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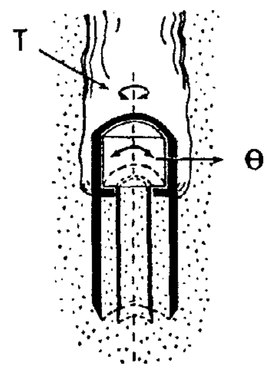
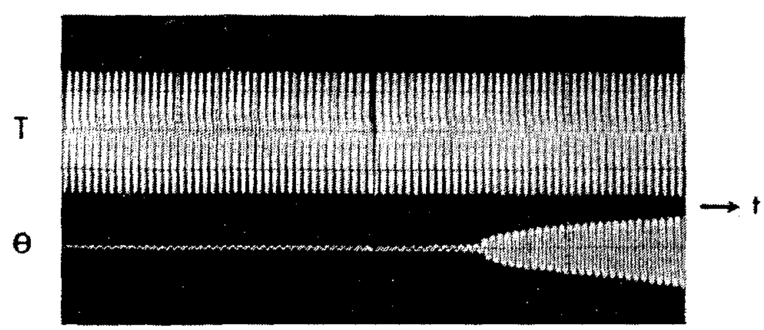
IN SITU TESTING PROCEDURE FOR OBTAINING DYNAMIC AND CYCLIC SOIL PROPERTIES





SBIR Phase II Report
Prepared for the
National Science Foundation
by

Dynamic In Situ Geotechnical Testing, Inc.
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16. Abstract (Limit: 200 words)

The purpose of the project is to bring to realization an in situ geotechnical testing procedure for providing reliable estimates of in situ cyclic and dynamic soil characteristics, including (1) resistances to liquefaction, degradation, and large deformations; and (2) undegraded, nonlinear, inelastic characteristics. The information provided is to be suitable for the advanced stages of the earthquake resistant design of critical systems. Researchers conducted laboratory tests using a prototype system. The procedure was found to be generally effective under controlled laboratory conditions and promising for field use.

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by
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SBIR Phase II Report
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We greatly appreciate the contributions of various organizations and individuals to the Phase II project discussed herein. Success in the project would not have been possible without these contributions.

We greatly appreciate support from the National Science Foundation, the Department of Energy, and the National Institute of Standards and Technology. We are grateful to both Mr. M. Minor of The Bechdon Company, Inc. and Mr. W. Gingras of Friendship Engineering. We are particularly grateful for their imaginative ideas which were critical for success. Mr. Minor supervised the design and construction of the large test chamber we used for our testing program. Mr. Gingras was mainly responsible for the final design and construction of the prototype testing system. Mr. Minor also contributed to the prototype testing system. We also appreciate the contributions of The Bechdon Company, Inc. throughout the project. We thank Mr. L. Kauffman and Mr. F. Rybak who, during our testing program, served as consultants on hydraulic and electronic matters. We thank The Johns Hopkins University for allowing us to use a laboratory and their facilities to conduct our testing program. We greatly appreciate the contributions of students who participated in the program: S. Choudhury, G. Liedtke, T. Rosenzweig, and J. Sheaffer.

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SUMMARY OF REPORT

Introduction

Herein we report on the second phase (Phase II) of a three phase project. The project is intended to advance our ability to design critical systems (buildings, offshore platforms, roadways, etc.) to resist earthquakes. Our work is to reduce losses of all kinds during future earthquakes.

Phase II was supported by both the National Science Foundation and the Department of Energy (based on a recommendation from the National Institute of Standards and Technology). The project falls under the domain of earthquake hazard mitigation.

For Phase II we evaluated the effectiveness of a proposed in situ geotechnical testing procedure for estimating cyclic and dynamic soil characteristics. We conducted laboratory tests using a prototype system. The procedure was generally found to be effective under controlled laboratory conditions and promising for field use.

Purpose of Project

Specifically, the purpose of our project is to bring to realization an in situ geotechnical testing procedure for providing, more reliably than is now possible, estimates of in situ cyclic and dynamic soil characteristics. The characteristics include 1) resistances to liquefaction (almost total loss of competence of soil), degradation (reduction in competence of soil), and large deformations, and 2) undegraded, nonlinear, inelastic characteristics. The information provided is to be suitable for the advanced stages of the earthquake resistant design of critical systems.

Our project is to advance our ability to analytically predict the behavior (liquefaction, deformations, motions, etc.) of soil deposits during earthquakes. Such behavior has been a major source of catastrophic losses. Analyses used to predict such behavior rely heavily on the soil characteristics in question. Results of analyses can be quite sensitive to these characteristics; thus, reliable estimates of the characteristics are needed to avoid unconservative or costly, excessively conservative designs.

Despite the catastrophic losses and the sensitivity of analyses, there do not seem to be procedures available for reliably estimating cyclic and dynamic soil characteristics for the design of critical systems. Improving our ability to estimate these characteristics will lead to greater safety, reliability, and economy.

History of Project

Our Phase II work is a major step toward our goal of realizing the proposed procedure in practice. Previous steps include conceiving the procedure, conducting feasibility studies (Phase I), patenting the procedure, and publishing our work. Steps to follow Phase II include field testing and commercialization.

Proposed Technical Approach

The proposed testing procedure is intended to provide more reliable information on soil characteristics by combining attractive features of existing procedures while minimizing shortcomings. Laboratory testing of samples is a powerful existing procedure. Earthquake-like cyclic or dynamic shearing loads can be applied. Appropriate behavior is induced and detailed information is provided. However, in situ conditions, which strongly affect behavior, can be greatly disturbed. In situ testing, an alternative procedure, preserves in situ conditions to a greater degree but earthquake-like cyclic shearing loads are not applied and appropriate behavior is not induced.

With the proposed procedure, we apply earthquake-like cyclic or dynamic (impulsive) shearing loads in situ and induce behavior expected during earthquakes. In situ conditions are expected to be well-preserved and detailed information is provided.

Potential Benefits

The proposed testing procedure is expected to have significant safety, economic, environmental, and other benefits worldwide.

Potential Commercial Applications and Users

The proposed testing procedure has several potential commercial applications worldwide. These include the design, construction, and maintenance of soil-structure-equipment systems which could be subject to earthquakes, large ocean waves, or vibrations.

The proposed testing procedure has several potential users worldwide. These include agencies of governments, universities, geotechnical engineering firms, oil companies, power companies, and construction firms.

Technical Objectives of Phase II

Our main technical objective was to evaluate the effectiveness of the proposed testing procedure by conducting carefully controlled laboratory tests using a prototype testing system. If we found results to be reasonable, consistent, and interpretable, and we did not encounter abnormal difficulties or major limitations, we would conclude that the procedure is effective under controlled laboratory conditions and promising for field use.

Most of our attention was to be directed toward cyclic testing for estimating resistances to liquefaction, degradation, and large deformations. Cyclic testing is to be the main capability of the proposed testing procedure. However, some attention was also to be directed toward impulse testing for estimating dynamic, undegraded, nonlinear, inelastic shear stress vs strain characteristics.

Main Tasks and Procedures of Phase II

Several tasks were carried out to evaluate the procedure. A prototype testing system and large test chamber were constructed. The chamber allows the testing of the prototype system in large uniform samples of sand subjected to representative confining pressures. We conducted cyclic and impulse tests with the prototype system at The Johns Hopkins University. We developed analyses of an intermediate level of descriptiveness for simulating cyclic and impulse tests. We used the analyses to interpret the results from tests. At appropriate stages we published our work.

Results and Discussions of Results of Phase II

The testing procedure was found to be effective under controlled laboratory conditions. Generally, results from cyclic and impulse tests were found to be reasonable, consistent when compared with published results from laboratory tests of a high quality, and repeatable when repeatability was considered. Generally, we found that we could interpret important aspects of cyclic and impulse tests. Results of analyses were found to be sensitive to shear stress vs strain characteristics. We did not encounter abnormal difficulties or limitations that we feel cannot be overcome.

Conclusions of Phase II

The proposed testing procedure is a promising means for estimating, more reliably than is now possible, in situ cyclic and dynamic shear stress vs strain characteristics of soil deposits. We also feel the procedure shows promise as an index-like test.

The procedure was found to be effective for estimating cyclic and dynamic shear stress vs strain characteristics under controlled laboratory conditions. We feel we experienced considerable success with cyclic testing and reasonable success with impulse testing. We feel the most effective step toward improving the testing procedure would be to develop more descriptive analyses for interpreting results from tests.

Because the proposed testing system is promising, further attention should be directed toward its realization and fully realizing its potential.

Further Work

We feel the most productive next step toward realization of the proposed testing procedure would be to conduct field tests. After initial field tests, it would be of great value for realizing the potential of the procedure to conduct further laboratory tests and to refine further the testing procedure.

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TERMINOLOGY AND NOMENCLATURE

In this section, several technical terms are explained as used herein. The terms relate to the characteristics of soils that affect the behavior of soil deposits during earthquakes. We also define the nomenclature used throughout this report.

Terminology

Undegraded Shear Stress vs Strain Characteristics--These are characteristics corresponding to the first cycle of the cyclic loading of an element of soil. A typical undegraded shear stress vs strain curve is shown in Figure 1. Under earthquake-like loadings behavior can be highly nonlinear and inelastic. The shear modulus, G, is the slope of the curve at any point. It represents the shearing stiffness of the element of soil for the level of strain in question.

Low Amplitude Dynamic Shear Modulus, G_o--The low amplitude dynamic shear modulus (see Figure 1) is the slope, at low levels of shear strain (<0.001%), of the shear stress vs strain curve for an element of soil loaded dynamically. Generally, behavior is linear at these levels of strain. Reference 18 provides greater detail.

Relative Density, D_r--The relative density of a cohesionless soil is a measure of the compactness of the arrangement of its grains. Relative density is indicated by a scale of 0 to 100%. A sand having a relative density of 0% ("loose") is structurally in its least compact state. Such a sand may be quite unstable during an earthquake. A sand having a relative density of 100% ("dense") is structurally in its most compact state. Such a sand may be quite stable during an earthquake. Reference 20 provides greater detail.

Degradation and Liquefaction Characteristics of Sands and Silts--Degradation, herein, refers to the cyclic decrease in shear stiffness (slope of straight line through peaks of shear stress vs strain curve for given cycle) that may occur in an element of soil subjected to large, earthquake-like, cyclic shear loads. Degradation can occur in actual soil deposits because of buildups in excess porewater pressure. As shown in Figure 2, the degradation of an element of soil, loaded cyclically with a uniform amplitude, appears as an increase in the amplitude of the cyclic shear strain of the element with an increase in the number of cycles of loading. Under loadings corresponding to large earthquakes, generally sands of low relative density (<50%) will show severe degradation while sands of high relative density (>70%) will show only mild degradation. After a sufficient number of cycles, "initial liquefaction" (19), the first instance of almost total loss of effective confining pressure, may occur. Thereafter, the sands of low relative density may undergo unrestrained deformation, termed liquefaction. Sands of high relative density usually will not liquefy because of the restraining effects of dilation, the expansion of the volume of the grain structure of a soil. Rather, such sands generally show only limited deformations regardless of the number of cycles of loading. References 19 and 20 provide more detail.

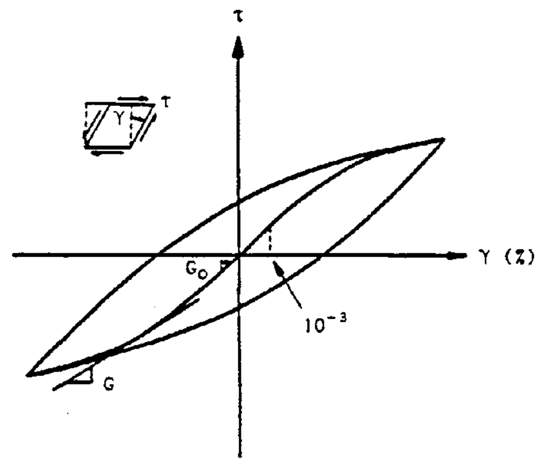


Figure 1: Nonlinear Shear Stress vs Strain Curve for Soils

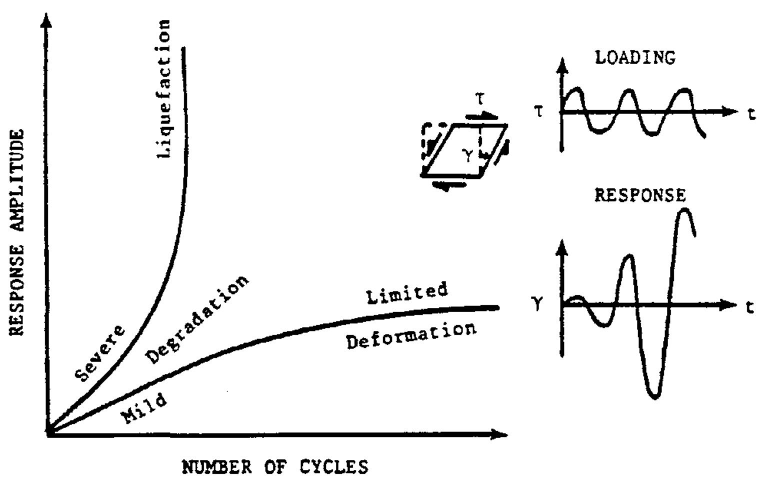


Figure 2: Degradation and Liquefaction

Nomenclature

a_1, a_2 = Linear tangential accelerations of instrumented head at diametrically opposed positions

C1, C2, C3, C4 = Parameters of degradation and liquefaction model

D_r = Relative density

e = Void ratio

G = Tangent shear modulus

G_o = Low amplitude dynamic shear modulus

I = Mass moment of inertia

K_o = Coefficient of earth pressure at rest

k_2 = Parameter of degradation and liquefaction model

m = Parameter of degradation and liquefaction model

N, Nc = Number of cycles

n = Parameter of degradation and liquefaction model

R = Parameter of Ramberg-Osgood equations

r = Radius

r_{ih} = Radius of instrumented head

T = Torque applied to instrumented head of probe

t = Time

u = Excess porewater pressure

α = Parameter of Ramberg-Osgood equations

γ = Shear Strain; Horizontally polarized shear strain developed in test soil

$\overline{\gamma}$ = Effective weight per unit volume of soil

Θ, $\dot{\Theta}$, $\ddot{\Theta}$ = Angular displacement, velocity, and acceleration of instrumented head of probe

ρ = Mass density of soil

σ_o' = Initial effective vertical stress

$\overline{\sigma}_o$ = Average effective confining pressure

$\overline{\sigma}_v$ = Effective vertical stress

τ = Shear stress; Horizontally polarized shear stress developed in test soil

τ_y = Parameter of Ramberg-Osgood equations

INTRODUCTION

This report, to the National Science Foundation (NSF) and the Department of Energy (DOE), covers work carried out for the second phase (Phase II) of a planned three phase project. The project is intended to advance our ability to design critical systems (buildings, offshore platforms, roadways, etc.) to resist earthquakes. Our work is to reduce losses of all kinds during future earthquakes.

Specifically, the purpose of the entire project is to bring to realization a proposed in situ geotechnical testing procedure for estimating, more reliably than is now possible, in situ cyclic and dynamic soil characteristics. For Phase I, we conducted a feasibility study, for Phase II we conducted a laboratory research study, and for Phase III we plan to conduct field tests and commercialize the testing procedure. Phase I research was supported by a Phase I Small Business Innovation Research (SBIR) grant awarded by NSF to our firm, Dynamic In Situ Geotechnical Testing, Inc. Phase II research was supported by a Phase II SBIR grant awarded by NSF to our firm. A prototype testing system, needed for Phase II research, was funded through an Energy-Related Inventions Program (ERIP) grant awarded to our firm by DOE. This grant was awarded based on a recommendation by the National Institute of Standards and Technology (NIST). Our project falls under the domain of the Earthquake Hazard Mitigation program of NSF.

For Phase II, we evaluated the effectiveness of the proposed testing procedure. We conducted laboratory tests using the prototype testing system. The procedure was generally found to be effective under controlled laboratory conditions and promising for field use.

Regarding organization, in the preceding portion of this report, we provide a summary of the report and a section on terminology and nomenclature. In the following sections, we present and discuss, in reasonable detail, the purpose of the project, the history of the project, the proposed technical approach and its potential benefits, and commercial applications and users. We then present, for Phase II, technical objectives, main tasks and procedures, results and discussions of results, and conclusions. We also identify further work and present references and appendices.

PURPOSE OF PROJECT

Our project is intended to advance our ability to design critical systems (buildings, offshore platforms, bridges, pipelines, roadways, etc.) to resist earthquakes. This is to reduce losses of all kinds during future earthquakes.

Specifically, the purpose of our entire project (Phases I, II, and III) is to bring to realization a proposed in situ geotechnical testing procedure. The procedure is to provide, more reliably than is now possible, estimates, for soil deposits, of in situ cyclic and dynamic shear stress vs strain characteristics. The characteristics include 1) resistances to initial liquefaction, cyclic degradation, and large deformations before and after initial liquefaction, and 2) undegraded, nonlinear, inelastic characteristics. The estimates are to be appropriate for use at the later stages of the earthquake resistant design of critical systems.

The proposed testing procedure is to advance our ability to analytically predict the behavior of soil deposits during earthquakes. It is of great importance to reliably predict the behavior of soil deposits during earthquakes. Catastrophic losses have been experienced (Alaska, 1964; Niigata, 1964; Mexico City, 1985; References 3, 20, and 27) due to such behavior. The 1989 Loma Prieta earthquake provides a recent striking example. Extensive liquefaction, excessive deformations, and settlements were reported to have occurred in many areas (1) (4) (22). The resulting damage was reported to include foundation bearing failures, building damage, pavement damage, subsidence and slumping of roadways, runway damage, bridge collapse, broken utility lines, and levee damage (4) (22). Preliminary studies indicate that amplified ground motions may have increased the occurrence of liquefaction (4).

Because of the importance of the behavior of soil deposits during earthquakes, there are various types of analyses which predict such behavior. These include earthquake site response analyses, earthquake soil-structure interaction analyses, and earthquake slope stability analyses. All require information on in situ cyclic or dynamic shear stress vs strain characteristics of soil deposits. Results of these analyses can be extremely sensitive to these characteristics, particularly if liquefaction is possible (16). Therefore, potentially powerful analyses can be and are severely limited by uncertainty in soil characteristics.

Even though the behaviors of soil deposits have caused great losses and in situ cyclic or dynamic shear stress vs strain characteristics must be estimated reliably for effective predictions of such behaviors, to our knowledge, there are no procedures for reliably estimating these characteristics for the advanced stages of the design of critical systems. By improving our ability to estimate soil characteristics reliably, we will realize more fully the potential of refined analyses. This will lead to greater safety, reliability, and economy of critical soil-structure-equipment systems located in seismically active areas.

HISTORY OF PROJECT

In this section, we summarize the main steps toward our long term goal of bringing to realization the proposed testing procedure.

1982 - Testing procedure conceived by R. Henke while working for Exxon Production Research Company. Idea product of field, laboratory, and analytical experiences in predicting behavior, during earthquakes, of sites of major offshore platforms.

1985 - Conducted theoretical and operational feasibility studies which indicated proposed testing procedure feasible. Studies supported by NSF Phase I SBIR grant. Title: "In Situ Testing Procedure for Obtaining Dynamic and Cyclic Soil Properties." Grant Number: #CEE-8460719. Award amount: $40,000. Period of performance: January 1, 1985 - June 30, 1985. Principal investigator: W. Henke.

1985 - Published and presented at conference results of theoretical and operational feasibility studies (see Reference 12 and APPENDIX B).

1987 - Constructed laboratory research prototype testing system. Work supported by ERIP grant awarded by DOE based on recommendation from NIST. Title: "Design and Construction of a Prototype In Situ Geotechnical Testing System," Grant number: #DE-FG01-87CE15305. Award amount: $79,860. Period of performance: December 23, 1986 - May 22, 1988. Principal investigator: W. Henke. Engineer responsible for design and construction of system: W. Gingras, Friendship Engineering.

1987 - Published and presented at conference paper on selected elements of prototype testing system (see Reference 11 and APPENDIX B).

1987-88 - Constructed large laboratory test chamber for testing of prototype system. Work supported by Dynamic In Situ Geotechnical Testing, Inc. Engineer responsible for design and construction of chamber: M. Minor, Bechdon Company, Inc.

1987-89 - Awarded patents for proposed testing procedure in United States, Canada, Australia, and New Zealand. Patent approved in Europe. Patents pending in Japan and Norway. Inventors: R. Henke and W. Henke.

1988-89 - Tested prototype testing system in test chamber in laboratory of The Johns Hopkins University. Work indicates proposed testing procedure promising. Work supported by NSF Phase II SBIR grant. Title: "In Situ Testing Procedure for Obtaining Dynamic and Cyclic Soil Properties." Grant number: #ISI-8601419. Award amount: $189,471. Period of performance: Aug.1, 1986 to July 31, 1989. Principal investigator: W. Henke.

1990 - Submitted abstracts to two conferences of papers on results of prototype tests (see References 13 and 14 and APPENDIX B).

1990 - Submitted proposal to NSF for project involving field testing of proposed procedure at sites affected by 1989 Loma Prieta Earthquake. Title: "An Analytical/Field Study of the Liquefaction, Deformations, Settlements, and Motions of Soil Deposits Caused by the 1989 Loma Prieta Earthquake." Amount requested: $233,795. Proposed period of performance: April 1, 1990 - March 31, 1991. Principal investigator: W. Henke. Co-principal investigator: R. Henke.

PROPOSED TECHNICAL APPROACH

In this section, we discuss the proposed testing procedure in detail. Also, we briefly discuss existing procedures in general terms.

The proposed procedure is intended to provide, more reliably than is now possible, detailed information on in situ cyclic and dynamic soil characteristics. These include 1) resistances to liquefaction, large deformations, settlements, and degradation and 2) undegraded, nonlinear, inelastic characteristics.

The proposed testing procedure is to provide greater reliability by effectively combining attractive features of existing procedures while minimizing shortcomings. Currently, cyclic and dynamic shear stress vs strain characteristics are estimated either by laboratory testing of soil samples recovered from a site or by in situ testing at a site (26).

Laboratory testing is powerful. Earthquake-like cyclic and dynamic shear loads can be applied directly to samples inducing behavior expected during earthquakes. Detailed information (for example, cyclic shear stress vs strain curves) needed by refined analyses is readily provided. Laboratory tests can be conducted on most soils of interest. Also, conditions different from those in situ may be considered. However, laboratory testing suffers from the serious problem of disturbances to in situ conditions (19). Disturbances can and often do create a level of uncertainty in estimated soil characteristics which we feel is excessive for the design of critical systems.

With in situ testing, in situ conditions are preserved to a greater degree. However, with existing in situ tests we cannot apply earthquake-like cyclic shear loads or induce behavior expected during earthquakes.

With the proposed procedure, cyclic earthquake-like shear loads are applied in situ to a well-defined element of soil in a simple but effective manner. The behavior of the test soil corresponds closely to what is thought to be the behavior of soil elements during earthquakes. Thus, the loading of the soil and its mode of failure should not be major sources of uncertainty. A number of steps are taken to preserve in situ conditions. Thus, the very important effects of in situ factors are expected to be captured to a high degree. Several features are provided to help induce the phenomena of interest and to simplify the interpretation of test results. The procedure should apply to most soils of interest. Also, the procedure should provide, with a minimum of intermediate interpretation, the soil characteristics required for earthquake analyses. Finally, the procedure requires only a single borehole, so that it may be used in confined or harsh environments.

Figure 3 shows, schematically, some of the main elements of the probe of the testing system as it was originally proposed (12). Equipment above the probe is not shown. Basically, two concentric, thin-walled cylinders are carefully penetrated below the base of a borehole. The test soil is the well-defined annular zone of soil between the two cylinders. During our testing program we also tested a version of the probe consisting of only the inner cylinder. Some of the main elements of this version are shown schematically in Figure 4. The test soil is the soil surrounding the cylinder. A cyclic or impulsive torque is applied to the active cylinder (inner or single cylinder) to induce earthquake-like shear stresses and strains in the test soil. In response, the cylinder rotates in a manner dependent on the shearing characteristics of the test soil. Both torque and

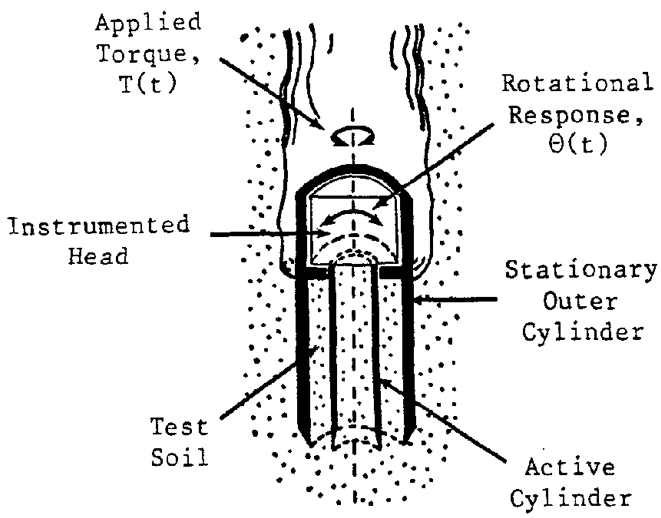


Figure 3: Main Elements of Double Cylinder Probe

rotations are measured by transducers in the instrumented head. Soil characteristics are inferred by simulating tests analytically. Soil characteristics are assumed for an appropriate analytical model. Measured torques are applied to the model and rotations of the model cylinder are computed. Soil characteristics are iteratively varied until measured and computed rotations agree acceptably. The characteristics providing the most representative simulations are considered to represent those of the test soil.

One test originally proposed, the cyclic test, is shown schematically in Figure 5(b) being conducted using the double cylinder probe.

This test, featuring the main capabilities of the proposed testing procedure, would be conducted to estimate resistances to liquefaction, degradation, large deformations, and settlements, and undegraded, cyclic, nonlinear, inelastic, shear stress vs strain characteristics. A cyclic torque having a uniform amplitude is applied to the active cylinder. As shown in Figure 5(b), the rate of increase in the amplitude of the cyclic angular displacement of the instrumented head and the ultimate value of this amplitude would be expected to be strongly related to soil characteristics. When testing highly degradable, liquefiable soils, under appropriate levels of loading, we would expect rapid and unrestrained increases in the amplitude of the angular

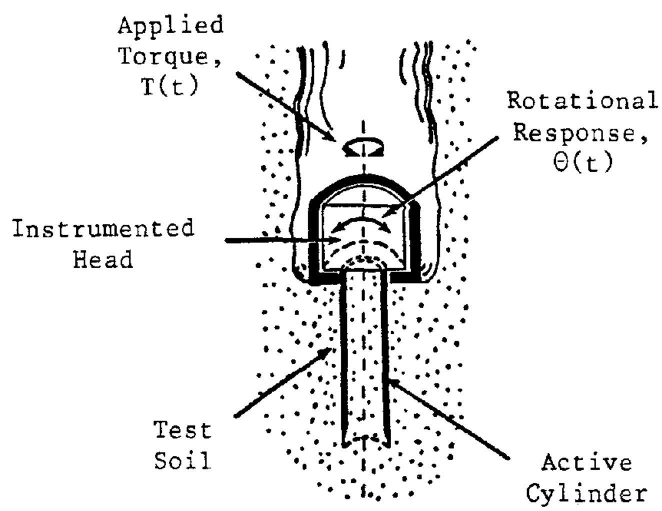


Figure 4: Main Elements of Single Cylinder Probe

displacement of the instrumented head with an increase in the number of cycles of loading. When testing moderately degradable, nonliquefiable soils, we would expect only gradual, limited increases in this amplitude.

A second test originally proposed, the impulse test, is shown schematically in Figure 5(a) being conducted using the double cylinder probe. This test would be conducted to estimate undegraded, dynamic, nonlinear, inelastic shear stress vs strain characteristics. An impulsive torque is applied to the active cylinder. As shown in Figure 5(a), the amplitude, frequency, and rate of decay of the oscillating rotational response of the instrumented head would be expected to be strongly related to the shear stress vs strain characteristics of the test soil. For example, when testing stiff soils we would expect the instrumented head to vibrate at low amplitudes and high frequencies.

The proposed testing procedure is to offer important features.

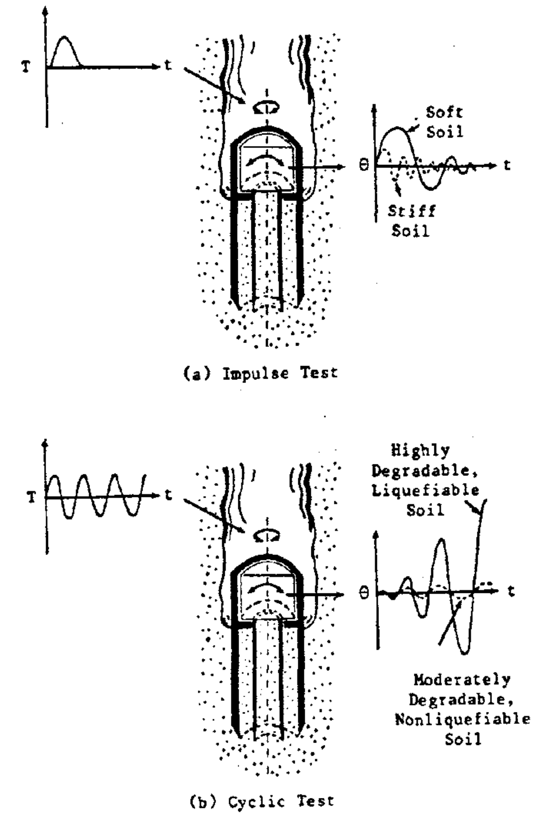


Figure 5: Possible Tests Using Double Cylinder Probe

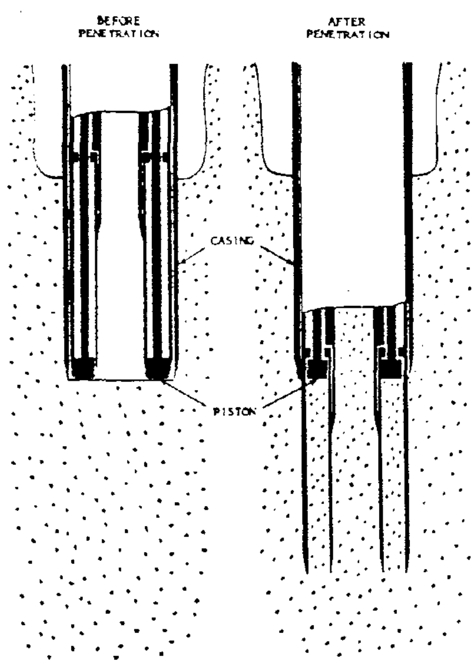


Figure 6: Operation of Piston System

Also, several steps are taken to preserve in situ conditions and to improve operability.

