29 Mar 2001, 4:00 pm - 6:00 pm

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Wanda Henke
Dynamic In Situ Geotechnical Testing Inc., Lutherville, MD

Robert Henke
Dynamic In Situ Geotechnical Testing Inc., Lutherville, MD

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Wanda Henke
Dynamic In Situ Geotechnical Testing, Inc.
Lutherville, Maryland-USA-21093

Robert Henke
Dynamic In Situ Geotechnical Testing, Inc.
Lutherville, Maryland-USA-21093

ABSTRACT

In this paper, we present and discuss an automated analysis procedure for interpreting results from torsional cylindrical impulse shear tests. The "impulse shear test" is an in situ geotechnical test that provides detailed information on in situ nonlinear inelastic shearing deformation characteristics needed for dynamic geotechnical earthquake engineering analysis procedures. The test addresses the issue of effects of disturbances to in situ conditions. The automated analysis procedure is intended to be a major improvement over our existing approach for interpreting results from impulse shear tests. We demonstrate the automated analysis procedure by using the procedure to interpret results from impulse shear tests conducted at the National Geotechnical Experimentation Site at the University of Massachusetts in Amherst, Massachusetts. The site consists of soft to stiff silty clays. The automated analysis procedure was found to produce reasonable results and to be highly efficient, allowing the soil characteristics of interest to be inferred in the field. Additionally, the need for judgment in interpreting results from impulse shear tests is eliminated.

INTRODUCTION

In this paper, we present and discuss an automated analysis procedure for interpreting results from torsional cylindrical impulse shear tests ("impulse shear tests"). This technology bears on predicting the behaviors of soil deposits (motions and occurrences of liquefaction) during earthquakes. We provide relevant background, describe the automated analysis procedure and demonstrate the procedure by interpreting results of impulse shear tests conducted using a prototype testing system constructed for the Federal Highway Administration (FHWA).

BACKGROUND

Symbols and Terminology

c_{Ti} = damping coefficient for ith torsional damping element; D = equivalent damping ratio; G = secant shear modulus; G_{max} and G_o = low strain shear modulus; I_i = mass moment of inertia of ith mass; k_{Ti} = stiffness of ith torsional spring; R = parameter of Ramberg-Osgood equations; T = applied torque; t = time; α = parameter of Ramberg-Osgood equations; γ = shear strain; θ = angular displacement of instrumented head of probe; $\ddot{\theta}_i$ = angular acceleration of ith mass; τ = shear stress; and τ_y = parameter of Ramberg-Osgood equations.

With respect to terminology, Fig. 1 shows some of the parameters that may be obtained using the impulse shear test. The parameters include low strain shear moduli (G_o), secant shear modulus reduction curves (G/G_o vs γ), and equivalent viscous damping ratio curves (D vs γ). Such information is needed for geotechnical earthquake engineering analysis procedures commonly used to predict the motions of and occurrences of liquefaction within soil deposits during earthquakes.

Impulse Shear Test.

The torsional cylindrical impulse shear test (Henke and Henke 1986, 1993a, 1994) is an in situ geotechnical test that provides, for soil deposits, detailed information on in situ nonlinear inelastic shearing deformation characteristics needed for commonly used geotechnical earthquake

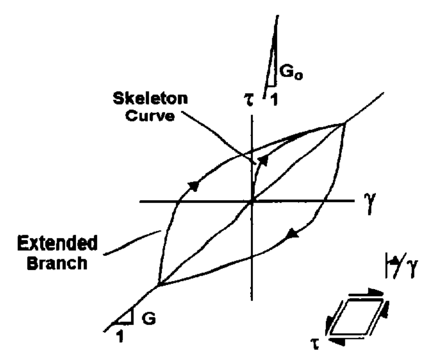

Fig. 1. Idealized nonlinear inelastic shear stress vs strain curves for soil deposits.

