Analytical study of simplified in situ torsional cylindrical impulse shear test

R. Henke, W. Henke

Dynamic In Situ Geotechnical Testing Inc., 7 Wyndam Court, Lutherville MD 21093, USA

Abstract

An analytical study of the simplified in situ torsional cylindrical impulse shear test is presented and discussed. This test is intended to provide, for soil deposits, detailed information on in situ undegraded nonlinear inelastic shear stress vs strain characteristics needed for commonly used geotechnical earthquake engineering analysis procedures. The study includes a sensitivity study and a resolution study. The study suggests that the torsional cylindrical impulse shear test will be sensitive to undegraded nonlinear inelastic shear stress vs strain characteristics of soils and able to resolve small differences in these characteristics.

1 Introduction

In this paper we present and discuss an analytical study in which the testing of an idealized saturated sand deposit using a simplified in situ torsional cylindrical impulse shear testing system ("simplified impulse testing system") was simulated. This system is a field prototype system we have constructed for the U.S. Federal Highway Administration [5]. The study was conducted to explore the potential sensitivity of this method of geotechnical testing to undegraded nonlinear inelastic shear stress vs strain characteristics of soils and its potential for resolving small differences in these characteristics. In the following sections, we summarize the simplified impulse shear test, discuss the analytical modeling scheme used for the study and the idealized soil profile considered, present and discuss results from a sensitivity study and a resolution study, and provide conclusions.
2 Simplified torsional cylindrical impulse shear test

The simplified torsional cylindrical impulse shear test, which is discussed in some detail by Henke & Henke [5], is intended to advance our ability to design critical constructed facilities to resist earthquakes. The test is to provide, for soil deposits, detailed information on in situ undegraded nonlinear inelastic shear stress vs strain characteristics needed for one-dimensional site response and other commonly used dynamic geotechnical earthquake engineering analysis procedures. Information is expected to be provided for the shear strain range of 0.001%-1.0% or greater. The test addresses the problem of obtaining such information without disturbing in situ conditions excessively.

The simplified impulse shear test, which is patented [1], is intended to provide information on soil characteristics that is suitable for dynamic earthquake analyses by effectively combining attractive features of existing methods. As in laboratory tests, shearing loads that are reasonably consistent with those commonly assumed in earthquake analyses are applied to an element of soil in a simple but effective manner. The behavior of the test soil is believed to correspond closely to what is thought to be behavior during earthquakes. Detailed information is provided. Tests, however, are conducted in situ with many steps being taken to preserve in situ conditions.

Figure 1 shows, schematically, the basic idea of the simplified impulse test. A single cylinder (diam. ~7 cm) located at the lower end of a probe is carefully penetrated into the soil below the base of a borehole. The test soil surrounds the cylinder. An impulsive torque is applied by an excitation system to the cylinder to induce shear stresses and strains in the test soil. The cylinder responds by rotating dynamically in a manner expected to be strongly dependent on the undegraded nonlinear inelastic shear stress vs strain characteristics of the test soil. The applied torque and resulting rotation are measured by measurement systems whose sensors (torque and motion) are mounted in an instrumented head attached to the top of the cylinder. Soil characteristics are inferred from the torque and rotation measurements by simulating tests analytically.

3 Model of test

To be able to simulate tests analytically, we have developed a refined analysis procedure that is moderately simplified ("existing impulse test analysis procedure"). The procedure describes important aspects of tests but also involves possibly significant simplifications. The procedure is intended to provide reasonably descriptive simulations. We are now extending the procedure for more refined simulations.

The general model of a test consists of a torsionally excited linear elastic cylinder partially embedded in an axisymmetric continuum. Solutions are obtained numerically for a selected sequence of times. Figure 2 shows the
complete basic model for the existing impulse test analysis procedure. As shown in Fig. 2, the model may, if desired, include a coupled electrical component that describes the electrical behaviors of a capacitive discharge power supply and a torsional impulse motor to which it provides power. We found this component to be useful for designing the prototype impulse testing system and conducting the sensitivity study presented herein. In this case, the excitation is the initial voltage across the capacitor. Alternatively, the model may be purely mechanical describing only behavior below the torsional load sensor. This model, described by Henke & Henke [2], is preferred for interpreting test results and was used for the resolution study presented herein. In this case, the excitation is the torque measured by the torsional load sensor (between \( I_o \) and \( I_i \) in Fig. 2). The dynamic behaviors of the electrical components, the instrumented head, and the cylinder are described using discrete parameter models. The dynamic behavior of the test soil is modeled using a continuum approach [3, 4] similar to the method of characteristics as applied to one-dimensional conditions [7]. The procedure describes only horizontally propagating, horizontally oriented shear stresses and
strains within the test soil; that is, nonuniform behavior is described radially but not vertically. The undegraded nonlinear inelastic shear stress vs strain behavior of the soil is described using Ramberg-Osgood equations [6].

