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Suction-controlled dynamic simple shear apparatus for measurement of dynamic properties of unsaturated soils

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Abstract. State variables such as confining pressures and the degree of saturation can have a profound effect on the dynamic properties of a soil. These dynamic properties are essential when performing seismic response analysis of geotechnical systems in the phreatic zone. In order to accurately obtain these properties, laboratory testing using a Dynamic Simple Shear system is often implemented. This paper concentrates on the advancements and modifications of a custom-built dynamic simple shear system at the University of New Hampshire to accommodate soils with unsaturated conditions by employing axis translation technique. Tests could be performed under drained (constant suction) or undrained (constant water content) conditions. The procedure for preparing an unsaturated soil sample and testing is discussed, followed by the methods for interpreting the data and the challenges involved. Preliminary data confirms the ability of the system to control and track suction during the cyclic simple shear test. Suction in unsaturated soil increased the shear modulus and decreased the damping ratio comparing with those in dry and saturated conditions.

1 Introduction

The surficial part of the earth is mostly partially saturated except where the water table is at shallow depths. The dynamic response of unsaturated/partially saturated soils is complex and differs from that of dry or saturated soils. Thus, characterizing the dynamic material properties of soils with various degrees of saturation is crucial in seismic analysis of geotechnical systems.

The Dynamic Simple Shear (DSS) apparatus at the University of New Hampshire (UNH) has been recently modified and upgraded for unsaturated soil testing and more accurate data acquisition. A summary of these developments, testing procedure, and experimental results verifying the performance of the system is presented and discussed in this paper.

2 Background

2.1 Dynamic Properties of Soils

The stress-strain dynamic response of soils is non-linear where the induced strain controls the soil stiffness modulus [1-3]. At extremely small strains soils tend to behave elastic while at medium to larger strains, however, soils lose a significant portion of their stiffness. The shear modulus, G, is the ratio between the shear stress and strain imposed to a particular soil element. The small-strain shear modulus, G_{max}, is basically the initial slope of the shear stress-strain curve. Both G and G_{max} have been investigated extensively resulted in several empirical equations. Further, the damping ratio represents the dissipated energy in the system. However, it increases in higher shear strains with a minimum at the small strain range. Accurate estimation of shear modulus and damping for varying induced shear strain levels during an earthquake is critical in better understanding and simulation of seismic response of geotechnical systems.

The reduction of shear modulus by increasing the shear strain is typically presented using normalized shear modulus reduction functions. This modulus reduction function has been improved over the past decade starting from a simple hyperbolic form. The most recent version of this equation, developed based on compilation of numerous dynamic laboratory test results, has been presented by Oztoprak and Bolton [4], as shown in Equation 1.

$$\frac{G}{G_{max}} = \frac{1}{[1+\left(\frac{\gamma-\gamma_e}{\gamma_r}\right)^a]} \quad (1)$$

where γ_r represents a reference shear strain when G/G_{max} is equal to 0.5. ; γ_e is the elastic threshold strain that signifies when the soil starts to experience stiffness degradation; and a is a curvature parameter [4].

In addition, damping ratio functions were also defined where damping increases proportional to the modulus reduction. Measuring the shear modulus and damping in medium to large strain requires accurate testing and measurement approaches that may differ between the

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testing apparatus such as cyclic triaxial, cyclic torsional shear, and dynamic simple shear tests.

2.2 Dynamics of Partially Saturated Soils

Both shear modulus and damping mainly depend on the effective stress in the soil. Thus, changes in effective stress due to fluctuation of degree of saturation could lead to different stiffness and damping values. Specifically, increasing the suction as a result of soil desaturation increases the effective stress; according to Bishop's effective stress formula presented in Equation 2.

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w) \qquad (2)$$

This equation is compliant with Terzaghi's classical effective stress equation. The parameter ($\sigma - u_a$) represents the net normal stress and (u_a - u_w) represents the matric suction applied to the soil element. The term χ is often called Bishops effective stress parameter; it is a function of the soil elements degree of saturation and typically ranges from 0 (completely dry) to 1 (fully saturated) [5, 6].