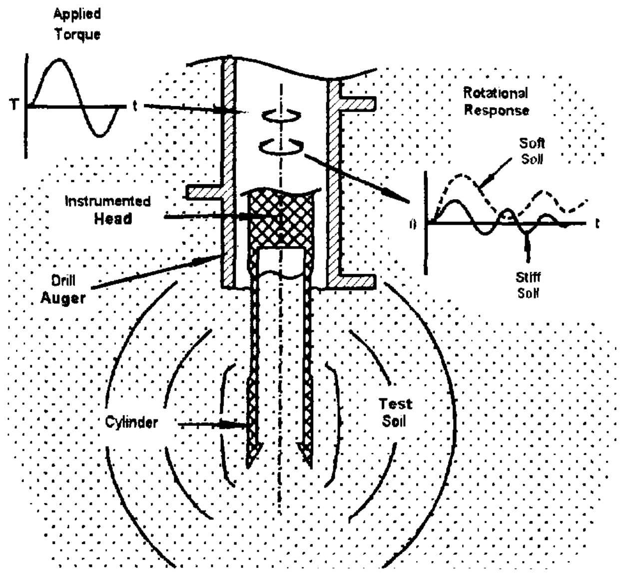

Fig. 2. Basic idea of impulse shear test.

engineering analysis procedures. To date, information has been provided for shear strains ranging from 0.001% to 2.5%.

Figure 2 shows, schematically, the basic idea of the impulse shear test. A single cylinder (diam. ~7 cm) attached to the bottom of a wireline probe (see Fig. 3) is penetrated carefully into the soil below the base of a borehole. The soil that is tested surrounds the outside of the lower portion of the cylinder. In a single test, an impulsive torque of a selected level is applied, through an instrumented head, to the cylinder to induce torsional shear stresses and strains in the test soil. The cylinder responds by rotating dynamically in a manner that is strongly dependent on the nonlinear inelastic shearing deformation characteristics of the soil. A series of such tests is conducted at a given depth. Normally, low strain tests, conducted using low levels of loading, are carried out first. The low strain tests are followed by high strain tests (herein, tests for which soil characteristics are noticeably nonlinear), conducted using higher levels of loading. The soil characteristics of interest are inferred from torque and angular acceleration measurements by simulating tests analytically.

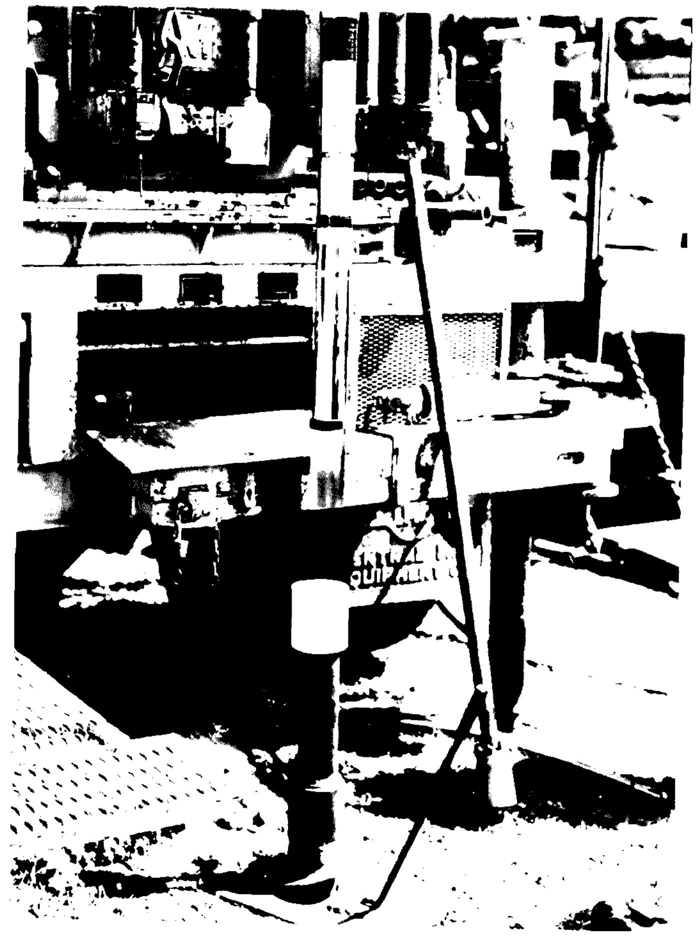

Fig. 3. Cylinder of prototype impulse shear testing system.

