HS2 sites. Details of each individual direct shear test are provided in Appendix A. The results from Table 4-2 were converted to the stress difference versus mean stress plot presented in Figure 4-5, including the recommended strength envelopes and corresponding equations for the SI10 and HS2 surface crust soils.

Table 4-2. Shear Strength Test Results for UTTR Surface Crust Soils

UTTR Direct Shear Results								
	Shear Stress/Normal Stress Space				Group Strength Envelope		Recommended Strength Envelope	
SI10 Sample Group	Normal Stress @ Failure, σ_n (MPa)	Peak Strength, τ (MPa)	Major Principal Stress, σ_1 (MPa)	Minor Principal Stress, σ_3 (MPa)	c (MPa)	ϕ (°)	c (MPa)	ϕ (°)
1a	1.7959	0.6269	2.6787	1.3508	0	19	0	25
1b	3.7606	1.2554	5.5032	2.8562				
1c	5.8279	2.0593	8.7396	4.3715				
2a	1.7939	0.7868	2.9982	1.2799	0	24		
2b	3.7552	1.6185	6.2153	2.6904				
2c	5.6548	2.4845	9.4602	4.0327				
3a	1.8119	0.8036	3.0474	1.2893	0	28		
3b	3.7552	1.8593	6.7505	2.6011				
3c	5.6553	3.1693	11.0645	3.7983				
4a	1.7939	1.1411	3.8721	1.1674	0.224	28		
4b	3.8594	2.3066	7.9250	2.5508				
4c	5.6553	3.1750	11.0790	3.7966				
HS2 Sample Group	Normal Stress @ Failure, σ_n (MPa)	Peak Strength, τ (MPa)	Major Principal Stress, σ_1 (MPa)	Minor Principal Stress, σ_3 (MPa)	c (MPa)	ϕ (°)	c (MPa)	ϕ (°)
1a	0.1047	0.2394	1.2498	0.0546	0.431	13	0.259	18
1b	0.3751	0.3850	1.3219	0.2186				
1c	0.7723	0.5611	1.8735	0.4864				
2a	1.7939	0.7361	2.8916	1.3003	0.157	19		
2b	3.7552	1.5786	6.1311	2.7064				
2c	5.6553	2.0850	8.6461	4.2018				
3a	1.7939	0.6935	2.8055	1.3185	0.179	18		
3b	2.3364	0.9260	3.6994	1.7073				
3c	3.7552	1.5696	6.1124	2.7101				
3d	5.6553	1.9256	8.3450	4.2768				
4a	1.5435	0.6474	2.5171	1.1130	0	24		
4b	1.7939	0.6733	2.7659	1.3275				
4c	3.7552	1.7451	6.4904	2.6419				

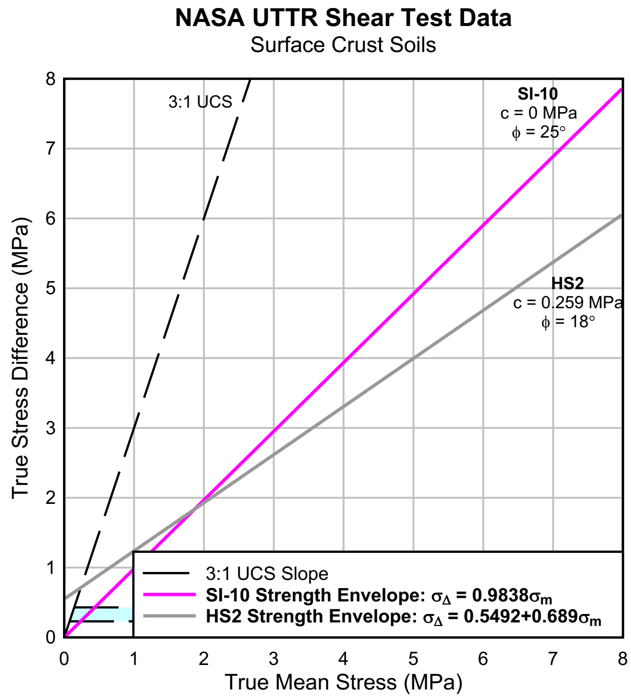

Figure 4-5. Surface Crust Strength Envelopes Converted to Stress Difference-Mean Stress Space

4.2 Silty Clay Soils

Triaxial compression tests were conducted on the UTTR silty clay soils at varying confining pressures to define their shear strength envelope. These soils were collected at the SM7 site. Table 4-3 summarizes the mass-volume properties of each sample tested. Samples with a "U" designation were collected from the upper 7.6 cm to 22.9 cm (3 in to 9 in) of soil. Samples designated as "L" were collected from 15.2 cm to 30.5 cm (6 in to 12 in) depth. Moisture tests were conducted on a portion of each sample after the triaxial compression test was completed.

Table 4-3. Mass-Volume Properties of UTTR Silty Clay Soil Triaxial Test Specimens

Sample ID	Test ID	Test Type	Confining Pressure (MPa)	Moisture Content	Dry Bulk Density (Mg/m^3)	Grain Density (Mg/m^3)	Porosity	Saturation
SM-7-U (2-1A) #3	F15A/B22	TXC	9.00	17.4%	1.671	2.720	38.6%	75.4%
SM-7-U (2-1B) #4	F16A/B22		2.99	16.5%	1.709	2.720	37.2%	75.7%
SM-7-U (3-1B) #6	F21A/B22		1.49	14.0%	1.717	2.649	35.2%	68.5%
			SM7-U Average	**16.0%**	**1.699**	**2.696**	**37.0%**	**73.2%**
SM-7-L (2-03) #21	D9A/B21	TXC	0.14	14.7%	1.719	2.765	37.8%	66.9%
SM-7-L (2-04) #22	D10A/B21		0.39	15.3%	1.663		39.9%	63.7%
SM-7-L (2-05) #23	D13A/B21		0.89	15.2%	1.668		39.7%	63.9%
SM-7-L (2-06) #24	D14A/B21		2.39	15.8%	1.715		38.0%	71.4%
SM-7-L (2-07) #25	D15A/B21		5.00	15.9%	1.708		38.2%	71.2%
			SM7-L Average	**15.4%**	**1.694**	**2.765**	**38.7%**	**67.4%**

Notes:
TXC = Triaxial compression

Figure 4-6 presents the triaxial compression test results from all of the SM7 silty clay soil samples. The plot on the left shows the tests from the upper samples while the plot on the right shows the results from the lower samples. For the SM7 upper soils, the total shear strength was found to be reduced at the highest confining pressure. The SM7 lower soils did not exhibit this strength reduction, with the strength instead approaching a constant value of roughly 1.5 MPa at confining pressures of 0.9 MPa or higher. The triaxial compression test results summarizing the maximum stress difference at each confining pressure for the silty clay soils are summarized in Table 4-4, and the detailed test data and specimen photographs are provided in Appendix B.

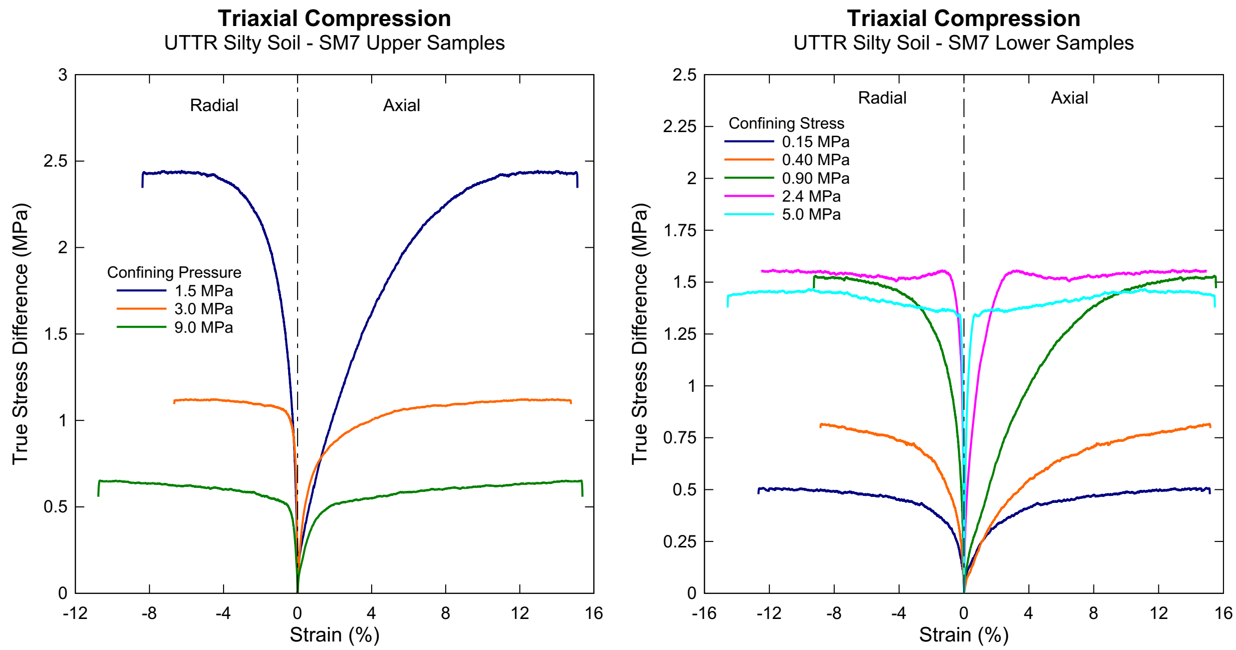

Figure 4-6. Triaxial Compression Test Data from UTTR Silty Clay Soils

Table 4-4. Triaxial Compression Test Results for UTTR Silty Clay Soils

Sample ID	Test ID	Measured Confining Pressure (MPa)	Mean Stress (MPa)	Maximum Stress Difference (MPa)
SM-7-U (2-1A) #3	F15A/B22	9.00	9.211	0.648
SM-7-U (2-1B) #4	F16A/B22	2.99	3.366	1.122
SM-7-U (3-1B) #6	F21A/B22	1.49	2.308	2.444
SM-7-L (2-03) #21	D9A/B21	0.14	0.309	0.505
SM-7-L (2-04) #22	D10A/B21	0.39	0.661	0.813
SM-7-L (2-05) #23	D13A/B21	0.89	1.400	1.522
SM-7-L (2-06) #24	D14A/B21	2.39	2.909	1.557
SM-7-L (2-07) #25	D15A/B21	5.00	5.485	1.466

The maximum stress difference for each test was used to derive the strength envelope as described in Section 3.3. Figure 4-7 plots the triaxial compression test data for the silty clay soils in terms of stress difference versus mean stress. The mean stress is input as the effective pressure (x_n) in Material Model 16 while the stress difference is equal to the yield stress of the shear failure surface (YS_n) as explained in Section 2. The recommended Material Model 16 yield surface for the UTTR silty clay soils tested is shown as the dashed line in Figure 4-7. As shown in the figure, the strength data follow a Mohr-Coulomb friction angle of 24 degrees until reaching a maximum stress difference of approximately 2.4 MPa, where the strength then decreases with increasing mean stress due to the saturated response of the soils.

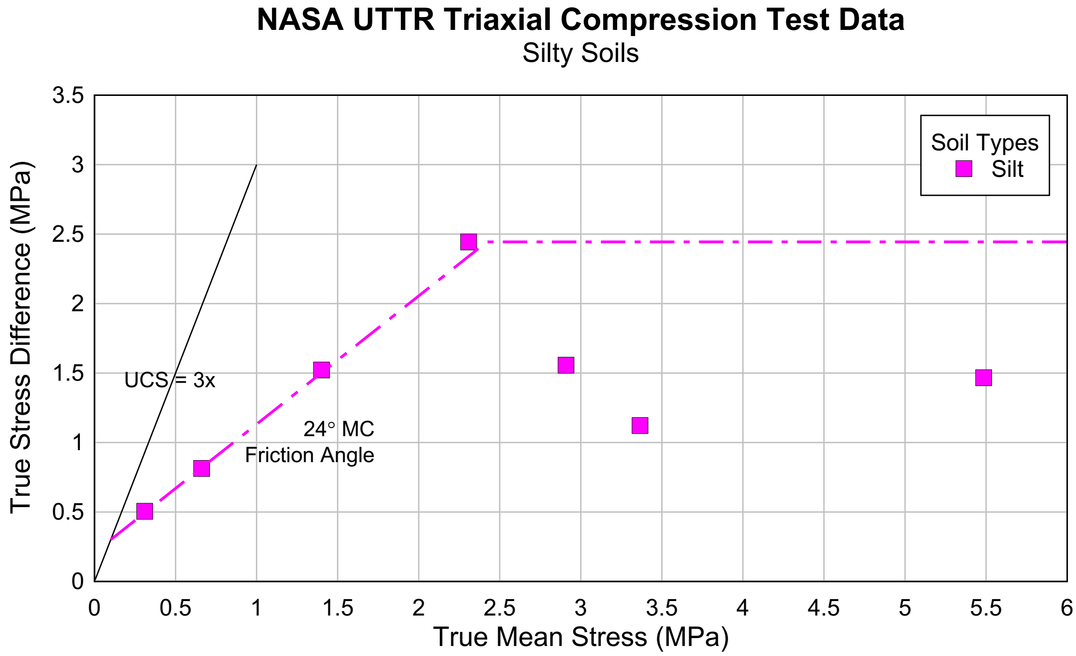

Figure 4-7. UTTR Silty Clay Soils Strength Envelope

4.3 Partially Saturated Clay Soils

Triaxial compression tests were conducted on UTTR partially saturated clay soils (less than 70 percent saturation) collected from the HS2 and the SM7 sites. Moisture tests were conducted on a portion of each sample after the triaxial test was completed. Table 4-5 summarizes the mass-volume properties of each sample tested. The two HS2 samples with "DRY" designation were collected from 0.0 cm to 15.2 cm (6 in) depth and then air-dried to a moisture content of 15% prior to mechanical testing. The samples labeled SM7-S were reconstituted from bulk samples of desiccated, loose silt and clay fines collected from the surface at the SM7 site.

Table 4-5. Mass-Volume Properties of UTTR Partially Saturated Clay Triaxial Test Samples

Sample ID	Test ID	Test Type	Confining Pressure (MPa)	Moisture Content	Dry Bulk Density (Mg/m^3)	Grain Density (Mg/m^3)	Porosity	Saturation
DRY-U-06	O14A/B20	TXC	2.50	15.0%	1.498	2.713	44.8%	50.1%
DRY-U-07	O14C/D20		4.99	15.0%	1.578		41.8%	56.7%
			DRY-U Average	**15.0%**	**1.538**	**2.713**	**43.3%**	**53.4%**
SM-7-S 2-1/2	A5A/B22	TXC	1.99	2.7%	1.229	2.696	54.4%	6.1%
SM-7-S 2-1/2	A6A/B22		2.69	2.6%	1.239		54.0%	6.1%
			SM7-S Average	**2.7%**	**1.234**	**2.696**	**54.2%**	**6.1%**

Notes:
TXC = Triaxial compression

Triaxial compression tests were performed on the partially saturated clay soils at varying confining pressures to define a strength envelope. Figure 4-8 presents all triaxial compression results from the unsaturated clay soils. The plot on the left shows both tests from the HS2 upper samples (air-dried) while the plot on the right shows results from the tests of the two samples that were reconstituted from the dry, loose soil collected from the surface at SM7.

The HS2 upper tests showed a similar, but very slight reduction in shear strength with increasing confining pressure. The SM7 surface samples exhibited a continuous increase in stress difference with increasing strain, which can be modeled with a Mohr-Coulomb friction angle fit. These two SM7 tests failed in a ductile manner, where no peak was encountered during each test. In this case, conventional geotechnical practice is to define failure at 15% axial strain. As shown in Table 4-5, the saturation of the SM7 surface reconstituted samples was much lower than the saturation of the HS2 (i.e., "DRY") samples. The triaxial compression test results for the partially saturated clay soil samples are summarized in Table 4-6 and the detailed test results and specimen photographs are provided in Appendix C.

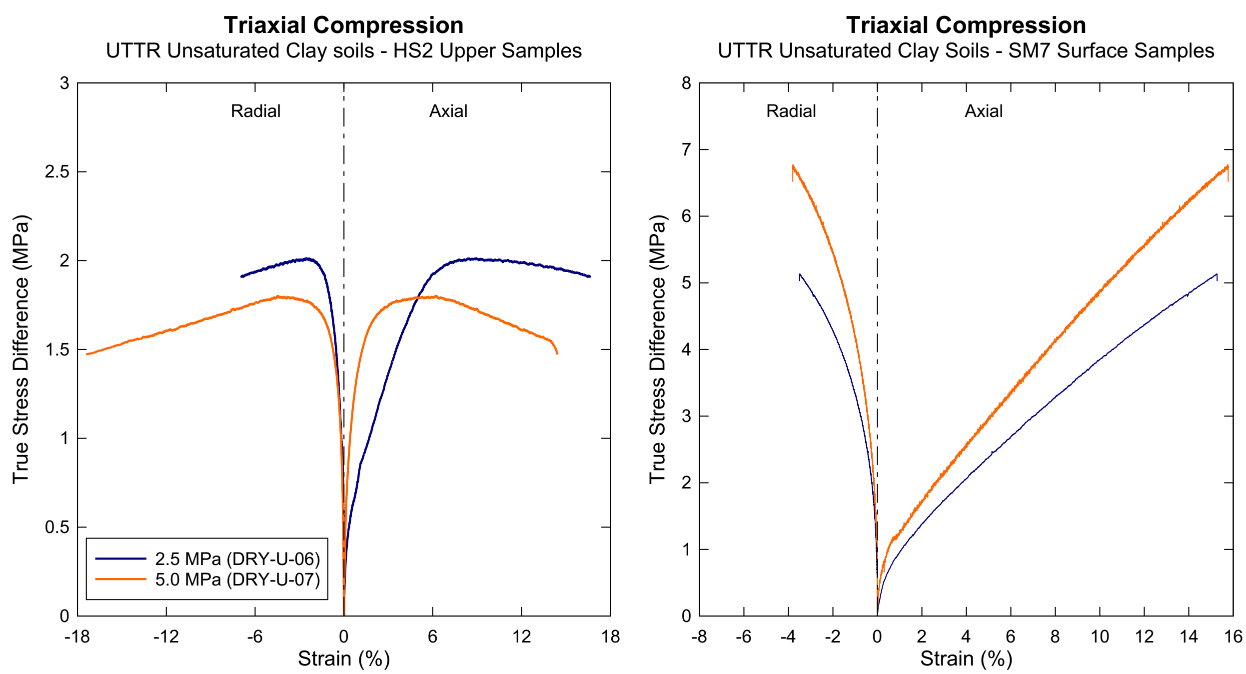

Figure 4-8. Triaxial Compression Data for UTTR Partially Saturated Clay Soils

Table 4-6. Triaxial Compression Test Results for UTTR Partially Saturated Clay Soils

Sample ID	Test ID	Measured Confining Pressure (MPa)	Mean Stress (MPa)	Maximum Stress Difference (MPa)
DRY-U-06	O14A/B20	2.50	3.166	2.013
DRY-U-07	O14C/D20	4.99	5.590	1.801
SM-7-S 2-1/2	A5A/B22	1.99	3.678	5.070
SM-7-S 2-1/2	A6A/B22	2.69	4.873	6.538

The triaxial compression test data were used to plot the individual strength envelopes in Figure 4-9 for the UTTR partially saturated clay soils in terms of stress difference versus mean stress. As shown in the figure, the test data produced two distinct strength envelopes. The two samples from the HS2 site exhibited a lower stress difference (i.e., shear strength) than the two tests from the reconstituted SM7 surface samples. The HS2 strength envelope at mean stresses greater than approximately 2.0 MPa was estimated as the average of the two data points (σ_{Δ} = 1.9 MPa). The strength envelope at lower mean stresses was estimated by a Mohr-Coulomb line with a friction angle of 24 degrees until it intersects with the horizontal failure envelope at 1.9 MPa. This approach is only an approximation, as there were not enough soil samples to perform additional tests in the low mean stress regime. At extremely low mean stress levels, the strength envelope was estimated to follow the 3:1 Unconfined Compressive Strength (UCS) stress path to the origin.

For the two triaxial compression tests (σ_{Δ} > 5 MPa) conducted with the dry, reconstituted SM7 surface soil, the strength envelope follows a Mohr-Coulomb line with a friction angle of approximately 34 degrees. Since only two data points are available for both the HS2 and SM7 data sets, the friction angles shown in Figure 4-9 at mean stresses less than about 2.0 MPa are approximations.

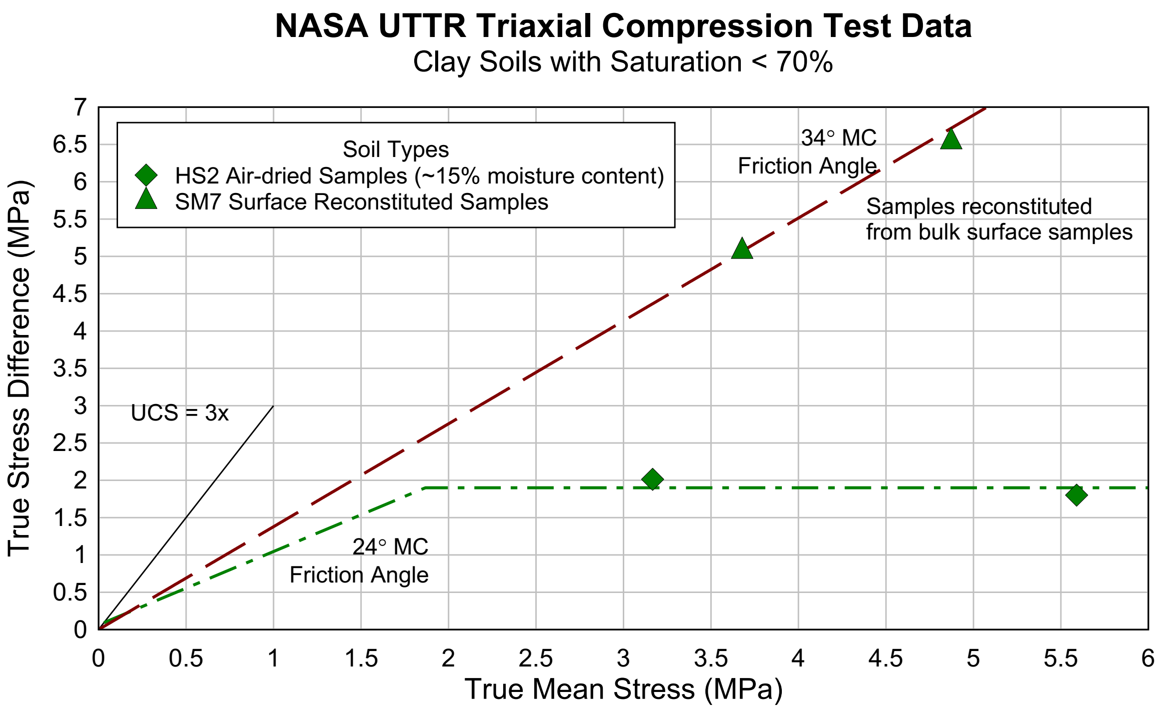

Figure 4-9. UTTR Partially Saturated Clay Soils Strength Envelope

4.4 Saturated Clay Soils

Unconfined compression tests and triaxial compression tests were conducted on clay soils with higher saturation levels (greater than 70 percent saturation) collected from the SP3 and HS2 (i.e., "DRY") sites at UTTR. Moisture tests were conducted on a portion of each sample after the test was completed. Table 4-7 summarizes the mass-volume properties from each saturated clay sample tested. The upper samples ("U" designation) were collected as soil cores from the surface to a depth of 15.2 cm (6 in), and the lower samples ("L" designation) were collected as soil cores from 15.2 cm to 30.5 cm (6 in to 12 in) depth. Detailed test results and specimen photographs are provided in Appendix D.

Table 4-7. Mass-Volume Properties of UTTR Saturated Clay Triaxial Test Samples

Sample ID	Test ID	Test Type	Confining Pressure (MPa)	Moisture Content	Dry Bulk Density (Mg/m^3)	Grain Density (Mg/m^3)	Porosity	Saturation
DRY-U-03	F13A20	UCS	0.00	26.0%	1.429	2.701	47.1%	78.8%
DRY-U-04	F14D/C20	TXC	2.50	27.1%	1.315		51.3%	69.3%*
DRY-U-05	F18A/B20		5.00	26.0%	1.411		47.7%	76.7%
			DRY-U Average	**26.3%**	**1.385**	**2.701**	**48.7%**	**74.9%**
DRY-L-04	F18C20	UCS	0.00	28.7%	1.444	2.701	46.5%	89.0%
DRY-L-05	F21A/B20	TXC	2.50	30.2%	1.433		46.9%	92.1%
DRY-L-06	F26C/D20		5.00	30.1%	1.423		47.3%	90.5%
			DRY-L Average	**29.7%**	**1.433**	**2.701**	**46.9%**	**90.6%**
SP3A-U-03	F19A20	UCS	0.00	35.2%	1.306	2.685	51.4%	89.4%
SP3A-U-04	F24A/B20	TXC	2.50	36.8%	1.311		51.2%	94.4%
SP3A-U-05	F27A/B20		5.00	39.9%	1.263		53.0%	95.1%
SP3A-U-07	G11A/B20		0.70	37.3%	1.272		52.6%	90.1%
			SP3A-U Average	**37.3%**	**1.288**	**2.685**	**52.1%**	**93.0%**
SP3A-L-04	F19B20	UCS	0.00	43.2%	1.224	2.749	55.5%	95.3%
SP3A-L-06	F24C/D20	TXC	2.50	42.8%	1.200		56.3%	91.1%
SP3A-L-07	F27C/D20		5.00	45.2%	1.177		57.2%	93.0%
			SP3A-L Average	**43.7%**	**1.200**	**2.749**	**56.3%**	**93.1%**
SP3B-U-03	F20A20	UCS	0.00	40.2%	1.213	2.701	55.1%	88.5%
SP3B-U-04	F25C/D20	TXC	2.50	32.9%	1.328		50.8%	86.1%
SP3B-U-05	F28A/B20		5.00	50.9%	1.069		60.4%	90.1%
SP3B-U-06	G12A/B20		1.20	40.5%	1.237	2.711	54.4%	92.2%
SP3B-U-07	G17A/B20		1.69	47.8%	1.106		59.2%	89.2%
			SP3B-U Average	**42.5%**	**1.191**	**2.706**	**56.0%**	**89.2%**
SP3B-L-04	F20B20	UCS	0.00	45.7%	1.187	2.760	57.0%	95.2%
SP3B-L-05	F26A/B20	TXC	2.50	46.8%	1.168		57.7%	94.7%
SP3B-L-06	F28C/D20		5.00	46.0%	1.079		60.9%	81.5%
			SP3B-L Average	**46.2%**	**1.145**	**2.760**	**58.5%**	**90.5%**

Notes:
UCS = Unconfined compression
TXC = Triaxial compression
* Sample DRY-U-04 had saturation of 69.3% and was included in saturated clays due to its close nature to 70% saturation

4.4.1 Unconfined Compression Results

Six unconfined compression tests were conducted on the saturated clay soils of UTTR during Phase 1 of this study. Figure 4-10 presents the results of all saturated clay unconfined compression tests, plotted together. As shown in the figure, the two tests from HS2 (i.e., "DRY") upper and lower samples produced a similar strength of approximately 0.13 MPa to 0.15 MPa. The four SP3A and SP3B upper and lower samples also produced consistent strength values, but their strengths were found to only be approximately 0.06 MPa to 0.08 MPa - significantly lower than the HS2 samples. Oscillations in test data are a result of the extremely low stress difference levels measured during the test, despite applying filtering methods to the test data.

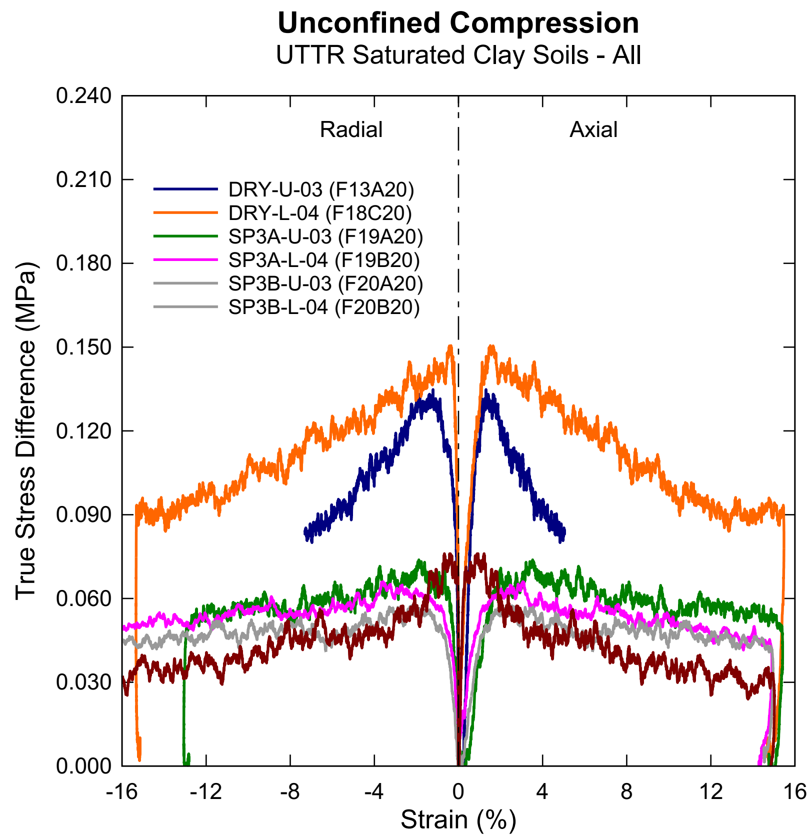

Figure 4-10. Unconfined Compression Test Data from UTTR Saturated Clay Soils

4.4.2 Triaxial Compression Results

Triaxial compression tests were conducted on UTTR saturated clay soils at varying confining pressures to define a strength envelope. Figure 4-11 presents the triaxial test data from the HS2 (i.e., "DRY") site with results from the upper samples provided on the left-hand plot and results from the lower samples on the right-hand plot. Figure 4-12 and Figure 4-13 present data from the triaxial compression tests performed on the SP3A and SP3B samples, respectively, with the results also presented on individual graphs for upper and lower samples. All saturated clay soil samples were collected as cores with upper samples acquired from the surface to 15.2 cm (6 in) deep and lower samples from 15.2 cm (6 in) to 30.5 cm (12 in) deep. The peak stress difference for each test was used to derive the total strength envelope as described in Section 3.3. The saturated clay triaxial test results are summarized in Table 4-8.

The HS2 saturated clays (upper and lower) did not show a reduction in shear strength with increasing confining pressure, but the stress differences did level-off and the results were essentially identical for the 2.5 and 5.0 MPa confining stress tests (Figure 4-11). The SP3A saturated clays (upper and lower) both showed a reduction in shear strength with increasing confining stress from 2.5 to 5.0 MPa (Figure 4-12). The SP3B upper soils showed a decrease in shear strength between confining pressures of 2.5 MPa and 5.0 MPa, but the shear strength of the lower soils increased slightly when the confining pressure was increased from 2.5 MPa to 5.0 MPa (Figure 4-13).

