IDEA

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NCHRP IDEA Program

DEVELOPMENT OF IN SITU CYCLIC BOREHOLE SHEAR SOIL TEST DEVICE

Final Report for
NCHRP IDEA Project 221

Prepared by:
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February 2023

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Development of In Situ Cyclic Borehole Shear Soil Test Device

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IDEA Project NCHRP-221

Prepared for

The NCHRP IDEA Program
Transportation Research Board
National Academies of Sciences, Engineering, and Medicine

by

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The conclusions expressed herein are those of the investigators and do not necessarily reflect the views of the sponsor organization.

GLOSSARY

AASHTO	American Association of State Highway and Transportation Officials
ABS	Acrylonitrile Butadiene Styrene
ABST	Automated Borehole Shear Test
ASCE	American Society of Civil Engineers
BST	Borehole Shear Test
CAD	Computer Aided Design
CBST	Cyclic Borehole Shear Test
CDSS	Cyclic Direct Simple Shear
CSR	Cyclic Stress Ratio
DAQ	Data Acquisition device
DOT	Department of Transportation
FHWA	Federal Highway Administration
IDEA	Ideas Deserving Exploratory Analysis
InTrans	Institute for Transportation
I/O	Input/Output
ISU	Iowa State University
LabVIEW	Laboratory Virtual Instrument Engineering Workbench
LL	Liquid Limit
LVDT	Linear Variable Differential Transformer
NCHRP	National Cooperative Highway Research Program
OSU	Oregon State University
PI	Principal Investigator of project, or Plasticity Index of soil (based on context)
PID	Proportional, Integral, Derivative
PL	Plastic Limit
PLA	Polyactic Acid
PVC	Polyvinyl Chloride
USB	Universal Serial Bus
USCS	Unified Soil Classification System
VISA	Virtual Instrument Software Architecture

EXECUTIVE SUMMARY

Static soil shear strength parameters in the form of friction angle and cohesion are required inputs for the safe design of foundations and earth retaining structures for virtually all transportation infrastructure including bridges, buildings, railways, wharves, piers, ports, tunnels, and pavements. Additionally, measuring the dynamic and cyclic behavior of soil in terms of stress-strain hysteresis loops as well as the associated evolution of pore water pressure is important for obtaining modulus and damping parameters for seismic design, determining post-cyclic strength, and liquefaction susceptibility analysis. These soil parameters are typically obtained by retrieving soil samples and testing them in the laboratory, which is time-consuming, expensive, and the results are sensitive to sample disturbance. Alternatively, the shear strength parameters may be estimated using empirical correlations to in situ penetration tests such as the Standard Penetration Test (SPT) or Cone Penetration Test (CPT). However, neither of these tests directly measure the shear strength of soil and instead rely upon empirical correlations that can be imprecise due to large statistical variability. Furthermore, the SPT and CPT do not subject the soil to repeated continuous cyclic loading conditions like those imposed by earthquakes or vibration sources. The goal of this project was to develop a new in situ testing device that could measure static and dynamic soil properties in the soil's natural setting, with less sample disturbance and requiring less time than laboratory tests.

In this project, a Cyclic Borehole Shear Test (CBST) device was developed to enable the rapid in situ measurement of cyclic behavior and monotonic shear strength properties of soil. Based on the results of several field testing trials, numerous refinements and modifications were made to the system including the physical testing apparatus inserted into the borehole, the electronic and pneumatic measurement and control system, and the software control program. Comparisons of field test results to those of conventional laboratory tests demonstrated that the device can measure meaningful cyclic behavior of soil in situ. Further research will be pursued to more rigorously relate the measured displacements from the device to shear strains in the soil surrounding the borehole, and to study applications of the device to in situ measurement of the liquefaction behavior of soils. With further research, the device thus has the potential to fundamentally transform the presently empirical techniques used in practice for assessment of soil liquefaction resistance into a more mechanistic physics-based framework.

IDEA PRODUCT

The goal of this research is to develop a Cyclic Borehole Shear Test (CBST) device to enable rapid in situ measurement of cyclic behavior as well as monotonic shear strength properties of soil (friction angle and cohesion), which are required parameters for the design of foundations and earth retaining structures for virtually all transportation infrastructure including bridges, buildings, railways, wharves, piers, ports, tunnels, and pavements. As detailed in the report, the project has produced a working cyclic borehole shear test prototype device ready for further development and commercialization and has demonstrated the capabilities of the device for measuring the in situ response of soil to cyclic loading. The CBST is unique in its ability to measure the parameters in the soil's natural setting, under cyclic loading, and in a matter of minutes whereas present laboratory techniques can require several weeks. By testing the soil in situ, the device will not only save time, but also reduce or avoid effects of soil sample disturbance which can significantly affect laboratory test results. The device will enable engineers to measure the in situ soil response under cyclic loading as occurs in earthquakes, and soil residual strengths which occur at large deformations in landslides. With further research, the device also has the potential to fundamentally transform the presently empirical techniques used in practice for assessment of soil liquefaction resistance, into a more mechanistic physics-based framework. This is because the device directly or indirectly measures the actual physical mechanisms responsible for liquefaction; namely stress, strain and pore water pressure. Therefore, the device has the potential to help advance the safety and sustainability of transportation infrastructure by improving the speed, reliability and accuracy with which daily foundation design inputs and liquefaction susceptibility of soils are assessed.

CONCEPT AND INNOVATION

Static soil shear strength parameters in the form of friction angle and cohesion are required inputs for the safe design of foundations and earth retaining structures for virtually all transportation infrastructure including bridges, buildings, railways, wharves, piers, ports, tunnels, and pavements. Additionally, measuring the dynamic and cyclic behavior of soil in terms of stress-strain hysteresis loops as well as the associated evolution of pore water pressure is important for obtaining modulus and damping parameters for seismic design, determining post-cyclic strength, and liquefaction susceptibility analysis. These parameters are typically obtained by retrieving soil samples and testing them in the laboratory, which is time-consuming, and the results are sensitive to sample disturbance. Alternatively, the shear strength parameters may be obtained from empirical correlations to in situ penetration tests such as the Standard Penetration Test (SPT) or Cone Penetration Test (CPT). However, neither of these tests directly measure the shear strength, and instead rely on empirical correlations that may be imprecise due to large statistical variability. There are a few other in situ tests that directly measure shear strength, such as the Vane Shear Test (VST), which only measures the special case of undrained shear strength of clay, or the Pressuremeter Test (PMT), which produces high-quality data but is slow, requires an expert technician, and is therefore costly and relatively rarely performed.

In contrast to laboratory direct shear tests which can take a week or two to produce friction angle and cohesion results, the in situ Borehole Shear Test (BST) can give the same information in under an hour (*1*). The BST tests the soil in its natural location, which can significantly reduce or avoid errors due to sample disturbance during extraction, transportation, and trimming that are required for laboratory tests. The BST essentially performs a direct shear test in a borehole, giving a shear strength failure envelope in terms of normal and shear stresses at failure. The device consists of a shear head with two opposing curved shear plates which apply normal and shear stresses to the borehole walls. Shear stress applied to the soil is measured by the shear gauge and its maximum value is recorded. The process is repeated using a range of normal stresses, and the peak shear stresses are plotted against the corresponding normal stresses to determine the soil's friction angle and cohesion.

The CBST device developed herein builds upon the BST device used in geotechnical practice for many decades and will enable cyclic soil behavior including pore pressure generation to be measured in situ much faster and with less disturbance than comparable laboratory tests, because the CBST does not require extraction, transportation, preparation, and trimming of soil specimens. Beyond the capability to measure soil friction and cohesion in monotonic tests like the traditional BST, the cyclic capabilities of the CBST developed herein may prove to be useful for a range of other problem types, such as residual shear strength relevant to landslides, nonlinear dependence of shear modulus and damping on shear strain and stress state relevant to seismic loading, irregular cyclic loads relevant to construction as well as traffic loading or wave action, and liquefaction phenomena relevant to earthquakes.

The project goal was to develop an in situ device that could produce measurements similar to the capabilities of laboratory cyclic direct simple shear (CDSS) test devices, such as those shown in Figure 1, by applying a controlled normal and shear stresses to the soil of a borehole wall as shown schematically in Figure 2. The CDSS data in Figure 1 show the measured cyclic shear stress of constant amplitude imposed on a soil specimen, while the shear strain gradually increases as the pore pressure builds up and reduces the effective vertical stress towards zero as the soil approaches a state of liquefaction (or cyclic mobility for some soils). The bottom right plot in Figure 1 shows the corresponding evolution of the hysteresis loops of shear stress versus shear strain throughout the test. The goal of this project is to develop a device that can enable measurement of such behavior in situ. However, because the laboratory CDSS device subjects a soil element to a uniform horizontal displacement on one end, the shear strain is simply calculated as the horizontal displacement divided by the specimen height. In contrast, the BST and CBST employ two serrated shear plates having an area of 5 $in.^2$ each, to engage the soil in shearing just beyond the borehole wall. As shown in Figure 2, the CBST first applies a normal stress to the borehole wall, then after a consolidation delay time, applies a cyclic vertical shear stress to the borehole wall. The vertical direction

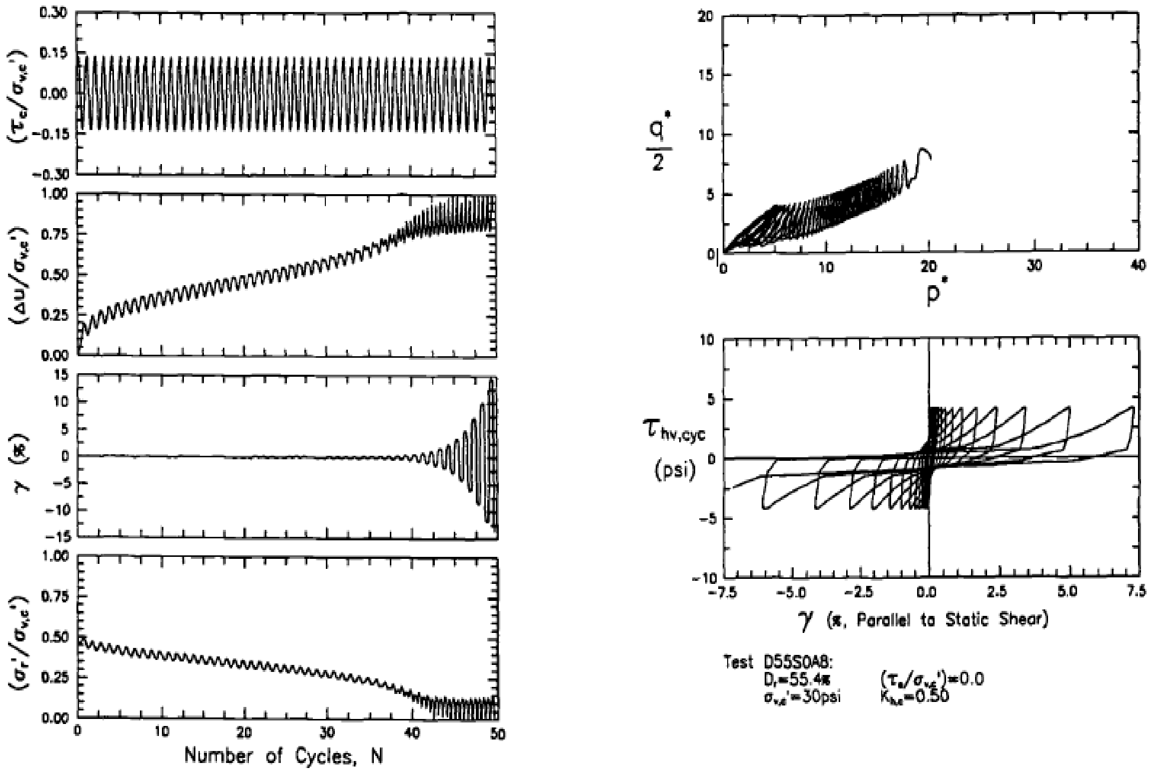


FIGURE 1 Example of data from stress-controlled laboratory CDSS test on saturated uniform fine river sand, from Boulanger et al. (*2*)

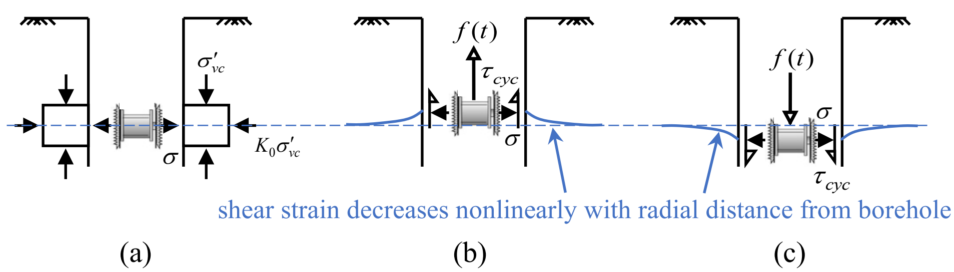


FIGURE 2 Stresses applied to soil by shear head in CBST: (a) normal stress applied to borehole wall, (b) upward and (c) downward cyclic shear stress applied to borehole wall. Cohesion and friction angle can also be measured by slowly applying monotonic shear stress to failure in either (b) or (c).

of the applied shear stress is one limitation of the CBST, as a horizontal shear stress may often be the goal in laboratory CDSS tests. Also, with appropriate instrumentation, the displacement of the shear plates can be accurately measured, but the shear strains in the surrounding soil vary with distance from the shear plates, also shown schematically in Figure 2. As will be discussed herein, the challenge of developing a functioning CBST device has been overcome in the present project, enabling future research on analytical and computational methods for determining appropriate shear strains from the measured displacements.

Previous approaches to measuring the in situ liquefaction behavior of soils include instrumented boreholes in passive schemes (i.e., waiting for an earthquake), or active schemes using downhole explosives. The former is not suitable for routine evaluation of project sites, while the latter lacks control over the loading duration and strain level and generates much more high frequency energy than seismic loading. A more promising recent approach is to install geophones and pore pressure transducers in a soil mass and monitor their response under dynamic loading imposed at the surface from a strong mobile shaker such as a Vibroseis truck (*3*). The CBST has different capabilities from the Vibroseis approach, namely that it requires only a single borehole and can be performed at specific targeted depths with controlled stresses and measurements of pore pressure and shear displacement. In another in situ approach developed in a previous IDEA project, a Torsional Cylindrical Impulse Shear Test (TCIST) device was successfully designed and tested by Henke and Henke (*4*), with the stated goal of measuring "the undegraded nonlinear inelastic characteristics of the first cycles of loading" (*5*). The TCIST was designed to measure stress-strain characteristics "prior to any significant degradation of these characteristics caused by cyclic loading" (*4*). As such, the TCIST is usually excited by a single impulse as its name implies, and is intended to avoid the degradation in strength that occurs with liquefaction under cyclic loading. Conversely, rather than applying a single impulse, the goal of the present project is to develop an in situ test that can apply continuous cyclic loading with pore pressure measurement for many cycles, possibly up to and including liquefaction.

Current practice for characterizing liquefaction resistance of soils in situ relies primarily upon empirical soil indices such as penetration resistances from SPT or CPT tests, or small-strain elastic shear wave velocities from geophysical tests. However, the loading conditions imposed by these tests do not realistically simulate the large-strain, continuous, and random nature of earthquake shaking, nor do they provide measurement of the physical parameters directly responsible for the phenomenon of liquefaction, namely; shear stress, shear strain, and pore pressure buildup under cyclic loading. With the exception of shear stress, these parameters are directly measured in the CBST. With further research, the shear displacement data from the CBST may also be used to estimate shear strain.

INVESTIGATION

Work in Stage 1 of the project focused on developing the CBST hardware and software, performing preliminary field testing of the device in Iowa, and refining the hardware and software based on issues identified during field tests. Stage 1 consisted of the following tasks:

Task 1: Hold kickoff meeting with Expert Advisory Panel for input on research plan

Task 2: Develop CBST hardware, electro-pneumatic control system, and software control program

Task 3: Perform preliminary field tests in Iowa and refine hardware and software to address issues identified during testing

Task 4: Prepare Stage 1 report and review progress

Work in Stage 2 focused on field testing of the CBST device in cooperation with DOTs and in situ testing firms, performance of laboratory tests for comparison with the field test results, and preparation of the final project report. Stage 2 consisted of the following tasks:

Task 5: Perform field tests with State DOTs and in situ testing firms and compare results to other test data where available

Task 6: Prepare final report

Throughout Stage 2, several additional modifications were made to the hardware and software to refine the CBST.

PRELIMINARY DEVELOPMENT, FIELD TESTS, AND DEVICE MODIFICATIONS DURING STAGE 1

Initial Prototype Device and Development of Hardware and Software Control System

The downhole portion of the initial prototype CBST device is shown in Figure 3. It is controlled from the ground surface using air or gas pressure and a software control program that interfaces with the downhole device using various sensors and electronics. The CBST is operated by creating a 3 inch borehole, inserting the downhole apparatus, and expanding the anchor head using air or gas pressure to secure the device in the borehole or in the bottom of a hollow-stem auger. The anchor head shown in Figure 3 consists of six serrated stainless steel curved anchor plates arranged around the circumference of a thick rubber membrane covering a stainless steel pipe against which the membrane is expanded. After expanding the anchor head, the shear head is expanded radially using controlled air or gas pressure to apply a chosen magnitude of normal stress to the soil through two opposing 2 in. × 2.5 in. shear plates (Figure 3) which penetrate the borehole surface to engage the soil along the ridges of their serrated teeth during the shearing phase. A short consolidation delay time (typically 5 to 10 minutes) is then allowed to elapse for dissipation of the excess pore pressure caused by the normal stress applied through the shear plates. A vertical pneumatic cylinder is then used to cyclically raise and lower the shear head using air or gas pressure controlled by a high speed directional proportional valve at the ground surface.

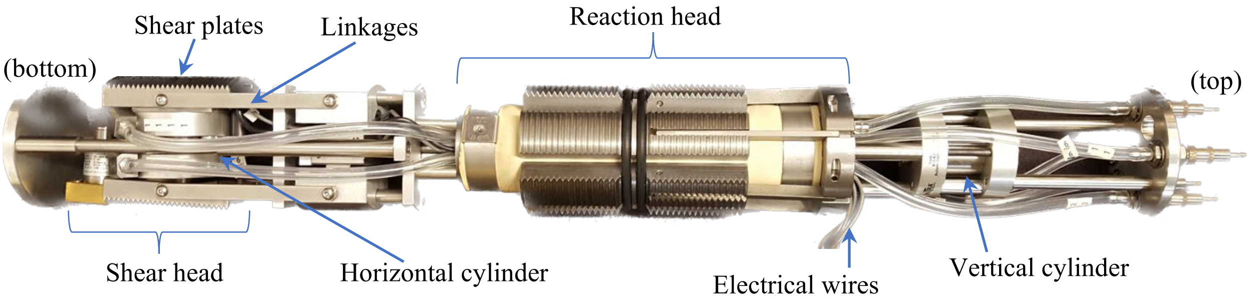


FIGURE 3 Initial prototype of downhole mechanical portion of CBST device before field testing and modifications

The air or gas is supplied to the vertical and horizontal pneumatic cylinders through four pressure tubes extending to the ground surface, with quick disconnects feeding through the top disk of the downhole device, as shown on the right side of Figure 3. The vertical cylinder connects to a rod which passes through the center of the anchor head and connects at its lower end to a block which transfers upward and downward forces to the shear plates through four linkages (shown at left in Figure 3). The linkages have bearings at the ends to allow them to rotate as the shear plates expand during application of normal stress to the borehole surface. A miniature horizontal Linear Variable Displacement Transducer (LVDT) is mounted between the shear plates to measure the shear head expansion. A vertical LVDT is installed inside the reaction head to measure the vertical displacement of the block and thereby the shear plates. A pore pressure transducer can be seen at left in Figure 3 for measurement of pore water pressure below one shear plate. Two vertical load cells pressing against the inside of a box section are used to measure the upward and downward forces applied by the block to the shear plates. The net vertical force is divided by the area of two shear plates to calculate the shear stress applied to the soil. In the initial prototype device, a horizontal load cell was also used behind one shear plate to measure the normal force applied between the two opposing shear plates, which was then divided by the area of one shear plate to obtain the normal stress.