In recent years, empirical equations have been developed to correlate the effective stress parameter to different hydraulic properties of soils such as van Genuchten Soil-Water-Retention-Curve parameters [6, 7]. For example, Lu et al. [8] proposed Equation 3 based on suction stress concept in unsaturated soils.

$$\chi = \left\{\frac{1}{1+[\alpha(u_a-u_w)]^n}\right\}^{1-\frac{1}{n}} \qquad (3)$$

where α and n are SWRC fitting parameters.

Recently, owing to the advancement of unsaturated soil mechanics, effect of suction on dynamic properties of soils has received more attention. This includes estimating the small strain shear modulus of unsaturated soils using resonant column or bender element tests [e.g. 9-12] and determining the strain-dependent modulus using cyclic triaxial systems [e.g. 13,14]. These studies consistently reported a higher modulus in unsaturated soils. However, less of these work have been on strain-dependent dynamic properties, which require further investigation.

2.3 Dynamic Simple Shear Apparatuses

The development of the Dynamic Simple Shear (DSS) apparatus was introduced by the Swedish Geotechnical Institute in the mid-20th century [15]. The objective of the project was to create a device in which uniform shear strains could be imparted onto soil samples that were subjected to shear loads. Prior to this time, most samples were tested using the standard direct shear box. The advantage of DSS apparatus over the direct shear test has been shown to impart uniform shear strains along the whole sample specimen instead of a single forced plane of shear that is applied in the direct shear test [16, 17].

In recent years, variations of these systems have been developed to produce different field conditions and loading patterns to the soil samples. Developers at UCLA have been able to effectively produce multidirectional horizontal loading using complex PID controls [18]. Additionally, the development of a double specimen DSS apparatus has also been developed to eliminate errors due to potential mechanical inaccuracies [3].

3 Description of the UNH DSS

3.1 Current System

The Dynamic Simple Shear system at the University of New Hampshire was developed in 1992 [19]. The system was initially built to study the small strain behaviour of Holliston 00 sand in relation to thixotropic effects. The system was then further modified in 1998 to effectively produce even smaller strains that could be applied to reconstructed Gulf of Mexico clay samples [20].

The system is comprised of multiple parts including (1) the framework, (2) vertical and horizontal actuators/movement, (3) a control system hardware/software and data acquisition (DAQ) system, and (4) a series of valves, piping, and a flow pump to provide saturation and various suction pressures. The framework of the system is comprised of a steel frame based on top of a steel table. Two sets of Thomson ball slides provide guides for the bottom platen of a soil sample system to be loaded in a horizontal direction, and a top platen to be loaded in the vertical direction. The soil sample cell is based off of the SGI-DSS configuration in which Teflon coated aluminium rings and membrane confine the soil. The soil cell is 10.16 cm (4 inches) in diameter and approximately 2.54 cm (1 inch) in height. The system schematic is shown in its entirety in Figure 1.

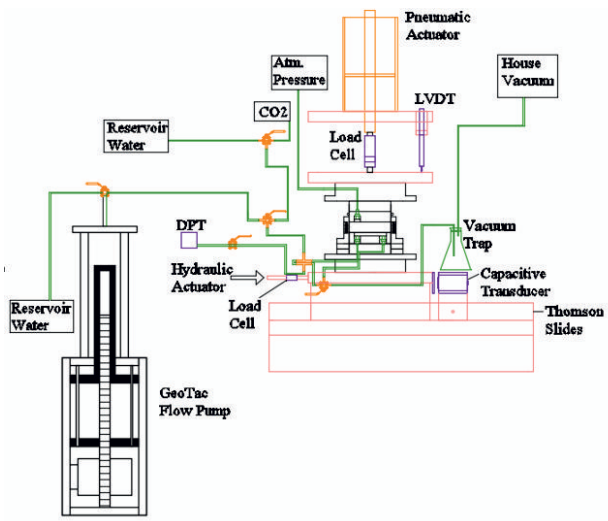

Figure 1. Schematic of the UNH DSS

One of the implications of using the DSS is that the lateral/horizontal confining pressures cannot be readily determined. This becomes critical when determining the mean effective stress that should be applied in the small strain modulus equation. The assumption of using the at-rest (K_0) pressure for the sides is often used to estimate the horizontal effective stress. In theory, this assumption

would be correct if the soil were tested in a static condition. However, since the soil sample is subjected to a horizontal cyclic load, the horizontal confining pressures would be in the active or passive condition depending if it is loaded or unloaded, respectively. Additionally, the confining rings cannot provide a coupling vertical shear force along the sides of the soil sample, thus limiting the capability to impart uniform shear forces along the sides of the sample [17].