Problem Addressed by Impulse Shear Test

The general problem addressed by the impulse shear test is predicting reliably, for engineering and land use planning purposes, the local behaviors of soil deposits during earthquakes. The behaviors of softer and looser deposits in particular have contributed greatly to a broad range of damage (catastrophic to subtle but costly and disruptive) during a number of recent earthquakes. The 1985 Mexico, 1989 Loma Prieta, and 1995 Great Hanshin earthquakes provide well-known and striking examples. It is widely held that an important aspect of predicting the behaviors of soil deposits reliably is estimating in situ soil characteristics. Many truly significant advances have been made in geotechnical testing technology for estimating in situ soil characteristics that bear on behaviors during earthquakes (Anderson and Espana 1978; EPRI 1991; Jamiolkowski et al. 1995; Woods 1991); however, further progress is still needed in various areas (EPRI 1991). The impulse shear test, and also other distinctly different tests currently under development (Roblee and Riemer 1998; Salgado et al. 1997), address the specific and well-known problem of obtaining detailed information on in situ nonlinear inelastic deformation characteristics needed for geotechnical earthquake engineering analysis procedures without disturbing in situ conditions excessively. Disturbances can create considerable uncertainty in predictions of behaviors that can lead to unconservative, or costly, overly conservative designs for constructed facilities located in seismically active areas.

Interpreting Results of Impulse Shear Tests

To interpret results of impulse shear tests in terms of the soil characteristics of interest, first a model is constructed of the probe-soil system. For most of our work, we have used the simple model shown in Fig. 4. This type of model is discussed in detail by Henke and Henke (1993b). The model is a practical model that describes important aspects of tests but also involves possibly significant simplifications. Extensions of the model are expected to be possible.

The model consists of a torsionally excited linear elastic cylinder partially embedded in an axisymmetric continuum.

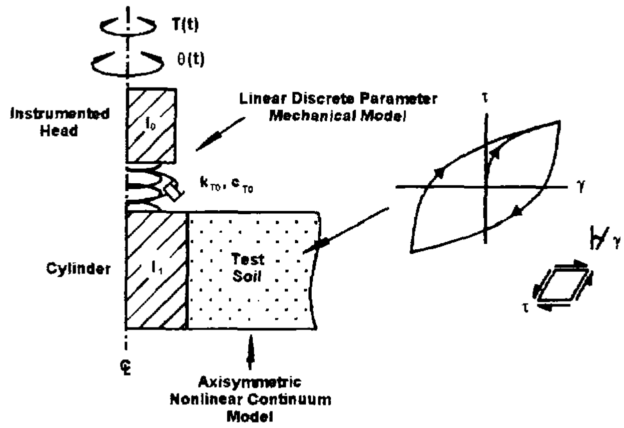

Fig. 4. Probe-soil model.

The only stresses and strains described for the continuum are torsional shear stresses and strains. Solutions are obtained numerically for a selected sequence of times. The dynamic behavior of the instrumented head and cylinder is described using a linear discrete parameter model. The dynamic behavior of the test soil, including the propagation of torsional shear waves, is described using an axisymmetric continuum approach that, in its most complete form, is multidimensional (Henke et al. 1982). This approach is similar in concept to the one-dimensional method of characteristics (Streeter et al. 1974). In the simple model shown in Fig. 4, only horizontally propagating shear stresses and strains are described within the continuum and these lie within horizontal planes; thus, nonuniform behavior is described radially but not vertically. In essence, the continuum model corresponds to a one-dimensional earthquake site response analysis model that is oriented horizontally rather than vertically, accounts for effects of radius, and is excited by the rotation of the cylinder of the probe rather than an earthquake. The nonlinear inelastic shear stress vs strain behavior of the test soil is described using Ramberg-Osgood equations (Richart 1975). These equations describe characteristics such as those shown in Fig. 1. The equation for the skeleton curve is given as