To interpret results of actual tests, reasonable shear stress vs strain characteristics are assumed for the continuum. The measured torque is applied to the model. Computed and measured motions of the instrumented head are compared. Simulations are repeated for ranges of soil characteristics. The characteristics providing the most representative simulations are considered to be representative of those of the test soil.

4 Idealized soil profile and various parameters

The idealized saturated sand deposit that was considered to be tested is described by the parameters shown in Fig. 3. Also, $I_0 = 0.001 \text{ kg-m}^2$, $I_1 = \ldots$
Soil Dynamics and Earthquake Engineering

0.0019 kg-m², I₂ = 0.0015 kg-m², k₁₀ = 23 kN-m/rad, k₁₁ = 150 kN-m/rad, c₀ = 0.13 kg-m²/s, c₁₁ = 0.68 kg-m²/s, kₘ = kₑ = 0.06 N-m/A, L = 0.01 mH, R = 0.07 Ω, and C = 0.019 F.

5 Sensitivity study

A sensitivity study, in which tests were simulated for depths of 3 m, 10 m, and 25 m, was conducted. Potential sensitivity of test results to shear stress vs strain characteristics is indicated by the variations in results for the different depths for a given level of excitation. A level of excitation, V₀ = 17.5 V, was selected so that the behavior at the mid-depth of 10 m corresponded to an intermediate level of nonlinear inelasticity.

The analytical results seem reasonable and are sensitive to soil characteristics. Results, including the applied torques vs time, the angular displacements of the instrumented head vs time, and shear stress vs strain curves for the test soil at the wall of the cylinder, are shown in Fig. 4. The results for the shallowest depth show the greatest level of nonlinear inelastic behavior while those for the greatest depth show the least. It should be noted that the applied torque varies with depth because it is a response as well as an excitation.

6 Resolution study

A resolution study, in which we focused on the test simulated for the mid-depth of 10 m, was conducted. The potential resolution of the simplified impulse test with respect to shear stress vs strain characteristics is indicated by the variations in the motion of the instrumented head, for a given applied torque, with variations in either G₀ or τ₀ from the correct value. It should be noted that the procedure for studying resolution corresponds to the process of inferring soil characteristics from actual test results (explained in section 3). A level of excitation, V₀ = 17.5 V, was selected so that the behavior showed an intermediate level of nonlinear inelasticity. As shown in Fig. 5, the value of τ₀ was varied so that the value of G/G₀ was 115% and 85% of the correct value at a shear strain of 0.1%. The value of G₀ was held constant.

The analytical results seem reasonable and suggest that the simplified impulse test will be able to resolve small differences in shear stress vs strain characteristics of soils. Results, including the applied torque vs time, the angular displacements of the instrumented head vs time, and shear stress vs strain curves for the test soil at the wall of the cylinder are shown in Fig. 6. The softer soil characteristics gave higher rotations than the correct characteristics while the stiffer soil characteristics gave lower rotations.
Figure 3: Parameters for idealized soil profile. $v_s$ = shear wave velocity, $\rho$ = density, and $z$ = depth.

Figure 4: Analytical results for sensitivity study.
Figure 5: Shear modulus reduction curves for resolution study. $G = \text{secant shear modulus.}$

Figure 6: Analytical results for resolution study.
10 Soil Dynamics and Earthquake Engineering

7 Conclusions

The results of the analytical study presented herein suggest that the simplified torsional cylindrical impulse shear test will be

1. sensitive to undegraded nonlinear inelastic shear stress vs strain characteristics of soil deposits needed for commonly used dynamic geotechnical earthquake engineering analysis procedures, and

2. able to resolve small differences in such characteristics.

References