In Stage 1 of the project, an electronics case was acquired and an aluminum control panel was fabricated for mounting the electronics needed to control the downhole portion of the device. Electronic components were also acquired, including a high speed proportional valve for controlling the vertical pneumatic cylinder, a USB data acquisition (DAQ) device for recording sensor data and generating the control signal for the high speed proportional valve, and a switching DC power supply with multiple outputs for powering the various sensors and devices. To control the device and acquire sensor data during tests, a new software program was created using the LabVIEW programming environment. As detailed in the remainder of this report, several revisions and additions were made to the computerized control system, downhole device, and software control program throughout the project based on the results of field trials.

Laboratory and Field Tests in Iowa and Subsequent Modifications

After holding a kickoff meeting and receiving input on the research plan from the Expert Advisory Panel, several laboratory and field tests were performed in Iowa. Various components of the downhole portion of the initial prototype device were then redesigned, fabricated, tested, and verified to solve problems identified in the field tests. A few different feedback control schemes were designed and programmed to enable the device to perform both monotonic and cyclic borehole shear tests. To validate the results of the monotonic tests performed with the CBST, nearby tests were also performed using an Automated Borehole Shear Test (ABST) device for comparison (*6*). The test results demonstrated that monotonic tests can be performed with the CBST to measure soil cohesion and friction angle despite the different actuation systems (i.e. , a stepper motor and gear system to pull the ABST shear head versus a pneumatic cylinder to push and pull the CBST shear head). The progress on field testing was slowed somewhat due to policies and restrictions on field and laboratory testing instituted by the university in response to the COVID-19 pandemic, but the research goals were ultimately achieved through a no-cost extension.

Specific refinements made to the device in Stage 1 included redesigning and manufacturing the following components: a new pair of shear plates to incorporate knife edges on their top and bottom, a pore pressure measurement port through the face of one shear plate rather than below it, a new horizontal load cell configuration for measuring normal stress, a new top disk design to accommodate additional connectors for tubing and electrical wires, a centralizing cone at the bottom of the device, new shear plate linkages to greatly reduce backlash, and a new horizontal pneumatic cylinder to eliminate interference with its linkages when the shear head is fully expanded. Many of the components were first prototyped in PLA thermoplastic using a 3D printer, and the final machined metal parts were tested in a borehole created in a soil pit or PVC pipe filled with compacted dry loess to verify their function. The redesigned shear plates, linkages, and load cell housing are shown in Figures 4 and 5. Upon additional testing, the horizontal load cell used to determine the normal stress applied by the shear plates to the soil was found to suffer from errors due to various sources of friction. The horizontal load cell was therefore removed and the CO_2 pressure actuating the horizontal cylinder was instead calibrated to the resulting normal force exerted by the shear plates. An electronic pressure sensor was then installed under the control panel to measure the expansion pressure of the shear head for determining the normal stress applied to the soil.

The traditional monotonic BST and ABST are essentially stress-controlled tests, because these devices apply a steadily but nonlinearly increasing force at the upper end of the pull rods of the device, which behaves like a nonlinear spring connected to the shear plates in the borehole. The CBST's pneumatically controlled system cannot directly duplicate this type of loading. However, monotonic tests with the CBST

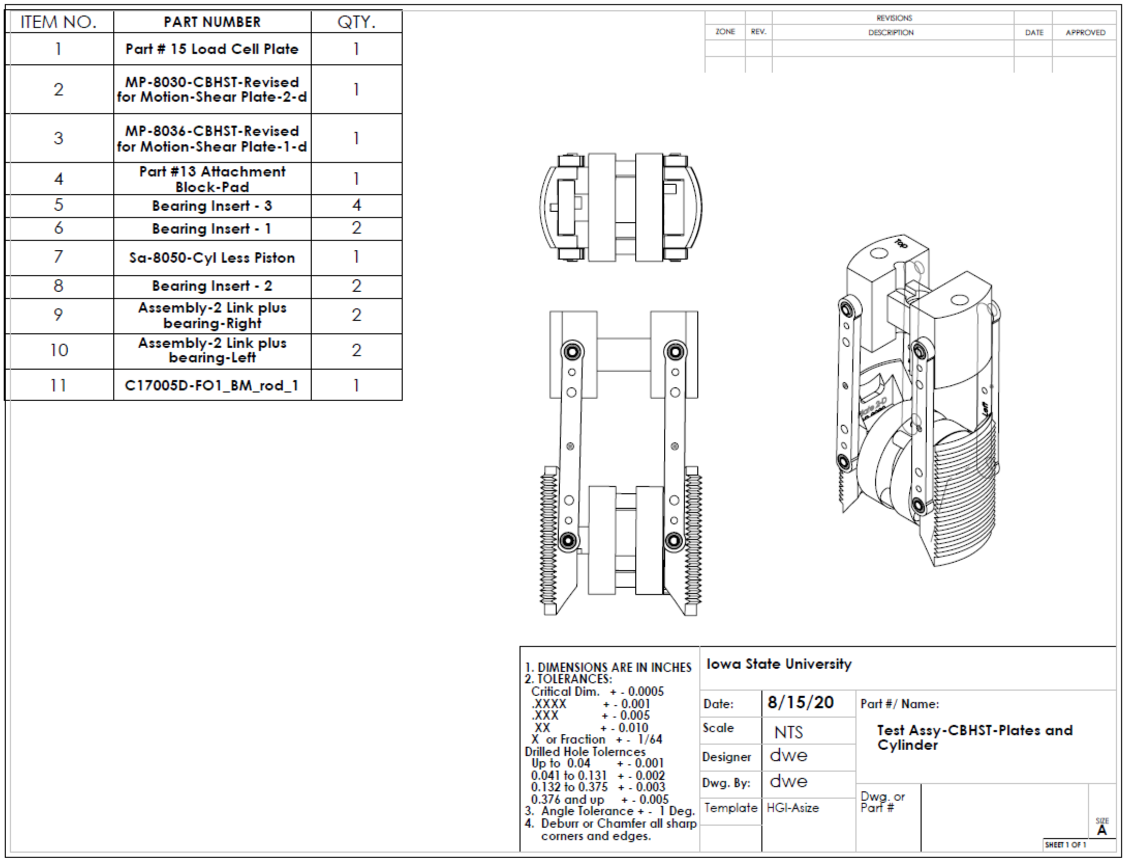


FIGURE 4 CAD drawing of CBST shear head with new shear plate linkages and load cell housing

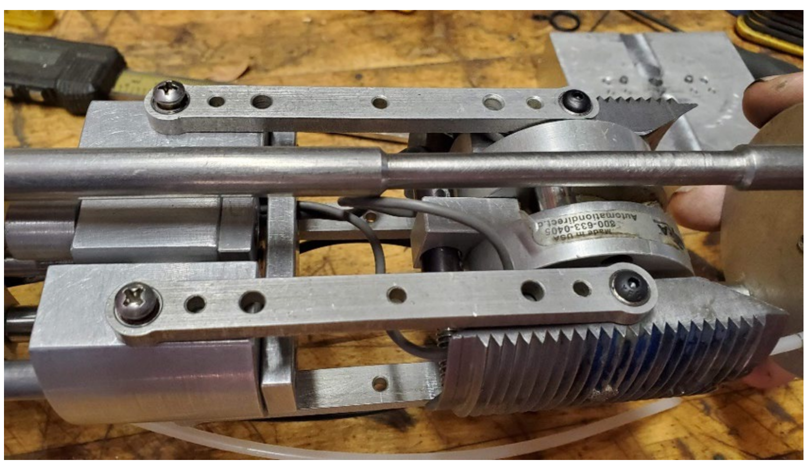


FIGURE 5 Photo of assembled shear head with modified backlash-eliminating linkages and modified load cell housing behind shear plate

device were simulated using feedback control aimed at applying similar rates of displacement or shear stress as observed before and after soil failure in previous ABST tests. Several types of stress-controlled and pseudo displacement-controlled tests were programmed and performed using feedback loops in the CBST

LabVIEW control program, which required empirical tuning of the Proportional, Integral, and Derivative (PID) feedback control parameters.

The final control scheme implemented for monotonic tests involves using the vertical displacement of the shear head as a feedback parameter to determine when the soil has failed, and the rate of load increase is then set to zero. Based on several tests, an effective criterion for identifying soil failure was determined to be when the shear head velocity averaged over one second exceeds 0.006 in./sec. When this occurs, the soil has reached its failure stress and the shear head is beginning to rapidly displace. The pneumatic valve is then used to unload the shear head until the measured shear stress is approximately zero, at which point the applied normal stress is increased to the next test value. This type of control scheme was found to best simulate the loading characteristics of the monotonic BST and ABST devices without the instabilities observed using other control schemes. An example of a monotonic test performed using compressed air as the pressure source with this feedback control scheme is shown in Figures 6 and 7, along with a previous test on the same soil by the ABST device. The soil was a western Iowa loess (USCS classification ML) with a liquid limit (LL) of 29% and plastic limit (PL) of 23%. The loess was compacted inside a 6 in. PVC pipe to its Standard Proctor maximum dry unit weight of 109 lb/ft^3 at an optimum moisture content of 17%. The ABST shear stress histories initially curve upwards because the traditional BST system stiffens nonlinearly in response to pulling, whereas the CBST's reaction head inside the borehole applies the shear force through a much shorter rod with much lower system compliance. This results in a more immediate increase in shear stress at the start of the test, similar to shear stress traces from laboratory direct shear tests. The monotonic CBST resulted in a friction angle of 37.4° and cohesion of 0.84 psi, compared to 36.2° and 0.96 psi for the ABST. These results are in good agreement, especially considering the small value of cohesion which has traditionally been the more difficult of the two parameters for the BST.

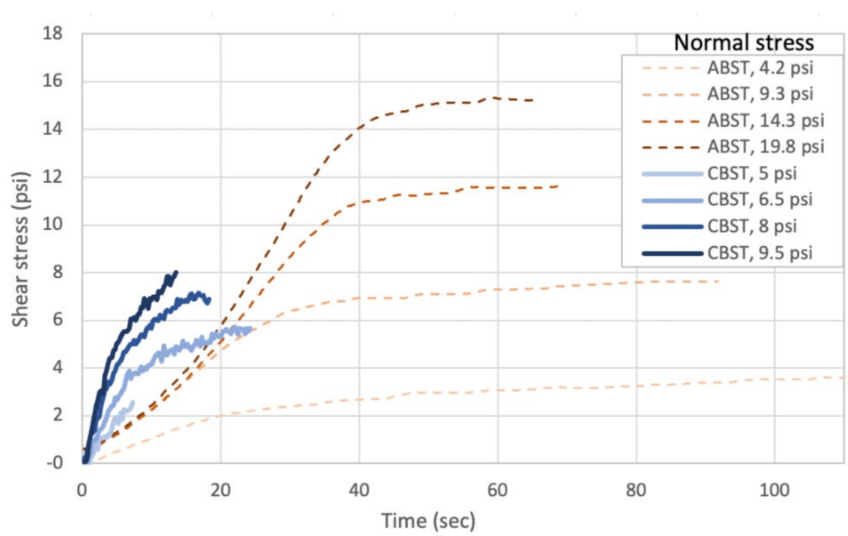


FIGURE 6 Shear stress history from monotonic tests performed with ABST and CBST devices

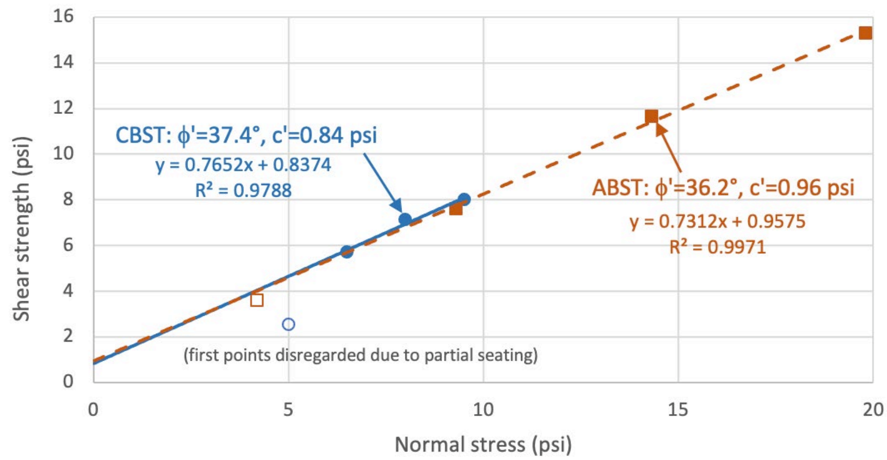


FIGURE 7 Failure envelopes from monotonic test performed with ABST and CBST devices (first data point is typically disregarded due to partial seating)

Cyclic loading capabilities were also programmed in Stage 1 of the project using open-loop control, as well as displacement and stress feedback control schemes. The cyclic tests were performed in the same borehole used for the monotonic tests, which was in the 6-in. diameter PVC pipe filled with compacted loess. First, an open-loop test was performed by sending a sinusoidal voltage signal to control the pneumatic proportional valve without any feedback. Due to the physical design of its pressure chambers, the pneumatic cylinder creates a 28.5% greater force when expanding than when retracting for the same applied air pressure. To achieve symmetric loading, the control signal was therefore scaled down by a factor of 0.77 in the positive (expansion) direction only, creating an asymmetric control signal. Tests were performed in the loess borehole using various values of control signal amplitude, frequency, phase, and offset to assess the cyclic loading capabilities of the CBST device. As shown in Figure 8, the open-loop asymmetric control scheme was able to successfully apply a very symmetric sinusoidal shear stress to the soil, which resulted in a sinusoidal displacement that was slightly offset from zero displacement by a fraction of an inch (Figure 9). Plotting the measured shear stress versus displacement gives the hysteresis loops shown in Figure 10. One possible application for these hysteresis loops is to determine their areas and backbone secant stiffnesses to calculate equivalent viscous damping ratios for dynamic and seismic problems. Additional preliminary cyclic tests were performed for normal stresses ranging from 10.1 to 14.3 psi with loading rates of 0.5 and 0.8 Hz, giving slightly different hysteresis loops.

To obtain more data points on the sides of the hysteresis loops, a triangular loading pattern was also investigated, and the loading frequency was reduced to 0.2 Hz. Examples of the resulting shear stress and displacement as functions of time for a stress-controlled test are shown in Figures 11 and 12, and the corresponding hysteresis loop is shown in Figure 13. As can be seen in the plots, more data points were obtained to delineate the sides of the loops, and the shear stress was large enough to fail the soil in the first

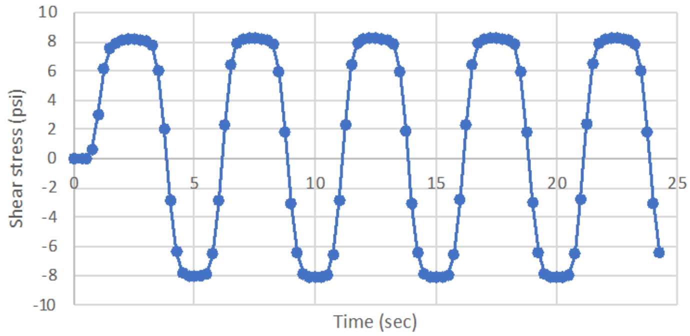


FIGURE 8 Shear stress history from open-loop cyclic test by CBST device

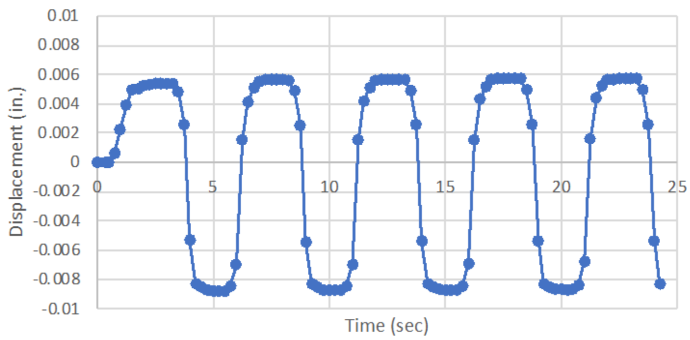


FIGURE 9 Shear head displacement history from open-loop cyclic test by CBST device

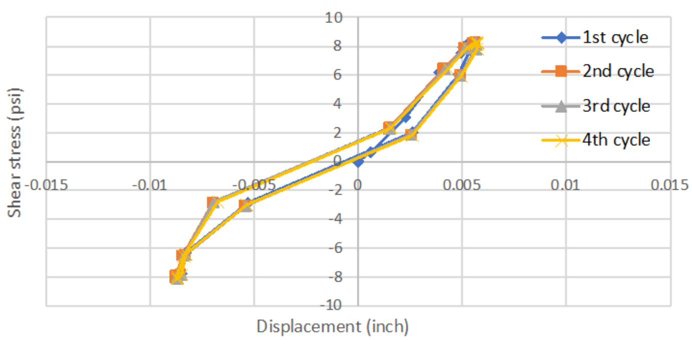


FIGURE 10 Hysteresis loops from four cycles of loading via CBST device (normal stress = 10.1 psi, frequency = 0.5 Hz)

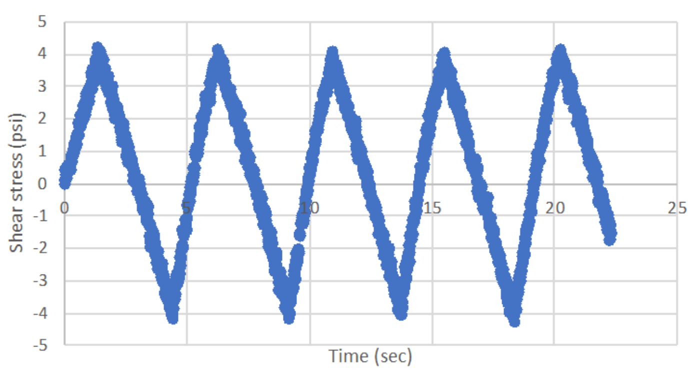


FIGURE 11 Shear stress history from stress-controlled cyclic test with triangular loading waveform (normal stress = 10 psi, frequency = 0.2 Hz)

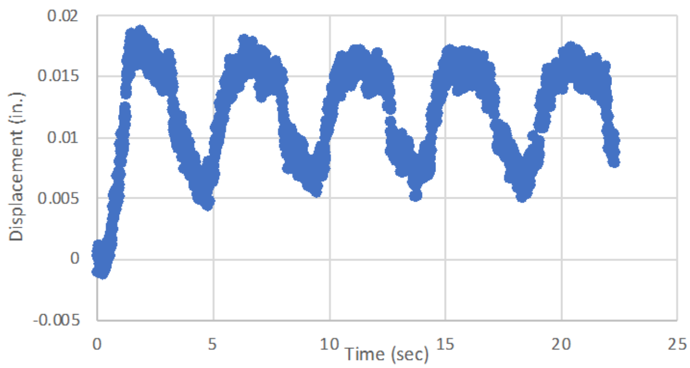


FIGURE 12 Displacement history from stress-controlled cyclic test with triangular loading waveform (normal stress = 10 psi, frequency = 0.2 Hz)

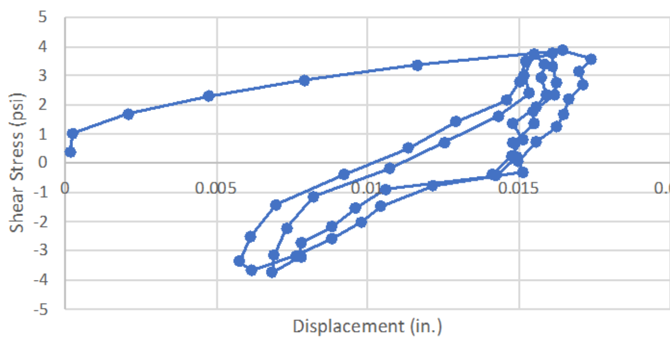


FIGURE 13 Hysteresis loop from stress-controlled cyclic test with triangular loading waveform (normal stress = 10 psi, frequency = 0.2 Hz)

cycle, causing the loop to shift to the right. These results demonstrated for the first time that the CBST device can successfully apply cyclic loading to soils in boreholes. In Stage 2 of the project, field tests of additional soil types and natural moisture contents were targeted, as will be explained below.

