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Michael F. Riemer
University of California, Berkeley, CA

Carlton Grizzle
University of California, Berkeley, CA

Osama Safaqah
University of California, Berkeley, CA

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MEASURMENT OF DYNAMIC PROPERTIES OF CLAY USING THE DOWNHOLE FREESTANDING SHEAR DEVICE

Michael F. Riemer
University of California, Berkeley
Berkeley CA 94720

Carlton Grizzle
University of California, Berkeley
Berkeley CA 94720

Osama Safaqah
University of California, Berkeley
Berkeley CA 94720

ABSTRACT

The Downhole Freestanding Shear Device is a new, in situ tool for measuring the dynamic properties of cohesive soil deposits. It has been designed and developed to perform cyclic torsional shear tests on freestanding specimens beneath the bottom of a cased borehole, with the goal of measuring local strains on soil which has not been significantly disturbed by the drilling, sampling, or unloading/reloading processes associated with conventional laboratory testing. The research team has completed the device, and is now in the process of validating its performance, first in a laboratory setting. The current paper presents results from the initial tests on soil, illustrating that this new device is capable of measuring shear modulus and damping over a wide range of shear strains, from 10^{-3} % to nearly 1%.

INTRODUCTION

The Downhole Freestanding Shear Device (DFSD) is a new in situ tool for the measurement of dynamic shear modulus (G) and damping of clays over the full strain range of interest to seismic research. As such, it will substantially extend the strain range over which the modulus can be measured in the field, and it will provide the first measures of damping ratio directly from the field. Its development has been prompted by the need to reconcile the values of dynamic properties measured in the laboratory on retrieved samples with the typically larger values of small strain modulus obtained in situ using wave velocity techniques. Since the discrepancies between these conventional types of measurements are often attributed to the disturbance incurred in the soil during and after the sampling process, particularly for soils at depth, the approach in developing the DFSD has been a direct one: "simply" move a high quality laboratory-type test to the undisturbed soil beneath the bottom of a borehole. In addition to the obvious desire to measure the stresses and strains accurately down to very small values, the most fundamental goals are to maintain the target soil's state of stress throughout the process, and to minimize the soil disturbance in the process of getting the necessary instrumentation into place.

The DFSD has a cylindrical shape, is nearly 3.2 m in length, and is designed to be deployed in a 20 cm diameter, cased borehole. It weighs approximately 3.6 kN, excluding the electrical, pneumatic and water lines which must extend from the ground surface to the depths of up to 30 m for which the device is presently configured to test.

The sequence of steps in performing a test can be summarized as follows:

(1) lower the DFSD into the cased borehole full of drilling mud
(2) lock the device against the casing walls by inflating three packers that surround it
(3) restore the vertical stress to the soil at the bottom of the borehole, though a pneumatic piston
(4) carve a "freestanding" column of soil (10 cm in diameter and up to 40 cm in length), while maintaining the preexisting stress state
(5) deploy an instrumented membrane around the soil column
(6) apply torsional loading to the soil and measure the torque and the resulting local deformations, and
(7) calculate shear stresses and strains and determine the shear modulus and damping directly from the hysteresis loops

Numerous engineering challenges have appeared in the process of developing a tool capable of the testing sequence noted above, and a complete description of the device is not possible within the current paper. Further details about the DFSD, and in particular about the disturbance during carving and the maintenance of the anisotropic stress state, can be obtained from Roblee et al. [1996], Li et al. [1997], and Roblee and Riemer [1998]. The more recent developments involving the torsional loading and local measurement of shear strains are described in this paper, which concludes with examples of the modulus degradation data obtained from large, reconstituted blocks of kaolinite which were cut and tested using the DFSD in the initial phase of laboratory validation.

KEY COMPONENTS FOR LOADING

Once the cylindrical soil specimen has been cut without unloading the stresses, a latex membrane with carefully positioned local strain gauges is applied by adjusting the pressures within the device. Because there have been no substantial effective stress changes, there is no need to wait for a "reconsolidation" phase to complete, which could be quite slow in such a large specimen of cohesive soil. The dynamic testing itself consists of a series of rotation- controlled torsional cyclic deformations of the solid cylindrical sample, beginning with strain amplitudes of approximately 10^{-3} %, and increasing up to amplitudes greater than 1% shear strain if desired. The components of the device responsible for the dynamic loading are described in the remainder of this section.

