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IN SITU MEASUREMENT OF DYNAMIC PROPERTIES USING THE DOWNHOLE FREESTANDING SHEAR DEVICE

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ABSTRACT

The current paper describes the initial field deployment of the Downhole Freestanding Shear Device (DFSD) at a soft soil site to make in situ measurements of the shear modulus (G) and damping (D) as functions of applied shear strain (γ). Following a brief description of the design and features of the DFSD and its previous laboratory validation, the field procedure for deployment is described in detail. Example field data is presented from a normally consolidated deposit of San Francisco Bay Mud, including both the directly measured parameters and the interpreted data. Comparisons with other available field data are included, as well as a discussion of the particular challenges encountered in the initial field use of this unique device.

Keywords: Dynamic properties, In situ testing, Modulus reduction, damping, sampling disturbance

INTRODUCTION

The variation of a soil's shear modulus (G) as a function of the shear strain magnitude (γ) is a key parameter for accurate site response analysis, particularly for soft soil sites. In the laboratory, the modulus can be measured from representative samples over a wide range of shear strains, using resonant column or velocity methods to measure G_{max} at small strains, and cyclic loading methods (cyclic simple shear, torsional shear, or even triaxial devices) to obtain the modulus at larger strain levels. In the best cases, a full suite of tests can be run on a single specimen, thus reducing the effect of specimen variability, and leading to a single curve which smoothly delineates the reduction of modulus from G_{max} at very small, elastic strain levels, through the much lower G values at strains in excess of 1%. It has long been recognized, however, that the resulting "laboratory curve" for modulus reduction may significantly underestimate the magnitude of the modulus in the field, as comparisons between these curves and carefully conducted shear wave velocity testing at the sites show that the in situ, small strain stiffness can be considerably higher than the value measured in the laboratory. This discrepancy is usually attributed to sampling disturbance – the idea that even if the soil is not significantly sheared or densified during sampling, it may nevertheless experience a significant reduction and re-orientation of effective stresses during the sampling, extrusion and specimen preparation process. This is particularly likely in the case of deeper soils, which undergo a greater degree of unloading. The effects of such unloading on the stiffness of soils have been noted for some time (eg. Athanasopoulos and Richart, 1984), and can vary depending on soil type and stress level.

A new in situ testing method, the Downhole Freestanding Shear Device (DFSD), has been developed to allow performance of high-quality dynamic testing of fine grained soils in situ. The device is deployed in a cased borehole, and currently can be used at depths up to 30 m – all without allowing

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the tested soil to experience appreciable changes from the initial effective stress state. The testing concept consists of performing torsional shear testing on a solid, freestanding cylinder of the soil, using local strain measurements on the undisturbed portion of the specimen under anisotropic stress conditions (Riemer et al, 2001). Many innovations were required to enable this device to meet an array of technical challenges, which are described in detail by Safaqah (2003).

IN SITU APPROACH TO MEASUREMENT OF DYNAMIC SOIL PROPERTIES

Unlike other field methods that seek to estimate dynamic properties by fitting the soil's response to a dynamic impulse through some assumed formulation, the intent of the DFSD is to measure the shear modulus and damping directly, in a manner analogous to a laboratory torsional shear test of a solid cylindrical specimen, in which the torque required to produce different shear strain levels is determined, and hysteresis loops of shear stress (τ) and shear strain (γ) are developed. Performing such a test remotely, at the bottom of a borehole, does introduce some complicating factors, however.

Accessing an "Undisturbed Sample"

In order to minimize the disturbance experienced by the soil in the field, a sample must be created that is not sheared or otherwise deformed in the process of applying the necessary instrumentation, or introducing the loading system. In addition, to bypass the unloading disturbance associated with conventional laboratory testing, it is also desirable to prevent any major changes in the effective stress state of the soil being measured.

The DFSD meets this requirement by carving a 10 cm diameter by approximately 40 cm tall cylindrical sample, the top of which consists of the soil initially forming the base of the borehole, and the bottom of which remains attached to the halfspace of soil below it (illustrated in Figure 1). This sample is created by advancing a "cutter tube", which rotates nearly five times for every centimeter it advances down into the soil, and which is fitted with four sharp blades on its leading edge. These blades carve an annular space approximately 2 cm in width that separates the specimen from the surrounding ground, discharging the excavated material up around the outside of the advancing tube, and leaving a freestanding sample that does not touch the inside of the advancing tube.

