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Prototype cyclic torsional cylindrical shear tests

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ABSTRACT: We present and discuss results from cyclic geotechnical tests conducted in the laboratory using a prototype in situ single cylinder torsional cylindrical shear testing system. The system is intended to advance our ability to effectively engineer critical facilities to resist earthquakes and evaluate land in seismically active areas for development. It is to do so by advancing our ability to analytically predict the behavior of soil deposits during earthquakes. The system is to provide, more reliably than we feel is now possible, estimates, for soil deposits, of key in situ cyclic shear stress vs strain characteristics needed by refined earthquake analyses (liquefaction, cyclic degradation and deformation, and undegraded nonlinear inelastic characteristics). We judged the testing system to be a promising means for reliably estimating such characteristics. Test results were found to be reasonable, interpretable, and consistent with published results. We did not encounter difficulties that we feel are insurmountable.

1 INTRODUCTION

We present and discuss results from cyclic geotechnical tests conducted in the laboratory using a prototype in situ single cylinder torsional cylindrical shear testing system. The system is intended to advance our ability to 1) effectively engineer critical constructed facilities to resist earthquakes and 2) evaluate land in seismically active areas for development. We judged the testing system to be effective under controlled laboratory conditions and promising for field use.

2 PROPOSED TESTING PROCEDURE

The torsional cylindrical shear test (Henke and Henke, 1985, 1987, 1990, 1991, 1992) is intended to advance our ability to predict the local behavior of soil deposits during earthquakes. It is to do so by providing, more reliably than we feel is now possible, estimates, for soil deposits, of key in situ cyclic shear stress vs strain characteristics needed by refined earthquake analyses. These characteristics include liquefaction, cyclic degradation and deformation, and undegraded nonlinear inelastic characteristics.

It is of great value to the well-being of society to reliably predict the local behavior of soil deposits during earthquakes. Such behavior has contributed greatly to a broad range of damage (catastrophic to subtle but costly and disruptive) during a number of recent earthquakes. However, despite many truly significant advances toward this goal (Woods, 1978, 1991), we feel there are no procedures available that are generally adequately reliable for estimating in situ cyclic soil characteristics for refined analyses.

The proposed test is to provide greater reliability by providing technological refinement while strongly preserving the very important effects of in situ conditions on cyclic soil characteristics. As in laboratory tests, earthquake-like cyclic shearing loads are applied to an element of soil. Cyclic shearing behavior expected during earthquakes is induced. Tests, however, are to be conducted in situ and in a manner to strongly preserve in situ conditions.

Figure 1 shows, schematically, some of the main elements of the probe for the single cylinder cyclic torsional cylindrical shear test (not an originally planned capability). Basically, a cylinder is to be carefully penetrated below the base of a borehole. The test soil surrounds the cylinder. A cyclic torque is applied to the cylinder to induce cyclic shear stresses and strains in the test soil. In response the cylinder rotates cyclically in a manner dependent upon the shear stress vs strain characteristics of the soil. Measurements of torque, T(t), and rotation, Θ(t), are expected to directly provide a great deal of useful insight into soil characteristics. Specific parameters are to be inferred by iteratively simulating tests analytically.

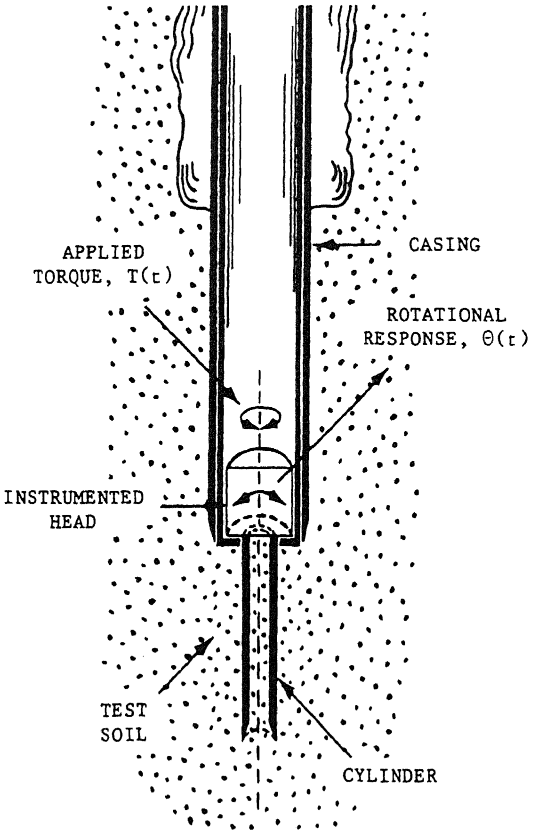


Figure 1. Main elements of single cylinder probe.