Prior to testing, a special casing is to be penetrated below the base of the borehole. The casing is to help preserve the original state of stress and reduce effects of drilling. The casing is shown schematically in Figure 6 along with the double cylinder probe. Before testing, the casing would be carefully cleaned out and the soil at the base would be carefully trimmed.

An important component of the probe is an annular piston also shown in Figure 6. The piston can move longitudinally and applies an appropriate vertical pressure to the test soil. Prior to penetration, the piston is advanced to the end of the probe and pressurized. Upon application of penetration force to the probe, the cylinder(s) advances relative to the piston into the test soil. This procedure of penetrating under pressure is expected to help reduce particle movements during penetration and to help preserve the original in situ state of stress.

During a test, the piston is operated in one of two modes: the constant volume mode or the constant pressure mode.

We would operate the piston in the constant volume mode, for example, when conducting cyclic tests on relatively permeable, freely draining soils (sands). This would allow us to induce in such soils, without buildups in porewater pressure, phenomena corresponding to those caused by earthquake-like cyclic loading under saturated undrained conditions (6). These phenomena include degradation and initial liquefaction due to densification, restiffening due to dilation, and large deformations before and after initial liquefaction (including limiting strains). Basically, these phenomena would come about as a result of changes in effective confining pressure. Such changes would occur under conditions of constant volume due to the tendencies for densification and dilation of grain structure caused by cyclic shearing loads. In the constant volume mode, the piston and the probe are locked into vertical position immediately prior to a test. Thus, during a test, a condition of relatively constant volume would be maintained in the region of the test soil. The volume would not remain completely constant mainly because of soil compressibility.

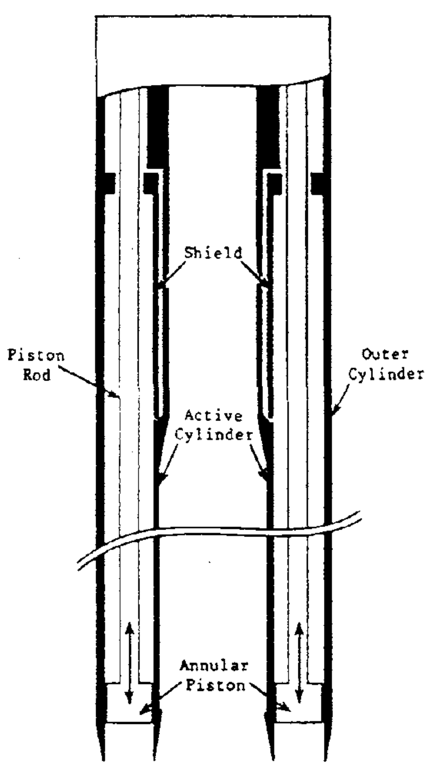


Figure 7: Features of Double Cylinder Probe

We would operate the piston in the constant pressure mode, for example, when conducting cyclic tests on relatively impermeable soils (silts, clays) and when conducting impulse tests. Degradation and liquefaction would be induced as a result of buildups in porewater pressure. In the constant pressure mode, the pressure applied by the piston would be maintained during a test. Thus, there would not be large changes in total confining pressure brought about by the tendencies for densification or dilation.

The proposed testing procedure offers other important features. The inner and outer cylinders have thin walls to avoid excessive disturbances. As shown in Figure 7, the penetrating edges of the cylinders are shaped to minimize disturbances to the test soil during penetration. The surfaces of the cylinders may be grooved longitudinally to reduce slip during testing while minimizing disturbances during penetration. The cylinders may be coated with a low friction material to further reduce disturbances during penetration in certain soils. We also include features to minimize the influence of the soil within the active cylinder on its motion. The inner wall of the cylinder is smooth and may be coated with a low friction material, soil is diverted away from the inner wall by jutted penetrating edges, and confining pressures on the soil within the active cylinder are minimized by providing excess volume. The upper portion of the active cylinder is shielded, as shown in Figure 7, to reduce effects of unloading and trimming. With the shield, the test soil is located some distance below the bottom of the casing. The shield is grooved longitudinally along with the active cylinder.

Analytically simulating tests is expected to be an effective means for inferring soil characteristics from results of tests. This is because tests are relatively simple to describe analytically. The geometry of a test and the torsional shear stresses and strains induced by the probe are relatively simple. Additionally, the soil models used in simulations are similar to those used in earthquake analyses (for example, DESRA, CHARSOIL; References 5 and 25). Therefore, shear stress vs strain characteristics needed for such analyses are provided with a minimum of intermediate interpretation.

POTENTIAL BENEFITS

In this section, we discuss the potential benefits of the proposed testing procedure. The procedure is expected to have safety, economic, environmental, and other benefits.

The proposed testing procedure is expected to produce significant safety benefits. For example, a loose sand sample may densify an unknown amount because of disturbances during recovery, transport, and test preparation. As a result, the sample may show greater resistance to liquefaction in a laboratory test than the sample had in the field. The same sample may also lead to overestimates in degradation resistance and shear stiffness. This may lead to unconservative estimates of earthquake ground motions for soil-structure-equipment systems with low natural frequencies (offshore structures, for example). The proposed testing procedure, which is expected to minimize disturbances, would be expected to reduce such a possibility.

The proposed testing procedure is also expected to produce significant economic benefits without reductions in targeted levels of safety. For example, a dense sand sample may be loosened during recovery, transport, and test preparation. As a result, in a laboratory test, the sample may show less resistance to liquefaction than the sample had in the field. The same sample may also lead to underestimates in degradation resistance and shear stiffness. This may lead to costly, excessively conservative predictions of earthquake ground motions for soil-structure-equipment systems with low natural frequencies. The proposed testing procedure, which is expected to minimize disturbances, would be expected to reduce such a possibility.

Additionally, the proposed testing procedure may affect feasibility decisions and design considerations. For example, more fully and accurately accounting for in situ factors may prove a liquefaction resistant system to be economically feasible at a marginal site. Similarly, for a reasonably competent site, the costly need to design and construct a structure to resist liquefaction may be eliminated. These possibilities arise as a result of the very significant effects of in situ factors (age, stress history, etc.) on liquefaction resistance (19). For example, it may be inferred that in situ factors can increase the resistance of a soil to initial liquefaction by a factor of 2 to 3.5 (19). Based on our experiences, we believe that such and even lesser factors can have dramatic effects on estimates of the potential for liquefaction and its extent. Thus, preserving in situ conditions to a high degree can be important to feasibility decisions and design considerations.

The proposed procedure may also have environmental benefits. By providing greater reliability in earthquake resistant designs, the testing procedure would reduce the likelihood of earthquake induced damage to the environment.

A unique potential benefit of the proposed testing procedure that is expected to encourage its application is that the basic elements of the procedure are easily understood. That a test can reasonably resemble an earthquake in situ is easy to see. The sudden development of large cyclic movements in the test soil subjected to earthquake-like loading (see Figure 26) is readily seen. The potential consequences of this are clear. That a gradual and limited increase in cyclic movement may be relatively safe is also easy to understand. This benefit is expected to make the test appealing to those not greatly familiar with geotechnical earthquake hazards and their mitigation but with the responsibility for design decisions.

POTENTIAL COMMERCIAL APPLICATIONS AND USERS

The proposed testing procedure has several potential commercial applications. These include the design, construction, and maintenance of soil-structure-equipment systems which could be subjected to earthquakes, large ocean waves, or vibrations.

The proposed testing procedure has several potential worldwide users. These include agencies of governments, universities, geotechnical engineering firms, oil companies, power companies, and construction companies.

TECHNICAL OBJECTIVES OF PHASE II

We had two main objectives for our Phase II research. Our first objective was to evaluate the effectiveness of the proposed testing procedure under controlled laboratory conditions. For this we conducted laboratory tests of a high quality using a laboratory research prototype testing system. If test results were found to be reasonable, interpretable, and consistent with published results of tests of a high quality, and if we did not observe major limitations of the testing procedure or encounter abnormal difficulties, then we would conclude that the proposed testing procedure is an effective means for determining cyclic and dynamic soil characteristics under controlled laboratory conditions. We would also conclude that the procedure is promising for field use. In the interest of quality, we departed somewhat from our originally proposed approach for evaluating effectiveness (see APPENDIX A).

Most of our attention was to be directed toward cyclic testing for estimating resistances to liquefaction, degradation, and large deformations. Cyclic testing is to be the main capability of the proposed testing procedure. However, some attention was also to be directed toward impulse testing for estimating dynamic, undegraded, nonlinear, inelastic shear stress vs strain characteristics.

Our second main objective was to define any further research and development needed to realize the testing procedure and its full potential. We would define needs based on our experiences during our testing program.

MAIN TASKS AND PROCEDURES OF PHASE II

The main tasks and procedures of Phase II are discussed in the following subsections. Several main tasks were carried out to meet our objectives. We had equipment constructed, conducted tests, developed analyses, and interpreted tests. We also published our work.

Construct Equipment

Our main equipment is discussed briefly in this section. The main equipment constructed for Phase II includes a laboratory research prototype testing system and a large laboratory test chamber. The testing system was designed and constructed by W. Gingras of Friendship Engineering. The test chamber was designed and constructed by The Bechdon Company, Inc. (Bechdon) under the supervision of M. Minor. After preliminary tests, the prototype testing system was modified by M. Minor and W. Henke.

The prototype testing system includes a probe and accessory equipment. The probe applies cyclic or dynamic torques to the active cylinder embedded in the test soil. It also provides measurements of the applied torque and the resulting rotations of the instrumented head. Elements of the single and double cylinder versions of the probe are shown in Figure 8.

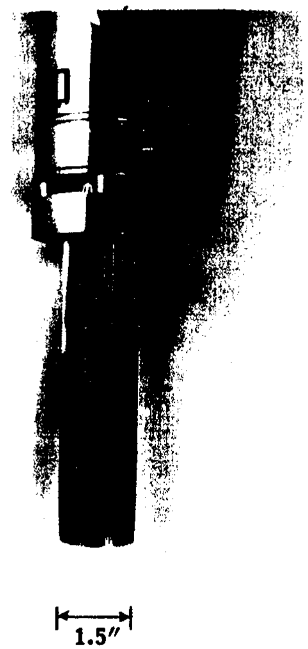
Accessory equipment for the testing system includes power supplies and controls for operating the motors of the probe, power supplies and signal conditioning equipment for transducers of the probe, a storage oscilloscope and camera for display and storage of analog data, an IBM PS/2 Model 80 computer with an analog to digital converter for digitizing, storing, and processing of data, and systems for operating the piston and the shield of the probe.

The large laboratory test chamber is shown in Figure 9 in a laboratory of The Johns Hopkins University. The test chamber was designed specifically for testing the prototype testing system in large uniform samples of sand subjected to representative confining pressures. The test chamber includes a chamber which holds the test sand and a frame and hydraulic equipment for penetrating the probe. The sample of sand is 4 ft in diameter and 2.67 ft high.

The sand is deposited uniformly in layers by raining from a hopper which travels at a constant speed over the chamber. A platform within the chamber is raised to the top of the chamber. The hopper rains several layers of sand onto the platform by a roller. The platform is then lowered by the amount deposited and several more layers of sand are deposited. This process is repeated until the chamber is filled. Thus, the height of fall, which can strongly affect the relative density of the sample, remains relatively constant. Several parameters can be adjusted to vary the characteristics of a sample. To date, relative densities from 55% to 95% have been obtained repeatably.

During deposition, we carefully place a specially designed seismic crosshole testing system in the sample. The system is useful for determining shear wave velocity and for checking on the shearing characteristics of samples. The system includes sources of shear waves, accelerometers for detecting the waves, and data acquisition equipment.

(a) Double Cylinder



(b) Single Cylinder

Figure 8: Elements of Probe

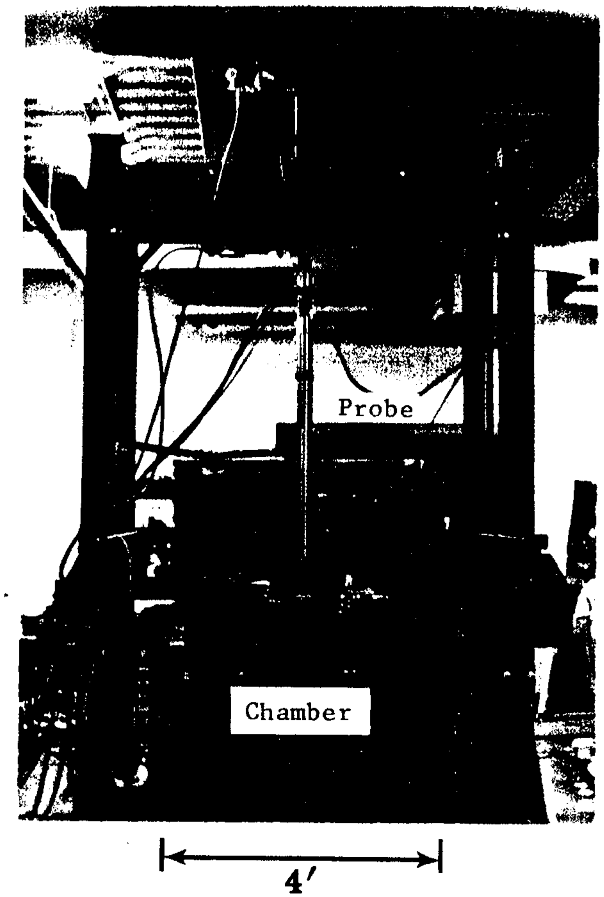


Figure 9: Test Equipment

After deposition, we apply representative confining pressures to the sample using pressure bags. Lateral pressure is applied by a bag surrounding the sample. Vertical pressure is applied by a bag located on the top of the sample. The pressure in each bag is independently controlled.

Accessory equipment for the test chamber includes electronic control systems for controlling the movement of the hopper and the speed of the roller, a power supply and controls for operating the penetration system, and systems for controlling the pressures in the pressure bags.

Conduct Tests

We conducted several types of tests. These include tests of the prototype testing system, tests of the test chamber, tests related to chamber samples, and conventional geotechnical tests.

A number of tests were conducted with the prototype testing system. These include both cyclic tests, the main focus of our program, and impulse tests. Each type of test was conducted using the single as well as the double cylinder probe. We conducted tests using the single cylinder probe to see if we could obtain results similar to those using the double cylinder probe. A single cylinder probe offers some operational advantages relative to the double cylinder probe.

We tested the prototype system under conditions for which the proposed testing procedure would be expected to be of greatest value. The prototype tests were conducted on samples of dry ottawa sand. This sand shows a distribution of grain sizes (see Figure 44) that falls within the bounds for the most liquefiable soils (2). We prepared the samples to medium dense relative densities. Deposits of medium dense sands are common and are borderline cases with respect to liquefaction. They present the greatest uncertainty in estimating behavior, which can vary greatly. A representative confining pressure of 10 psi (lateral pressure = vertical pressure) was applied to each test sample. This pressure corresponds roughly to the effective confining pressure at a depth of 35 ft in a deposit of normally consolidated, saturated sand. This depth is representative of the shallow depths at which liquefaction generally takes place (19).

To prepare for a test, several steps were taken after depositing the test sand and applying the confining pressure. A special thin-walled casing was carefully penetrated into the sample. The casing was cleaned out and the soil at the bottom of the casing was carefully trimmed. The penetration system was then precisely aligned with the casing. The probe was attached to the penetration system and a series of check tests was conducted. The piston of the probe was advanced and pressurized appropriately. The probe was penetrated slowly (0.04 cm/sec) into the sample. After penetration, the penetration force was relieved to a level needed to balance the force on the piston and the shield was raised slightly. We then allowed a short period of time to pass before conducting tests to allow grains to readjust.

Cyclic tests were conducted in the constant volume mode (see pg. 8) to bring out, in the dry sand, the main effects of cyclic loading under saturated, undrained conditions. The cyclic tests were conducted by applying a sinusoidal torque of preselected amplitude to the active cylinder at a frequency of 1 cycle per second. This frequency is representative of frequencies observed in soil deposits during earthquakes. The applied torque and the angular displacement of the instrumented head were measured.

Impulse tests were conducted in the constant pressure mode (see pg. 8) so that there would not be a loss of confining pressure during a series of tests. A series was conducted by applying a sequence of impulsive torques to the active cylinder. The sequence consisted of pairs of torsional impulses of alternating polarity which increased in amplitude. This sequence was used to provide information for a broad range of strains while avoiding excessive disturbance. The applied torques and the tangential horizontal linear accelerations of the perimeter of the instrumented head were measured. The angular accelerations of the instrumented head were inferred from these tangential accelerations.

For both cyclic and impulse tests analog data was displayed on a storage oscilloscope. The face of the oscilloscope was photographed for a permanent record of the data. Digitized data was also recorded by our computing system.

A series of tests of the test chamber was conducted to establish the settings needed to deposit, repeatably, the sand at a medium dense relative density. Our goal was to deposit the sand with a uniform, vertical rain. Relative densities were estimated from unit weights determined using the procedure described below. We photographed the rains to establish their characteristics.

Tests we conducted related to the chamber samples include unit weight tests and seismic crosshole tests. Before preparing each sample, we conducted unit weight tests. Precisely machined containers of known volume and weight were placed on the raised platform of the test chamber. Sand was deposited into the containers and carefully trimmed. The full containers were weighed. Unit weights and relative densities were calculated. Seismic crosshole tests (26) were conducted within each chamber sample. These were conducted to provide shear wave velocities for checking on the shearing characteristics of samples. In these tests, we activated sources of horizontally polarized torsional shear waves. The arrivals of waves were detected by appropriately located and oriented accelerometers.

We conducted conventional geotechnical tests to determine various properties of our sand. We conducted grain size analyses to determine distributions of grain sizes. We also carried out tests to estimate minimum and maximum unit weights of the test sand. The sand was brought to its minimum unit weight by gentle deposition through a pipe in a graduate cylinder. The sand was brought to its maximum unit weight in layers by vibrations.

Develop Analyses

We developed numerical analyses for simulating cyclic and impulse tests. The analyses were used to infer soil characteristics from results of tests. The analyses are of an intermediate level of descriptiveness. They are easy to use and model many important aspects of tests but also involve assumptions and simplifications. In practice, we would expect to use the intermediate analyses to make preliminary estimates of soil characteristics. These estimates would then be revised using more costly and consuming refined analyses (currently being developed). Originally, for Phase II, we planned to develop refined analyses (see APPENDIX A) for simulating tests more descriptively. However, we were unable to advance to this stage of our planned program.

There are several features common to the analyses for simulating impulse and cyclic tests. Our model of a test consists of a torsionally excited, linear elastic cylinder partially embedded in an axisymmetric continuum. A schematic diagram of the basic model for intermediate analyses is shown in Figure 10. The model can describe the distributed torsional flexibility and mass moment of inertia of the instrumented head and the active cylinder. The continuum represents the test soil. Nonuniform behavior of the test soil in the radial direction is described in detail. However, behavior is not allowed to vary in the vertical direction. Thus, we describe only horizontally polarized shear stresses and strains in the test soil.

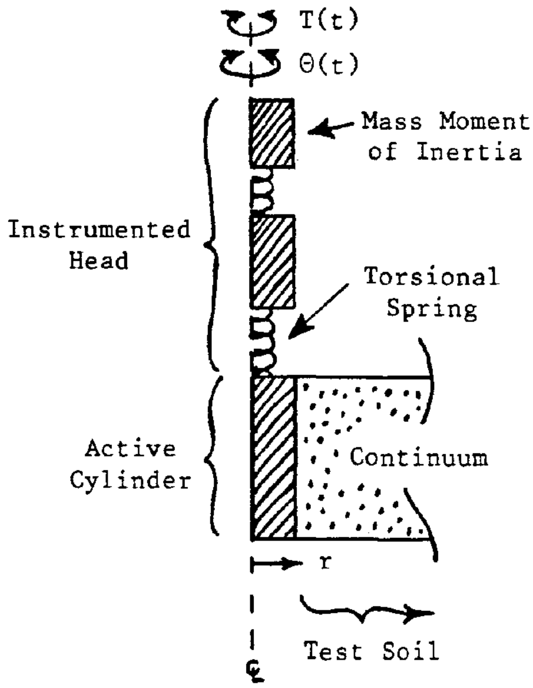


Figure 10: Basic Model for Intermediate Analysis Procedure for Simulating Tests

The analyses for simulating impulse and cyclic tests differ mainly in two respects. First, the cyclic test analysis is a slow cyclic analysis whereas the impulse test analysis is a dynamic analysis. When simulating cyclic tests, we obtain solutions for a selected sequence of times. However, while the behavior of the active cylinder and instrumented head may be modeled dynamically, the behavior of the test soil is not. The test soil is modeled using the finite element method and effects of inertia are neglected. This simplification is judged to be reasonable. When simulating impulse tests, we fully represent dynamic behavior. Solutions are obtained for a selected sequence of times. The active cylinder and the instrumented head are modeled as a dynamic multiple degree of freedom system. The test soil is modeled using a dynamic continuum approach originated by R. Henke (7) (8) (9) (10).

Secondly, the analyses for simulating cyclic and impulse tests differ in the treatment of the shearing characteristics of the continuum. When simulating impulse tests, the test soil is described as a nonlinear, inelastic continuum. When simulating cyclic tests, the test soil is described as a nonlinear, inelastic continuum which can degrade cyclically and liquefy. In each case, stress vs strain behavior is described using Ramberg-Osgood equations (18). Degradation and liquefaction are described using the approach proposed by Martin, Finn, and Seed (15).

These numerical analysis procedures were validated in several ways. If possible, we compared special linear solutions to available closed-form solutions. We used an energy balance (7) to check solutions of nonlinear problems for which closed-form solutions are not available. Additionally, we checked solutions by examining computed shear stress vs strain behavior and all solutions were checked judgmentally.

Our intermediate analysis procedures involve several assumptions and simplifications which may be significant. These include uniform behavior of the test soil in the vertical direction, not accounting for all initial and test-induced nonuniformities of the test soil, not accounting for all important aspects of cyclic or dynamic shear stress vs strain characteristics, not accounting for friction or viscous damping arising from the test apparatus or viscous damping of the test soil, and not accounting for slip.

Interpret Tests

We interpreted the results of our prototype tests in terms of shear stress vs strain characteristics by simulating tests analytically. For this we used the intermediate analysis procedures discussed in the preceding section. To interpret soil characteristics we first assumed reasonable characteristics for the continuum of our model. The torques measured during a test were applied to the model of the instrumented head. Angular motions of the instrumented head were computed. Computed motions were compared to measured motions and soil characteristics were iteratively varied until computed and measured motions agreed as well as was reasonably possible. The characteristics providing the most representative simulations were considered representative of those of the test soil.

Publish Work

We published the results of work related to the project discussed herein to help bring the proposed testing procedure to realization. We have written progress reports on our work. We have also published and presented papers for two conferences and have submitted abstracts for papers for two more conferences.

RESULTS AND DISCUSSIONS OF RESULTS OF PHASE II

In this section, we present and discuss results from our tests. We also present and discuss our interpretations of results from prototype tests.

Test Results

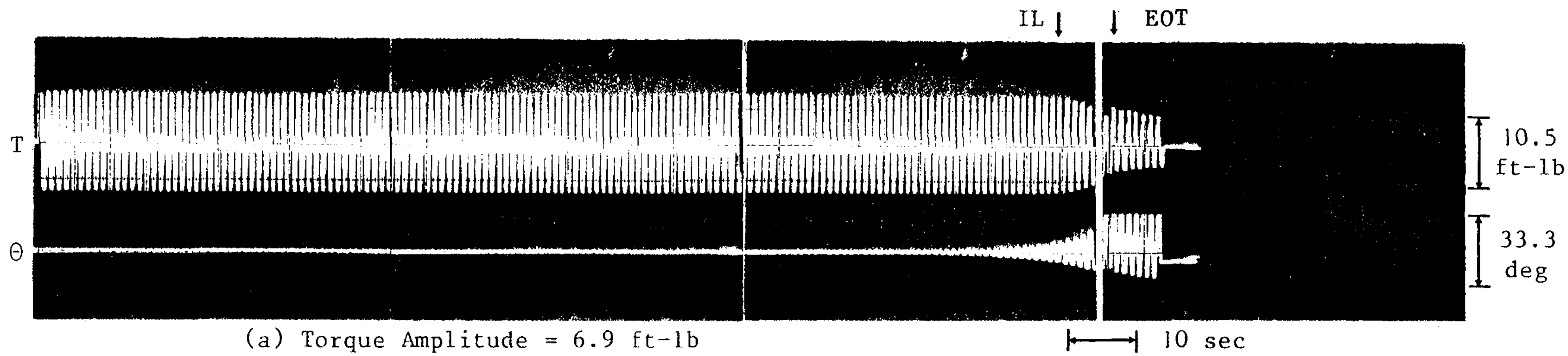
In this subsection, we present and discuss results from cyclic and impulse tests conducted in the laboratory using the prototype testing system. Our results include photographs from an oscilloscope face and processed digitized test data. We also present and discuss relevant results from tests related to chamber samples and conventional geotechnical tests.

Cyclic Tests (Double Cylinder)--Results from cyclic tests conducted using the double cylinder probe were found to be reasonable and consistent with published results from laboratory cyclic tests of a high quality. We did not encounter abnormal difficulties or major limitations. The average relative density of the test samples for these tests is 58.1%. The active cylinder was grooved and uncoated, and the outer cylinder was smooth and uncoated.

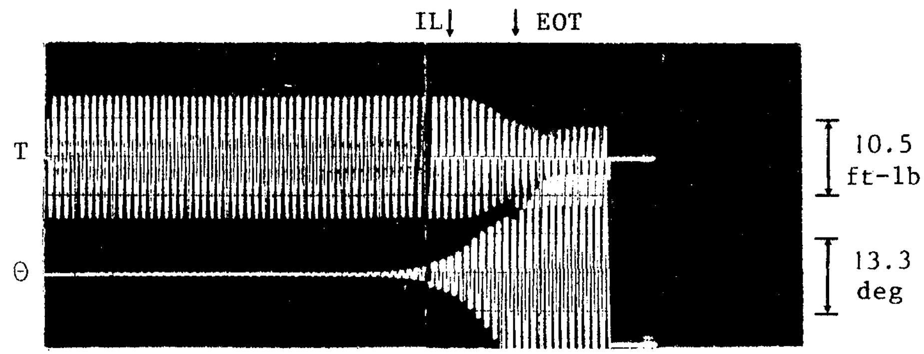
Our results, presented in Figures 11, 12, 15, 16, 18, 20, and 21, are reasonable and generally consistent with published results obtained from laboratory cyclic tests conducted on undrained, saturated sands. The published results are shown in Figures 13, 14, 17, 19, and 20 (2). Results for medium dense sands, which correspond to our samples, may be judged to fall between the results published for loose sands and dense sands.

The curves of the angular displacement of the instrumented head vs time shown in Figures 11 and 12 show an intermediate level of degradation. For each test, the amplitude of the angular displacement increases, at an intermediate rate, to a relatively high level with an increase in the number of cycles of loading. Without mechanical stops, we feel this amplitude would have reached a limited value due to dilation. Also, the torque vs angular displacement curves presented in Figure 15 show nonlinearity, inelasticity, cyclic degradation, behavior corresponding to "initial liquefaction" due to densification, and restiffening due to dilation. The curves presented in Figure 16 show the identification of the cycles in which "initial liquefaction" (for prototype tests, first instance for which torsional stiffness almost zero, $\Delta T/\Delta\Theta \simeq 0$) occurred. These curves may be compared to corresponding published curves shown in Figure 17. Figure 18 presents a "liquefaction" curve. The number of cycles to initial liquefaction decreases as the amplitude of the cyclic torque increases. As shown by Figure 19, this is consistent with liquefaction curves presented in the literature (2) for laboratory cyclic tests. Additionally, this consistency suggests repeatability of test results.

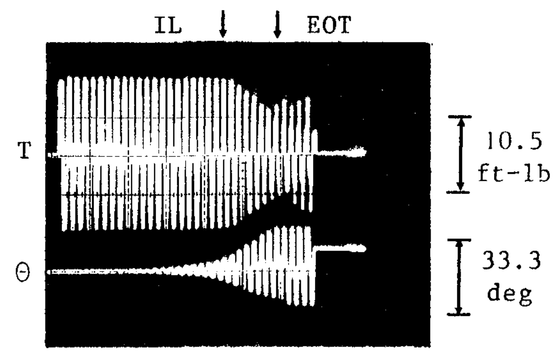
We further show consistency with laboratory cyclic tests by superimposing, on the published liquefaction curves shown in Figure 19, a roughly equivalent liquefaction curve for our prototype tests (Figure 20). Our curve shows somewhat greater resistance to initial liquefaction than the corresponding published results. There are a number of possible reasons for this difference. These include the nature of our estimates of equivalent shear stress ratio, not accounting for compressibility at the boundaries of the test soil, differences in soil type and manner of deposition, etc. Our equivalent curve was obtained in an approximate manner. Equivalent shear stress ratios were based on equivalent shear stresses and equivalent vertical



(a) Torque Amplitude = 6.9 ft-lb



(b) Torque Amplitude = 8.0 ft-lb



(c) Torque Amplitude = 10.1 ft-lb

Figure 11: Results from Cyclic Tests Conducted Using Double Cylinder Probe - Photographs from Face of Oscilloscope. Average Relative Density = 58.1%. EOT = End of Test due to Striking of Stops. IL = Initial Liquefaction ($\Delta T/\Delta\Theta \simeq 0$).