$$\gamma = (\tau / G_o)\,(1 + \alpha\,|\tau / \tau_y|^{R-1}) \qquad (1)$$

Currently, the objective of the process of interpreting results from impulse shear tests is to establish values for the Ramberg-Osgood equation parameters (G_o, τ_y, α, and R) that provide idealized nonlinear shear stress vs strain and related curves that are considered to represent the corresponding in situ curves for the test soil. In our original approach for interpreting results of an impulse shear test, after an appropriate probe-soil model is constructed, shear stress vs strain characteristics are assumed for the continuum model by specifying values for G_o, τ_y, α, and R. Then the test is simulated by applying the torque measured during the test to the model. Computed and measured angular accelerations of the instrumented head are compared. Simulations are repeated for ranges of shear stress vs strain characteristics for the continuum model (ranges of values for G_o, τ_y, α, and R). The characteristics providing the most representative simulations are considered to be representative of those of the test soil; the corresponding values for the Ramberg-Osgood equation parameters are the product of the test. These values may then be introduced into the appropriate equations (Idriss et al. 1978) to provide, for the tested soil, idealized descriptions of in situ shear stress vs strain, shear modulus reduction, and damping ratio curves.

With respect to details, for simplicity, to date we have partially calibrated the Ramberg-Osgood equations before interpreting test results; values have been chosen for α and R that result in shear stress vs strain curves that are representative of particular soils of interest (Richart 1975). Thus, only values for G_o and τ_y have been varied in simulations. The partial calibrations of the Ramberg-Osgood equations is judged to be appropriate since we are at an early stage in the development of the impulse shear test. Our procedures for establishing the desired values for G_o and τ_y were formulated recognizing that at low strains for which soil behavior is linear G_o dominates soil behavior and that only at higher strains for which soil behavior is nonlinear does τ_y become relevant. First, we use low strain test results to provide estimates for G_o. The values of τ_y are held high in initial simulations of low strain tests. Generally, in our simulations of low strain tests, soil behavior has been largely linear. Then, we infer values for τ_y from the results of appropriate high strain tests using the values of G_o inferred from the results of the low strain tests. Our simulations of high strain tests have involved highly nonlinear behavior of the test soil. It should be noted that, in our work, τ_y has not taken on a physical meaning.

AUTOMATED ANALYSIS PROCEDURE

The automated analysis procedure is a new scheme for interpreting results of impulse shear tests that is a significant advance over our original approach, improving efficiency greatly and eliminating the need for judgement.

Our original approach for interpreting results from impulse shear tests is most consuming and requires judgment. For each trial value of a Ramberg-Osgood parameter we compare plots of measured and computed angular accelerations. We select most representative simulations by inspection. On the order of eight trial values are needed to be able to provide a respectable value for a single Ramberg-Osgood equation parameter (either G_o or τ_y).

Basically, the automated analysis procedure provides values for G_o and τ_y automatically. The procedure used for low strain tests (provide values for G_o) is, in essence, identical to that used for high strain tests (provide values for τ_y). In using the procedure, an initial value is specified for the appropriate parameter (G_o or τ_y). Also, a tolerance is specified that gives the precision to which the value of the parameter is to be obtained. With this information, the automated analysis simulates the impulse shear test of interest using, for the soil model, the initial value for this parameter. The measured and computed records of the angular acceleration of the