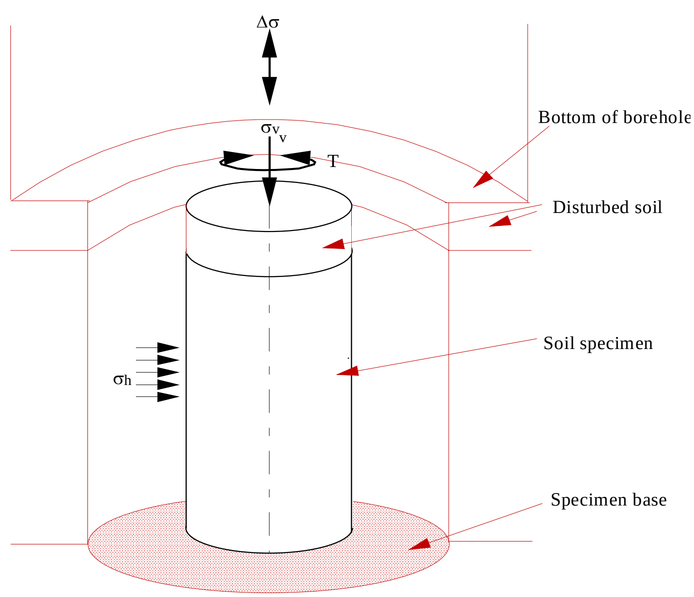

Figure 1. Schematic representation of the freestanding specimen carved below the borehole

In order to maintain the original stress state, an air pressure equal to the estimated total lateral stress is applied during the carving, as is a vertical deviatoric load, calculated to replace the original deviatoric stress present prior to drilling the borehole. Given the uncertainties in accurately predicting such values for the target soil, the applied values are chosen to be slightly below the expected values, as a slight unloading of the material, particularly in the deviatoric condition, is preferable to introducing any additional shearing tendency. In saturated, undrained clays, a minor underestimate in total isotropic stress will be simply be reflected in a slightly lower pore water pressure, with negligible change in the effective stress level.

Despite these measures, it is recognized that the top portion of the resulting sample will already be disturbed by the drilling process even prior to the placement of the DFSD: for this reason it is important to make local measurements of strain on the lower portion of the sample, which is far enough below the borehole to remain essentially undisturbed.

Measurements of Stress and Strain

While the applied torque is constant for all horizontal sections of the sample, and can be measured by the dual-axis load cell at the top cap, the inevitable disturbance of the upper portion of the sample requires that local strains be measured near the sample base. To accomplish this, the sample is enclosed within an instrumented membrane, consisting of a conventional latex membrane to which four Elastomer Gauges (EGs) have been previously attached around the circumference, at a 45˚ angle to the horizontal. These simple but unusual extensional strain gauges have the ability to measure a wide range of strain levels, and can withstand the large degree of stretching required when the membrane is inflated away from the soil during cutting of the specimen. Further details on the development, fabrication, and use of these sensors is described by Safaqah and Riemer (2006).

LABORATORY VALIDATION OF THE DFSD

In order to validate the design and performance of the completed device and its various components, a laboratory program was conducted on two different types of clay, which were reconstituted into large block samples to simulate a deposit in the field. The clay was consolidated from a thick slurry within consolidation chambers (0.3 m diameter) that were equipped with pneumatic pistons at the base, so that controlled levels of pressure could be applied vertically to the slurry, and excess pore pressures could dissipate through porous stones at the top and bottom. Once fully consolidated, the top was replaced by a section of the same 20 cm diameter casing used in the field, and the DFSD was lowered down to the soil surface, as if to the bottom of a borehole, and testing proceeded (Fig. 2)

There were several advantages to validating the DFSD in this manner. Naturally, it was desirable to initially test the device under the controlled conditions available in a laboratory setting, but testing such "young" soil also ensured that there would be no significant aging effects on the stiffness. As a result, samples which were taken using thin-walled Shelby tubes, pushed into identically consolidated blocks of the same clay, could be tested using conventional laboratory methods (Resonant Column/Torsional Shear, performed at UT Austin, and Cyclic Simple Shear, performed at UC Los Angeles), and the maximum shear modulus at small strains should be comparable to those measured using the DFSD.