Load Application and Measurement

The actual torsional loading is supplied by a Dynaserv 1060B brushless torsional servo motor, which has a maximum torque of approximately 34 N*m, a resolution of over 100,000 steps per revolution, and which can be operated in load, velocity or displacement modes. In the current configuration, the DFSD uses the motor solely in the displacement mode, though achieving the desired larger strain levels at conventional frequencies (0.2 to 2 Hz) requires the use of a supplementary indexer. The torque motor is the primary component in the load module, which is located near the top of the DFSD, above the 3 concentric stainless steel tubes that comprise the cutting module. The torque is transmitted through a spline shaft to the nearly 8 ft (2.3 m) long loading rod, which in turn transmits the torque to the soil specimen.

To minimize errors due to friction and system compliance, the torque is measured beneath all the torsional bearings by a dual-axis load cell, which is mounted rigidly to the top cap, directly above the soil specimen. This load cell actually consists of four independently and fully gauged arms, two of which measure axial load on the specimen and two of which measure the torque applied to the specimen. In addition to providing redundancy in case an individual channel should fail during testing, the presence of duplicate loads cells can also provide some indication of misalignment or bending, though the two torsional load cell, in particular, usually compare extremely closely.

Control System

The control software for the cyclic loading was written in-house, using the National Instruments' LABVIEW programming platform. As currently configured, the tests can be run at a variety of frequencies and with variable wave forms, and are closed-loop controlled based on direct digital feedback of the motor's position. This bypasses potential instabilities that might occur due to the distortional effects of compliance and friction if the actual applied torque or local strains were used as feedback channels. The dynamic loading program also serves as the data acquisition system, recording up to 16 channels of single-ended signals with 16 bit resolution at speeds up to 500 Hz. Because of the long travel path and potential for electrically noisy environments in the field, the 8 channels typically dedicated to the load and strain measurement on the specimen are amplified and analog filtered within the device itself using custom designed circuit boards for signal conditioning.

Strain Measurement

The soil at the top of the tested specimen in the field is necessarily unloaded and disturbed during the creation of the borehole, and thus global strain measurements based on the relative rotation between the top and bottom of the specimen will not provide undisturbed dynamic properties. Instead, it is necessary to measure the strains locally on the lower portion of the specimen, below the region that was unloaded during drilling. As no conventional strain instrumentation could be identified that could be deployed remotely and would be capable of measuring the desired shear strains, efforts were focused on developing and/or adapting new techniques to meet the requirements.

Two different technologies emerged from this work: the *Flexgauge*, a high-frequency resonating coil that senses strain through changes in inductance, which was conceived and developed and described by Li [1996], and the *Elastomer Gauge* (EG), a simpler resistance-based device made of urethane and liquid alloy, which is adapted from a design developed in the 1970's for large strain testing of flexible systems. While both systems have demonstrated promise in laboratory settings, the simpler elastomer gauges have proven to produce more stable signals, provide higher resolution of small strains (below 10^{-3} %), and be better suited to the hardships of remote deployment on a previously instrumented membrane. For these reasons, the DFSD is proceeding solely with the elastomer gauges, and the local strain data shown in the remainder of this paper are measured using these instruments.

The concept of the elastomer gauge is very simple. It consists of a relatively long (50 mm), very thin (diameter = 0.025 mm) capillary of liquid metal alloy encased in a flexible strip of urethane. Stretching of the gauge decreases the cross-sectional area of the conductive alloy and thereby increases the resistance across the gauge, in much the same way as a conventional foil strain gauge. By incorporating the gauge as one arm of a Wheatstone bridge, and including a balancing potentiometer as another arm, amplified sensitivities as high as 40 volts/mm have been successfully achieved. For use in the DFSD, typically four elastomer gauges are applied to the inside surface of a conventional latex membrane at a 45 degree angle to the horizontal (two slanting each way). Once the membrane is applied to the soil specimen surface, the gauge is in direct contact with the soil, and torsional shearing of the soil produces proportional strains in the gauge. Further details on the design, fabrication and verification of this new type of strain instrumentation will be forthcoming in a dedicated article in a technical journal.