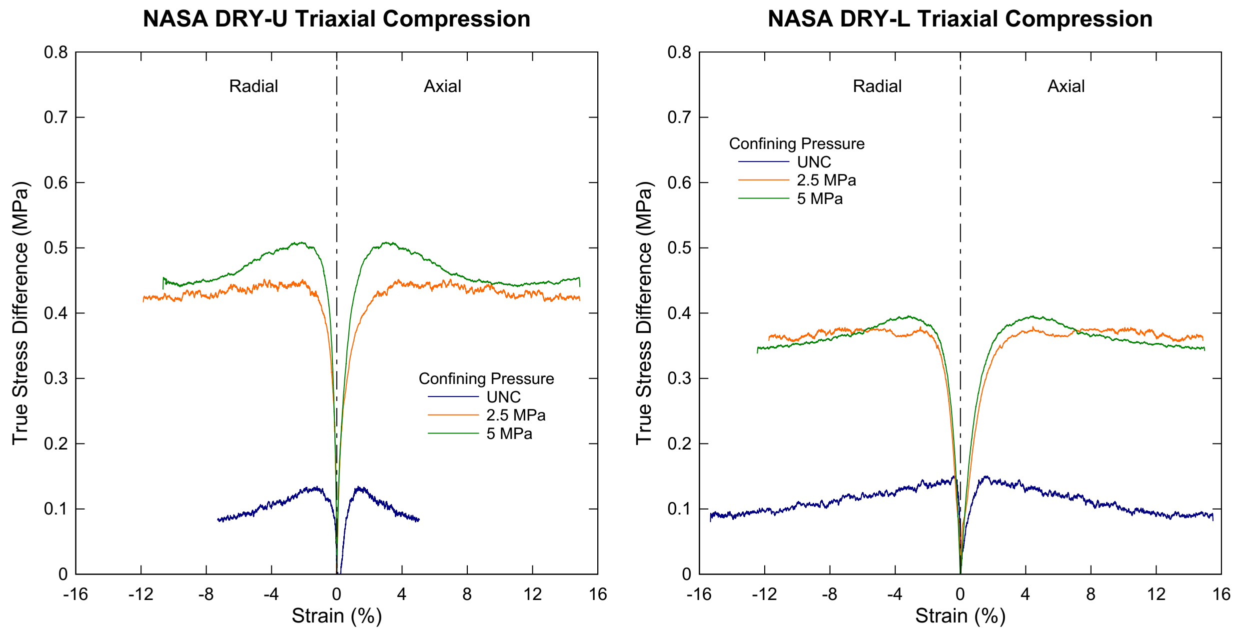

Figure 4-11. Triaxial Compression Test Data from the HS2 Saturated Clay Soils

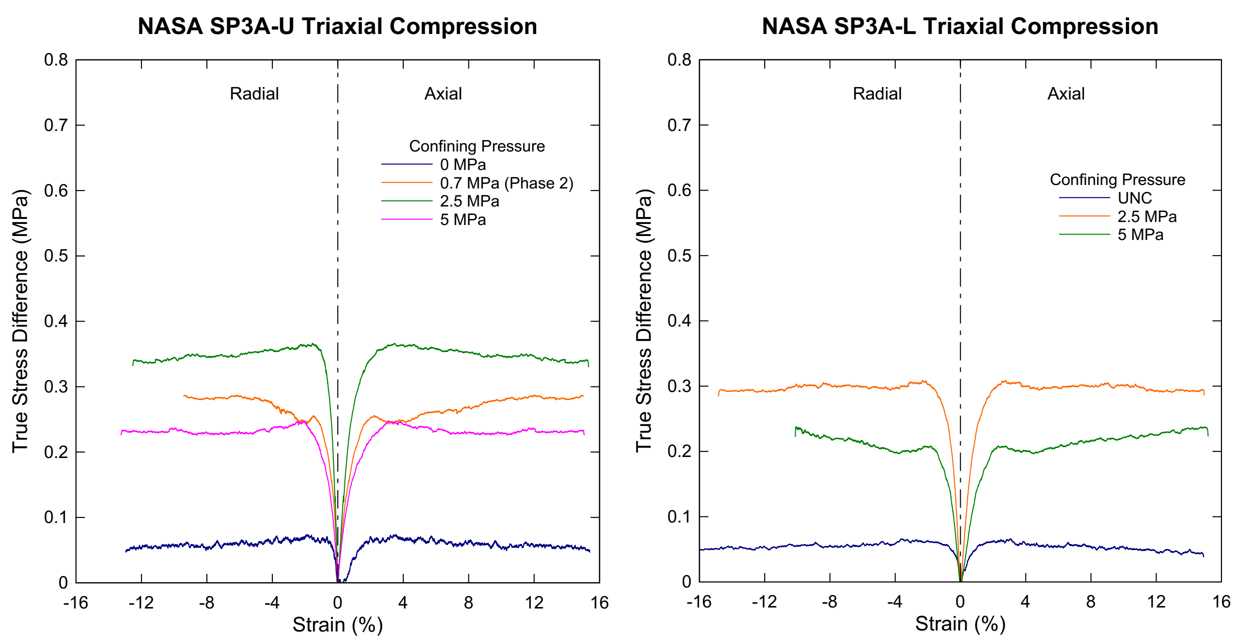

Figure 4-12. Triaxial Compression Test Data from the SP3A Saturated Clay Soils

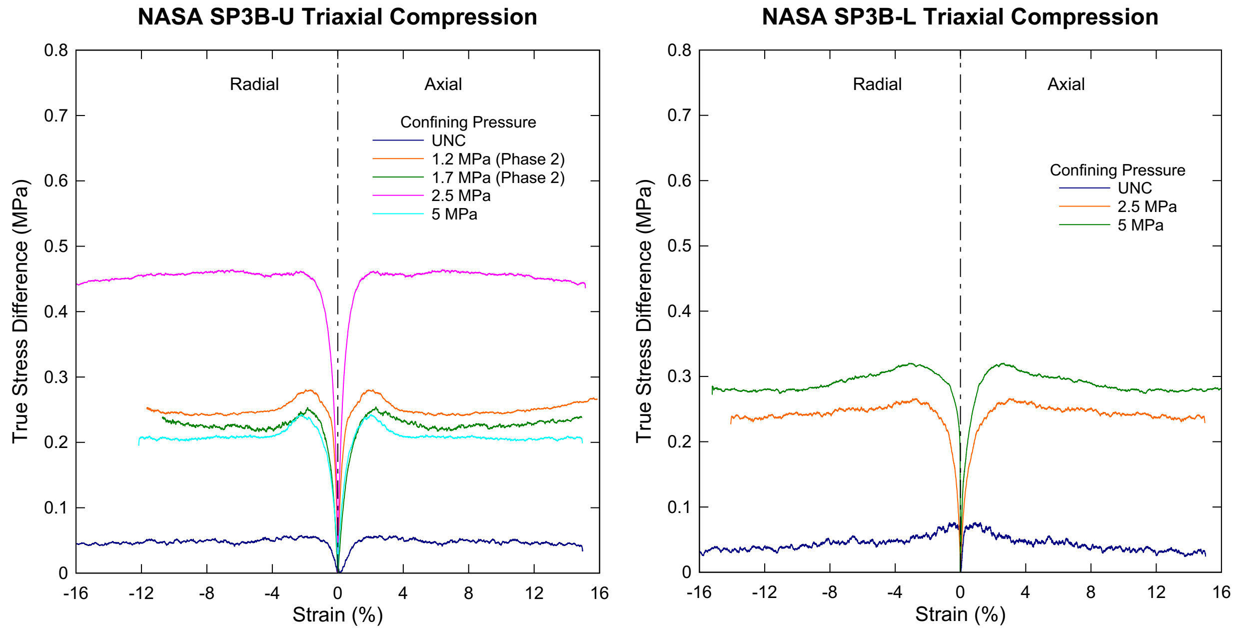

Figure 4-13. Triaxial Compression Test Data from the SP3B Saturated Clay Soils

Table 4-8. Triaxial Compression Test results for UTTR Saturated Clay Soils

Sample ID	Test ID	Measured Confining Pressure (MPa)	Mean Stress (MPa)	Maximum Stress Difference (MPa)
DRY-U-03	F13A20	0.00	0.045	0.135
DRY-U-04	F14D/C20	2.50	2.650	0.451
DRY-U-05	F18A/B20	5.00	5.170	0.509
DRY-L-04	F18C20	0.00	0.050	0.151
DRY-L-05	F21A/B20	2.50	2.626	0.379
DRY-L-06	F26C/D20	5.00	5.132	0.396
SP3A-U-03	F19A20	0.00	0.025	0.074
SP3A-U-04	F24A/B20	2.50	2.622	0.366
SP3A-U-05	F27A/B20	5.00	5.083	0.248
SP3A-U-07	G11A/B20	0.70	0.780	0.256
SP3A-L-04	F19B20	0.00	0.022	0.066
SP3A-L-06	F24C/D20	2.50	2.603	0.309
SP3A-L-07	F27C/D20	5.00	5.079	0.238
SP3B-U-03	F20A20	0.00	0.019	0.057
SP3B-U-04	F25C/D20	2.50	2.654	0.462
SP3B-U-05	F28A/B20	5.00	5.081	0.242
SP3B-U-06	G12A/B20	1.20	1.292	0.281
SP3B-U-07	G17A/B20	1.69	1.777	0.254
SP3B-L-04	F20B20	0.00	0.025	0.076
SP3B-L-05	F26A/B20	2.50	2.589	0.266
SP3B-L-06	F28C/D20	5.00	5.107	0.320

The peaks from Figures 4-11 through 4-13 were used to create the strength envelope for UTTR saturated clays shown in Figure 4-14. As shown in the figure, the soil samples produced some variability in shear strength at given values of mean stress. The solid blue curve plotted through the data represents the average shear strength of approximately 0.33 MPa for the data points with mean stresses above 0.5 MPa. The dashed lines on either side of the average shear strength are bounds of ± 1 standard deviation (σ), or ± 0.09 MPa, which capture most of the remaining data points in this subset.

The unconfined compression test data, see Figure 4-10, are used to establish the strength envelope at mean stresses below 0.5 MPa. As shown in Figure 4-14, the test data fall along the 3:1 Unconfined Compression Strength (UCS) stress path in this regime. Therefore, the recommended strength envelope for saturated clays at UTTR can be represented by the 3:1 UCS stress path beginning at the origin and then intersecting the average shear strength of 0.33 ± 0.09 MPa.

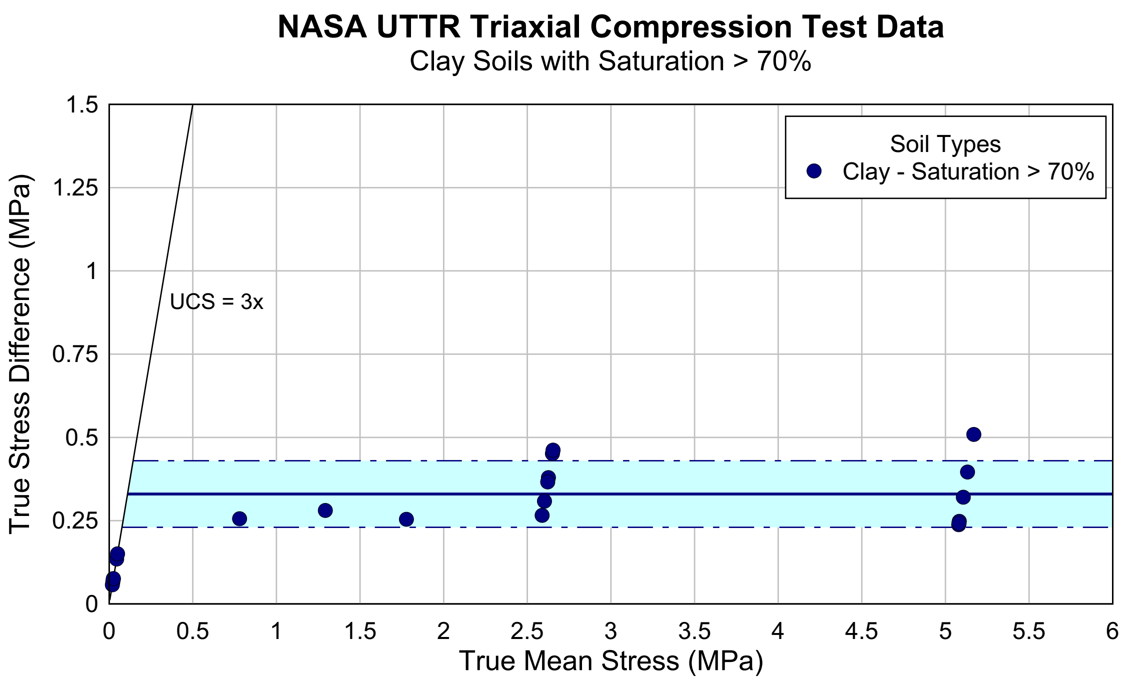

Figure 4-14. UTTR Saturated Clay Soils Strength Envelope

5 UTTR Soil Compressibility Testing Results

The following sections present the compressibility data for the UTTR soils evaluated in this study. Compressibility testing included hydrostatic compression tests, uniaxial strain tests, and oedometer tests using the methodologies explained in Sections 3.5, 3.6, and 3.7, respectively.

5.1 Surface Crust Soils

Compressibility tests were conducted on eleven surface crust soil samples collected from the SI10 and HS2 sites at UTTR. As noted in Section 3.7, the compressibility testing on the surface crust was conducted using hydrostatic compression tests and oedometer tests (replacing uniaxial strain tests) due to the sample thickness limitations. Table 5-1 summarizes the mass-volume properties of the surface crust samples used for the compressibility tests.

Table 5-1. Mass-Volume Properties of UTTR Surface Crust Compressibility Test Samples

Sample ID	Test ID	Test Type	Moisture Content	Dry Bulk Density (Mg/m^3)	Grain Density (Mg/m^3)	Porosity	Saturation
SI10-01	N9A22	HST	7.6%	1.254	2.719	53.9%	17.7%
SI10-02	N11A22		10.7%	1.334	2.719	50.9%	28.1%
SI10-03	J16A23	OD	9.1%	1.233	2.719	54.6%	20.6%
SI10-04	J17A23		9.1%	1.288	2.719	52.6%	22.2%
SI10-05	J17B23		8.8%	1.192	2.719	56.2%	18.6%
SI10 Average			**9.1%**	**1.260**	**2.719**	**53.6%**	**21.4%**
HS2-4-01	N15A22	HST	7.0%	1.521	2.713	43.9%	24.1%
HS2-4-02	N16A22		6.7%	1.524	2.713	43.8%	23.1%
HS2-4-03	N18A22		5.9%	1.483	2.713	45.4%	19.3%
HS2-4-04	J18A23	OD	6.0%	1.465	2.729	46.3%	19.1%
HS2-4-05	J18B23		6.5%	1.491	2.729	45.4%	21.4%
HS2-4-06	J19A23		6.1%	1.478	2.729	45.9%	19.7%
HS2 Average			**6.4%**	**1.494**	**2.721**	**45.1%**	**21.1%**

Notes:
HST = Hydrostatic compression test
OD = Oedometer test

5.1.1 Hydrostatic Compression Results

Two hydrostatic compression tests were performed on the SI10 surface crust soil. The data from these two tests are plotted in Figure 5-1. The first test (SI10-01) was to be conducted with confining pressure load/unload cycles of 2, 4, 8, 12, 20, and 40 MPa, however, the jacket on the sample developed a leak prior to the loading cycle up to 20 MPa. Therefore, Figure 5-1 only shows the data through the 12 MPa load/unload cycle for this specimen.

As shown in Figure 5-1, the SI10-01 test initially produced a high volumetric strain of nearly 5% with very little confining stress being applied to the sample. This high volumetric strain may be due to sample disturbance or initial settling of the sample; however, the same phenomenon was not measured in the second SI10 surface crust test (SI10-02). The second SI10 hydrostatic compression test was a standard test (i.e., no intermediate unloading cycles) with a maximum confining pressure of 30 MPa. Figure 5-1 presents the results of the two hydrostatic tests conducted on the SI10 surface crust, showing mean stress as a function of volumetric strain.

Three hydrostatic compression tests were conducted on the HS2 surface crust samples. The first HS2 hydrostatic test (HS2-4-01) was a standard test with a peak confining pressure of 30 MPa, while the second test (HS2-4-02) was a standard test up to 40 MPa confining pressure. The third test (HS2-4-03) was a cycled hydrostatic compression test with confining pressure load/unload cycled of 4, 8, 16, 30, and 50 MPa. The results of these tests are presented in Figure 5-2. Table 5-2 presents the results of the surface crust hydrostatic compression tests from both UTTR sites, including the loading and unloading bulk moduli derived using the techniques described in Section 3.5. The detailed hydrostatic test results for the surface crust soils including specimen photographs are provided in Appendix A.

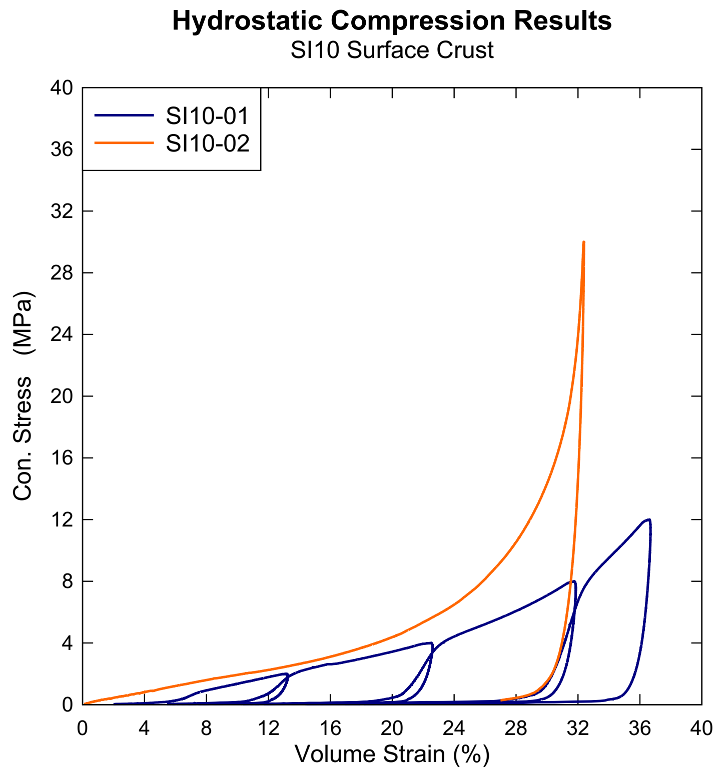

Figure 5-1. Hydrostatic Compression Data from the SI10 Surface Crust

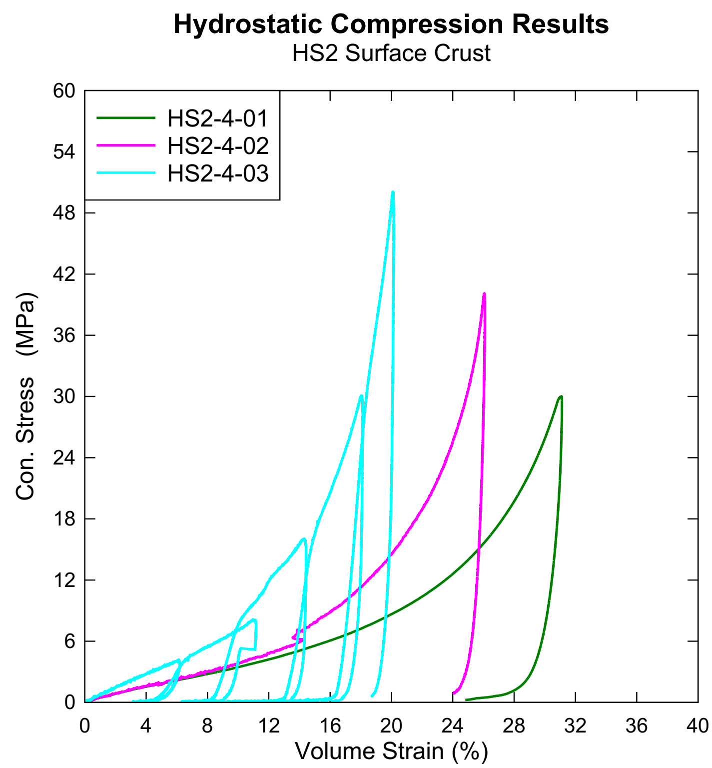

Figure 5-2. Hydrostatic Compression Data from the HS2 Surface Crust

Table 5-2. UTTR Surface Crust Bulk Moduli Derived from Hydrostatic Tests

Sample ID	Test ID	Type	Bulk Modulus (GPa)			
			K_1	K_2	K_3	K_u
SI10-01	N9A22	HST	0.046	0.021	0.104	1.155
SI10-02	N11A22		0.019	n/a	1.912	2.848
HS2-4-01	N15A22	HST	0.031	n/a	0.450	2.621
HS2-4-02	N16A22		0.036	n/a	1.226	5.368
HS2-4-03	N18A22		0.065	n/a	1.071	15.112

5.1.2 Oedometer Results

Six oedometer tests were conducted on the surface crust samples collected from the SI10 and the HS2 sites, three from each site as shown in Table 5-1. Each test was conducted up to a maximum axial stress of either 40 MPa or 50 MPa. The axial stress and axial (volume) strains were recorded during each test. Figure 5-3 presents the data from the three SI10 surface crust oedometer tests. Figure 5-4 presents the HS2 surface crust oedometer test data. The constrained loading and unloading moduli for each surface crust sample were derived from the oedometer data using the methods described in Section 3.6. Table 5-3 presents the derived moduli from the oedometer tests for the SI10 and HS2 surface crust samples.

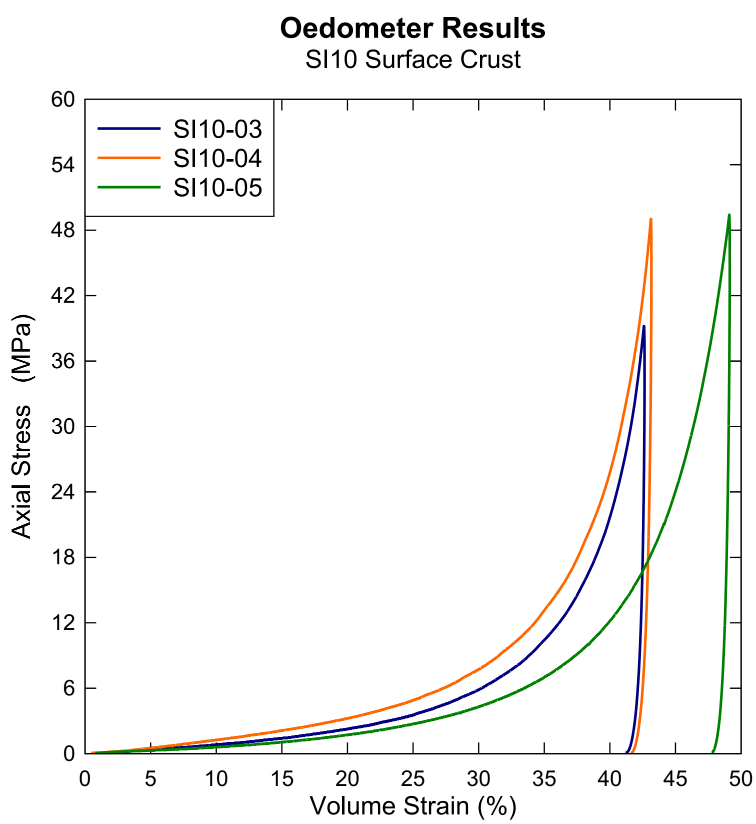

Figure 5-3. Oedometer Test Data from the SI10 Surface Crust Soil

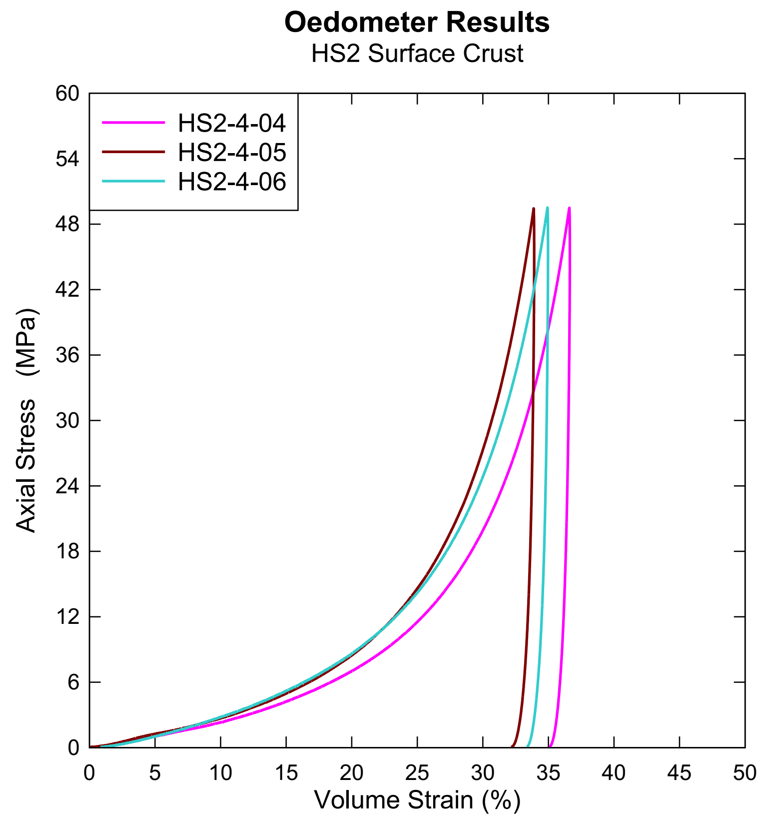

Figure 5-4. Oedometer Test Data from the HS2 Surface Crust Soil

Table 5-3. UTTR Surface Crust Constrained Moduli Derived from Oedometer Tests

Sample ID	Test ID	Type	Constrained Modulus (GPa)		
			M_1	M_2	M_u
SI10-03	J16A23	OD	0.009	1.05	9.2
SI10-04	J17A23		0.014	1.26	8.7
SI10-05	J17B23		0.005	0.88	9.9
HS2-4-04	J18A23	OD	0.024	0.74	7.9
HS2-4-05	J18B23		0.028	0.78	7.3
HS2-4-06	J19A23		0.037	0.72	8.2

5.2 Silty Clay Soils

Hydrostatic compressibility tests and uniaxial strain tests were conducted on the silty clay soils sampled from the SM7 site at UTTR. Table 5-4 summarizes the mass-volume properties from each sample tested. Moisture tests were conducted on a portion of each sample after the triaxial test was completed. Upper samples marked with a "U" designation were collected as soil cores from a depth of 7.6 cm to 22.9 cm (3 in to 9 in). The lower samples marked with an "L" designation were collected as soil cores from a depth of 15.2 cm to 30.5 cm (6 in to 12 in). Detailed test results and specimen photographs are provided in Appendix B.

Table 5-4. Mass-Volume Properties of UTTR Silty Clay Compressibility Test Samples

Sample ID	Test ID	Test Type	Moisture Content	Dry Bulk Density (Mg/m^3)	Grain Density (Mg/m^3)	Porosity	Saturation
SM-7-U (6-1A) #11	F22A22	HST	14.0%	1.411	2.696	47.7%	41.5%
SM-7-U (6-1B) #12	F11A22	Uniax	16.3%	1.488	2.737	45.6%	53.0%
SM7 Upper Average			**15.2%**	**1.450**	**2.717**	**46.7%**	**47.3%**
SM-7-L (2-02) #20	D7A21	HST	15.5%	1.687	2.765	39.0%	67.1%
SM-7-L (2-01) #19	D1A21	Uniax	14.2%	1.658		40.0%	58.8%
SM-7-L (2-08) #26	F10A22		15.7%	1.673		39.5%	66.5%
SM7 Lower Average			**15.1%**	**1.673**	**2.765**	**39.5%**	**64.1%**

Notes:
HST = Hydrostatic compression test
Uniax = Uniaxial strain test

5.2.1 Hydrostatic Compression Results

Two hydrostatic compression tests of silty clay soils were conducted, including intermediate load/unload cycles, with a peak confining pressure of 40 MPa. The test data are presented in Figure 5-5. The drier sample (SM-7-U (6-1A)) accommodated a larger volumetric strain at low stress compared to the more saturated sample (SM-7-L (2-02)). The abrupt increase in stiffness at approximately 12% and 24% volumetric strains indicates that all air voids were crushed out and pore water pressure began to develop as the samples reached saturation. The loading and unloading moduli obtained from the hydrostatic compression tests on the UTTR silty clay soils are presented in Table 5-5.

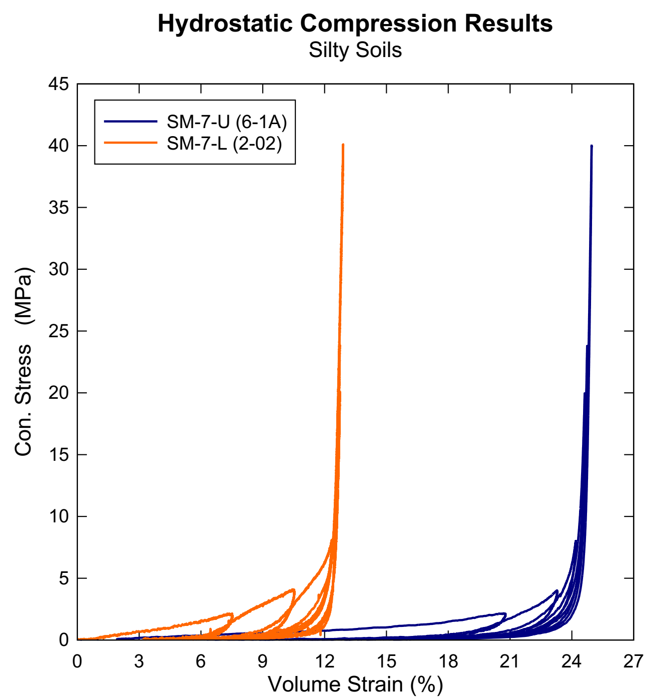

Figure 5-5. Hydrostatic Compression Test Data from UTTR Silty Clay Soils

Table 5-5. UTTR Silty Clay Soil Moduli Obtained from Hydrostatic Compression Tests

Sample ID	Test ID	Type	Bulk Modulus (GPa)	
			K_1	K_u
SM-7-U (6-1A) #11	F22A22	HST	0.006	12.1
SM-7-L (2-02) #20	D7A21		0.023	8.4
Silty Clay Hydrostatic Compression Average			**0.015**	**10.3**

5.2.2 Uniaxial Strain Results

Figure 5-6 presents the data from the three uniaxial strain tests conducted with the silty clay soils at UTTR. The left-hand plot presents the uniaxial test data in terms of axial stress versus axial strain, used to derive the soil's constrained moduli (M) as described in Section 3.6. The right-hand plot presents the test data in terms of axial stress versus confining stress, which is used to derive the material's Poisson's ratio (v) as described in Section 3.6.

The SM7 silty soils proved very difficult to conduct uniaxial strain tests. For the SM7 upper sample and the first SM7 lower sample, it was difficult for the lab operator to maintain uniaxial strain conditions (i.e., no radial strain). This resulted in slightly discontinuous curves in the axial stress versus axial strain plots. Additional engineering judgement was used in fitting the curves to determine the moduli and Poisson's ratio values for these tests.

A summary of the properties obtained from the uniaxial strain tests on the silty clay soils of UTTR is presented is presented in Table 5-6.

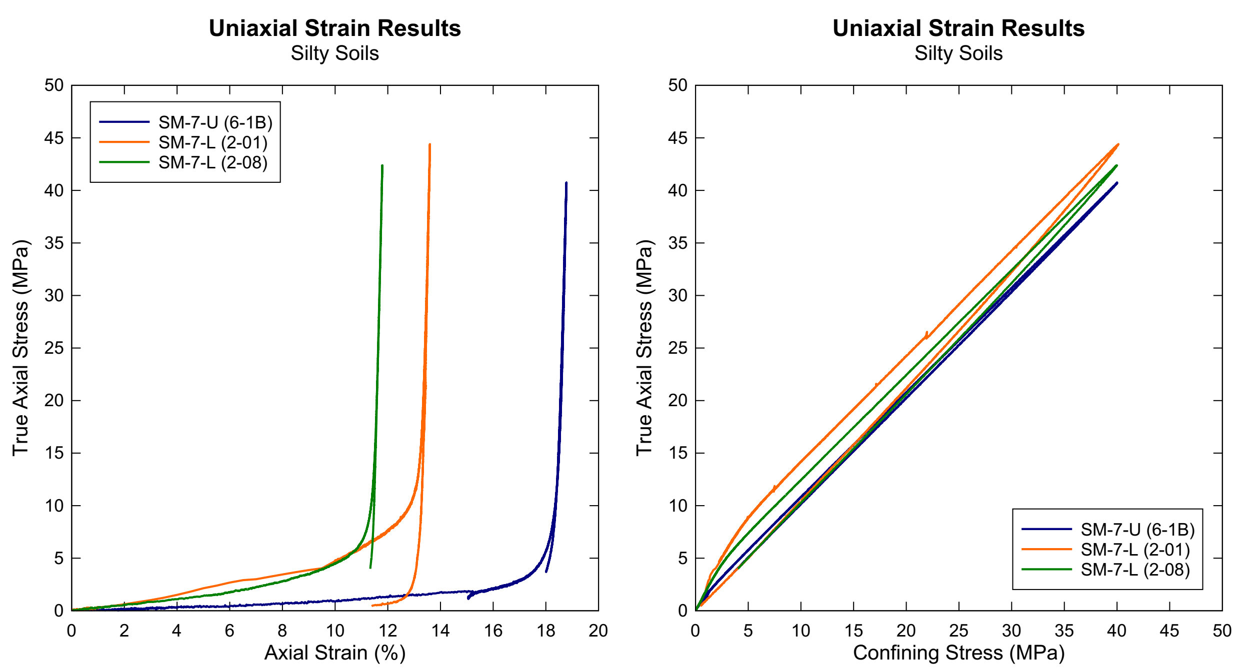

Figure 5-6. Uniaxial Strain Test Data from UTTR Silty Clay Soils

Table 5-6. Properties for UTTR Silty Clay Soils Obtained from Uniaxial Strain Tests

Sample ID	Test ID	Type	Constrained Modulus (GPa)		Poisson's Ratio
			M_1	M_u	ν_1
SM-7-U (6-1B) #12	F11A22	Uniax	0.012	9.2	0.43
SM-7-L (2-01) #19	D1A21		0.042	13.4	0.37
SM-7-L (2-08) #26	F10A22		0.027	11.6	0.34
Silty Clay Uniaxial Strain Average			**0.027**	**11.4**	**0.38**

5.3 Partially Saturated Clay Soils

Four compressibility tests were conducted on partially saturated clay soils (less than 70% saturation) collected from the HS2 and SM7 sites at UTTR. Table 5-7 summarizes the mass-volume properties of each sample tested. The two specimens marked with an "S" designation were reconstituted from bulk samples of the dry, desiccated silt and clay fines on the surface of the SM7 site. The upper sample from the HS2 site (DRY-U-08) was collected as a soil core from 0.0 cm to 15.2 cm (0 in to 6 in) depth. The lower sample from the HS2 site (DRY-L-08) was collected as a soil core from 15.2 cm to 30.5 cm (6 in to 12 in) depth. The two HS2 samples were air-dried to a gravimetric moisture content of approximately 15% before the hydrostatic compression tests were conducted. Detailed test results are provided in Appendix C.

Table 5-7. Mass-Volume Properties of UTTR Partially Saturated Clay Compressibility Samples

Sample ID	Test ID	Type	Moisture Content	Dry Bulk Density (Mg/m^3)	Grain Density (Mg/m^3)	Porosity	Saturation
DRY-U-08	O20A20	HST	15.0%	1.605	2.713	40.8%	59.0%
DRY-L-08	N9A20	Uniax	14.7%	1.363	2.701	49.5%	40.5%
HS2 Average			**14.9%**	**1.484**	**2.707**	**45.2%**	**49.8%**
SM-7-S 2-1/2 (bulk)	A4A22	HST	2.7%	1.243	2.696	53.9%	6.2%
SM-7-S 2-1/2 (bulk)	A1A22	Uniax	2.7%	1.245		53.8%	6.3%
SM7 Surface Average			**2.7%**	**1.244**	**2.696**	**53.9%**	**6.3%**

Notes:
HST = Hydrostatic compression test
Uniax = Uniaxial strain test

5.3.1 Hydrostatic Compression Results

Figure 5-7 presents the hydrostatic compression results from the partially saturated clay soils at UTTR, which were sampled at the HS2 and SM7 sites, in terms of confining stress versus volumetric strain. Compared to the hydrostatic compression tests of the silty clay soils that were conducted up to a confining pressure of 40 MPa (see Section 5.2.1), a lower peak confining pressure of 20 MPa was selected for the partially saturated clay samples. As shown in the figure, the volumetric strain of the HS2 upper sample was approximately 15%, while the SM7 surface sample showed a much softer compressibility response of roughly 30%. A summary of the properties obtained from the hydrostatic compression tests on the partially saturated clay soils of UTTR is presented in Table 5-8.

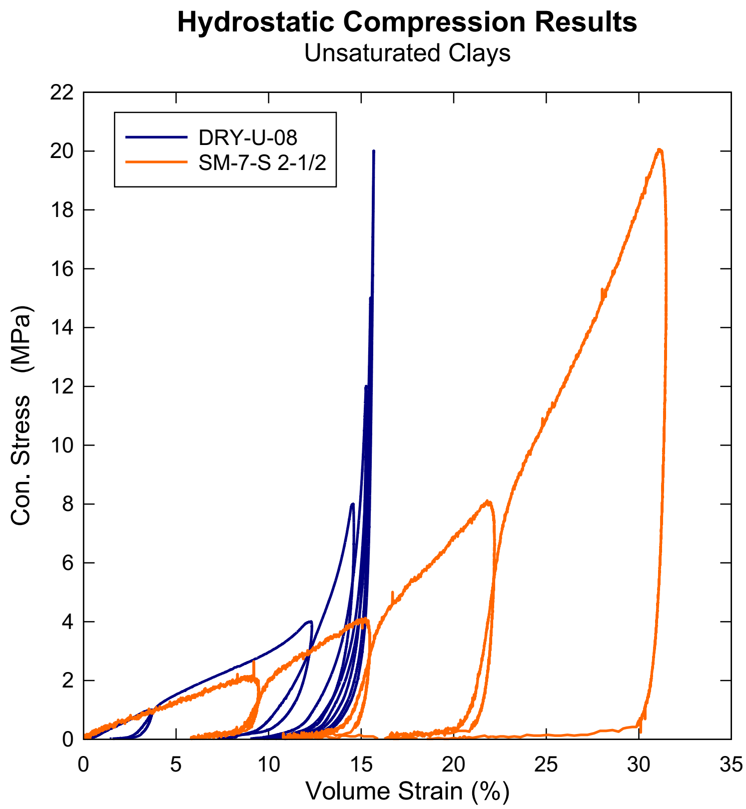

Figure 5-7. Hydrostatic Compression Test Data from UTTR Partially Saturated Clays

Table 5-8. Bulk Moduli of Partially Saturated Clays obtained from Hydrostatic Compression Tests

Sample ID	Test ID	Type	Bulk Modulus (GPa)	
			K_1	K_u
DRY-U-08	O20A20	HST	0.031	5.9
SM-7-S 2-1/2	A4A22		0.023	23.1
Hydrostatic Compression Average			**0.027**	**14.6**

5.3.2 Uniaxial Strain Results

Figure 5-8 presents the uniaxial strain results from the partially saturated clay soils at UTTR, in terms of axial stress versus axial/volume strain (left) and in terms of axial stress versus confining stress (right). The reconstituted SM7 specimen proved very difficult to conduct uniaxial strain tests due to the delicate nature of the sample. For the SM7 test, it was difficult for the lab engineer to maintain uniaxial strain conditions (i.e., no radial strain). This resulted in a discontinuous axial stress versus axial strain curve. In regions where uniaxial strain control fluctuated, results were computed by holding radial strain at zero and computing stress results using available lab test data. This method assumed isotropic compressibility and applied Hooke's law to derive the response. Engineering judgement was used in curve fitting to determine the modulus and Poisson's ratio values. A summary of the properties obtained from the uniaxial strain tests on the partially saturated clay soils of UTTR is presented in Table 5-9.