The testing procedure offers several important features, most to avoid excessive disturbances to the test soil.

Prior to testing, a special casing is to be penetrated below the base of the borehole (see Figure 1). Soil is to be carefully removed from the casing and the soil at its base is to be carefully trimmed. These steps are to help reduce effects of drilling.

The probe includes an annular piston, shown in Figures 2 and 3. The piston can move longitudinally and applies an appropriate vertical pressure to the leveled surface of the test soil. Prior to penetration, the piston is advanced to the end of the probe and pressurized. Upon application of sufficient vertical force to the probe, the cylinder advances relative to the piston into the test soil. Penetrating under pressure is believed to help reduce particle movements during penetration and preserve the original in situ state of stress.

Additionally, the penetrating edge of the cylinder is shaped to minimize disturbances to the test soil during penetration (see Figure 3). The surface of the cylinder may be smoothed, grooved longitudinally to reduce slip during testing, and/or coated with a low friction material. The influence of the soil within the cylinder on its motion is minimized by smoothing and coating its inner wall, diverting soil from the wall by using a jutted penetrating edge, and minimizing confining pressure on the soil within the cylinder by providing excess volume. The upper portion of the cylinder is shielded (see Figure 3) to reduce effects of unloading and trimming.

During a test, the piston is operated in either the constant volume or constant pressure mode. Only the constant volume mode

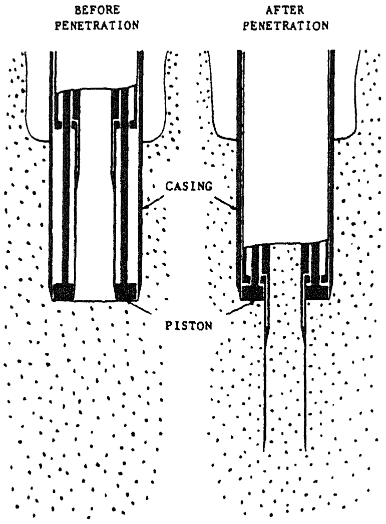


Figure 2. Operation of piston system.

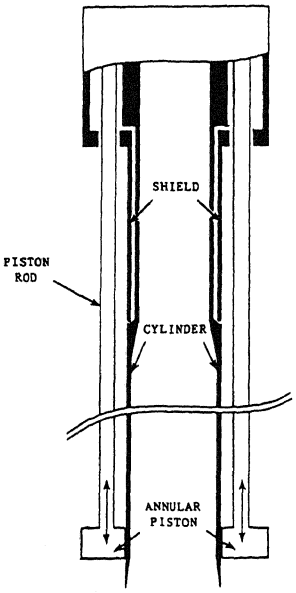


Figure 3. Features of probe.

is relevant to this paper. The concept of laboratory constant volume testing is discussed by Finn, et al. (1982). In the constant volume mode, the piston and probe are locked into vertical position immediately prior to a test. Thus, a condition of relatively constant volume (constant volume ideal not completely realized) is maintained in the region of the test soil. This mode, to be used for testing relatively permeable or dry soils, allows inducing, without changes in porewater pressure, behavior corresponding to cyclic degradation and initial liquefaction/restiffening, and either limited or relatively unrestrained cyclic deformations. Basically, these are related to changes in effective confining pressure caused by the combined tendencies for densification, rebound, and dilation.

3 OBJECTIVE OF TESTING PROGRAM

The main objective of the laboratory testing program discussed herein was to explore the potential of the single cylinder cyclic torsional cylindrical shear test.

4 TEST EQUIPMENT, PROCEDURES, AND DETAILS

Our main test equipment included a prototype testing probe (see Figure 4) and a laboratory test chamber (see Figure 5) for testing the probe in large uniform samples of sand (1.2 m in diameter, 0.81 m high) subjected to confining pressures.

The test sand was deposited uniformly in layers by raining from a hopper/roller system that traveled at a constant speed over the chamber. To build a sample, a platform within the chamber was raised to its top. Several layers of sand were rained onto the platform. The platform was then lowered by the height deposited and several more layers were added. This process was repeated until the chamber was filled. Thus, the height of fall, which can strongly affect relative density, Dr (Bieganousky and Marcuson, 1976), remained reasonably constant. This process provided good repeatability. After deposition, we applied confining pressures to the sample using pressure bags.

To prepare for a test, a prototype casing was carefully penetrated into the sample. Soil was removed from the casing and the soil at its bottom was carefully trimmed using a prototype trimming system. The probe was penetrated slowly (0.04 cm/sec) into the sample. After penetration, the penetration force was reduced to an appropriate level. Then, a test was conducted.