In addition, preparing the clay from slurry allowed the incorporation of both an accelerometer array and several pore pressure transducers along the central axis of the eventual specimen to be tested. This instrumentation provided the opportunity to assess the degree of disturbance incurred during the cutting of the specimen (which proved to be very slight) and also to measure directly the shear wave velocity (V_S) of the identical soil that was later tested using the DFSD to measure G_{max}. Detailed discussion of the observations relating to disturbance are presented in Safaqah and Riemer (2004).

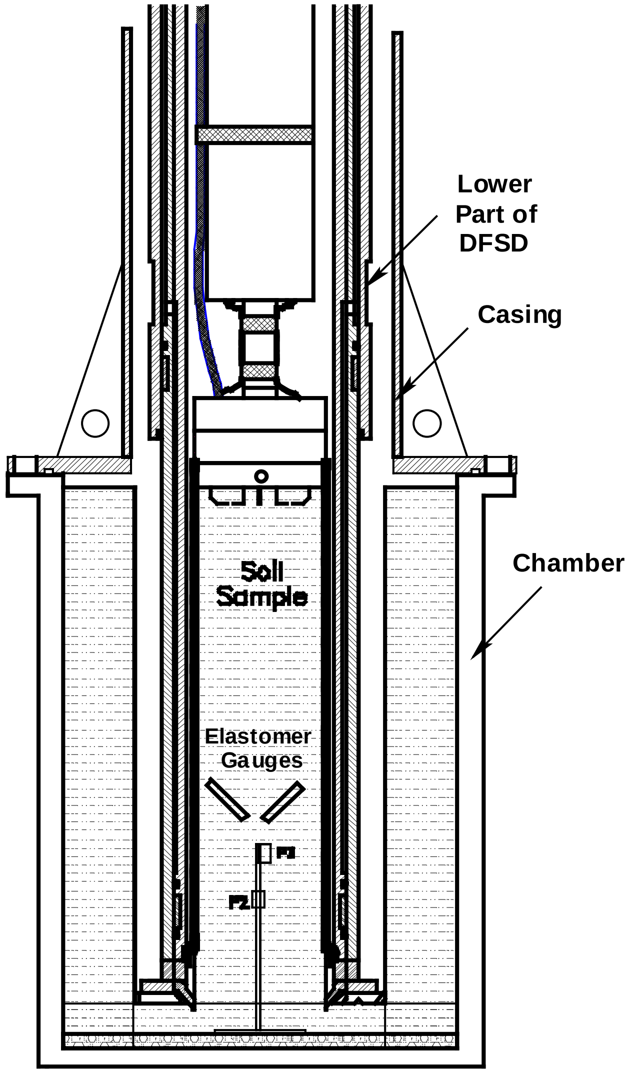

Figure 2. The consolidation chamber, casing and lower portion of the DFSD after cutting sample for laboratory validation. Instrumented membrane is shown deployed on the sample.

Summary data from the laboratory validation testing on reconstituted San Francisco Bay Mud is shown in Fig. 3, including the absolute (non-normalized) values of shear modulus as measured using the DFSD, by the Resonant Column/Torsional Shear Device, and by the Double Specimen Direct Simple Shear method. For comparison, the modulus implied by the recorded shear wave velocity is also included, and can be seen to agree quite well with the DFSD and RC/TS values of G_{max}

