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Seismic Flat Dilatometer Tests in Connecticut Valley Varved Clay

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ABSTRACT: Downhole shear wave velocity measurements have been incorporated within a "Marchetti" flat dilatometer by placing a velocity transducer in a connecting rod just above the blade. The hybrid of combining downhole seismic with flat dilatometer, termed the seismic dilatometer test (SDMT), has the superior advantages of determining both the routine estimates of soil properties and stratigraphic information, while also measuring the small-strain stiffness within a single sounding. The SDMT is rapid, simple, and cost effective, requiring essentially no more time than a conventional dilatometer sounding. Results of seismic dilatometer testing in clays at the National Geotechnical Experimental Test Site (NGES) in Amherst, Massachusetts are presented and compare favorably with results from companion series of seismic cone penetrometer tests.

KEYWORDS: clay, downhole test, flat dilatometer, geophysics, penetration tests, shear wave velocity, shear modulus, shear wave, small-strain modulus, stiffness

The flat dilatometer was introduced for the rapid characterization of subsurface soils for geotechnical investigations (Marchetti 1975, 1980). The apparatus consists of a stainless steel blade 95 mm wide, 220 mm long, and 14 mm thick with a 60-mm-diameter expandable steel membrane on one face. After the blade has been inserted to the desired depth, generally at 20 or 30-cm intervals, regulated gas pressure is applied to the membrane to displace it horizontally into the soil. In the traditional test, two readings are taken at particular displacements and used in correlations to estimate soil type, unit weight (γ), at-rest coefficient (K_0), overconsolidation ratio (OCR), undrained shear strength of clays (s_u), and other parameters. In some testing procedures, a third reading corresponding to the deflation of the A-reading (termed C-reading) is taken to infer hydrostatic pressures in sand deposits. For further information about the dilatometer procedures and interpretations, refer to Marchetti (1980), Schmertmann (1986), Lutenegger (1988), and Lacasse and Lunne (1988).

The determination of the shear wave velocity (V_s) is important for assessing both static and dynamic properties of soils and rocks (Tatsuoka and Shibuya 1992). The small-strain shear modulus ($G_{max} = \rho V_s^2$) is a fundamental measure of the finite stiffness and relevant to deformation analyses for geotechnical design and engineering (Burland 1989). Traditional test methods for evaluating the in-situ dynamic behavior of soils such as crosshole and downhole tests can be costly, time consuming, and somewhat difficult because they involve laborious drilling, casing, and grouting holes to ensure good soil contact with seismic receivers. Due to an increase in the interest of the dynamic behavior of soil, several new testing methods have been developed (Campanella 1994). Perhaps the most successful development has been the incorporation of seismic capabilities into penetration tests such as the cone penetrometer (Robertson et al. 1986). By including a velocity transducer with direct-push technologies, good contact with the soil is assured with no added effort of drilling, casing, or grouting. Another benefit of the hybrid test is that two tests are essentially performed in one sounding. Thus, data from the cone penetrometer or dilatometer provide stratigraphic and strength information, while downhole measurements from the geophone transducer provides shear moduli (Hepton 1988). By the addition of a downhole velocity transducer and an oscilloscope to the standard dilatometer setup, the seismic dilatometer test (SDMT) can provide stratigraphic information, high-strain response (strength), intermediate strain stiffness (E_D = dilatometer modulus), and small-strain stiffness (G_{max}) from a single sounding.

Test Apparatus

The test apparatus consists of a high-strength stainless steel dilatometer blade, dual-gage control panel, oscilloscope, and two velocity geophones. A receiver geophone is positioned above the blade, as seen in Fig. 1, and consists of a Geospace Type 14 Model L9 with a natural frequency of 28 Hz and sensitivity of 0.236 V/cm/s. A source geophone, which is a Mark Products Model L-410, is attached to a horizontal plank to determine the start time of the shear wave. Both geophones are connected to a four-channel HP 54601A oscilloscope to determine the travel time of the wave from the source to the receiver. A portable matrix-dot printer is used to print each wave signal for later reference.