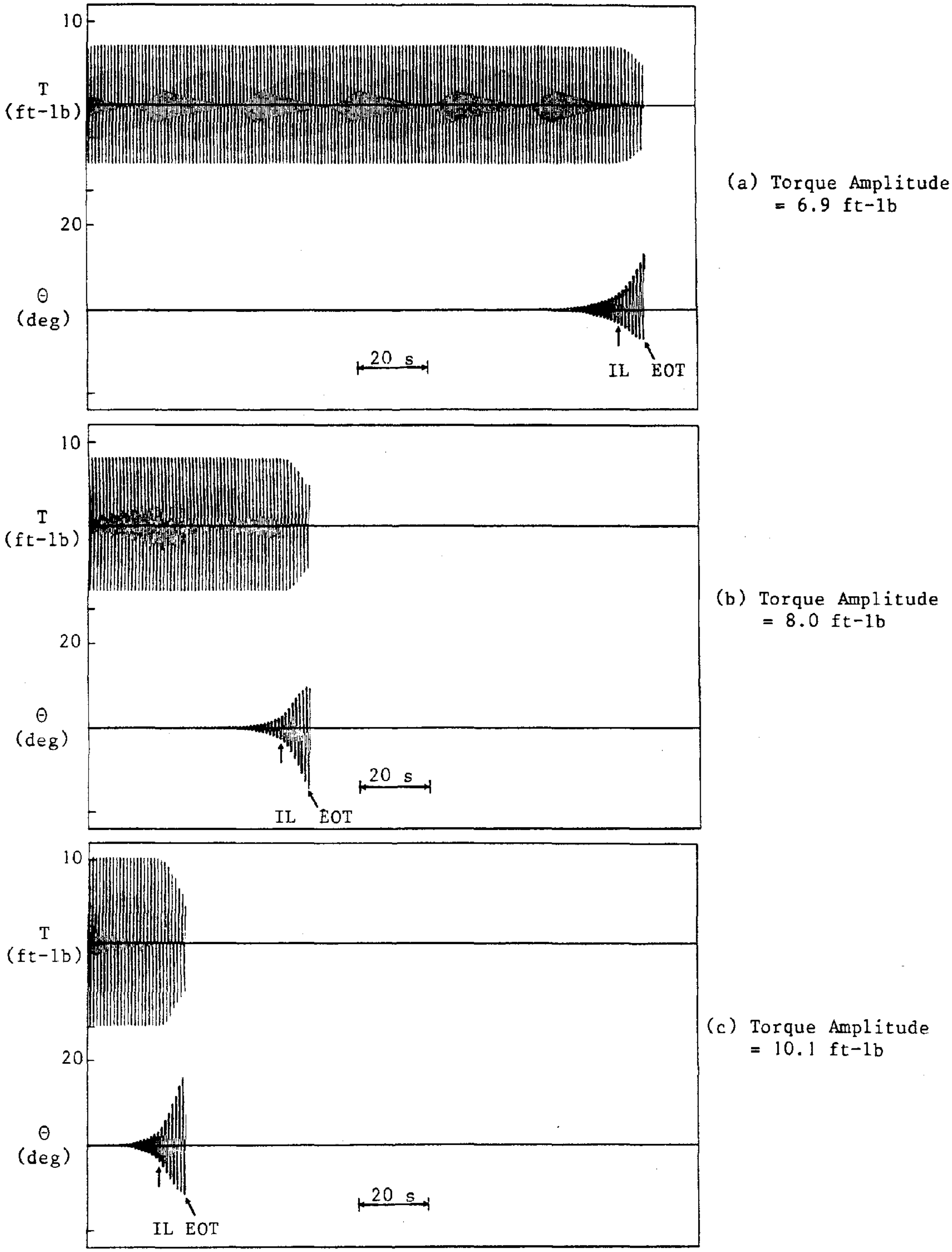


Figure 12: Results from Cyclic Tests Conducted Using Double Cylinder Probe - Digitized Traces. Average Relative Density = 58.1%. EOT = End of Test due to Striking of Stops. IL = Initial Liquefaction ($\Delta T/\Delta\Theta \simeq 0$).

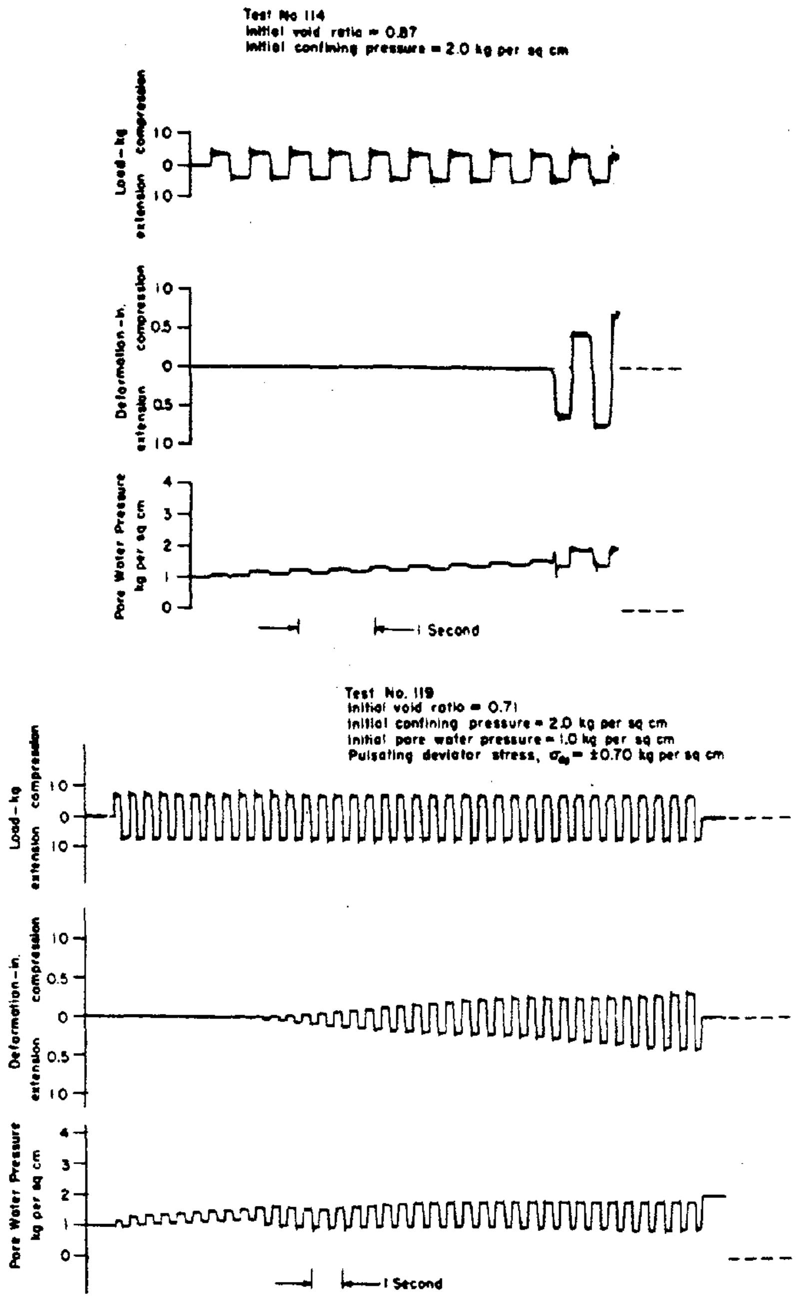


FIGURE 2-26 Results from isotropically consolidated cyclic triaxial tests. The top test (114) is for loose sand; the bottom test (119) is for dense sand. Source: Seed and Lee (1966).

Figure 13: Published Results from Laboratory Cyclic Tests Conducted on Loose and Dense Sands (2)

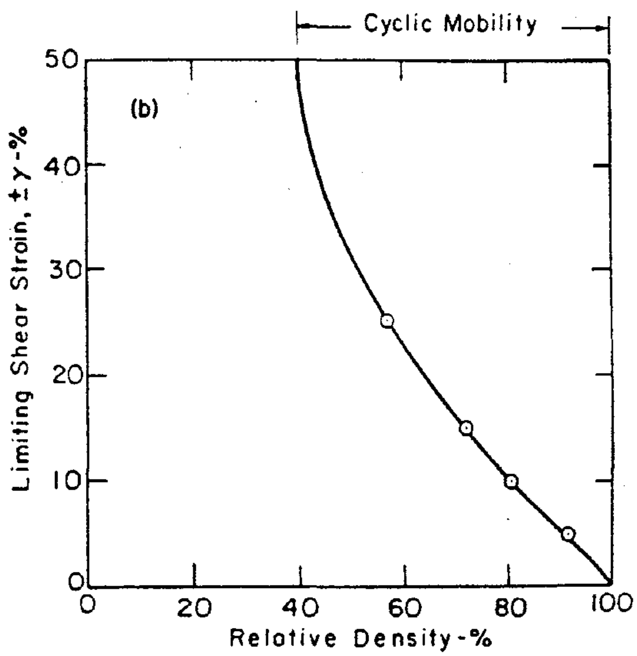
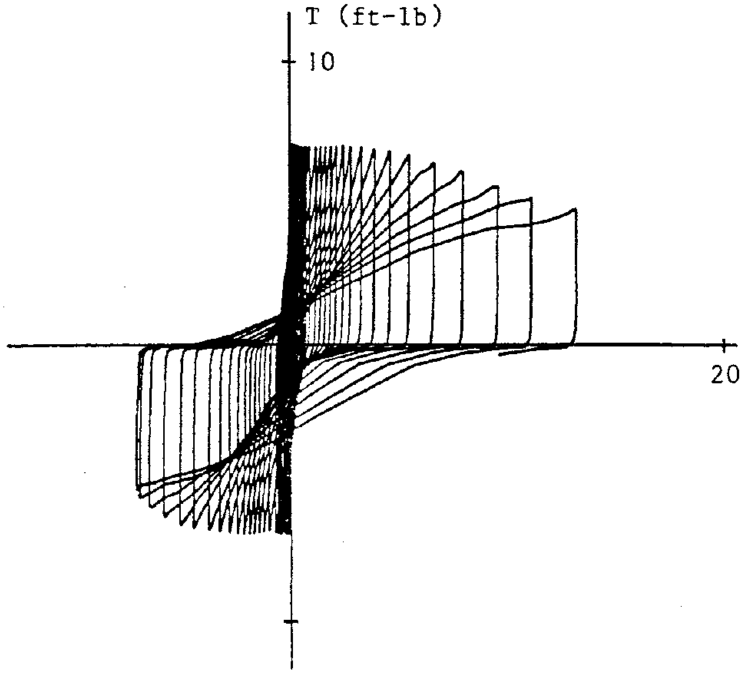
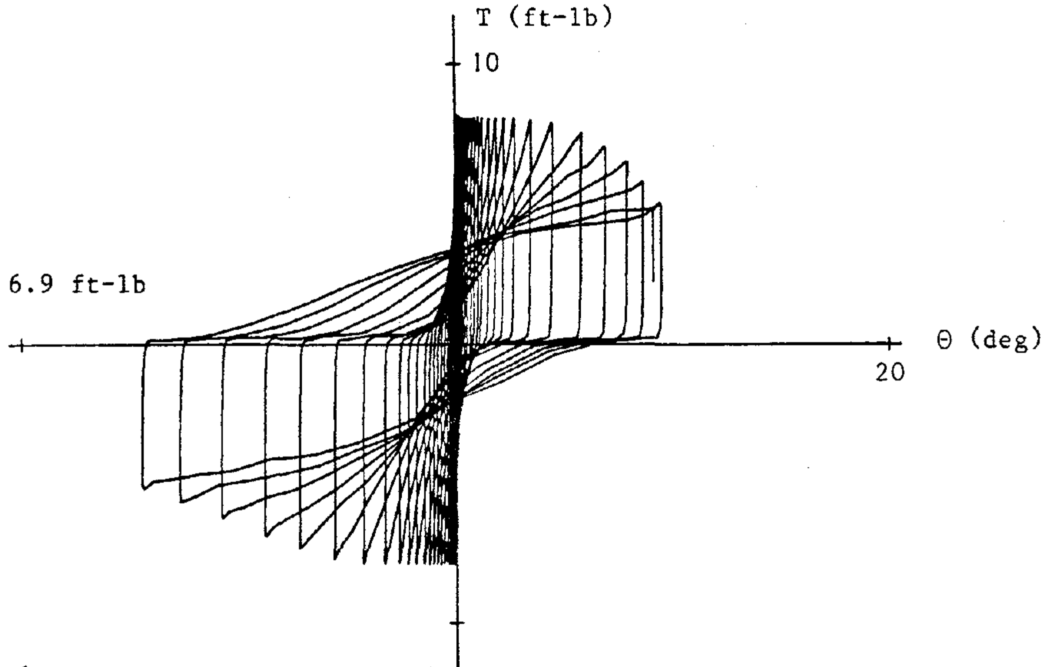


FIGURE 2-31 Limiting shear strains during shaking table tests. Source: Seed (1976).

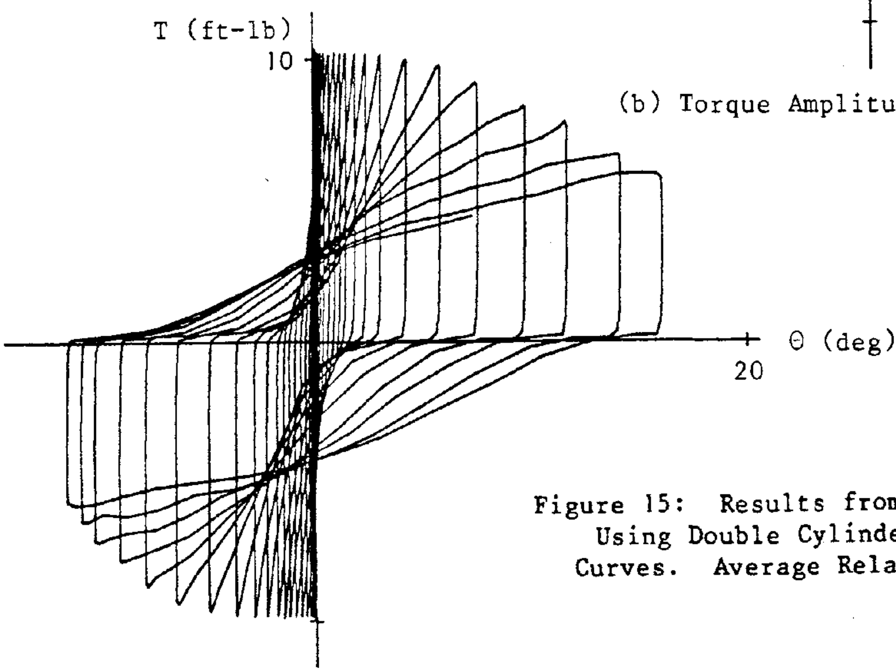
Figure 14: Published Results from Laboratory Cyclic Tests Conducted on Sands (2)



(a) Torque Amplitude = 6.9 ft-lb

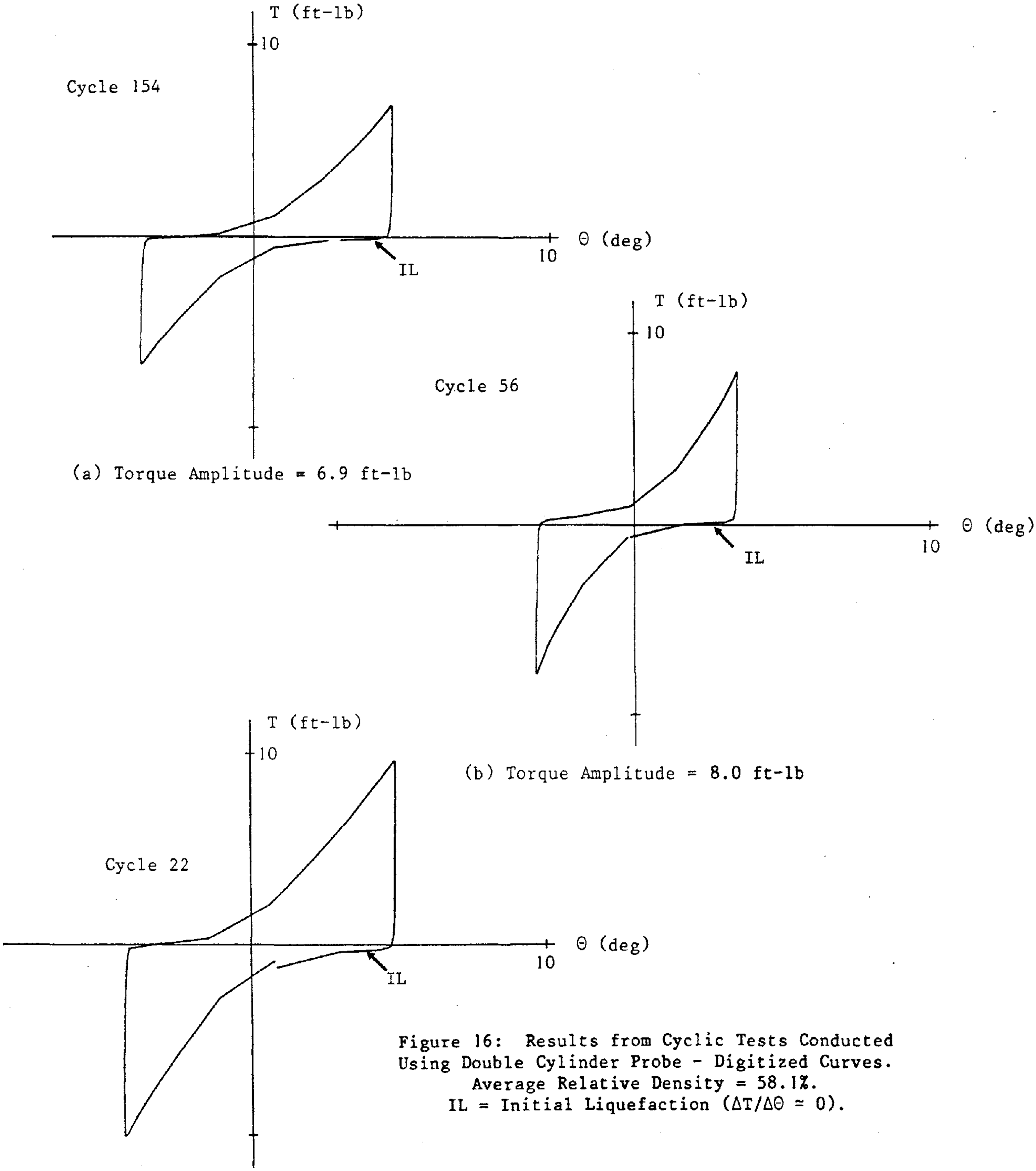


(b) Torque Amplitude = 8.0 ft-lb



(c) Torque Amplitude = 10.1 ft-lb

Figure 15: Results from Cyclic Tests Conducted Using Double Cylinder Probe - Digitized Curves. Average Relative Density = 58.1%.



(c) Torque Amplitude = 10.1 ft-lb

Figure 16: Results from Cyclic Tests Conducted Using Double Cylinder Probe - Digitized Curves. Average Relative Density = 58.1%. IL = Initial Liquefaction ($\Delta T/\Delta\Theta \simeq 0$).

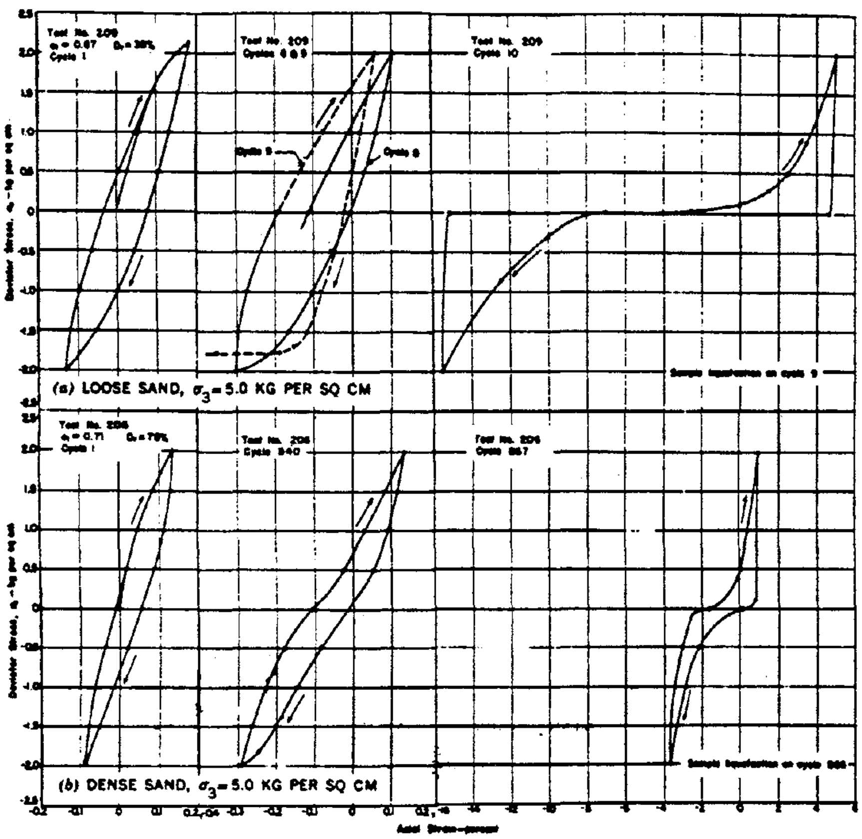


FIGURE 2-33 Hysteresis loops before and after initial liquefaction of loose and dense sands in triaxial tests. Source: Seed and Lee (1966).

Figure 17: Published Results from Laboratory Cyclic Tests Conducted on Loose and Dense Sands (2)

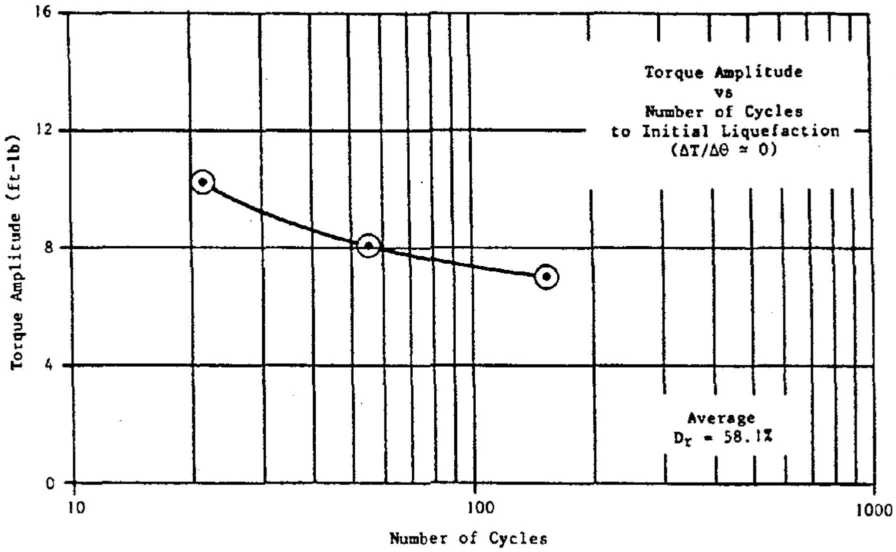


Figure 18: Results from Cyclic Tests Conducted Using Double Cylinder Probe

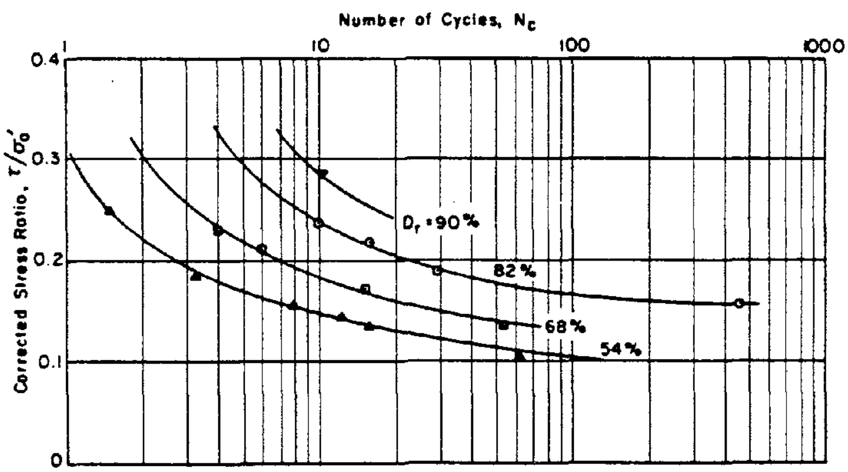


FIGURE 2-29 Stress ratio τ_d/σ'_{vo} versus number of cycles to initial liquefaction, from tests on a shaking table. Source: DeAlba et al. (1976).

Figure 19: Published Results from Laboratory Cyclic Tests Conducted on Sands (2)

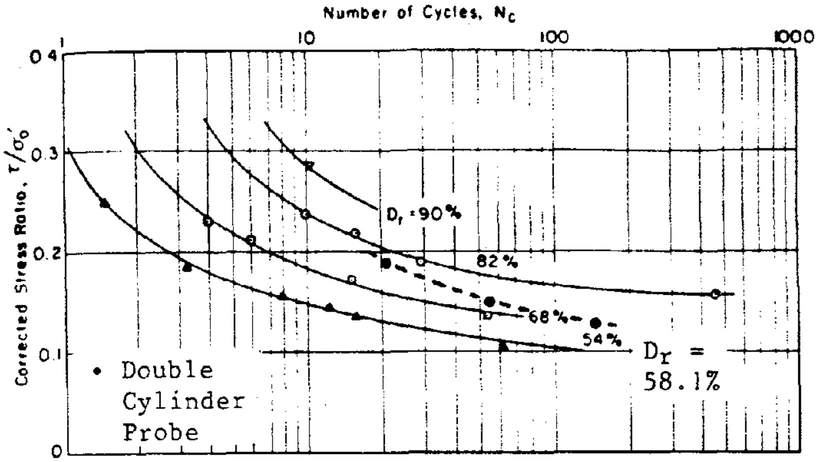


FIGURE 2-29 Stress ratio τ_d/σ'_{vo} versus number of cycles to initial liquefaction, from tests on a shaking table. Source: DeAlba et al. (1976).

Figure 20: Comparison Between Approximately Interpreted Results from Cyclic Tests Conducted Using Double Cylinder Probe and Results from Laboratory Cyclic Tests Conducted on Sands (2)

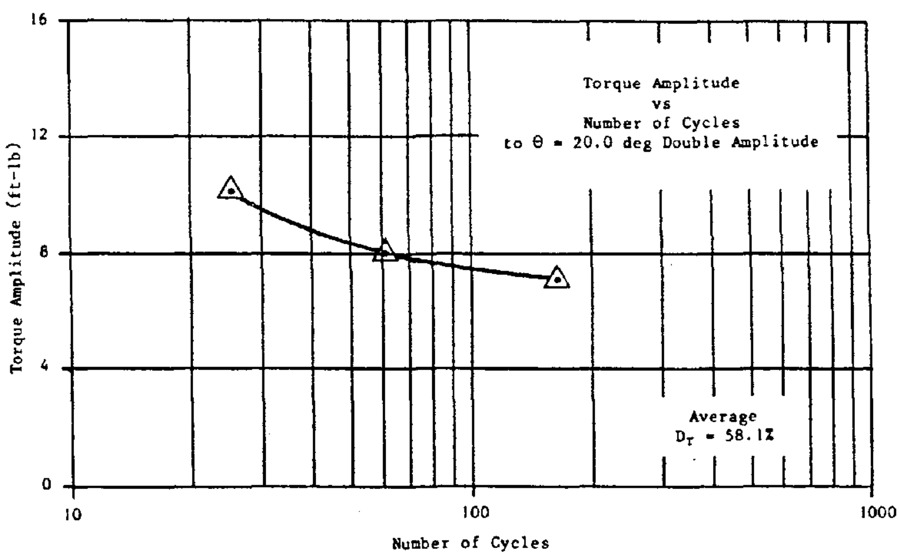


Figure 21: Results from Cyclic Tests Conducted Using Double Cylinder Probe

effective stress. The equivalent shear stresses were estimated by averaging the shear stresses within the volume of the test soil covered by the piston. The shear stresses and volume correspond to those represented by our analytical model for simulating tests (see pg. 18). The equivalent vertical effective stress is the vertical stress which would produce, under conditions of normal consolidation, the confining pressure for our prototype tests. For this we assumed $K_o = 0.5$ (24).

We show an alternate form of presentation of results in Figure 21. This figure shows the amplitude of the cyclic torque vs the number of cycles to a specified double amplitude of cyclic angular displacement. The figure shows that the number of cycles to the specified angular displacement decreases as the amplitude of the cyclic torque increases.

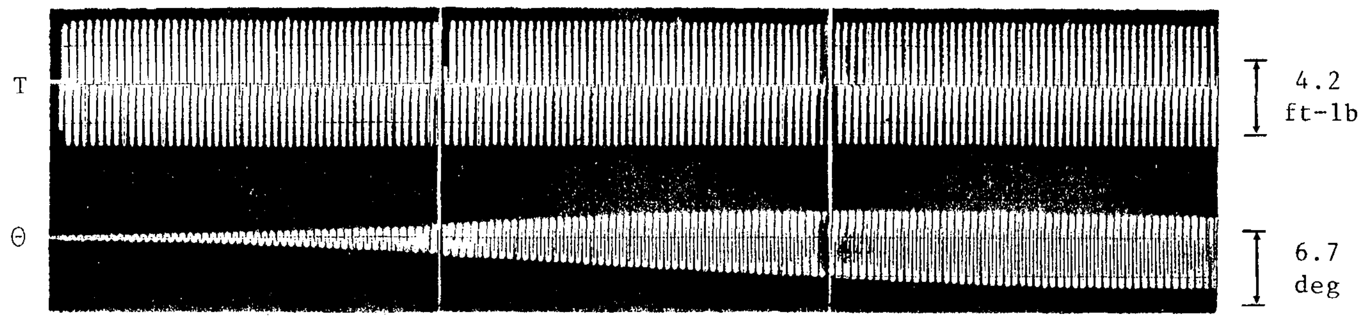
Some difficulties were encountered during testing but we feel these are neither abnormal nor insurmountable. We experienced difficulties in measuring accurately the small angular displacements developed during early cycles of loading. Also, we experienced some difficulty with the piston system; the piston did not retract entirely during penetration. We feel we will be able to overcome these difficulties with further engineering.