3.2 Modifications for Unsaturated soil Testing

Figure 2 shows the general setup for most of the modified soil cells for laboratory testing of partially saturated soils. The High Air Entry Value (HAEV) ceramic disk that is often used allows for water to pass through the disk, while prohibiting the flow of air through (past a certain threshold value). The HAEV disk utilized in the UNH-DSS system is rated at ½ bar (50 kPa). A schematic and picture of the modified cell in UNH DSS system is shown in Figure 3.

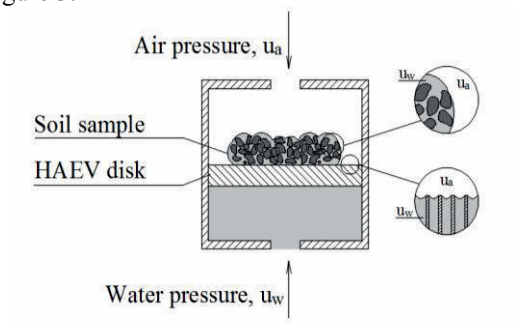

Figure 2. Soil sample in a hypothetical soil cell [6]

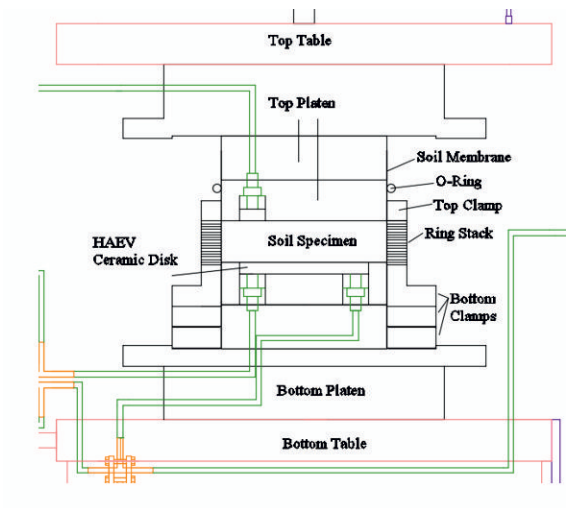

Figure 3. Schematic of modified cell in UNH DSS system.

The axis translation technique was implemented to control the matric suction in a soil sample. In order to use this technique a differential pressure transducer was installed to read the pressure difference between the air at the top of the sample (could be taken as the atmospheric pressure) and the water pressure in the soil sample. The reference axis used for this project was established at the mid height of the sample. As the water level was lowered in the specimen through the use of a Geo-Tac flow pump, the matric suction in the sample was increased. It is critical to ensure that when the matric suction is measured that the sample is at a steady state condition and that the flow of water is nearly non-existent.

4 Testing program

4.1. Testing material

F-75 Ottawa sand, a fine, uniform poorly graded (SP), silica sand was used in this study. The grain size distribution curve was created by performing sieve analysis and is shown in Figure 4. A summary of the geotechnical properties of the tested sand is shown in Table 1 [21, 22].

Prior to running dynamic tests SWRC were determined using the axis translation set up in the system both on wetting and drying paths, as shown in Figure 5. The results are consistent with previously reported SWRC for the same sand [23], thus verifying the success of the system in suction control.