Verification of Components in Benchtop Tests

To test the various components of the loading system and to ensure that they could be used together successfully, a "benchtop", or laboratory version of the loading system was assembled. The same types of actuators, control hardware and software, and load and displacement instrumentation was incorporated in this system, though a conventional pressure chamber for holding and confining specimens took the place of the specimen cutting hardware of the DFSD. This benchtop system was used to test a cylindrical urethane standard specimen, which had been manufactured and calibrated in 1994 at the University of Texas. Because the urethane is essentially linear (though not elastic), and thus should have the same shear modulus at all strain levels, it is especially useful for evaluating whether a testing system contains sources of compliance. Shear modulus results of urethane tests are compiled in Fig. 1(a), and include modulus based on the local strain measurements using elastomer gauges, simultaneous values based on global strain measurements using proximitors in the benchtop system, and the original values of modulus measured following fabrication using proximitors. While the values do not all agree perfectly, they are quite similar, and the discrepancy between the values based on the proximitors could be a function of the aging of the material. The higher values obtained using the elastomer gauges may be related to the local rather than global nature of the measurement, a discrepancy that has been noted by many previous researchers.

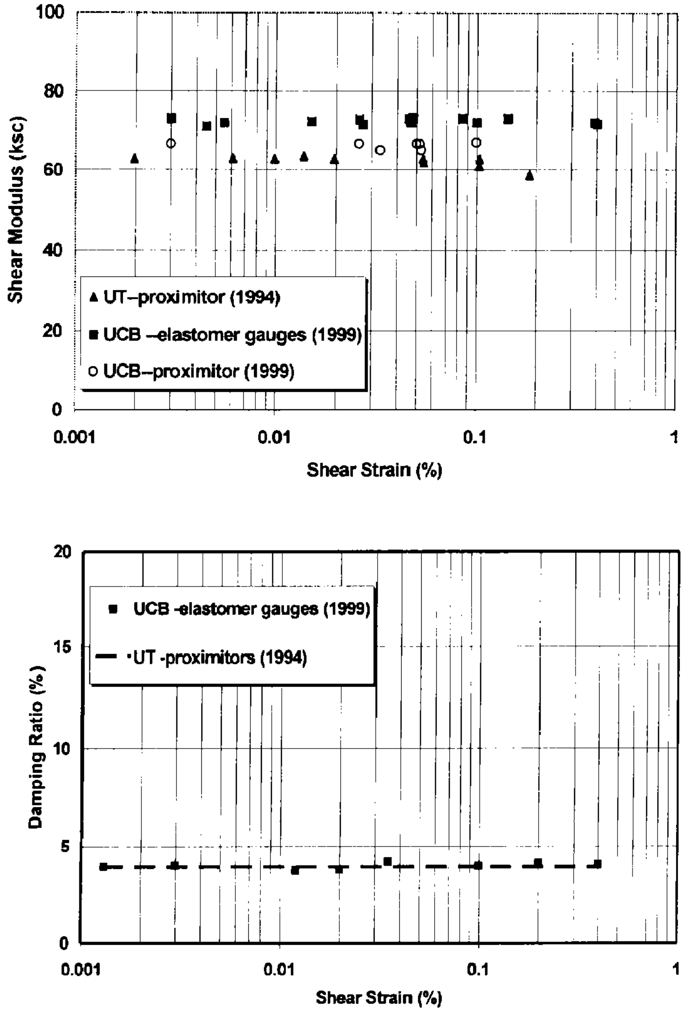

*Fig 1: **Summary of urethane data (a) modulus, (b) damping***

When the stress and strain time histories are combined to look at the hysteretic behavior of the soils, the level of damping ratio can be evaluated directly from these tests. This was done for the data from the urethane testing on the benchtop, and compiled data are shown in Fig 1(b). As the figure shows, the level of damping observed in the benchtop testing was constant across the full range of strains, at approximately 4 %, which is the value reported by UT at the time the urethane specimen was fabricated. Taken together with the modulus results, the benchtop testing on a standard material provided a great deal of confidence that the selected components could be used effectively in the downhole device.