FIELD TESTS AND DEVICE MODIFICATIONS DURING STAGE 2

The laboratory tests revealed that depending on the device's alignment, the linkages that move the shear plates up and down could sometimes interfere with one shear plate, restricting its horizontal movement thus preventing it from fully engaging the soil surface. When this occurs, the actual normal stress applied to the borehole wall by the shear plate will be less than the value calculated using the measured air or gas pressure. A new curved "dog-leg" linkage design was therefore created and fabricated to solve the problem (Figure 14). The new linkages enable the entire shear head assembly to move horizontally in either direction by approximately 3/8in. when the shear head is fully retracted. After performing several tests, it also became apparent that the rather thick shear plates may be incurring additional resistance from soil contact around their top, bottom, and side walls as they embed further into the soil. In contrast, the shear plates used on the traditional BST device for the past several decades have knife-edges on top and bottom, and sharp over-

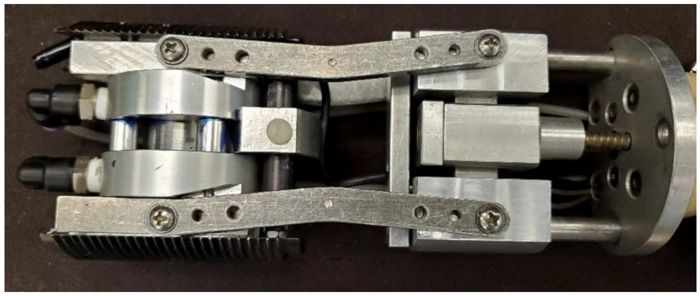


FIGURE 14 Modified curved linkages between bearing plate and shear plates

hanging teeth on the sides, which results in a negligible increase in surface contact area as the shear plates embed into the soil. For fabrication and repair, it will also be more convenient for the CBST device to employ the same shear plates that have been standard on the BST device for over 50 years. Therefore, the CBST device was modified to accept the standard BST shear plates, which also required a redesign of the horizontal LVDT's mounting bracket (Figure 15). Another benefit of this redesign is that the porous disk for measurement of pore-pressure comes pre-installed in the face of one BST shear plate (Figure 16).

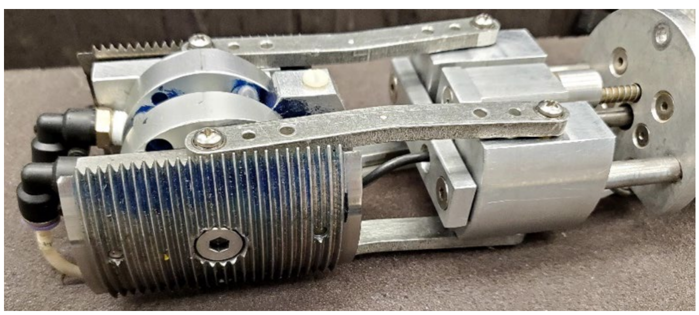


FIGURE 15 Shear head modified to accept standard BST shear plates, with redesigned horizontal LVDT mount

FIGURE 16 Shear plate with porous disk for pore water pressure measurement

To collect data from the CBST load cells and pressure sensor, a custom 100-ft long CPT cable was purchased from Vertek, along with a standard CPT mating connector for the downhole cable end and a LEMO connector with a mating panel mount receptacle for the uphole cable end (Figure 17). A brass

FIGURE 17 CPT cable and connectors

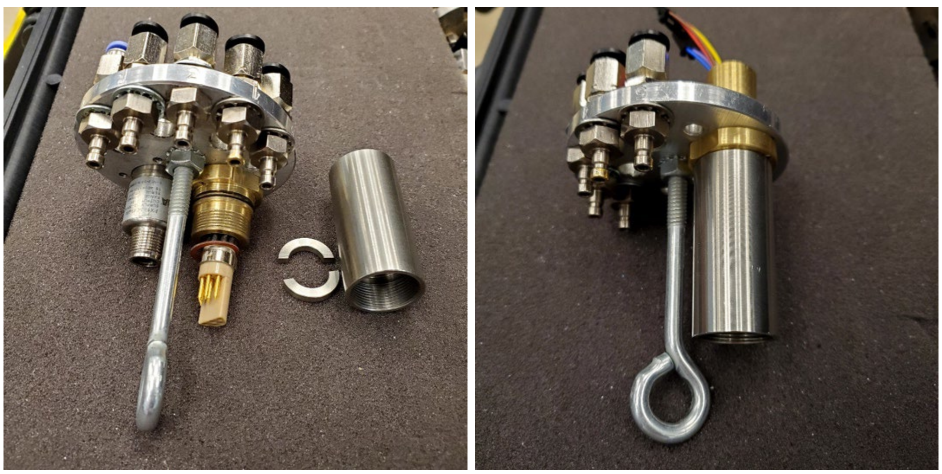


FIGURE 18 Brass feedthrough connector and adapter tube for CPT cable connector disassembled (left) and assembled (right)

feedthrough connector was fabricated and attached through the top disk of the CBST device to accept the downhole connector using a standard CPT adapter tube that has internal threads and O-rings on both ends for a watertight seal (Figure 18). The electronics control panel was also modified to accept the new CPT cable connector.

Field Tests in South Carolina and Subsequent Modifications

Field tests were performed in Piedmont residual fat clay soil on an active slope failure in South Carolina on May 12-14, 2021 (Figure 19), alongside Roger Failmezger who was performing BST and vane shear tests at the site. The soil was a reddish brown, moist to wet fat clay with a USCS classification of CH (sandy fat clay) with a moisture content of 26.8%. The CBST tests were useful in that they revealed several issues needing refinement. One issue was that the noise levels in the sensor signals were higher than those

FIGURE 19 CBST performed in South Carolina: (a) view from bottom of slope, (b) control unit setup, (c) CBST device before insertion into borehole, (d) CBST inserted in borehole with anchor head expanded, (e and f) soft clayey residual Piedmont soil on shear plates after tests

observed in any prior field tests, preventing the feedback control system from properly functioning and executing a test. Several possible fixes were attempted including checking cables for shorts or open circuits and moving potential sources of electromagnetic interference away from the control and data acquisition system. An inverter generator was used to power the device during the tests while an air compressor was used as the pressure source. Based on previous experience, it was hypothesized that the generator may not have produced a sufficiently clean AC power signal. The generator was originally located at the top of the slope with a 75-ft extension cord connected to the CBST at the bottom of the slope. Eventually, the sensor noise level was greatly reduced by moving the generator within 15 ft of the CBST device at the bottom of the slope and grounding the generator with a rod inserted into the soil. Also, it was found that simply elevating the power cord above the ground surface by a few inches reduced the noise levels even further, possibly due to electromagnetic interference between the power cord, saturated soil, and underground utilities.

Traditional monotonic tests were first attempted to determine the soil's friction angle and cohesion for comparison with traditional BSTs performed at the site by Mr. Failmezger. The traditional BSTs gave a friction angle of 19.8° and cohesion of 0.2 psi for the wet fat clay. However, the electrical noise issues prevented acquisition of usable monotonic test data with the CBST device. Cyclic tests were then performed, but the shear head was observed to reach the vertical stroke limit of the device during the tests. The cyclic test data still possessed a greater than normal amplitude of noise, but the noise was reduced enough that tests could be completed using the feedback control system. After testing was completed, the noise in the data was reduced using a Butterworth low-pass filter, giving the test results shown in Figure 20.

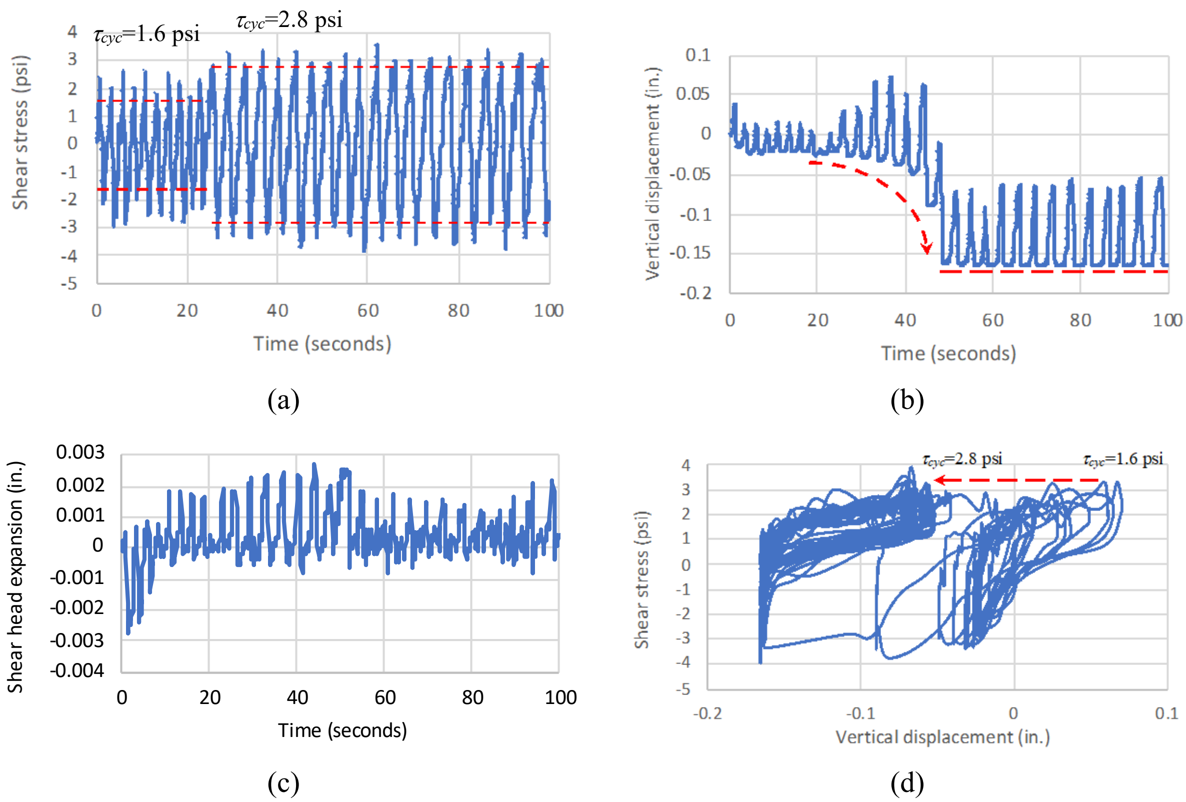


FIGURE 20 Stress-controlled CBST field test in South Carolina with 10 psi normal stress and target cyclic shear stress amplitude increasing from 1.6 to 2.8 psi; (a) shear stress vs. time, (b) vertical displacement vs. time, (c) shear head expansion vs. time, (d) shear stress vs. vertical displacement

A constant normal stress of 10 psi was applied for this test, along with a target cyclic shear stress amplitude of 1.6 psi for the first nine cycles of loading, increasing to 2.8 psi for the remaining cycles. Due to the soft soil conditions and increased signal noise levels, the actual measured shear stress overshot the target, particularly during the first nine loading cycles at the smaller target shear stress (Figure 20a). The vertical displacement of the shear head remained within the device limits during the first nine cycles but reached its lower limit under the higher shear stress of the later cycles (Figure 20b), which caused the hysteresis loops to migrate to the left (Figure 20d). The LVDT measuring horizontal expansion of the shear head also exhibited some cyclic noise (Figure 20c), which was later determined to be caused by a loose wire.

Based on these field test results, the CBST device was modified to increase the vertical stroke of the shear plates from 0.4 to 0.9 inches by redesigning and fabricating the four curved shear plate linkages. Procedures for saturating the porous filter element and tubing that connects it to the pressure transducer were also developed. The saturation procedure involves filling the pressure tubing with water before connecting it to the shear plate which is also submerged under water. The upper end of the tubing is then placed in a second container of water held at a higher elevation. Water is siphoned from the upper container until it flows out through porous stone without air bubbles, then the upper end of the tube is plugged by a thumb and connected to the pressure transducer, and silicone grease is applied to the porous stone. Upon performing this procedure, the pressure transducer was verified to respond with high sensitivity as the elevation of the submerged shear head was raised and lowered. However, the existing pressure transducer could only measure positive pressures. Because the pressure transducer was relocated to the top disk which is above the measurement location on the shear plate, it would not register any change in pressure for cases in which the sensor was above the water table while the pressure sensor was below the water table. Therefore, a new pressure sensor with a measurement range of -15 to +30 psi was purchased and installed, which required machining a new mounting block (Figure 21).

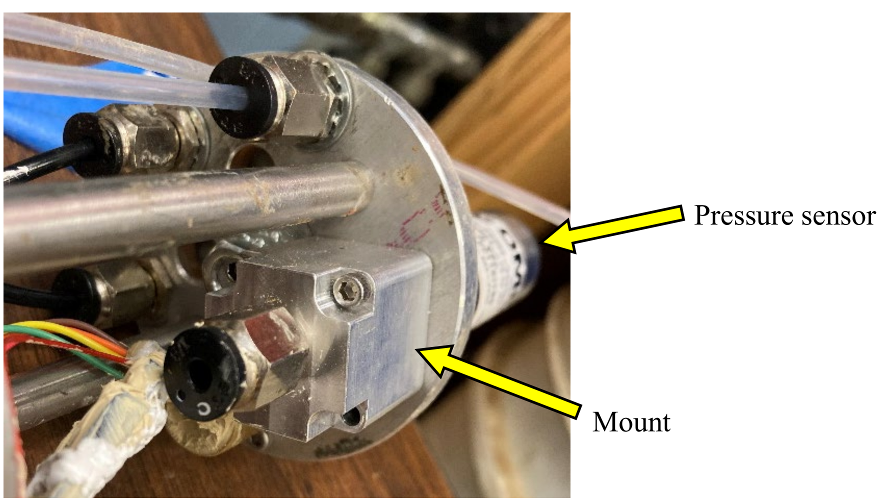
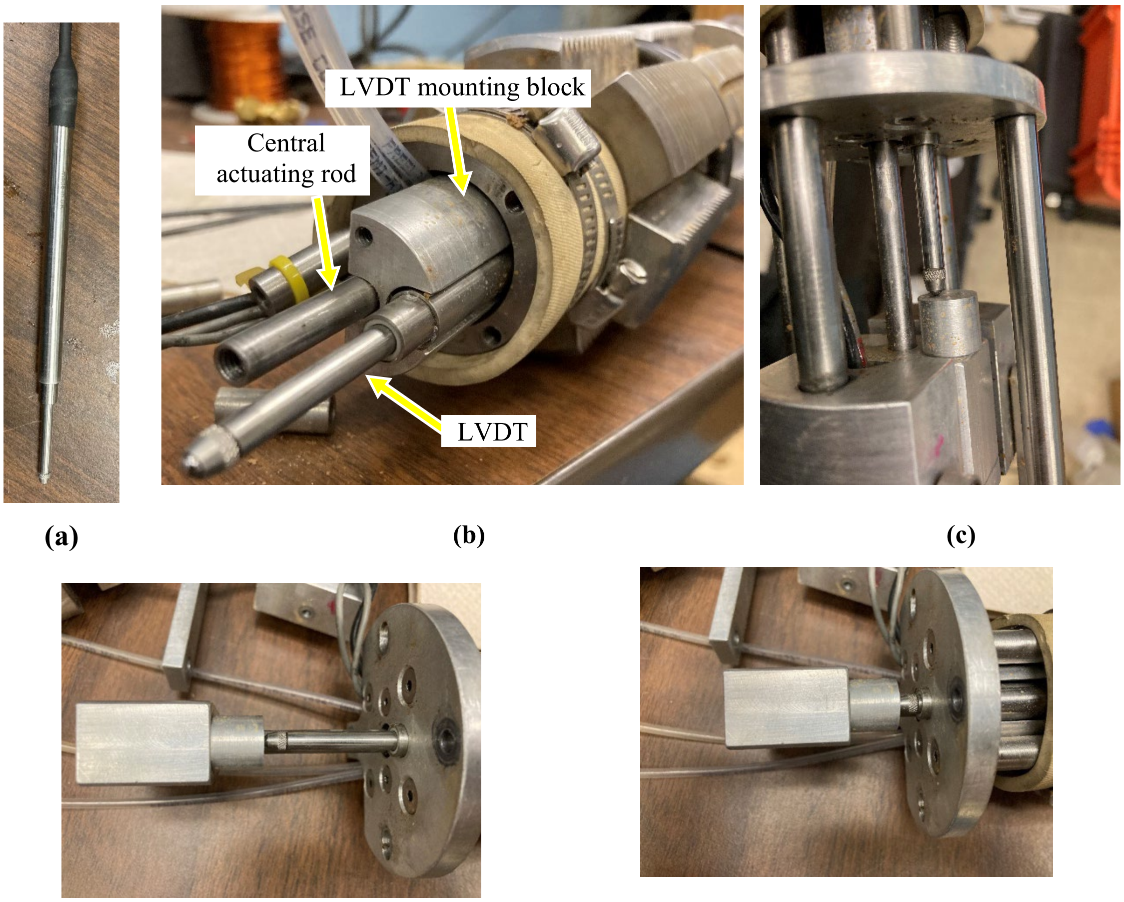


FIGURE 21 Mount for -15 to +30 psi water pressure sensor installed under top disk of CBST device

A rubber bellows was modified to encapsulate and waterproof the horizontal LVDT, and a new submersible LVDT was purchased for measurement of vertical displacement. Because the submersible LVDT was larger than the original one, the device was modified by machining the central actuating rod to a smaller diameter over part of its length and enlarging the hole in the LVDT mounting block (Figure 22).



(a) **(b)** **(c)**

(d) **(e)**

FIGURE 22 Modifications to accommodate waterproof LVDT for measuring vertical displacement of shear plates; (a) LVDT, (b) modified LVDT mounting block and central actuating rod, (c) LVDT mounted in CBST device, (d) LVDT in fully extended position, (e) LVDT in fully retracted position

Unlike the previous sensor, the new LVDT uses an AC excitation signal which required the use of the last available pin in the CPT data cable and re-wiring of all electrical connectors on the device. The AC LVDT's power supply and signal conditioner were also incorporated into the electronics case by designing and fabricating a 3D-printed mount, and the control program was modified to accept the sensor's output voltage signal.

Based on issues identified during the South Carolina field tests, modifications were also made to the control program to increase reliability and performance. Specifically, the state-machine programming construct was expanded to include a queue message handler. This had the effect of reducing and potentially eliminating race conditions which could cause the program to hang. Additionally, functional global variables were implemented to solve problems with timing issues that could slow the response rate of the program's graphical interface and result in inconsistent sampling intervals in the measured data.