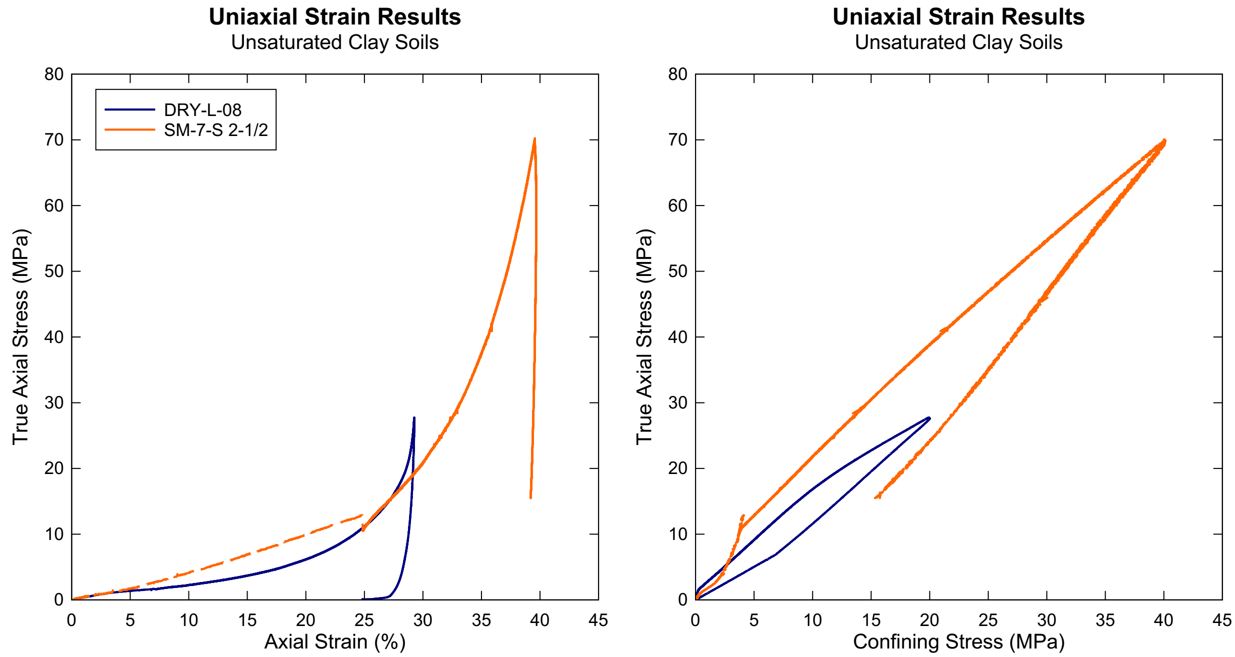

Figure 5-8. Uniaxial Strain Results from UTTR Partially Saturated Clay Soils

Table 5-9. Properties for Partially Saturated Clay Soils Obtained from Uniaxial Strain Tests

Sample ID	Test ID	Type	Constrained Modulus (GPa)		Poisson's Ratio
			M_1	M_u	ν_1
DRY-L-08	N9A20	Uniax	0.022	3.9	0.36
SM-7-S 2-1/2	A1A22		0.043	10.5	0.35
Uniaxial Strain Average			**0.033**	**6.5**	**0.36**

5.4 Saturated Clay Soils

Twelve compressibility tests were conducted on samples of UTTR saturated clay (> 70% saturation) collected from the HS2 (i.e., "DRY"), SP3A and SP3B sites. Table 5-10 summarizes the mass-volume properties from the saturated clay samples tested. Upper samples designated with a "U" were collected as soil cores from 0.0 cm to 15.2 cm (0 in to 6 in) depth. The lower samples identified with an "L" were collected as soil cores between 15.2 cm and 30.5 cm (6 in and 12 in) depth. Detailed test results and specimen photographs are provided in Appendix D.

5.4.1 Hydrostatic Compression Results

Figure 5-9 presents the hydrostatic compression results from the saturated clay soils at UTTR, which were collected from the HS2, SP3A and SP3B sites, in terms of confining stress versus volume strain. As shown in the figure, the volumetric strains ranged from approximately 1.5% for the SP3A lower sample to about 7% for the HS2 (i.e., "DRY") upper sample. A summary of the bulk moduli properties obtained from the hydrostatic compression tests on the saturated clay soils of UTTR is presented in Table 5-11.

Table 5-10. Mass-Volume Properties of Saturated Clay Compressibility Test Samples

Sample ID	Test ID	Test Type	Moisture Content	Dry Bulk Density (Mg/m^3)	Grain Density (Mg/m^3)	Porosity	Saturation
DRY-U-01	D19A19	HST	27.4%	1.430	2.701	47.1%	83.2%
DRY-U-02	J14A20	Uniax	25.8%	1.411		47.8%	76.3%
HS2 Upper Average			**26.6%**	**1.421**	**2.701**	**47.5%**	**79.8%**
DRY-L-01	J7A20	HST	26.8%	1.425	2.701	47.2%	80.7%
DRY-L-02	J14B20	Uniax	29.1%	1.448		46.4%	90.7%
HS2 Lower Average			**28.0%**	**1.437**	**2.701**	**46.8%**	**85.7%**
SP3A-U-01	J8A20	HST	36.3%	1.305	2.685	51.4%	92.2%
SP3A-U-02	J15A20	Uniax	33.2%	1.377		48.7%	93.9%
SP3A Upper Average			**34.8%**	**1.341**	**2.685**	**50.1%**	**93.1%**
SP3A-L-01	J8B20	HST	44.8%	1.190	2.749	56.7%	94.0%
SP3A-L-02	J16A20	Uniax	42.0%	1.174		57.3%	85.9%
SP3A Lower Average			**43.4%**	**1.182**	**2.749**	**57.0%**	**90.0%**
SP3B-U-01	J9A20	HST	34.2%	1.279	2.701	52.7%	83.0%
SP3B-U-02	J17A20	Uniax	38.1%	1.198		55.6%	82.0%
SP3B Upper Average			**36.2%**	**1.239**	**2.701**	**54.2%**	**82.5%**
SP3B-L-01	J10A20	HST	47.5%	1.103	2.760	60.0%	87.3%
SP3B-L-02	J17B20	Uniax	48.1%	1.134		58.9%	92.6%
SP3B Lower Average			**47.8%**	**1.119**	**2.760**	**59.5%**	**90.0%**

Notes:
HST = Hydrostatic compression test
Uniax = Uniaxial strain test

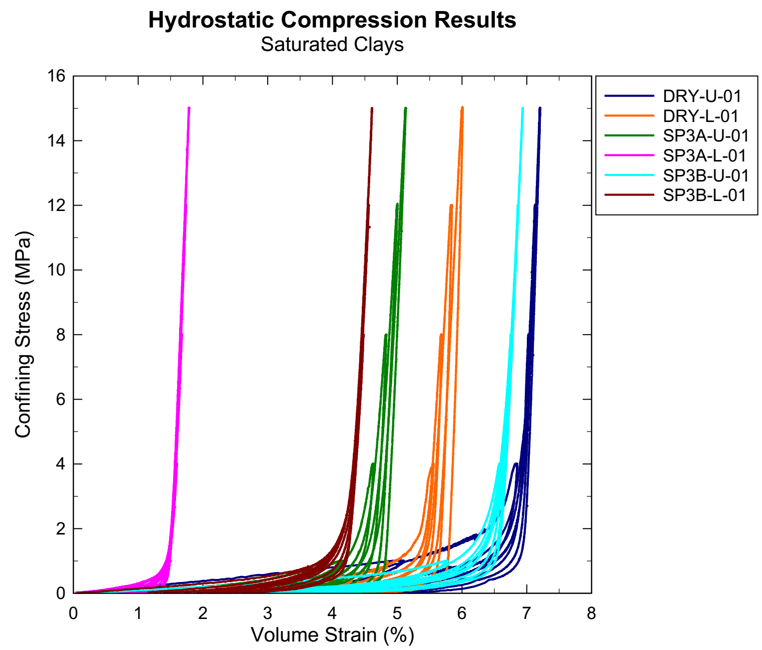

Figure 5-9. Hydrostatic Compression Test Data from UTTR Saturated Clays

Table 5-11. UTTR Saturated Clay Bulk Moduli Obtained from Hydrostatic Compression Tests

Sample ID	Test ID	Test Type	Bulk Modulus (GPa)	
			K_1	K_u
DRY-U-01	D19A19	HST	0.020	6.0
DRY-L-01	J7A20		0.009	6.1
		HS2 Average	**0.014**	**6.1**
SP3A-U-01	J8A20	HST	0.008	4.8
SP3A-L-01	J8B20		0.019	5.1
		SP3A Average	**0.014**	**5.0**
SP3B-U-01	J9A20	HST	0.008	4.5
SP3B-L-01	J10A20		0.011	4.4
		SP3B Average	**0.010**	**4.5**

5.4.2 Uniaxial Strain Results

Figure 5-10 presents the uniaxial strain results from UTTR clay soils with higher saturation levels, in terms of axial stress versus axial strain (left) and in terms of axial stress versus confining stress (right). As shown in the figure, the axial strain ranged from approximately 2% for the SP3A upper sample to about 7% for the HS2 (i.e., "DRY") upper sample. The initial constrained modulus ranged from 0.013 GPa for the HS2 upper sample to 0.021 GPa for the SP3A lower sample. A summary of the properties obtained from the uniaxial strain tests on the saturated clay soils of UTTR is presented in Table 5-12.

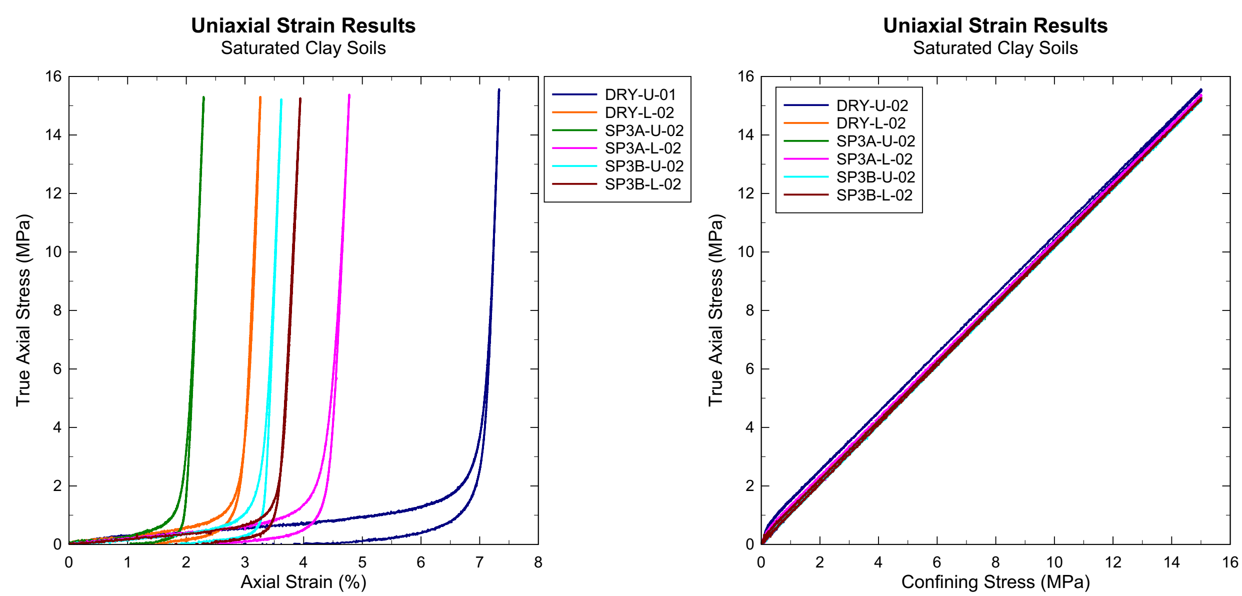

Figure 5-10. Uniaxial Strain Test Data from UTTR Saturated Clay Soils

Table 5-12. Properties for Saturated Clay Soils Obtained from Uniaxial Strain Tests

Sample ID	Test ID	Type	Constrained Modulus (GPa)		Poisson's Ratio	
			M_1	M_u	ν_1	ν_2
DRY-U-02	J14A20	Uniax	0.013	6.0	0.30	0.499
DRY-L-02	J14B20		0.017	5.0	0.22	0.499
HS2 Average			**0.015**	**5.5**	**0.26**	**0.499**
SP3A-U-02	J15A20	Uniax	0.018	5.2	0.38	0.498
SP3A-L-02	J16A20		0.021	4.5	0.29	0.499
SP3A Average			**0.020**	**4.9**	**0.34**	**0.499**
SP3B-U-02	J17A20	Uniax	0.017	5.5	0.33	0.499
SP3B-L-02	J17B20		0.017	4.2	0.33	0.499
SP3B Average			**0.017**	**4.9**	**0.33**	**0.499**

6 Conclusions

Laboratory tests of UTTR soil samples were conducted by Applied Research Associates to assist NASA in developing soil material models to simulate landings of the Mars Sample Return Earth Entry System. A total of 90 tests were completed, consisting of 33 triaxial or unconfined compression tests, 25 direct shear tests, 15 hydrostatic compression tests, and 17 uniaxial strain or oedometer tests. The laboratory tests were conducted on four types of soils encountered at UTTR including hard surface crust soil, silty clay soil, partially saturated clay soil, and saturated clay soil.

The laboratory tests were tailored to determine the strength and compressibility of the different soil types to capture their strength and stiffness behavior with varying levels of moisture saturation. From these test results, ARA derived constitutive model inputs for LS-DYNA Material Model 16 (MAT016), Pseudo-Tensor, and LS-DYNA Equation of State 8 (EOS8), Tabulated Compaction, which are being used by NASA to model the MSR-EES impact with the ground surface at UTTR. The soil models in this report are based on static strength and compressibility tests. No attempt was made at impact loading the soil samples or accounting for strain rate effects.

The laboratory tests conducted in this study provide bounding results for expected UTTR soil responses during an MSR-EES impact event based on soil type and saturation conditions. The constitutive models are valid for a mean stress up to 5 MPa, which is the maximum soil mean stress predicted by NASA's LS-DYNA landing simulations. Material properties for computations above 5 MPa mean stress should be revaluated to account for differences in soil response at the higher stress levels.

7 References

[1] United States Department of Agriculture - Natural Resources Conservation Service, "Soil Survey of Tooele Area, Utah," National Cooperative Soil Survey, 2000.

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[3] American Society for Testing and Materials (ASTM) D2487, "Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)," American Society for Testing and Materials, West Conshohocken, PA, 2017.

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[5] American Society for Testing and Materials (ASTM) D6913, "Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis," American Society for Testing and Materials, West Conshohocken, PA, 2017.

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[8] J. O. Hallquist, *LS-DYNA Theoretical Manual,* Livermore, CA: Livermore Software Technology Corporation, 2006.

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[10] American Society for Testing and Materials (ASTM) D854, "Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer," American Society for Testing and Material, West Conshohocken, PA, 2014.

[11] American Society for Testing and Materials (ASTM) D2216, "Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass," American Society for Testing and Materials, West Conshohocken, PA, 2019.

[12] American Society for Testing and Materials (ASTM) D3080-03, "Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions," American Society for Testing and Materials, West Conshohocken, PA, 2017.

8 Acronyms and Abbreviations

ARA: Applied Research Associates

ASTM: American Society for Testing and Materials

cm: Centimeters

DS: Direct Shear Test

EES: Earth Entry System

EOS: Equation of State

GPa: Gigapascals

HST: Hydrostatic Compression Test

in: Inches

LaRC: Langley Research Center

LVDT: Linear Variable Differential Transformer

m: Meter

Mg: Megagram

ml: Milliliter

MPa: Megapascals

MSR: Mars Sample Return

NASA: National Aeronautics and Space Administration

NIST: National Institute of Standards Technology

OD: Oedometer Test

TXC: Triaxial Compression Test

UCS: Unconfined Compression Strength

Uniax: Uniaxial Strain Test

UTTR: Utah Test and Training Range

Appendix A

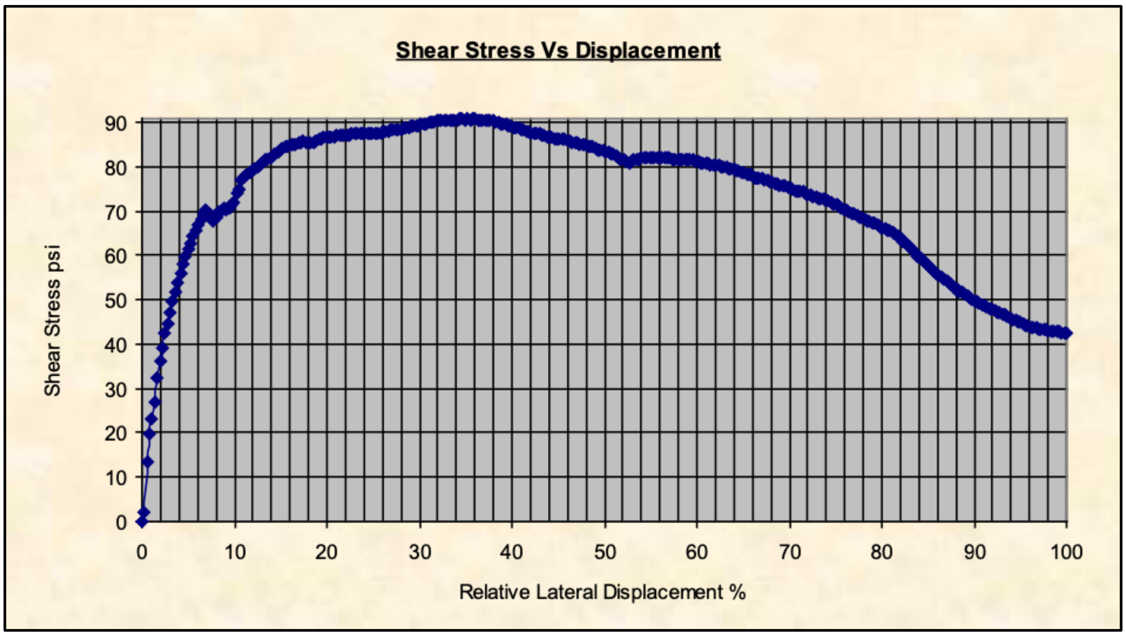
Surface Crust Soil Detailed Test Results

Direct Shear Tests
Hydrostatic Compression Tests
Oedometer Tests

UTTR Surface Crust Direct Shear Test
Sample SI10-1 (Group 1a)

Specimen Details			
Specimen Reference	B	**Description**	
Depth within Sample	0.0000in	**Orientation within Sample**	
Initial Height	0.5000 in	**Area**	1.41020 in2
Structure / Preparation		**Initial Water Content***	9.80 % (trimmings: 8.20 %)
Initial Wet Unit Weight	90.86 lbf/ft3	**Degree of Saturation**	25.97 %
Initial Dry Unit Weight	82.75 lbf/ft3	**Initial Voids Ratio**	1.000
Final Wet Unit Weight	111.66 lbf/ft3	**Final Water Content**	8.23%
Final Dry Unit Weight	103.16 lbf/ft3	**Dry Mass**	0.0338 lb
Tested Dry or Submerged	Dry		
Comments			

* Calculated from initial and dry weights of whole specimen

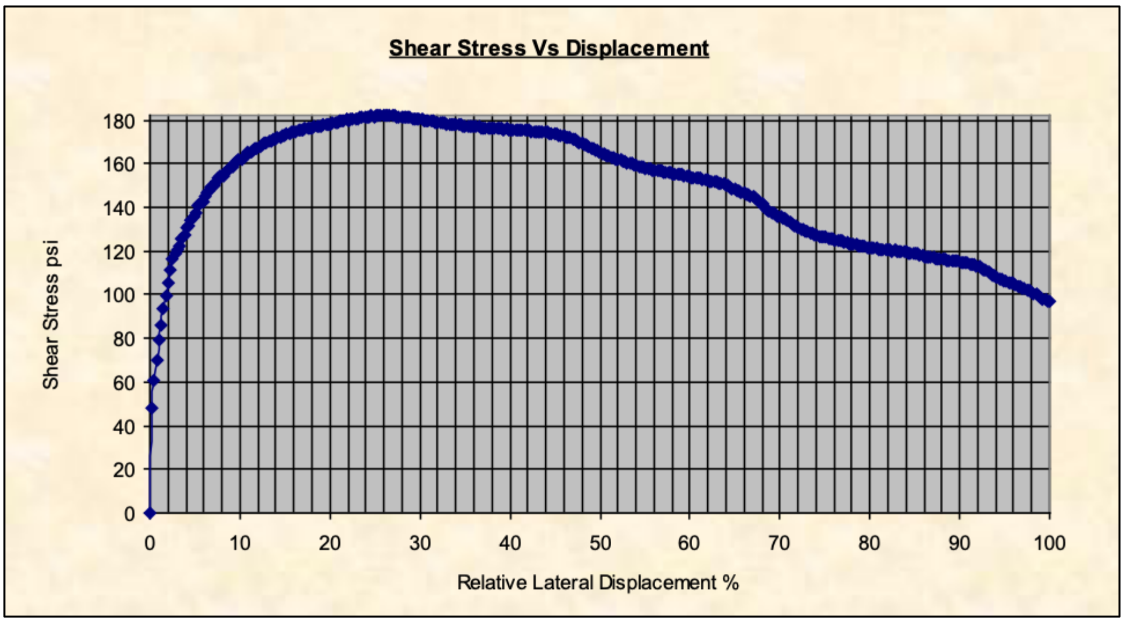


Conditions at Failure	
Normal Stress	260.48 psi
Peak Strength	90.92 psi
Horizontal Deformation	0.1348 in
Residual Stress	0.00 psi
Vertical Deformation	0.1050 in

UTTR Surface Crust Direct Shear Test
Sample SI10-2 (Group 1b)

Specimen Details			
Specimen Reference	B	**Description**	
Depth within Sample	0.0000in	**Orientation within Sample**	
Initial Height	1.0000 in	**Area**	2.95590 in2
Structure / Preparation		**Initial Water Content***	10.75 % (trimmings: 10.00 %)
Initial Wet Unit Weight	95.90 lbf/ft3	**Degree of Saturation**	31.26 %
Initial Dry Unit Weight	86.59 lbf/ft3	**Initial Voids Ratio**	0.911
Final Wet Unit Weight	121.46 lbf/ft3	**Final Water Content**	10.02%
Final Dry Unit Weight	110.40 lbf/ft3	**Dry Mass**	0.1481 lb
Tested Dry or Submerged	Dry		
Comments			

* Calculated from initial and dry weights of whole specimen

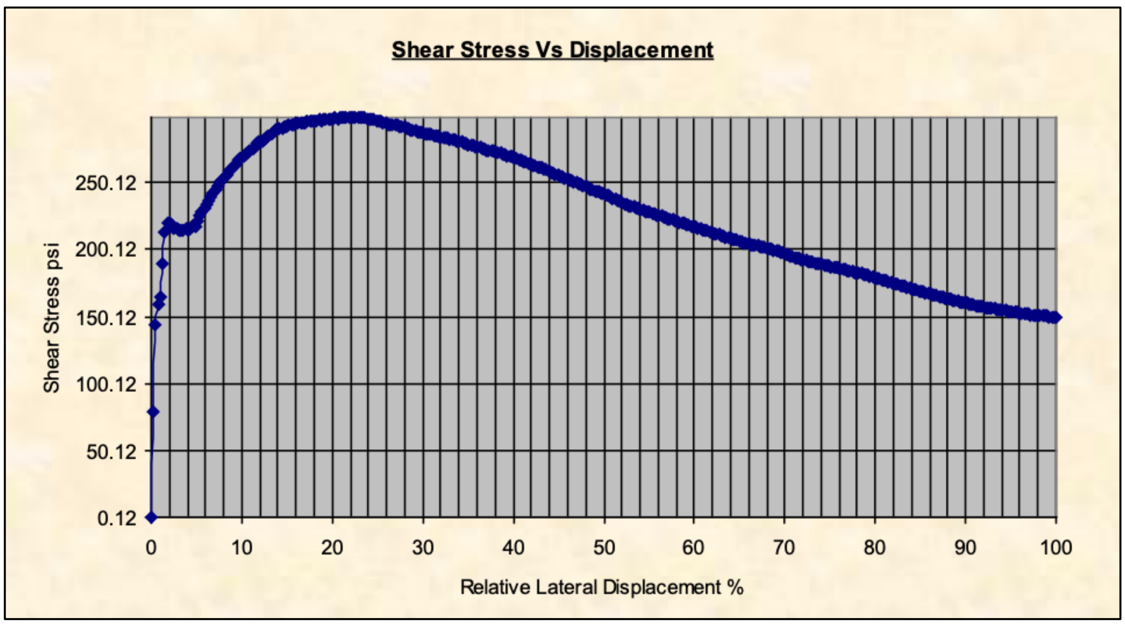


Conditions at Failure	
Normal Stress	545.43 psi
Peak Strength	182.08 psi
Horizontal Deformation	0.1076 in
Residual Stress	0.00 psi
Vertical Deformation	0.2119 in

UTTR Surface Crust Direct Shear Test
Sample SI10-1 (Group 1c)

Specimen Details			
Specimen Reference	D	**Description**	
Depth within Sample	0.0000in	**Orientation within Sample**	
Initial Height	0.5000 in	**Area**	1.41020 in2
Structure / Preparation		**Initial Water Content***	11.40 % (trimmings: 9.60 %)
Initial Wet Unit Weight	111.93 lbf/ft3	**Degree of Saturation**	46.70 %
Initial Dry Unit Weight	100.48 lbf/ft3	**Initial Voids Ratio**	0.647
Final Wet Unit Weight	151.08 lbf/ft3	**Final Water Content**	9.58%
Final Dry Unit Weight	137.87 lbf/ft3	**Dry Mass**	0.0410 lb
Tested Dry or Submerged	Dry		
Comments			

* Calculated from initial and dry weights of whole specimen

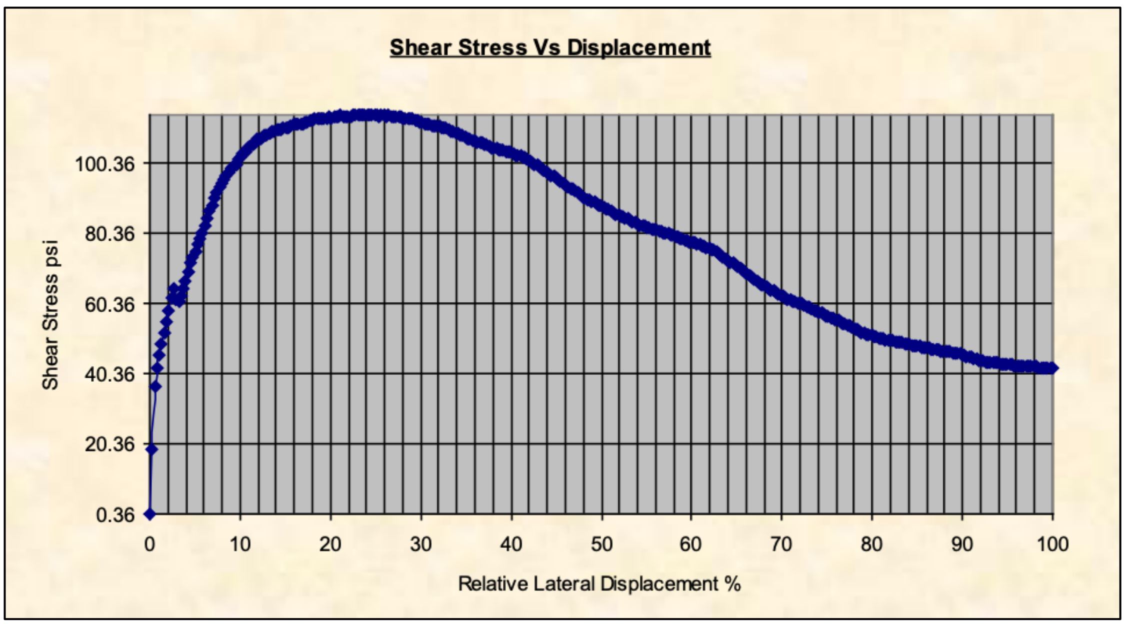


Conditions at Failure	
Normal Stress	845.27 psi
Peak Strength	298.67 psi
Horizontal Deformation	0.0892 in
Residual Stress	0.00 psi
Vertical Deformation	0.1431 in

UTTR Surface Crust Direct Shear Test
Sample SI10-5 (Group 2a)

Specimen Details			
Specimen Reference	C	**Description**	
Depth within Sample	0.0000in	**Orientation within Sample**	
Initial Height	0.5000 in	**Area**	1.41020 in2
Structure / Preparation		**Initial Water Content***	9.04 % (trimmings: 8.40 %)
Initial Wet Unit Weight	108.85 lbf/ft3	**Degree of Saturation**	36.42 %
Initial Dry Unit Weight	99.83 lbf/ft3	**Initial Voids Ratio**	0.658
Final Wet Unit Weight	109.10 lbf/ft3	**Final Water Content**	7.58%
Final Dry Unit Weight	101.42 lbf/ft3	**Dry Mass**	0.0407 lb
Tested Dry or Submerged	Dry		
Comments			

* Calculated from initial and dry weights of whole specimen

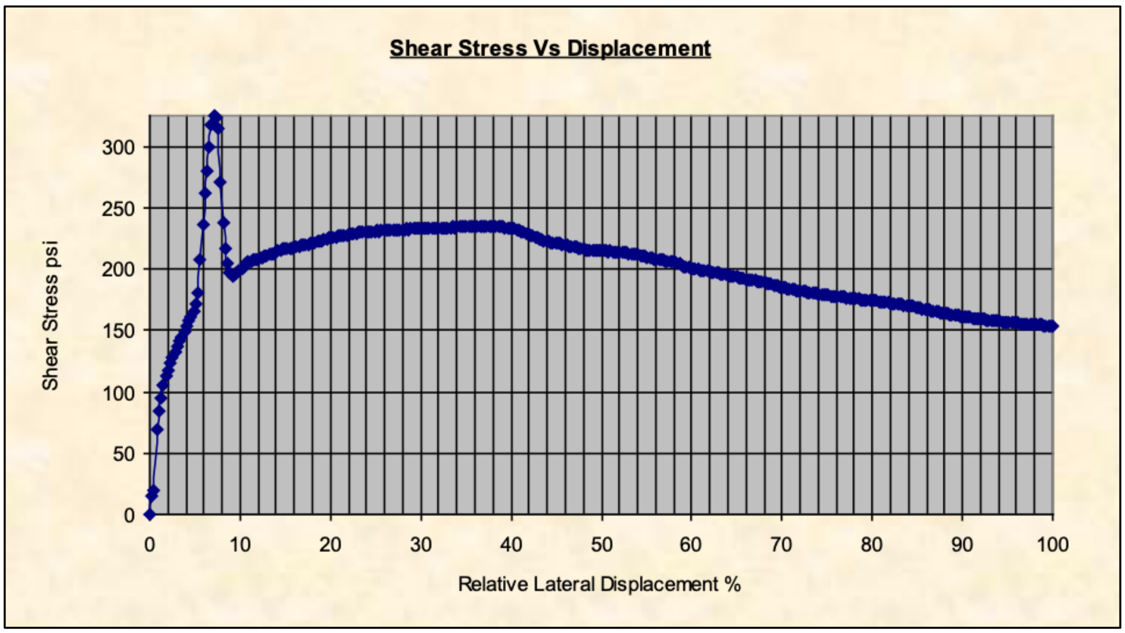


Conditions at Failure	
Normal Stress	260.19 psi
Peak Strength	114.12 psi
Horizontal Deformation	0.0946 in
Residual Stress	0.00 psi
Vertical Deformation	-0.0022 in

UTTR Surface Crust Direct Shear Test
Sample SI10-2 (Group 2b)

Specimen Details			
Specimen Reference	D	**Description**	
Depth within Sample	0.0000in	**Orientation within Sample**	
Initial Height	0.5000 in	**Area**	1.41020 in2
Structure / Preparation		**Initial Water Content***	9.46 % (trimmings: 8.00 %)
Initial Wet Unit Weight	113.23 lbf/ft3	**Degree of Saturation**	41.79 %
Initial Dry Unit Weight	103.45 lbf/ft3	**Initial Voids Ratio**	0.600
Final Wet Unit Weight	147.68 lbf/ft3	**Final Water Content**	14.79%
Final Dry Unit Weight	128.66 lbf/ft3	**Dry Mass**	0.0422 lb
Tested Dry or Submerged	Dry		
Comments			

* Calculated from initial and dry weights of whole specimen

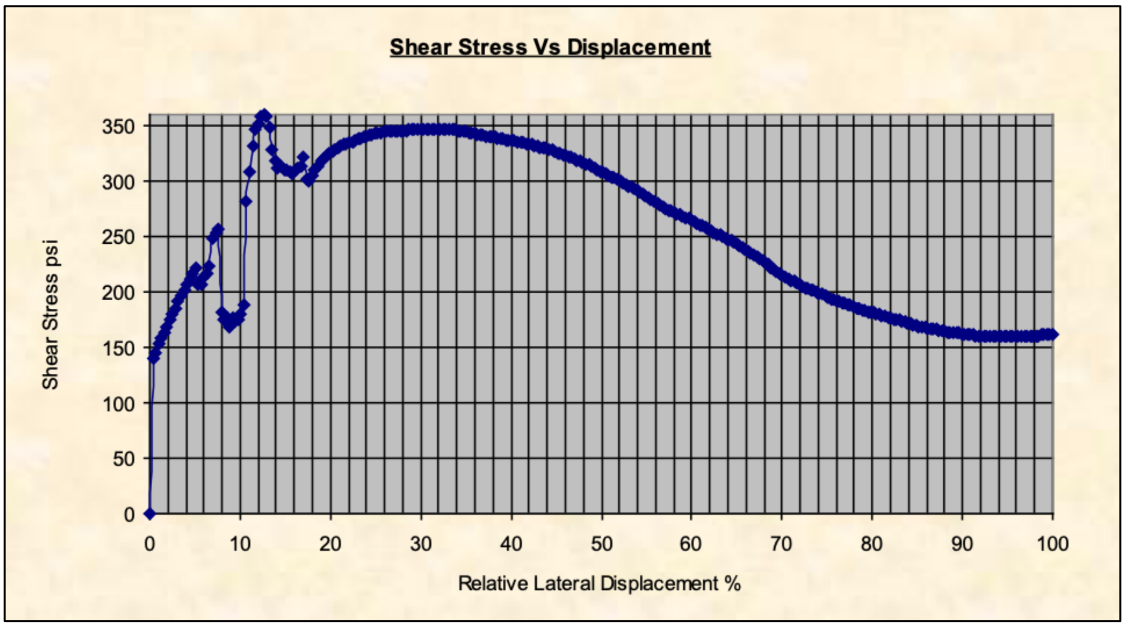


Conditions at Failure	
Normal Stress	544.65 psi
Peak Strength	234.75 psi
Horizontal Deformation	0.1511 in
Residual Stress	0.00 psi
Vertical Deformation	0.1006 in