VALIDATION

Complete validation of the device would consist of demonstrating that the DFSD measures the "true" shear modulus and damping values in the field. As discussed earlier, however, the intent of the device is to improve the measurements over those obtained by conventional lab methods, and substantially extend the range of strains for field measurements, so the choice of a "correct" standard of comparison is not an obvious one.

A two-step approach is being taken to validate the DFSD: as a first step, data will be obtained using the full device in the laboratory under carefully controlled conditions that can be reasonably well simulated in conventional laboratory tests. Results will be compared directly to those obtained from independent laboratories performing these equivalent tests. For example, homogeneous samples of cohesive soils reconstituted and consolidated to low stresses should not be substantially affected by the sampling and unloading/reloading processes. Therefore, for this case the DFSD results should be similar to those obtained by high-quality shear testing of specimens sampled from blocks of identically prepared soil. Following laboratory validation, the DFSD will be used at two well characterized field sites, to compare the data with other field and laboratory methods.

Laboratory Simulation of Field Case

Simulating the full field environment in the laboratory is complicated by the scale of the DFSD, and by the desire to test reconstituted, homogeneous specimens under controlled conditions. To date, these tests have been performed on two types of soil (low plasticity kaolinite, and a higher plasticity natural silty clay) by mixing the soil into a thick slurry, and consolidating it one-dimensionally in stainless steel chambers approximately 0.3 m in diameter, and 0.5 m in height. Each chamber is equipped with a piston which allows air pressure introduced at the base of the chamber to squeeze the soil up against a floating porous stone, which is held in place by a rigid upper plate at the top of the chamber. The consolidation load on the soil is measured by a load cell placed between the upper plate and the stone. During consolidation, the vertical displacement of the piston is monitored using a wire potentiometer, and the pore pressure within the soil is measured using a small (0.5 cm diameter) pressure transducer. A schematic illustration of this consolidation apparatus is shown in Fig. 2.

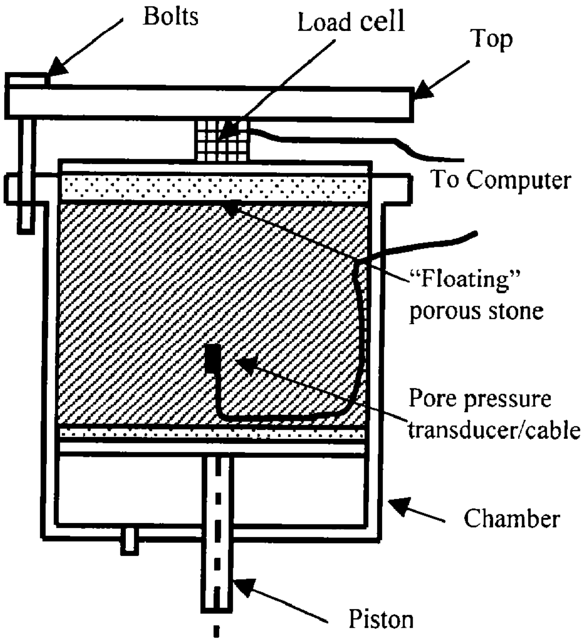

Fig. 2. Schematic of equipment used for consolidation

When consolidation to the desired vertical stress is complete, the plate and porous stone are removed and a 1.5 m length of the 0.2 m diameter casing is rigidly attached and sealed to the top of the chamber. The DFSD is then lowered into the casing, onto the soil surface, vertical stress is reapplied to the soil through the top cap, and the testing progresses just as it would in the field. Disturbance during carving is minimized by the excavation of an annular ring of soil, which is sliced away by four slightly inclined blades on the base of the cutting tube, which rotates as the tool extends. Cuttings from this process are flushed off the blades and up the borehole around the device by streams of water directed onto the blades. The actual surface of the specimen is carved by a thin-walled ring which is advanced slightly ahead of the blades. Once the specimen has been cut to the desired height, the instrumented membrane, which had been inflated away from the soil during carving, is pressed against the soil by adjusting pressures within the device.