The co-axial cable for the receiver geophone has been taped parallel with the DMT tubing so that the installation process takes minimal additional time. After the cable/tubing has been threaded through the rods and the blade positioned, the downhole geophone

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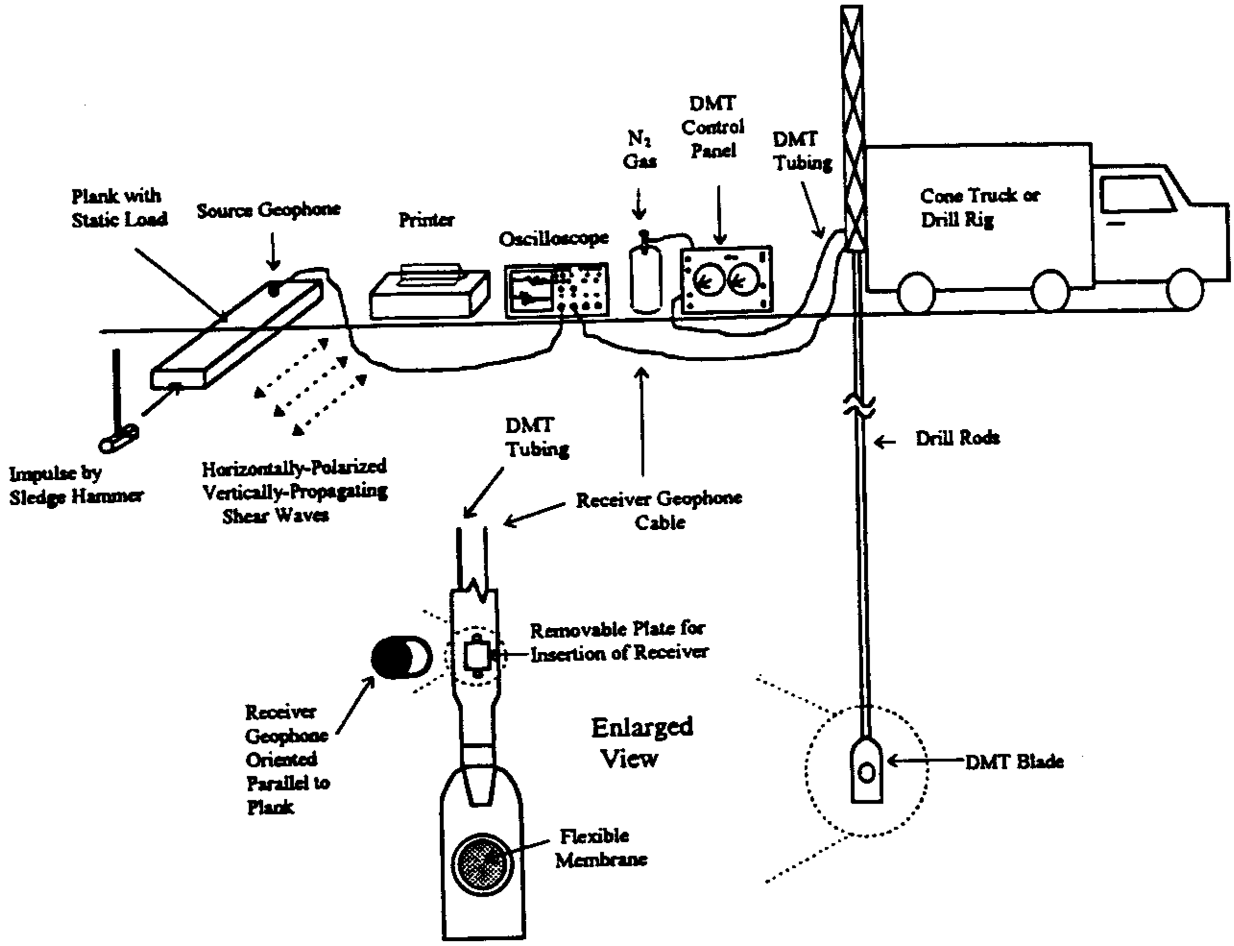

FIG. 1—*Seismic flat dilatometer apparatus and field setup.*

is added to the adaptor rod directly above the blade. A removable plate, as seen in Fig. 1, has been cut from the rod so that the geophone can be added with ease and precision of location. The plate is removed simply by loosening two set screws. Once the geophone is inserted and cable connected, the test is ready to proceed.