Field Tests in Maryland and Subsequent Modifications

In early January 2022, cyclic field tests were performed alongside BST tests performed by Roger Failmezger on an Army Corps of Engineers drilling project in Beltsville, MD (Figure 23). The soil was a wet silty clay and compressed nitrogen was used as the pressure source for the tests. Preliminary subsurface exploration at the site revealed the presence of very stiff Potomac clays that were anticipated to exceed the stress range of the CBST device. Because the maximum normal and shear stresses that can be applied by the CBST are limited by the force ratings of the horizontal and vertical pneumatic cylinders, a smaller set of shear plates was machined to increase the range of stresses that can be applied to the soil. The smaller plates are shown next to the original shear plates in Figure 24. The original shear plates are 7.2 cm tall by 4.4 cm wide, while the smaller plates are 7.2 cm tall by only 2.7 cm wide. If a borehole is encountered in which the teeth of the standard shear plates cannot fully penetrate a stiff soil, then the shear plates can be replaced with the smaller ones to increase the maximum useable normal and shear stresses by 63%. However, very soft clays were encountered at the Maryland CBST test location, so the smaller shear plates were not used.

During testing, both the data acquisition device and the high-speed servo-electric directional valve that controls the vertical cylinder stopped functioning due to outdoor temperatures below 0°C, which is below the rated operating temperature range of both devices. The electronics case and directional valve were therefore placed in the cab of a truck with the heater running, with the electronic and pneumatic lines running to the CBST device in the borehole. This enabled the electronics to be brought up to a working temperature and the testing to continue. A series of cyclic tests were then performed in the very soft clay with good hysteresis loops obtained. The Panasonic Toughbook laptop computer used for field testing was also having trouble and operating very slowly in the cold weather, so an executable program had to be created and installed on a different laptop. Unfortunately, an error in the program related to the file storage path on the new computer was not detected, which resulted in complete loss of the data files for the day. To avoid loss of data in future tests, the program was later modified to periodically write temporary backup files during testing, and a testing protocol of verifying and copying the data files to an external drive after each individual test was created.

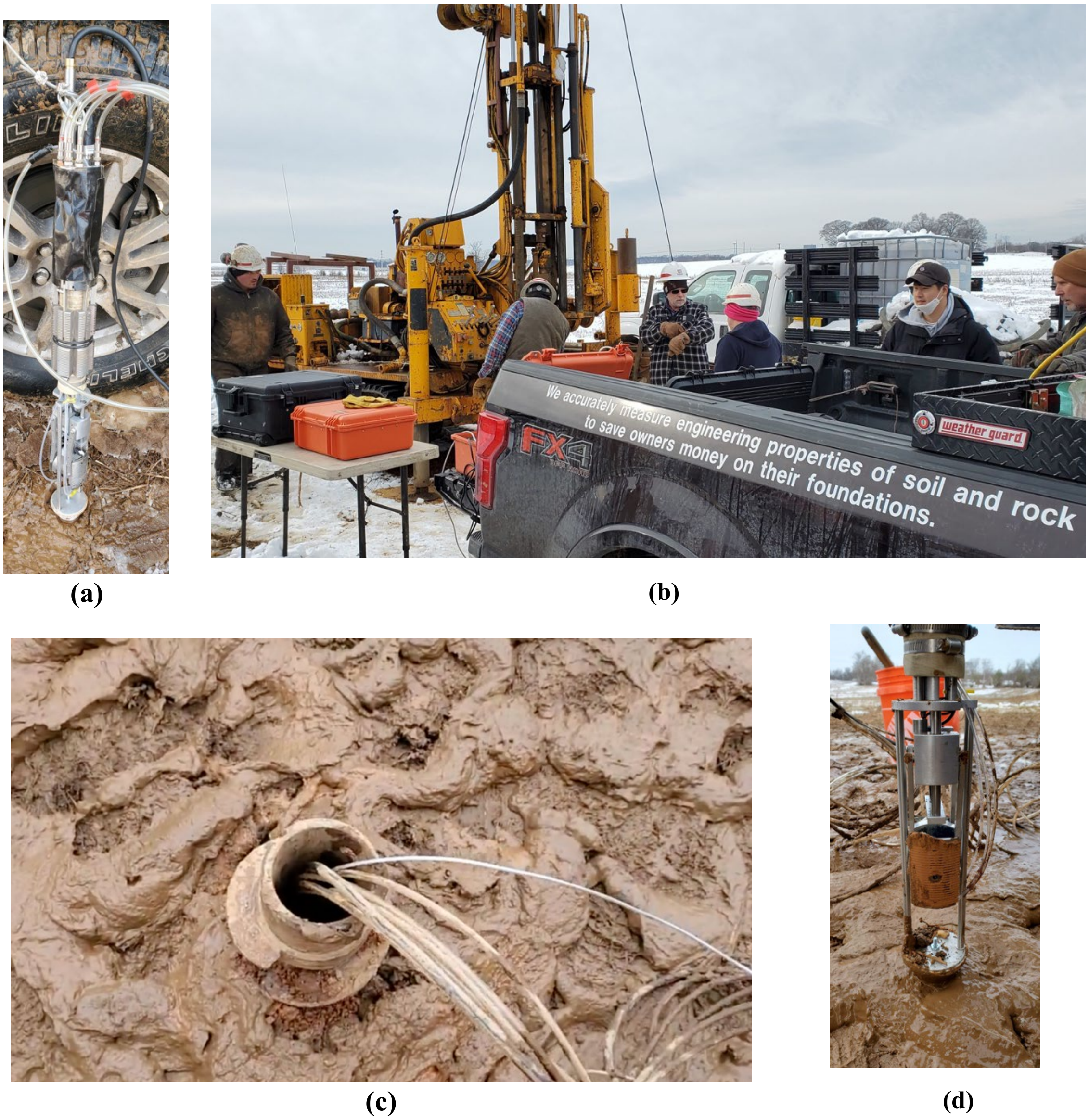


FIGURE 23 Field tests in Beltsville, MD; (a) CBST device ready for test, (b) drill rig and initial outdoor equipment setup, (c) CBST device inserted below hollow stem auger, (d) CBST shear plates after test in soft clay

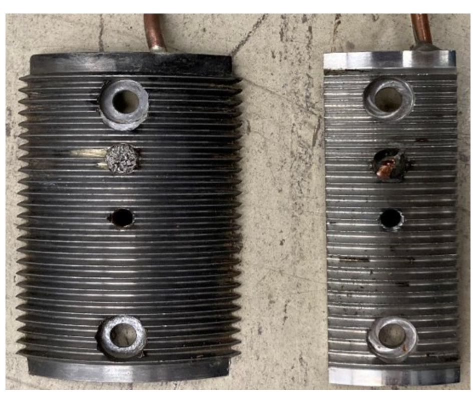


FIGURE 24 Original (left) and reduced area shear plate to enable testing at higher stresses (right)

Additional field tests in Iowa and Further Refinements to CBST Device and Software

Based on lessons learned from the first few field trials, several changes were made to improve the data quality, accuracy of the feedback control system, and ease of use of the CBST device. These changes are detailed below.

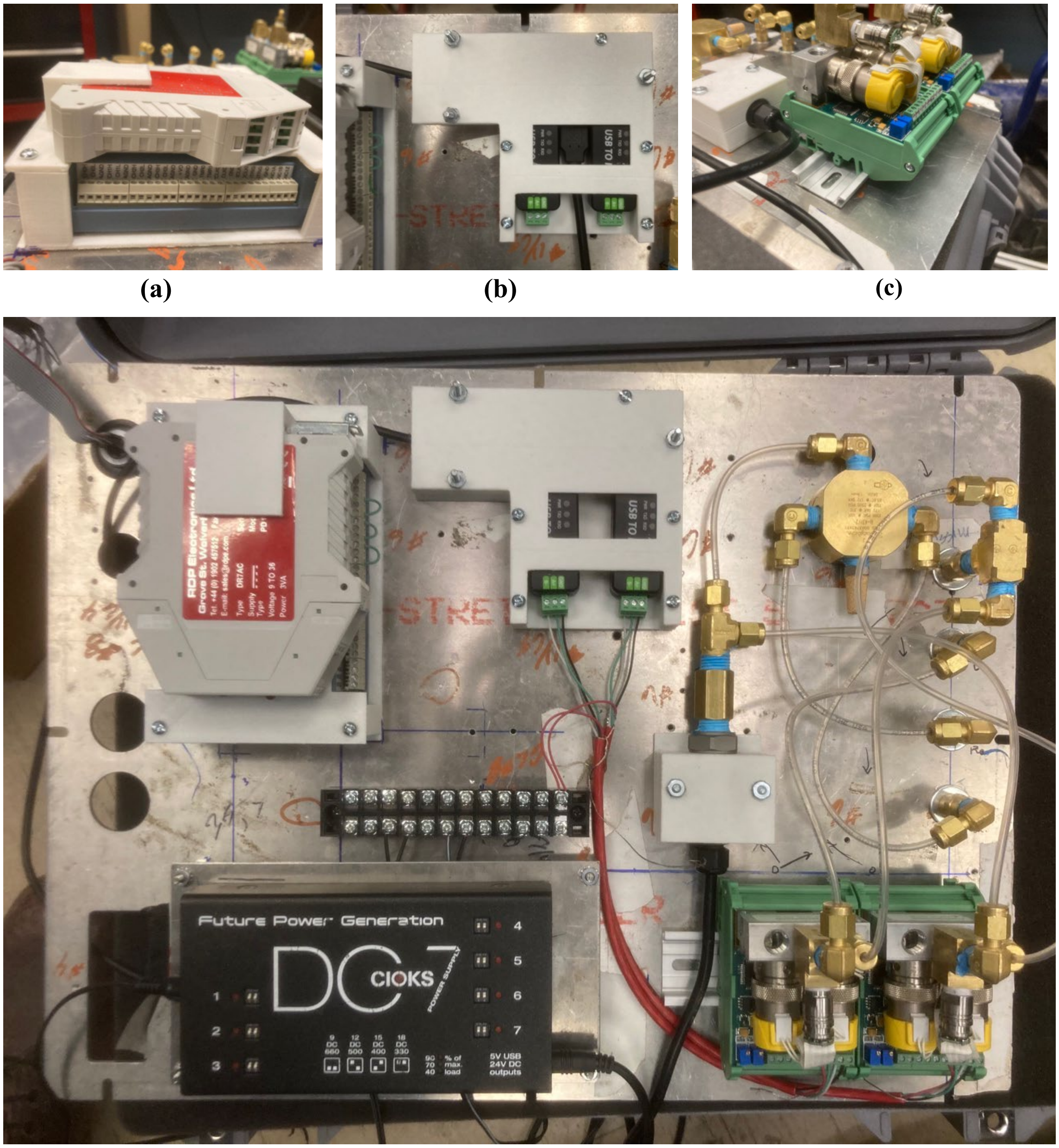
Addition of Digital Pressure Regulators to Control Normal Stress and Anchor Head Pressure

Two digital electro-pneumatic pressure regulators were purchased to automate control of the shear head's normal stress and the anchor head's expansion pressure, both of which were previously controlled manually with a hand pump. To enable computer control of these two digital pressure regulators, a USB hub and two USB-to-RS485 converters were also installed in the electronics case using ABS plastic mounts that were designed by the graduate student and 3D printed by the project PI. To accommodate the new components, the back side of the control panel was modified with new pressure tubing connectors and valves, and additional 3D-printed ABS mounting brackets were designed and fabricated to secure the various other components (Figure 25). To communicate with the digital pressure regulators using the USB-to-RS485 converters, the virtual instrument software architecture (VISA) I/O standard was added to the existing CBST LabVIEW program.

Change to 12-Volt Marine Battery and Pure Sine Wave Inverter to Reduce Electrical Noise

When working with low-voltage sensor signals from load cells and LVDTs in the field, it is important to have a clean power supply voltage signal. Ordinary gasoline generators do not provide clean 120 Volt AC power signal waveforms, which can easily result in signal-to-noise ratios well below 1.0, meaning that the electrical noise is much larger than the sensor signals. This is especially problematic when the signals are used as inputs for a feedback control system as in the CBST, because a noisy input signal will result in a noisy command signal causing more erratic motion. During most of Stage 1 of the project, a Yamaha EF1000iS inverter generator was used for the field tests in Iowa, because it generates cleaner power than an ordinary generator. However, the inverter generator occasionally resulted in excessive signal noise despite using a grounding rod.

To minimize noise as much as possible, the inverter generator was replaced with a 12 V marine battery powering a pure sine wave DC-to-AC inverter. This power supply setup greatly reduced the random noise in the sensor signals, as can be seen in the subsequent data plots of this report. The Cioks DC7 unit shown in Figure 25d is a switched-mode DC power supply that requires 120 V AC input power. It features seven isolated power outputs selectable between 9, 12, 15 and 18 Volts DC capable of providing between 330 and 660 mA of current depending on voltage, and provides a 24 V DC passthrough and a 5V Type A USB charging port. It is used to provide isolated power to the downhole sensors including the horizontal LVDT,



(a) (b) (c)

(d)

FIGURE 25 Modifications to underside of CBST control panel; (a) mount for DAQ and AC LVDT signal conditioner, (b) mount for USB hub and RS485 to USB converters, (c) mount surrounding pressure sensor and electro-pneumatic pressure regulators mounted on DIN rail, (d) back side of control panel with new pressure tubing, valve, and fittings installed

vertical load cells, and pressure sensor. It also provides power to components in the electronics case including the two pneumatic pressure regulators, shear head expansion pressure sensor, AC signal conditioner for the vertical LVDT, two ventilation fans, and the high speed proportional valve outside the electronics case. The DAQ and the USB-to-RS485 converters receive power from the host laptop over their USB connections.

Change from Air Compressor to CO_2 Gas

Previously, the compressed air for the high speed valve controlling the vertical pneumatic cylinder for applying shear stress was supplied by an air compressor that was also powered by the generator, which created additional electronic noise. The reaction shear head and the horizontal pneumatic cylinder that applies normal stress were also previously pressurized using a hand pump and three manual valves. To simplify device operation and reduce noise, the air compressor and hand pump were eliminated from the test setup and replaced by a single CO_2 tank with a T-connection. Control of the expansion pressure for both the anchor head and shear head were then automated using the two new digital electropneumatic pressure regulators. The control program now maintains a constant pressure using these two regulators, freeing the operator from manually monitoring and adjusting their values during a test. This will also result in more nearly constant values of normal stress and anchor head pressure during testing.

Addition of Filtering Algorithms to the Control Program

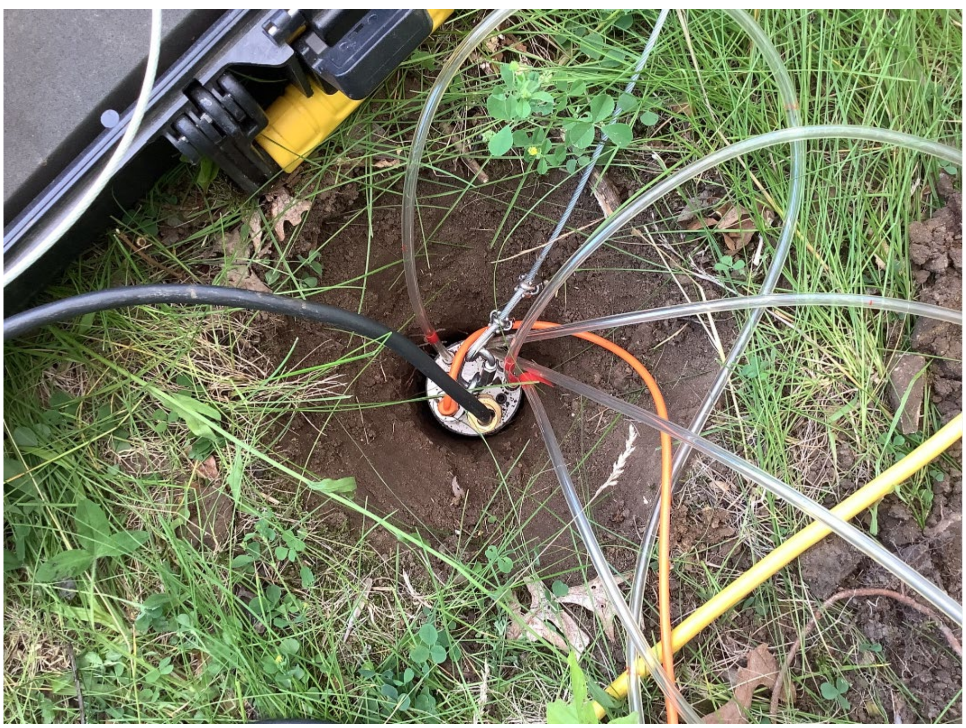
To further reduce effects of electrical noise in the signals and improve the feedback control accuracy, the control program was modified to apply a low-pass filtering algorithm to the measured signals. This is beneficial because the frequency of the cyclic stresses applied to the soil are on the order of a few Hertz, whereas the sensor signals still contained some degree of higher frequency noise. By filtering out the higher frequency electrical noise, the actual soil response at lower frequencies can be more accurately measured. To prevent the low-pass filtering algorithm from introducing additional relative phase shifts between different sensor signals (beyond those contributed by the soil's damped dynamic response), the same filter algorithm was uniformly applied to all input signals. Switching to the marine battery and using low-pass filtering greatly reduced the level of noise in the sensor data, which in turn enabled the PID feedback control algorithm to more closely follow the desired command signal. The control program was further modified to include a delay time to allow a single operator to lower the CBST device into position before the anchor head is pressurized, and to directly specify the frequency of cyclic loading, whereas the frequency was previously adjusted manually by changing the PID feedback loop parameters during a test.

To validate the new components and program changes, additional field tests were performed in Ames, Iowa (Figure 26) using CO_2 pressure in a glacial till classifying as sandy lean clay (CL). An example of the results is shown in Figure 27, illustrating greatly improved data quality and more precise control of the device relative to previous tests.

Additional Field Tests in Iowa to Assess Modifications

To further assess the quality, repeatability, and sensitivity of CBST measurements after making the modifications described above, three tests with increasing normal stress values of 4, 8 and 10 psi were

(a)



(b)

FIGURE 26 Field tests in Ames, IA; (a) New CBST setup including 12 V marine battery, pure sine wave DC-AC inverter, digital pressure regulators (inside grey control case), and CO_2 cylinder, (b) CBST device in shallow borehole ready for test

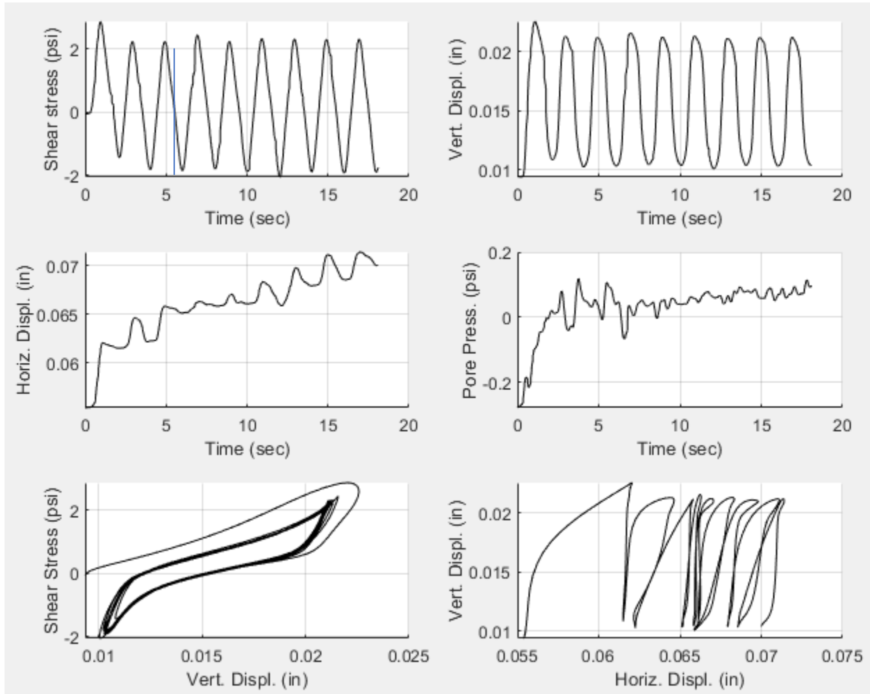


FIGURE 27 Data from CBST with 10 psi normal stress and 2 psi cyclic shear stress at 0.5 Hz, showing cleaner sensor signals and improved control of cyclic shear stress amplitude and frequency

performed at the same depth within a borehole of sandy lean clay (CL) having a moisture content of 12%. A target cyclic shear stress amplitude of 2 psi and frequency of 0.5 Hz were specified, and the shear head was retracted and recentered vertically between tests but was not otherwise removed or cleaned. The results, shown in Figure 28, reveal that the CBST device and feedback system produced very repeatable graphs of shear stress vs. time for the three different applied normal stress values, although the first shear stress peak slightly overshoots the target of 2 psi (Figure 28a).