Single cylinder cyclic tests were conducted on three samples of dry medium ottawa sand. Each sample was subjected to a representative confining pressure of 68.9 kPa (lateral pressure = vertical pressure). The average rela-

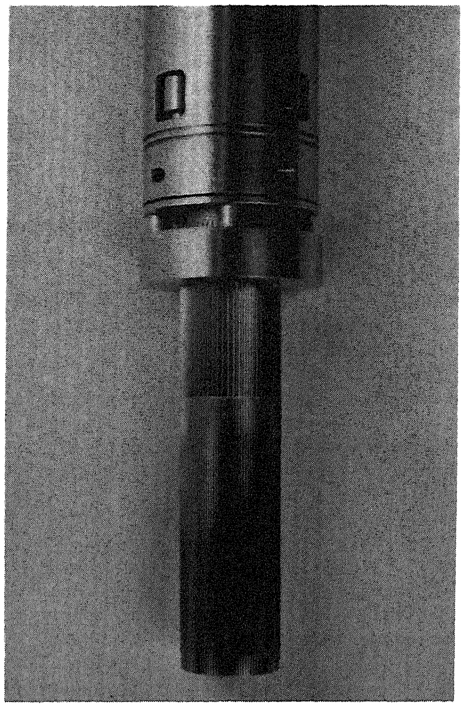


Figure 4. Testing elements of prototype single cylinder probe.

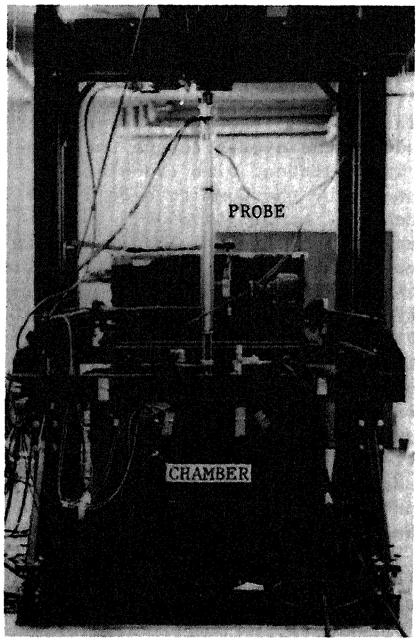


Figure 5. Testing equipment.

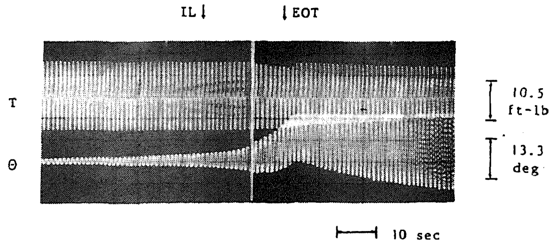
tive density of the samples was 61.0%. The cylinder was grooved and uncoated. The tests were conducted in the constant volume mode. We applied sinusoidal torques at a frequency of 1 cps. Analog data was displayed on a storage oscilloscope and photographed. Digitized data was also recorded.

5 TEST RESULTS AND PRELIMINARY INTERPRETATIONS

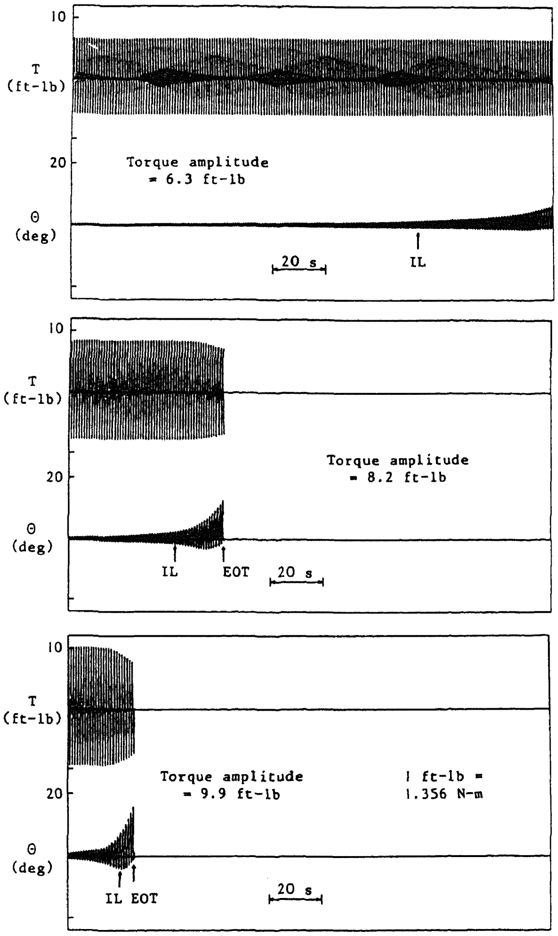
Test results were found to be reasonable, interpretable, and consistent with published results from comparable laboratory cyclic tests conducted on undrained, saturated samples of sand. We did not encounter difficulties that we feel are insurmountable.