UTTR Surface Crust Direct Shear Test
Sample SI10-3 (Group 2c)

Specimen Details			
Specimen Reference	C	**Description**	
Depth within Sample	0.0000in	**Orientation within Sample**	
Initial Height	0.5000 in	**Area**	1.41020 in2
Structure / Preparation		**Initial Water Content***	8.28 % (trimmings: 9.90 %)
Initial Wet Unit Weight	117.33 lbf/ft3	**Degree of Saturation**	41.62 %
Initial Dry Unit Weight	108.36 lbf/ft3	**Initial Voids Ratio**	0.527
Final Wet Unit Weight	141.68 lbf/ft3	**Final Water Content**	7.44%
Final Dry Unit Weight	131.87 lbf/ft3	**Dry Mass**	0.0442 lb
Tested Dry or Submerged	Dry		
Comments			

* Calculated from initial and dry weights of whole specimen

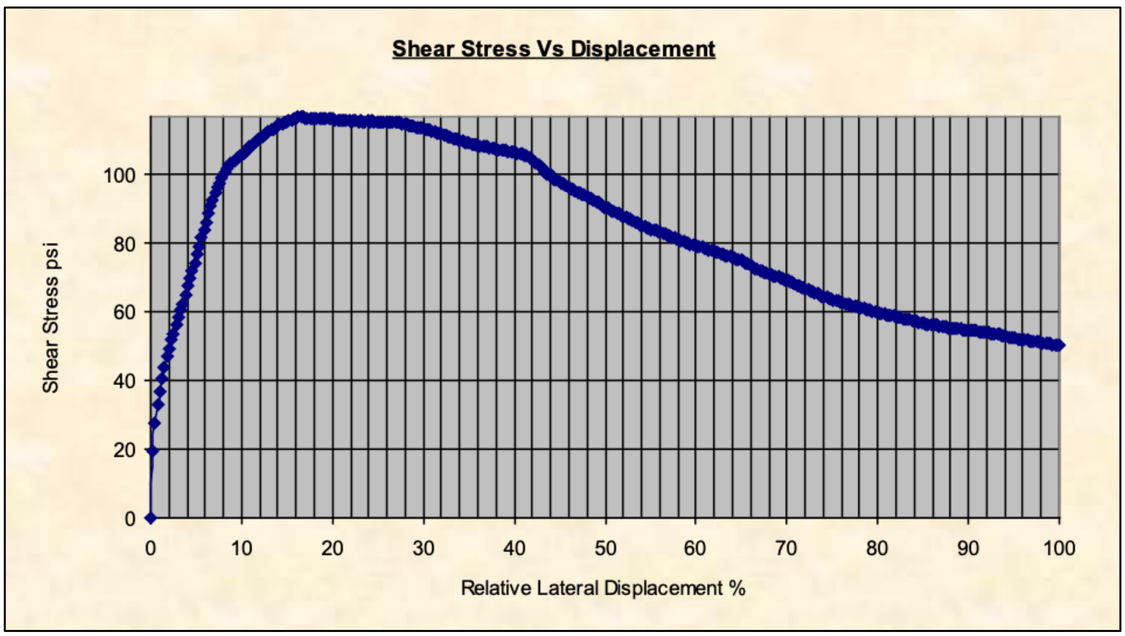


Conditions at Failure	
Normal Stress	820.16 psi
Peak Strength	360.35 psi
Horizontal Deformation	0.0435 in
Residual Stress	0.00 psi
Vertical Deformation	0.0895 in

UTTR Surface Crust Direct Shear Test
Sample SI10 (Group 3a)

Specimen Details			
Specimen Reference	A	**Description**	
Depth within Sample	0.0000in	**Orientation within Sample**	
Initial Height	0.7800 in	**Area**	2.95500 in2
Structure / Preparation	trimmed in lab	**Initial Water Content***	14.17 % (trimmings: 9.70 %)
Initial Wet Unit Weight	97.57 lbf/ft3	**Degree of Saturation**	40.09 %
Initial Dry Unit Weight	85.47 lbf/ft3	**Initial Voids Ratio**	0.936
Final Wet Unit Weight	122.11 lbf/ft3	**Final Water Content**	9.69%
Final Dry Unit Weight	111.32 lbf/ft3	**Dry Mass**	0.1140 lb
Tested Dry or Submerged	Dry		
Comments			

* Calculated from initial and dry weights of whole specimen

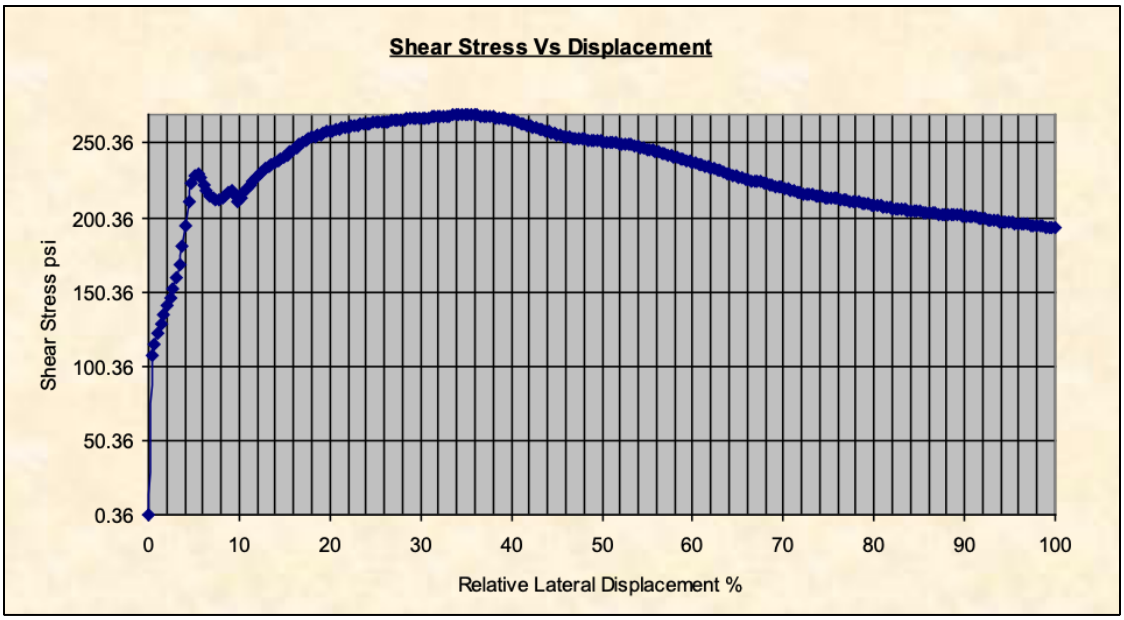


Conditions at Failure	
Normal Stress	262.80 psi
Peak Strength	116.55 psi
Horizontal Deformation	0.0696 in
Residual Stress	0.00 psi
Vertical Deformation	0.1823 in

UTTR Surface Crust Direct Shear Test
Sample SI10-4 (Group 3b)

Specimen Details			
Specimen Reference	D	**Description**	
Depth within Sample	0.0000in	**Orientation within Sample**	
Initial Height	0.5000 in	**Area**	1.41020 in2
Structure / Preparation		**Initial Water Content***	11.21 % (trimmings: 10.10 %)
Initial Wet Unit Weight	110.42 lbf/ft3	**Degree of Saturation**	44.56 %
Initial Dry Unit Weight	99.29 lbf/ft3	**Initial Voids Ratio**	0.667
Final Wet Unit Weight	144.16 lbf/ft3	**Final Water Content**	10.94%
Final Dry Unit Weight	129.94 lbf/ft3	**Dry Mass**	0.0405 lb
Tested Dry or Submerged	Dry		
Comments			

* Calculated from initial and dry weights of whole specimen

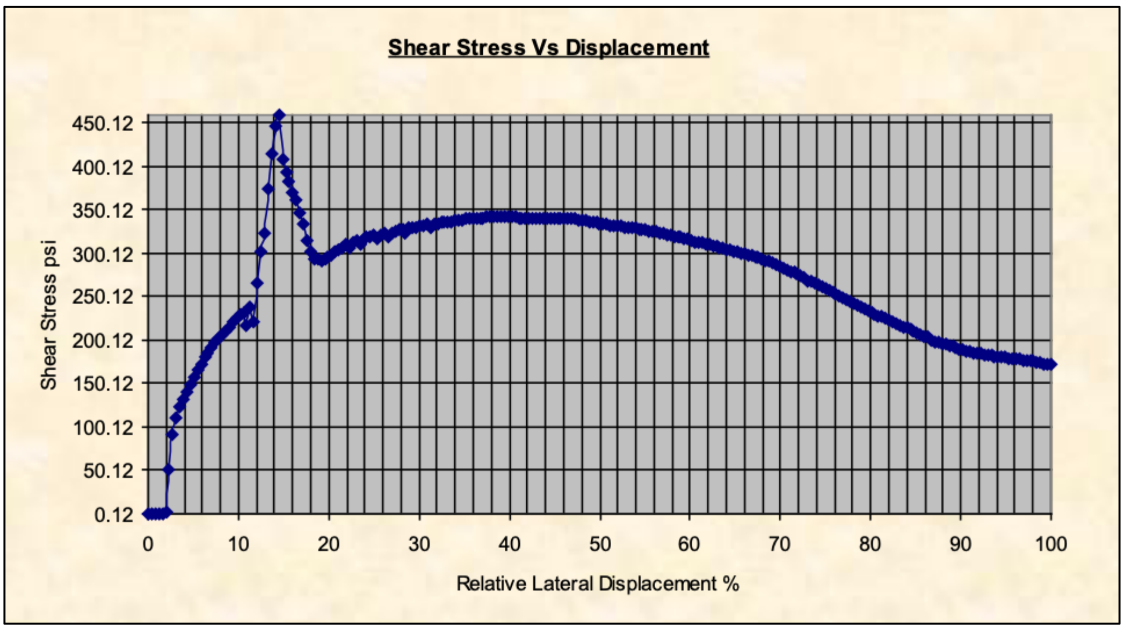


Conditions at Failure	
Normal Stress	544.65 psi
Peak Strength	269.67 psi
Horizontal Deformation	0.1131 in
Residual Stress	0.00 psi
Vertical Deformation	0.1310 in

UTTR Surface Crust Direct Shear Test
Sample SI10-3 (Group 3c)

Specimen Details			
Specimen Reference	D	**Description**	
Depth within Sample	0.0000in	**Orientation within Sample**	
Initial Height	0.5000 in	**Area**	1.41020 in2
Structure / Preparation		**Initial Water Content***	7.27 % (trimmings: 9.90 %)
Initial Wet Unit Weight	104.42 lbf/ft3	**Degree of Saturation**	27.53 %
Initial Dry Unit Weight	97.34 lbf/ft3	**Initial Voids Ratio**	0.700
Final Wet Unit Weight	129.01 lbf/ft3	**Final Water Content**	6.27%
Final Dry Unit Weight	121.40 lbf/ft3	**Dry Mass**	0.0397 lb
Tested Dry or Submerged	Dry		
Comments			

* Calculated from initial and dry weights of whole specimen

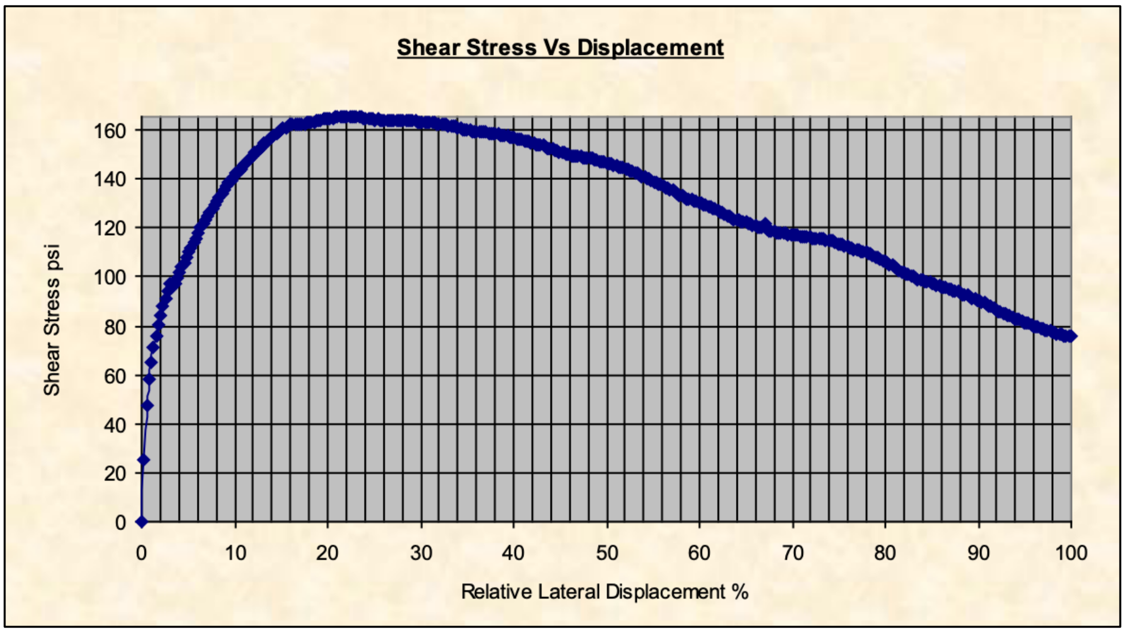


Conditions at Failure	
Normal Stress	820.23 psi
Peak Strength	459.67 psi
Horizontal Deformation	0.0402 in
Residual Stress	0.00 psi
Vertical Deformation	0.0988 in

UTTR Surface Crust Direct Shear Test
Sample SI10-5 (Group 4a)

Specimen Details			
Specimen Reference	B	**Description**	
Depth within Sample	0.0000in	**Orientation within Sample**	
Initial Height	0.5000 in	**Area**	1.41020 in2
Structure / Preparation		**Initial Water Content***	7.60 % (trimmings: 8.00 %)
Initial Wet Unit Weight	108.51 lbf/ft3	**Degree of Saturation**	31.42 %
Initial Dry Unit Weight	100.84 lbf/ft3	**Initial Voids Ratio**	0.641
Final Wet Unit Weight	116.48 lbf/ft3	**Final Water Content**	8.00%
Final Dry Unit Weight	107.86 lbf/ft3	**Dry Mass**	0.0411 lb
Tested Dry or Submerged	Dry		
Comments			

* Calculated from initial and dry weights of whole specimen

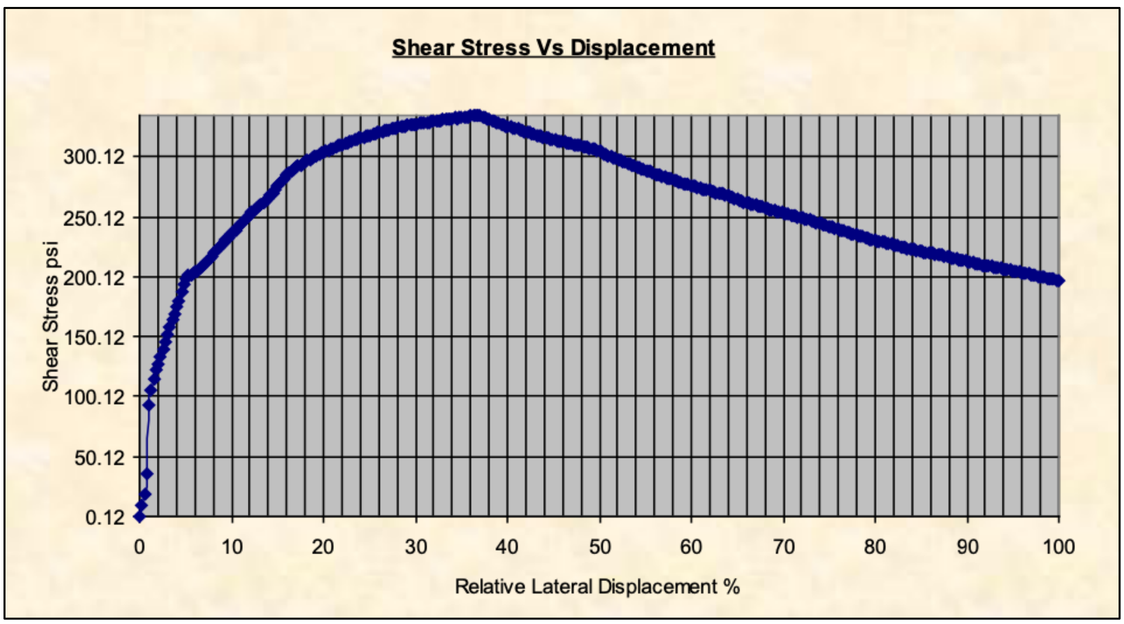


Conditions at Failure	
Normal Stress	260.19 psi
Peak Strength	165.50 psi
Horizontal Deformation	0.0924 in
Residual Stress	0.00 psi
Vertical Deformation	0.0437 in

UTTR Surface Crust Direct Shear Test
Sample SI10-1 (Group 4b)

Specimen Details			
Specimen Reference	C	**Description**	
Depth within Sample	0.0000in	**Orientation within Sample**	
Initial Height	0.5000 in	**Area**	1.41020 in2
Structure / Preparation		**Initial Water Content***	9.28 % (trimmings: 8.20 %)
Initial Wet Unit Weight	107.67 lbf/ft3	**Degree of Saturation**	36.19 %
Initial Dry Unit Weight	98.53 lbf/ft3	**Initial Voids Ratio**	0.680
Final Wet Unit Weight	143.10 lbf/ft3	**Final Water Content**	8.28%
Final Dry Unit Weight	132.15 lbf/ft3	**Dry Mass**	0.0402 lb
Tested Dry or Submerged	Dry		
Comments			

* Calculated from initial and dry weights of whole specimen

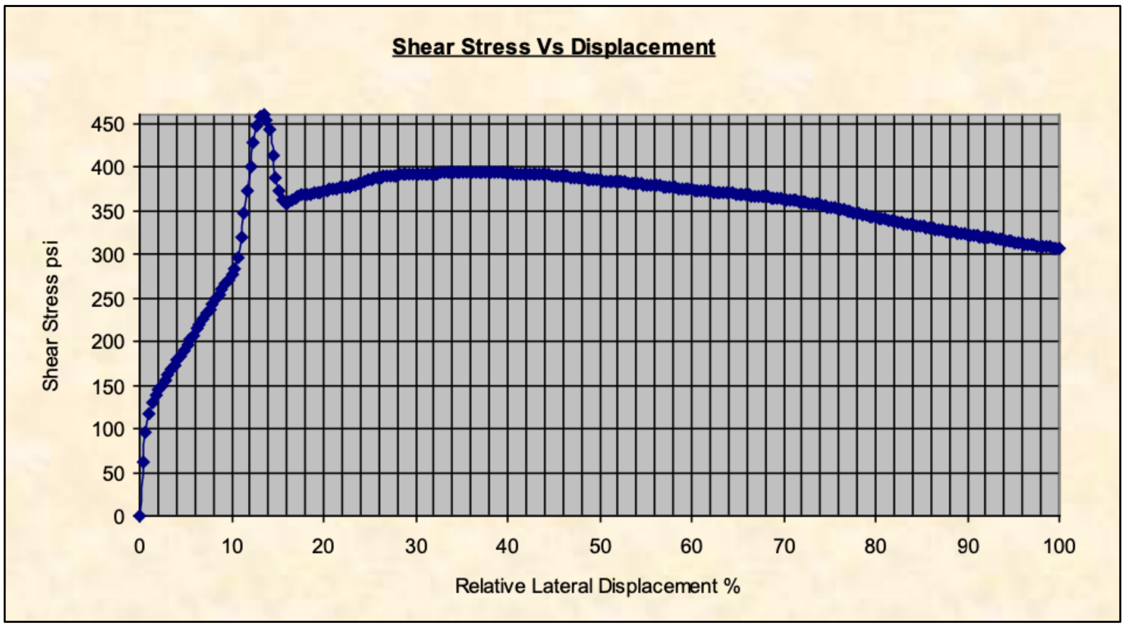


Conditions at Failure	
Normal Stress	559.76 psi
Peak Strength	334.54 psi
Horizontal Deformation	0.1566 in
Residual Stress	0.00 psi
Vertical Deformation	0.1369 in

UTTR Surface Crust Direct Shear Test
Sample SI10-3 (Group 4c)

Specimen Details			
Specimen Reference	A	**Description**	
Depth within Sample	0.0000in	**Orientation within Sample**	
Initial Height	0.5000 in	**Area**	1.41020 in2
Structure / Preparation		**Initial Water Content***	11.18 % (trimmings: 9.30 %)
Initial Wet Unit Weight	114.42 lbf/ft3	**Degree of Saturation**	48.73 %
Initial Dry Unit Weight	102.91 lbf/ft3	**Initial Voids Ratio**	0.608
Final Wet Unit Weight	153.95 lbf/ft3	**Final Water Content**	9.30%
Final Dry Unit Weight	140.86 lbf/ft3	**Dry Mass**	0.0420 lb
Tested Dry or Submerged	Dry		
Comments			

* Calculated from initial and dry weights of whole specimen

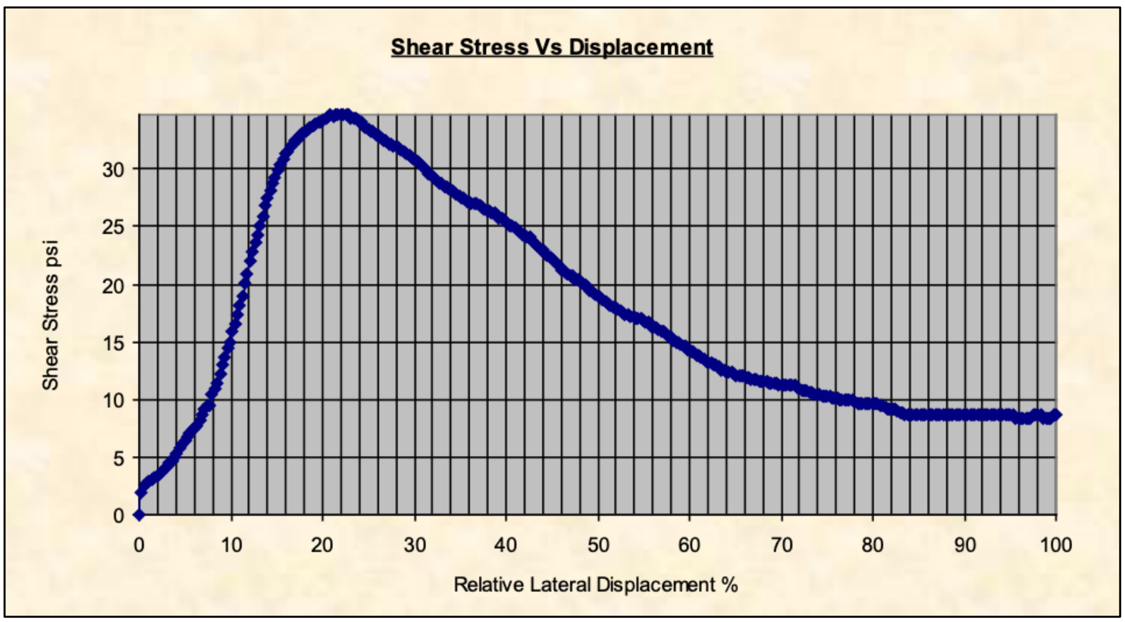


Conditions at Failure	
Normal Stress	820.23 psi
Peak Strength	460.50 psi
Horizontal Deformation	0.0424 in
Residual Stress	0.00 psi
Vertical Deformation	0.1342 in

UTTR Surface Crust Direct Shear Test
Sample HS2-1-5 (Group 1a)

Specimen Details			
Specimen Reference	A	**Description**	
Depth within Sample	0.0000in	**Orientation within Sample**	
Initial Height	0.7500 in	**Area**	1.41020 in2
Structure / Preparation		**Initial Water Content***	9.14 % (trimmings: 9.50 %)
Initial Wet Unit Weight	101.07 lbf/ft3	**Degree of Saturation**	30.79 %
Initial Dry Unit Weight	92.60 lbf/ft3	**Initial Voids Ratio**	0.787
Final Wet Unit Weight	100.76 lbf/ft3	**Final Water Content**	8.68%
Final Dry Unit Weight	92.71 lbf/ft3	**Dry Mass**	0.0567 lb
Tested Dry or Submerged	Dry		
Comments			

* Calculated from initial and dry weights of whole specimen

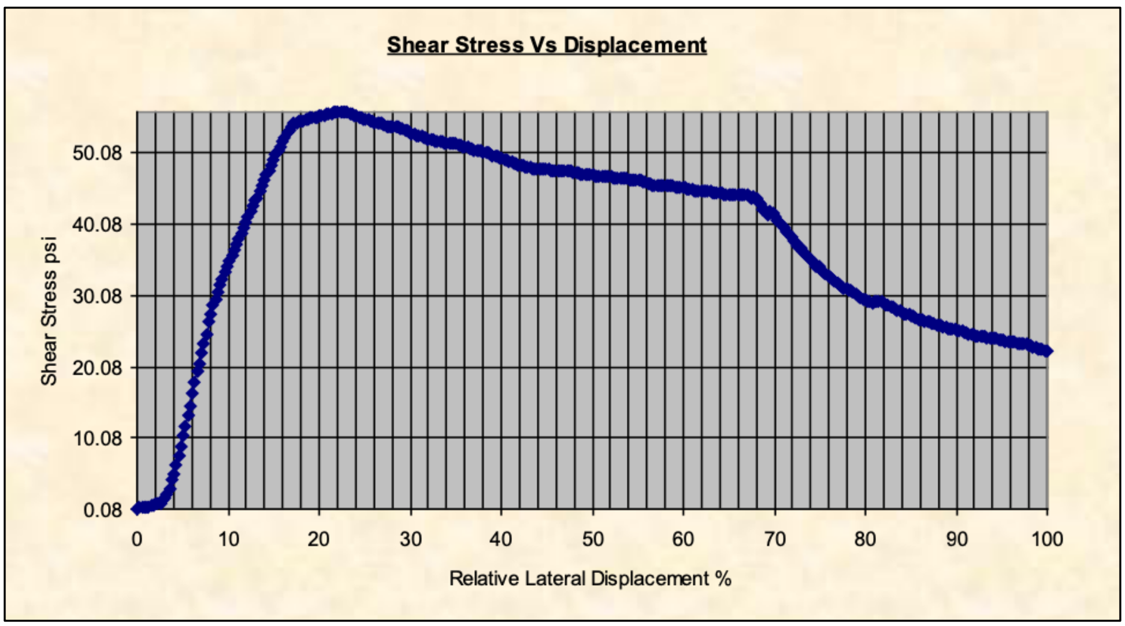


Conditions at Failure	
Normal Stress	15.18 psi
Peak Strength	34.72 psi
Horizontal Deformation	0.0716 in
Residual Stress	0.00 psi
Vertical Deformation	-0.0022 in

UTTR Surface Crust Direct Shear Test
Sample HS2-1-5 (Group 1b)

Specimen Details			
Specimen Reference	C	**Description**	
Depth within Sample	0.0000in	**Orientation within Sample**	
Initial Height	0.7500 in	**Area**	1.41020 in2
Structure / Preparation		**Initial Water Content***	9.94 % (trimmings: 9.55 %)
Initial Wet Unit Weight	100.39 lbf/ft3	**Degree of Saturation**	32.43 %
Initial Dry Unit Weight	91.31 lbf/ft3	**Initial Voids Ratio**	0.813
Final Wet Unit Weight	103.80 lbf/ft3	**Final Water Content**	9.12%
Final Dry Unit Weight	95.13 lbf/ft3	**Dry Mass**	0.0559 lb
Tested Dry or Submerged	Dry		
Comments			

* Calculated from initial and dry weights of whole specimen

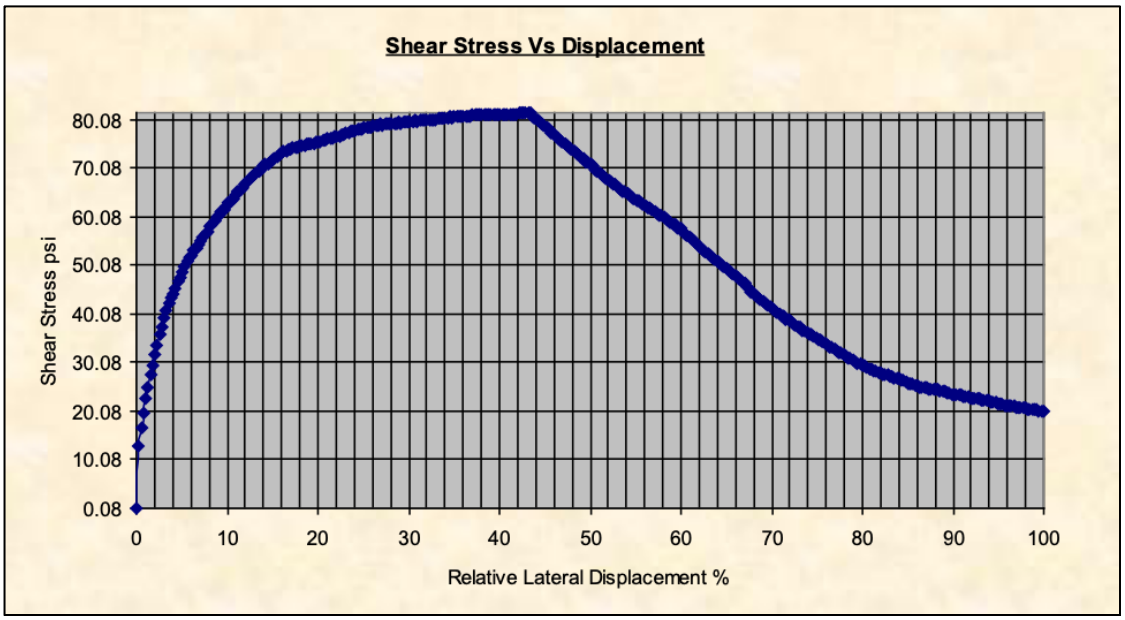


Conditions at Failure	
Normal Stress	54.41 psi
Peak Strength	55.84 psi
Horizontal Deformation	0.0779 in
Residual Stress	0.00 psi
Vertical Deformation	0.0121 in

UTTR Surface Crust Direct Shear Test
Sample HS2-1-5 (Group 1c)

Specimen Details			
Specimen Reference	D	**Description**	
Depth within Sample	0.0000in	**Orientation within Sample**	
Initial Height	0.7500 in	**Area**	1.41020 in2
Structure / Preparation		**Initial Water Content***	11.71 % (trimmings: 9.55 %)
Initial Wet Unit Weight	99.67 lbf/ft3	**Degree of Saturation**	36.31 %
Initial Dry Unit Weight	89.22 lbf/ft3	**Initial Voids Ratio**	0.855
Final Wet Unit Weight	109.87 lbf/ft3	**Final Water Content**	11.11%
Final Dry Unit Weight	98.89 lbf/ft3	**Dry Mass**	0.0546 lb
Tested Dry or Submerged	Dry		
Comments			

* Calculated from initial and dry weights of whole specimen



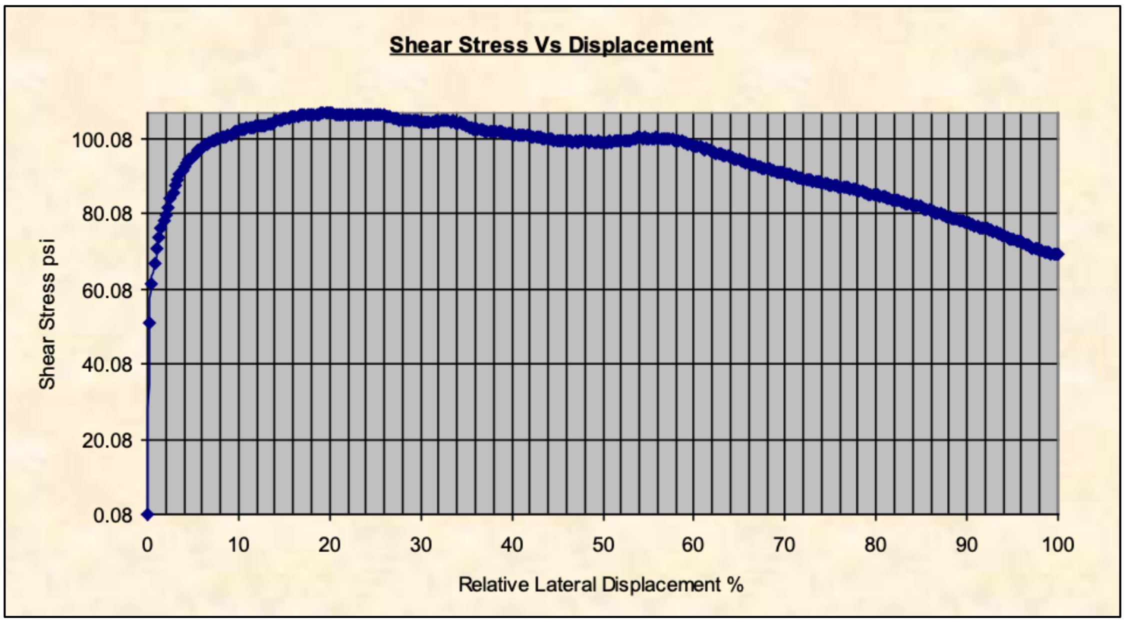
Conditions at Failure	
Normal Stress	112.01 psi
Peak Strength	81.38 psi
Horizontal Deformation	0.1495 in
Residual Stress	0.00 psi
Vertical Deformation	0.0642 in

UTTR Surface Crust Direct Shear Test

Sample HS2-1-4 (Group 2a)

Specimen Details			
Specimen Reference	C	**Description**	
Depth within Sample	0.0000in	**Orientation within Sample**	
Initial Height	0.7500 in	**Area**	1.41020 in2
Structure / Preparation		**Initial Water Content***	9.46 % (trimmings: 9.55 %)
Initial Wet Unit Weight	92.67 lbf/ft3	**Degree of Saturation**	26.26 %
Initial Dry Unit Weight	84.66 lbf/ft3	**Initial Voids Ratio**	0.955
Final Wet Unit Weight	106.11 lbf/ft3	**Final Water Content**	9.46%
Final Dry Unit Weight	96.94 lbf/ft3	**Dry Mass**	0.0518 lb
Tested Dry or Submerged	Dry		
Comments			