While the applied shear stress histories were practically the same in the three tests (Figure 28b), the resulting displacement response of the soil is consistent with expectations based on theoretical soil mechanics, in that an increase in normal stress resulted in a stiffer response manifesting as a decrease in cyclic displacement amplitude (Figures 28b and 28c). Additionally, the constant normal stress represents a static bias that causes the shear plates to displace horizontally into the soil during the tests, which is not plotted in Figure 28 but can be seen in the two plots involving horizontal displacement in the previous Figure 27. A static bias in the vertical (shearing) direction was also observed, in that the vertical displacements do not oscillate about zero (Figure 28b). This may be partially caused by the overshooting of the first shear stress peak as exhibited in Figure 28a and is a limitation of the proportional valve.

The area enclosed by a given hysteresis loop in Figure 28c is proportional to the energy dissipated because of the nonlinear stress-strain response of the soil (i.e., material damping), as well as any contributions from

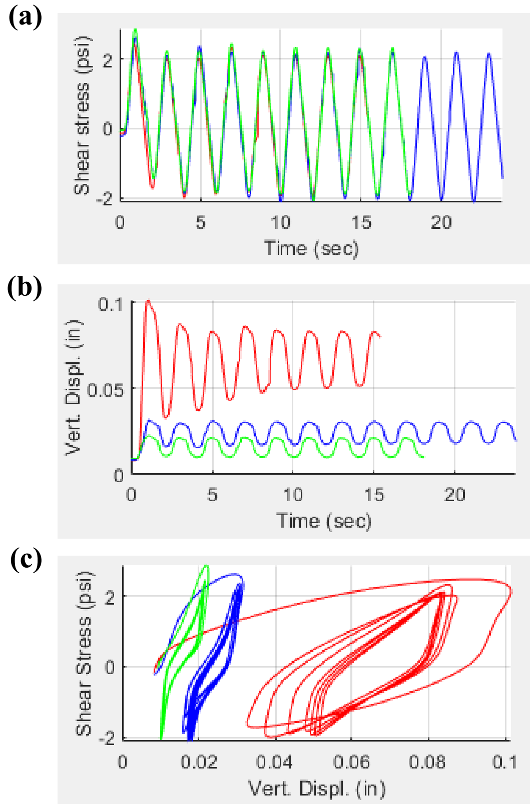
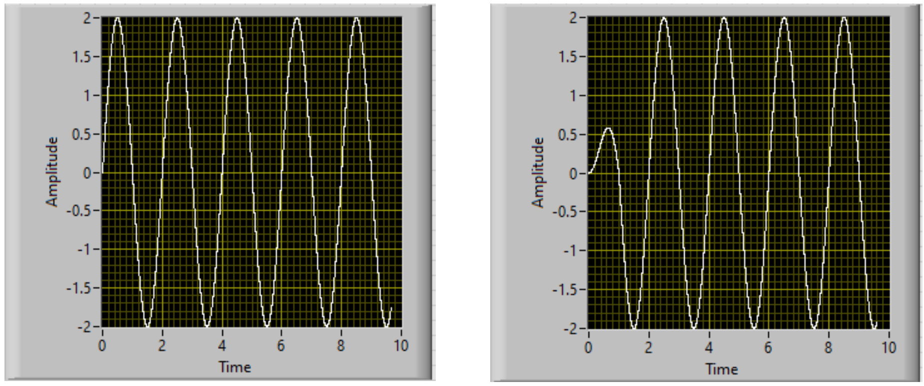


FIGURE 28 CBST results for target cyclic shear stress of 2 psi at 0.5 Hz with normal stress values of 4 psi (red), 8 psi (blue), and 10 psi (green) performed in the same location; (a) shear stress vs. time, (b) vertical displacement vs. time, (c) hysteresis loops of shear stress vs. vertical displacement

viscous damping phenomena which may be relatively minor at low frequencies around 0.1 Hz. However as previously discussed, the shear strains for the field CBST are not known, similar to laboratory direct shear tests. In future research, analytical and computational methods will be examined to estimate representative shear strains from the measured CBST displacements. The measured loops of Figure 28c agree with expectations, in that the lowest normal stress of 4 psi results in the largest loop with the greatest initial displacement excursion in the first cycle, while the higher normal stresses result in stiffer responses characterized by smaller and more nearly vertical loops as well as smaller initial displacement excursions.

Additional modifications were made to the control program to reduce the consistent overshooting of the first shear stress peak exhibited in Figure 28a. For example, one implemented approach was to reduce the amplitude of the first peak in the sinusoidal PID control signal as shown in Figure 29. This helps to compensate for the soil's shear modulus which initially has a maximum value at small displacements (or small shear strains) and decreases nonlinearly with increasing displacement, making the first half loop different from subsequent loops. The front panel of the CBST control program after making all refinements discussed above is shown in Figure 30. On the panel, "EU" stands for Engineering Units which may be inches and psi, or mm and kPa



(a) (b)

FIGURE 29 Original (a) and modified (b) PID setpoint control signals for high-speed proportional valve, with first setpoint peak decreased to reduce overshoot of first measured shear stress peak

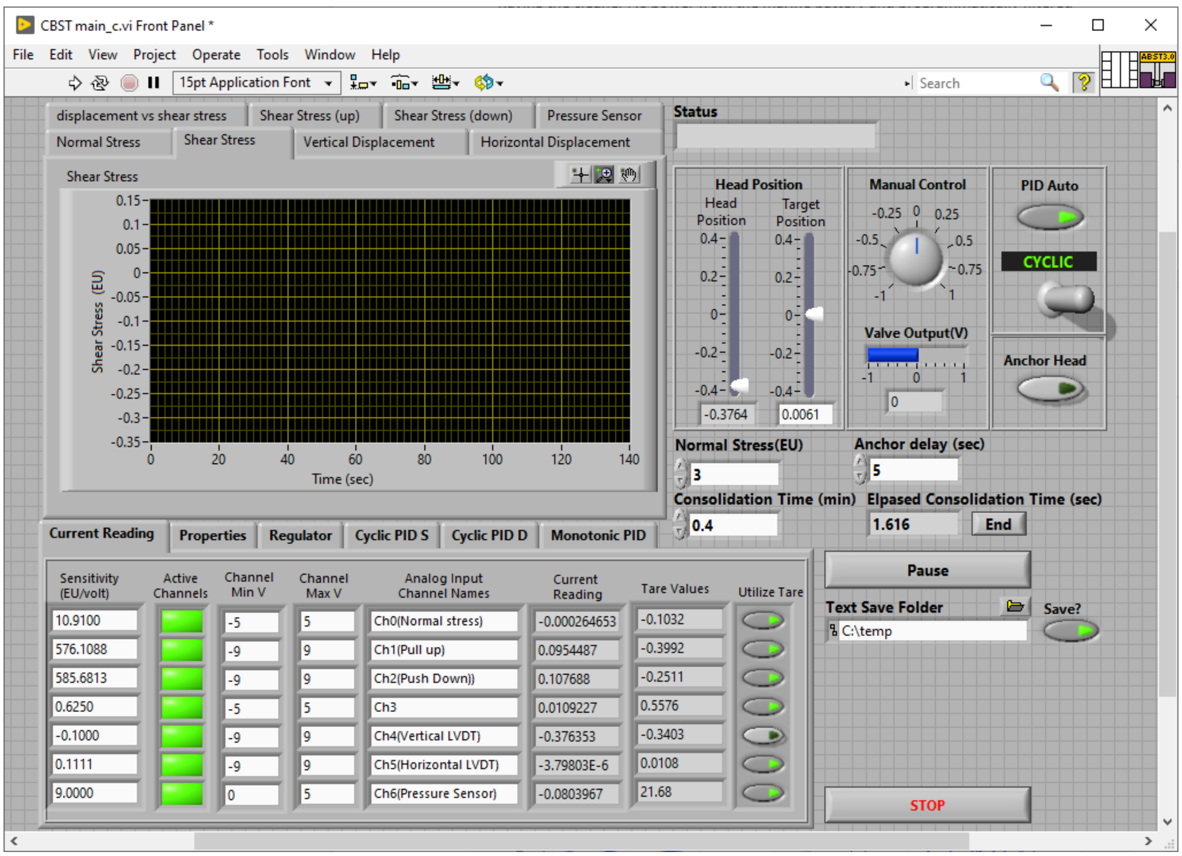


FIGURE 30 Front panel of CBST control program

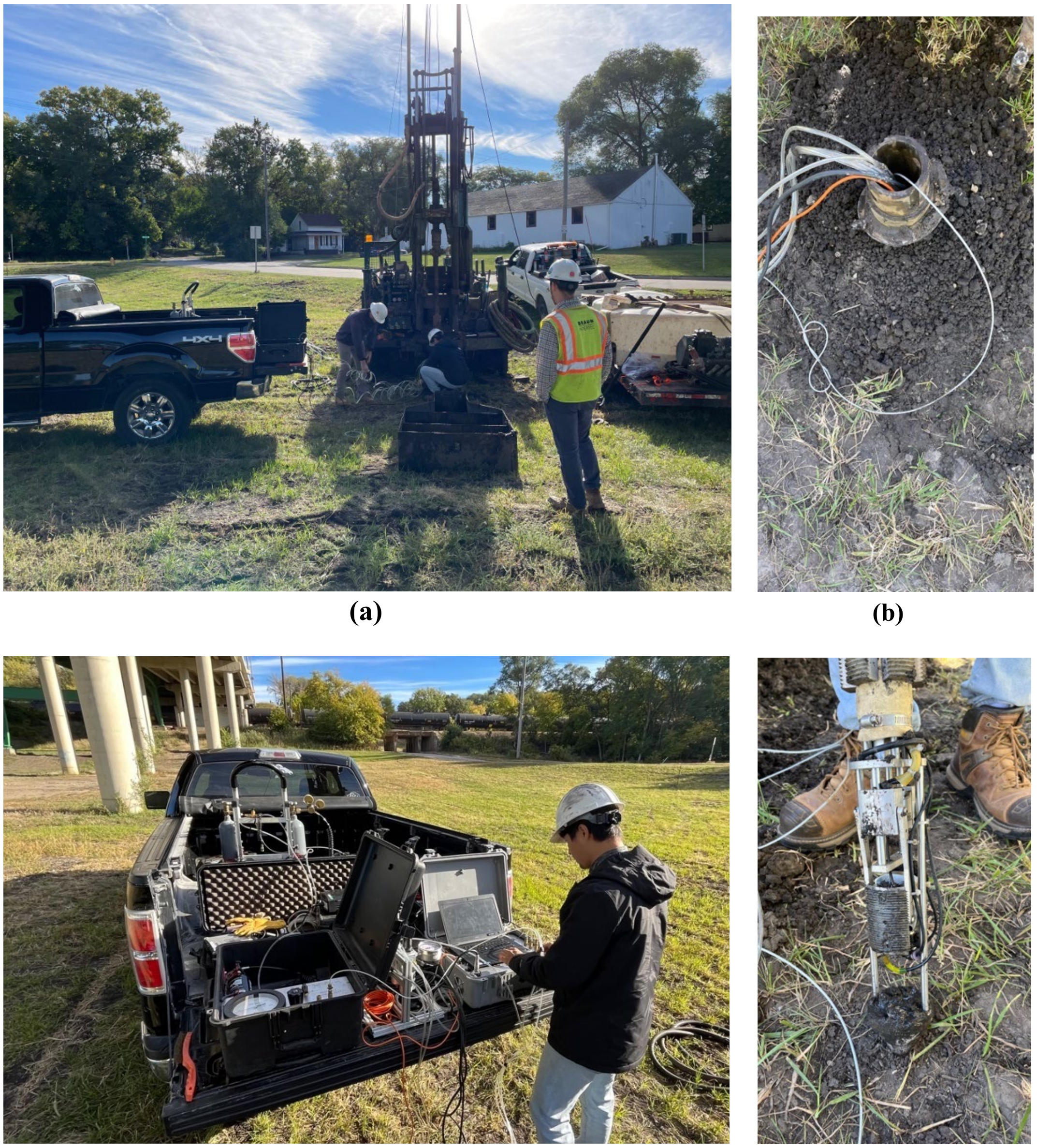
depending on which units the user chooses to enter in the Sensitivity fields in the bottom left corner of the screen. Eight tabs in the upper left portion of the screen allow the user to select from a variety of different data plots during a test, while six tabs below the plots allow the user to enter sensitivities and adjust PID parameters for different soils or select open-loop control. The new anchor head delay time (labeled "Anchor delay (sec)") can be seen in the middle right portion.

Field Tests with Iowa DOT and Comparison to CDSS Tests

Field tests were performed at an Iowa DOT project site in Fort Dodge, Iowa on September 29, 2022 (Figure 31) using CO_2 pressure. The electropneumatic regulators were damaged by an airline during a previous trip to Virginia and were at the manufacturer for repair. Therefore, the shear head was expanded by a manual hand pump for these tests, and the anchor head was expanded using the CO_2 pressure regulator from an ABST device. Mud rotary drilling was used at the site, which provided an opportunity to test the waterproofing measures applied to the CBST. The waterproofing measures appeared to be sufficient, as the sensors continued to function throughout the tests.

Cyclic tests were performed in a clayey sand fill (USCS classification SC, m.c.=22%, SPT blowcount=8, LL=26, PL=13) at depths of 5 ft and 10 ft, both of which were above the water table and before drilling mud was added. The measured pore water pressures were not significant for these tests because they were performed above the water table in unsaturated soil. After drilling mud was added, a third test was performed at a depth of 15 ft in a layer of decomposed very soft shale. In the field tests, a target normal (horizontal) stress of 7.5 psi was applied, the soil was allowed to consolidate for approximately one minute, then cyclic vertical shear stress was applied with 10 cycles at each of several increasing shear stress amplitudes. The target loading frequency was 0.5 Hz, but it was later determined that the actual frequency of loading was 0.6 Hz due to a programming error. For the test at 10 ft depth, the data revealed that the borehole may have been too large or the soil too weak, because the shear head immediately reached the upper end of the vertical displacement range upon application of a small cyclic shear stress of 1 psi, then became fully expanded with further cyclic loading (Figure 32). Similar results were obtained for the test at 15 ft.

The test at 5 ft gave the most usable results (Figure 33), and a Shelby tube specimen from 6 to 8 ft depth was therefore transferred to the research team for lab testing. Because the CBST shears the soil on a vertical plane which is at a right angle to most typical CDSS specimens, two CDSS tests were performed, one on a horizontally trimmed specimen and another on a vertically trimmed specimen. The specimens were tested in a bi-directional CDSS device at ISU using only one of the two horizontal shearing directions (Figure 34). To simulate the field CBST tests in the CDSS device, a normal (vertical) stress of 7.5 psi was applied, the specimens were not saturated, and loading was applied using a frequency of 0.5 Hz with 10 cycles at each of several increasing shear stress amplitudes.



(a) (b) (c) (d)

FIGURE 31 Field tests in Fort Dodge, IA; (a) Drill rig with mud rotary equipment, (b) CBST device inserted into Shelby tube cavity below hollow stem auger, (c) CBST equipment with CO_2 supply tank in truck bed and ABST regulator on tailgate for anchor head, (d) CBST shear plates after test in sandy lean clay fill