Selected results are presented in Figures 6, 7, 8, and 9. The curves of the angular displacement of the instrumented head vs time (see Figure 6) show an intermediate level of degradation (offsets at later stages caused by inexperience with prototype equipment). For each test, the amplitude of the angular displacement increased, at an intermediate rate, to a relatively high level. Without mechanical stops, it seems this amplitude would have reached a limited value due to dilation. The representative torque vs angular displacement curve presented in Figure 7 shows nonlinearity, inelasticity, cyclic degradation, and behavior corresponding to initial liquefaction due to densification and restiffening due to dilation. The representative curve presented in Figure 8 shows the identification of the cycle in which initial liquefaction (for our tests, first instance for which torsional stiffness almost zero, $\Delta T/\Delta\Theta \simeq 0$) occurred. This curve is comparable to corresponding curves presented by the Committee on Earthquake Engineering, et al. (1985). Figure 9 presents a liquefaction curve. The number of cycles to initial liquefaction decreases as the amplitude of the cyclic torque increases. This curve is consistent with liquefaction curves presented by the Committee on Earthquake Engineering, et al. (1985).

We carried out very preliminary interpretations of test results in terms of initial liquefaction characteristics. The interpretations suggest that the soil samples were moderately liquefiable. In Figure 10 we show, superimposed on liquefaction curves presented by the Committee on Earthquake Engineering, et al. (1985), a roughly equivalent liquefaction curve for our tests. This curve is comparable to the published curves. Our curve shows somewhat greater resistance to initial liquefaction than the corresponding published results. The main reasons for this difference are likely the very approximate nature of our estimates (Henke and Henke, 1990) and differences in soil conditions.



(a) Representative photographs of oscilloscope face - torque amplitude = 8.2 ft-lb



(b) Digitized traces

Figure 6. Test results. Average Dr = 61.0%. EOT = End of test due to striking of stops. IL = Initial liquefaction ($\Delta T/\Delta\Theta \simeq 0$).

In addition to studying liquefaction characteristics, we also studied the undegraded nonlinear inelastic characteristics of the first cycles of loading. In this, we are limited to qualitative observations because of measurement difficulties we only recently

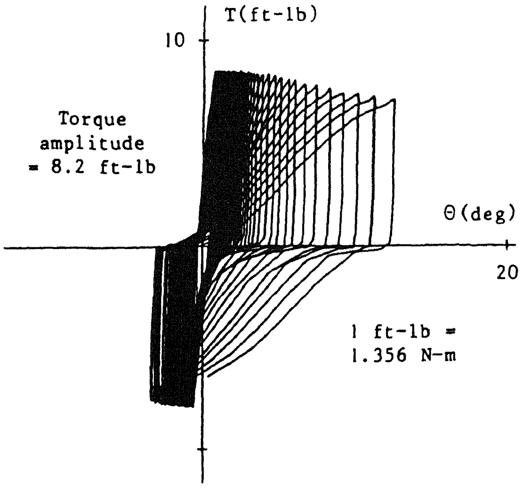


Figure 7. Representative test results - all cycles.

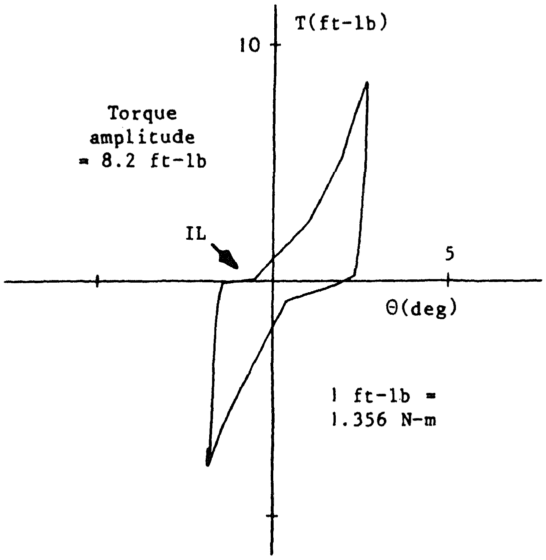


Figure 8. Representative test results - cycle 42. IL = Initial liquefaction ($\Delta T/\Delta\Theta \approx 0$).

identified. We feel these difficulties can be overcome and do not affect the promise of the proposed method for providing undegraded nonlinear inelastic characteristics. Torque vs rotation curves for the first cycles of loading are shown in Figure 11. These curves are comparable to corresponding curves presented by the Committee on Earthquake Engineering, et al. (1985). The rotations, however, may include a component caused by flexibility of a laboratory torsional restraint. The restraint was used during single cylinder cyclic tests to constrain reactionary cyclic rotations of the housing of the probe.