Test Procedures

The dilatometer portion of the test is conducted according to ASTM suggested procedures (Schmertmann 1986) whereby the blade is hydraulically pushed at regular depth intervals of either 200 or 300 mm, and two pressure readings are taken. Regulated compressed nitrogen is used to expand the flexible membrane and obtain the lift-off pressure (p_0) and expansion pressure (p_1). At each change in rods (typically every 1 m), the seismic portion of the SDMT is conducted as a conventional downhole test with vertically propagating horizontally polarized shear waves. Since the rod change takes about 30 s and the wave travels in typically less than 0.1 s, there is no loss in production time over conventional dilatometer testing.

The shear wave is generated from a horizontal plank situated at the surface and statistically loaded to assure good coupling with the soil. From the onset, the blade orientation is positioned such that the horizontal axis of the downhole geophone is parallel with the plank. The plank is struck with a sledge hammer to instigate a wave that is rich in shear and low in compression. The surface geophone attached to the hammer marks the initial time on one channel of the oscilloscope. The downhole geophone, located just above the blade depth, signals when the shear wave has arrived through the soil. A pseudo-interval shear wave velocity is computed incrementally by dividing the travel distance by the travel time between successive velocity readings (Campanella 1994).

Field Tests

Initial field trials of the seismic dilatometer were performed at the National Geotechnical Experimentation Site (NGES) located at the University of Massachusetts at Amherst. Five dilatometer tests, three with seismic measurements, and a series of seismic cone tests were performed over a 60 by 60 m section of the property. The site is generally flat with elevations ranging from +44 to +45.5 m above mean sea level. The subsurface soils were formed as a result of glacial movement during the Pleistocene age and are composed of lacustrine sediments from Lake Hitchcock, locally referred to as Connecticut Valley varved clay (Lutenegger and Miller 1994). At the test site, about 1 m of variable clay fill overlies a 3-m-thick desiccated clay crust that is underlain by a deep deposit of soft gray varved silty clay extending to depths of 25 m (Lally 1993).

The dilatometer pressure readings were generally collected at 0.2-m intervals, and the shear wave arrival times measured at each rod break (approximately 0.9-m intervals). For each seismic event, two travel time measurements were taken at each interval and printed for later reference. The time difference between Trials 1 and 2 was always less than 5%; therefore, the average of the two travel times was used in calculations and the results presented here. Shear wave velocity was calculated as a pseudo-interval type due to the use of only one downhole receiver (Baldi 1994; Burghignoli et al. 1991).

Five DMT soundings were advanced to depths of about 11 m, and the corrected dilatometer stress readings (p_0 and p_1) are presented in Fig. 2. While some minor scatter is evident in the upper clay fill (0 to 1 m) and clay crust (1 to 4 m), very consistent results are noted for measurements taken in the natural soft varved clay at depths exceeding 4 m. Soil classification evaluations using the material index (I_D) agree well with index tests and grain size analyses on recovered samples (Kates 1996). In the lower soft clay deposit, undrained shear strengths evaluated from dilatometer data indicated $s_u \approx 50$ kPa and were comparable to field vane strengths, which measured around 40 kPa (Lally 1993).

The travel time arrivals of shear waves determined during seismic dilatometer testing are also presented in Fig. 2 and indicate consistent results between the individual soundings. The shear wave velocity (V_s) was calculated over each 0.9-m depth interval between successive events and thus represents the pseudo-interval V_s. An improved accuracy would be obtained with a true-interval velocity; however, two downhole receivers must be used to capture each event (Burghignoli et al. 1991), and the field procedure becomes more complex because two sets of coaxial cables plus tubing must be placed within the rods.

The mean profile of shear wave velocity determined from the three SDMTs is shown in Fig. 3. The profile of V_s initially increases at shallow depths in the clay fill and reaches a maximum value of about 250 m/s in the desiccated clay crust, then decreases to a value of about 150 m/s in the soft normally consolidated varved clay before the termination depths of about 11 m.