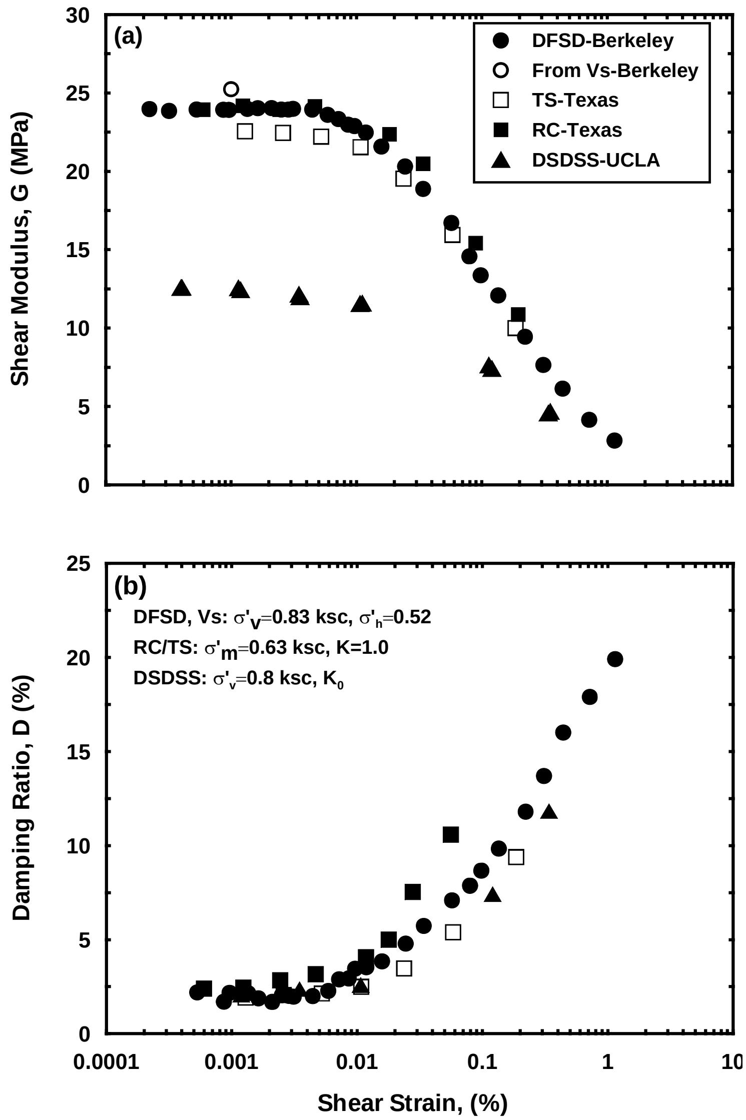

Figure 3. Summary of shear modulus and damping as functions of shear strain for reconstituted Bay Mud, using state of the art laboratory methods to compare with the DFSD.

PROCEDURE FOR FIELD DEPLOYMENT

Preparation of the Borehole

As noted earlier, the DFSD operates within a 20 cm diameter cased borehole. Prior to running a test series, therefore, a drilling contractor advances a borehole initially to within approximately 0.5 m of the desired testing depth, ideally by rotary wash methods and a side discharge bit. The diameter of the borehole is typically somewhat larger than the casing itself, and the boring is full of drilling mud. The 20 cm casing is then installed in 3.2 m segments. The casing is threaded, so instead of joining casing segments using external couplings, consecutive segments thread directly together (which creates a smoother inside surface, and also simplifies determination of the exact depth of the casing in the ground). The casing is extended to a depth such that the tip of the casing is embedded approximately 0.2 m into the soil at the base of the borehole. The casing is then rigidly fixed to the drill rig throughout the subsequent testing process by employing hydraulic clamps on the Fraste rig. This can prove to be very important in soft soils, in which the ungrouted casing could be prone to continued downward settlement in soft soils, particularly as the sample is cut. A different bit is then used within the casing, carefully removing the soil down to the level of the bottom of the casing. It is important that this last portion of drilling be completed as delicately as possible, since excessive downward force on the bit could disturb the soil significantly below the level excavated.

One feature that has already proven to be important in the switch to field testing has been the quality of the bottom of the borehole. While in the laboratory validation, the DFSD had the luxury of working from a very smooth and flat surface across the bottom of the device (as in Figure 2), it is of course very difficult to prepare a borehole to such a state. In order to improve the bottom surface of the borehole in the field, a special "cleanout" fitting has been fabricated from steel pipe and sheet metal, which can be attached to the drill rod, lowered to the base of the borehole immediately prior to insertion of the DFSD itself, and which flattens and smoothes the base of the borehole prior to testing.