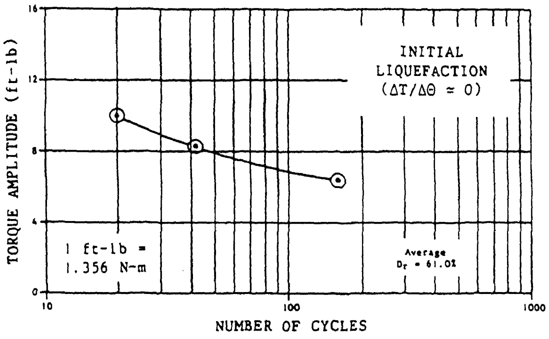


Figure 9. Test results.

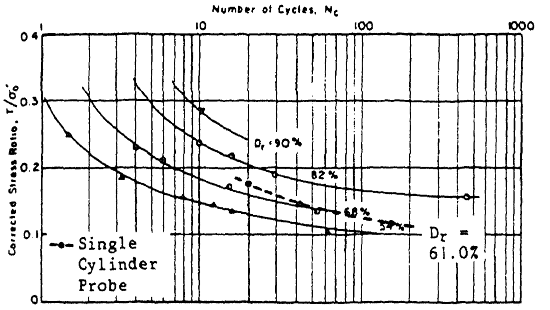


FIGURE 2-29 Stress ratio τ_c/σ'_{vo} versus number of cycles to initial liquefaction, from tests on a shaking table. Source: DeAlba et al. (1976).

Figure 10. Comparison between results from torsional cylindrical shear tests and laboratory cyclic tests conducted on sands and presented by the Committee on Earthquake Engineering, et al. (1985).

Recently, we conducted experiments that suggest such rotations may have been significant components of the rotations measured during the first cycles. This work also suggests, however, that the nonlinear torque vs rotation curves shown in Figure 11 are qualitatively representative. The effect of the reactionary rotations becomes increasingly subdued at later cycles as rotations caused by soil deformations increase. The effect is estimated to be small at the cycles of initial liquefaction. We feel we will be able to overcome this difficulty with further engineering.

With respect to disturbances, our results suggest, qualitatively and quantitatively, that the test soil may not have been excessively disturbed, either consistently or irregularly, by testing. Basically, the tests show the behavior expected for cyclically loaded samples of medium dense sand. Also, the consistency among results from tests of this series and from tests of a second similar series conducted using a double cylinder version of the probe (Henke and Henke, 1990, 1991) suggests high repeatability and little scatter. Because of their sensitivity to soil

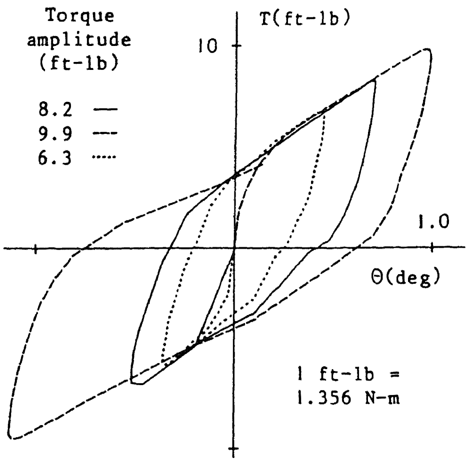


Figure 11. Test results - first cycle.

conditions (Seed, 1976), we feel liquefaction characteristics are a particularly strong indicator of disturbances. We feel that disturbances may have been largely avoided because of the many steps taken to reduce disturbances - using a casing, trimming the test soil, penetrating under pressure, using a shield, and testing in place, etc. The issue of disturbances is addressed in some detail by Henke and Henke (1992).

6 CONCLUSIONS

The single cylinder cyclic torsional cylindrical shear test is a promising means for estimating reliably in situ cyclic shear stress vs strain characteristics of soil deposits. These characteristics include liquefaction, cyclic degradation and deformation, and undegraded nonlinear inelastic characteristics. The test was judged to be effective under representative controlled laboratory conditions. Results from tests were found to be reasonable, interpretable, and consistent with published results and were judged to be repeatable. No difficulties were encountered that we feel are insurmountable.

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