We did not identify any limitations of the testing system.

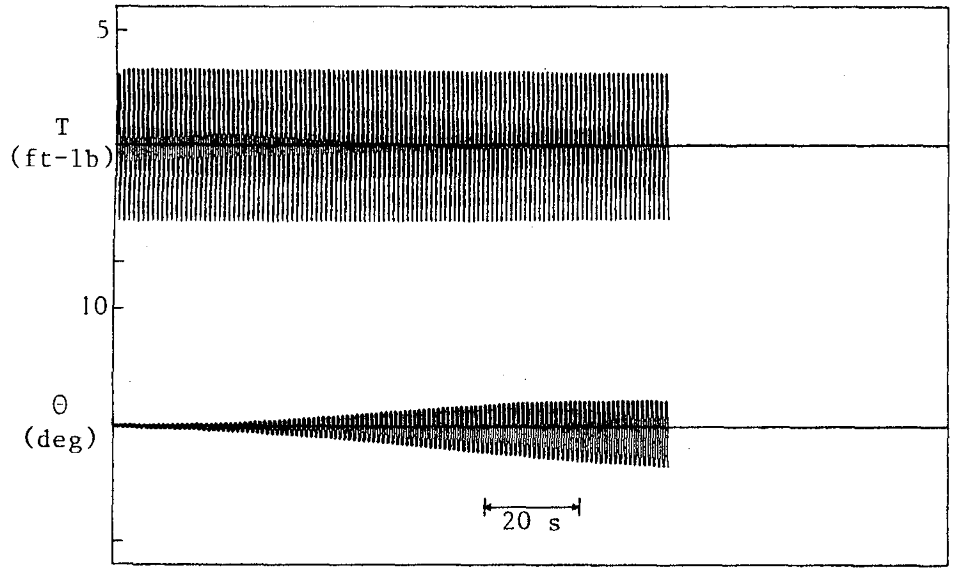
<u>Practice Cyclic Tests (Double Cylinder)</u>--Practice tests were conducted informally in preparation for the formal cyclic tests discussed above. In this subsection, we present selected results which demonstrate behavior not brought out by the formal tests. Results from the practice cyclic tests were also found to be reasonable and consistent with published results from laboratory cyclic tests of a high quality.

Results, shown in Figures 22 and 24, from one practice test are reasonable and consistent with published results obtained from laboratory cyclic tests conducted on saturated, undrained dense sands (2). The published results are shown in Figures 23 and 25. Our results are for a test conducted on a sample having a relative density of 65.2%. Both cylinders were coated and grooved. The curve of the angular displacement of the instrumented head vs time shows degradation. The amplitude of the angular displacement gradually increases with an increase in the number of cycles of loading. Additionally, this amplitude reaches a limited value due to dilation. The torque vs angular displacement curve also shows the development of limited angular displacements.

Results, shown in Figure 26, from a second practice test are consistent with published results obtained from laboratory cyclic tests conducted on saturated, undrained loose sands (2). The published results are shown in Figure 27. The relative density of our sample is unknown but was probably low considering the manner in which the soil was deposited. The active cylinder was uncoated and grooved. The outer cylinder was smooth and uncoated. The curve of angular displacement vs time shows a period of mild degradation followed by a sudden large increase in the amplitude of the angular displacement. This sudden increase is interpreted as the onset of liquefaction.



(a) Photographs from Face of Oscilloscope



(b) Digitized Curves

Figure 22: Results from Practice Cyclic Test Conducted Using Double Cylinder Probe - Relative Density = 65.2%.

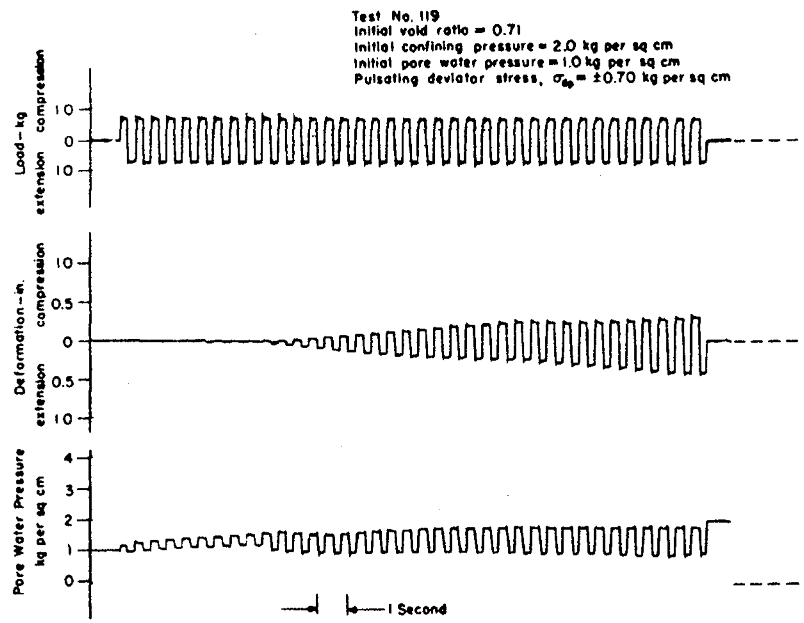


FIGURE 2-26 Results from isotropically consolidated cyclic triaxial tests. The top test (114) is for loose sand; the bottom test (119) is for dense sand. Source: Seed and Lee (1966).

Figure 23: Published Results from Laboratory Cyclic Test Conducted on Dense Sand (2)

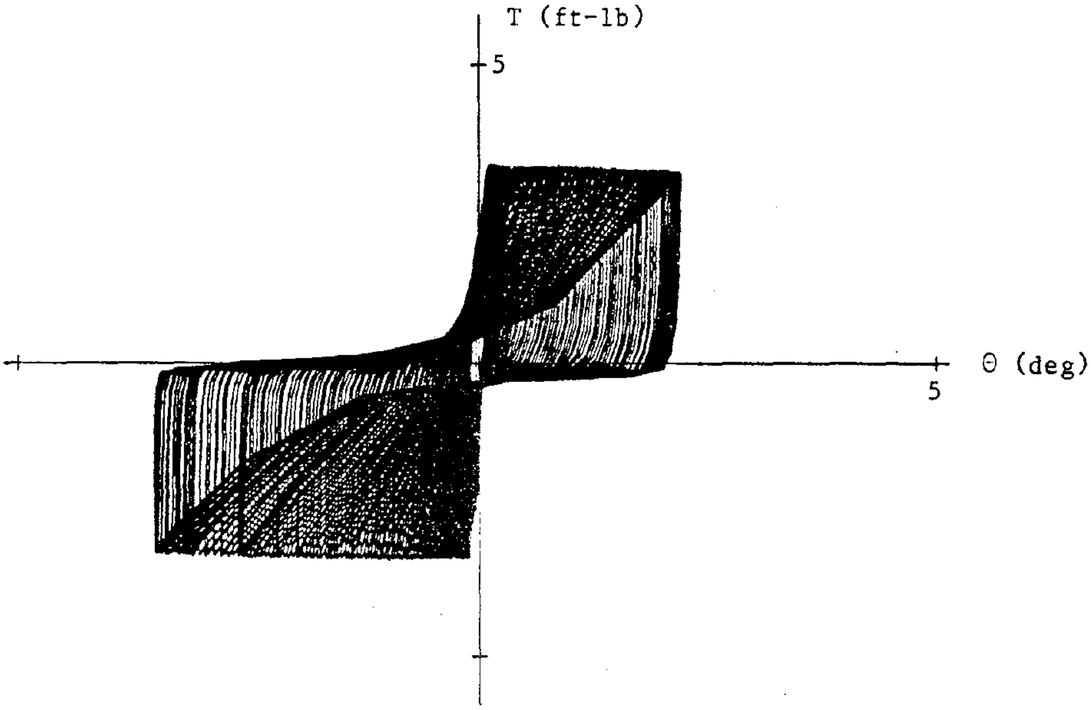


Figure 24: Results from Practice Cyclic Test Conducted Using Double Cylinder Probe - Digitized Curves. Relative Density = 65.2%.

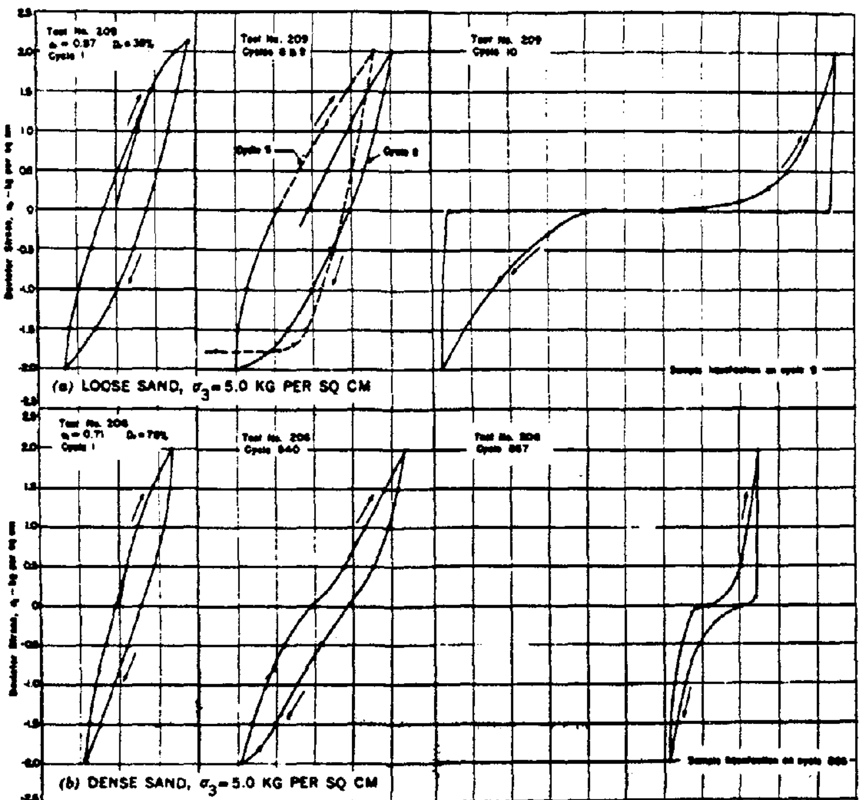


FIGURE 2-33 Hysteresis loops before and after initial liquefaction of loose and dense sands in triaxial tests. Source: Seed and Lee (1966).

Figure 25: Published Results from Laboratory Cyclic Tests Conducted on Loose and Dense Sands (2)

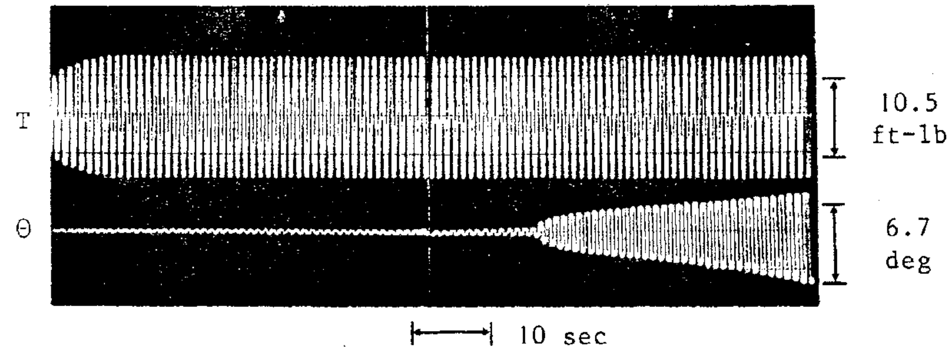


Figure 26: Results from Practice Cyclic Test Conducted Using Double Cylinder Probe - Photographs from Face of Oscilloscope. Relative Density Unknown but Probably Low.

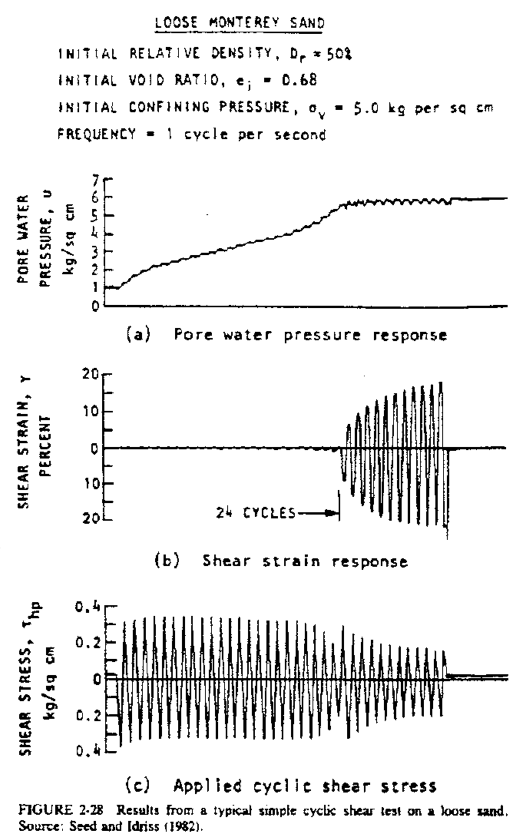


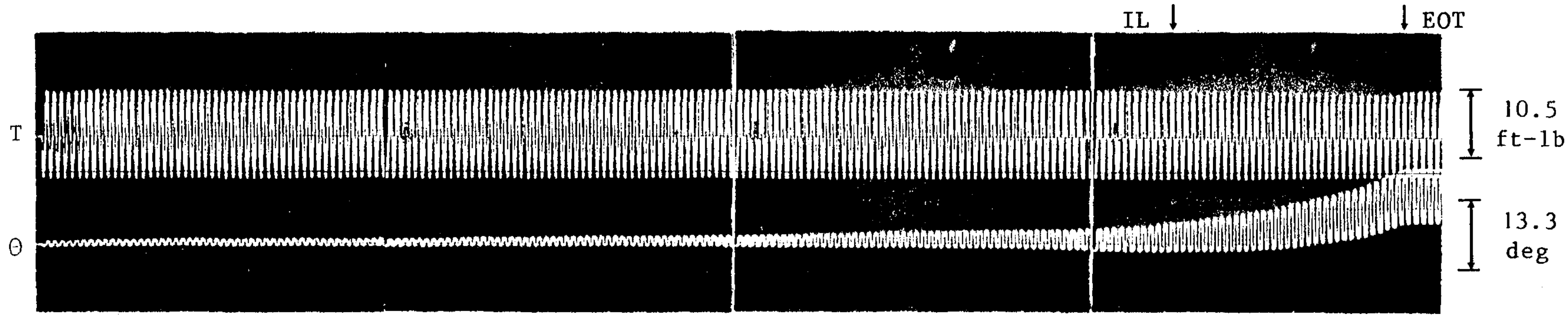
Figure 27: Published Results from Laboratory Cyclic Test Conducted on Loose Sand (2)

Cyclic Tests (Single Cylinder)--Results from cyclic tests conducted using the single cylinder probe were found to be reasonable and consistent with published results from laboratory cyclic tests of a high quality. We did not encounter difficulties or limitations. The average relative density of the test samples for these tests is 61.0%. The active cylinder was grooved and uncoated.

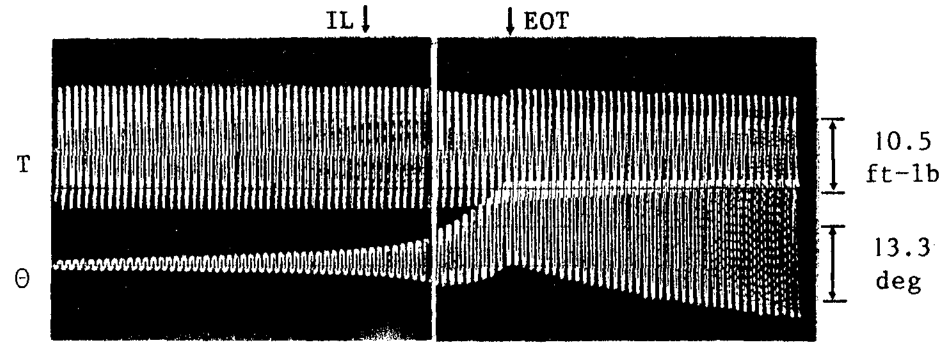
Our results, presented in Figures 28, 29, 32, 33, 34, 36, 38, and 39, are reasonable and consistent with published results obtained from laboratory cyclic tests conducted on undrained, saturated sands. The published results are shown in Figures 30, 31, 35, 37, and 38 (2). Results for medium dense sands, which correspond to our samples, may be judged to fall between the results published for loose sands and dense sands.

The curves of angular displacement of the instrumented head vs time in Figures 28 and 29 show moderate degradation. For each test, the amplitude of the angular displacement gradually increases to a relatively high level with an increasing number of cycles of loading. Without mechanical stops, we feel, based on the observed behavior, that this amplitude would have reached a limited value due to dilation. The torque vs angular displacement curves presented in Figure 32 show nonlinearity, inelasticity, cyclic degradation, behavior corresponding to "initial liquefaction" due to densification, and restiffening due to dilation. Undegraded, nonlinear torque vs angular displacement curves for the first cycle of loading are shown in Figure 33. These may be compared to corresponding published curves shown in Figure 35. The torque vs angular displacement curves of Figure 34 show the identification of the cycles in which "initial liquefaction" (for prototype tests, first instance for which torsional stiffness almost zero, $\Delta T/\Delta\Theta \simeq 0$) occurred. These curves may also be compared to corresponding published curves shown in Figure 35. Figure 36 presents a "liquefaction" curve. This figure shows that the number of cycles to "initial liquefaction" decreases as the amplitude of the cyclic torque increases. As shown by Figure 37, this is consistent with liquefaction curves presented in the literature (2) for laboratory cyclic tests. Additionally, this consistency suggests repeatability of test results.

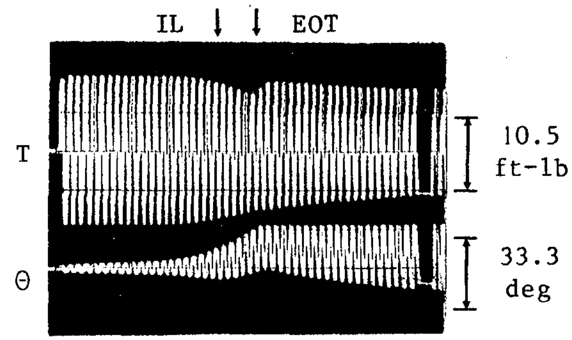
We further show consistency with laboratory cyclic tests by superimposing, on the published liquefaction curves shown in Figure 37, a roughly equivalent liquefaction curve for our tests (Figure 38). As in the double cylinder cyclic tests discussed above, our curve shows somewhat greater resistance to initial liquefaction than the corresponding published results. Again, there are a number of possible reasons for this difference. These include the nature of our estimates of equivalent shear stress ratio, not accounting for compressibility at the boundaries of the test soil, differences in soil type and manner of deposition, etc. Our equivalent curve was obtained in an approximate manner. Equivalent shear stress ratios were based on equivalent shear stresses and equivalent vertical effective stress. The equivalent shear stresses were estimated by averaging the shear stresses within the volume of the test soil covered by the piston. The shear stresses and volume correspond to those represented by our analytical model for simulating tests (see pg. 18). The equivalent vertical effective stress was the vertical stress which would produce, under conditions of normal consolidation, the confining pressure for our prototype tests. For this we assumed $K_o = 0.5$ (24).



(a) Torque Amplitude = 6.3 ft-lb



(b) Torque Amplitude = 8.2 ft-lb



(c) Torque Amplitude = 9.9 ft-lb

Figure 28: Results from Cyclic Tests Conducted Using Single Cylinder Probe - Photographs from Face of Oscilloscope. Average Relative Density = 61.0%. EOT = End of Test Due to Striking of Stops. IL = Initial Liquefaction ($\Delta T/\Delta\Theta \simeq 0$).

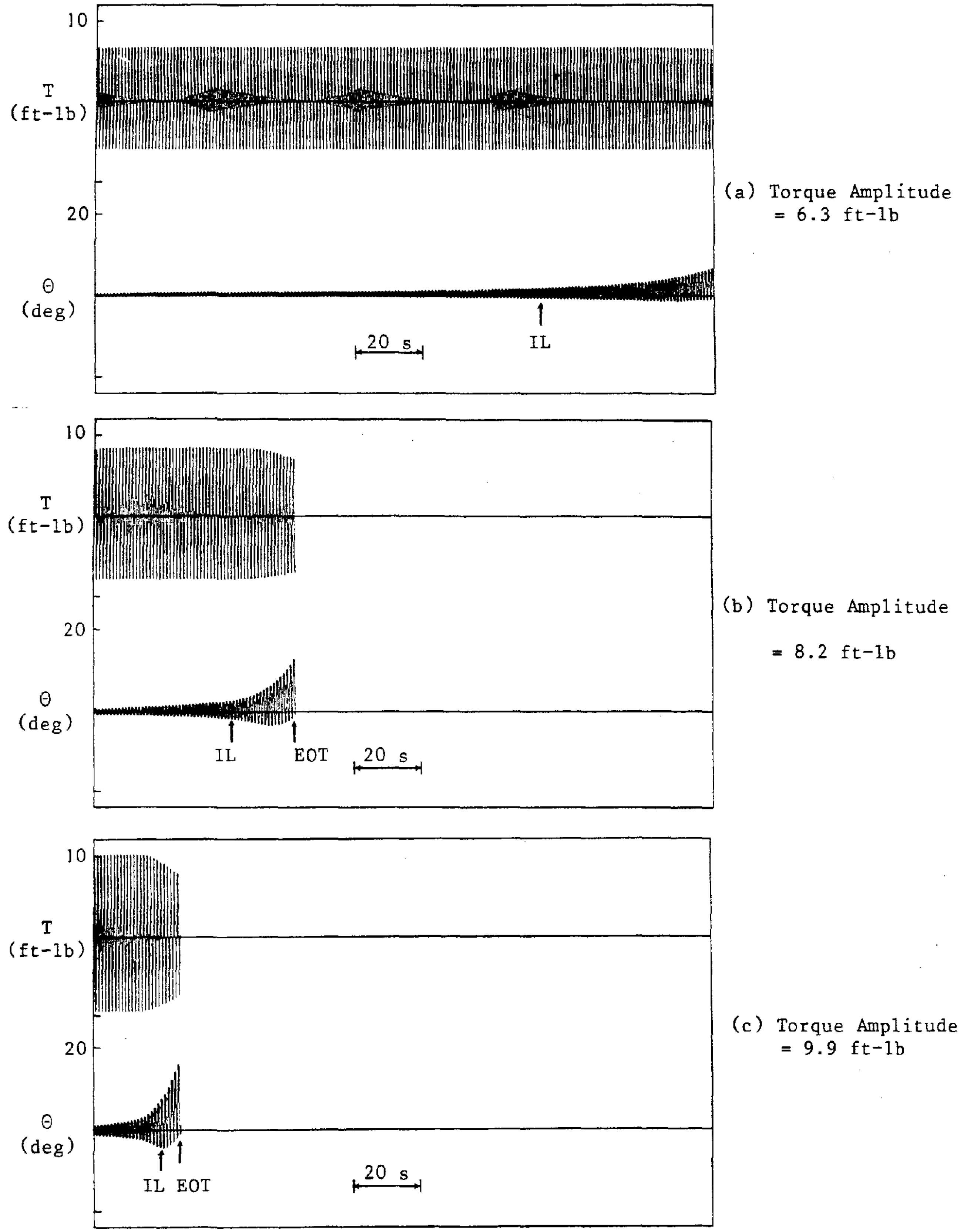


Figure 29: Results from Cyclic Tests Conducted Using Single Cylinder Probe - Digitized Traces. Average Relative Density = 61.0%. EOT = End of Test Due to Striking of Stops. IL = Initial Liquefaction ($\Delta T/\Delta\Theta \simeq 0$).

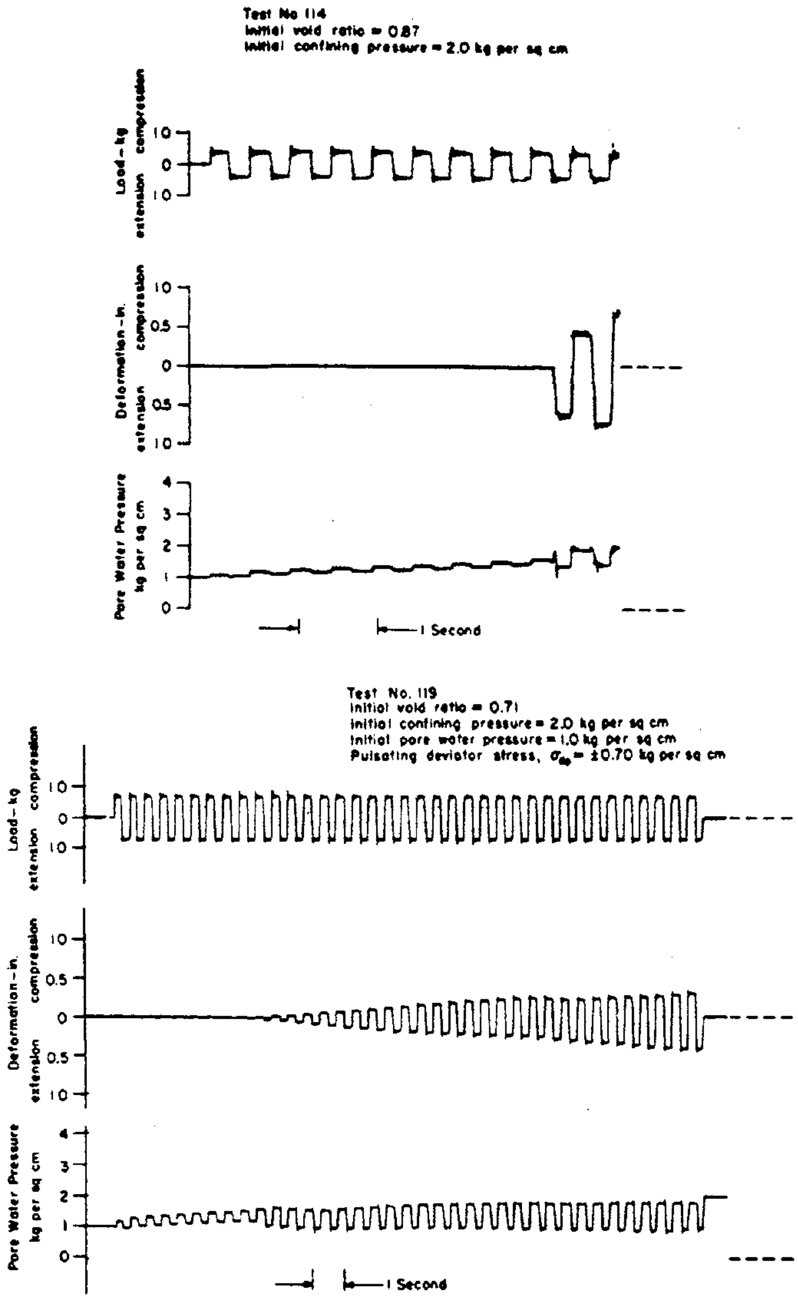


FIGURE 2-26 Results from isotropically consolidated cyclic triaxial tests. The top test (114) is for loose sand; the bottom test (119) is for dense sand. Source: Seed and Lee (1966).

Figure 30: Published Results from Laboratory Cyclic Tests Conducted on Loose and Dense Sands (2)

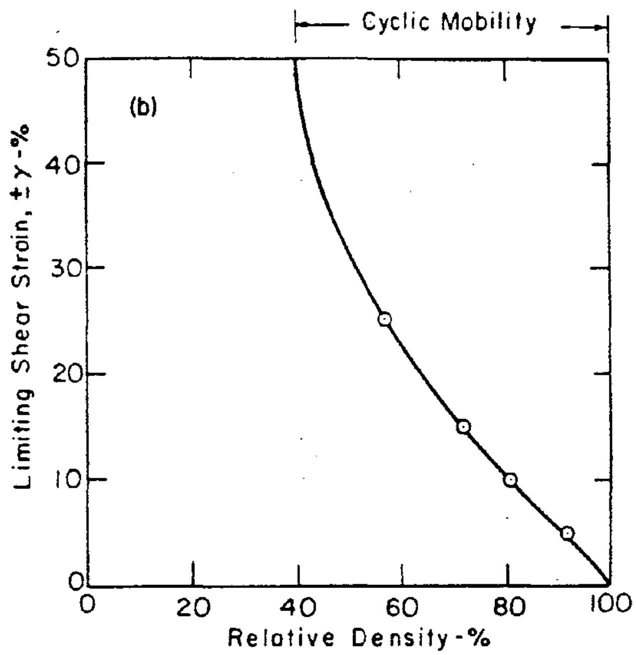
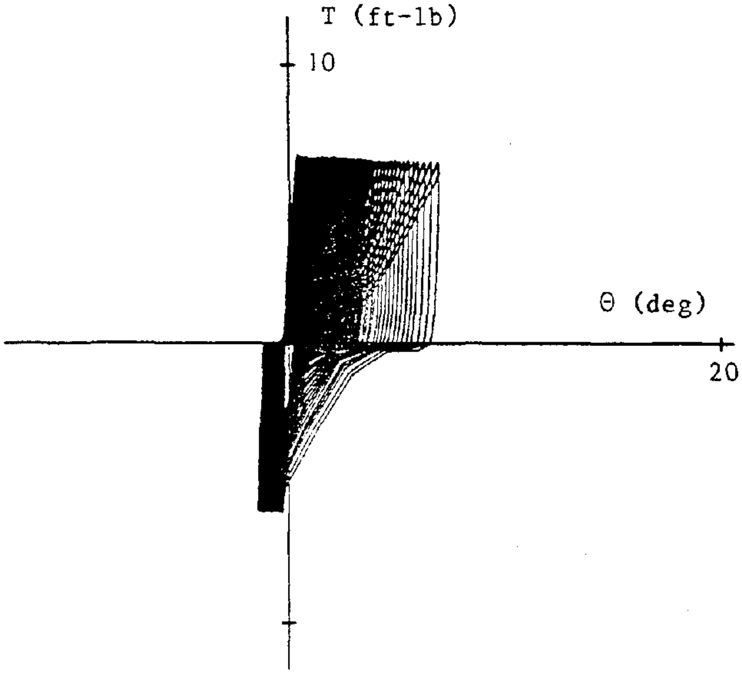
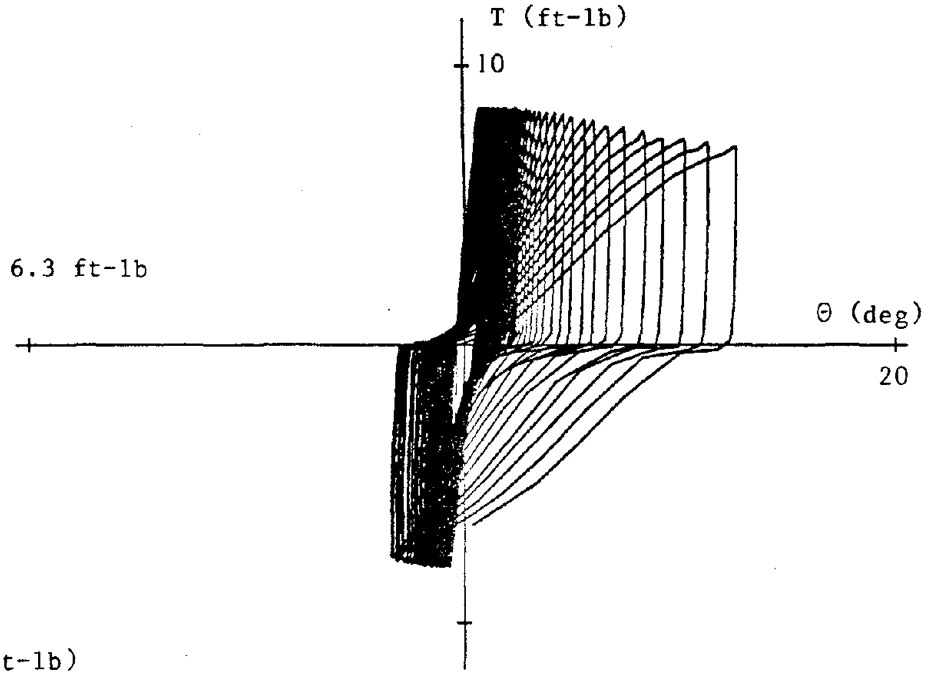


FIGURE 2-31 Limiting shear strains during shaking table tests. Source: Seed (1976).