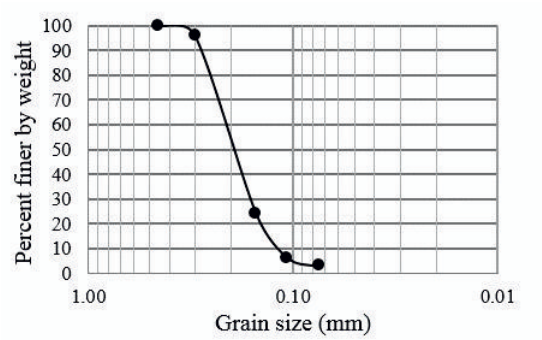

Figure 4. Grain size distribution of the tested material

Table 1. Properties of F75 – Ottawa Sand

Property	Value
Specific Gravity	2.65
e_{min}, e_{max}	0.805, 0.486
ρ_{min}, ρ_{max} (kg/m^3)	1468, 1781
Coefficient of Uniformity	1.83
Coefficient of Curvature	1.09
Specimen Relative Density	45%
Friction Angle (°)	40
van Genuchten's fitting parameters:	
Alpha	0.25
N	8
Residual Water Content (%)	7.15
Saturated Water Content (%)	38.88

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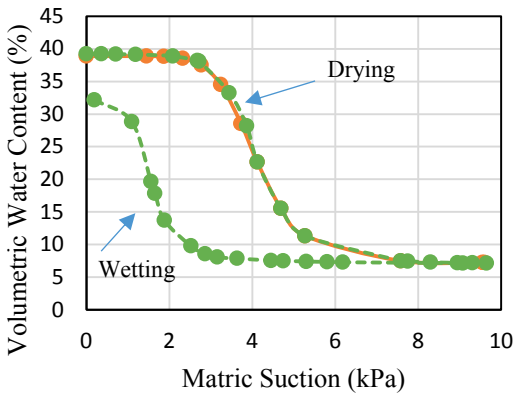

Figure 5. Soil Water Characteristic Curve for F-75 Sand

4.2 Sample Preparation

The soil sample was constructed on top of a bottom platen. Various rings were attached to the platen and were used to clamp a soil membrane around the base of the soil sample. Vacuum grease and O-rings were attached to the membrane to create a seal. A stack of Teflon rings were then inserted onto the sample and made flush with the base. A vacuum mold was installed onto the platen and the membrane was stretched over the top of the mold. A picture of the assembled bottom system before sample preparation is shown in Figure 6.

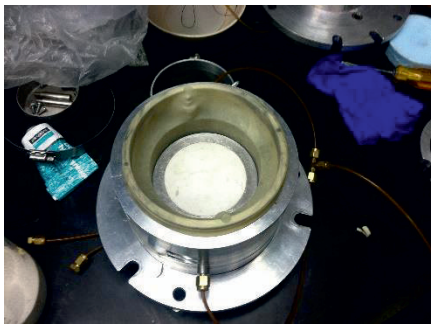

Figure 6. Bottom platen of cell with assembled vacuum mold

A piece of filter paper was then inserted inside the membrane. Ottawa sand was then dry pluviated into the mold to the desired density. It is then levelled off and another piece of filter paper was inserted on top of the sand. A regular porous disk was placed on top of the filter paper and guiding rods were then installed around the edges of the bottom platen. The top platen was then slowly lowered onto the guide rods and on top of the porous disk. An annular clamp was then installed to secure the membrane to the top platen. The vacuum mold was then removed. The soil sample was inserted into the DSS system and clamped into place using T-Clamps that were embedded into the top and bottom platens of the soil chamber. The guide rods were then removed at the end. A picture of fully assembled DSS system ready for testing is shown in Figure 7.

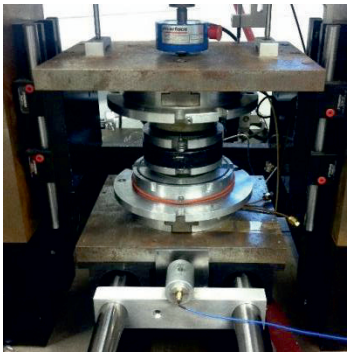

Figure 7. Assembled soil sample chamber in UNH-DSS

4.3 Testing procedure

After preparing the specimen, the sample was vertically confined using a pneumatic actuator and regulator. The vertical load and displacement were manually measured and recorded. The sample was then fully saturated by connecting the sample to a reservoir tank and letting the water flow slowly through the base of the sample and up through the top of the soil sample. After the soil was saturated target matric suction was applied and controlled using the flow pump, which extracts water from the sample. The differential pressure transducer provides an indication of where the water/suction level is compared to the reference axis that was previously mentioned.