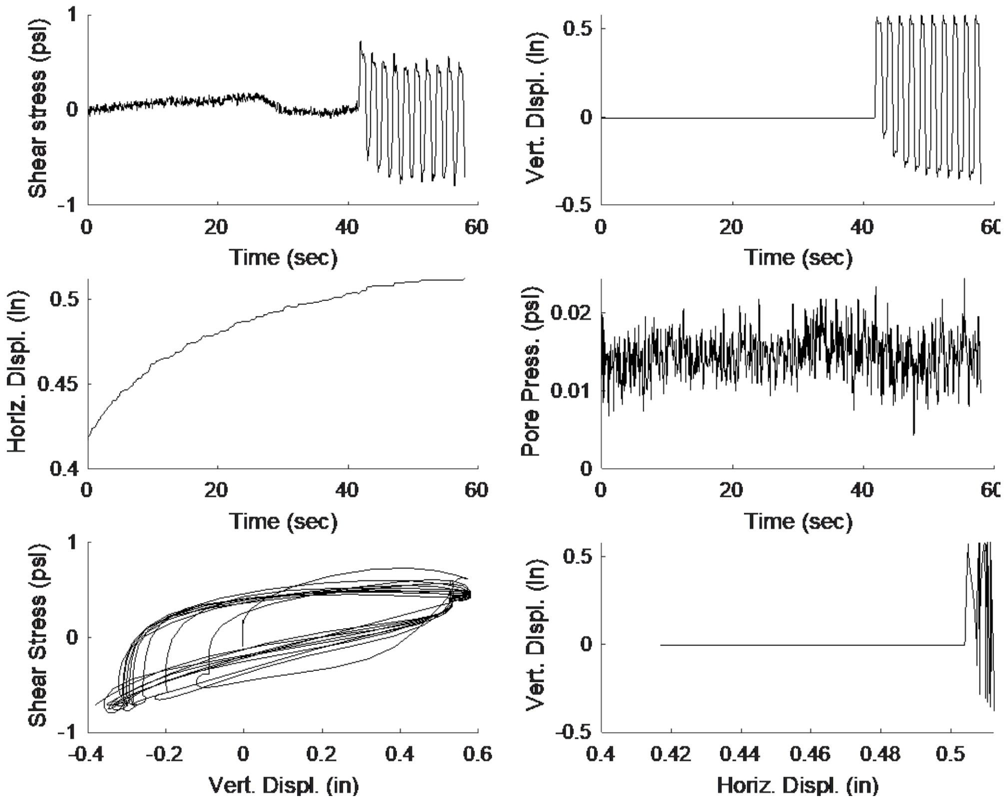


FIGURE 32 Fort Dodge CBST at depth of 10 ft

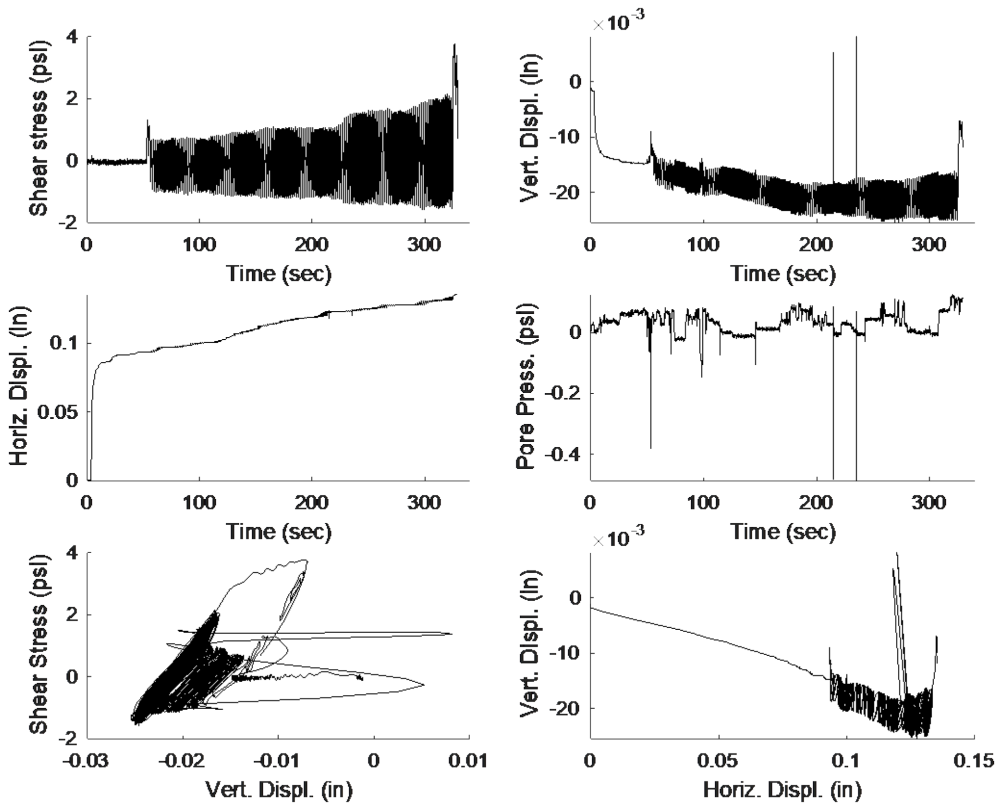
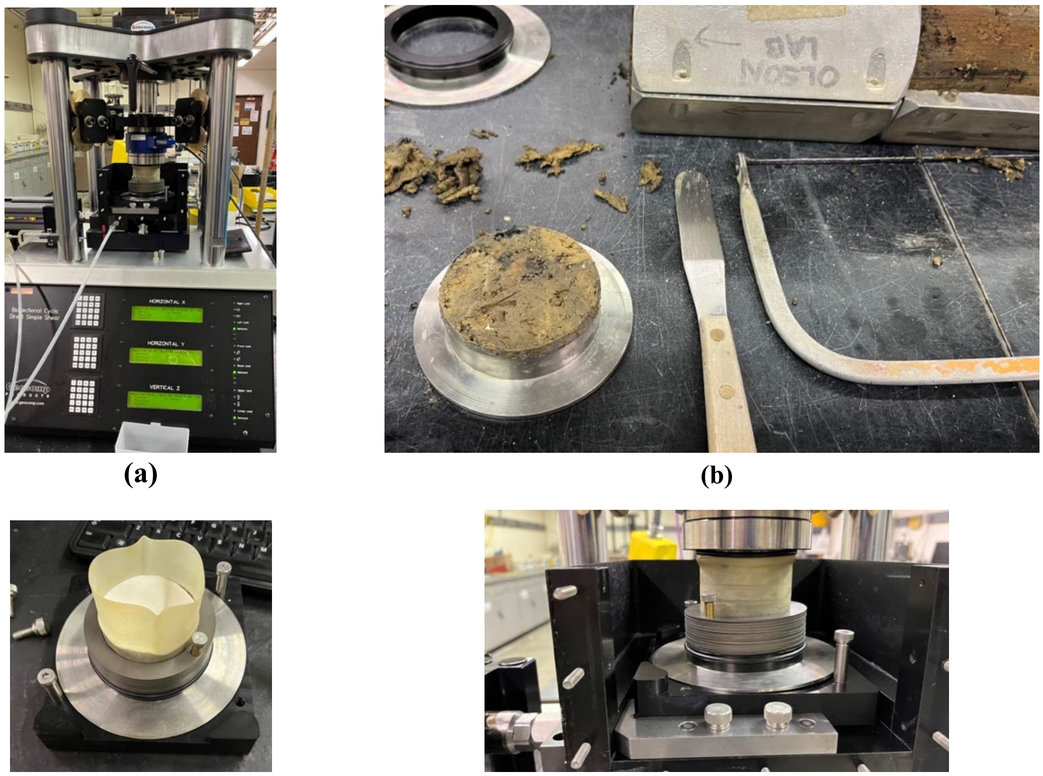


FIGURE 33 Fort Dodge CBST at depth of 5 ft



(a) (b) (c) (d)

FIGURE 34 CDSS tests on Fort Dodge specimens; (a) Bi-directional CDSS device, (b) horizontally trimmed specimen, (c) specimen in stacked rigid rings, (d) specimen in CDSS device prior to test

The CBST data are compared to those of the CDSS test on the vertically trimmed specimen in Figure 35. The results show that while the laboratory CDSS device accurately controlled the amplitudes of cyclic shear stress, the CBST had more difficulty doing so because of the increased challenge of testing in situ, as well as a noticeable level of noise that was later determined to be caused by a loose grounding wire. For a closer comparison, the stress-displacement loops corresponding to the target shear stress amplitude of 1 psi were extracted, as shown in Figure 36. The results show somewhat similar shear stress-displacement loops, with a greater initial offset for the CBST partially due to overshooting the first shear stress peak (see previous Figure 33).

As described previously, the CBST results will be more useful for geotechnical design and analysis if the measured displacements can be related to shear strains. For CDSS tests, the uniform shear strain in the specimen at any time during shearing is simply calculated by dividing the change in horizontal displacement by the height of the specimen taken at the end of the consolidation phase just before shearing starts (*7*). For the CBST, however, the shear strains are not uniform in the soil surrounding the shear plates but decrease nonlinearly with distance (see previous Figure 2). Due to the small size of the shear plates and the small vertical shearing displacements applied, the thickness of the soil zone around the shear plates that

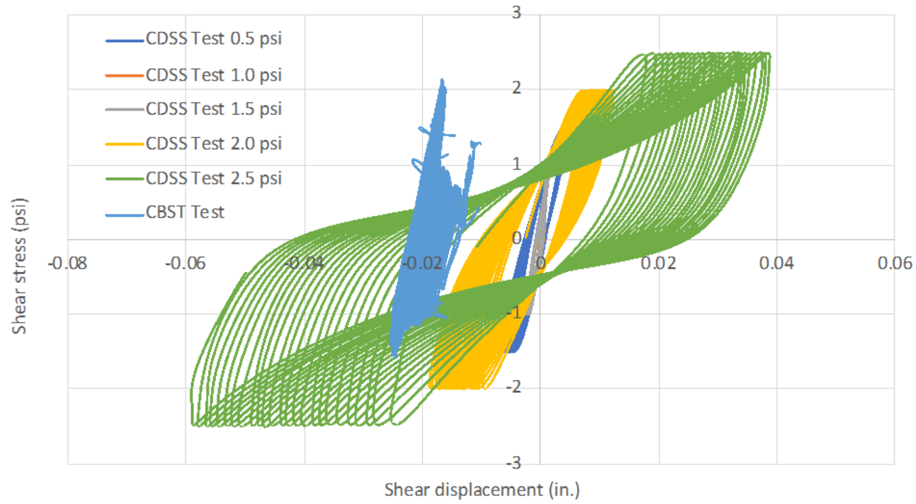


FIGURE 35 Shear stress-displacement loops for Fort Dodge CBST and vertically trimmed CDSS specimen

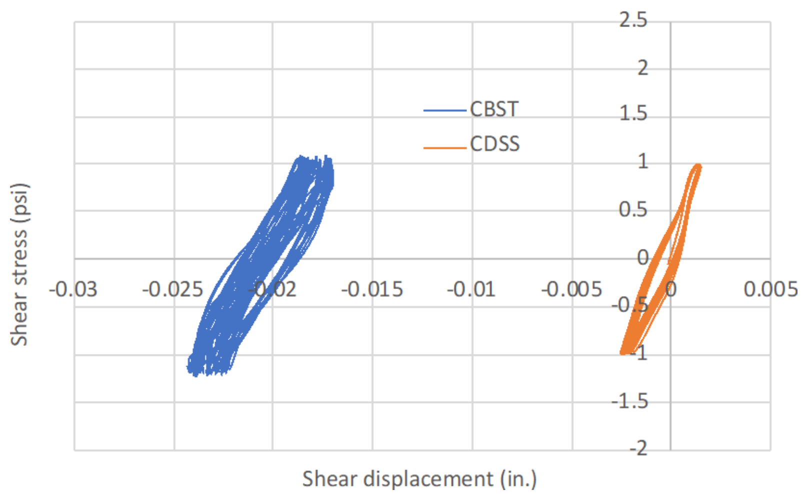


FIGURE 36 Shear stress-displacement loops at target shear stress of 1 psi for Fort Dodge CBST and vertically trimmed CDSS specimen

experiences significant shear strains is expected to be smaller than typical CDSS specimens for stiff soils. Bechtum (2012) performed a finite element analysis of stress and strain in the soil for the BST and determined that significant total logarithmic shear strains decreased approximately linearly with distance from the borehole and were negligible beyond 1.4 in. from the shear plate. Thus, although the shear strains around the borehole are not uniform as in the CDSS tests, it may be possible to assume a representative shear zone thickness which the CBST displacements can be divided by to obtain representative average shear strain amplitudes. Such representative shear strains may depend on soil type, moisture condition, stiffness, and shear strength among other parameters, the nature of which are topics for future research.

To explore the concept, the CBST shear displacements were divided by an assumed representative thickness to estimate shear strains as a first approximation, and the loops were shifted horizontally to center them. The assumed thickness was then varied to achieve the best visual match between the CBST and CDSS stress-strain curves to determine if the thickness values were reasonable. The results for the vertically trimmed case are shown in Figures 37 and 38 for the target shear stress amplitudes of 1.0 and 1.5 psi, respectively, using an assumed thickness of 1.4 in. for both figures. Note that the same axis limits are used in both figures for ease of comparison. Although a good match is achieved for the 1.0 psi test, it is evident that a different assumed thickness is needed to better match the 1.5 psi test, as the effect of the assumed thickness is to simply scale the CBST data along the shear strain axis. For example, the 1.5 psi test is better matched using an assumed thickness of 0.68 in. for shear strain calculation, as shown in Figure 39.

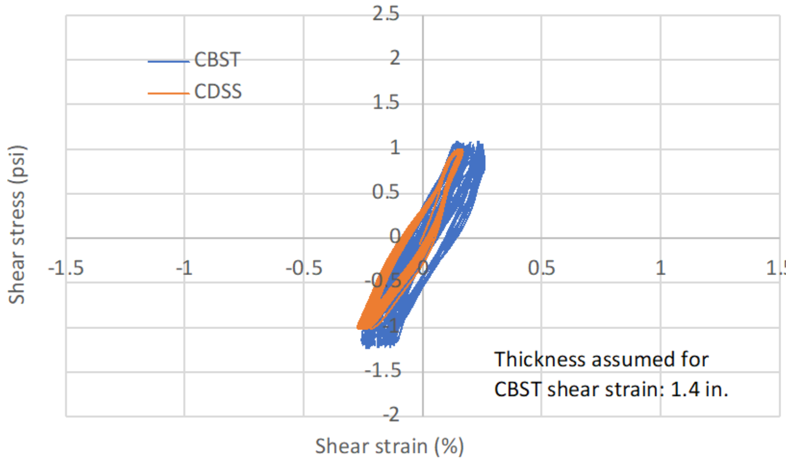


FIGURE 37 Shear stress-strain loops at target shear stress of 1 psi for Fort Dodge CBST (1.4 in. assumed thickness) and vertically trimmed CDSS specimen

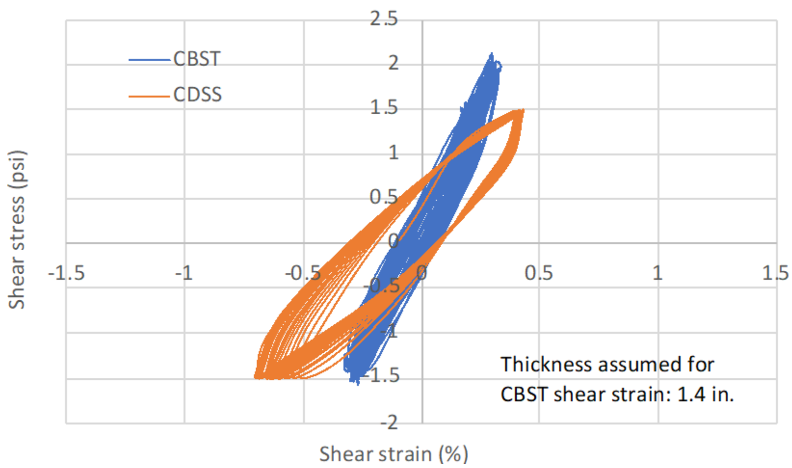


FIGURE 38 Shear stress-strain loops at target shear stress of 1.5 psi for Fort Dodge CBST (1.4 in. assumed thickness) and vertically trimmed CDSS specimen

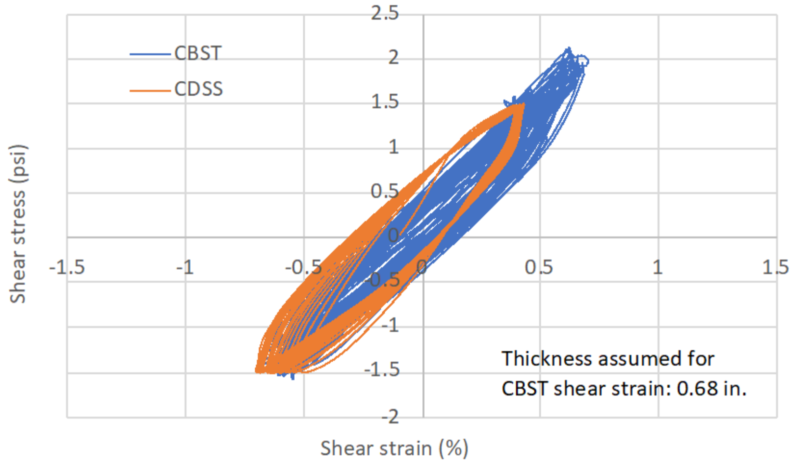


FIGURE 39 Shear stress-strain loops at target shear stress of 1.5 psi for Fort Dodge CBST (0.68 in. assumed thickness) and vertically trimmed CDSS specimen

The same CBST data is compared to the CDSS results for the horizontally trimmed specimen in Figure 40. Comparing CDSS results for the vertically and horizontally trimmed CDSS specimens in Figures 35 and 40 reveals that the horizontally trimmed specimen had greater static bias and reached greater strains for the same shear stress ratios, and the CDSS device reached its horizontal displacement limit during the first loop for the shear stress of 2.5 psi (Figure 40). The 1 psi and 1.5 psi shear stress-strain loops for the horizontally trimmed specimen were best matched using assumed thicknesses of 0.75 in. and 0.35 in., respectively, for the CBST shear strain calculation (Figures 41-43). The ratios of the best-fit assumed thicknesses for the 1.0 psi and 1.5 psi cyclic shear stress levels are similar for the vertically trimmed (i.e., 1.4 in./0.68 in.=2.06) and horizontally trimmed specimen (0.75/0.35=2.14).

Despite the noise and control issues with the CBST data, the comparisons with laboratory CDSS tests are promising. Assuming the representative thickness approach can be validated with further research, these results suggest that the CBST device can capture relevant and useful in situ cyclic soil behavior much more efficiently (i.e., several tests can be completed within minutes of drilling) than comparable laboratory tests.

After the Fort Dodge tests, the repaired digital electropneumatic regulators were received from the manufacturer and mounted in a more protected orientation inside the electronics case. The 3D printed mounts for the other devices were also redesigned to improve airflow and accommodate inflow and outflow ventilation fans which were needed because of the heat generated by the electropneumatic regulators. The AC signal conditioner was separated from the DAQ and mounted vertically to enhance cooling of both components. The final layout of the components under the control panel is shown in Figure 44.

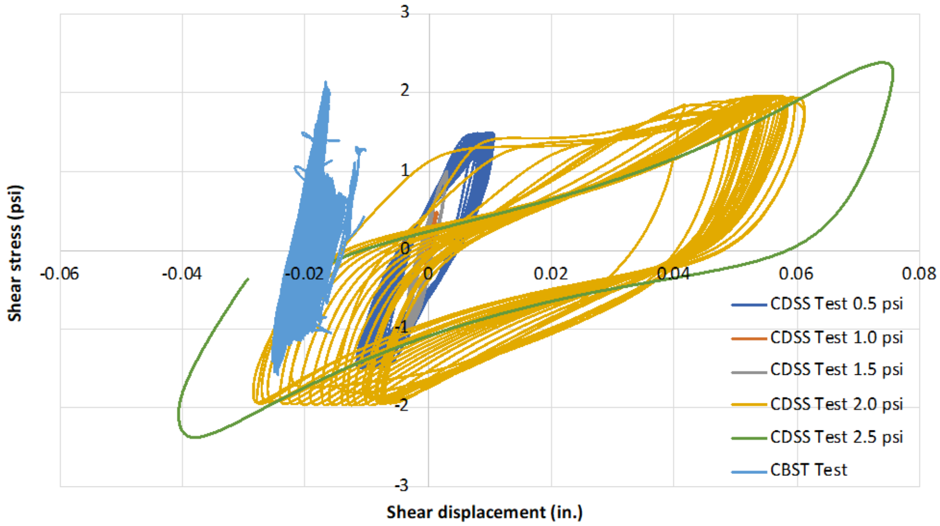


FIGURE 40 Shear stress-displacement loops for Fort Dodge CBST and horizontally trimmed CDSS specimen

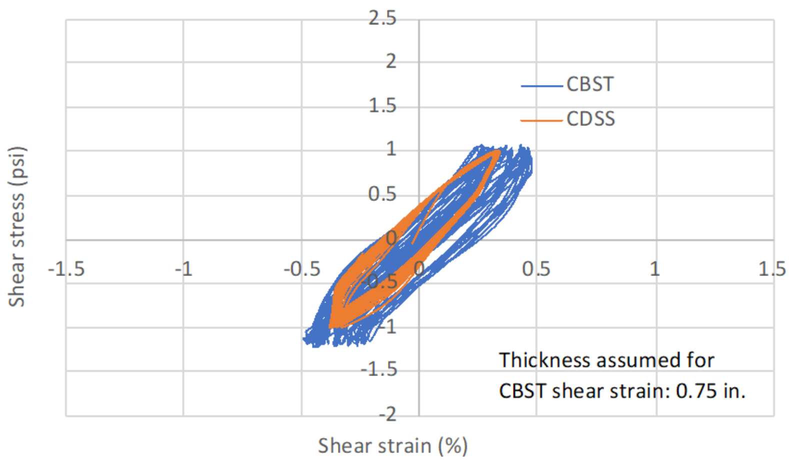


FIGURE 41 Shear stress-strain loops at target shear stress of 1 psi for Fort Dodge CBST (assumed thickness 0.75 in.) and horizontally trimmed CDSS specimen