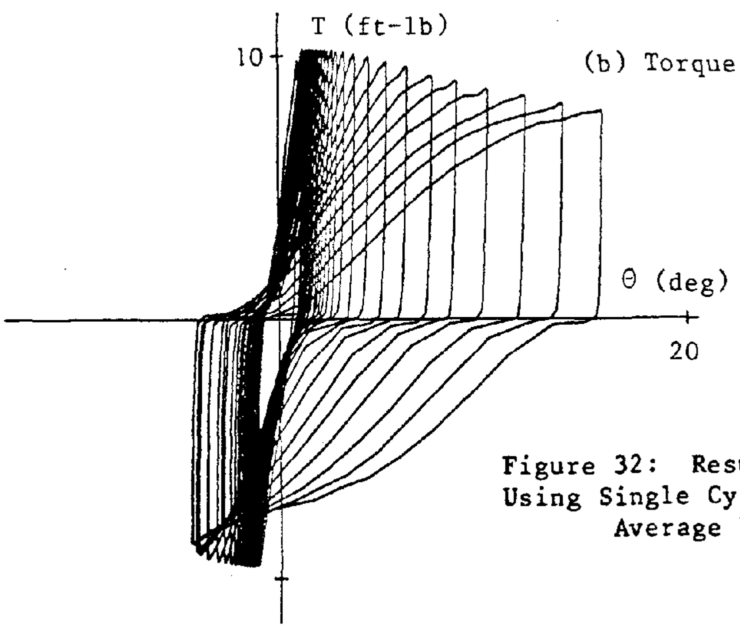
Figure 31: Published Results from Laboratory Cyclic Tests Conducted on Sands (2)



(a) Torque Amplitude = 6.3 ft-lb



(b) Torque Amplitude = 8.2 ft-lb



(c) Torque Amplitude = 9.9 ft-lb

Figure 32: Results from Cyclic Tests Conducted Using Single Cylinder Probe - Digitized Curves. Average Relative Density = 61.0%.

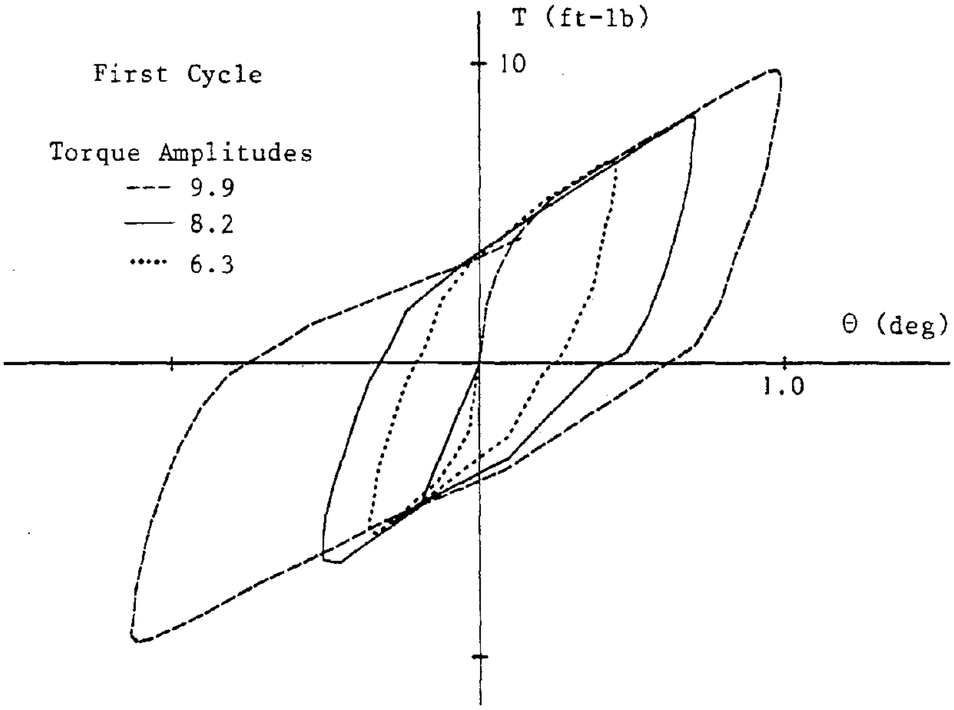
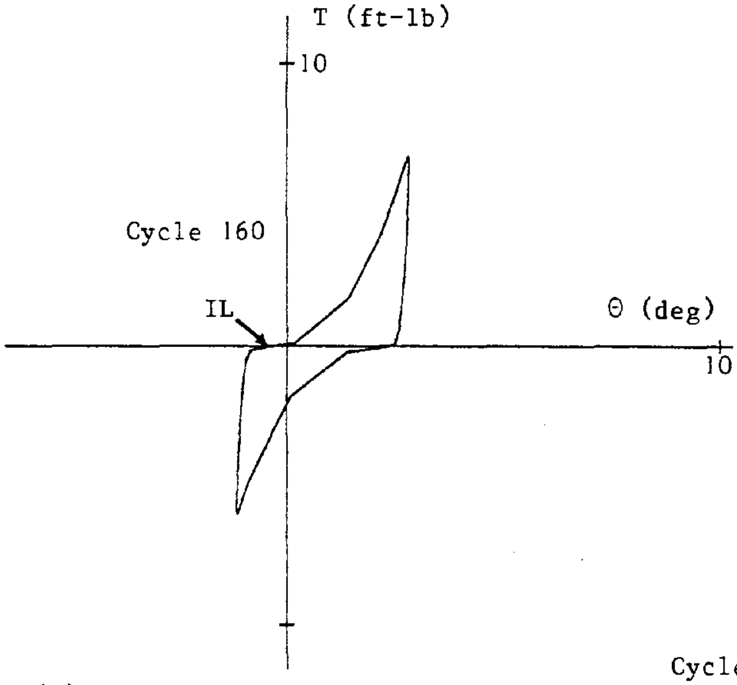
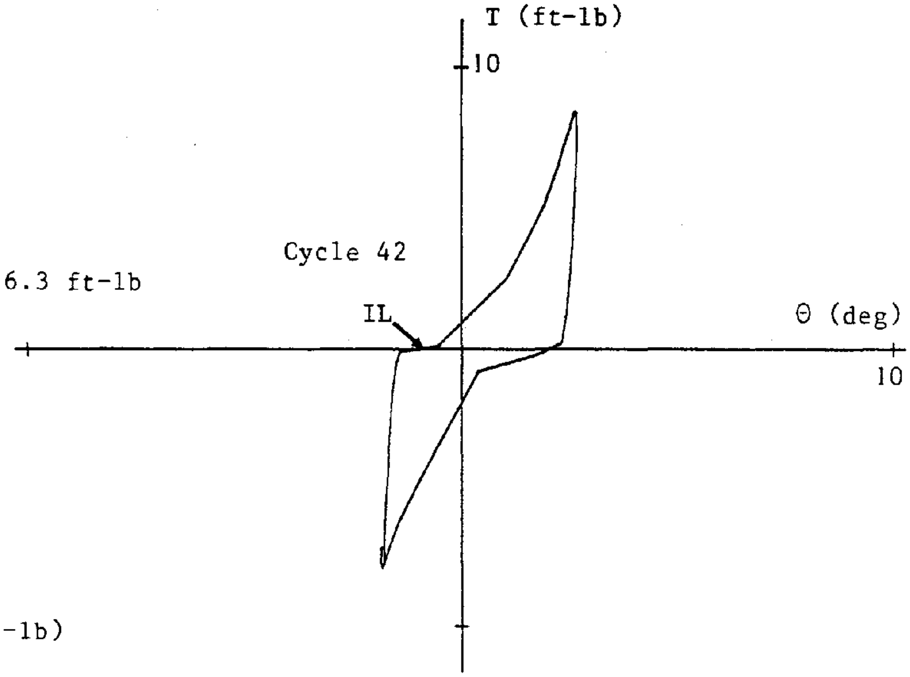


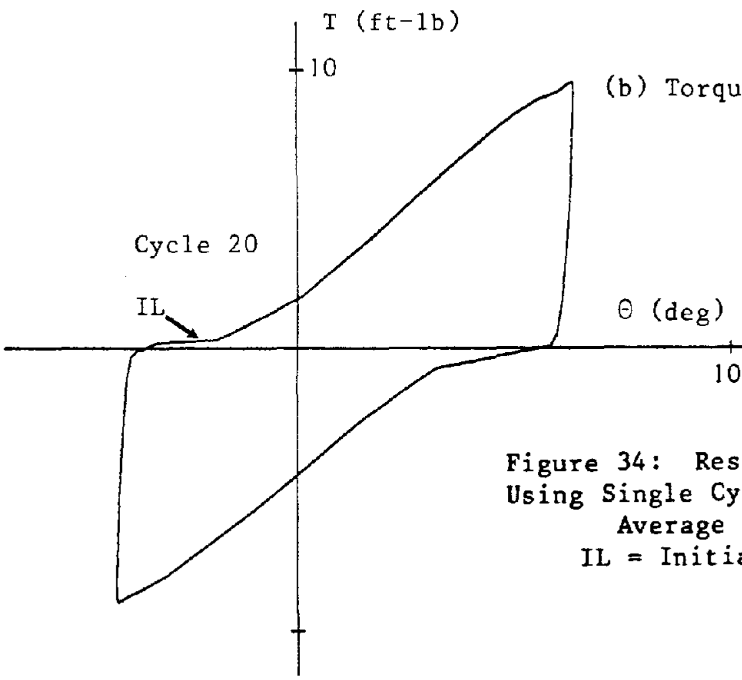
Figure 33: Results from Cyclic Tests Conducted Using Single Cylinder Probe - Digitized Curves. Average Relative Density = 61.0%.



(a) Torque Amplitude = 6.3 ft-lb



(b) Torque Amplitude = 8.2 ft-lb



(c) Torque Amplitude = 9.9 ft-lb

Figure 34: Results from Cyclic Tests Conducted Using Single Cylinder Probe - Digitized Curves. Average Relative Density = 61.0%. IL = Initial Liquefaction ($\Delta T/\Delta\Theta \simeq 0$).

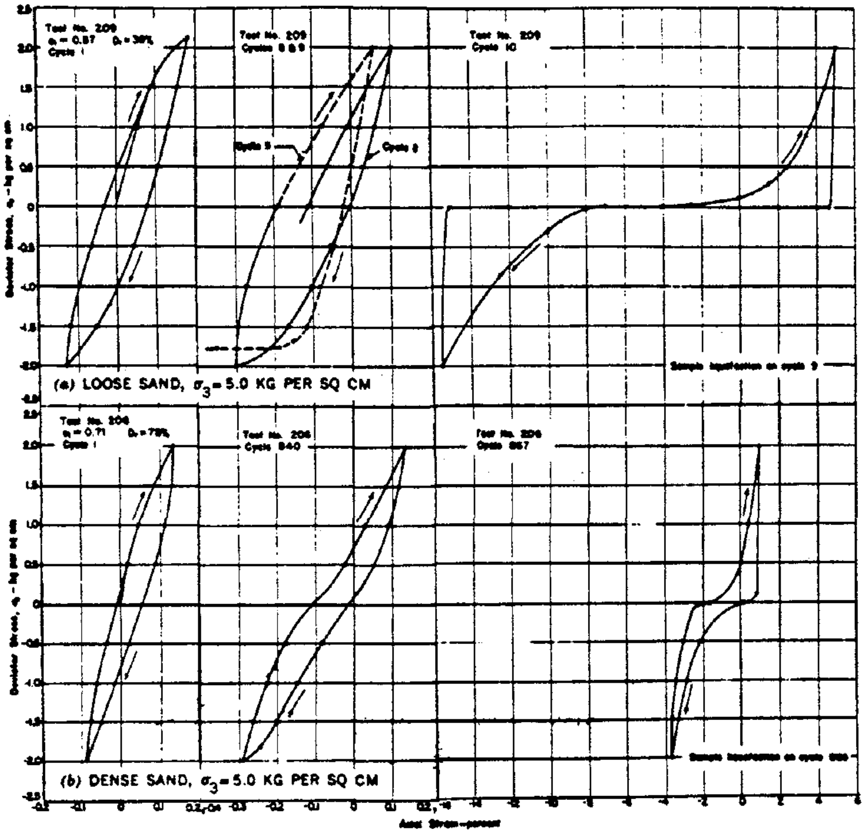


FIGURE 2-33 Hysteresis loops before and after initial liquefaction of loose and dense sands in triaxial tests. Source: Seed and Lee (1966).

Figure 35: Published Results from Laboratory Cyclic Tests Conducted on Loose and Dense Sands (2)

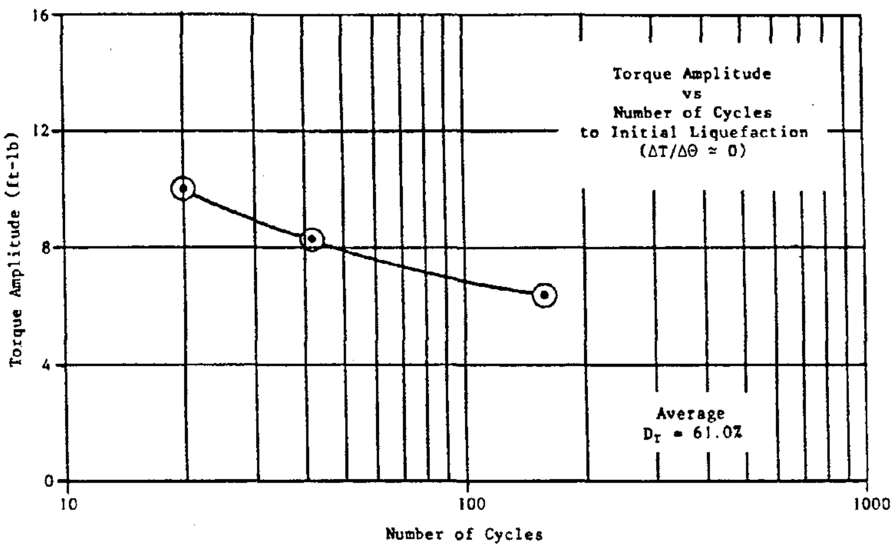


Figure 36: Results from Cyclic Tests Conducted Using Single Cylinder Probe

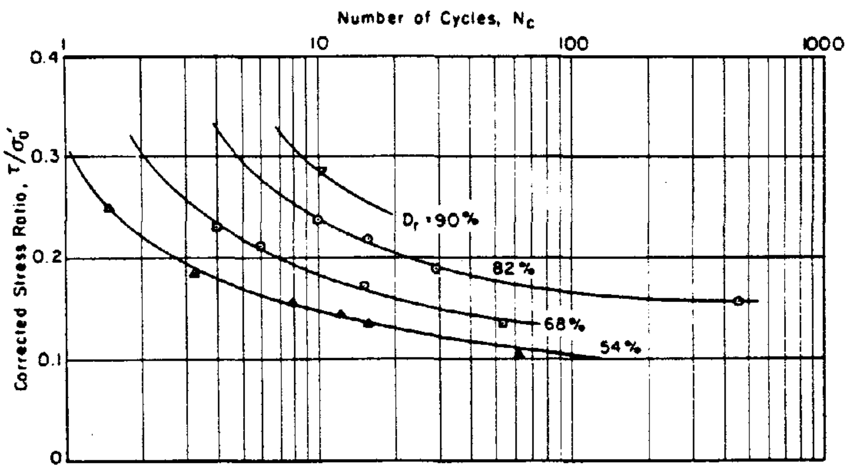


FIGURE 2-29 Stress ratio τ_d/σ'_{vo} versus number of cycles to initial liquefaction, from tests on a shaking table. Source: DeAlba et al. (1976).

Figure 37: Published Results from Laboratory Cyclic Tests Conducted on Sands (2)

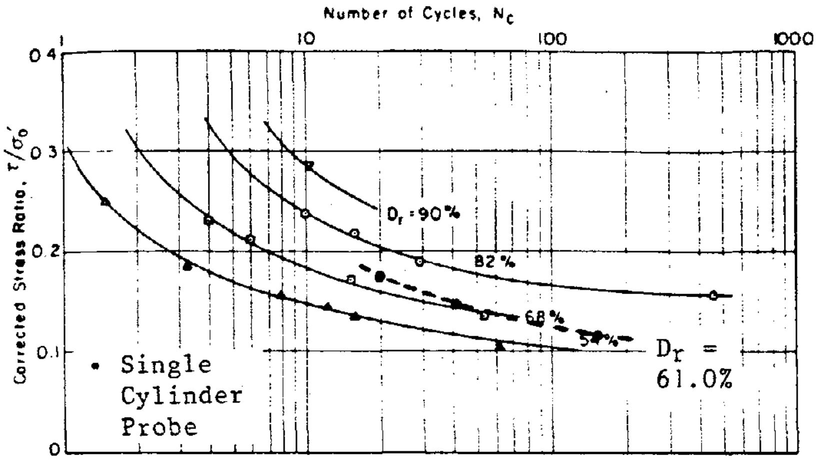


FIGURE 2-29 Stress ratio τ_d/σ'_{vo} versus number of cycles to initial liquefaction, from tests on a shaking table. Source: DeAlba et al. (1976).

Figure 38: Comparison Between Approximate Interpretations of Results from Cyclic Tests Conducted Using Single Cylinder Probe and Results from Laboratory Cyclic Tests Conducted on Sands (2)

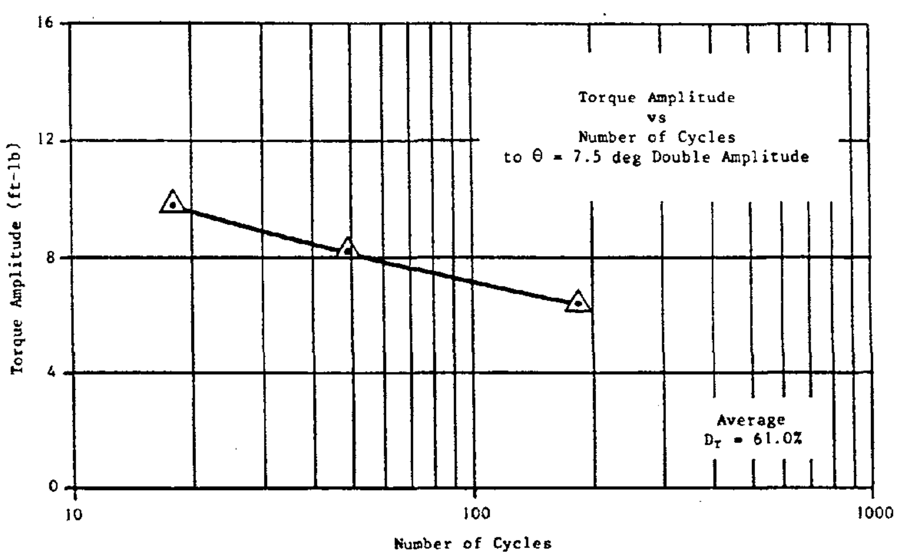


Figure 39: Results from Cyclic Tests Conducted Using Single Cylinder Probe

We show an alternate form of presentation of results in Figure 39. This figure shows the amplitude of the cyclic torque vs the number of cycles to a specified double amplitude of cyclic angular displacement. The figure shows that the number of cycles to the specified angular displacement decreases as the amplitude of the cyclic torque increases.

We did not experience any difficulties during testing nor did we encounter any limitations.

Impulse Tests (Single Cylinder)--Results from impulse tests conducted using the single cylinder probe were found to be reasonable; however, we were unable to effectively compare our test results with ones reported in the literature because of the nature of the test. We did not encounter abnormal difficulties or limitations. The active cylinder was grooved and uncoated.

Our results, presented in Figures 40 and 41, seem reasonable. These figures present applied torque, and linear tangential accelerations and angular accelerations of the instrumented head as functions of time for a sequence of increasing torques. The linear accelerations and the related angular accelerations show decaying vibrations. Also, the level of the accelerations increases with an increasing level of applied torque.

Some difficulty was encountered during testing but we feel the difficulty is neither major nor insurmountable. Electric noise was present in some of our data. We feel that by adopting additional noise reduction techniques, the noise can be reduced considerably.

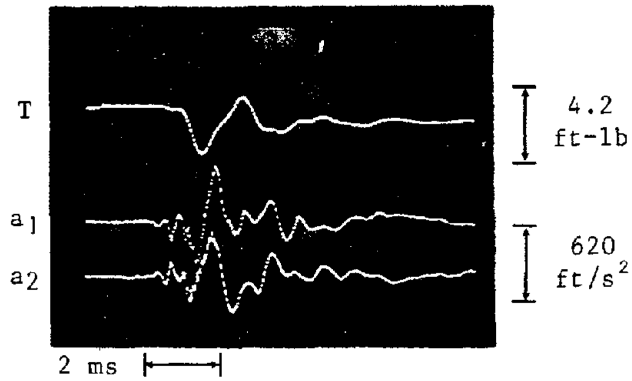
We did not identify any limitations.

Impulse Tests (Double Cylinder)--Results from impulse tests conducted using the double cylinder probe were found to be reasonable. However, as with the single cylinder impulse test, we were unable to compare our test results with ones reported in the literature because of the nature of the test. We did not encounter abnormal difficulties or limitations. The active cylinder was uncoated and grooved and the outer cylinder was uncoated and smooth.

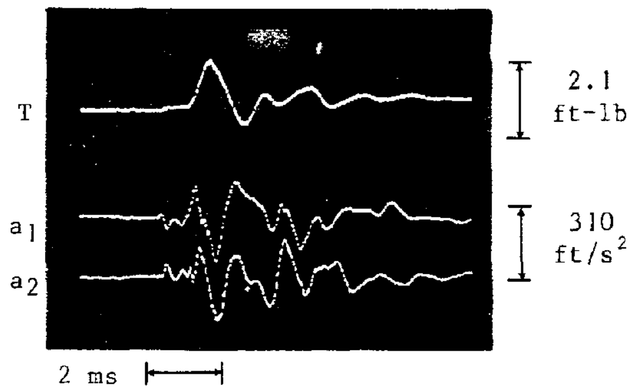
Our results, presented in Figures 42 and 43, seem reasonable. These figures present applied torque, and linear tangential accelerations and angular accelerations of the instrumented head as functions of time for a sequence of increasing torques. The linear tangential accelerations of the instrumented head show that rotations did not dominate the motions of the instrumented head as they did for the impulse tests conducted using the single cylinder probe. Comparable translations are seen in the results. The angular accelerations show decaying vibrations. Also, the level of the angular accelerations increases with an increasing level of applied torque.

Some difficulties were encountered during testing but again we feel these are neither major nor insurmountable. Electric noise was again present in some of our data. We feel that by adopting additional noise reduction techniques, the noise can be reduced considerably. Additionally, the higher levels of translational movements of the instrumented head suggest that we excited the test soil in an undesirable mode. We feel that we can reduce these movements through further design and machining.

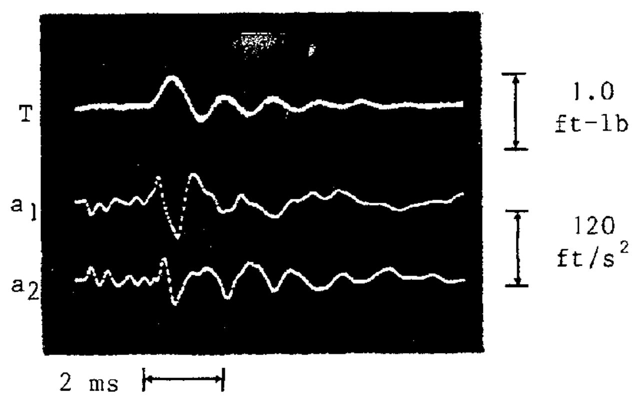
We did not identify any limitations during testing.



(a) Maximum Torque = 2.6 ft-lb

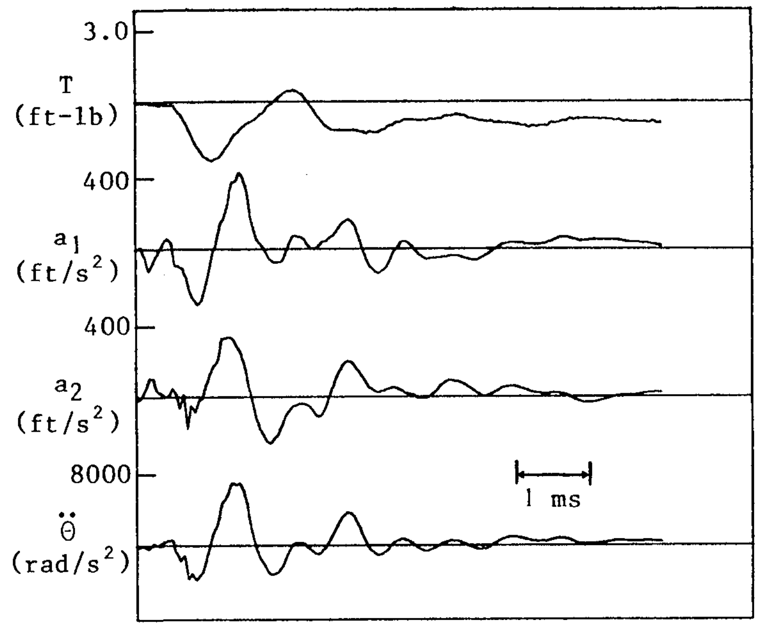


(b) Maximum Torque = 1.3 ft-lb

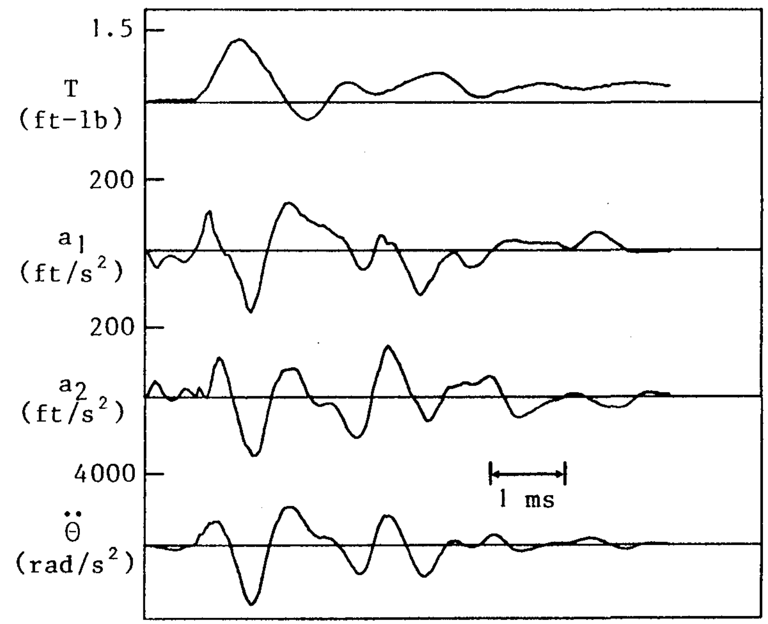


(c) Maximum Torque = 0.4 ft-lb

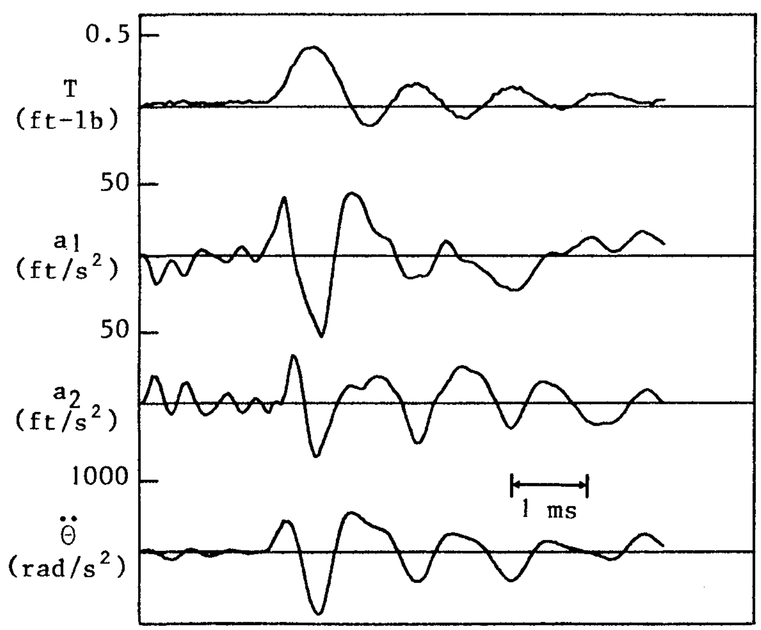
Figure 40: Results from Impulse Tests Conducted Using Single Cylinder Probe - Photographs from Face of Oscilloscope



(a) Maximum Torque = 2.6 ft-lb

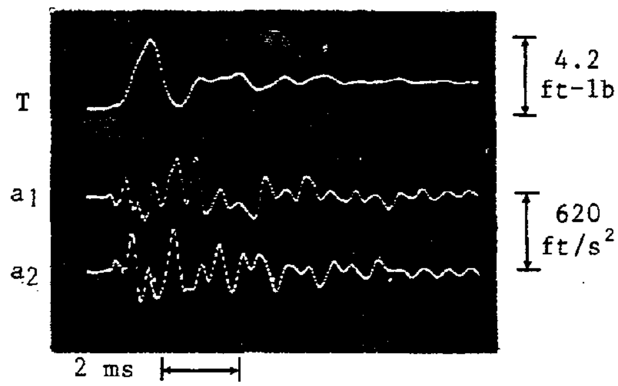


(b) Maximum Torque = 1.3 ft-lb

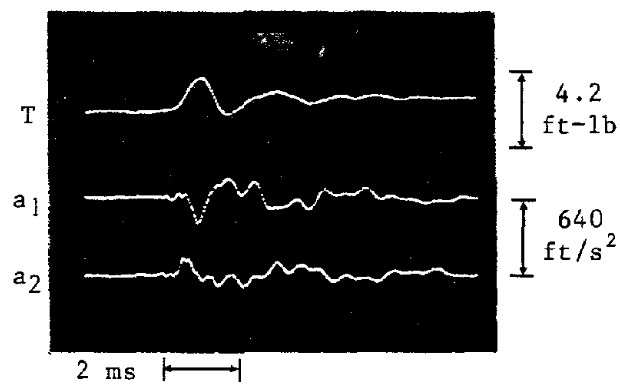


(c) Maximum Torque = 0.4 ft-lb

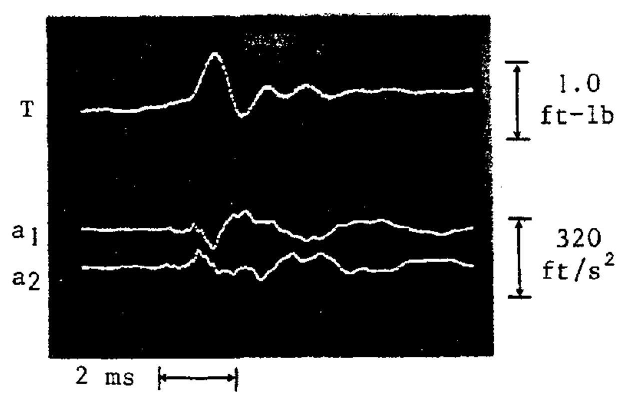
Figure 41: Results from Impulse Tests Conducted Using Single Cylinder Probe - Digitized Traces.
$\ddot{\Theta}(t) = [a_1(t) + a_2(t)] / 2 r_{ih}$.