* Calculated from initial and dry weights of whole specimen

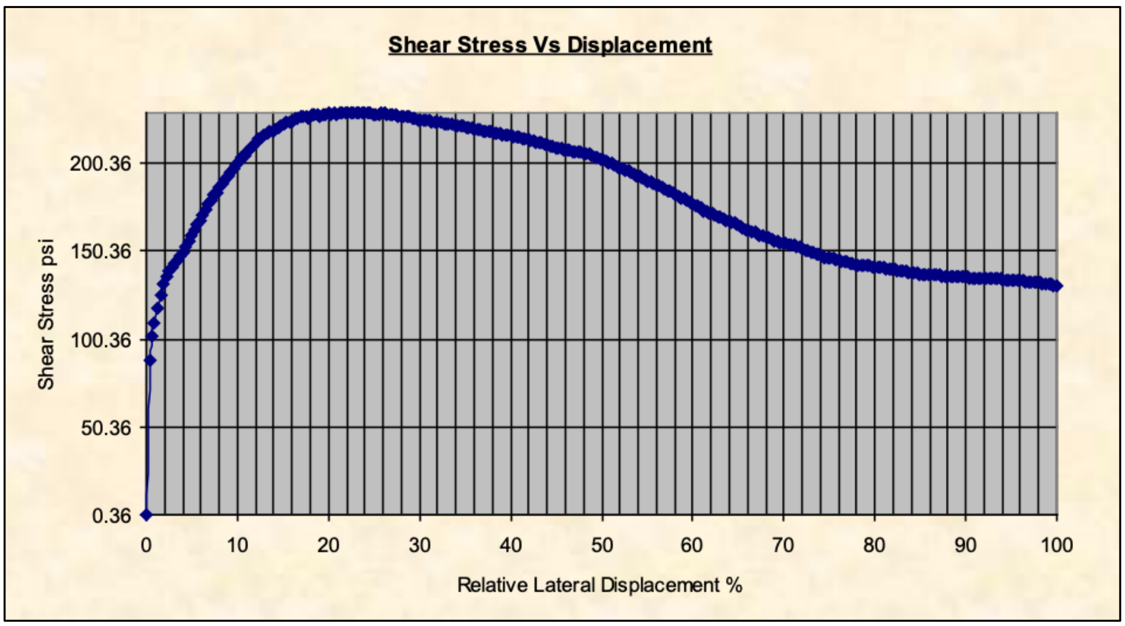


Conditions at Failure	
Normal Stress	260.19 psi
Peak Strength	106.76 psi
Horizontal Deformation	0.0671 in
Residual Stress	0.00 psi
Vertical Deformation	0.0853 in

UTTR Surface Crust Direct Shear Test
Sample HS2-1 (Group 2b)

Specimen Details			
Specimen Reference	B	**Description**	
Depth within Sample	0.0000in	**Orientation within Sample**	
Initial Height	0.7500 in	**Area**	1.41020 in2
Structure / Preparation		**Initial Water Content***	10.47 % (trimmings: 8.39 %)
Initial Wet Unit Weight	104.00 lbf/ft3	**Degree of Saturation**	36.60 %
Initial Dry Unit Weight	94.14 lbf/ft3	**Initial Voids Ratio**	0.758
Final Wet Unit Weight	135.80 lbf/ft3	**Final Water Content**	10.00%
Final Dry Unit Weight	123.45 lbf/ft3	**Dry Mass**	0.0576 lb
Tested Dry or Submerged	Dry		
Comments			

* Calculated from initial and dry weights of whole specimen

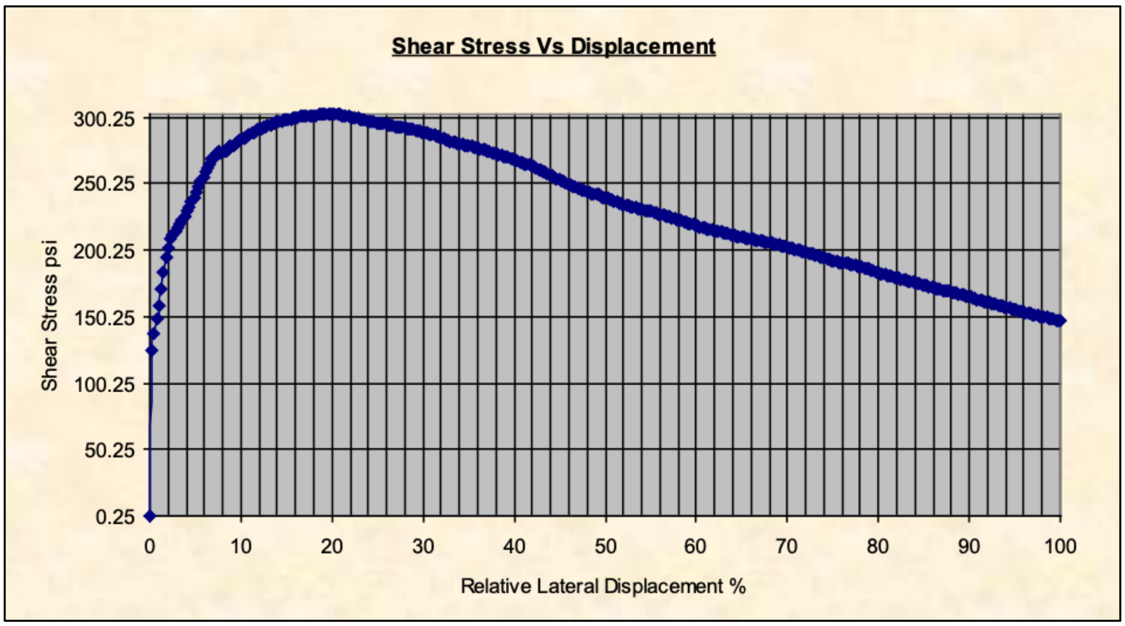


Conditions at Failure	
Normal Stress	544.65 psi
Peak Strength	228.95 psi
Horizontal Deformation	0.0707 in
Residual Stress	0.00 psi
Vertical Deformation	0.1800 in

UTTR Surface Crust Direct Shear Test
Sample HS2-1-3 (Group 2c)

Specimen Details			
Specimen Reference	B	**Description**	
Depth within Sample	0.0000in	**Orientation within Sample**	
Initial Height	0.7500 in	**Area**	1.41020 in2
Structure / Preparation		**Initial Water Content***	11.38 % (trimmings: 9.55 %)
Initial Wet Unit Weight	98.05 lbf/ft3	**Degree of Saturation**	34.28 %
Initial Dry Unit Weight	88.03 lbf/ft3	**Initial Voids Ratio**	0.880
Final Wet Unit Weight	134.61 lbf/ft3	**Final Water Content**	10.60%
Final Dry Unit Weight	121.70 lbf/ft3	**Dry Mass**	0.0539 lb
Tested Dry or Submerged	Dry		
Comments			

* Calculated from initial and dry weights of whole specimen

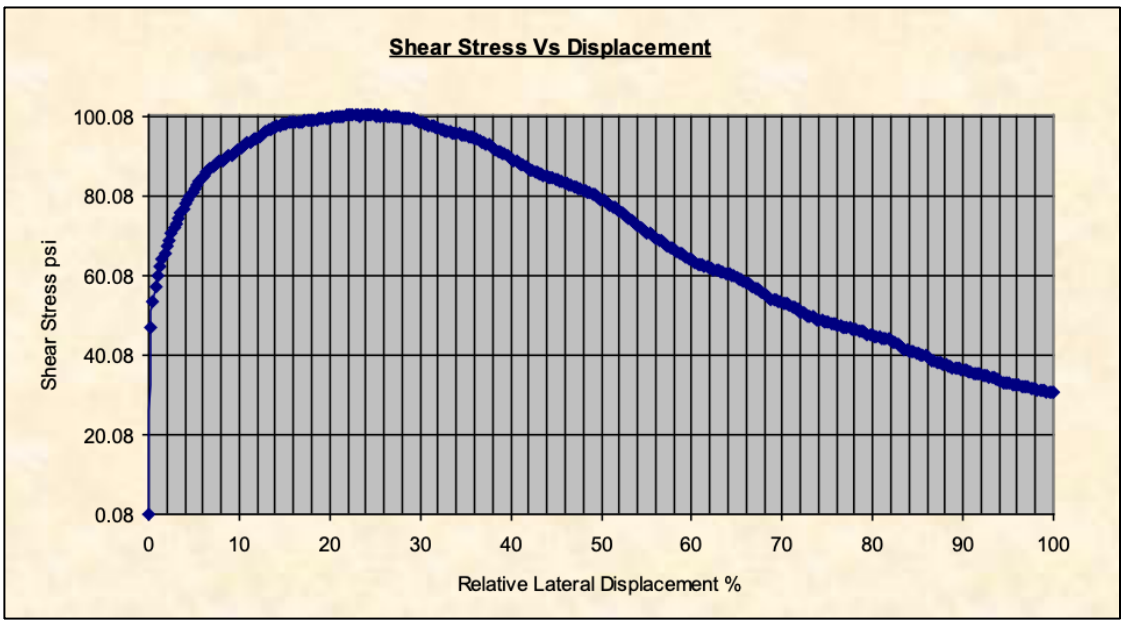


Conditions at Failure	
Normal Stress	820.23 psi
Peak Strength	302.40 psi
Horizontal Deformation	0.0671 in
Residual Stress	0.00 psi
Vertical Deformation	0.2082 in

UTTR Surface Crust Direct Shear Test
Sample HS2-1-4 (Group 3a)

Specimen Details			
Specimen Reference	A	**Description**	
Depth within Sample	0.0000in	**Orientation within Sample**	
Initial Height	0.7500 in	**Area**	1.41020 in2
Structure / Preparation		**Initial Water Content***	10.62 % (trimmings: 7.80 %)
Initial Wet Unit Weight	95.26 lbf/ft3	**Degree of Saturation**	30.53 %
Initial Dry Unit Weight	86.12 lbf/ft3	**Initial Voids Ratio**	0.922
Final Wet Unit Weight	110.59 lbf/ft3	**Final Water Content**	9.70%
Final Dry Unit Weight	100.81 lbf/ft3	**Dry Mass**	0.0527 lb
Tested Dry or Submerged	Dry		
Comments			

* Calculated from initial and dry weights of whole specimen

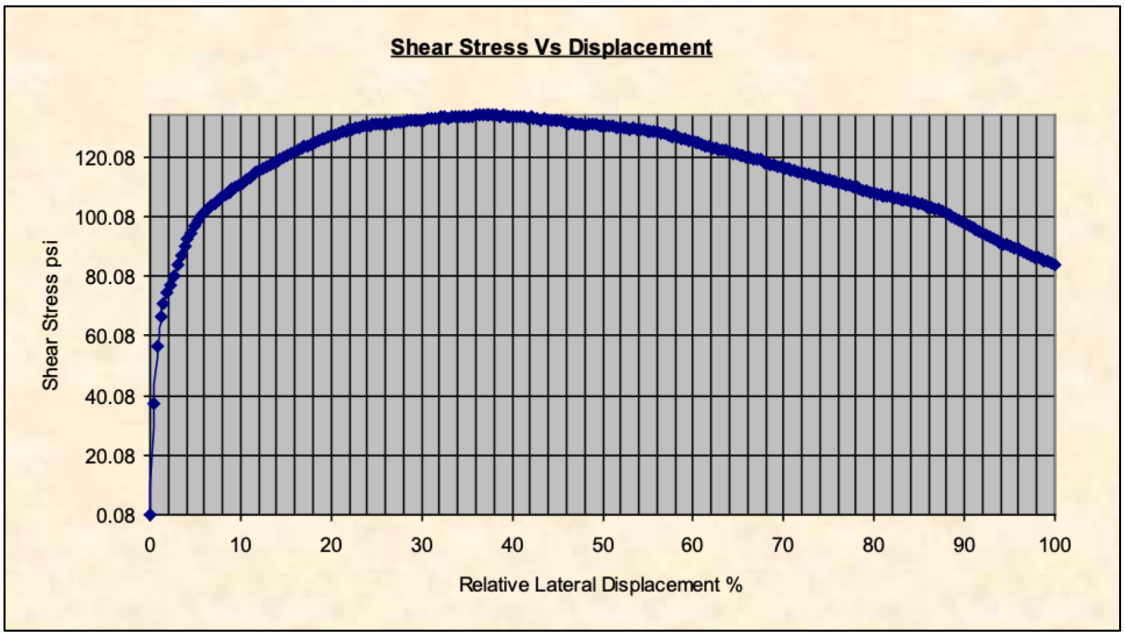


Conditions at Failure	
Normal Stress	260.19 psi
Peak Strength	100.58 psi
Horizontal Deformation	0.0788 in
Residual Stress	0.00 psi
Vertical Deformation	0.1098 in

UTTR Surface Crust Direct Shear Test
Sample HS2-2-5 (Group 3b)

Specimen Details			
Specimen Reference	B	**Description**	
Depth within Sample	0.0000in	**Orientation within Sample**	
Initial Height	0.7500 in	**Area**	1.41020 in2
Structure / Preparation		**Initial Water Content***	10.53 % (trimmings: 9.30 %)
Initial Wet Unit Weight	107.05 lbf/ft3	**Degree of Saturation**	39.38 %
Initial Dry Unit Weight	96.86 lbf/ft3	**Initial Voids Ratio**	0.709
Final Wet Unit Weight	128.68 lbf/ft3	**Final Water Content**	10.01%
Final Dry Unit Weight	116.97 lbf/ft3	**Dry Mass**	0.0593 lb
Tested Dry or Submerged	Dry		
Comments			

* Calculated from initial and dry weights of whole specimen

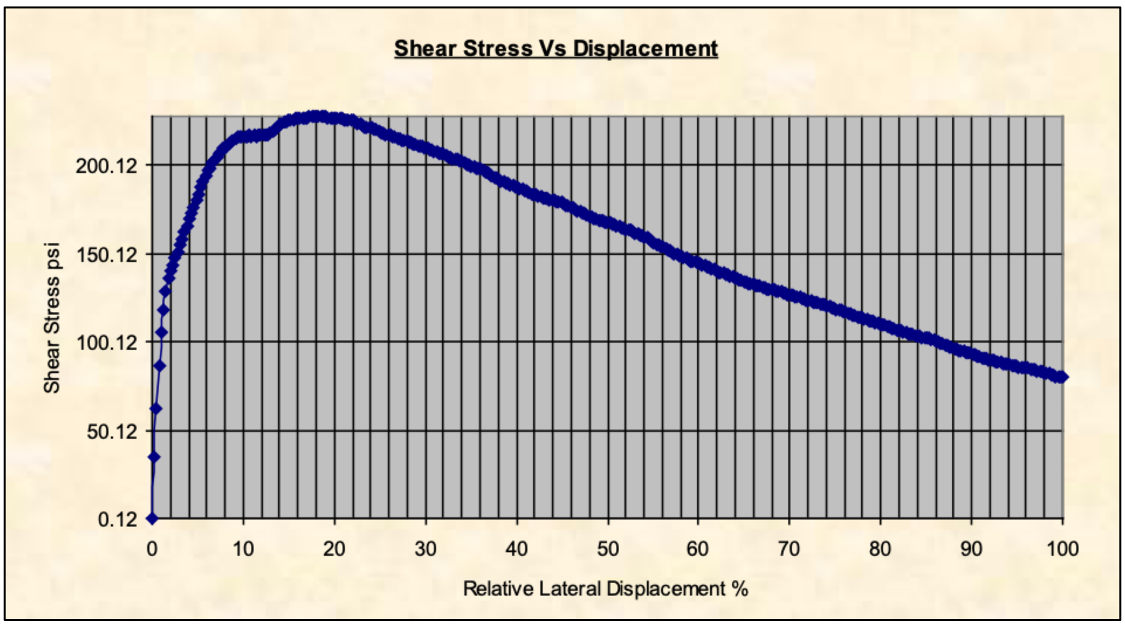


Conditions at Failure	
Normal Stress	338.86 psi
Peak Strength	134.30 psi
Horizontal Deformation	0.0859 in
Residual Stress	0.00 psi
Vertical Deformation	0.1183 in

UTTR Surface Crust Direct Shear Test
Sample HS2-1 (Group 3c)

Specimen Details			
Specimen Reference	A	**Description**	
Depth within Sample	0.0000in	**Orientation within Sample**	
Initial Height	0.7500 in	**Area**	1.41020 in2
Structure / Preparation	1.34" x 0.75" Mold	**Initial Water Content***	7.93 % (trimmings: 8.40 %)
Initial Wet Unit Weight	104.60 lbf/ft3	**Degree of Saturation**	29.69 %
Initial Dry Unit Weight	96.92 lbf/ft3	**Initial Voids Ratio**	0.708
Final Wet Unit Weight	131.19 lbf/ft3	**Final Water Content**	8.63%
Final Dry Unit Weight	120.76 lbf/ft3	**Dry Mass**	0.0593 lb
Tested Dry or Submerged	Dry		
Comments			

* Calculated from initial and dry weights of whole specimen

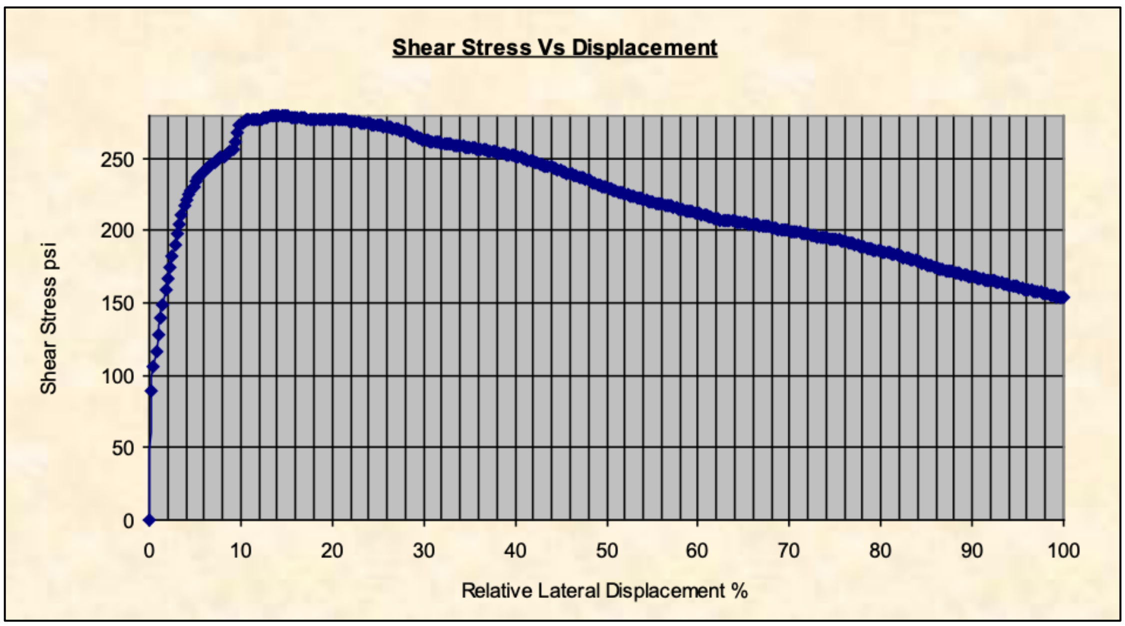


Conditions at Failure	
Normal Stress	544.65 psi
Peak Strength	227.65 psi
Horizontal Deformation	0.0739 in
Residual Stress	0.00 psi
Vertical Deformation	0.1550 in

UTTR Surface Crust Direct Shear Test
Sample HS2-1-3 (Group 3d)

Specimen Details			
Specimen Reference	A	**Description**	
Depth within Sample	0.0000in	**Orientation within Sample**	
Initial Height	0.7500 in	**Area**	1.41020 in2
Structure / Preparation		**Initial Water Content***	11.13 % (trimmings: 9.55 %)
Initial Wet Unit Weight	103.46 lbf/ft3	**Degree of Saturation**	37.93 %
Initial Dry Unit Weight	93.10 lbf/ft3	**Initial Voids Ratio**	0.778
Final Wet Unit Weight	136.01 lbf/ft3	**Final Water Content**	10.34%
Final Dry Unit Weight	123.26 lbf/ft3	**Dry Mass**	0.0570 lb
Tested Dry or Submerged	Dry		
Comments			

* Calculated from initial and dry weights of whole specimen

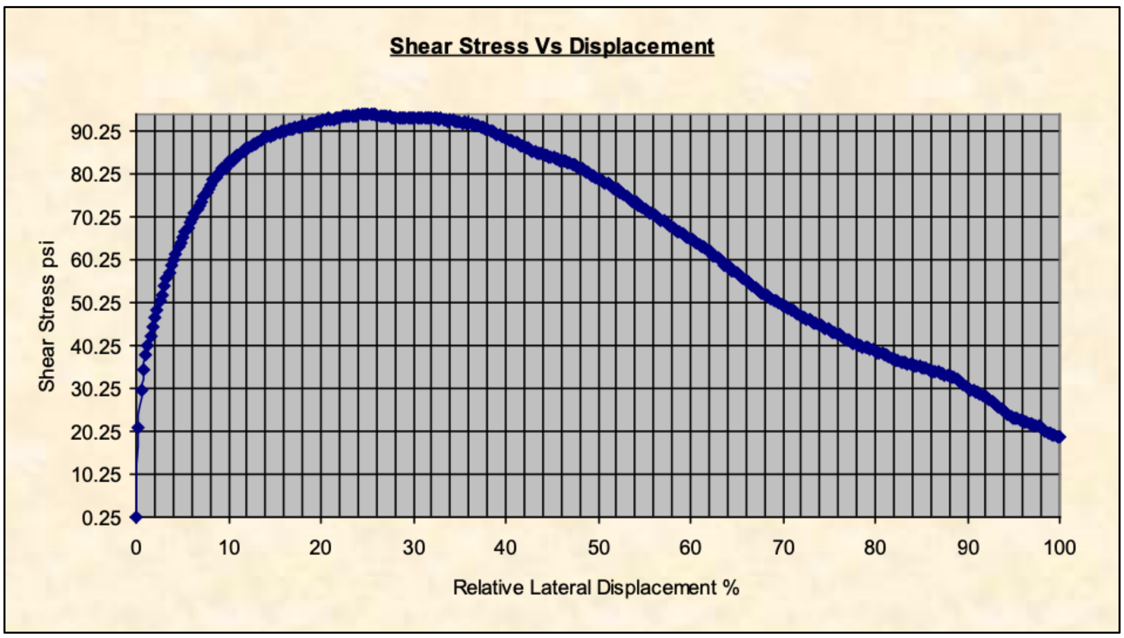


Conditions at Failure	
Normal Stress	820.23 psi
Peak Strength	279.28 psi
Horizontal Deformation	0.0510 in
Residual Stress	0.00 psi
Vertical Deformation	-0.3352 in

UTTR Surface Crust Direct Shear Test
Sample HS2-2-5 (Group 4a)

Specimen Details			
Specimen Reference	A	**Description**	
Depth within Sample	0.0000in	**Orientation within Sample**	
Initial Height	0.7500 in	**Area**	1.41020 in2
Structure / Preparation		**Initial Water Content***	11.25 % (trimmings: 8.68 %)
Initial Wet Unit Weight	98.88 lbf/ft3	**Degree of Saturation**	34.60 %
Initial Dry Unit Weight	88.88 lbf/ft3	**Initial Voids Ratio**	0.862
Final Wet Unit Weight	111.84 lbf/ft3	**Final Water Content**	10.92%
Final Dry Unit Weight	100.83 lbf/ft3	**Dry Mass**	0.0544 lb
Tested Dry or Submerged	Dry		
Comments			

* Calculated from initial and dry weights of whole specimen

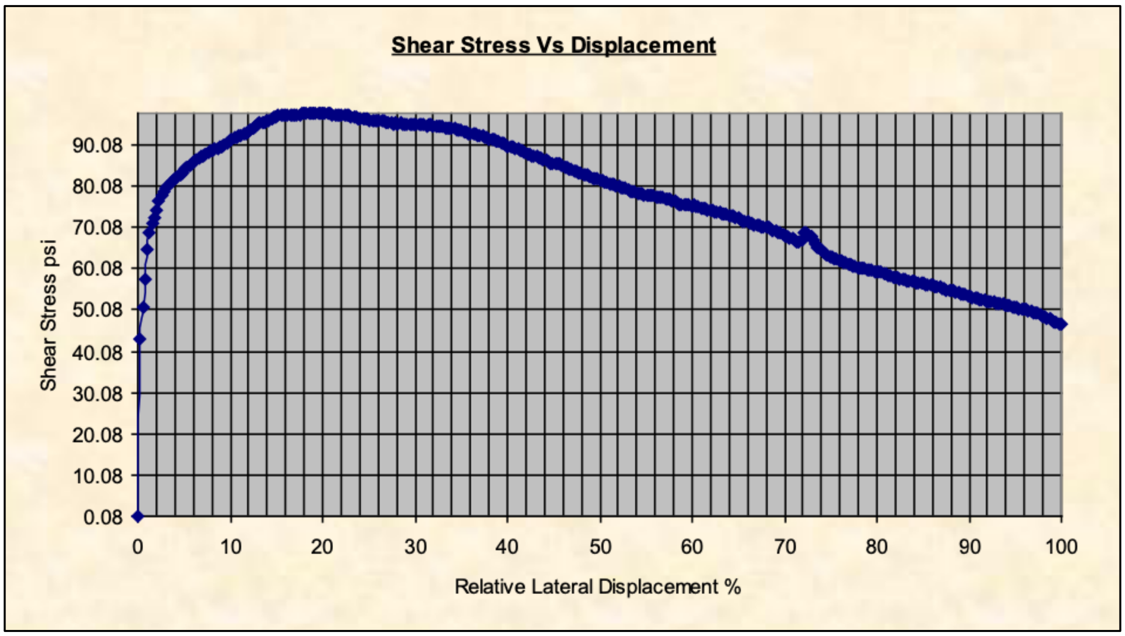


Conditions at Failure	
Normal Stress	223.87 psi
Peak Strength	93.90 psi
Horizontal Deformation	0.0868 in
Residual Stress	0.00 psi
Vertical Deformation	0.0962 in

UTTR Surface Crust Direct Shear Test
Sample HS2-1-4 (Group 4b)

Specimen Details			
Specimen Reference	B	**Description**	
Depth within Sample	0.0000in	**Orientation within Sample**	
Initial Height	0.7500 in	**Area**	1.41020 in2
Structure / Preparation		**Initial Water Content***	9.09 % (trimmings: 9.55 %)
Initial Wet Unit Weight	95.12 lbf/ft3	**Degree of Saturation**	26.83 %
Initial Dry Unit Weight	87.20 lbf/ft3	**Initial Voids Ratio**	0.898
Final Wet Unit Weight	109.01 lbf/ft3	**Final Water Content**	8.51%
Final Dry Unit Weight	100.46 lbf/ft3	**Dry Mass**	0.0533 lb
Tested Dry or Submerged	Dry		
Comments			

* Calculated from initial and dry weights of whole specimen

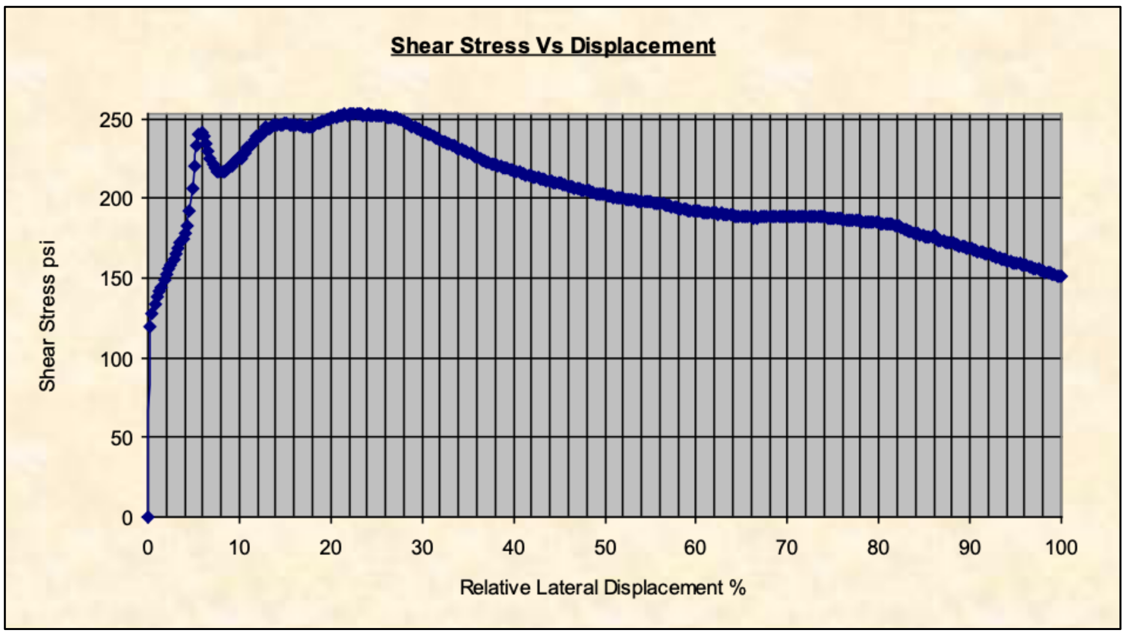


Conditions at Failure	
Normal Stress	260.19 psi
Peak Strength	97.66 psi
Horizontal Deformation	0.0627 in
Residual Stress	0.00 psi
Vertical Deformation	0.0996 in

UTTR Surface Crust Direct Shear Test
Sample HS2-1 (Group 4c)

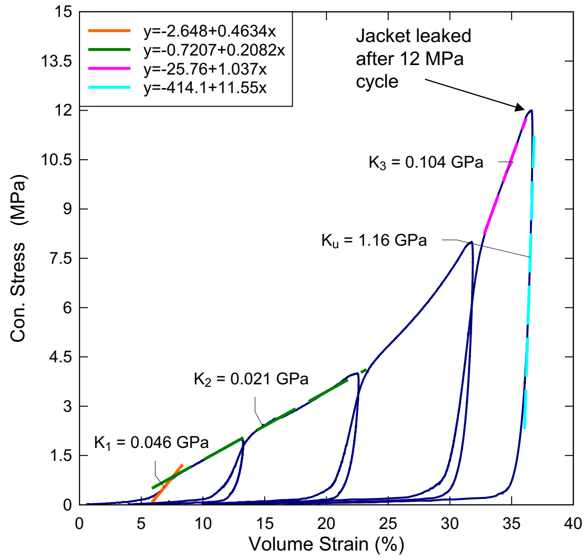
Specimen Details			
Specimen Reference	C	**Description**	
Depth within Sample	0.0000in	**Orientation within Sample**	
Initial Height	0.7500 in	**Area**	1.41020 in2
Structure / Preparation		**Initial Water Content***	7.49 % (trimmings: 8.39 %)
Initial Wet Unit Weight	109.80 lbf/ft3	**Degree of Saturation**	32.00 %
Initial Dry Unit Weight	102.15 lbf/ft3	**Initial Voids Ratio**	0.620
Final Wet Unit Weight	137.60 lbf/ft3	**Final Water Content**	9.42%
Final Dry Unit Weight	125.75 lbf/ft3	**Dry Mass**	0.0625 lb
Tested Dry or Submerged	Dry		
Comments			

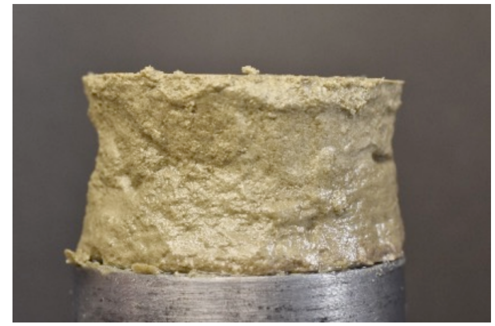
* Calculated from initial and dry weights of whole specimen



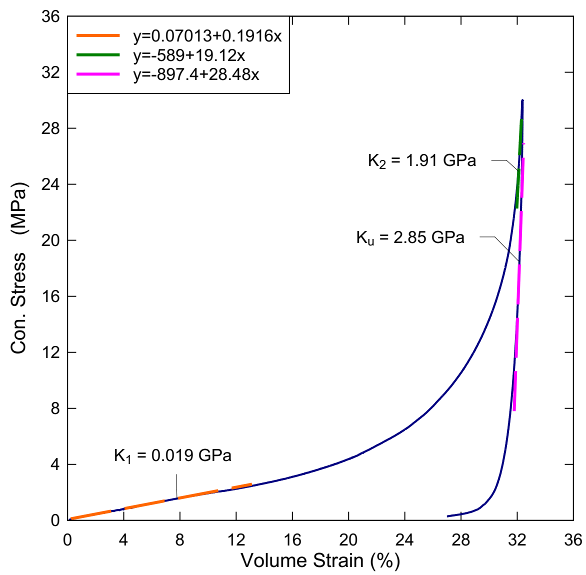
Conditions at Failure	
Normal Stress	544.65 psi
Peak Strength	253.10 psi
Horizontal Deformation	0.0924 in
Residual Stress	0.00 psi
Vertical Deformation	0.1512 in

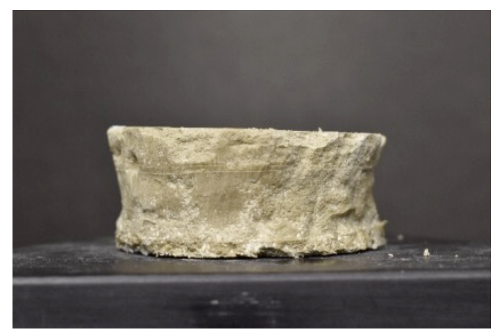
Hydrostatic Test (N9A22)
SI10-01 - UTTR Soil Surface Crust

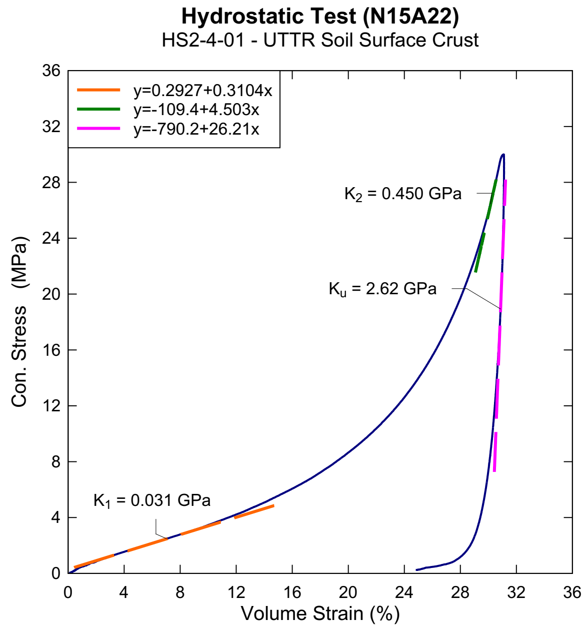


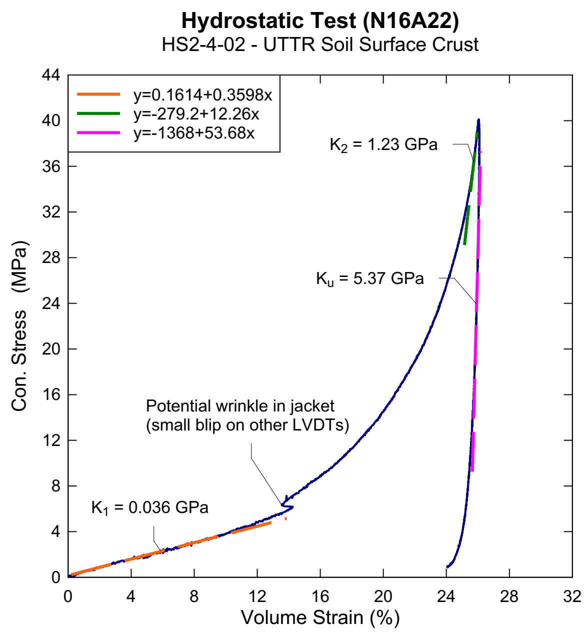


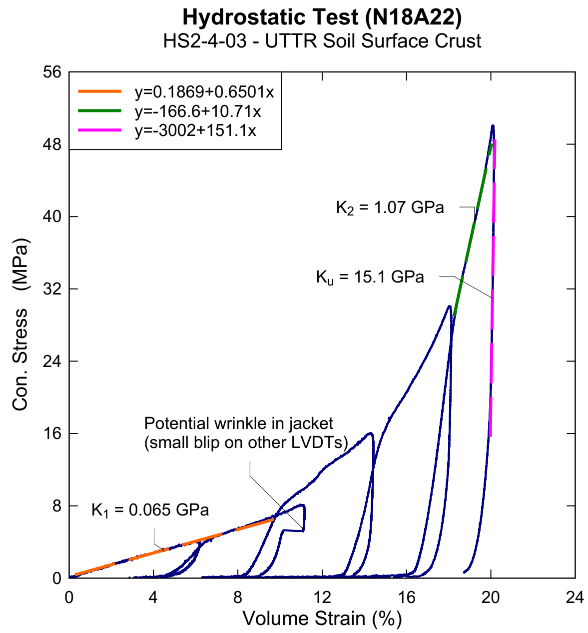
Hydrostatic Test (N11A22)
SI10-02 - UTTR Soil Surface Crust