Preparation of DFSD

Because the DFSD carves its own specimen, runs a suite of tests on a single in situ specimen, and then returns to the ground surface in the extended position (ideally with the specimen retained inside), the device does require significant attention between consecutive tests. After a successful test, this includes: 1) returning the cutter tube to the proper starting position; 2) removing the sample and the instrumented membrane from the device; 3) removing the outer shell from the load module, to allow disconnection of the load rod from the torque motor; 4) re-installation of the instrumented membrane (if the EGs all remain functional), or a replacement membrane, if necessary; 5) re-attachment of the load rod to the loading system, and replacement of the outer shell; and 6) re-attachment of the cutter rings and slicer blades to the base of the cutter tube. These steps can all be carried out while the DFSD is resting horizontally on its transport cart, either in or near the support trailer

This "re-loading" process of the device is rather involved, and while it may be possible to streamline the process somewhat in the future, to date it has not proven feasible to complete this process quickly enough to conduct multiple tests at multiple depths on a single day. Currently, the most reasonable approach is to prepare the device the evening before a test is to take place, work with the drillers to conduct a single test series at a particular depth, then retrieve the device and spend the remainder of the day preparing for the following test.

Handling of the DFSD

Lifting the device from its transport cart to a vertical position over the casing was accomplished through a series of steps, complicated to some extent by the considerable length of the device when fully assembled (nearly 3 m), and the fact that a large number of "utilities" (pressure hoses, water hoses, and electrical cables) connect to the device at its upper bulkhead. Rather than connecting all the utilities first while the device was horizontal, and then trying to lift and orient the support chains around them, it was easier to lift the DFSD into vertical position first, from solid lifting points near the center of the device, transfer the weight to a shock absorbing support system at the top, and then attach all of the utilities prior to entering the casing. The lifting process is simplified by the use of a split collar that is clamped around the base of the DFSD, and which has a large semi-circular groove on one edge. This groove rests within a rigid cylindrical bar attached to the cart, which acts as a hinge for the device during lifting (Figure 4).

Once the device is suspended vertically over the open casing, and all of the utilities have been tightly mounted to their connections on the bulkhead, the DFSD is slowly lowered into the mud-filled casing in approximately 2 m increments (Figure 5). This must be done in a controlled fashion, because throughout this process an internal air pressure is being adjusted to insure that air pressure within the device is sufficient to prevent intrusion of the drilling mud into the open space around the sample cap at the base of the device. In addition, care must be taken to feed all of the utility lines smoothly into the casing to prevent binding or tangling of the many cables and hoses. It is also crucial to keep close account of the exact depth to which the device has been lowered, to be sure that the DFSD has come to rest on the flat bottom of the hole, and not hung up on some protrusion along the edge of the casing. Contact with the floor of the borehole can also be confirmed by observing an increase in vertical load on the dual-axis load cell. After the placement of the device is confirmed, the DFSD is clamped against the casing by the inflation of three fire hoses positioned around the circumference of the device, which expand between the outer housing and inside surface of the casing, and which are connected with check valves to prevent movement of air back and forth between them. With the device clamped to the casing, and the casing clamped to the drill rig, the pneumatic actuator within the device can then be used to apply a vertical force through the top cap against the bottom of the borehole. This force replaces the overburden stress of the soil removed in creating the borehole, and thus restores the state of stress in the soil below the device to a close approximation of its original levels. This force also embeds the protruding vanes of the top cap into the soil that will form the top of the sample.

Figure 4. Lifting the DFSD off the transport cart, into vertical position prior to deployment.

Cutting the Sample

With the anisotropic stress state restored to the soil, the sample is then cut by carving the annular space down around the 10 cm diameter, cylindrical sample. The cutting process is accomplished by the rotation of the cutter tube around a central threaded rod within the device, and powered by four DC motors running in parallel at approximately 26 volts. The process is carefully monitored within the control trailer, where the outputs of the vertical loads cells, the vertical position of the top cap, and the air pressures within the device all provide important clues as to the success of the cut. Throughout the cutting process, the membrane is kept inflated away from the soil sample and against the inner wall of the device – a state which is confirmed by watching to make sure that the output from the Elastomer Gauges remain stretched and out of measuring range.