(a) Maximum Torque = 3.8 ft-lb

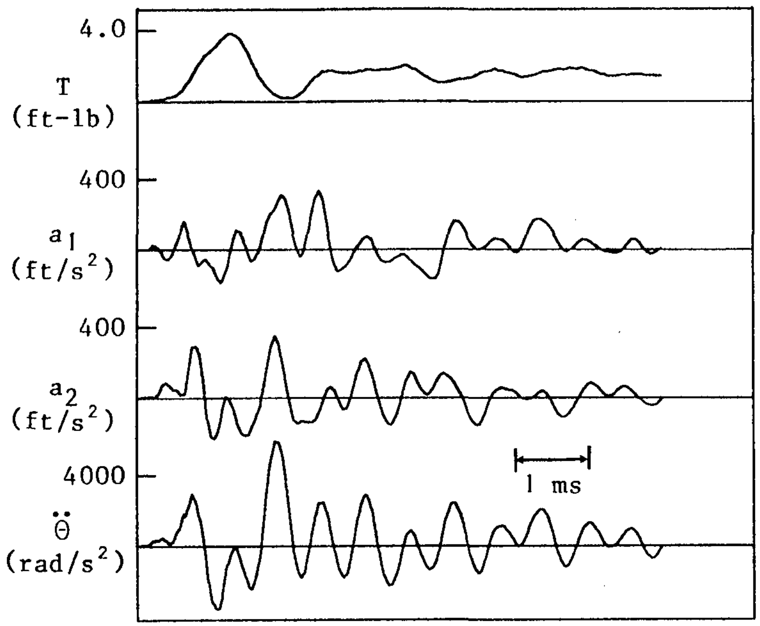


(b) Maximum Torque = 1.9 ft-lb

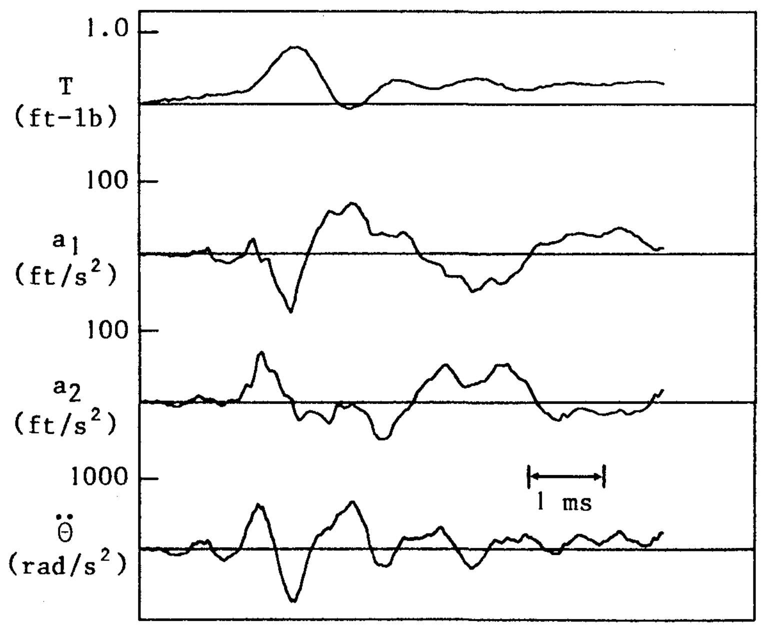


(c) Maximum Torque = 0.8 ft-lb

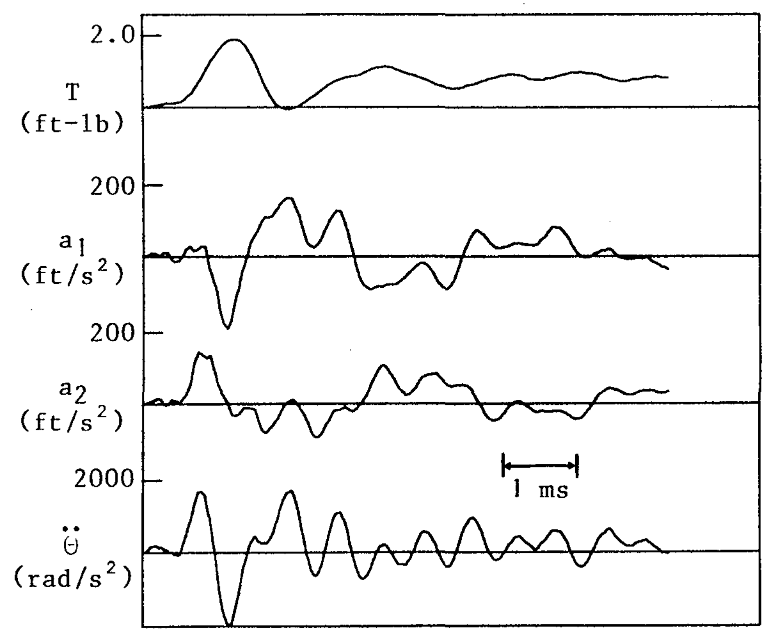
Figure 42: Results from Impulse Tests Conducted Using Double Cylinder Probe - Photographs from Face of Oscilloscope



(a) Maximum Torque = 3.8 ft-lb



(c) Maximum Torque = 0.8 ft-lb



(b) Maximum Torque = 1.9 ft-lb

Figure 43: Results from Impulse Tests Conducted Using Double Cylinder Probe - Digitized Traces. $\ddot{\theta}(t) = [a_1(t) + a_2(t)] / 2\ r_{ih}$.

Tests Related to Chamber Samples--The results we present from tests related to our test chamber samples include shear wave velocities, dynamic shear moduli, unit weights, void ratios, and relative densities. Results, presented in Table 1, are presented only for the samples prepared for the formal cyclic and impulse tests discussed in the preceding subsections.

Conventional Geotechnical Tests--The results from the conventional geotechnical tests we conducted on our test sand include distributions of grain sizes and maximum and minimum unit weights. The test sand was an ottawa quartz sand having rounded grains. The specific gravity of the sand is 2.66. A representative grain size distribution curve for the test sand is presented in Figure 44. Table 1 presents maximum and minimum unit weights for the test sand. Small changes were observed in the distributions of grain sizes and maximum and minimum unit weights over the course of the testing program. These changes are believed to have been caused by abrasive processes including raining the sand by a roller and recovering the sand by vacuum. Considering the early stage of our work, we feel the changes are not particularly significant.

Interpretations of Test Results

In this section, we present and discuss our interpretations of the results of cyclic and impulse tests conducted using our prototype testing system. The results were interpreted in terms of either cyclic or dynamic shear stress vs strain characteristics by simulating tests analytically.

Cyclic Tests (Double Cylinder)--We were able to interpret important aspects of results of cyclic tests conducted using the double cylinder probe. The cyclic shear stress vs strain model parameters found to provide the most representative simulations of tests are G_o = 1,500,000 psf, τ_y = 500 psf, α = 1.0, R = 3.0, C1 = 0.0875, C2 = 5.525, C3 = 1.988, C4 = 4.65, m = 0.43, n = 0.62, and k_2 = 0.00357. We encountered some difficulties and limitations in interpreting test results; however, we feel it is possible to overcome these problems.

We were able to describe effectively aspects of tests related to initial liquefaction. Curves of torque amplitude vs number of cycles to initial liquefaction are presented in Figure 45 for prototype tests and for analytical simulations of tests.

We were also able to describe effectively deformations developed during early stages of tests. This is shown by Figure 46, which presents representative curves of measured and computed angular displacements of the instrumented head as functions of time.

However, we experienced difficulties and limitations in describing aspects of behavior shortly before and after initial liquefaction. As shown by Figure 46, we did not represent the large angular displacements of the instrumented head that occurred prior to initial liquefaction or behavior after initial liquefaction. Additionally, we experienced difficulties in describing details of curves of applied torque vs angular displacement of the instrumented head. As shown by Figure 47, we were unable to describe the changes in shape that occur in these curves as the soil degrades. We feel these difficulties are caused by general limitations in the modeling of the degradation and liquefaction of denser sands. We are not familiar with any models that overcome these difficulties. Our test results seem reasonable.

Tests	Torque Amplitude (ft-lb)	Date Conducted	Shear Wave Velocities (fps)[a]			Unit Weight (pcf)	Density (slugs/ft^3)	Average Low Amplitude Dynamic Shear Modulus (10^6 psf)[c]
			SH1[b]	SH2[b]	Average			
Cyclic Tests - Double Cylinder Probe	8.0	11/17/89	645.2	625.0	635.1	104.33	3.24	1.307
	10.1	11/22/89	625.0	634.9	630.0	103.56	3.22	1.278
	6.9	11/29/89	629.9	655.7	642.8	103.76	3.22	1.330
Cyclic Tests - Single Cylinder Probe	8.2	10/13/89	634.9	661.2	648.0	104.47	3.24	1.360
	6.3	10/19/89	661.2	666.7	664.0	104.45	3.24	1.429
	9.9	10/24/89	666.7	666.7	666.7	104.12	3.23	1.436
Impulse Tests - Single Cylinder Probe	Not Applicable	12/11/89	655.7	620.2	638.0	103.68	3.22	1.311
Impulse Tests - Double Cylinder Probe	Not Applicable	12/18/89	640.0	634.9	637.5	103.68	3.22	1.309

Notes: a - Best estimate
b - SH1 and SH2 have opposite directions of propagation
c - G_o = density X (shear wave velocity)^2

Table 1 (continued on following page): Geotechnical Information on Test Sand and Test Samples in Test Chamber. Test Sand Is Ottawa Quartz Sand. Specific Gravity = 2.66.

Tests	Torque Amplitude (ft-lb)	Date Conducted	Void Ratio	Relative Density (%)	Average Relative Density (%)	Average Maximum Unit Weight (pcf)	Average Minimum Unit Weight (pcf)
Cyclic Tests - Double Cylinder Probe	8.0 10.1 6.9	11/17/89 11/22/89 11/29/89	0.591 0.603 0.600	60.8 56.2 57.4	58.1		
Cyclic Tests - Single Cylinder Probe	8.2 6.3 9.9	10/13/89 10/19/89 10/24/89	0.589 0.589 0.594	61.7 61.6 59.6	61.0	111.36	95.01
Impulse Tests - Single Cylinder Probe	Not Applicable	12/11/89	0.601	57.0	57.0		
Impulse Tests - Double Cylinder Probe	Not Applicable	12/18/89	0.601	57.0	57.0		

Table 1 (continued from previous page): Geotechnical Information on Test Sand and Test Samples in Test Chamber. Test Sand Is Ottawa Quartz Sand. Specific Gravity = 2.66.

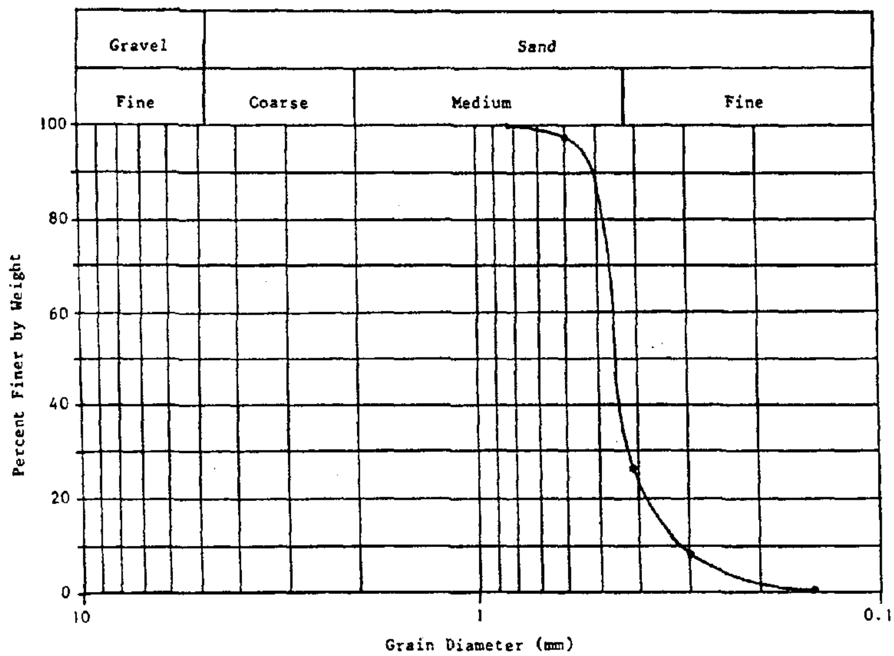


Figure 44: Representative Distribution of Grain Sizes for Ottawa Test Sand

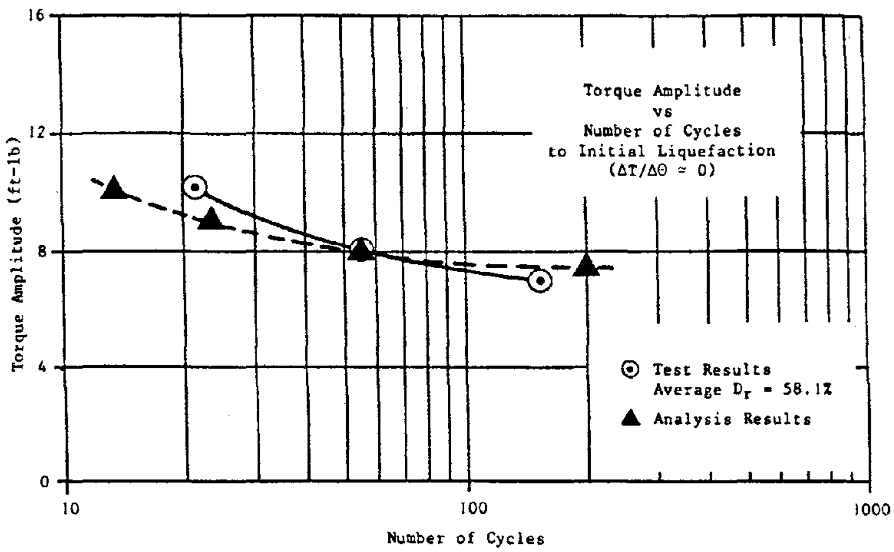


Figure 45: Results from Cyclic Tests Conducted Using Double Cylinder Probe and Results from Most Representative Analytical Simulations

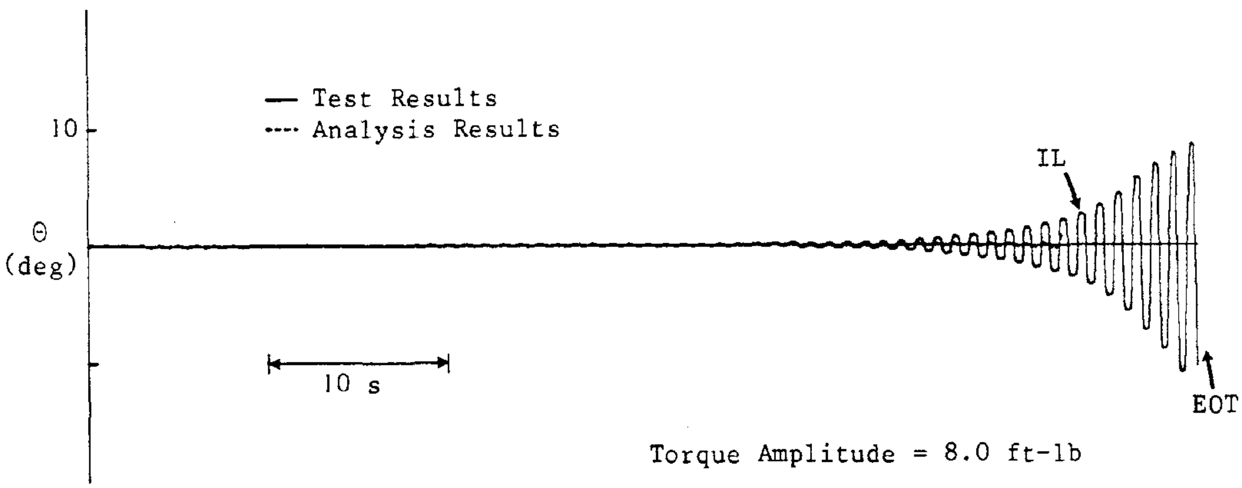
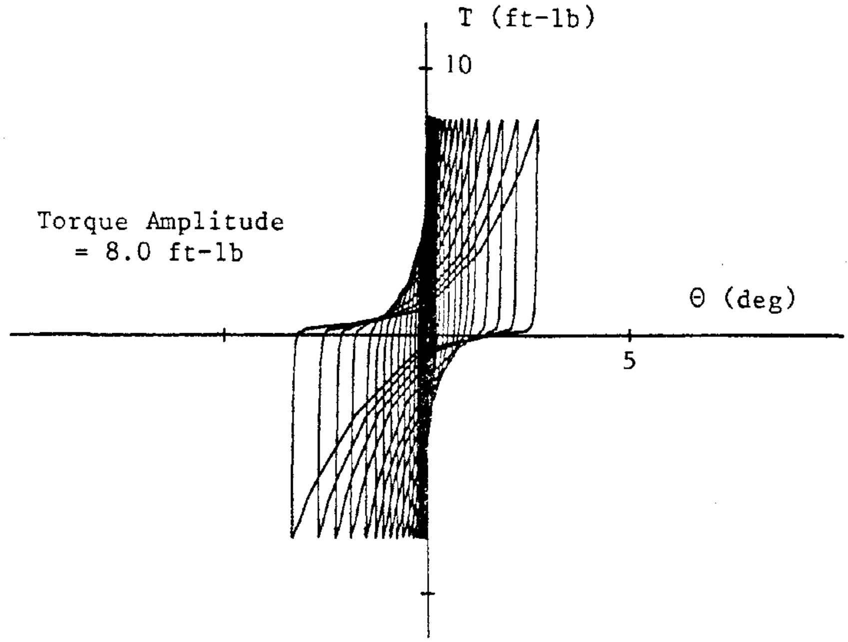
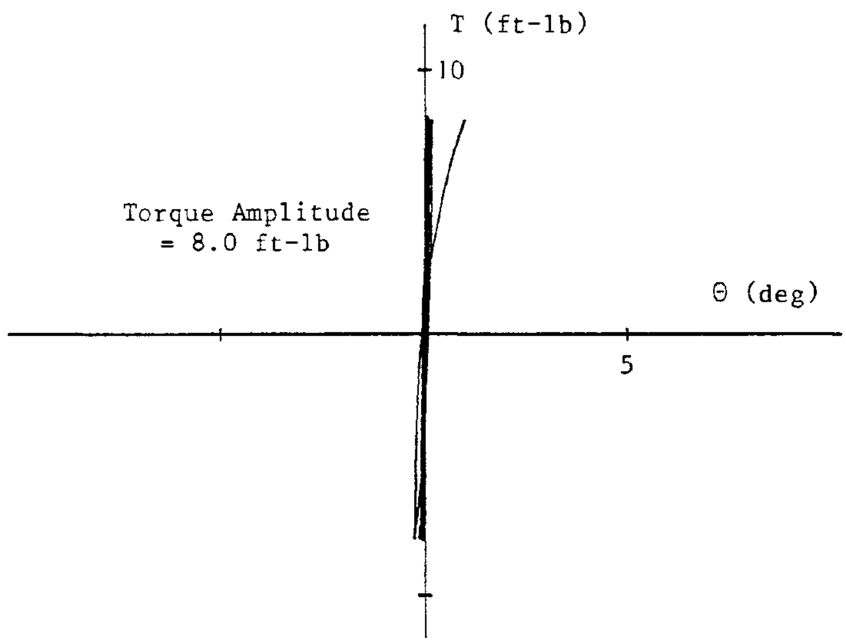


Figure 46: Results from Cyclic Tests Conducted using Double Cylinder Probe and Results from Most Representative Analytical Simulations. EOT = End of Test Due to Striking of Stops. IL = Initial Liquefaction ($\Delta T/\Delta\Theta \simeq 0$).



(a) Test Results



(b) Analysis Results

Figure 47: Results from Cyclic Test Conducted Using Double Cylinder Probe and Results from Corresponding Most Representative Simulation

Shear strains we roughly inferred for the test soil, both for the first cycle and for the cycle of initial liquefaction, seem reasonably consistent with those inferred for laboratory cyclic tests (see Figure 17). Also, as shown by Figures 15, 16, and 17, the changes we observed in the shapes of our curves of applied torque vs angular displacement are reasonably consistent with the changes in the shapes of published curves of stress vs strain for laboratory cyclic tests. The changes are caused by the combination of densification and dilation of grain structure.

We feel these difficulties can be resolved by extending our capabilities for modeling cyclic shear stress vs strain characteristics to describe important aspects of behavior that to our knowledge are not described by available models.

Cyclic Tests (Single Cylinder)--We were able to interpret important aspects of results from cyclic tests conducted using the single cylinder probe. The cyclic shear stress vs strain model parameters found to provide the most representative simulations of tests in a relatively limited study are G_O = 1,500,000 psf, τ_y = 120 psf, α = 6.0, R = 3.0, C1 = 0.002, C2 = 196.0, C3 = 0.0002, C4 = 28.0, m = 0.43, n = 0.62, and k_2 = 0.00357. We encountered some difficulties and limitations in interpreting tests results; however, we feel it is possible to overcome these problems.

We were able to describe reasonably effectively important aspects of tests related to initial liquefaction. Curves of torque amplitude vs number of cycles to initial liquefaction are presented in Figure 48 for prototype tests and for analytical simulations of tests.

Also, we were able to describe effectively deformations developed during early stages of tests. This is shown by Figure 49 which presents representative curves of measured and computed angular displacements of the instrumented head as functions of time.

However, we experienced some uncertainty in interpreting shear stress vs strain characteristics from results of tests. The characteristics we interpreted give, for higher levels of shear strain, seemingly soft behavior. We feel that one possible source of this problem is not modeling multidimensional behavior. At higher levels of strain multidimensional effects may be quite important for the single cylinder test.

Our first step toward resolving this difficulty would be to simulate tests using three-dimensional axisymmetric models. We are currently developing such models.

We also encountered difficulties and limitations in describing behavior shortly before and after initial liquefaction. As shown by Figure 49, we could not represent well the angular displacements of the instrumented head that occurred just prior to initial liquefaction or behavior after initial liquefaction. Additionally, as in the double cylinder test, we experienced difficulties in describing details of the curves of applied torque vs angular displacement of the instrumented head. As shown by Figure 50, we were unable to describe the changes in shape that occur in these curves. Again, we feel these difficulties are caused by general limitations in the modeling of the degradation and liquefaction of denser sands. We are not familiar with models that overcome these difficulties. Important aspects of our test results seem reasonable. The shear strains we roughly inferred for the test soil for the cycle of initial liquefaction seems reasonably consistent with those inferred

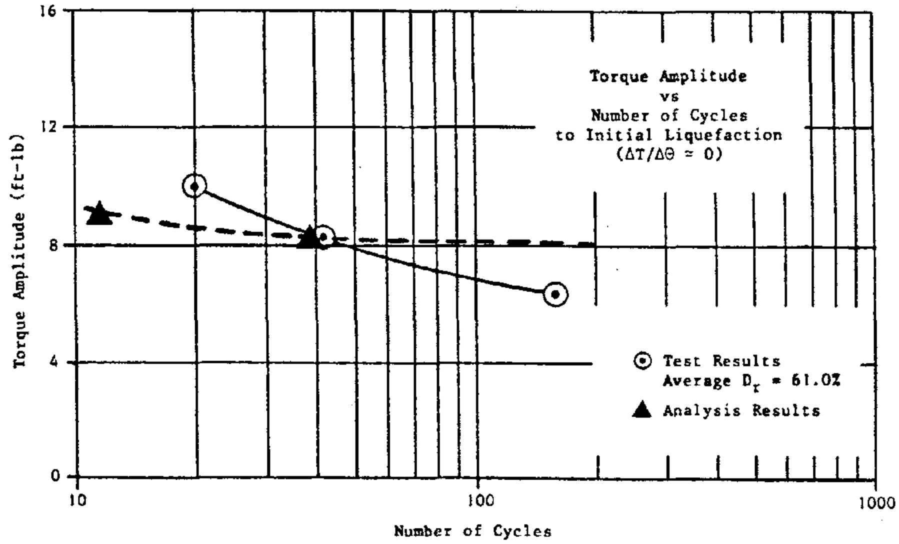


Figure 48: Results from Cyclic Tests Conducted Using Single Cylinder Probe and Results from Most Representative Analytical Simulations

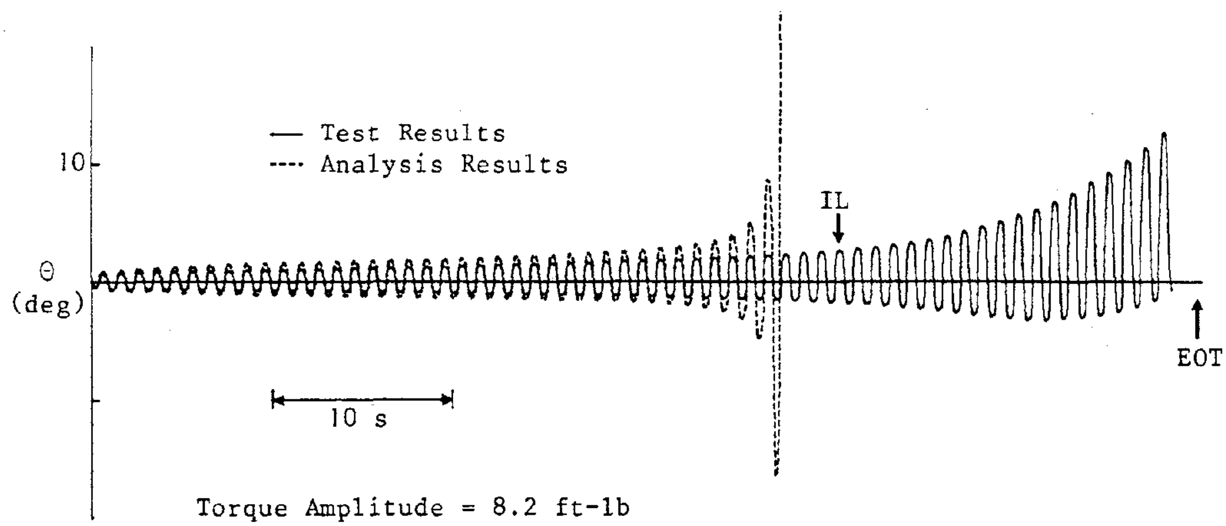
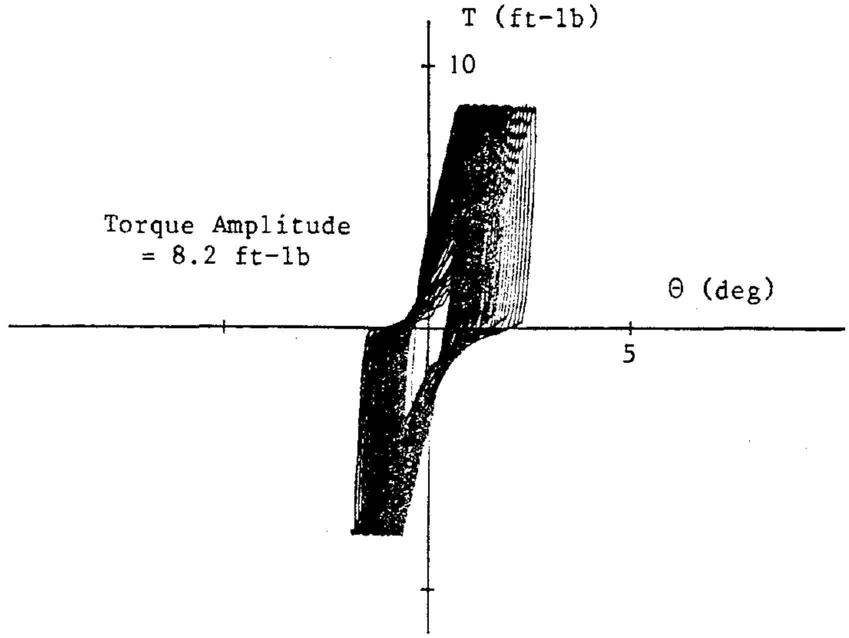
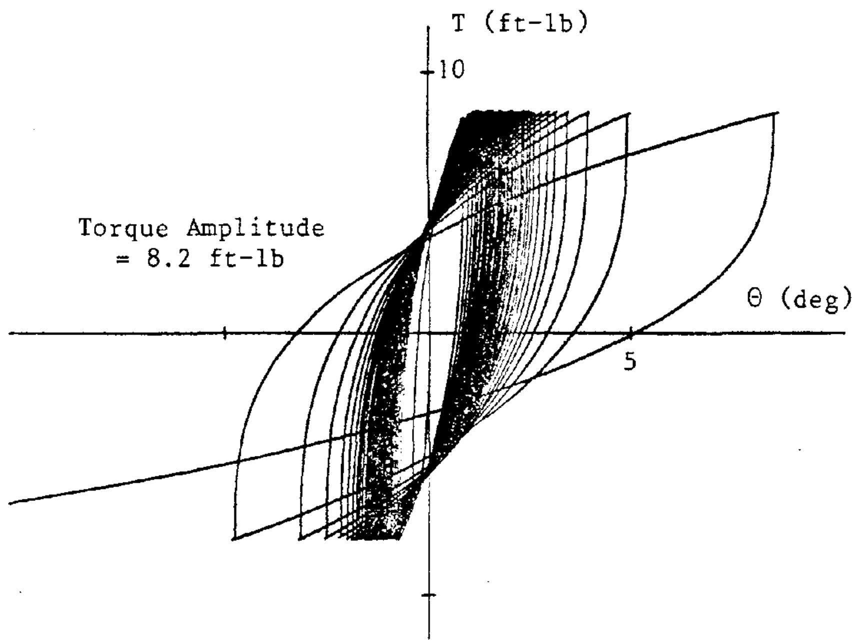


Figure 49: Results from Cyclic Test Conducted Using Single Cylinder Probe and Results from Corresponding Most Representative Simulation. EOT = End of Test Due to Striking of Stops. IL = Initial Liquefaction ($\Delta T/\Delta\Theta \approx 0$).