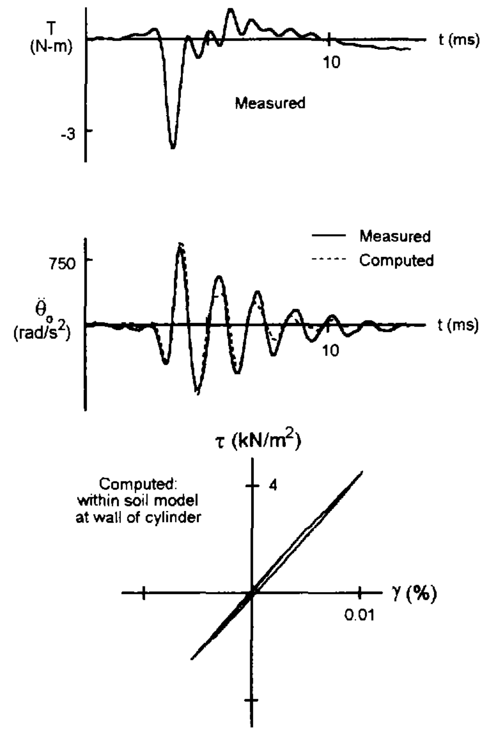

Fig. 5. Results from low strain impulse shear test conducted at the depth of 5.18 m at the University of Massachusetts site and most representative simulation (G_o = 47.2 MN/m^2).

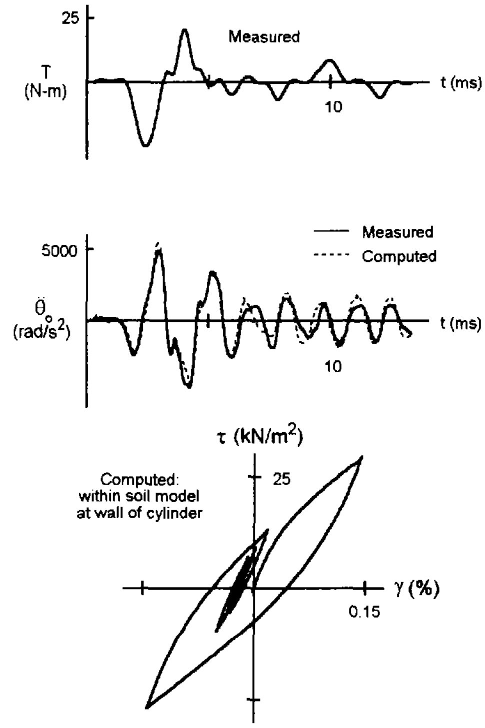

Fig. 6. Results from high strain impulse shear test conducted at the depth of 5.18 m at the University of Massachusetts site and most representative simulation (τ_y = 30.0 kN/m^2).

instrumented head are compared by computing the sum of the squares of the differences between the two records for the duration of the simulation. Then, the automated analysis procedure selects a second value for the parameter of interest that is a certain fraction greater than the initial specified value. The test is again simulated but using this new value and again the sum of the squares of the differences between the measured and computed angular accelerations is computed. This new sum is compared to the original sum; a new trial value for the parameter of interest is obtained based on the better of the initial and second trial values; and a new trial simulation is carried out. This process of selecting an improved trial value for the parameter of interest, conducting a simulation using the improved value, and obtaining a measure of the agreement between the measured and newly computed angular acceleration records is repeated until a final value for the parameter of interest is obtained such that increasing or decreasing this value by the specified tolerance does not result in an improved simulation. The simulation carried out using the final value is considered to be the most representative simulation and this final value is the product of the automated analysis procedure.

DEMONSTRATION OF AUTOMATED PROCEDURE

In this section, we demonstrate the application of the automated analysis procedure. A low strain impulse shear test and a high strain impulse shear test, each conducted at a depth of 5.18 m at the National Geotechnical Experimentation Site at the University of Massachusetts in Amherst, Massachusetts, are considered. The site consists of a 5-6 m stiff overconsolidated clayey soil near the surface changing to a medium stiff to soft more normally consolidated clayey soil with greater depth (Lutenegger 1995). The soil at the depth of 5.18 m showed an intermediate level of stiffness. Also, herein, results are shown together for impulse shear tests conducted in two boreholes. The site is considered to be fairly uniform laterally (Lutenegger 1996). We used the basic probe-soil model shown in Fig. 4 to interpret the results of the tests. The following are values we used for parameters that describe the probe: $I_0 = 2.72 \times 10^{-3}$ kg-m^2, $I_1 = 2.08 \times 10^{-3}$ kg-m^2, k_{T0} = 158 kN-m/rad, and c_{T0} = 0.83 kg-m^2/s. The density of the soil model was assigned a value of 1730 kg/m^3 (Bonus 1995). The parameters α and R of the Ramberg-Osgood equations were assigned values of 1.8 and 2.5, respectively. These are values that are representative of clayey soils (Richart 1975).