Cutting the sample typically requires about 30 minutes to complete, and once the cutter tube has extended down to its desired depth below the initial position (usually between 35 and 40 cm), the DC motors are turned off, and the air pressure on the outside of the membrane is increased to a value slightly higher than that on the inside. This deploys the membrane against the surface of the soil, with the four Elastomer Gauges in direct contact with the lower portion of the soil. It is quite common for the EGs to remain out of measuring range at this point, so they typically must be re-zeroed by adjusting a potentiometer located in the control trailer for each one.

Figure 5. Using the drill rig to lower the DFSD into the mud filled casing. Note flat white hoses for clamping, thinner blue hoses supplying water, and the large hydraulic clamps holding the casing in place.

Cyclic Testing

Because there are no significant stress changes during cutting, there is fortunately no need to wait for the specimen to consolidate prior to testing. Instead, a suite of cyclic torsional tests are performed, beginning with very small rotations and extending up to larger strains. The loading is rotation controlled, applied by a torsional stepper motor built into the upper load module of the device, and controlled by a customized software program developed through the Labview platform. Most of the cyclic loading to date has been performed at frequencies of between 0.25 and 0.5 Hz, though this is adjustable. Typically between 3 and 8 cycles of loading are applied at any given amplitude, with smaller numbers used at larger strains. During the cyclic loading, data is acquired at a rate of approximately 200 readings per cycle, and includes two measures of the vertical load, two measures of the torque, up to four strain measurements provided by the EGs (if all are in range for a particular test), as well as the vertical position of the top cap and air pressures within the device. Figure 6 presents examples of data from a small strain cyclic test performed in Bay Mud, at the West Grand Avenue site near the Bay Bridge in Oakland, from testing at a depth of approximately 10 m, including the two independent measures of torque, and an example of the output from an Elastomer Gauge (note that the polarity of the EG output depends on its orientation, with gauges on opposite sides of the sample being intentionally out of phase to provide more robust measurement).

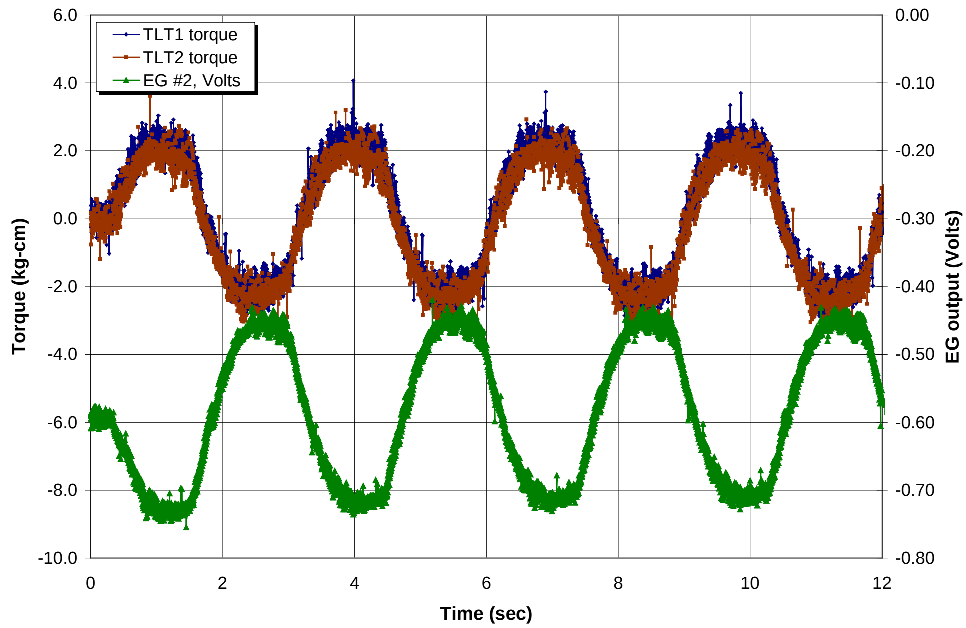

Figure 6. Examples of raw data collected from a small strain cyclic test in Bay Mud