Hydrostatic Test (N15A22)
HS2-4-01 - UTTR Soil Surface Crust
y=0.2927+0.3104x
y=-109.4+4.503x
y=-790.2+26.21x
K2 = 0.450 GPa
Ku = 2.62 GPa
K1 = 0.031 GPa
Con. Stress (MPa)
Volume Strain (%)

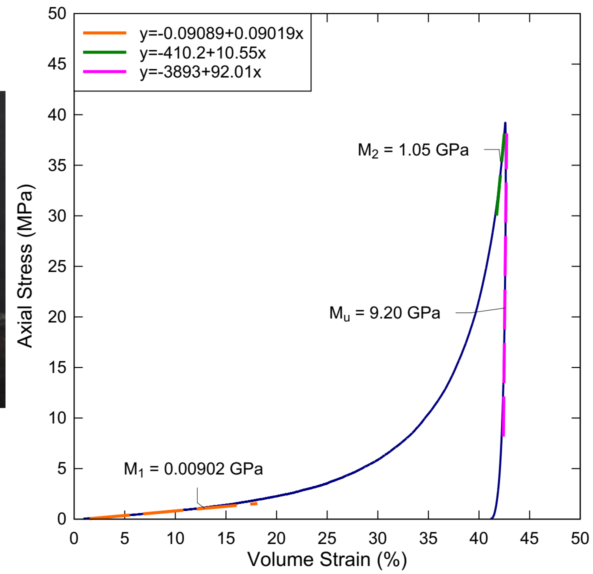

Hydrostatic Test (N16A22)
HS2-4-02 - UTTR Soil Surface Crust
y=0.1614+0.3598x
y=-279.2+12.26x
y=-1368+53.68x
K2 = 1.23 GPa
Ku = 5.37 GPa
Potential wrinkle in jacket
(small blip on other LVDTs)
K1 = 0.036 GPa
Con. Stress (MPa)
Volume Strain (%)

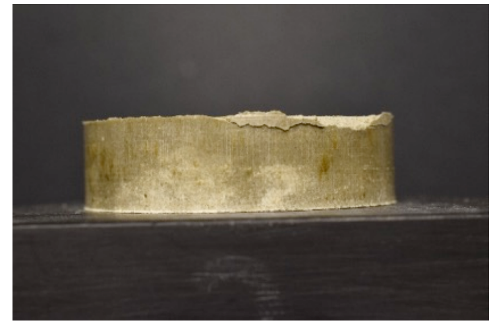


Hydrostatic Test (N18A22)
HS2-4-03 - UTTR Soil Surface Crust
y=0.1869+0.6501x
y=-166.6+10.71x
y=-3002+151.1x
K2 = 1.07 GPa
Ku = 15.1 GPa
Potential wrinkle in jacket
(small blip on other LVDTs)
K1 = 0.065 GPa
Con. Stress (MPa)
Volume Strain (%)
0
8
16
24
32
40
48
56
0
4
8
12
16
20
24

SI10 Surface Crust Oedometer

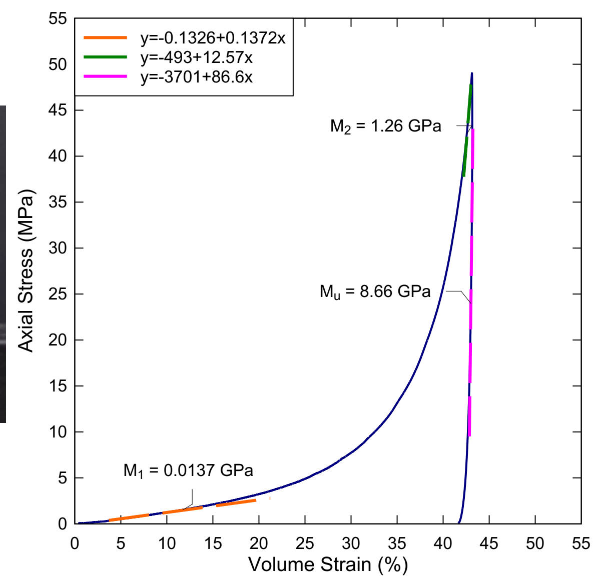
SI10-03 - UTTR Soil Surface Crust

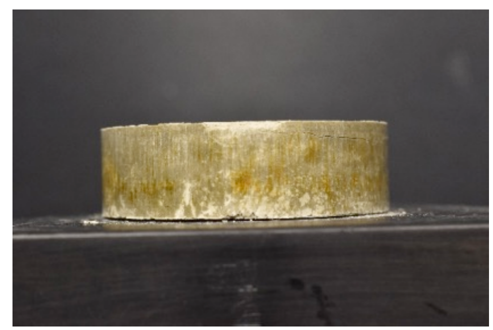


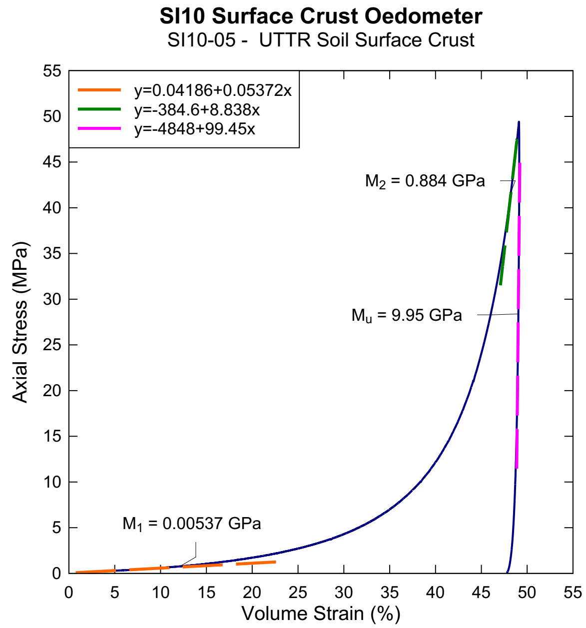


SI10 Surface Crust Oedometer

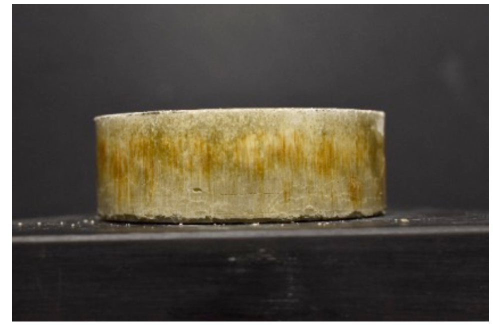
SI10-04 - UTTR Soil Surface Crust

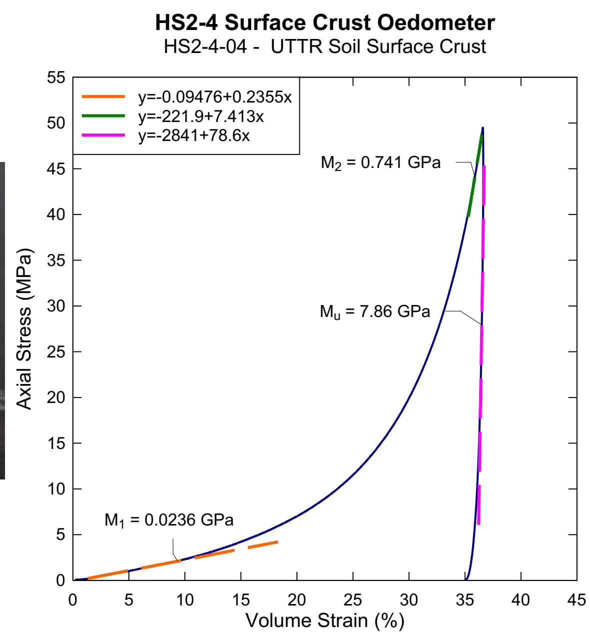




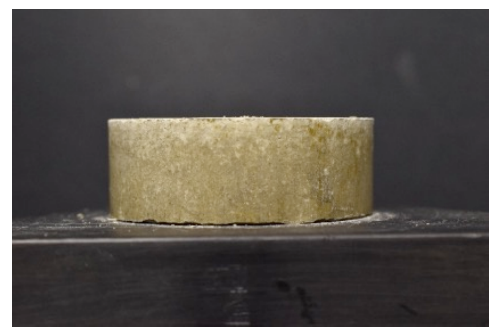


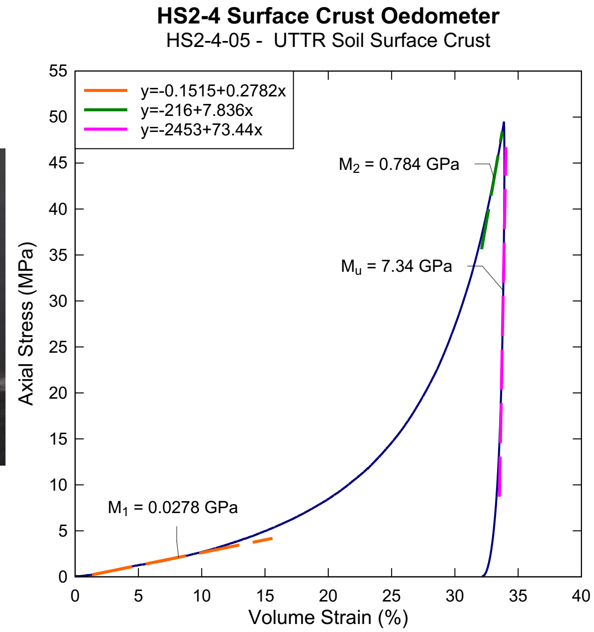
SI10 Surface Crust Oedometer
SI10-05 - UTTR Soil Surface Crust
y=0.04186+0.05372x
y=-384.6+8.838x
y=-4848+99.45x
M2 = 0.884 GPa
Mu = 9.95 GPa
M1 = 0.00537 GPa
Axial Stress (MPa)
Volume Strain (%)
0
5
10
15
20
25
30
35
40
45
50
55

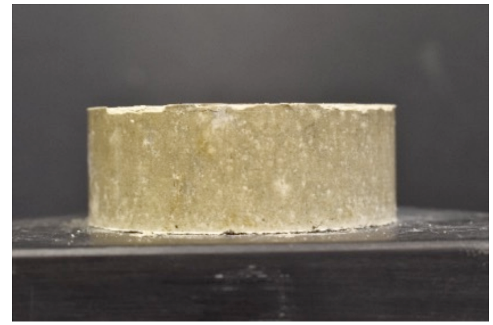


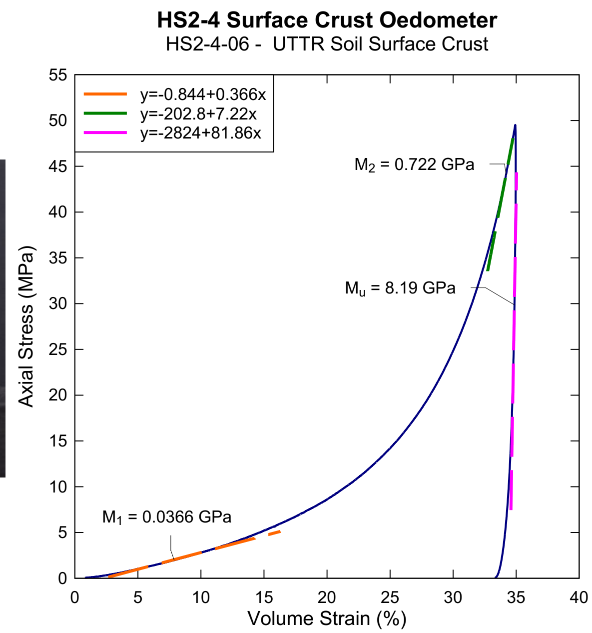


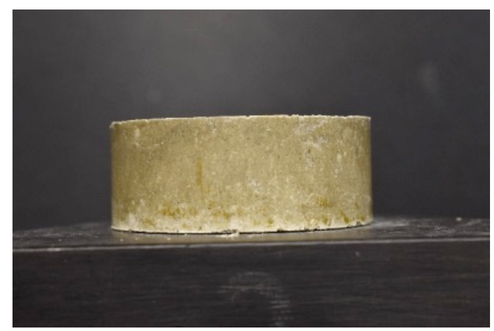
HS2-4 Surface Crust Oedometer
HS2-4-04 - UTTR Soil Surface Crust
y=-0.09476+0.2355x
y=-221.9+7.413x
y=-2841+78.6x
M2 = 0.741 GPa
Mu = 7.86 GPa
M1 = 0.0236 GPa
Axial Stress (MPa)
Volume Strain (%)
0
5
10
15
20
25
30
35
40
45
50
55




HS2-4 Surface Crust Oedometer
HS2-4-05 - UTTR Soil Surface Crust
y=-0.1515+0.2782x
y=-216+7.836x
y=-2453+73.44x
M2 = 0.784 GPa
Mu = 7.34 GPa
M1 = 0.0278 GPa
Axial Stress (MPa)
Volume Strain (%)



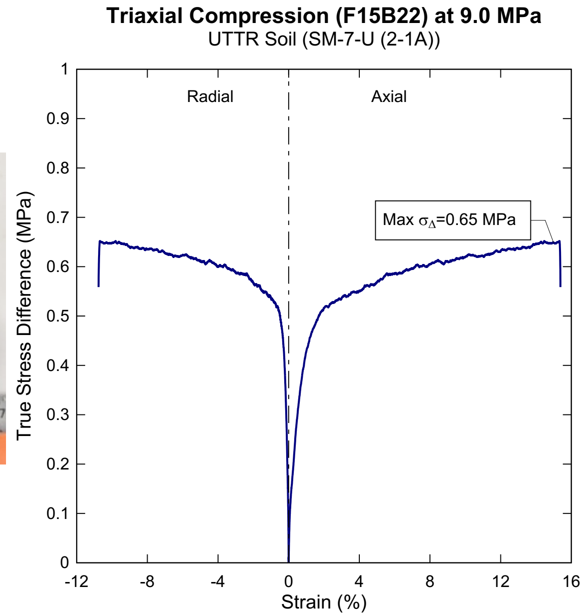

HS2-4 Surface Crust Oedometer
HS2-4-06 - UTTR Soil Surface Crust
y=-0.844+0.366x
y=-202.8+7.22x
y=-2824+81.86x
M2 = 0.722 GPa
Mu = 8.19 GPa
M1 = 0.0366 GPa
Axial Stress (MPa)
Volume Strain (%)

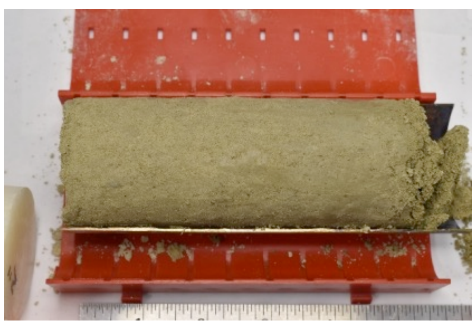


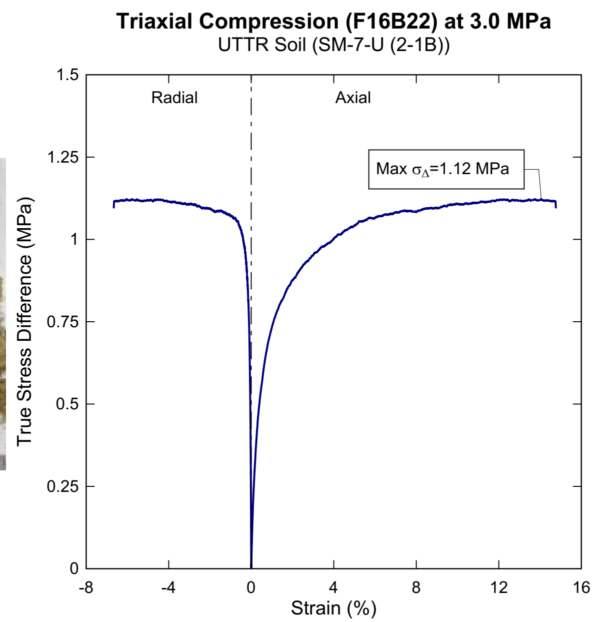
Appendix B

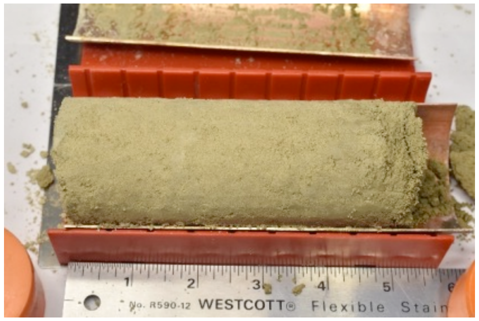
Silty Clay Soil Detailed Test Results

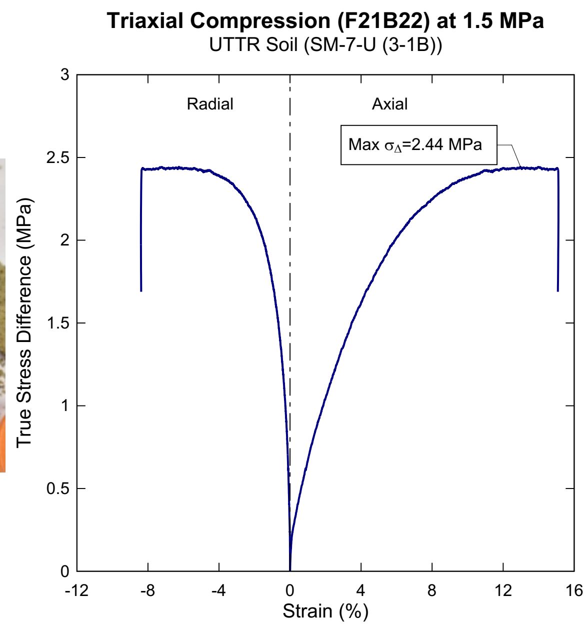
Triaxial Compression Tests
Hydrostatic Compression Tests
Uniaxial Strain Tests

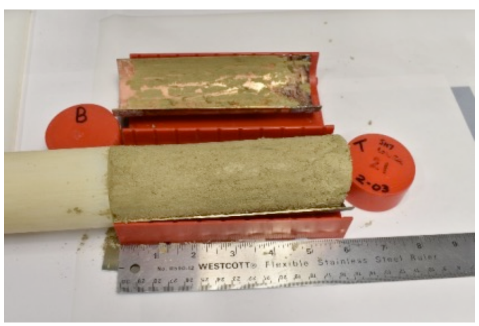

Triaxial Compression (F15B22) at 9.0 MPa
UTTR Soil (SM-7-U (2-1A))
Radial
Axial
Max σ_Δ=0.65 MPa
True Stress Difference (MPa)
Strain (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-12
-8
-4
0
4
8
12
16

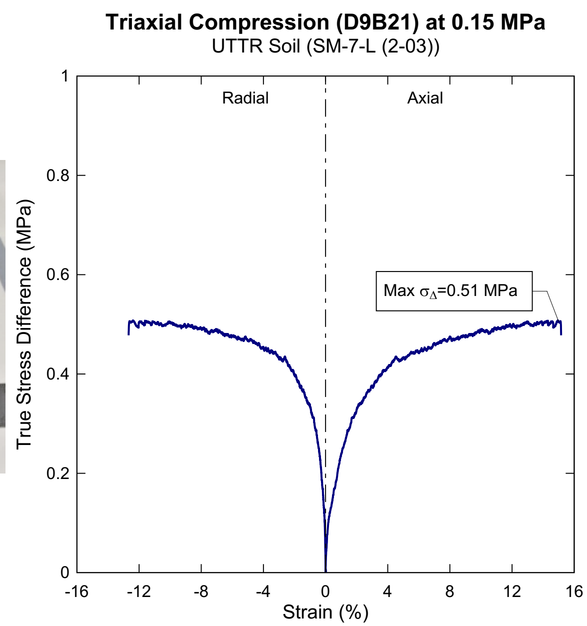



Triaxial Compression (F16B22) at 3.0 MPa
UTTR Soil (SM-7-U (2-1B))
Radial
Axial
Max σ_Δ=1.12 MPa
True Stress Difference (MPa)
Strain (%)
1.5
1.25
1
0.75
0.5
0.25
0
-8
-4
0
4
8
12
16

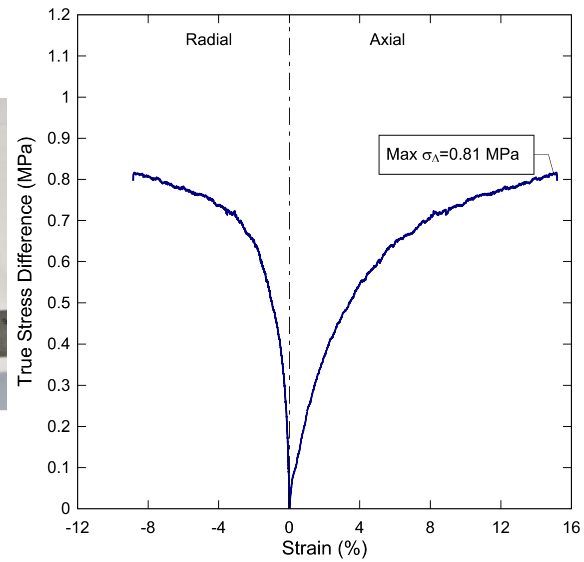

WESTCOTT
Flexible


Triaxial Compression (F21B22) at 1.5 MPa
UTTR Soil (SM-7-U (3-1B))
Radial
Axial
Max σ$_\Delta$=2.44 MPa
True Stress Difference (MPa)
Strain (%)
0
0.5
1
1.5
2
2.5
3
-12
-8
-4
0
4
8
12
16

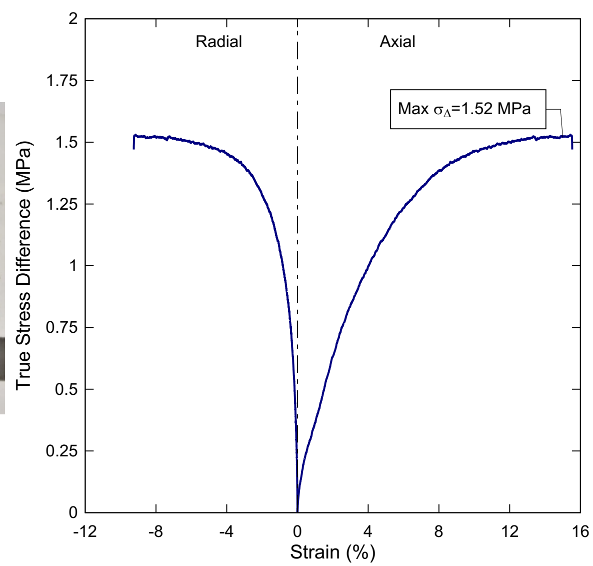

B
T
2-03
WESTCOTT


Triaxial Compression (D9B21) at 0.15 MPa
UTTR Soil (SM-7-L (2-03))
Radial
Axial
Max σ$_\Delta$=0.51 MPa
True Stress Difference (MPa)
Strain (%)
0
0.2
0.4
0.6
0.8
1
-16
-12
-8
-4
0
4
8
12
16

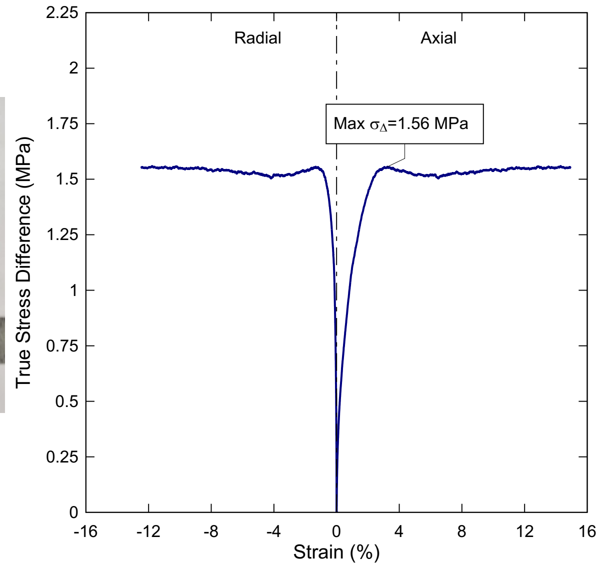
Triaxial Compression (D10B21) at 0.4 MPa
UTTR Soil (SM-7, Lower, 6-12") (SM-7-L (2-04))



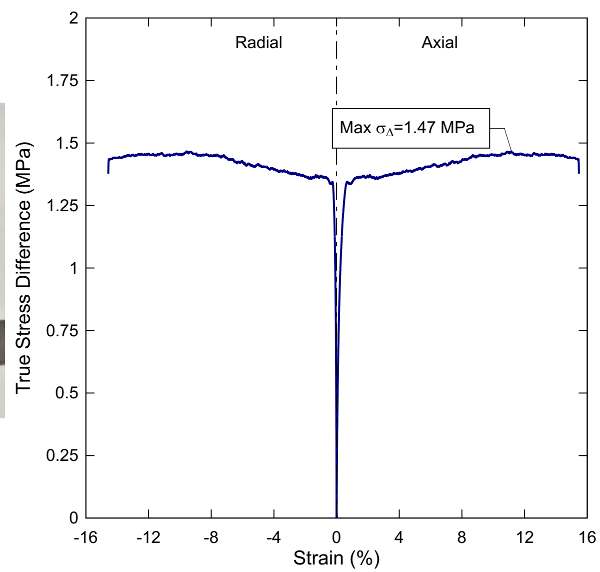
Triaxial Compression (D13B21) at 0.9 MPa
UTTR Soil (SM-7-L (2-05))



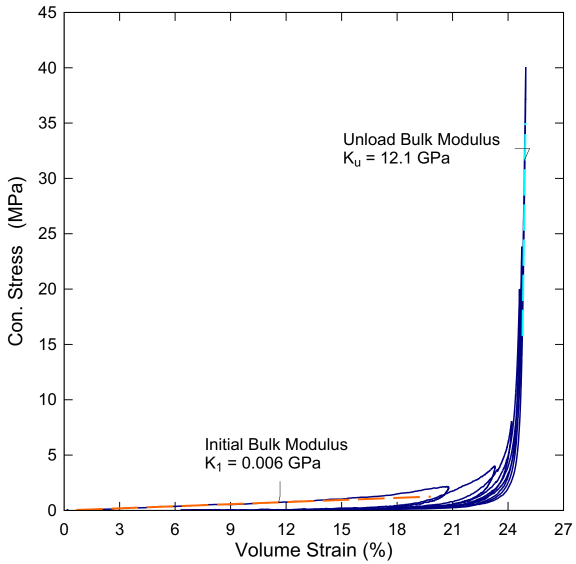
Triaxial Compression (D14B21) at 2.4 MPa
UTTR Soil (SM-7-L (2-06))



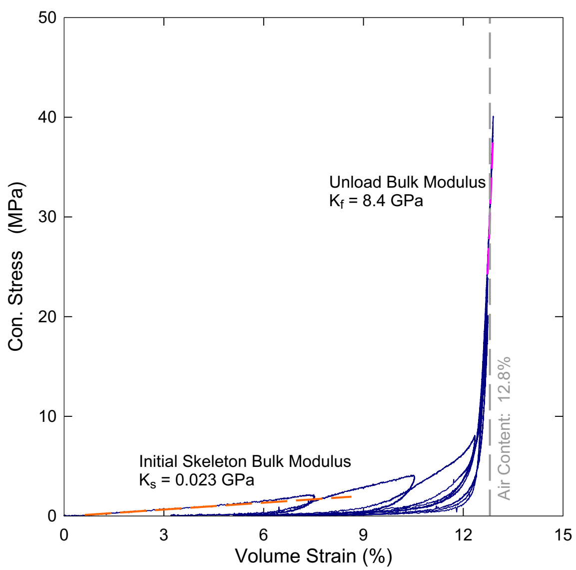
Triaxial Compression (D15B21) at 5.0 MPa
UTTR Soil (SM-7-L (2-07))



Hydrostatic Test (F22A22)
UTTR Soil (SM-7-U (6-1A))

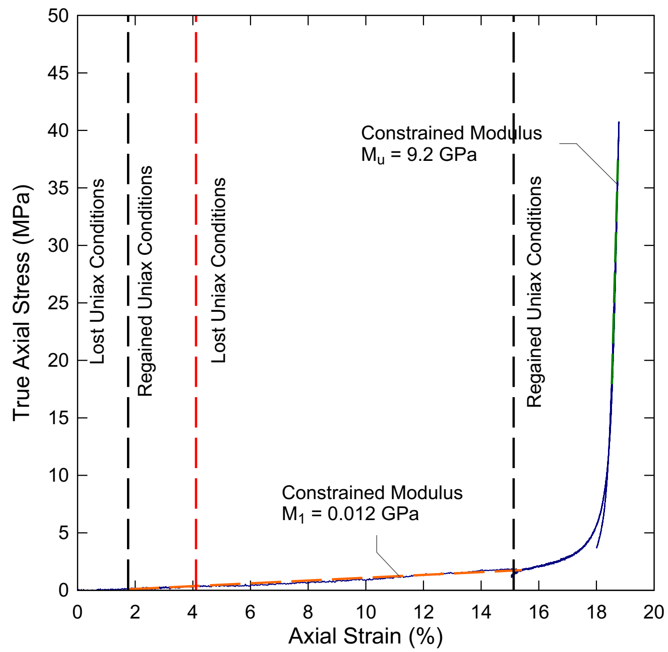


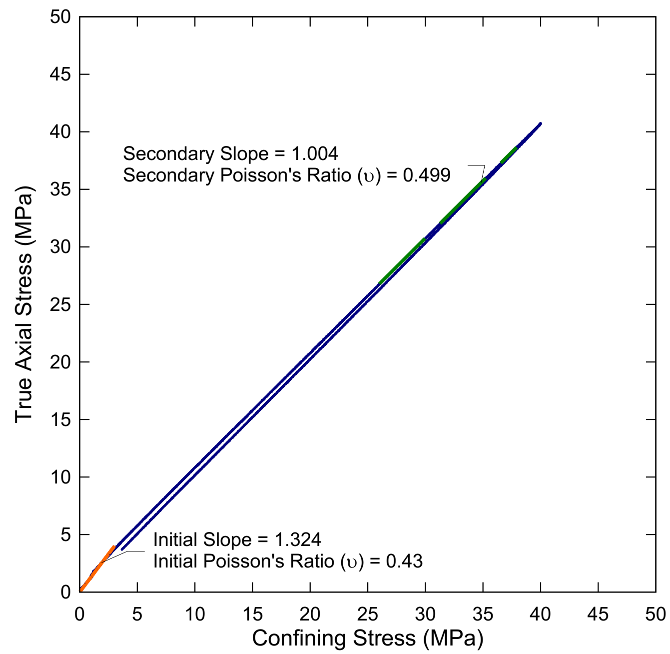
Hydrostatic Test (D7A21)
UTTR Soil (SM-7-L (2-02))



Uniaxial Strain Test (F11A22) at 40 MPa

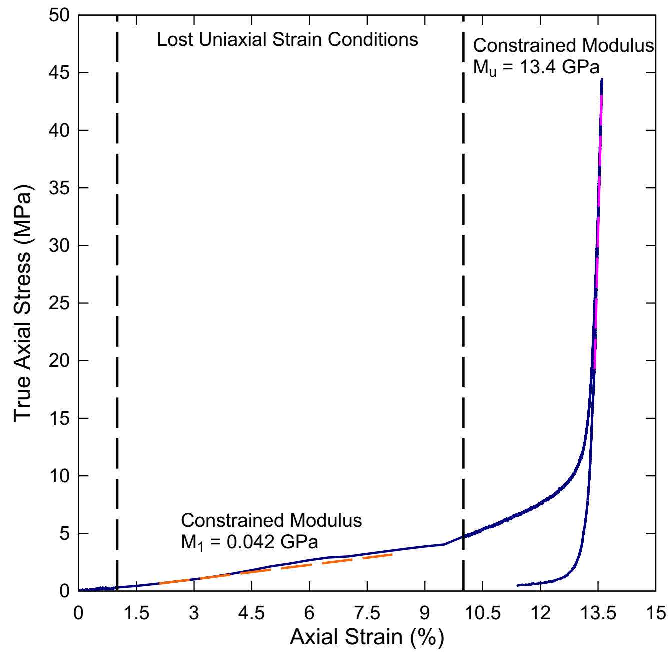
UTTR Soil (SM-7-U (6-1B))

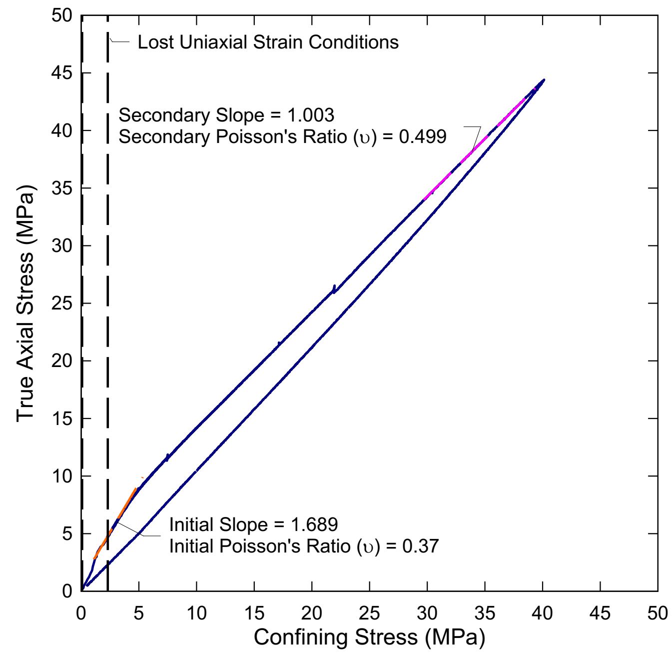




Uniaxial Strain Test (D1A21) at 40 MPa

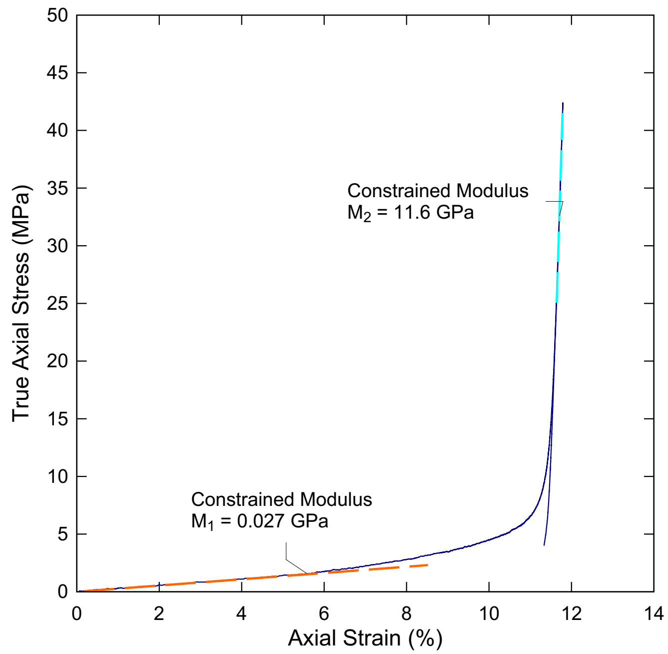
UTTR Soil (SM-7-L (2-01))