With respect to the low strain test, our initial trial value for G_o was 30 MN/m^2 and we specified a tolerance of 5%. Results from the test and the most representative simulation are shown in Fig. 5. As can be seen from the figure, the soil behavior was largely linear. With respect to the high strain test, our initial trial value for τ_y was 50 kN/m^2 and we specified a tolerance of 5%. Results from the test and the most representative simulation are shown in Fig. 6. As can be seen from the figure, the soil behavior was highly nonlinear.

With respect to computing issues, in the low strain case and also in the high strain case, twelve simulations were needed to satisfy the specified tolerance. Using a Toshiba Satellite computer with a 200 MHz Pentium processor and 96 MB of

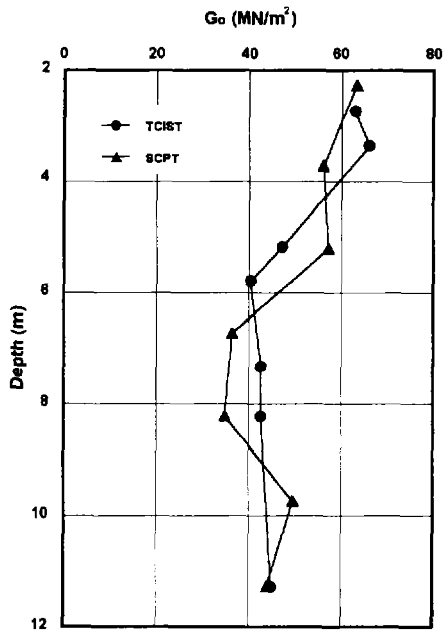

Fig. 7. Low strain information inferred from results of torsional cylindrical impulse shear tests (TCIST) and seismic cone penetration tests (SCPT) conducted at the University of Massachusetts site; SCPT curve estimated by authors based on unpublished test results provided by A. Lutenegger.

random access memory, in each case, the twelve simulations were completed in about 4 min. Thus, using the automated analysis procedure, results of impulse shear tests may be easily interpreted in the field.

Low strain results provided by the automated analysis procedure appear to be reasonable. For example, in Fig. 7 we show a low strain shear modulus profile inferred for the University of Massachusetts site using the automated analysis procedure. The profile is consistent with one we inferred previously using the inspection method (Dynamic In Situ Geotechnical Testing, Inc. 1996a). The profile is shown compared to a low strain shear modulus profile we estimated based on results obtained from seismic cone penetration tests (SCPT) conducted at this site and provided to us by A. Lutenegger. The two profiles are in reasonable agreement.

High strain results provided by the automated analysis procedure also appear to be reasonable. For example, in Fig. 8 we show representative average shear modulus reduction and damping ratio curves inferred for the University of Massachusetts site, using the automated analysis procedure, superimposed on corresponding published information taken from Vucetic and Dobry (1991). The curves shown for the impulse shear tests are the averages of the individual curves obtained for the University of Massachusetts site over the depth range of 2.74 – 11.28 m and are consistent with those inferred previously using the inspection method (Dynamic In Situ Geotechnical Testing, Inc. 1996a). The individual curves covered a rather narrow range suggesting that the site is rather uniform. The published information consists of shear modulus reduction and damping ratio curves presented as functions of