Data Interpretation

Because the load and displacement data are measured directly, the data processing is straightforward and similar to that used in conventional torsional shear testing. The primary difference is that the strains are measured locally, on the exterior surface of the sample, rather than being calculated from a measure of rotation. The Elastomer Gauges are calibrated directly as extensional sensors, in units of percent strain per volt of output for a given excitation, and the shear strain on a horizontal plane is easily shown to be twice the amplitude of the extensional strain of the gauges oriented at a 45˚ angle. Since the EGs are distributed around the perimeter of the sample, averaging the results of the EGs provides a measure of correction against slight bending or other departures from the assumed loading conditions. Simple filtering of the data to remove high frequency noise is also performed.

Finally, since a solid cylinder experiences a variation of strain as a function of radial distance from the axis of the sample, equivalent average shear strain is calculated by multiplying the measured values on the outer surface by a factor of 0.82, as described by Isenhower et al (1987). Although the nonlinear response of soils suggests that a material-specific and amplitude dependent relationship is theoretically required to relate these, for practical purposes a constant factor is adequate until large strains are applied (Safaqah, 2003).

The shear stress and shear strain histories developed from the example test are plotted in Figure 7, showing that this test reached peak strain amplitudes of approximately 0.017% strain, requiring approximately 1 kPa of shear stress to do so. Unfortunately, only one of the four EGs on the membrane provided reliable data during this testing series, so the shear strain data is both noisier and more subject to loading irregularities than was the case for the laboratory data presented earlier. The hysteretic behavior of several of the cycles is illustrated in Figure 8. From these loops, the conventional dynamic properties are easily identified, with the shear modulus, G, being the slope of the loops from peak to peak (in this case, 6.0 MPa), and the damping, D being characterized as the area within the loop normalized by a measure of elastic energy (in this case, nearly 11%):

$$D = \frac{\text{(Area within hysteretic Loop)}}{2\,\pi\,*\text{(Area of Elastic Triangles)}} \qquad (1)$$

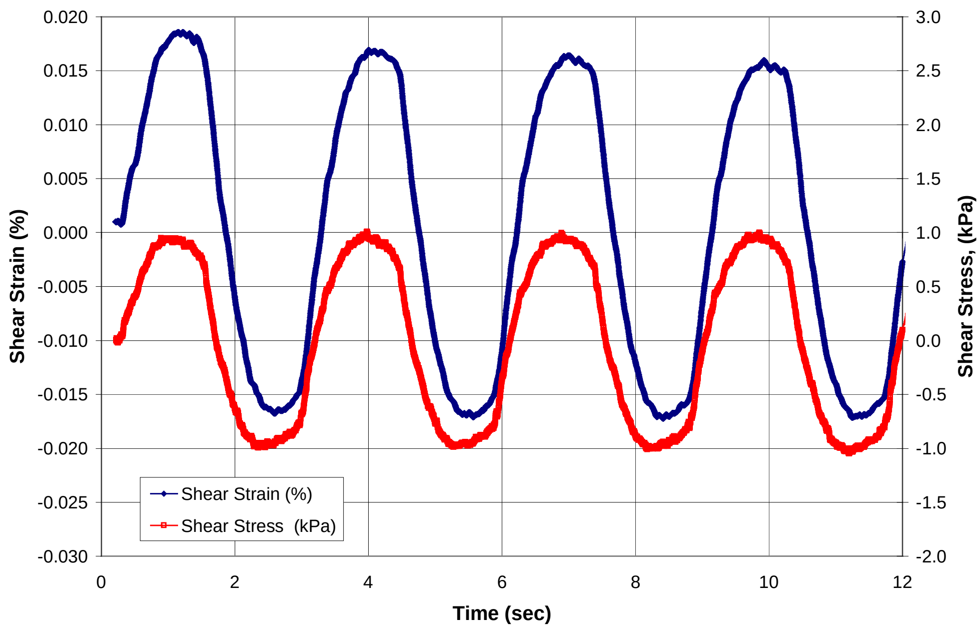

Figure 7. Processed data time histories of stress and strain from data in Figure 6