(a) Test Results



(b) Analysis Results

Figure 50: Results from Cyclic Test Conducted Using Single Cylinder Probe and Results from Corresponding Most Representative Analytical Simulation

for laboratory cyclic tests (see Figure 35). Also, as shown by Figures 32, 34, and 35, the changes we observed in the shapes of our curves of applied torque vs angular displacement are reasonably consistent with the changes in the shapes of published curves of stress vs strain for laboratory cyclic tests. The changes are caused by the combination of densification and dilation of grain structure.

Again, we feel these difficulties can be resolved by extending our capabilities for modeling cyclic shear stress vs strain characteristics to describe important aspects of behavior that to our knowledge are not described by available models.

Impulse Tests (Single Cylinder)--We were able to interpret results from impulse tests conducted using the single cylinder probe. The dynamic shear stress vs strain model parameters found to give the most representative simulations of tests are G_o = 1,500,000 psf, τ_y = 120 psf, α = 1.0, and R = 3.0. Our interpretations of dynamic shear stress vs strain characteristics seem qualitatively reasonable. Also, we found that results from analyses are sensitive to these characteristics. We experienced some difficulty in interpreting test results; however, we feel that it is possible to overcome this difficulty. We did not encounter any limitations.

The dynamic shear stress vs strain characteristics we interpreted from test results seem qualitatively reasonable. Results from our most representative analytical simulations are presented in Figure 51 along with results from tests. Corresponding shear stress vs strain curves described by the analyses for the test soil along the wall of the active cylinder are shown in Figure 52. The shear stress vs strain curves presented show both linear, elastic and nonlinear, inelastic behavior. The greater the intensity of the loading, the greater is the degree of nonlinearity and inelasticity. The nonlinear shear stress vs strain curves suggest permanent deformations. Also, the value inferred for the low amplitude dynamic shear modulus agrees reasonably well with that estimated from seismic crosshole tests (see Table 1).

We found results of our simulations to be sensitive to dynamic shear stress vs strain characteristics. Sensitivities are shown by Figure 53.

We experienced some uncertainty in interpreting shear stress vs strain characteristics from results of tests. The characteristics we interpreted give, for higher levels of shear strain, seemingly soft behavior. As in the case of the single cylinder cyclic test, we feel that one possible source of this problem is not modeling multidimensional behavior. At higher levels of strain multidimensional effects may be quite important for the single cylinder test.

Our first step toward resolving this difficulty would be to simulate tests using three-dimensional axisymmetric models. We are currently developing such models.

Impulse Tests (Double Cylinder)--Using the intermediate analysis procedure (see pg. 17) in a relatively limited study, we were unable to interpret adequately results from impulse tests conducted using the double cylinder probe. Thus, we do not report dynamic shear stress vs strain curve parameters found to give the most representative simulations of tests. Basically, results from our analytical simulations do not entirely match the

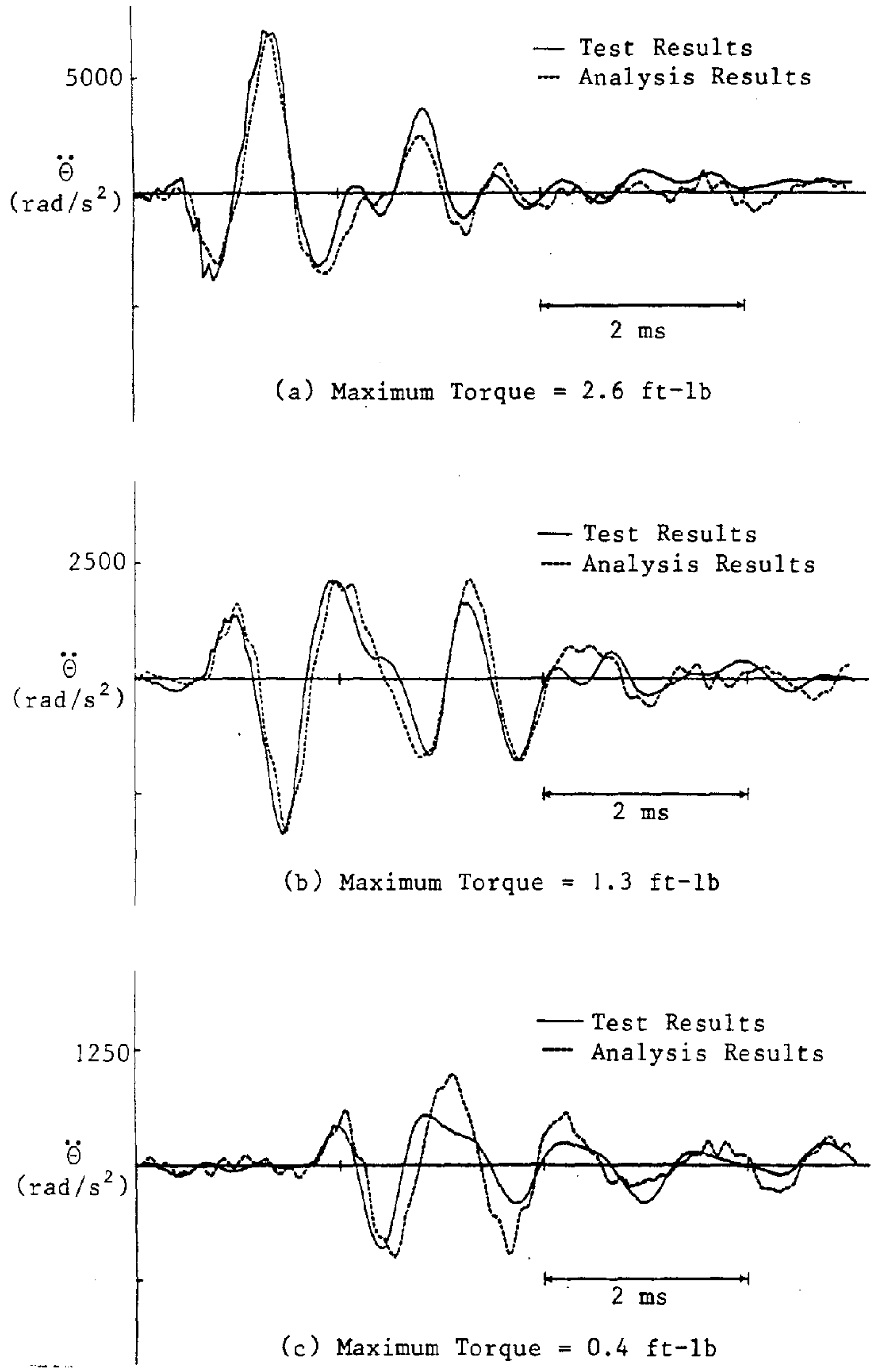
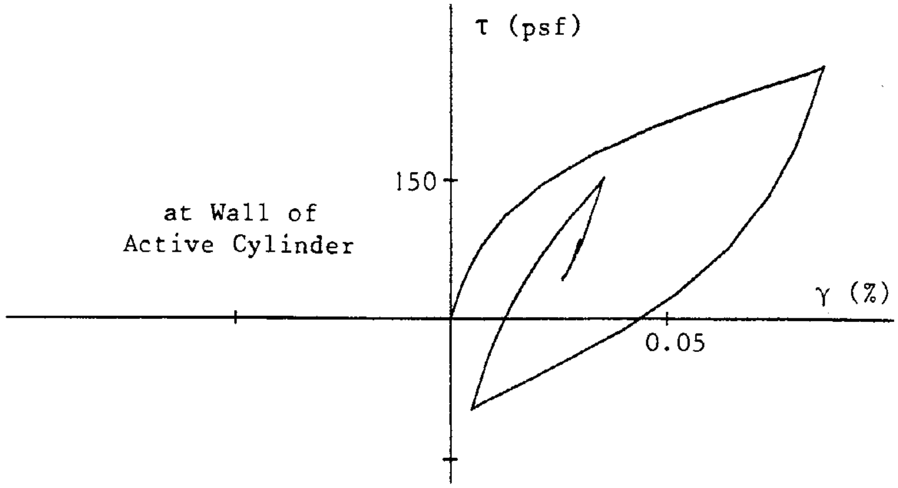
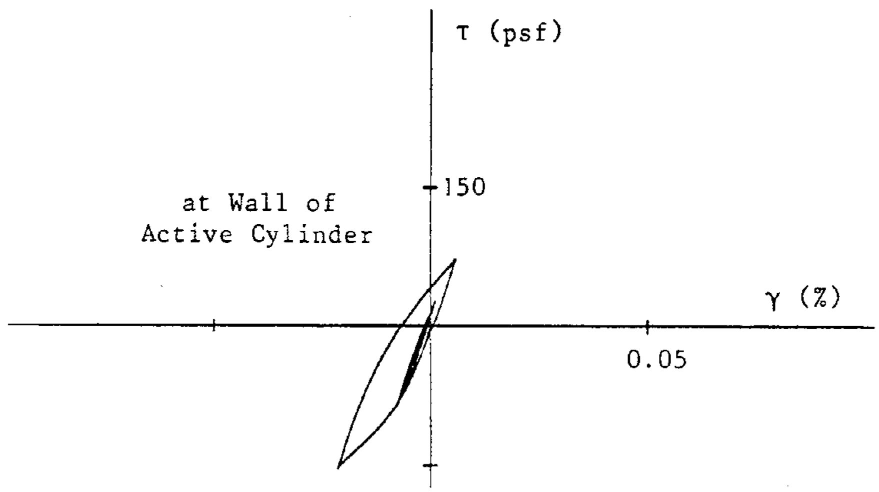


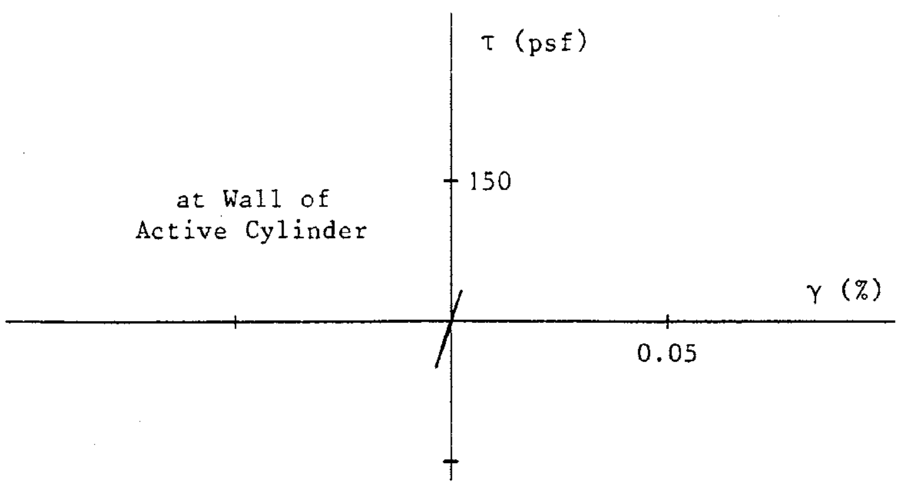
Figure 51: Results from Impulse Tests Conducted Using Single Cylinder Probe and Results from Most Representative Analytical Simulations



(a) Maximum Torque = 2.6 ft-lb

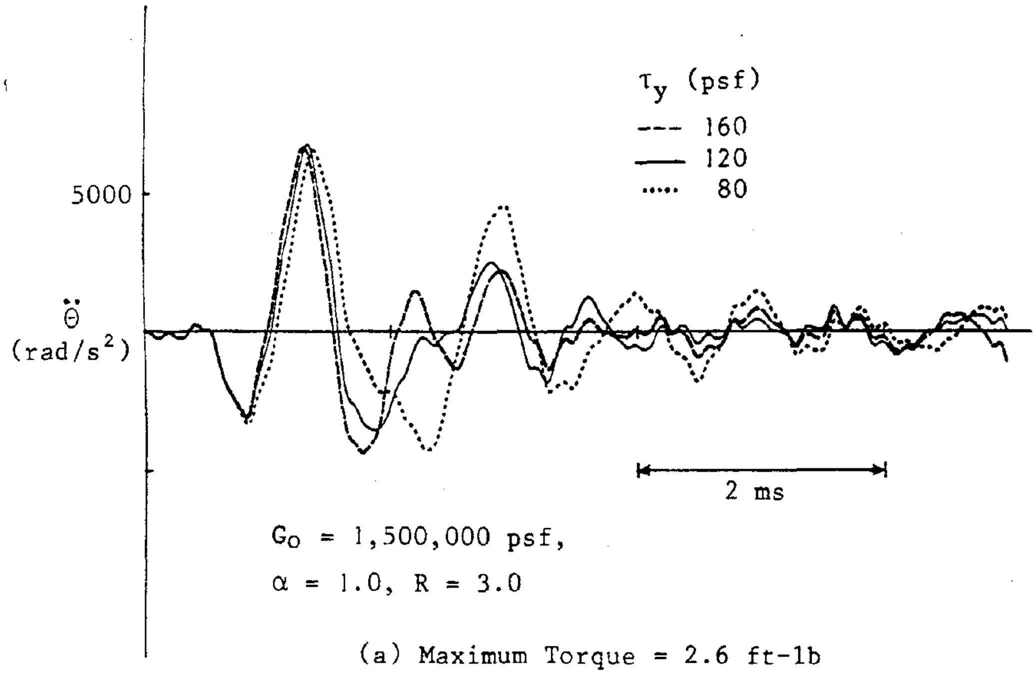


(b) Maximum Torque = 1.3 ft-lb

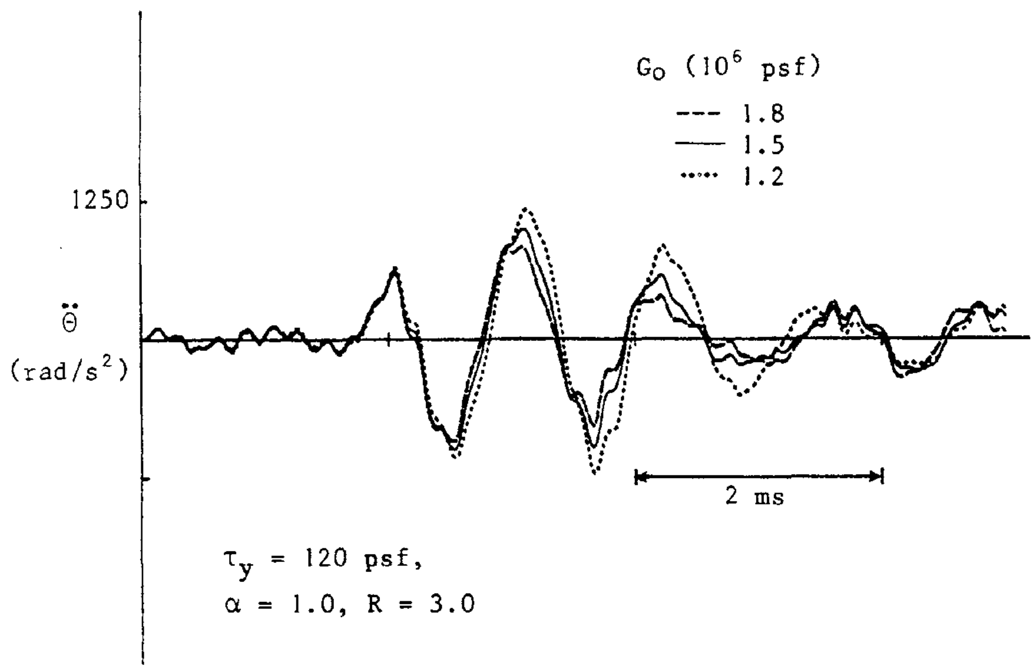


(c) Maximum Torque = 0.4 ft-lb

Figure 52: Results from Most Representative Analytical Simulations of Impulse Tests Conducted Using Single Cylinder Probe



(a) Maximum Torque = 2.6 ft-lb



(b) Maximum Torque = 0.4 ft-lb

Figure 53: Results from Analytical Simulations of Impulse Tests Conducted Using Single Cylinder Probe

character of the results from tests. We feel the cause of this is that our intermediate analysis does not model all important aspects of double cylinder impulse tests. We feel that this is a solvable problem but one that will likely require focused detailed study. We are now conducting preliminary studies toward resolving this problem.

CONCLUSIONS OF PHASE II

Several main conclusions arise from our work.

1) The proposed testing procedure is a promising means for estimating reliably in situ cyclic and dynamic shear stress vs strain characteristics of soil deposits. These characteristics include 1) resistances to initial liquefaction, degradation, and large deformations before and after initial liquefaction, and 2) undegraded, nonlinear, inelastic characteristics. Estimates of characteristics are expected to be appropriate for use at the advanced stages of the earthquake resistant design of critical systems. We also feel the proposed testing procedure shows promise as an index-like test for the early stages of design.

2) The proposed testing procedure was found to be an effective means for estimating cyclic and dynamic shear stress vs strain characteristics under controlled laboratory conditions. Generally, test results were found to be reasonable, consistent, and reasonably interpretable. We did not encounter difficulties or limitations that we feel cannot be overcome.

We feel we experienced considerable success in our project with cyclic tests. Results from cyclic tests were found to be reasonable, consistent with published results from laboratory cyclic tests of a high quality, and repeatable. Cyclic testing is the main capability of the proposed testing procedure and was the main focus of our project. Cyclic tests were found to bring out important aspects of cyclic shear stress vs strain characteristics of cohesionless soils: initial liquefaction due to densification, cyclic restiffening due to dilation, cyclic degradation, deformations before and after initial liquefaction including limiting strains, and undegraded, nonlinear, inelastic characteristics. Only relatively minor technical difficulties were experienced.

We found we could interpret important aspects of results from cyclic tests by simulating these tests analytically using analyses of an intermediate level of descriptiveness. We were able to interpret initial liquefaction characteristics and deformations during early stages of tests. However, we did experience difficulties and limitations in describing behavior shortly before and after initial liquefaction and details of shear stress vs strain behavior. We feel these difficulties and limitations can be overcome by extending available shear stress vs strain modeling capabilities to describe behavior that, to our knowledge, is not described by available models. Also, we experienced some uncertainty in interpreting results from cyclic tests conducted using the single cylinder probe. We feel that our first step toward resolving this difficulty should be to model tests using more descriptive analyses.

We feel we experienced reasonable success with impulse tests. Results from impulse tests were found to be reasonable. We were unable to study consistency with published results and did not study repeatability. Only relatively minor technical difficulties were encountered.

We found we could interpret results from impulse tests conducted using the single cylinder probe by simulating tests analytically using analyses of an intermediate level of descriptiveness. The results of our simulations seem reasonable showing both linear, elastic and nonlinear, inelastic characteristics for the test soil, and signs of permanent deformations. Also, analytical results were found to be sensitive to dynamic shear stress vs strain characteristics. We experienced some uncertainty in interpreting results from impulse tests, more with the double cylinder probe than with the single cylinder probe. We feel that our first step toward resolving this difficulty should be to model tests using more descriptive analyses.

3) Cyclic tests provided, more effectively than impulse tests, information on shear stress vs strain characteristics for higher levels of shear strain. Impulse tests provided, more effectively than cyclic tests, information on shear stress vs strain characteristics for lower levels of strain.

4) Because the proposed testing procedure is promising, further attention should be directed toward its realization and toward realizing its full potential.

FURTHER WORK

We feel further work would be of great value first, toward realizing the proposed testing procedure and then, toward fully realizing its potential. There are three main areas in which further work would be worthwhile. These include field testing, laboratory testing, and refinement of the testing procedure.

We feel that the most productive step, at this time, toward realizing the procedure would be to conduct field tests. In view of the complexity of reality, we now feel that at our stage field testing is the only truly effective means of evaluating the proposed testing procedure. Additionally, field testing would expose us to any special constraints that the field may impose.

After successful field testing it would be of great value for realizing the potential of the procedure to continue laboratory testing and conduct related analytical studies. The tests and studies would be conducted to evaluate effects of parameters such as relative density, cylinder sizes and finishes, and disturbances caused by penetration of the probe. Further laboratory testing would also help define the limits of the testing procedure.

It would be of equal value to refine the testing procedure. Both the probe and the analyses for simulating tests could be improved. For example, steps should be taken to improve measurements of angular displacements and the performance of the piston system, and to reduce electric noise. Likewise, our intermediate axisymmetric analyses for simulating tests should be extended to three dimensions, and our models of shear stress vs strain behavior should be extended to describe aspects of behavior that are quite important but are not, to our knowledge, described by available models.

REFERENCES

1. Anderson, W.A., "Loma Prieta Earthquake Research Recommendations," Memorandum from Earthquake Hazard Mitigation Section of National Science Foundation, December, 1989.

2. Committee on Earthquake Engineering, Commission on Engineering and Technical Systems, and the National Research Council, "Liquefaction of Soils During Earthquakes," Report for the National Science Foundation, National Academy Press, Washington, D.C., 1985.

3. Consejo Nacional de Ciencia y Tecnologia and Committee on Earthquake Engineering and the National Research Council, "Research Agenda: Learning from the 19 September 1985 Mexico Earthquake," A joint report, January, 1986.

4. Earthquake Engineering Research Institute, "Loma Prieta Earthquake, October 17, 1989," A Preliminary Reconnaissance Report, November, 1989.

5. Finn, W.D.L., "Dynamic Response Analyses of Saturated Sands," Soil Mechanics-Transient and Cyclic Loads, John Wiley and Sons, New York, 1982, pp. 105-131.

6. Finn, W.D.L., Bhatia, S.K., and Pickering, D.J., "The Cyclic Simple Shear Test," Soil Mechanics-Transient and Cyclic Loads, John Wiley and Sons, New York, 1982, pp. 583-607.

7. Henke, R., "Numerical Procedure for Predicting the Torsional Dynamic Response of Solid Media," dissertation presented to the University of Michigan, Ann Arbor, MI, in partial fulfillment of the requirements for the degree of Doctor of Philosophy, 1980.

8. Henke, R., Richart, F.E., Jr., and Woods, R.D., "Nonlinear Torsional Dynamic Response of a Footing," Journal of Geotechnical Engineering, Proc. ASCE, Vol. 109, No. 1, Jan, 1983, pp. 72-88.

9. Henke, R., Wylie, E.B., and Richart, F.E., Jr., "Torsional Dynamic Response of Solid Systems," Journal of the Engineering Mechanics Division, Proc. ASCE, Vol. 108, No. EM6, Dec., 1982, pp. 1067-1085.

10. Henke, R. and Wylie, E.B., "Torsional Dynamic Response of Solid Media," Journal of the Engineering Mechanics Division, Proc. ASCE, Vol. 108, No. EM1, Feb., 1982, pp. 73-94.

11. Henke, R. and Henke, W., "Laboratory Prototype of In Situ Cyclic and Dynamic Geotechnical Testing System," Soil Dynamics and Liquefaction, Proceedings, 3rd International Conference on Soil Dynamics and Earthquake Engineering, Princeton University, Princeton, New Jersey, June 22-24, 1987, pp. 299-305.

12. Henke, R. and Henke, W., "In Situ Testing Method for Obtaining Cyclic and Dynamic Soil Properties," Soil Dynamics and Earthquake Engineering, Proceedings, 2nd International Conference on Soil Dynamics and Earthquake Engineering, on board the ocean liner Queen Elizabeth 2, sailing from New York to Southampton, June/July, 1985, pp. 2-47 to 2-56.

13. Henke, W. and Henke, R., "Cyclic Tests Conducted Using Laboratory Prototype of In Situ Geotechnical Testing System," abstract submitted to Second International Conference on Geotechnical Earthquake Engineering and Soil Dynamics to be held in St. Louis, Missouri, March 11-15, 1991.

14. Henke, W. and Henke, R., "Impulse Tests Conducted Using Laboratory Prototype of In Situ Geotechnical Testing System," abstract submitted to Geotechnical Engineering Congress, 1991, to be held in Boulder, Colorado, June 10-12, 1991.

15. Martin, G.R., Finn, W.D.L., and Seed, H.B., "Fundamentals of Liquefaction under Cyclic Loading," Journal of the Geotechnical Engineering Division, Proc. ASCE, Vol. 101, No. GT5, May, 1975, pp. 423-437.

16. Martin, G.R., Lam, I.P., McCaskie, S.L., and Tsai, C.-F., "A Parametric Study of an Effective Stress Liquefaction Model," International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, University of Missouri - Rolla, 1981, pp. 699-705.

17. National Science Foundation and U.S. Geological Survey, "Proposals for Research Loma Prieta Earthquake," Announcement 7637, November, 1989.

18. Richart, F.E., Jr., "Some Effects of Dynamic Soil Properties on Soil-Structure Interaction," Journal of the Geotechnical Engineering Division, Proc. ASCE, Vol.101, No. GT12, December, 1975, pp. 1193-1240.

19. Seed, H.B., "Evaluation of Soil Liquefaction Effects on Level Ground During Earthquakes," State-of-the-Art Paper, Liquefaction Problems in Geotechnical Engineering, Preprint 2752, ASCE Annual Convention, Sept. 27-Oct. 1, 1976, Philadelphia, PA, pp. 1-104.

20. Seed, H.B. and Idriss, I.M., Ground Motions and Soil Liquefaction During Earthquakes, Earthquake Engineering Research Institute Monograph, 1982, 134 pp.

21. Seed, H.B. and Lee, K.L., "Liquefaction of Saturated Sands During Cyclic Loading," Journal of the Soil Mechanics and Foundations Division, Proc. ASCE, Vol. 92, No. SM6, June, 1966, pp. 105-134.

22. Seed, R.B., Presentation on Geotechnical Aspects of 1989 Loma Prieta Earthquake, Dynamic Soil Property and Site Characterization for Earthquake Resistant Design and Analysis, National Science Foundation and Electric Power Research Institute Workshop, Palo Alto, California, November 8-10, 1989.

23. Shannon and Wilson, Inc., and Agbabian Associates, "Determination of Soil Liquefaction Characteristics by Large-Scale Laboratory Tests," Report No. NUREG-0027, prepared by Shannon and Wilson, Inc., Seattle, Washington, and Agbabian Associates, El Segunda, California, for the U.S. Nuclear Regulatory Commission, Washington, D.C., May, 1975.

24. Sowers, G.B. and Sowers, G.F., Introductory Soil Mechanics and Foundations, The Macmillan Company, New York, 1970.

25. Streeter, V.L., Wylie, E.B., and Richart, F.E., Jr., "Soil Motion Computations by Characteristics Method," Journal of the Geotechnical Engineering Division, Proc. ASCE, Vol. 100, No. GT3, March, 1974, pp. 247-263.

26. Woods, R.D., "Measurement of Dynamic Soil Properties," Proceedings of the ASCE Geotechnical Engineering Division Specialty Conference, Volume 1, Pasadena, CA, June 19-21, 1978.

27. Wiegel, R.L., Editor, Earthquake Engineering, Prentice-Hall, Englewood Cliffs, New Jersey, 1970.

APPENDIX A

In this appendix, we provide excerpts from our 1985 NSF Phase II SBIR proposal. Included are the sections entitled PHASE II RESEARCH OBJECTIVES, PHASE II RESEARCH PLAN, and REFERENCES.

PHASE II RESEARCH OBJECTIVES

In this section, we present the two main objectives of Phase II research.