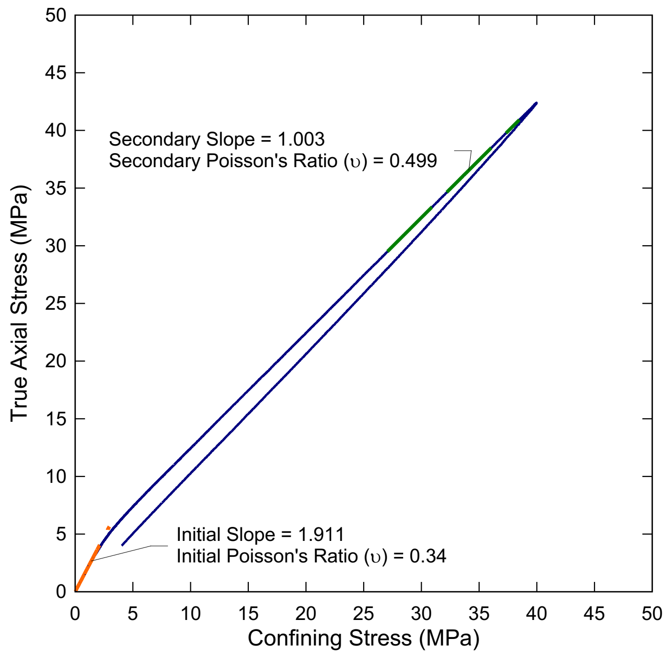




Uniaxial Strain Test (F10A22) at 40 MPa

UTTR Soil (SM-7-L (2-08))



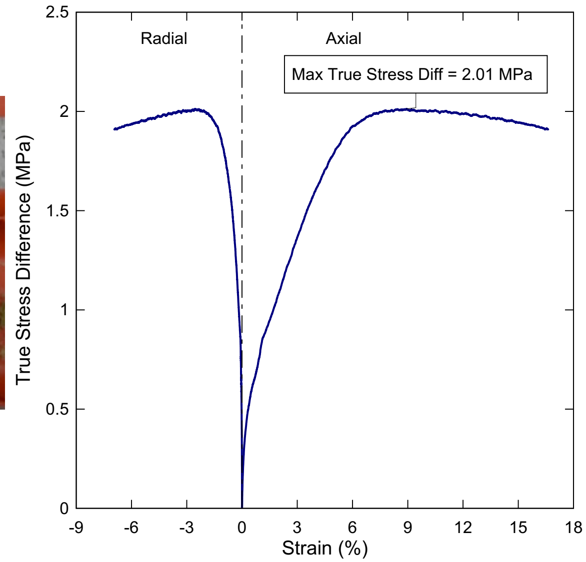


Appendix C

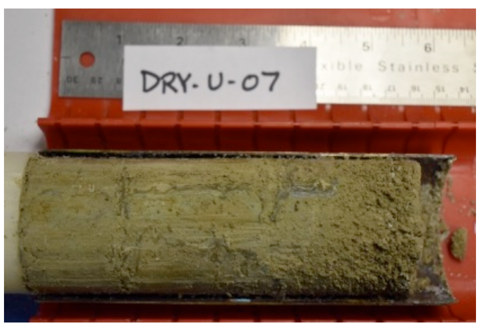
Partially Saturated Clay Soil Detailed Test Results

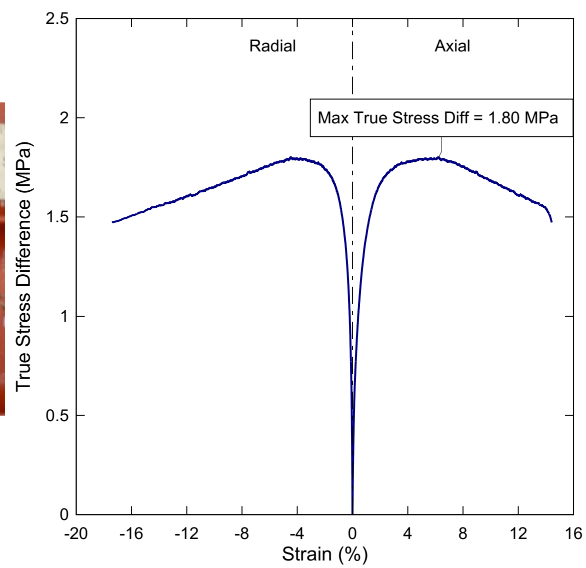
Triaxial Compression Tests
Hydrostatic Compression Tests
Uniaxial Strain Tests

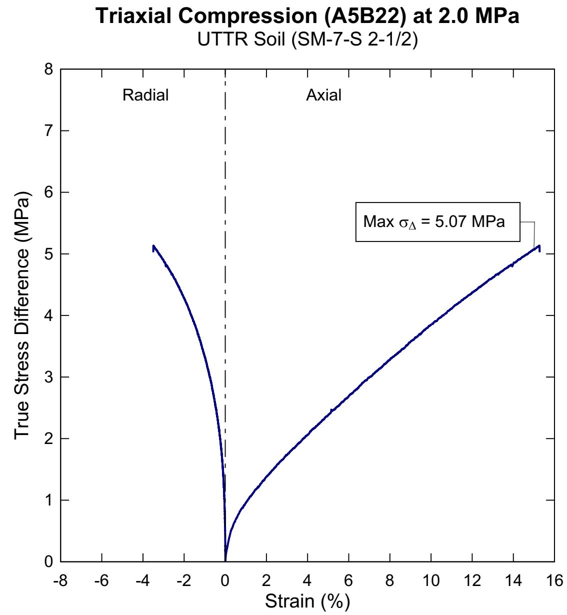
Triaxial Compression (O14B20) at 2.5 MPa
UTTR Soil (DRY-U-06)



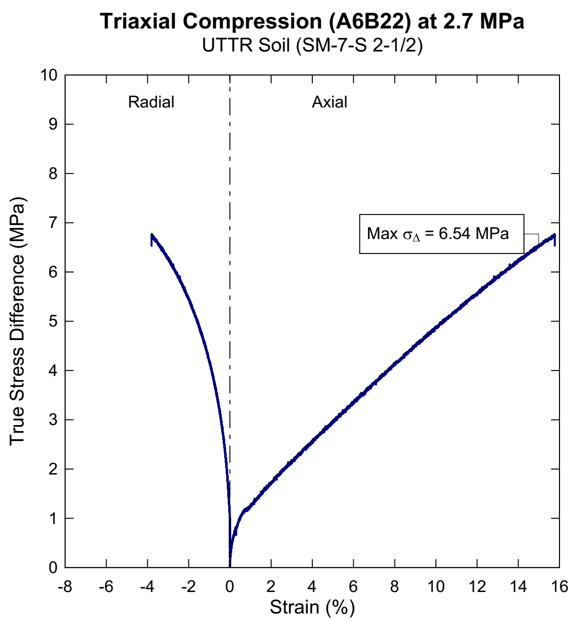
Triaxial Compression (O14D20) at 5.0 MPa
UTTR Soil (DRY-U-07)





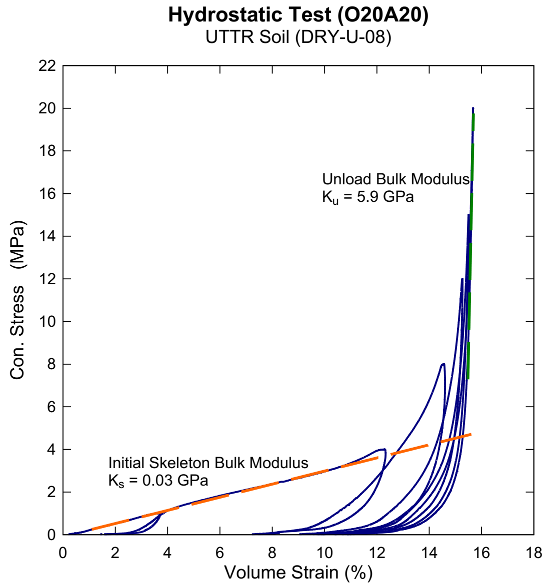


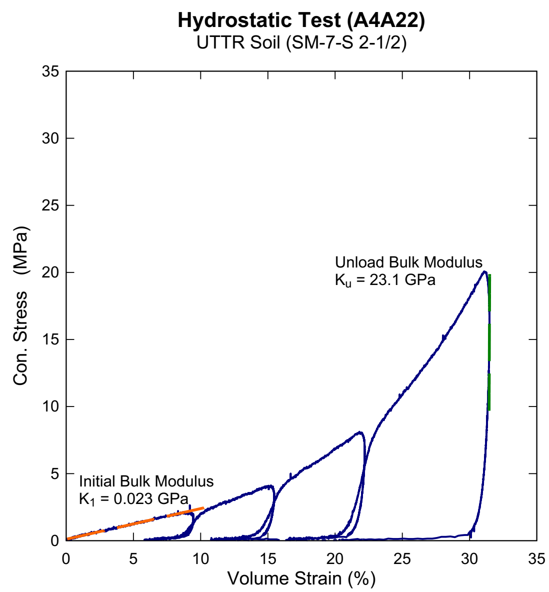
Triaxial Compression (A5B22) at 2.0 MPa
UTTR Soil (SM-7-S 2-1/2)
Radial
Axial
Max σΔ = 5.07 MPa
True Stress Difference (MPa)
Strain (%)



Triaxial Compression (A6B22) at 2.7 MPa
UTTR Soil (SM-7-S 2-1/2)
Radial
Axial
Max σΔ = 6.54 MPa
True Stress Difference (MPa)
Strain (%)

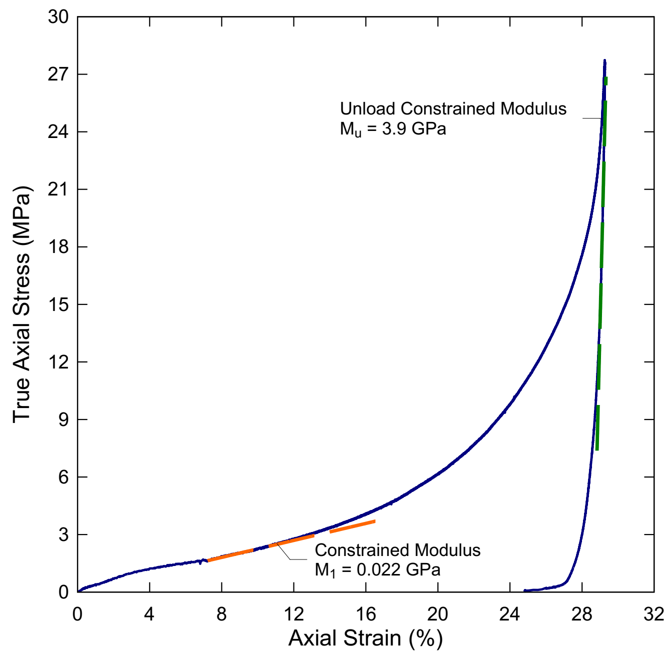

DRY-U-08

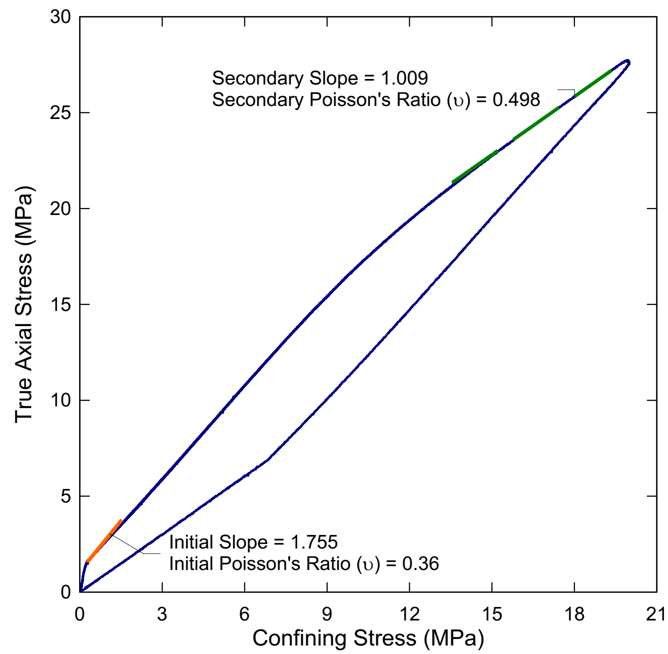

Hydrostatic Test (O20A20)
UTTR Soil (DRY-U-08)
Unload Bulk Modulus
K_u = 5.9 GPa
Initial Skeleton Bulk Modulus
K_s = 0.03 GPa
Con. Stress (MPa)
Volume Strain (%)
0
2
4
6
8
10
12
14
16
18
20
22


Hydrostatic Test (A4A22)
UTTR Soil (SM-7-S 2-1/2)
Unload Bulk Modulus
K_u = 23.1 GPa
Initial Bulk Modulus
K_1 = 0.023 GPa
Con. Stress (MPa)
Volume Strain (%)
0
5
10
15
20
25
30
35

Uniaxial Strain Test (N9A20) at 20 MPa

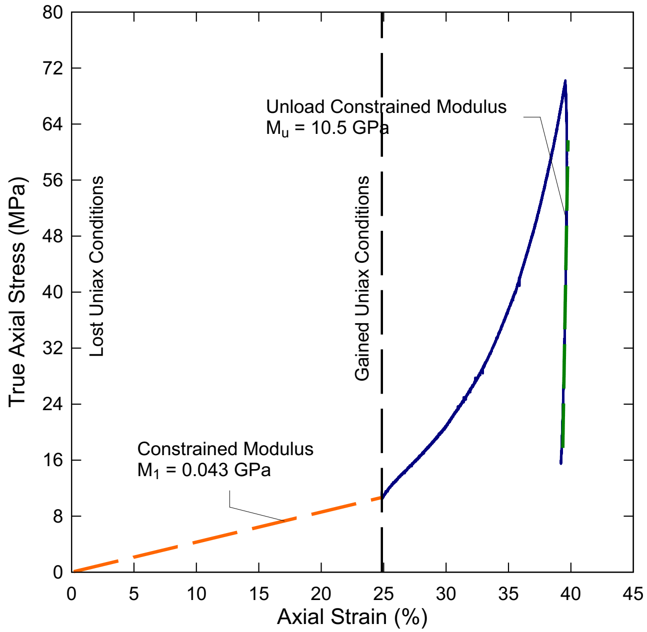
UTTR Soil (DRY-L-08)

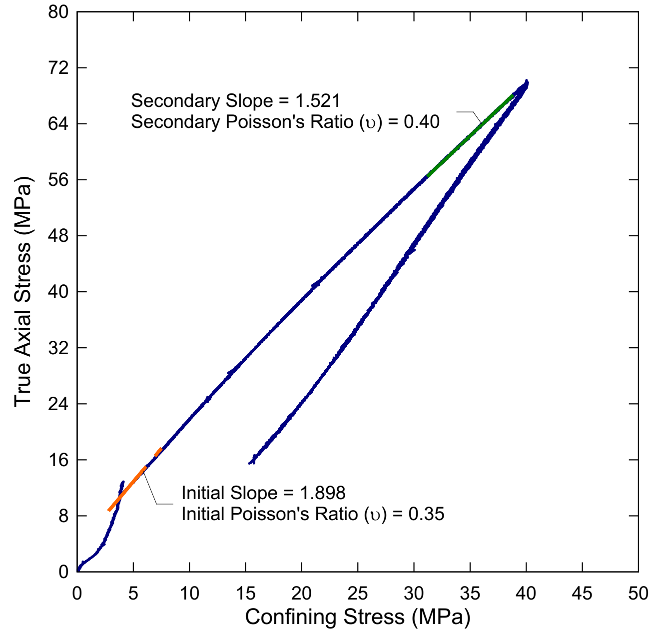




Uniaxial Strain Test (A1A22) at 40 MPa

UTTR Soil (SM-7 Surface 2-1/2)



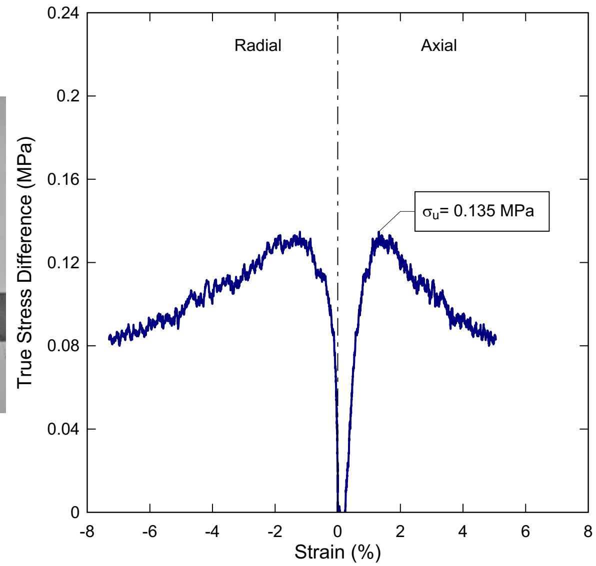


Appendix D

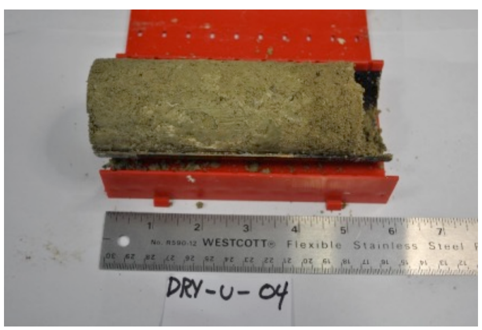
Saturated Clay Soil Detailed Test Results

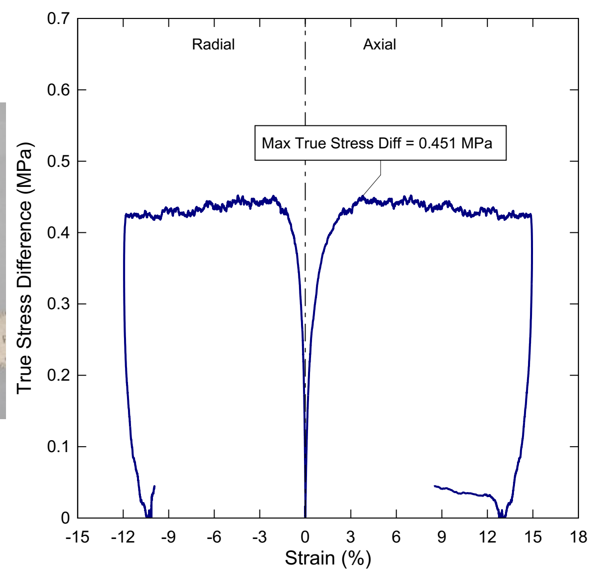
Triaxial Compression Tests
Unconfined Compression Tests
Hydrostatic Compression Tests
Uniaxial Strain Tests

Unconfined Compression Test (F13A20)
UTTR Soil (DRY-U-03)



Triaxial Compression (F14D20) at 2.5 MPa
UTTR Soil (DRY-U-04)



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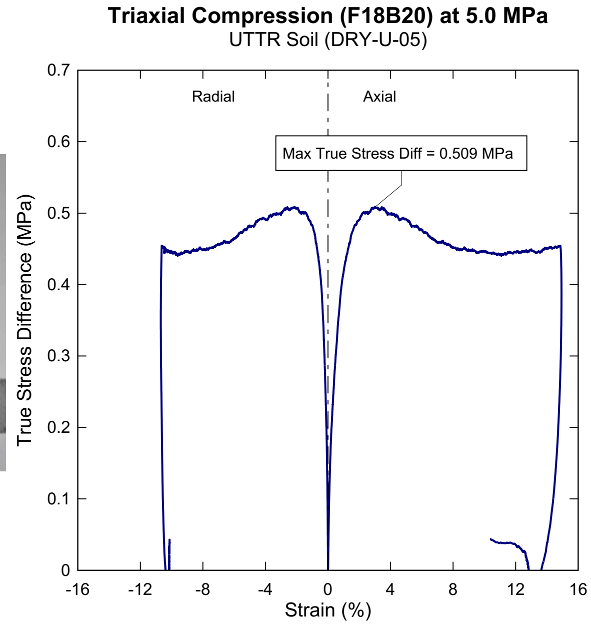
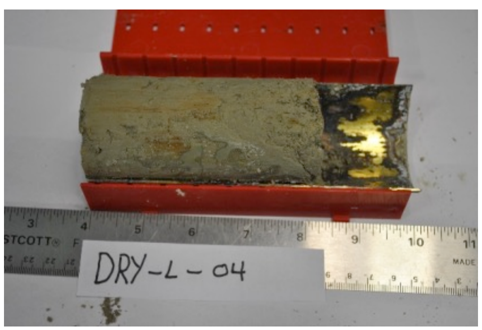
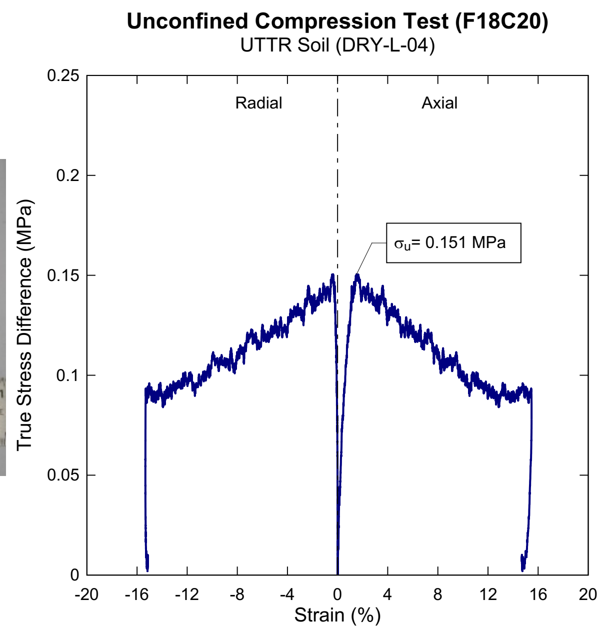
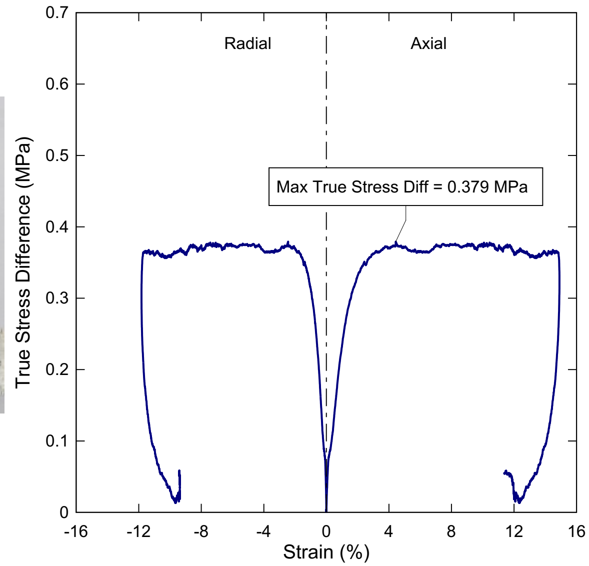
DRY-U-05


Triaxial Compression (F18B20) at 5.0 MPa
UTTR Soil (DRY-U-05)
Radial
Axial
Max True Stress Diff = 0.509 MPa
True Stress Difference (MPa)
Strain (%)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-16
-12
-8
-4
0
4
8
12
16

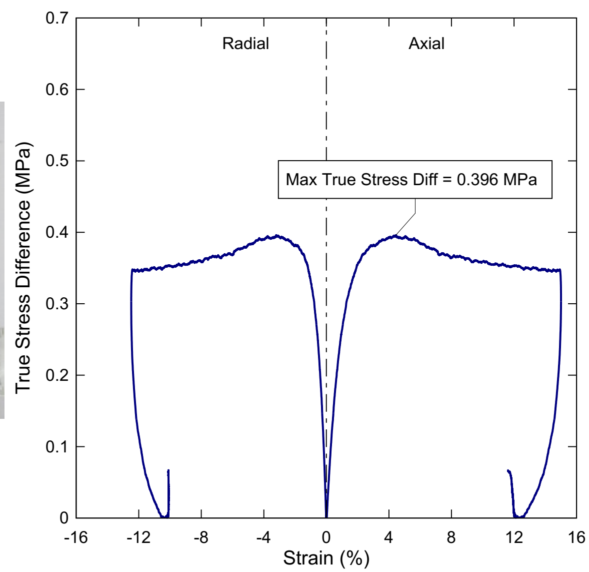

DRY-L-04


Unconfined Compression Test (F18C20)
UTTR Soil (DRY-L-04)
Radial
Axial
σ_u= 0.151 MPa
True Stress Difference (MPa)
Strain (%)
0.25
0.2
0.15
0.1
0.05
0
-20
-16
-12
-8
-4
0
4
8
12
16
20

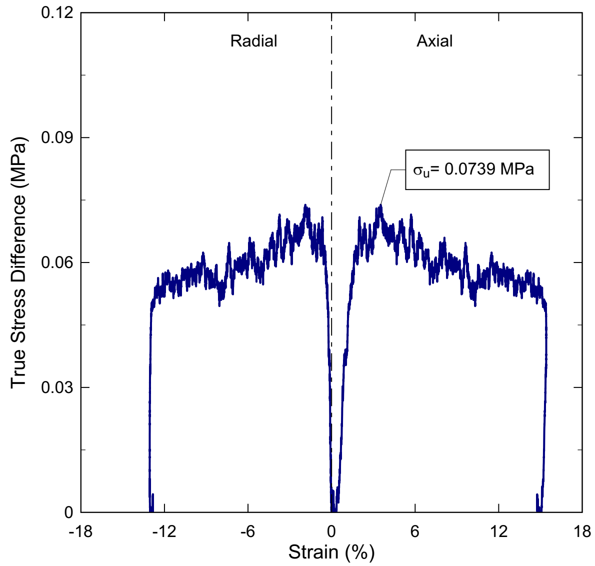
Triaxial Compression (F21B20) at 2.5MPa
UTTR Soil (DRY-L-05)



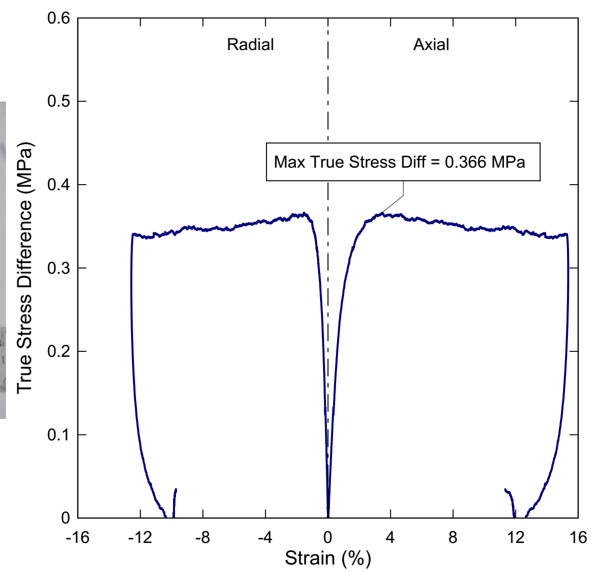
Triaxial Compression (F26D20) at 5.0 MPa
UTTR Soil (DRY-L-06)



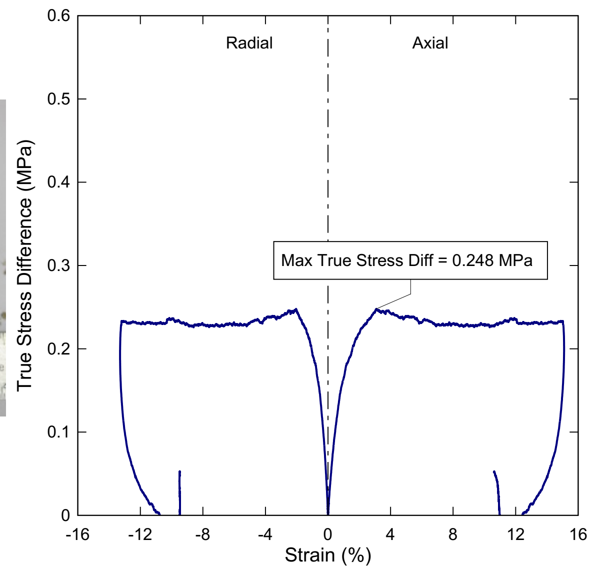
Unconfined Compression Test (F19A20)
UTTR Soil (SP3A-U-03)



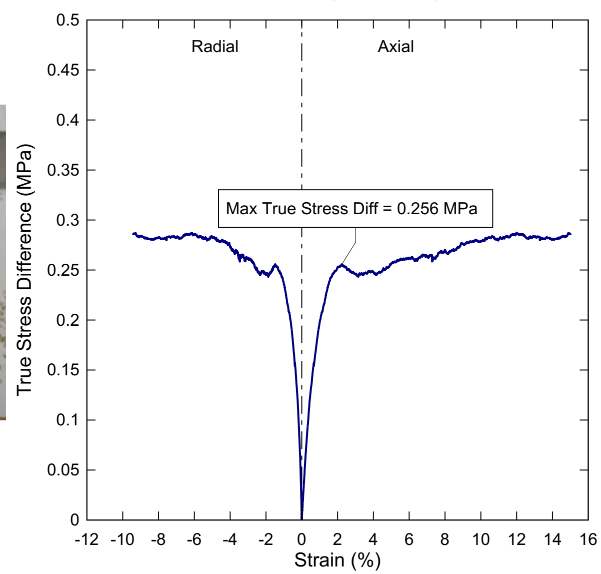
Triaxial Compression (F24B20) at 2.5 MPa
UTTR Soil (SP3A-U-04)



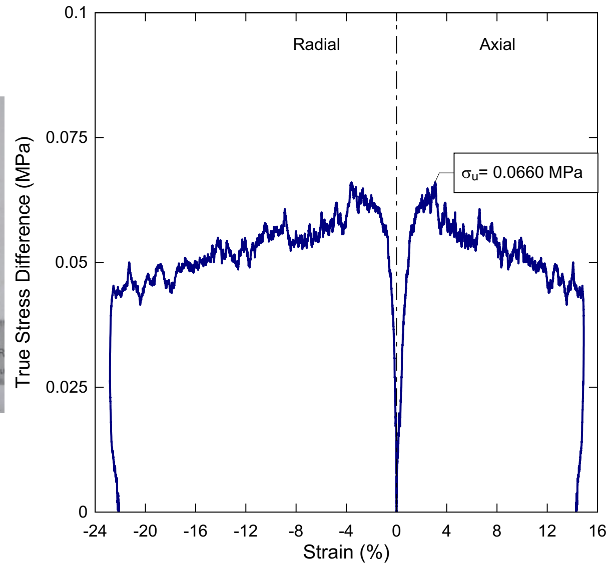
Triaxial Compression (F27B20) at 5.0 MPa
UTTR Soil (SP3A-U-05)



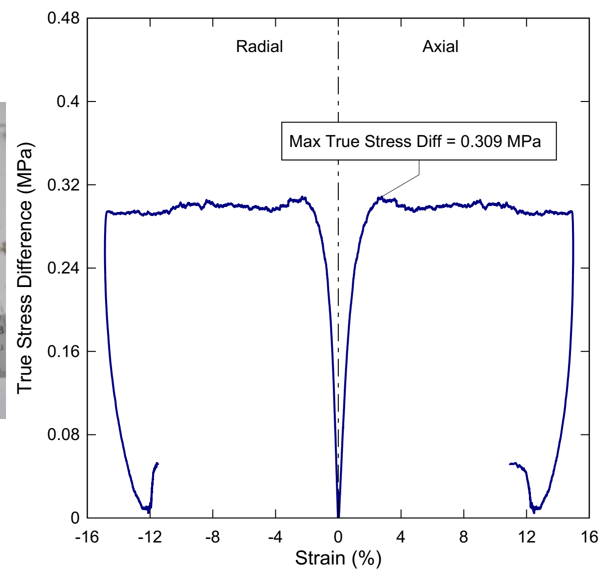
Triaxial Compression (G11B20) at 0.7 MPa
UTTR Soil (SP3A-U-07)



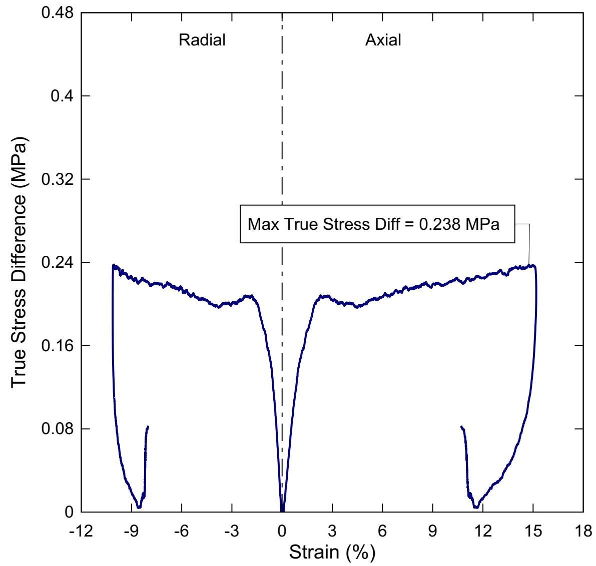
Unconfined Compression Test (F19B20)
UTTR Soil (SP3A-L-04)



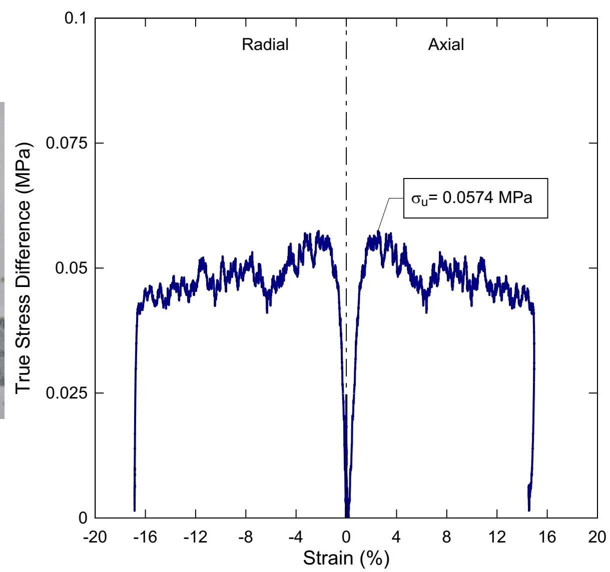
Triaxial Compression (F24D20) at 2.5 MPa
UTTR Soil (SP3A-L-06)