After the target matric suction level is reached and considered to be at a steady state condition, the horizontal cyclic motion was applied to the sample using the hydraulic actuator. Tests were performed under drained (constant suction) condition where the pump maintains the suction on the specimen.

In order to provide the cyclic motion, the hydraulic actuator requires a few preliminary steps to function properly. Since the capacitive transducer provides feedback for the PID loop, the initial position of the sensor was placed approximately .025 inches from a target sensor that is mounted on the bottom table. The hydraulic pump was turned on and the control program was activated. The motion parameters (i.e. number of cycles, amplitude, and frequency) for the cyclic motion were inputted into the program. The program was then executed and the displacements and forced were measured and recorded using the displacement transducers and load cells.

4.4 Test program

Although the majority of the system controls have been established and calibrated, the UNH DSS is still in the process of fine tuning the apparatus to provide reasonable results. Three tests were conducted consecutively on a prepared F-75 Ottawa sand and were tested at a strain level of 0.032%. A completely dry, fully saturated, and four partially saturated samples were prepared with matric suctions of 4, 6, 8, and 10 kPa.

A vertical confining pressure of 50 kPa (7.25 psi) was exerted onto the sample. This would correspond with a soil element that would approximately be 3.2 meters

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(10.5 feet) deep (at a relative density of 45%). Each sample was also subjected to 5 cycles of horizontal cyclic loading at a frequency of 1 Hz.

5 Results and Data Analysis

The data that was recorded by the Data Acquisition System (DAQ) was in terms of electrical voltages. Proper calibration techniques were utilized to ensure that the correct stress and strain values were obtained when converting the electrical signals to actual measurements. The data were then corrected to account for the initial stresses and strains that were in the system prior to cyclic horizontal loading. The normal and shear stresses and strains were estimated from the measured displacements and loads throughout the cyclic loading.

As a result, shear stress–shear strain hysteresis loops, similar to the one shown in Figure 8, were obtained from the analysed data.

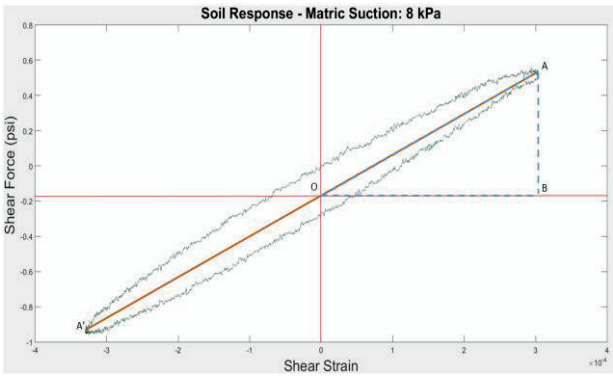

Figure 8. Hysteresis loop of a tested soil sample (8kPa suction)

In this figure, the secant shear modulus was obtained through taking the slope of line A – A'. Points A and A' represent the top and bottom peaks of the cycle. The damping ratio was calculated through the following equation.

$$\zeta = \frac{1}{4\pi} * \frac{Areaof\ Triangle\ OAB}{Area\ of\ Hysteresis\ Loop} \quad (4)$$

Using the methods proposed above the secant shear modulus and damping were calculated for cycles 2-4 in each test and then averaged. The changes of shear modulus with suction and degree of saturation are shown in Figures 9 and 10, respectively. In order to avoid confusion between fully saturated and dry data (in representing soils not subjected to suction), the results of the dry tests are not presented in Figures 9. The shear modulus increases under higher suction (lower degrees of saturation) up to the point of residual water content (at about 8-10 kPa suction). However, the modulus is lower in dry sand comparing with partially saturated ones. This is consistent with previously observed pattern in shear modulus [11].