Figure 3 illustrates the DFSD after completing the carving of a specimen in the consolidation chamber, immediately prior to torsional loading. Note that the pore pressure transducer is placed within the soil mass such that the DFSD cuts around it, and thus the pressure transducer provides data on pore pressure changes both during the cutting of the specimen, and during dynamic testing.

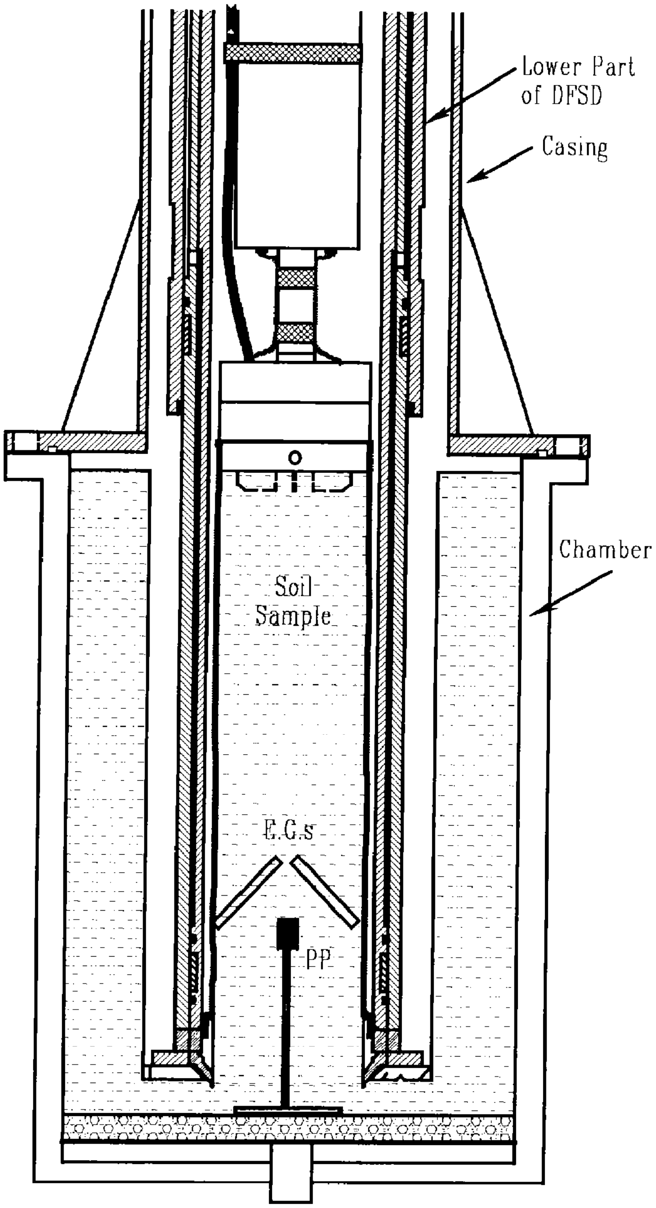

Fig. 3: Schematic of DFSD with sample in chamber

Results

Figure 4 shows the results of tests performed on the reconstituted kaolinite, both in terms of the normalized shear modulus, G/G_{max} (Fig. 4a) and the measured damping ratio (Fig. 4b). Overlain on the plots are published (Vucetic and Dobry, 1991) generic curves for the dynamic properties for PI values of 0 and 15. These figures show that full downhole device is capable of measuring the properties of interest over a wide range of shear strains, including several measurements that are within the elastic range for this low plasticity material. Furthermore, the values of normalized modulus are consistent with what would be expected for a material of this plasticity (PI=10). While the damping values are perhaps slightly higher than expected at these small