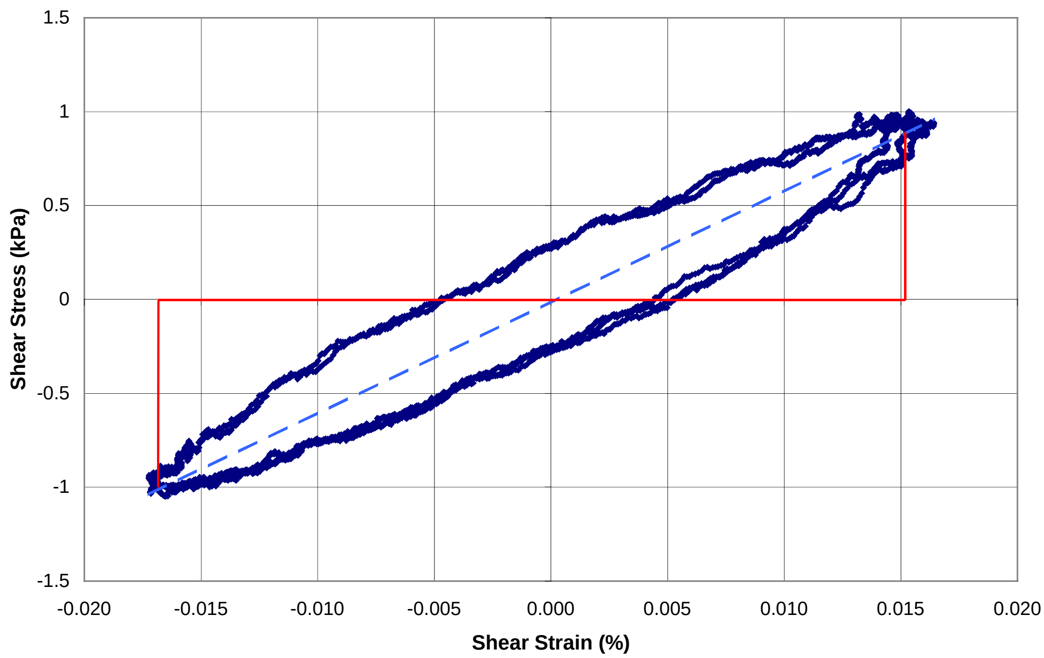

Figure 8. Hysteresis loops of shear stress and strain from data in Figure 7

Discussion of Data

The data presented in Figures 6 through 8 demonstrate the ability of the DFSD to measure both the dynamic shear modulus and damping of saturated, fine grained soils in situ. Unfortunately, due to problems with the seating of the device and with several of the Elastomer Gauges, a complete modulus reduction curve could not be obtained during this initial field test. However, some measure of the reliability of the data can be garnered through comparison with other available data from the same site. Shear wave velocity (V_S) profiles and conventional borings of this Bay Mud deposit were conducted in a separate study at the site approximately 12 years earlier. At the depth of interest, V_S was found to be 90 m/sec, and the mass density was reported as being 1600 kg/m^3. These values imply a maximum shear modulus of about 13 MPa for the soil being tested. In this context, the values presented earlier as measured by the DFSD (γ = 0.016%, G = 6.0 MPa, G/G_{max} = 0.46, D = 11%) seem quite reasonable, though the modulus is perhaps slightly lower than expected, and the damping is somewhat higher than would be expected at this level of strain (as can be inferred from Figure 3, for example).

CONCLUSIONS

The initial deployment of the Downhole Freestanding Shear Device encountered several challenges in terms of handling the device, developing a workable field procedure in coordination with the drillers, and in bringing the base of the borehole to the desired state prior to testing. As was expected, the procedure for successful use of this complex equipment is lengthy and requires consistent attention to detail. While the data obtained from the initial test series was not complete in terms of recording the dynamic properties over the full strain range of interest, the data that was obtained seems reasonable in comparison to the other available data at the site. Perhaps more importantly, the procedures for preparing, handling, carving the specimen and performing the cyclic loading tests were proven to be feasible in the field environment. The authors look forward to performing the next series of tests and presenting enhanced data from this site, using this new device, in the near future.

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