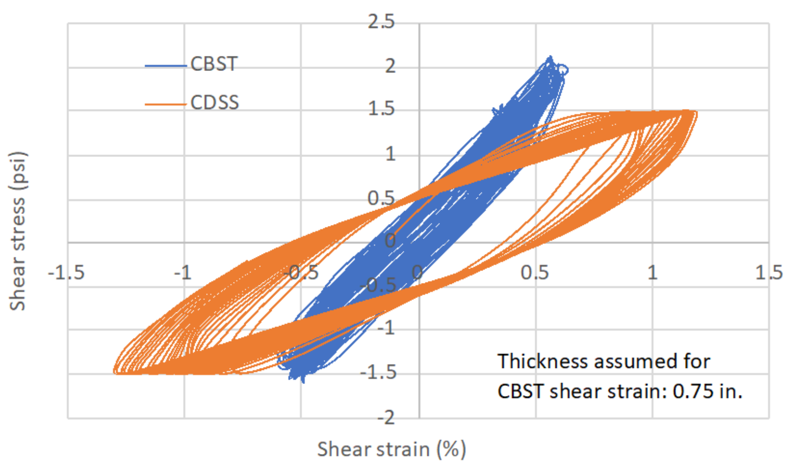


FIGURE 42 Shear stress-strain loops at target shear stress of 1.5 psi for Fort Dodge CBST (assumed thickness 0.75 in.) and horizontally trimmed CDSS specimen

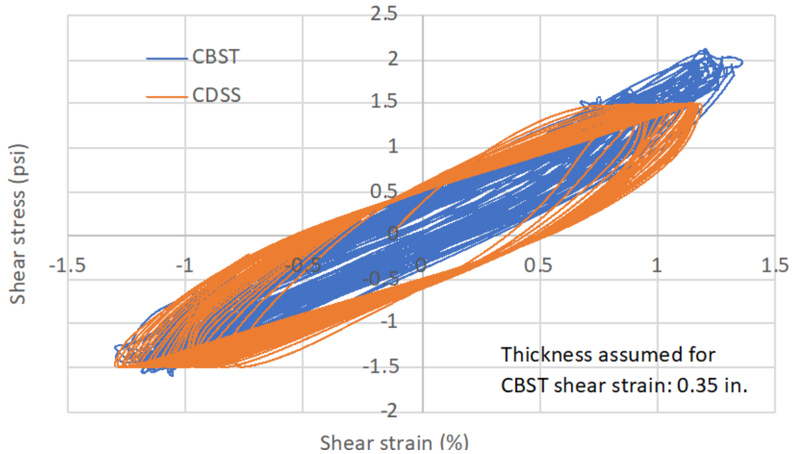


FIGURE 43 Shear stress-strain loops at target shear stress of 1.5 psi for Fort Dodge CBST (assumed thickness 0.35 in.) and horizontally trimmed CDSS specimen

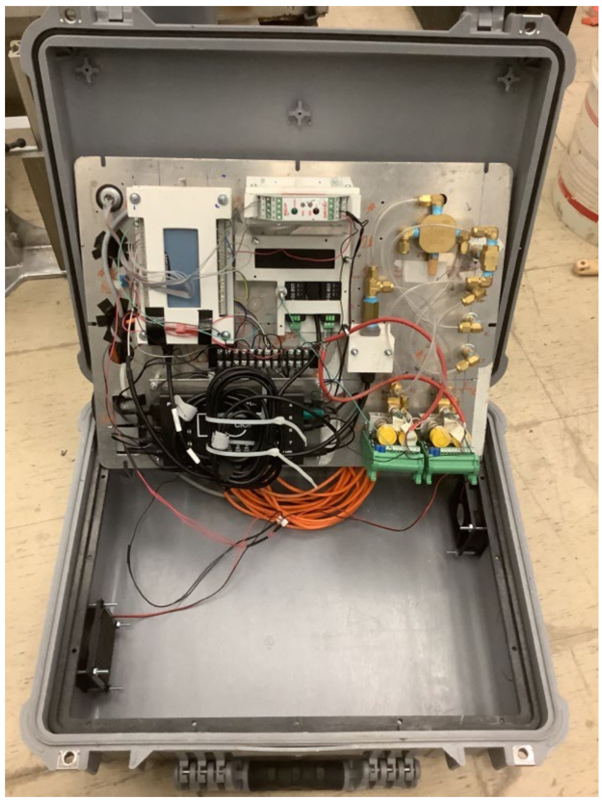


FIGURE 44 Final layout of components under control panel of CBST electronics case

Field Tests in Oregon and Comparison to CDSS Tests

The final round of field testing was performed on October 13, 2022 in Corvallis, Oregon at a site from a previous study featuring extensive laboratory CDSS tests (*8*, *9*). Photos of the site and CBST setup using CO_2 pressure are shown in Figure 45. A hand auger and BST trimming shield were used to create a new borehole approximately four feet from that of the previous study, and tests were performed in Willamette

(a) **(b)**

FIGURE 45 Field tests in Corvallis, Oregon; (a) Test site next to Van Buren bridge over Willamette River, (b) Field test setup with borehole trimming device shown at top

River silt at depths ranging from 54 to 104 inches. Because the repaired digital pressure regulators were used, the pressures supplied to the shear head and anchor head were more accurately controlled than in previous tests. Additionally, modifications were made to the control program to slow the loading rate to 0.1 Hz to match those from the previous study. After performing the first test in PID-feedback control mode, it was determined that the data could be improved by running all subsequent tests in open-loop mode and manually adjusting the supply pressure to the high speed proportional valve. In each subsequent test, the CO_2 pressure was therefore manually increased after 10 cycles of loading at each shear stress amplitude to reach the next shear stress amplitude. Each time the pressure was increased, the static bias of the cyclic shear stress signal was also manually adjusted by changing a bias compensation value on the front panel of the LabVIEW control program. For future development of the CBST, it may be possible to program the feedback loop to control an additional digital regulator to adjust the CO_2 pressure feeding the proportional valve. Such a control scheme may provide more precise control of the cyclic shear stress magnitude while eliminating the need for manual adjustment of the supply pressure.

For the laboratory CDSS tests in the previous study (*9*), an initial vertical effective stress equal to the in situ value of 7.25 psi (50 kPa) was applied, as detailed in Table 1. The specimens in that study had an overconsolidation ratio of 1.9 and were reported to be susceptible to cyclic softening rather than liquefaction.

TABLE 1 Parameters of laboratory CDSS tests from Oregon site (Stuedlein et al., 2022)

Test ID	Test depth (in.)	Vertical effective consolidation stress (psi)	Overconsolidation ratio	Void ratio	Plasticity Index
B-13-15	111	7.25	1.9	1.35	16
B-13-18	112			1.38	15
B-13-19	113			1.35	14
B-13-20	114			1.47	15
B-13-21	115			1.50	15

Based on the information in the previous study, the in situ CBST tests presented herein were performed in a low plasticity silt (ML) with average LL=47, average PI=15, and 94% fines content with approximately 73% silt-sized particles. The list of CBSTs performed at the Oregon site are detailed in Table 2

TABLE 2 Parameters of field CBSTs performed at Oregon site

Test ID[a]	Test depth (in.)	Normal stress (psi)	Consolidation time (sec)	Loading frequency (Hz)	Shear plate Orientation[b]	Control method
0202	54	7.25	213	0.1	E-W	PID
0222	75	7.25	213	0.1	E-W	Open loop
0258	75	7.25	213	0.1	N-S	Open loop
0515	94	7.25	213	0.1	E-W	Open loop
0543	90	4.5	213	0.1	E-W	Open loop
None (test failed)	104	4.5	213	0.1	E-W	Open loop
0637	104	4.5	213	0.1	N-S	Open loop

[a]Test end time HHMM in Central time zone, [b]East-West or North-South

As previously described, the shear stress applied in laboratory CDSS tests is typically on a horizontal plane relative to the in situ sample whereas the CBST applies shear stress on a vertical plane. Therefore, two different values of normal stress were examined for the field CBSTs. In the first four tests, a normal stress of 7.25 psi was applied to achieve the same normal stress applied in CDSS tests, while in the final three tests a normal stress of 4.5 psi was applied to restore the estimated value of in situ horizontal effective stress that was removed by creation of the borehole. A range of cyclic shear stress amplitudes was selected for the CBSTs to give a similar range of cyclic stress ratio (CSR) values used in the previous study (*9*). However, the previous study involved saturated specimens and the application of only one CSR amplitude to each specimen, whereas the in situ CBSTs were not performed on saturated soil and involved an increase in shear stress (or CSR) after every 10 cycles. Because the soil was not saturated in the CBSTs, the hysteresis loops did not expand to larger shear displacements like the CDSS tests.

Overall, the CBST data from the Oregon site were the highest quality obtained throughout the project, as can be seen in Figure 46 for Test 0637. For closer inspection, the data for a 300-second interval containing 30 loading cycles was extracted from this test and is shown in Figure 47. The data exhibits very clean hysteresis loops with relatively good control of the shear stress amplitudes, which as previously mentioned were manually increased every 100 seconds (i.e., every 10 cycles at 0.1 Hz). The plot of horizontal displacement in Figure 46 shows that the shear head initially expands by approximately 0.26 in. to meet the borehole wall and apply normal stress, then continues to expand an additional 0.01 in. during the consolidation phase prior to shearing. In Figure 47, the horizontal displacement plot shows that the shear head ratchets outward very slightly with increasing cycles of loading. The pore water pressure initially increased during the consolidation phase but decreased upon the start of cyclic shearing and became negative after the 27th loading cycle (Figure 46). Similar negative pore pressure responses were observed in most tests above the water table in this study, which may be due to soil dilation or partial saturation. Future tests will target soils below the water table to ensure that the CBST can generate and measure positive excess pore pressures during shearing, and possibly capture liquefaction type phenomena.

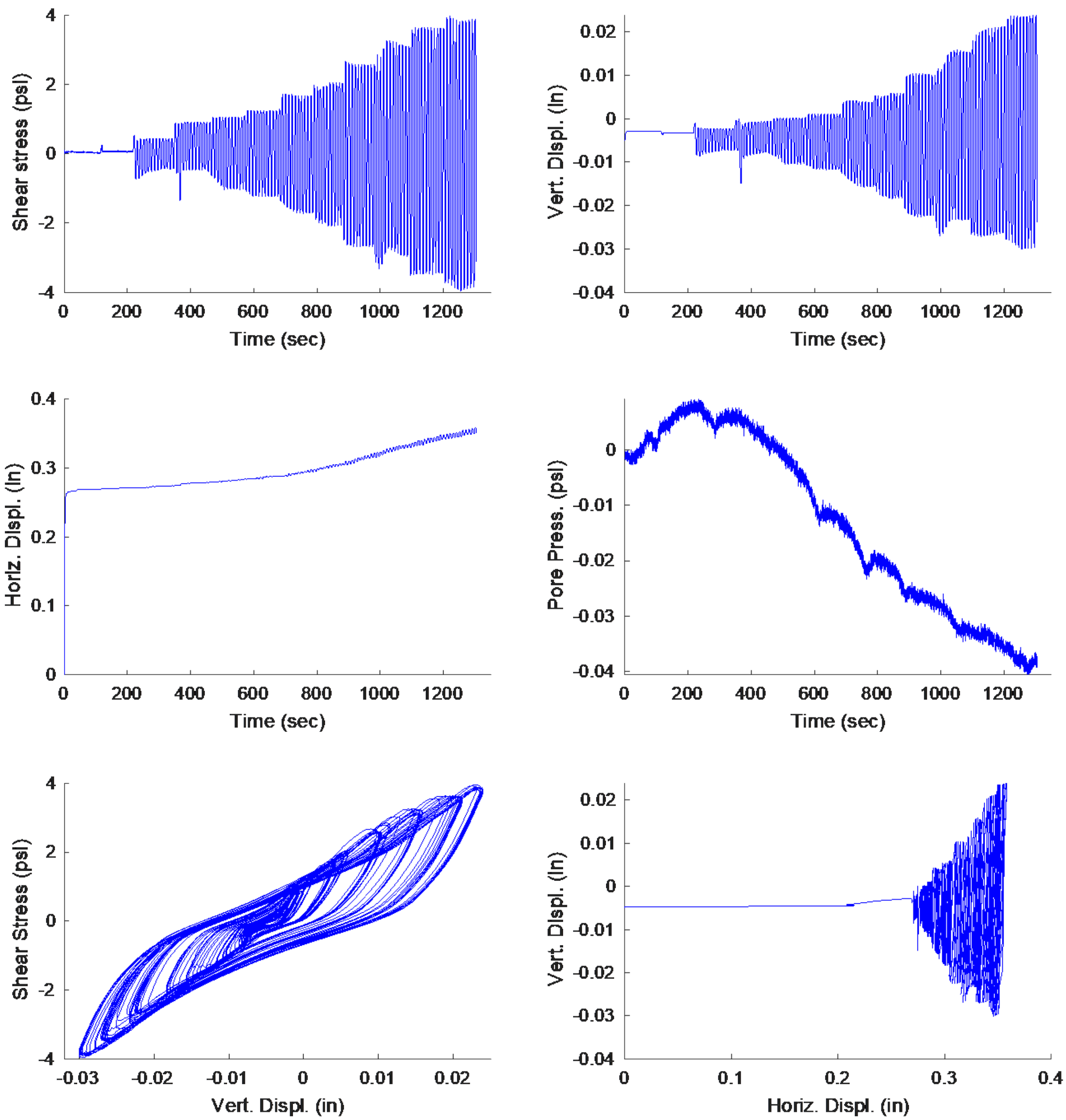


FIGURE 46 CBST Test 0637 at Oregon site at 104 in. depth with 4.5 psi normal stress, 0.1 Hz frequency, consolidation time of 213 seconds, and open-loop control

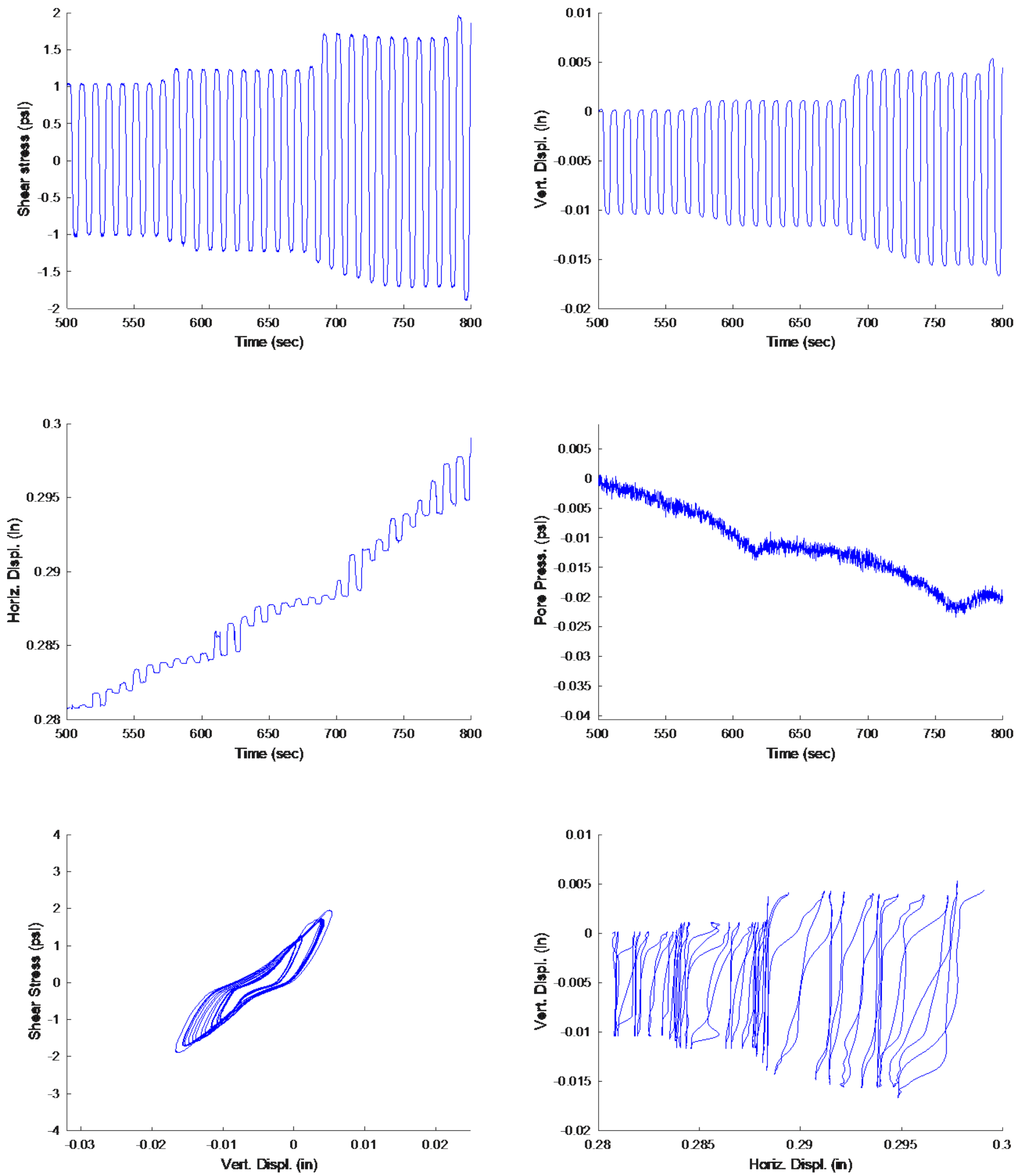


FIGURE 47 Data from previous figure extracted for 500 ≤ t ≤ 800 sec, illustrating the degree of control over loading frequency of 0.1 Hz (period of 10 sec) and shear stress amplitude

The measured in situ shear stress vs. shear displacement hysteresis loops for Tests 0515 and 0637 are compared in Figure 48. The results show the expected behavior in that Test 0515 with the larger applied normal stress of 50 kPa (7.25 psi) results in greater stiffness and smaller shear displacements than Test 0637 which has a lower applied normal stress of 31 kPa (4.5 psi).