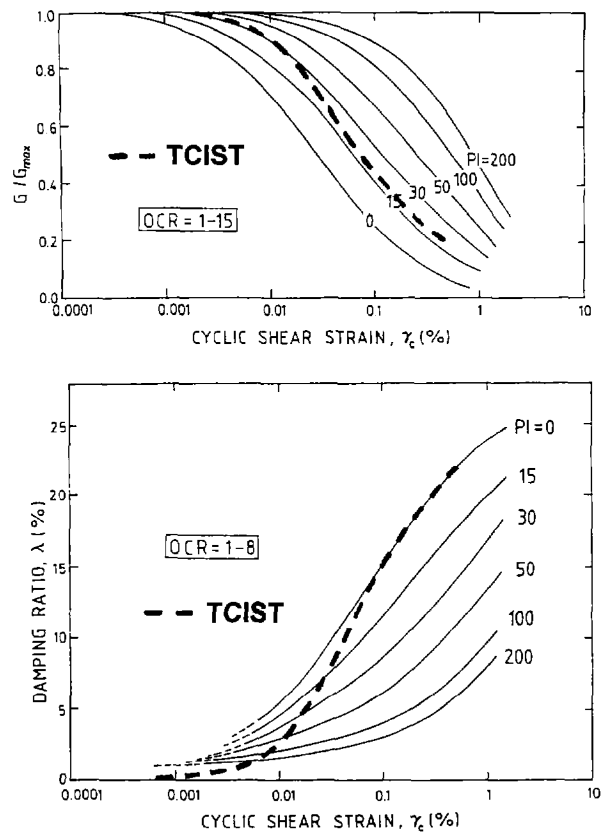

Fig. 8. High strain information inferred from results of torsional cylindrical impulse shear tests (TCIST) conducted at the University of Massachusetts site (representative average curves) superimposed on corresponding information taken from Vucetic and Dobry (1991); the average plasticity index for this site over the depth range of interest was calculated to be 19.4 by Dynamic In Situ Geotechnical Testing, Inc. (1996b) from information obtained from FHWA (1995).

plasticity index. The agreement between the curves inferred from the results of the impulse shear tests and the published curves is reasonable.

We should note that the inferred damping ratio curve in Fig. 8 appears to show somewhat higher values at larger strains than would be expected considering the inferred shear modulus reduction curve. This matter is discussed in detail by Dynamic In Situ Geotechnical Testing, Inc. 1998). The apparent overestimate of damping ratios at higher strains appears to be seated in the partial calibration of the Ramberg-Osgood equations. This matter is being addressed. With respect to damping ratios at lower strains, such damping ratios are underestimated. The main reason for this is that we do not yet describe viscous damping of the soil in our simulations of impulse shear tests and, at lower strains, the damping associated with the Ramberg-Osgood equations approaches zero.

CONCLUSIONS

Herein, we outlined a scheme for automating the analysis procedure for inferring the soil characteristics of interest from the results of torsional cylindrical impulse shear tests. The use of the automated analysis procedure was demonstrated by interpreting results of impulse shear tests conducted at the silty clay site of the University of Massachusetts at Amherst.

The soil characteristics provided for the University of Massachusetts site using the automated analysis procedure were found to be reasonable. Additionally, the procedure is efficient and computer requirements are mild. Thus, the soil characteristics of interest may be inferred in the field. Lastly, no judgment is needed in interpreting results from impulse shear tests.

ACKNOWLEDGMENTS

The field geotechnical testing program reported herein was sponsored in part by FHWA and in part by the National Science Foundation (NSF) under NSF grant no. CMS-9416175. We greatly appreciate this support and the support provided by FHWA for the design and construction of the prototype testing system used for the program. In particular, we appreciate the efforts of A. DiMillio and C. Ealy of FHWA and C. Astill of NSF toward these undertakings. Additionally, we appreciate the efforts of A. Lutenegger of the Univ. of Massachusetts for the help he provided toward our testing program. We also wish to thank John, Patrick, and Steve of Connecticut Test Borings, Inc. for their contributions. Lastly, we wish to thank the Bechdon Company, M. Minor of this company, and F. Rybak of Artek Associates for their efforts toward the development of the impulse shear testing system.

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