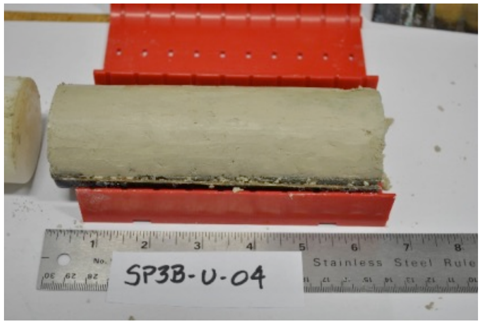
Triaxial Compression (F27D20) at 5.0 MPa
UTTR Soil (SP3A-L-07)

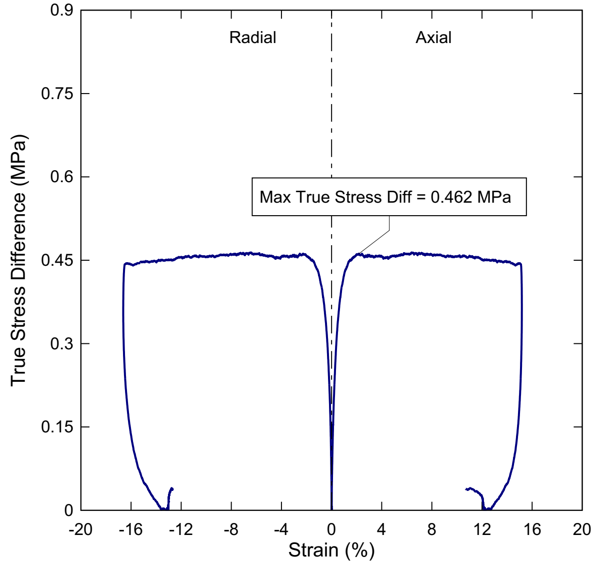


Unconfined Compression Test (F20A20)
UTTR Soil (SP3B-U-03)

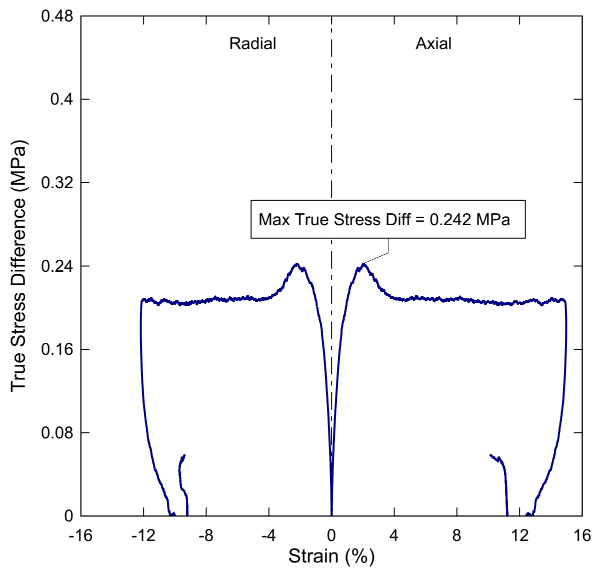


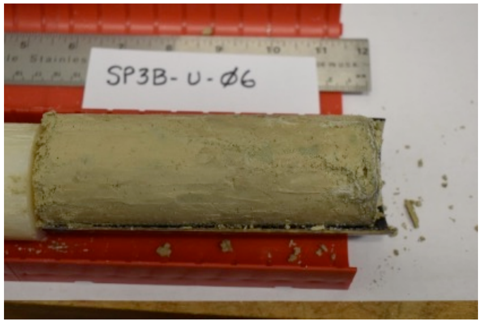
Triaxial Compression (F25D20) at 2.5 MPa
UTTR Soil (SP3B-U-04)

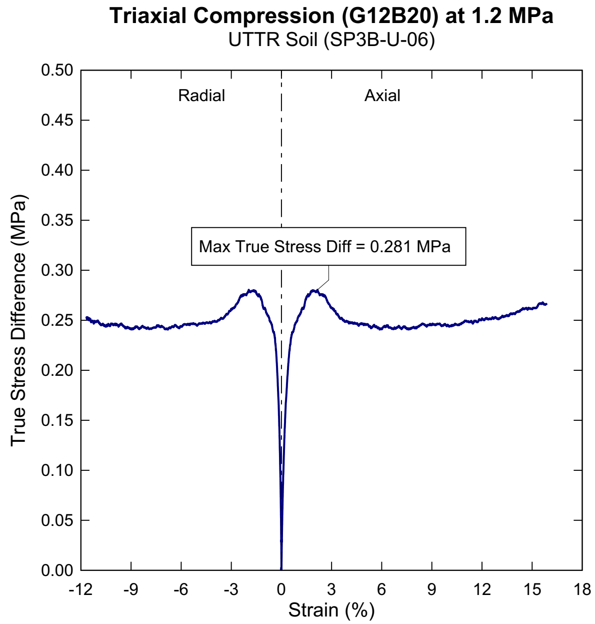


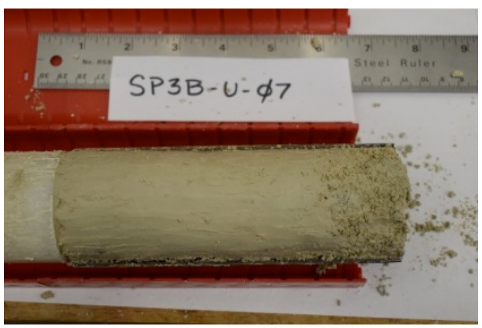


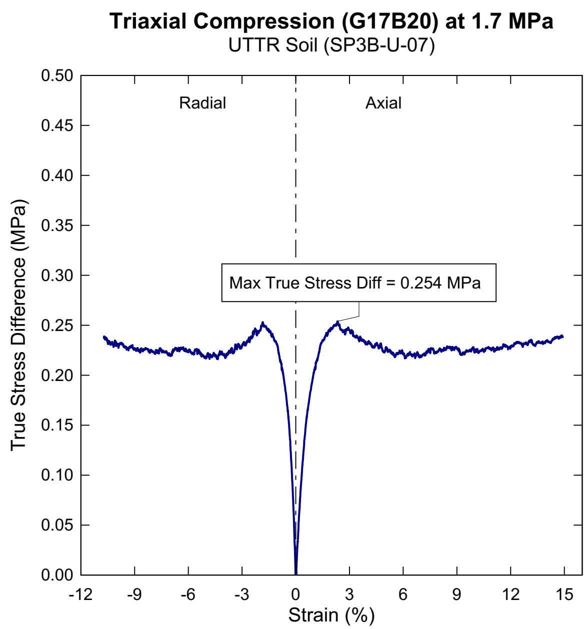
Triaxial Compression (F28B20) at 5.0 MPa
UTTR Soil (SP3B-U-05)



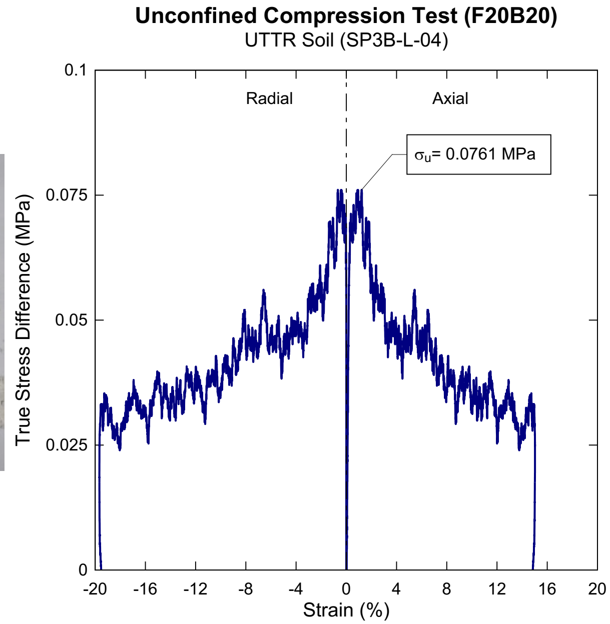

SP3B-U-Ø6


Triaxial Compression (G12B20) at 1.2 MPa
UTTR Soil (SP3B-U-06)
Radial
Axial
Max True Stress Diff = 0.281 MPa
True Stress Difference (MPa)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
-12
-9
-6
-3
0
3
6
9
12
15
18
Strain (%)

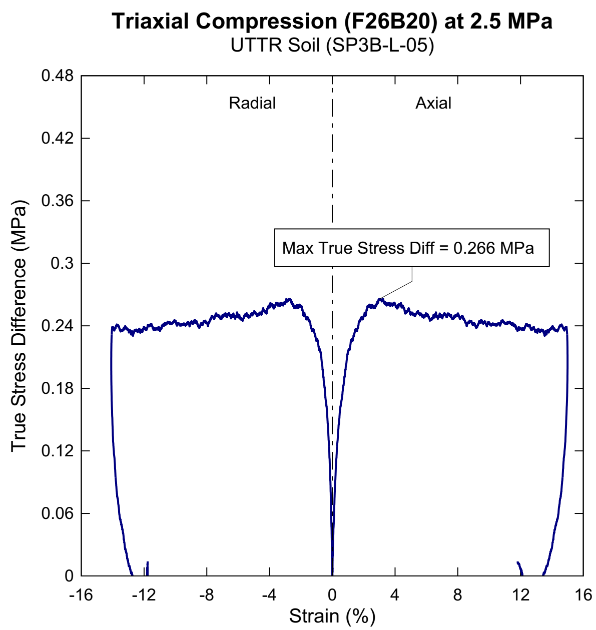

SP3B-U-φ7
Steel Ruler

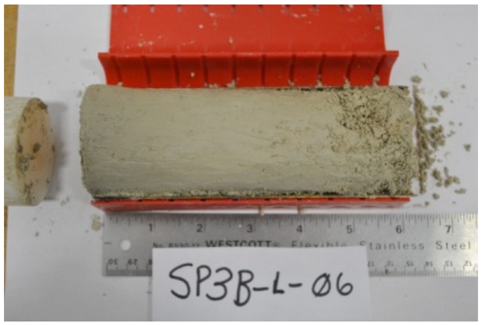

Triaxial Compression (G17B20) at 1.7 MPa
UTTR Soil (SP3B-U-07)
Radial
Axial
Max True Stress Diff = 0.254 MPa
True Stress Difference (MPa)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
-12
-9
-6
-3
0
3
6
9
12
15
Strain (%)

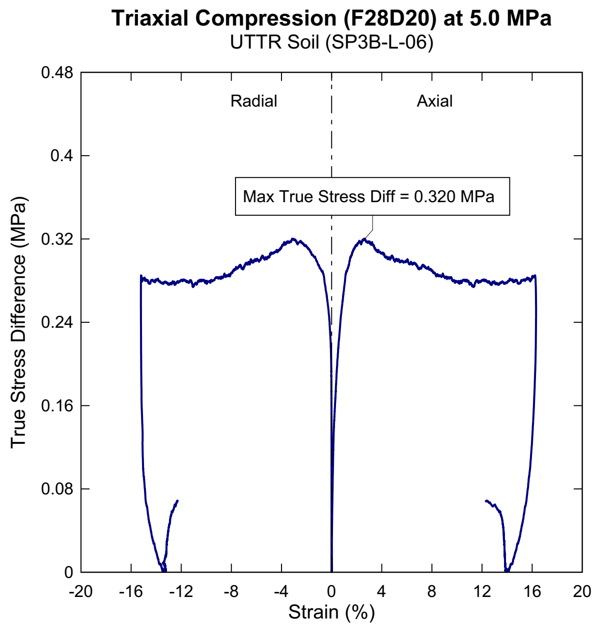

SP3B-L-04
Stainless Steel Ruler


Unconfined Compression Test (F20B20)
UTTR Soil (SP3B-L-04)
Radial
Axial
σu= 0.0761 MPa
True Stress Difference (MPa)
Strain (%)
0.1
0.075
0.05
0.025
0
-20
-16
-12
-8
-4
0
4
8
12
16
20

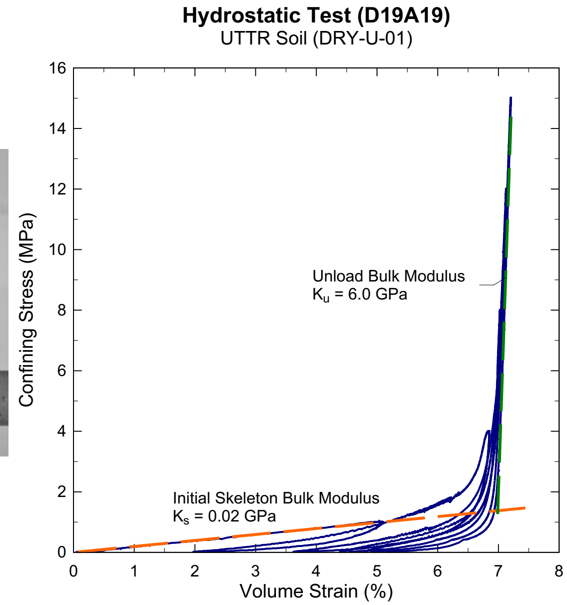

SP3B-L-05
Stainless Stee

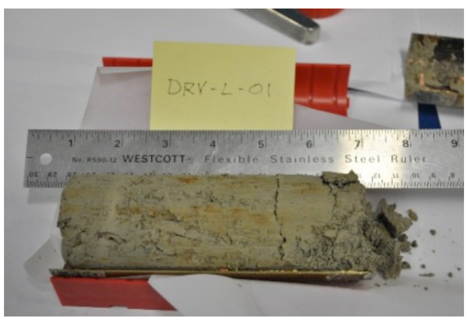

Triaxial Compression (F26B20) at 2.5 MPa
UTTR Soil (SP3B-L-05)
Radial
Axial
Max True Stress Diff = 0.266 MPa
True Stress Difference (MPa)
Strain (%)
0.48
0.42
0.36
0.3
0.24
0.18
0.12
0.06
0
-16
-12
-8
-4
0
4
8
12
16

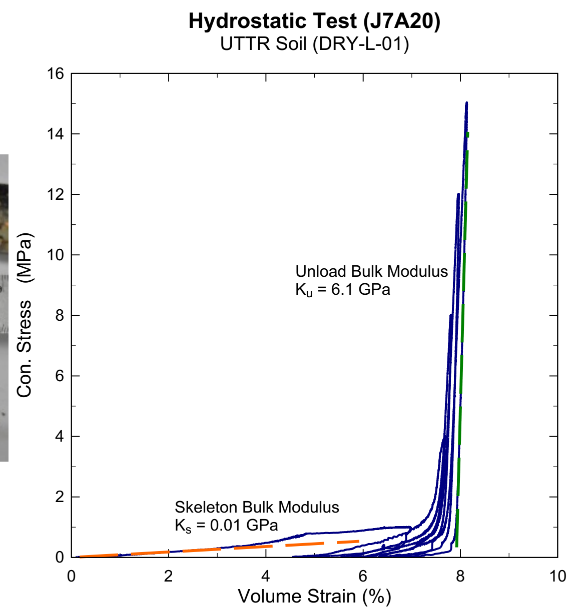

SP3B-L-06


Triaxial Compression (F28D20) at 5.0 MPa
UTTR Soil (SP3B-L-06)
Radial
Axial
Max True Stress Diff = 0.320 MPa
True Stress Difference (MPa)
Strain (%)
0.48
0.4
0.32
0.24
0.16
0.08
0
-20
-16
-12
-8
-4
0
4
8
12
16
20

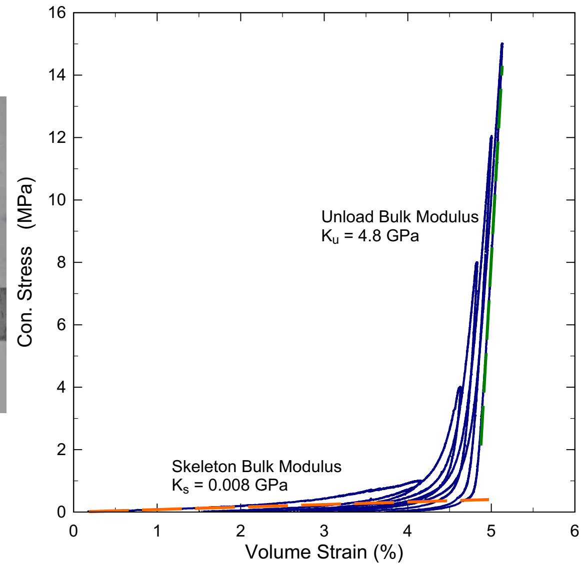

DRY-U-01
WESTCOTT Flexible Stainless Steel Ruler


Hydrostatic Test (D19A19)
UTTR Soil (DRY-U-01)
Confining Stress (MPa)
Volume Strain (%)
Unload Bulk Modulus
K_u = 6.0 GPa
Initial Skeleton Bulk Modulus
K_s = 0.02 GPa

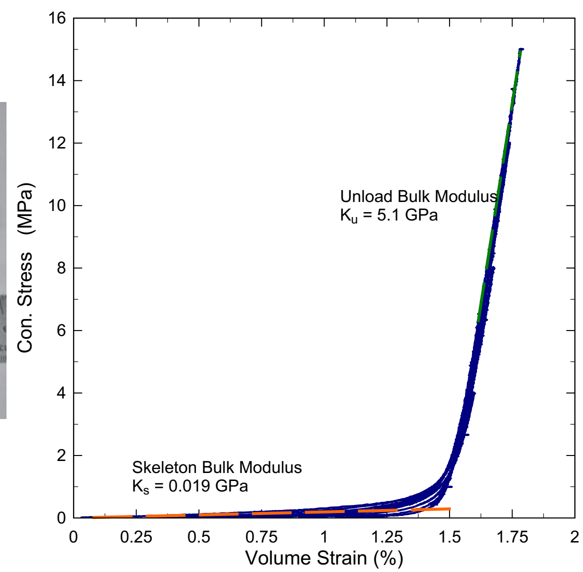

DRY-L-01
WESTCOTT Flexible Stainless Steel Ruler


Hydrostatic Test (J7A20)
UTTR Soil (DRY-L-01)
Con. Stress (MPa)
Volume Strain (%)
Unload Bulk Modulus
K_u = 6.1 GPa
Skeleton Bulk Modulus
K_s = 0.01 GPa

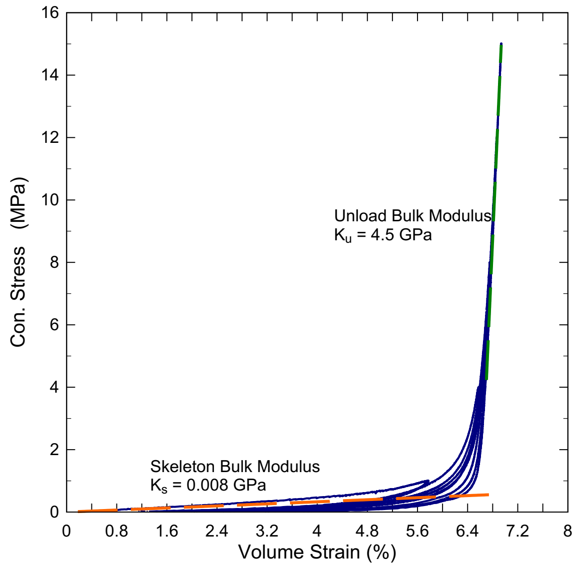
Hydrostatic Test (J8A20)
SP3A-U-01 - UTTR Soil (SP3A-U-01)

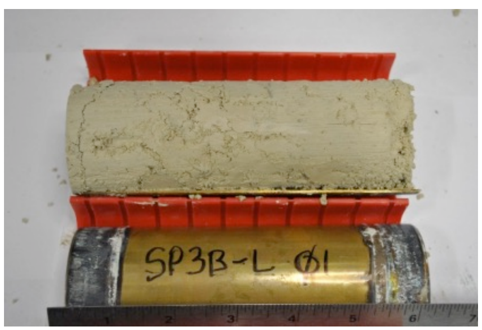


Hydrostatic Test (J8B20)
UTTR Soil (SP3A-L-01)

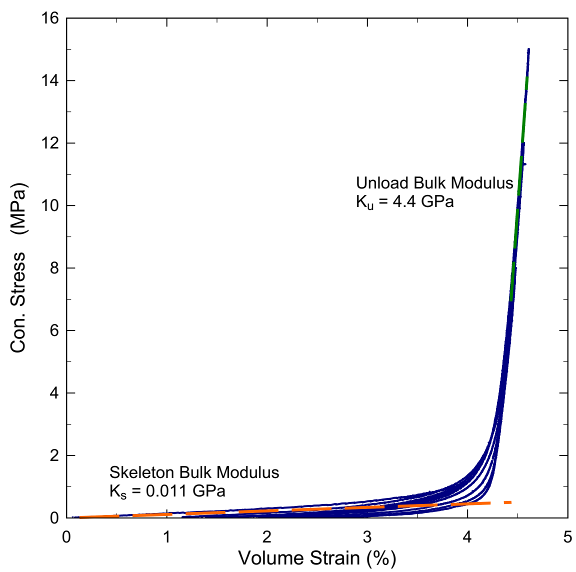


Hydrostatic Test (J9A20)
UTTR Soil (SP3B-U-01)



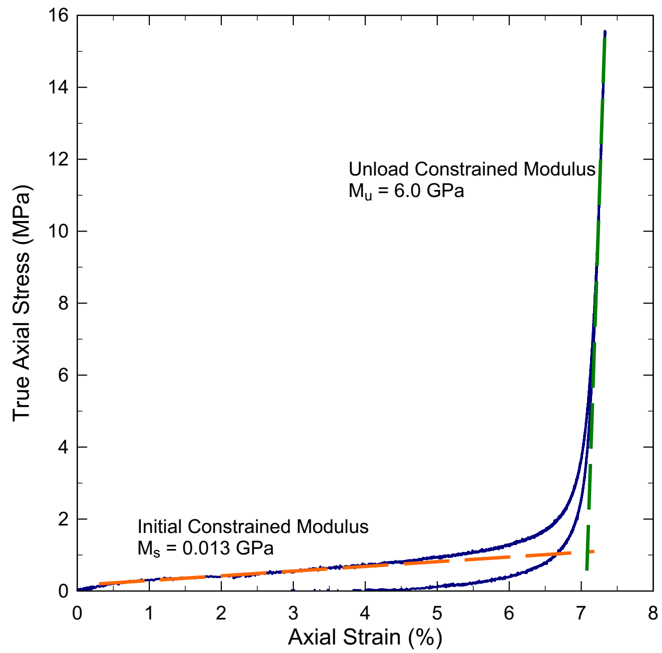


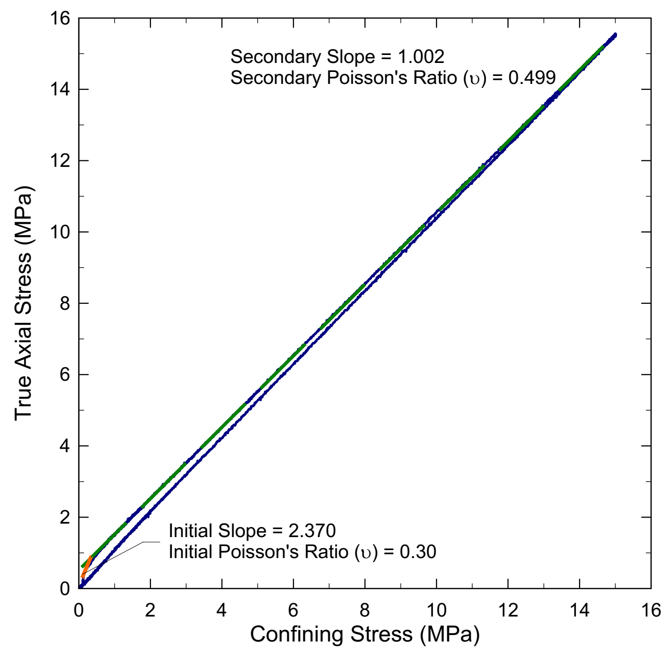
Hydrostatic Test (J10A20)
UTTR Soil (SP3B-L-01)



Uniaxial Strain Test (J14A20) at 15 MPa

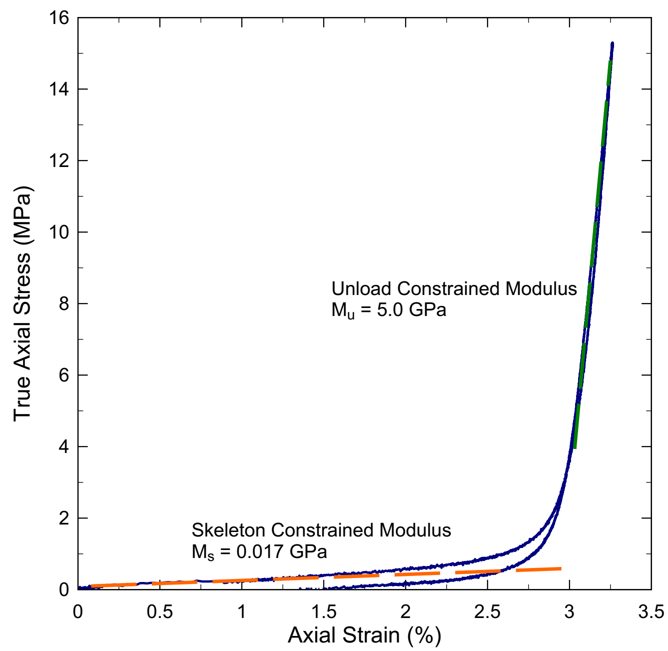
UTTR Soil (DRY-U-02)

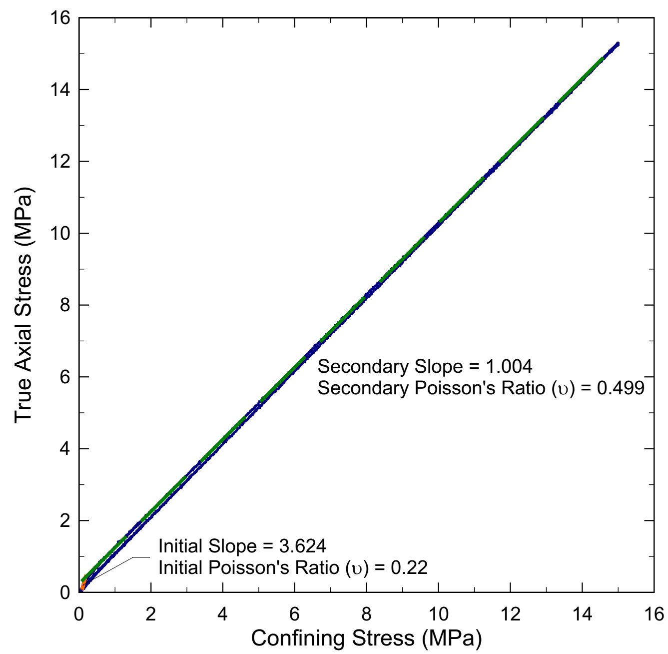




Uniaxial Strain Test (J14B20) at 15 MPa

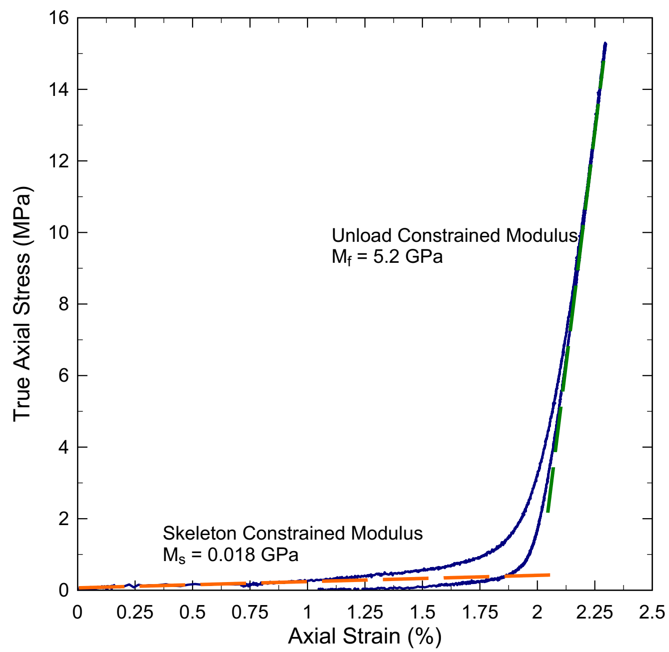
UTTR Soil (DRY-L-02)

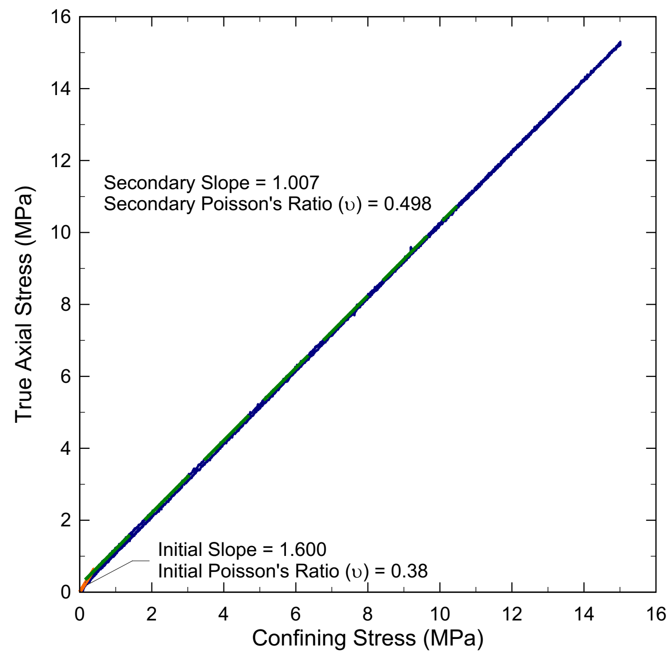




Uniaxial Strain Test (J15A20) at 15 MPa

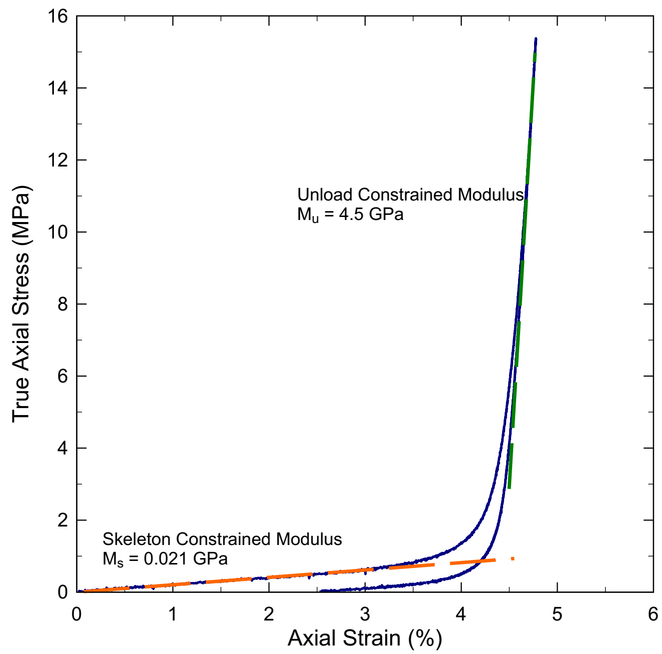
UTTR Soil (SP3A-U-02)

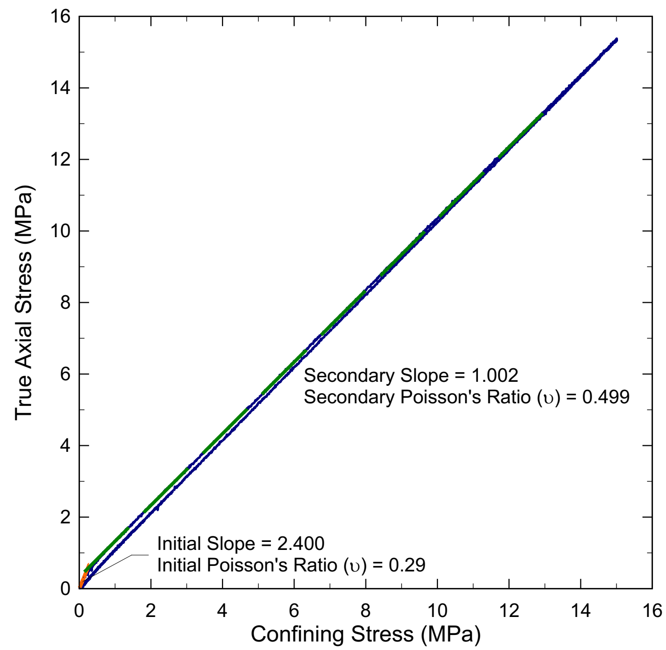




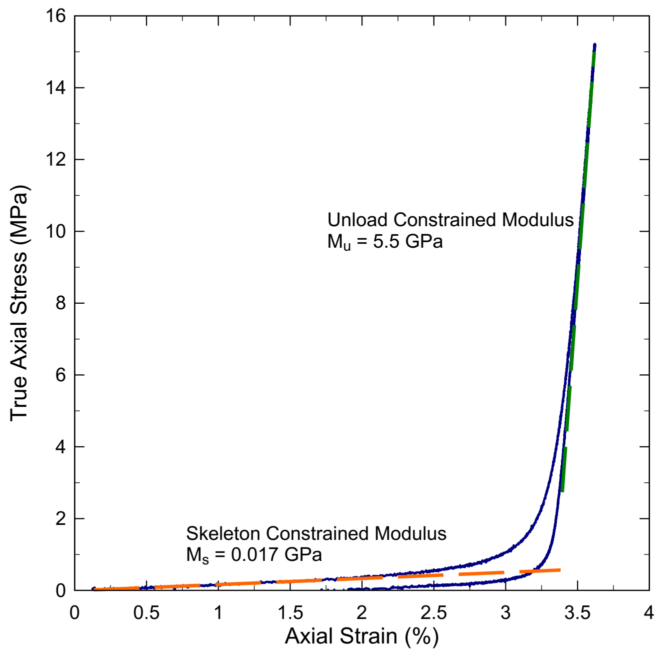
Uniaxial Strain Test (J16A20) at 15 MPa

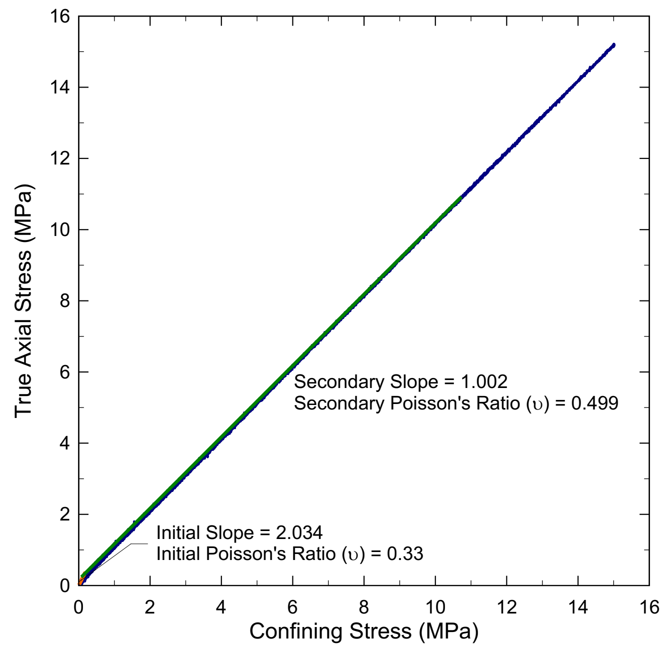
UTTR Soil (SP3A-L-02)





Uniaxial Strain Test (J17A20) at 15 MPa
UTTR Soil (SP3B-U-02)





Uniaxial Strain Test (J17B20) at 15 MPa

UTTR Soil (SP3B-L-02)