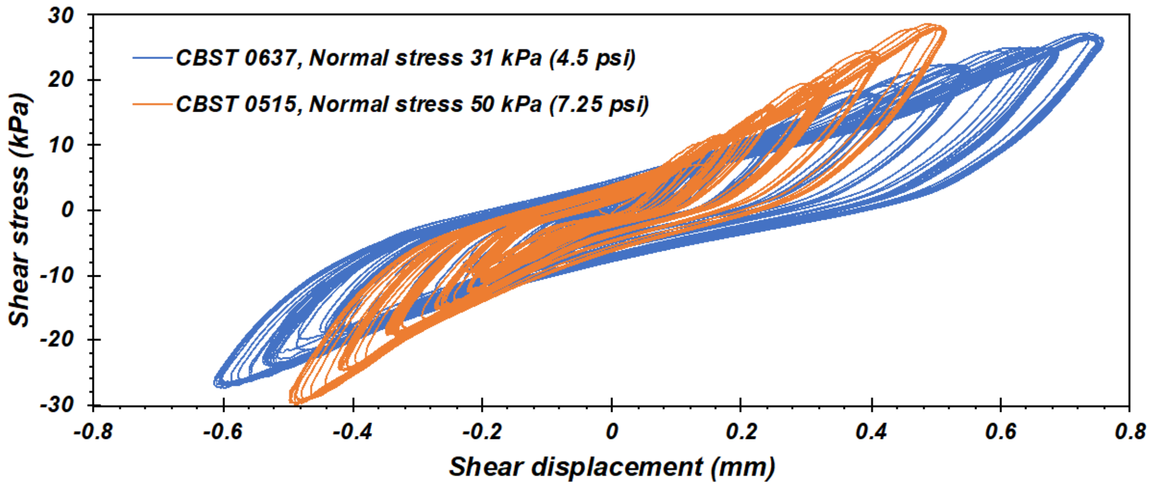
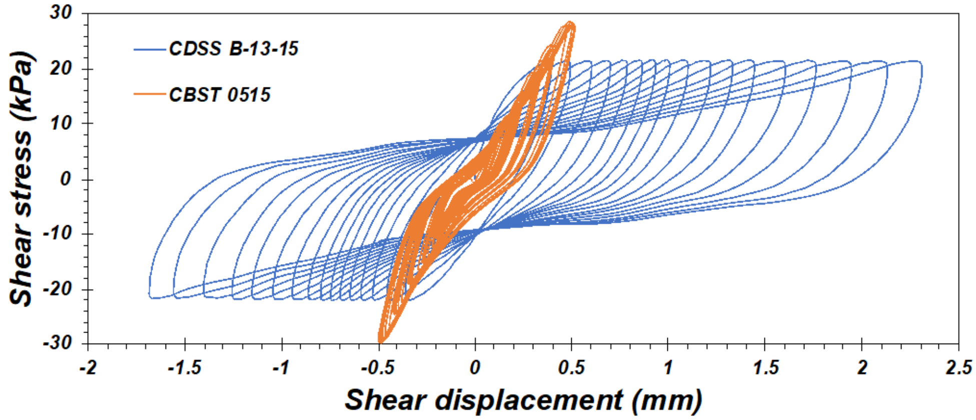


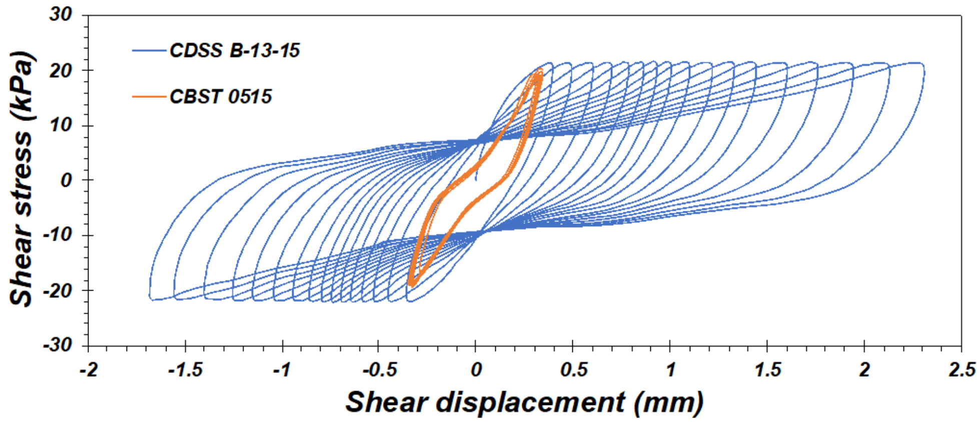
FIGURE 48: Shear stress-displacement hysteresis loops for CBST Test 0515 with normal stress of 50 kPa (7.25 psi) and Test 0637 with normal stress of 31 kPa (4.5 psi)

Hysteresis loops from the laboratory CDSS test B-13-15 are also compared to those from the in situ CBST Tests 0515 and 0637 in Figures 49 and Figure 50, respectively. Similar results were obtained for the other CBST tests of Table 2. To make direct comparisons with the unaltered CDSS results, the CBST data were converted to SI units for these figures. The assumed thickness values for converting the measured CBST shear displacements to shear strains for these two figures were 20.3 mm (0.8 in.) for Test 0515 and 30 mm (1.2 in.) for Test 0637. Overall, the comparisons look promising in that similarly shaped hysteresis loops indicative of cyclic mobility were exhibited in both the laboratory and in situ tests. The results also suggest that it would be useful to increase the maximum usable stresses of the CBST, which may be possible by using larger pneumatic cylinders or switching to air-over-oil control, or replacing the vertical pneumatic cylinder with a servo-electric linear actuator if feasible.

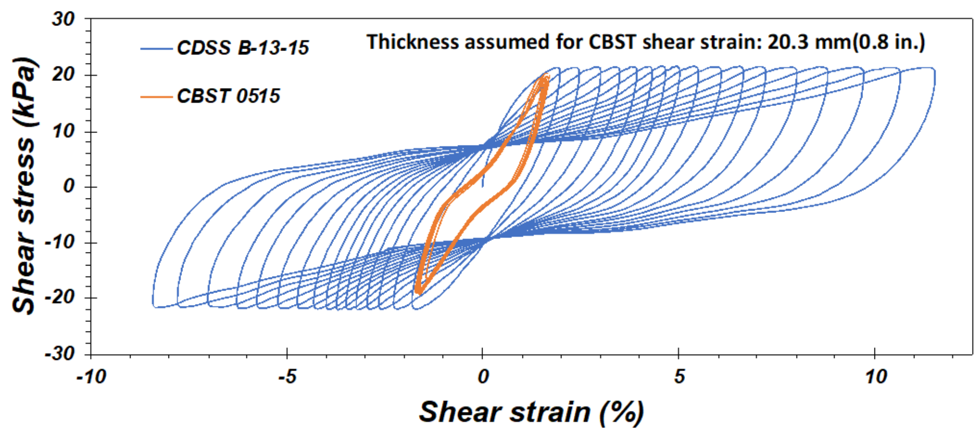
During this suite of tests, the hand auger was used up to the maximum possible depth but the water table was not encountered. Therefore, the tests were not performed on saturated soil as planned, and this objective remains a target for future research. One of the original research goals was also to demonstrate the CBST for Caltrans. However, several more field trips were performed than initially planned for the project and the team was not able to make a trip to Caltrans. Instead, videos of the testing process were created during the Oregon field trip with the help of three graduate assistants. The videos and test results are being edited to create a video to demonstrate the capabilities of the device to Caltrans, and the research team will pursue future opportunities to demonstrate the CBST to Caltrans in person.



(a)

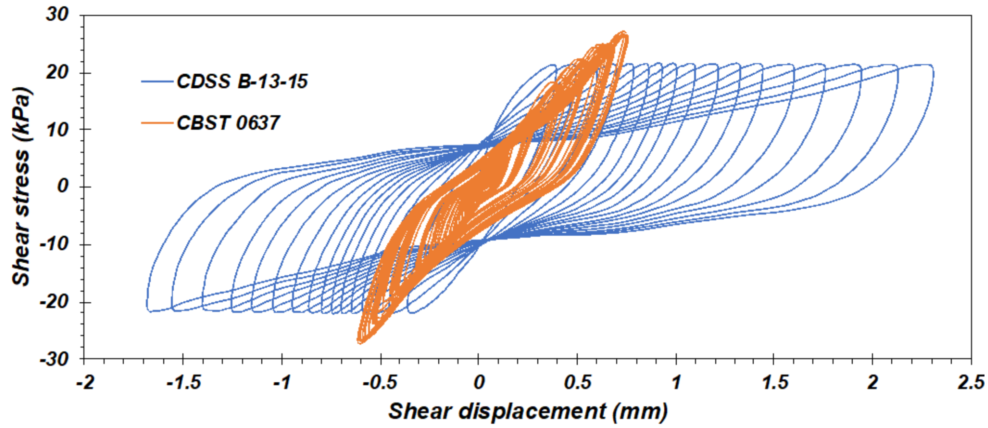


(b)

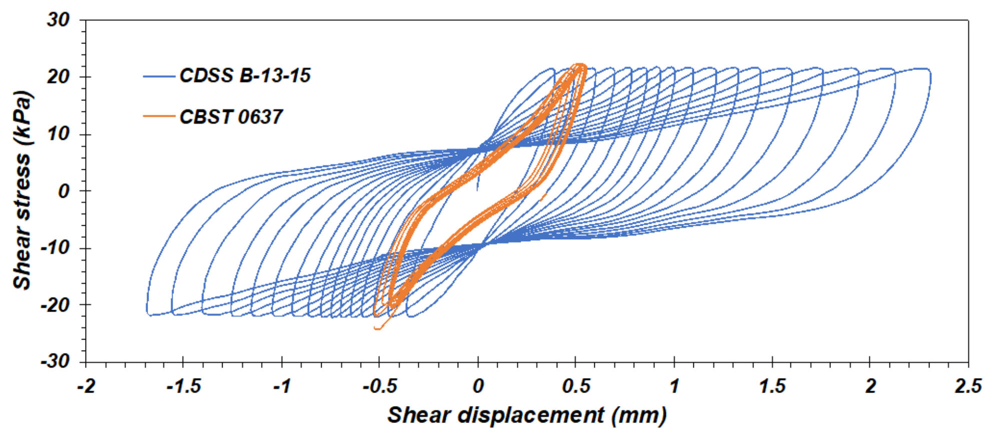


(c)

FIGURE 49 Comparison of hysteresis loops for CDSS Test B-13-15 and CBST Test 0515; (a) Complete CBST data with 10 cycles at each of several increasing shear stress amplitudes, (b) CBST loops extracted for shear stress amplitude of approximately 20 kPa, (c) 20 kPa loops plotted vs. shear strain using assumed representative thickness of 20.3 mm (0.8 in.) for CBST



(a)



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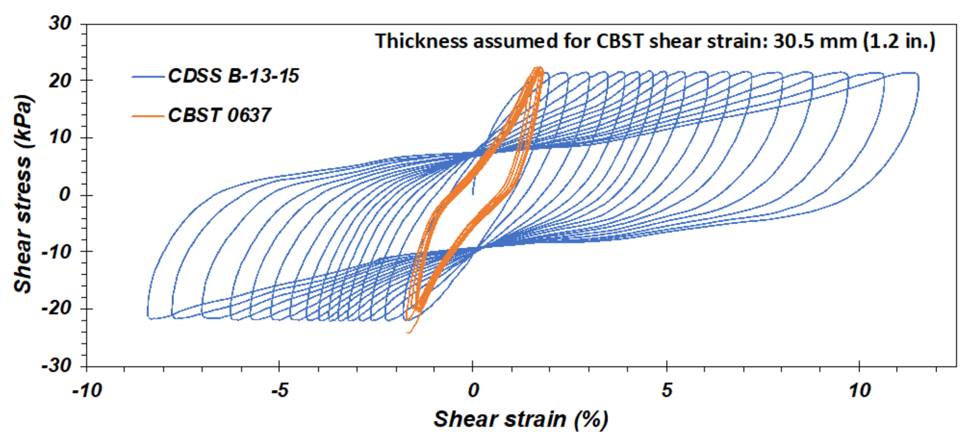

(c)

FIGURE 50 Comparison of hysteresis loops for CDSS Test B-13-15 and CBST Test 0637; (a) Complete CBST data with 10 cycles at each of several increasing shear stress amplitudes, (b) CBST loops extracted for shear stress amplitude of approximately 20 kPa, (c) 20 kPa loops plotted vs. shear strain using assumed representative thickness of 30.5 mm (1.2 in.) for CBST

PLANS FOR IMPLEMENTATION

The potential user base for the CBST consists of DOTs as well as geotechnical design firms who presently offer in situ or laboratory testing services, specialty contractors who perform drilling and sampling and/or in situ testing, certain government agencies such as the USDA, and academic researchers. The implementation plan is to continue to use the device in demonstration tests for potential users including the Iowa DOT and Caltrans, and to submit proposals for further research projects. The stated purpose of Type 2 IDEA project grants is to develop and test prototypes of proven concepts. Since this Type 1 IDEA project successfully developed a working prototype that demonstrated that cyclic soil properties including pore pressure can be measured in situ, a proposal will be submitted for a Type 2 IDEA grant. An FHWA/State DOT-sponsored pooled fund study may also be pursued.

The data from the Oregon test site will also be analyzed further in collaboration with researchers from OSU, and the results will be disseminated through technical journal papers, conference papers, and presentations. Further research on the CBST device developed in this study will focus on tests in saturated soils with comparison to laboratory CDSS tests, and numerical modeling to determine appropriate relationships for estimating in situ shear strains for the soil in a representative volume adjacent to the CBST shear plates.

To facilitate technology transfer, a link to the final report will be hosted on the InTrans website at ISU and the PI will apply to give presentations and webinars on the CBST to technical subcommittees of AASHTO, including the Materials and Pavements Committee. To reach a wider audience of potential DOT and industry users, the PI will also apply to deliver AASHTO and ASCE webinars. To reach the academic community, the research team and collaborators will publish project results in scholarly journals and conference proceedings. The PI will also work to develop ASTM and AASHTO standard test methods on the performance of Cyclic Borehole Shear tests. The PI served as Chairman of ASTM Subcommittee D18.09 on Cyclic and Dynamic Properties of Soils for six years and as vice-chairman for six years, and has experience drafting and revising ASTM standards.

The commercialization plan is for the technology to be licensed through the ISU Research Foundation (ISURF) of the ISU Office of Intellectual Property and Technology Transfer. It is anticipated that Handy Geotechnical Instruments, Inc. (HGI) will obtain a license or option from ISURF for the software control program. During both the commercialization and implementation phases, the PI will adhere to the conditions of his Conflict of Interest and Commitment Management Plan. According to the requirements set forth by this plan, HGI was not involved in the IDEA research project and will not be involved in the implementation phase, after which the PI will work solely through his role with HGI during the commercialization phase.

CONCLUSIONS

In this project, a Cyclic Borehole Shear Test device was developed to enable the rapid in situ measurement of cyclic behavior and monotonic shear strength properties of soil. The CBST is unique in its ability to measure the parameters in the soil's natural setting, under cyclic loading, and in a matter of minutes whereas present laboratory techniques can require several weeks. By testing the soil in situ, the device will save time and money, while reducing effects of soil sample disturbance which can significantly affect laboratory test results. Based on the results of several field testing trials, numerous refinements and modifications were made to the system including the physical testing apparatus inserted into the borehole, the electronic and pneumatic measurement and control system, and the software control program. Comparisons of field CBST results to those of conventional laboratory cyclic direct simple shear tests demonstrated that the device can measure meaningful cyclic behavior of soil in situ.

Further research will be pursued to determine the shear strains more rigorously in the soil surrounding the borehole using the measured displacements, and to study applications of the device to in situ measurement of the liquefaction behavior of soils. With further research, the device thus has the potential to fundamentally transform the presently empirical techniques used in practice for assessment of soil liquefaction resistance into a more mechanistic physics-based framework. The device also has several other potential applications such as measurement of residual shear strengths relevant to landslides, in situ characterization of the nonlinear dependence of shear modulus and damping on shear strain and stress state relevant to seismic and dynamic problems, and soil behavior under general cyclic loading relevant to a wide variety of geotechnical problems such as pavement subgrades and foundations of offshore structures, wind turbines, bridges, and marine retaining walls among others.

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APPENDIX: RESEARCH RESULTS

TITLE:

Development of In Situ Cyclic Borehole Shear Soil Test Device

SUBHEAD:

This research developed a Cyclic Borehole Shear Test (CBST) device to enable more efficient measurement of cyclic soil behavior in the ground rather than in a laboratory. The device has many potential applications in geotechnical engineering including soils and foundations subjected to earthquakes.

WHAT WAS THE NEED?

Soil shear strength parameters are required inputs for the safe design of foundations and earth retaining structures for virtually all transportation infrastructure including bridges, buildings, railways, wharves, piers, ports, tunnels, and pavements. Additionally, measurement of dynamic and cyclic soil behavior is important for problems in seismic design, post-cyclic strength, and liquefaction susceptibility analysis. These parameters are typically obtained by retrieving soil samples and testing them in the laboratory, which is time-consuming, and the results are sensitive to disturbance that is unavoidable in the sampling and preparation procedures for the laboratory tests. Alternatively, the shear strength parameters may be obtained from empirical correlations to common in situ penetration tests such as the Standard Penetration Test or Cone Penetration Test. However, neither of these tests directly measure the shear strength, and instead rely on empirical correlations that may be imprecise due to large statistical variability. Furthermore, the common in situ tests do not subject the soil to continuous cyclic stress reversals as experienced during earthquakes or under sources of vibration loads. To help advance the state of the art for characterization and assessment of dynamic soil behavior, this project addressed the need to measure the in situ response of soils to continuous cyclic loading including the evolution of pore water pressure.

WHAT WAS OUR GOAL?

The goal was to develop a soil testing device for measuring the cyclic behavior of soils in the ground rather than in a laboratory, with the ability to apply constant normal stress along with continuous cyclic shear stresses like those experienced by soils in earthquake or repeated loading scenarios, while measuring the resulting change in pore water pressure. This would enable engineers to obtain measurements of soil parameters more efficiently and possibly more accurately, for design of foundations of civil infrastructure.

WHAT DID WE DO?

During the research project, the following goals were accomplished:

- Developed a prototype in situ test device to apply normal stress and cyclic shear stress to the soil surrounding a borehole
- Performed several field trials in Iowa, South Carolina, Maryland, Virginia, and Oregon
- Made several rounds of revisions to the downhole device, sensors, measurement system, control system, and software program based on the results of field tests
- Compared field test results to those of traditional cyclic laboratory tests performed on soil specimens from the same test locations
- Developed a plan for implementation and technology transfer and identified future directions for research and commercialization of the working prototype device
- Received support or assistance from several organizations and individuals including the Iowa DOT, Oregon DOT, Caltrans, In-Situ Soil Testing LC, Roger Failmezger, Bob Hunsicker, Eichner Engineering, Southern Engineering, US Army Corps of Engineers, SEQ Drilling Inc., Stable Ground In-Situ, McClure Engineering, Braun Intertec, Foundation Engineering Inc., and Oregon State University

WHAT WAS THE OUTCOME?

The project developed a new in situ cyclic soil test to provide rapid measurement of cyclic and static soil properties relevant to a wide range of civil infrastructure such as buildings, bridges, levees, and dams. Field tests were performed in five states and the entire testing system and software were refined several times based on the results. Through comparison to laboratory tests, the device was demonstrated to produce meaningful data on cyclic soil behavior including the generation of pore water pressure. Directions for future research and commercialization of the device were identified, including analytical and computational studies for relating the displacement measurements to shear strains.

WHAT IS THE BENEFIT?

The new CBST device enables rapid in situ measurement of cyclic soil behavior needed for design of foundations subject to dynamic or repeated loading conditions such as earthquakes or vibration sources. The device measures the actual physical mechanisms responsible for liquefaction; namely, stress, displacement (related to strain), and pore-water pressure. It has the potential to fundamentally transform the empirical techniques currently used in practice for assessment of soil liquefaction resistance into a more mechanistic, physics-based framework. Thus, the CBST may help advance the safety and sustainability of transportation infrastructure by improving the reliability and accuracy with which foundations are designed and the liquefaction susceptibility of soils is assessed.

LEARN MORE

A link to the final report may be found on the InTrans website at ISU; intrans.iastate.edu

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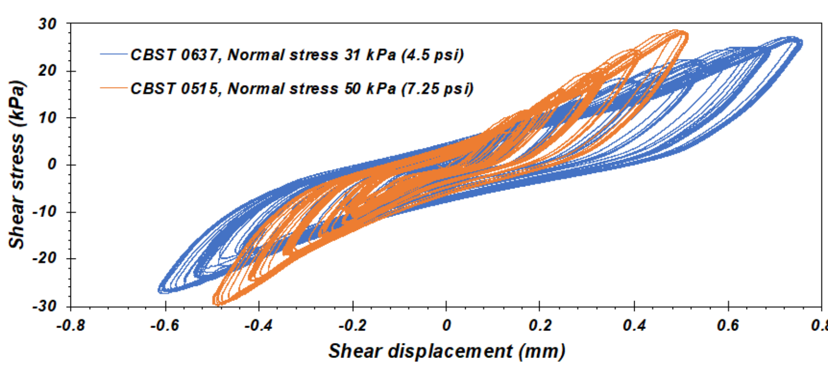
IMAGES

(a) (b)

Field tests in Fort Dodge, IA; (a) CBST control and data acquisition equipment, (b) downhole device after test in sandy lean clay fill



Measured stress-displacement loops from two tests in the same borehole with different applied normal pressures in Corvallis, OR

Sidebar Info

Program Steering Committee: NCHRP IDEA Program Committee

Month and Year: February 2023
Title: Development of In Situ Cyclic Borehole Shear Soil Test Device

Project Number: NCHRP-221
Start Date: January 1, 2020
Completion Date: December 31, 2022

Product Category: Highway

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