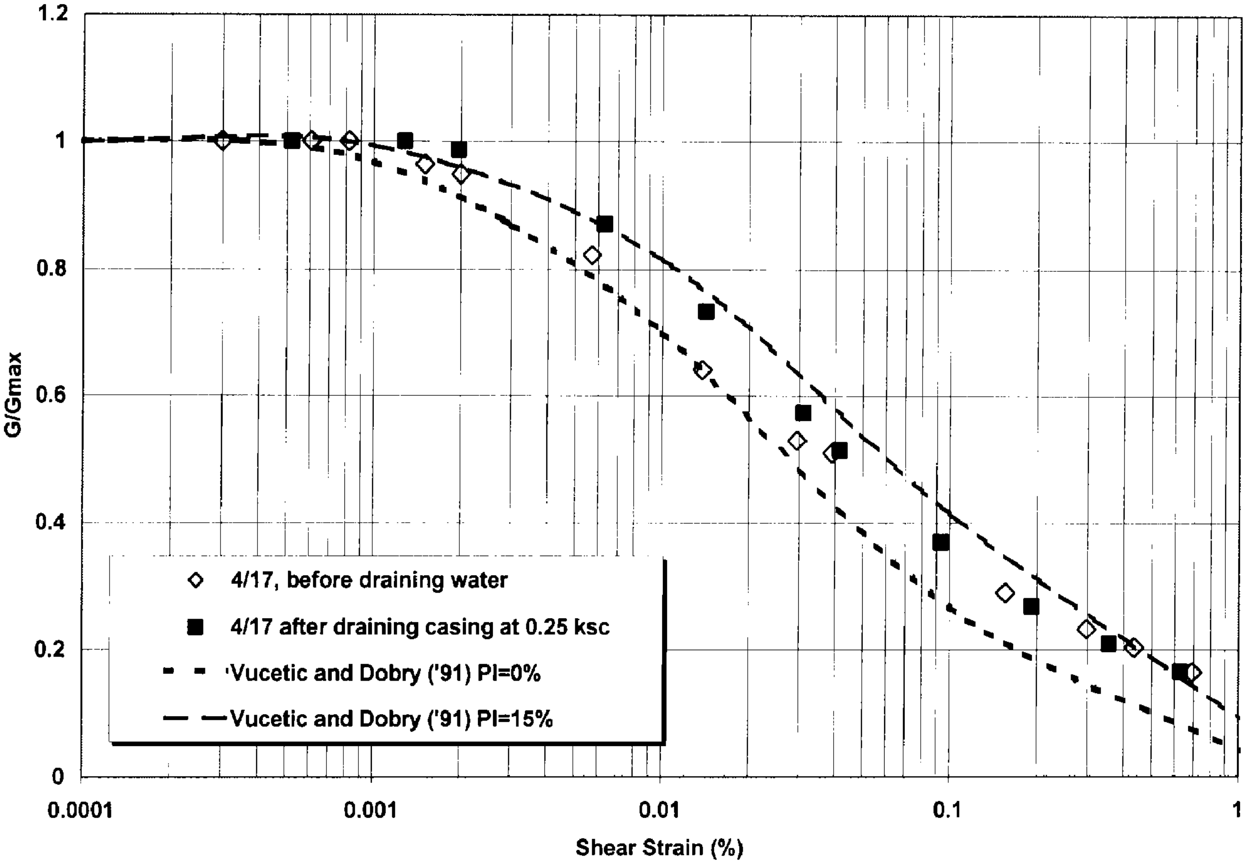

Fig. 4(a). Degradation of normalized shear modulus for two DFSD test series on kaolinite