During this testing program, a complementary set of seismic cone penetration tests (SCPT) were performed within 15 m of the seismic dilatometers. The seismic readings from the SCPTs were collected on both the Hogentogler system and the HP oscilloscope for comparison of field data acquisition systems. Both systems gave similar performance. The mean V_s profile from three nearby SCPTs is shown to be in general agreement with the downhole results from the SDMTs. At shallow depths, minor observed differences are due to variability of the clay fill and crustal layers. In both systems, some uncertainty is incurred due to the difficulties in discerning the initial arrival of the shear wave with the pseudo-interval method and interpretations made by different operators (Baldi 1994).

Discussion

The evaluation of soil parameters from flat dilatometer tests often relies on empirical correlations between reference test data

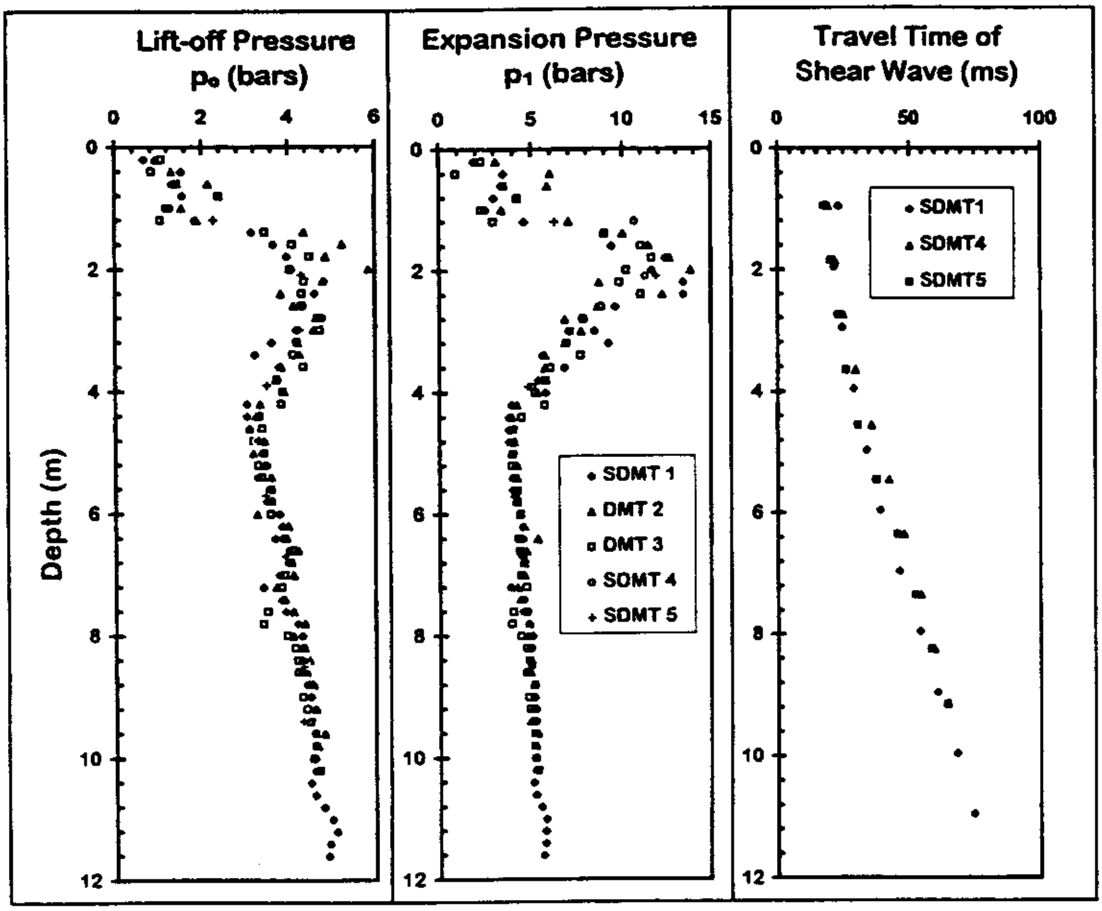

FIG. 2—*Results from seismic dilatometer tests in varved clay at the Amherst site.*

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