Further, the damping ratio for tests on different suction and degrees of saturation over cycles 2-4 were estimated and averaged based on Equation 4, and shown in Figures 11 and 12, respectively. Expectedly, stiffer soil in unsaturated condition comparing with the dry and saturated soils resulted in lower damping.

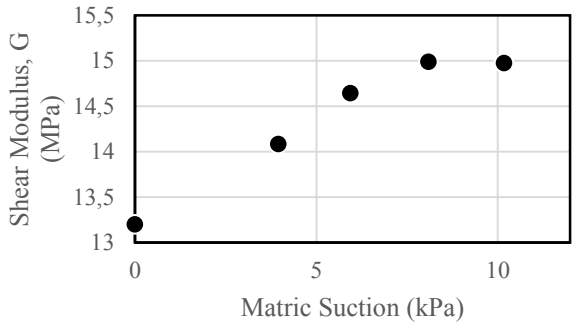

Figure 9. Effects of Matric Suction on Shear Modulus

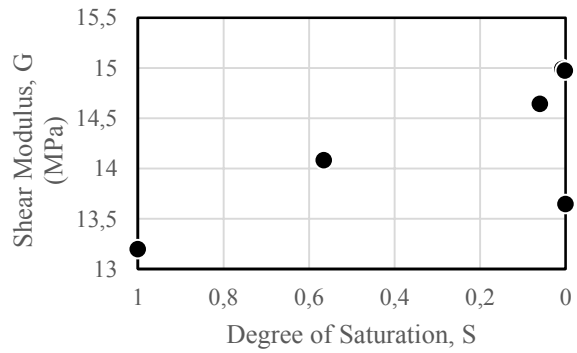

Figure 10. Effects of Degree of Saturation on Shear Modulus

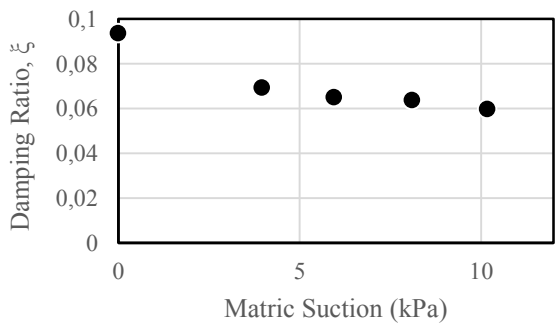

Figure 11. Effects of Matric Suction on Damping Properties

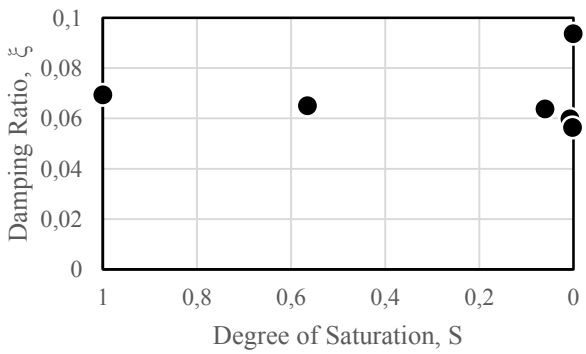

Figure 12. Effects of the Degree of Saturation on Damping Properties

The vertical strain after each test was monitored to track the changes of relative density. The total changes of

relative density before the first and after the last test was less than 5%, which is in the acceptable range considering the accuracy of the sample preparation relative density. Although these tests were performed under constant suction condition, some changes in pore pressure during cyclic loading was expected. However, due to the relatively small shear strain and the resulting minor volume change very little suction change was measured in DPT.

6 Conclusions

The UNH-DSS system was upgraded with new DAQ and modified for unsaturated soil testing using axis translation technique. The data that was obtained through the use of this system has been shown to provide consistent results. A set of constant suction cyclic simple shear test was performed on a sandy soil. The suction in unsaturated soil increased the shear modulus comparing with that of dry and saturated soils. In addition, stiffer unsaturated soil resulted in lower damping ratio. Despite imposing drained condition, changes in suction would be expected in higher shear strain cyclic loads, but it was minimal in low strain cyclic tests presented in this paper.

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