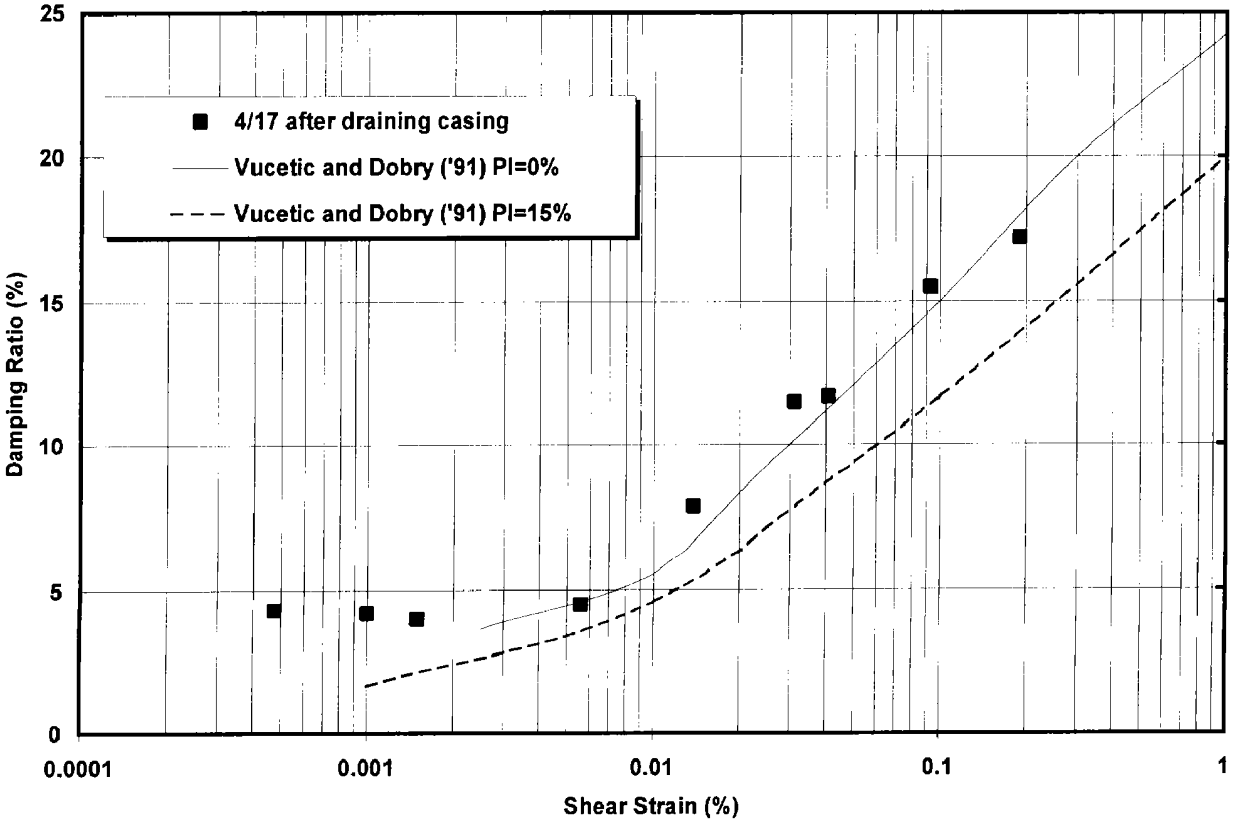

Fig. 4(b). Damping ratio as a function of strain from DFSD test series on kaolinite strains, the agreement for damping with the generic values are also quite good over the range of strains commonly measured in the laboratory. Unfortunately, due to a malfunction in the pore pressure transducer, the effective stress on the specimen was not known for this sample, and thus the absolute shear modulus cannot be compared directly with parametrically calculated values.

Laboratory validation is continuing with similar experiments at various levels of consolidation stress (with known effective stress conditions during testing). In parallel with the DFSD tests, batches of the same soil are consolidated to the same stress states, carefully sampled using Shelby tubes, and sent to two external laboratories for independent verification of the dynamic properties. Resonant column/ torsional shear tests are being performed at the University of Texas, and Double Specimen Direct Simple Shear tests are being performed at UCLA. In addition, benchtop testing of retrieved samples will be performed at UC Berkeley (using the same torsional device described earlier) for direct comparison with the DFSD values.

FURTHER WORK

Following the validation of the device under laboratory conditions, the DFSD will be initially deployed at two field sites, testing at multiple depths. These sites will be selected based on the uniformity of the deposits and the degree to which the properties are already well documented, so that the in situ performance can be evaluated. Field validation will also include additional conventional testing, both in situ and laboratory based, to compare the DFSD results with those obtained using the state of practice methods.

ACKNOWLEDGEMENTS

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