The first objective of Phase II research is to determine the effectiveness of a laboratory research prototype testing system for determining selected cyclic and dynamic properties of a test soil under controlled conditions. The properties include cyclic degradation and liquefaction characteristics, and dynamic shear moduli. We will determine the effectiveness of the prototype system by comparing soil properties determined using the prototype system to soil properties determined from comparable conventional laboratory tests. If the properties agree acceptably, if the repeatability of test results is good, if we do not observe major limitations in the testing procedure, and if we do not encounter excessive difficulties in the application of the testing procedure, then we will conclude that the proposed testing procedure is an effective means for determining the properties of interest under controlled laboratory conditions.

Assuming Phase II research proves the proposed testing procedure to be promising, the second main objective of Phase II research would be to define the future research and development needed to realize the full potential of the procedure. We will define future research and development needs by carefully reviewing the results of our Phase II work to identify areas where meaningful improvements are possible.

PHASE II RESEARCH PLAN

In this section, we discuss in detail the main aspects of the research that we are planning for Phase II. We discuss both the main procedures of the research and the major tasks and subtasks required to carry out the proposed work. We also provide a performance schedule. Our principal investigator will be responsible for all Phase II work and will perform, with guidance from our technical advisor, the research to be carried out by our firm. The procedures, tasks, and subtasks are discussed in the following subsections.

Procedures

In this subsection, we discuss the main procedures required to satisfy the main objectives of Phase II research (see PHASE II RESEARCH OBJECTIVES, p. 24).

To determine the effectiveness of the laboratory research prototype testing system, we will basically compare soil properties determined using the prototype system to soil properties determined from conventional laboratory tests. The laboratory tests conducted using the prototype system will be carefully controlled. Test soil conditions will be varied to vary the soil properties of interest. Applied loads will be selected to induce behaviors of interest. Properties will be inferred from prototype test results using soil-probe interaction analyses. An intermediate level analysis procedure will be used for preliminary and intermediate estimates of soil properties while a more refined procedure will be used for check purposes and more refined estimates. At the same time, corresponding soil properties will be determined from the results of carefully controlled conventional laboratory tests conducted under test conditions comparable to those of the prototype tests. Properties determined using the two different methods will be compared. Agreement, repeatability, and any observed limitations or difficulties encountered will be noted. Comparative testing, rather than relying on published test data, is required to insure consistency in sample preparation and to obtain necessary detailed information such as the histories of shear strain and excess porewater pressure. We will also compare results from prototype tests with published test data when possible. Finally, we will review all results. Based on agreement, repeatability, and any observed limitations or difficulties encountered, we will draw our conclusions concerning the effectiveness of the proposed testing procedure for determining the soil properties of interest.

Since the proposed testing procedure is a new approach and so that our Phase II research will be as effective as possible, we propose to study only the essential characteristics of the testing system. Using the simplest configuration of the testing system, we will vary only those test conditions which must be varied to effectively establish the fundamental behavior of the system. Broader testing, refinements, and limitations will be emphasized during later stages of research and development.

With the simplest configuration of the testing system, the only variables to be measured during testing will be the torque applied to the inner cylinder and the resulting rotational motion of the inner cylinder. These measurements are required to establish the effectiveness of the testing system. Also, the simplest configuration will feature the simpler of the two vertical pressure systems being considered (see Technical Approach, pp. 14-15). This system will be capable of imposing on the test soil a state of stress corresponding to that developed in a normally consolidated, horizontally layered deposit of soil. This is a practical state of stress and behavior under other states of stress may be roughly estimated from behavior under this state of stress.

Testing conditions, such as the type of soil and test pressures, will be limited. We plan to only test sand. Sand is the easiest soil to work with in a laboratory and a broad range of soil properties may be readily obtained with sand. By varying the relative density of the sand and selectively varying the confining pressure acting on the sand, we will be able to cover reasonably well the behaviors expected from most soils during earthquakes. For tests to determine the effectiveness of the testing system for determining cyclic degradation and liquefaction characteristics, we will only vary relative density. Thus, while we will vary cyclic degradation and liquefaction characteristics over a broad range, we will not study the effects of confining pressure on degradation and liquefaction characteristics. Basic degradation and liquefaction characteristics are not expected to vary qualitatively a great deal with confining pressure. Also, the pressure of the porewater prior to testing will be limited to that needed to develop an adequate degree of saturation. Thus, initial porewater pressures are to correspond to those which would be encountered in onshore testing.

To define future research and development needed to realize the full potential of the proposed testing procedure, we will carefully review the results of our Phase II work. Areas in which meaningful improvements are expected to be possible will be identified.

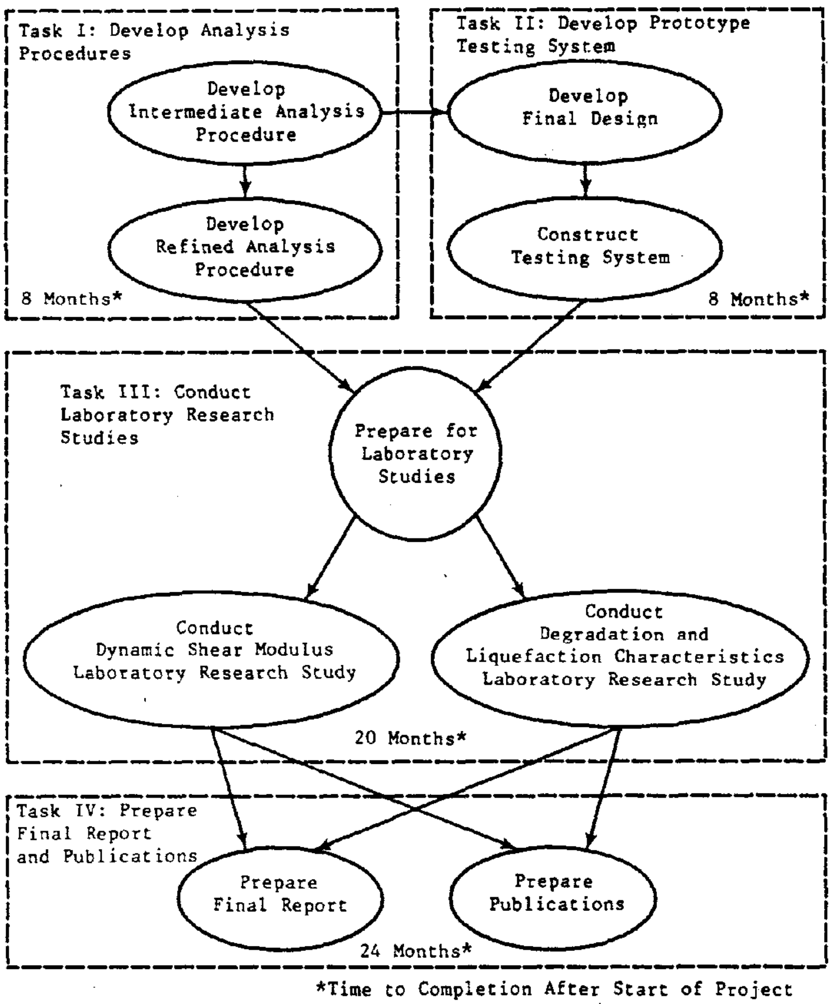


Figure 6: Flow Chart Showing Tasks and Subtasks of Phase II Work

Major Tasks

In this subsection, we discuss the major tasks which will make up Phase II work. As shown in Fig. 6, there are four major tasks: I) Develop Analysis Procedures, II) Develop Prototype Testing System, III) Conduct Laboratory Research Studies, and IV) Prepare Final Report and Publications. Figure 6 also includes a performance schedule. The four major tasks are subdivided into subtasks, as shown in Fig. 6, and these are discussed in detail in the subsections that follow this subsection.

For Task I, we will develop two main analysis procedures: an intermediate soil-probe interaction analysis procedure and a refined soil-probe interaction analysis procedure. The intermediate procedure is required to develop an effective final design of the laboratory research prototype testing system. The intermediate analysis procedure is also needed to make initial estimates of soil properties from results of tests using the prototype system. The intermediate procedure will model many important aspects of tests but will also involve a number of significant assumptions and simplifications. The refined analysis procedure will be developed so that soil properties may be inferred more accurately. In practice, most of the modeling of a test would be carried out using the simpler, less costly intermediate procedure. Then, the refined analysis procedure would be used to check and refine initial estimates of soil properties. Task I should be complete 8 months following the start of the project.

For Task II, a laboratory research prototype testing system will be developed. The probe of this system is expected to be identical to that of the field system to be developed during Phase III; however, some components which are not expected to affect test results, such as a drillbit latching system, will not be included in the laboratory system. First, a final design of the prototype system will be developed by an outside mechanical engineering firm. Our firm does not have the expertise or manpower required for this work. This design will be a revision of the preliminary design developed as part of Phase I research. Then, a prototype, based on the final design, will be constructed by the mechanical engineering firm. Task II should be complete 8 months following the start of the project.

For Task III, the main task of Phase II, we will prepare for and conduct laboratory research studies. We will conduct a study to determine the effectiveness of the laboratory research prototype testing system for determining cyclic degradation and liquefaction characteristics and a study to determine the effectiveness of the system for determining dynamic shear moduli. Each study will involve the comparison of soil properties determined from prototype test results and soil properties determined from the results of corresponding conventional laboratory tests. The conventional tests will be conducted by an outside organization since our firm does not have the equipment or staff to conduct this work. Task III should be complete 20 months following the start of the project.

For Task IV, we will publish the results of our work. We will prepare a final report covering, in detail, all Phase II work. Reports covering work carried out by outside organizations will be attached to the final report. Additionally, we will prepare two publications summarizing our research. One publication will cover the study concerning cyclic degradation and liquefaction characteristics and the second publication will cover the study concerning dynamic shear moduli. The report and publications will be complete 24 months following the start of the project.

Subtasks of Task I

As indicated in Fig. 6, for Task I we will develop the analysis procedures required for Phase II work. Task I will be part of an ongoing staged development. During Phase I we developed procedures which were more approximate than those which will be developed during Phase II. Likewise, procedures developed after Phase II will be more refined than those developed as part of Phase II research. During Phase II, we plan to develop the analytical capabilities which are judged to be most important and reasonably within the state-of-the-art. We will simplify procedures where necessary and will refine procedures only as needed.

As indicated in Fig. 6, there are two main subtasks of Task I: 1) Develop Intermediate Analysis Procedure and 2) Develop Refined Analysis Procedure. These subtasks are discussed in the following subsections.

Develop Intermediate Analysis Procedure--An intermediate soil-probe interaction analysis procedure will be developed for two purposes. First it will be used to develop the final design criteria for the prototype testing system. Considering the estimated cost of the proposed testing system (see Estimated Total Project Costs, pp. 21-22), we concluded that the simple single-degree-of-freedom soil-probe interaction analysis procedure used to develop preliminary design criteria for the system during Phase I was inadequate for developing final design criteria. Additionally, the intermediate analysis procedure will be used to make initial estimates of soil properties from results of tests using the prototype testing system. The intermediate procedure is expected to model, with relative ease, many important aspects of prototype tests, and thus, provide reasonable accuracy. A more costly and refined analysis procedure will be developed for use in checking and refining the initial estimates of soil properties. The intermediate analysis procedure is discussed in the following paragraphs.

There are several important aspects of prototype tests which should be modeled by the intermediate analysis procedure for reasonable accuracy. The dynamic behavior of the inner cylinder, the instrumented head, and the test soil should be modeled reasonably accurately. The test soil should be modeled as a continuum. The nonlinear, inelastic, degrading stress-strain behavior of the test soil should be modeled. Also, any significant rotational flexibility of the inner cylinder should be modeled reasonably descriptively.

The basic framework of an analysis method which satisfies the requirements for the intermediate analysis procedure is described by our technical advisor, Dr. R. Henke, in References 18, 19, 20, and 21. This method was originated by Dr. Henke. Basically, the method is capable of describing the development of a dynamic, three-dimensional, axisymmetric, torsional state of stress and strain in a continuum. The continuum may be modeled as a nonlinear, inelastic material. Solutions are obtained by integrating the continuum equations describing the behavior of a modeled system in a step by step manner. Properties of the continuum are assumed to be constant during computational time intervals. The method has been applied successfully in predicting the torsional dynamic behavior of a rigid disk resting on a nonlinear, inelastic test bed (18) (19). The extension of the method to model the continuum as a degrading, nonlinear, inelastic material which may liquefy will closely follow other recent similar efforts, such as that discussed in Reference 13.

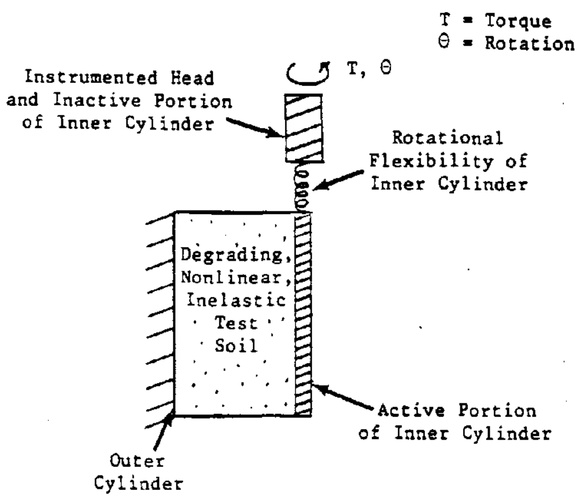


Figure 7: Schematic Diagram of Model for Intermediate Analysis Procedure

The intermediate analysis procedure will offer several features. A schematic diagram showing various elements of the model for the procedure is given in Fig. 7. The intermediate analysis procedure will describe the dynamic behavior of the test soil, the inner cylinder, and the instrumented head. The nonuniform behavior of the test soil in the radial direction will be modeled in detail. The distributed mass and stiffness of the test soil will be properly modeled by considering the test soil as a continuum. The active portion of the inner cylinder will be treated as a rigid cylinder with an appropriate lumped mass. The inactive portion of the inner cylinder and the instrumented head will be treated as a single-degree-of-freedom system consisting of a rigid mass and a linear spring. The outer cylinder will be treated as a rigid boundary. Impulse tests (see Technical Approach, p. 13) will be simulated using basic Ramberg-Osgood equations (27) to describe the nonlinear, inelastic shear stress-strain characteristics of the test soil. These equations offer good flexibility in the description of stress-strain behavior. Cyclic tests (see Technical Approach, pp. 13-14) will be simulated using a stress-strain model proposed by Martin, Finn, and Seed (24). This model describes the cyclic degradation of the shear stress-strain characteristics of a sand or silt due to a buildup in excess porewater pressure. The model also describes liquefaction of the soil. In this model, hyperbolic equations are used to describe the degrading, nonlinear, inelastic shear stress-strain characteristics of the soil. It may prove effective to modify the approach by Martin, Finn, and Seed (24), to model behavior under conditions of constant volume imposed by relatively rigid boundaries (see Technical Approach, pp. 16, 17). This modification is not expected to be excessively difficult.

As was the case for Phase I analysis procedures (see Phase I Final Report, Solution Procedures, pp. 33-36), simplifying the analysis procedures developed during Phase II may prove effective. For example, to simulate cyclic tests for which dynamic effects may be small, we may develop a static approach. Basically, dynamic effects, including effects of inertia and viscous damping, would be ignored. The static approach would be based on finite difference or finite element equations. Otherwise, modeling would be similar to that of the dynamic approach. Static equilibrium would be satisfied at selected instances during cyclic loading. Such a simplification would be expected to considerably reduce computing time and costs.

The intermediate analysis procedure will be validated using a number of methods. We will compare special linear solutions to available closed-form solutions when possible. We will use an energy balance to check nonlinear solutions (21). Additionally, we will check nonlinear solutions by examining computed stress-strain behavior. All solutions will be checked judgmentally to insure that the solutions are reasonable.

The intermediate analysis procedure will involve a number of assumptions and simplifications which may limit the accuracy obtainable. Potentially significant assumptions and simplifications include the following: uniform behavior in the vertical direction, single-degree-of-freedom system modeling of the inner cylinder, not accounting for the flow of porewater in response to induced gradients in excess porewater pressure, not accounting for all initial and test-induced nonuniformities of the test soil, not accounting for dilation, simple shear conditions to describe behavior of test soil under cyclic loading, independence of the behavior of soil with respect to the surfaces on which shear stresses develop, independence of the shear stress-strain behavior of the test soil on one surface with respect to shear stresses and strains acting on a perpendicular surface, not accounting for friction or viscous damping arising from the test apparatus or viscous damping from the test soil, and not accounting for slip.

The intermediate analysis procedure is expected to be appropriately descriptive for developing final design criteria for a laboratory research prototype testing system and for making initial estimates of soil properties from results of prototype tests. However, because of the simplifications and assumptions involved with the intermediate analysis procedure, we believe this procedure will not be adequate for accurately inferring soil properties from results of tests conducted using the prototype system. We propose to develop a refined analysis procedure to provide the accuracy required for this purpose.

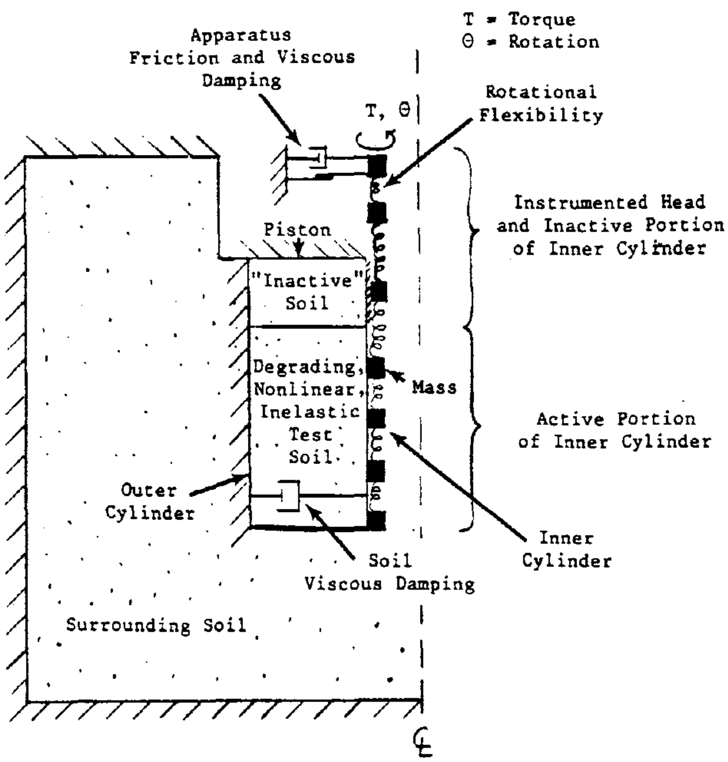


Figure 8: Schematic Diagram of Model for Refined Analysis Procedure

<u>Develop Refined Analysis Procedure</u>-- The refined soil-probe interaction analysis procedure is expected to be necessary for inferring soil properties accurately from results of tests carried out using the prototype testing system. The refined procedure will be used to check and refine soil properties estimated from prototype test results using the intermediate analysis procedure.

The refined procedure will be developed by modifying the intermediate analysis procedure. Figure 8 is a schematic diagram showing various elements of the model for the refined procedure. We will incorporate appropriate boundary conditions for the upper and lower boundaries of the test soil. This will permit the description of nonuniform behavior of the test soil in the vertical direction. We will model, in greater detail than for the intermediate procedure, the distributed mass and rotational stiffness properties of the inner cylinder and the instrumented head. This will permit more accurate descriptions of the behavior of the inner cylinder and the instrumented head and the interaction between the test soil and the inner cylinder. We will model the flow of porewater which may occur within and out of the test soil during the cyclic testing of permeable soils in the constant pressure mode (see <u>Technical Approach</u>, pp. 16, 17). Our modeling of the flow of porewater will be based on that discussed by Finn (14). We will model the friction and viscous damping that may arise from the test apparatus and the viscous damping from the test soil using lumped parameters. This level of modeling for damping and friction is expected to be sufficient to accurately infer the properties of interest. We will also model slip between the soil and appropriate components of the testing system.

The refined analysis procedure will be validated using a number of methods. We will validate special linear solutions using available closed-form solutions when possible. We will use an energy balance to check nonlinear solutions (21). Additionally, we will check nonlinear solutions by examining computed stress-strain behavior. All solutions will be checked judgmentally to insure that the solutions are reasonable.

Since the refined analysis procedure will describe many important aspects of a test, the refined analysis procedure should be effective for accurately inferring soil properties from results of tests carried out using the prototype testing system. However, we believe there will still be a potential for worthwhile improvement. For example, refinements which could be undertaken as part of future research to reduce limitations or improve accuracy include incorporating into analysis procedures more complete modeling of initial and test-induced nonuniformities and improved descriptions of soil behavior.

Subtasks of Task II

As indicated in Fig. 6, for Task II a laboratory research prototype testing system will be developed. The probe of the prototype testing system will be identical to the probe of the field unit to be developed during Phase III. However, the prototype system will not include an integral electronics package, a drillbit latching system, a downhole probe penetration system, a field cable, or a winch. These items will be included during Phase III when the prototype system is to be adapted for field use.

Since the prototype testing system will be relatively expensive and complex, we will devote considerable attention to the final design of the system. Thus, costly redesigns and time consuming problems should be minimized.

As indicated in Fig. 6, there are two subtasks under Task II: 1) Develop Final Design and 2) Construct Testing System. These subtasks are discussed in detail in the following subsections.

Develop Final Design--To develop a final design of the laboratory research prototype testing system we will first complete the preliminary design of the system. The preliminary design is discussed in detail in our Phase I Final Report. Then, we will reanalyze and, if necessary, revise the preliminary design.

To complete the preliminary design, we will re-evaluate and possibly modify existing features, and also design components or features not strongly considered during Phase I. The completion of the preliminary design is discussed in the PROPRIETARY INFORMATION section, page 54.

Construct Testing System--The construction of the testing system will involve several steps. First, components such as transducers and motors will be ordered from appropriate manufacturers. Components requiring modifications, such as the motors and angular displacement transducers (see Phase I Final Report, Appendix C, pp. 18-20 and 25-26), will be appropriately modified. Appropriate machining will be carried out and then the laboratory research prototype testing system will be assembled.

Subtasks of Task III

As indicated in Fig. 6, for Task III, the main task of Phase II work, we will conduct laboratory research studies. A study will be conducted to determine the effectiveness of the prototype testing system for determining cyclic degradation and liquefaction characteristics and a study will be conducted to determine the effectiveness of the system for determining dynamic shear moduli. The basic procedure for both studies is presented and discussed in the subsection entitled Procedures, pp. 25-26. Briefly, in each study we will compare soil properties determined from results obtained using the prototype testing system and soil properties determined from the results of corresponding conventional laboratory tests. Additionally, we will make use of available published test data when possible. For each study we will conduct only the number of precisely controlled tests necessary to meet the stated objectives.

As indicated in Fig. 6, there are three subtasks under Task III: 1) Prepare for Laboratory Studies, 2) Conduct Dynamic Shear Modulus Laboratory Research Study, and 3) Conduct Degradation and Liquefaction Characteristics Laboratory Research Study. These subtasks are discussed in the following subsections.

Prepare for Laboratory Studies--The main steps in preparing for the laboratory research studies will be to calibrate the transducers used in tests and to develop a methodology for preparing test beds.

We intend to calibrate or have calibrated all transducers used in testing. Transducers will be used in the testing system itself and in the test chamber, which will contain the test beds. For the calibrations, we will try to reproduce the test environment of the transducers as closely as possible. Calibrations will be checked at appropriate intervals during Phase II research.

Developing a methodology for preparing test beds will involve establishing techniques for the various steps in preparing test beds and procedures for determining test bed characteristics. With the test chamber, we plan to be able to 1) permeate the test bed with carbon dioxide and apply a back pressure to the porewater of the test soil to help saturate the soil, 2) apply a vertical pressure to the test bed to simulate effects of overburden, 3) induce a lateral state of stress in the test bed corresponding to that expected in a normally consolidated, horizontally layered soil deposit, and 4) simulate roughly the creation of a borehole. The test bed will consist of Monterey No. 0 sand. This type of sand was used in large scale tests for determining initial liquefaction characteristics (33). We plan to compare published results from these tests to results from our tests. We will establish techniques for depositing the test soil at the desired relative density, trimming the test soil, and permeating the test soil with carbon dioxide. We will also establish pressurization sequences and durations. References 5, 26, and 33 offer possible approaches to several of these steps. We will also establish procedures for determining the vertical and horizontal uniformity and the relative density of the test bed before and after application of the ultimate vertical pressure to the test soil, the repeatability of the relative density of the test bed, and the degree of saturation of and the lateral stress within the test bed. References 5 and 26 offer possible approaches to several of these steps.

Conduct Dynamic Shear Modulus Laboratory Research Study--In this subsection, we discuss the steps planned for the dynamic shear modulus laboratory research study. We present and discuss expected results and discuss aspects of this study which will be reviewed to develop conclusions.

The dynamic shear modulus study will be conducted using the general procedure described in the subsection entitled Procedures, pp. 25-26. Basically, dynamic shear moduli determined from tests conducted for a range of test conditions using the laboratory research prototype testing system will be compared to dynamic shear moduli determined from tests conducted under comparable conditions using resonant column apparatus. Comparative results will be obtained from resonant column tests because resonant column testing gives reliable results for laboratory samples, is widely accepted, and is readily available.

A broad range of soil conditions will be considered. Relative densities will be varied from low to high. This will help provide a broad range of low amplitude dynamic shear moduli and variations in the dynamic shear modulus with shear strain. This will also allow us to study the effects of disturbance due to penetration of the probe over a broad range of disturbances, since penetration of the probe into a test bed having high relative density is expected to dilate the test soil while penetration into a test bed having low relative density is expected to densify the test soil. Confining pressures will also be varied over a broad range. This will also help provide a broad range of low amplitude dynamic shear moduli and variations in dynamic shear modulus with shear strain. Additionally, this will help us identify any operational limitations due to confining pressure. We will impose a state of stress in the test bed corresponding to that developed in normally consolidated, horizontally layered deposits. This is a practical as well as simple state of stress. The soil will be saturated for consistency with cyclic degradation and liquefaction characteristics tests.

A broad range of loading conditions, required to provide the information of interest, will be considered. Load amplitudes will be varied from low to high to obtain dynamic shear moduli over a broad range of strain.

REPEATABILITY TESTS			REMAINING TESTS		
Number of Tests	Relative Density	Confining Pressure	Number of Tests	Relative Density	Confining Pressure
3	low	low	1	high	medium
3	high	low	1	medium	low
3	low	high	1	medium	medium
3	high	high	1	medium	high
			1	low	medium

Table 1: Testing Program - Dynamic Shear Modulus Study

The proposed testing program is designed to determine the repeatability of tests and to cover adequately the range of shear moduli of interest. The testing program for the comparative tests will be the same as that for the prototype tests. As indicated in Table 1, the program includes twelve tests which will be carried out for the extremes of soil conditions to determine repeatability. Five additional tests will be carried out for intermediate soil conditions to adequately cover the range of shear moduli of interest.

Two main parameters will be studied: the low amplitude dynamic shear modulus and the variation in the dynamic shear modulus with shear strain. We may also study equivalent viscous damping ratios.

The expected character of test results is shown in Figs. 9 and 10. Figure 9 presents the expected relationship between the low amplitude dynamic shear modulus, G_o, and the confining pressure, $\bar{\sigma}_o$, for bounding conditions. Figure 10 presents the expected relationship between the ratio of the dynamic shear modulus, G, to the low amplitude dynamic shear modulus and the shear strain, γ, for bounding conditions. Figures 9 and 10 are included here for illustrative purposes only. More revealing forms of presentation may be used in the actual shear modulus study, especially for the variation in shear modulus with shear strain.

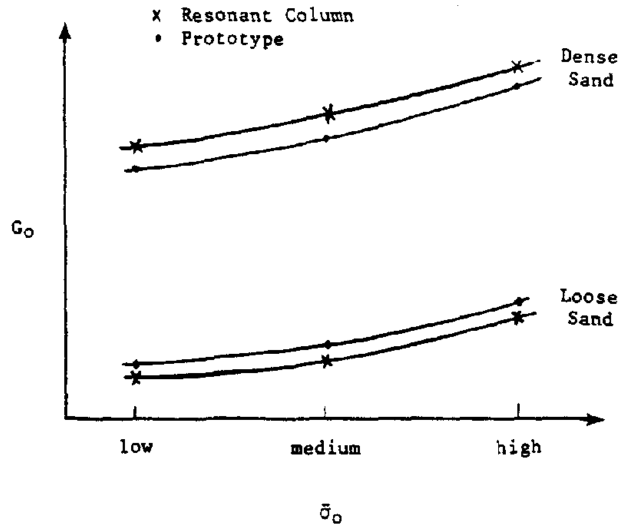


Figure 9: Selected Expected Results - Dynamic Shear Modulus Laboratory Research Study

As shown in Fig. 9, we expect greater low amplitude dynamic shear moduli with higher relative densities and higher confining pressures. Differences between properties obtained using the prototype testing system and properties obtained from resonant column tests may arise from several sources. Figure 9 indicates the nature of the differences which may occur as a result of disturbance to the test soil due to the penetration of the probe of the prototype testing system into the test soil. When testing a dense sand, which would be expected to dilate as a result of penetration, we would expect to underestimate the low amplitude dynamic shear modulus. When testing a loose sand, which would be expected to densify as a result of penetration, we would expect to overestimate the low amplitude dynamic shear modulus.

As shown in Fig. 10, we expect a decrease in the ratio of the dynamic shear modulus to the low amplitude dynamic shear modulus with an increase in shear strain. Differences between properties obtained using the prototype testing system and properties obtained from resonant column tests may arise from several sources. Figure 10 presents an example of the differences which might occur as a result of disturbance to the test soil due to the penetration of the probe. When testing a dense sand, which would be expected to dilate as a result of penetration, we might underestimate the ratio of the dynamic shear modulus to the low amplitude dynamic shear modulus. When testing a loose sand, which would be expected to densify as a result of penetration, we might overestimate the ratio of the dynamic shear modulus to the low amplitude dynamic shear modulus. The actual nature and extent of the differences will depend on the relative effect of the disturbance on the numerator and denominator of the plotted ratio.

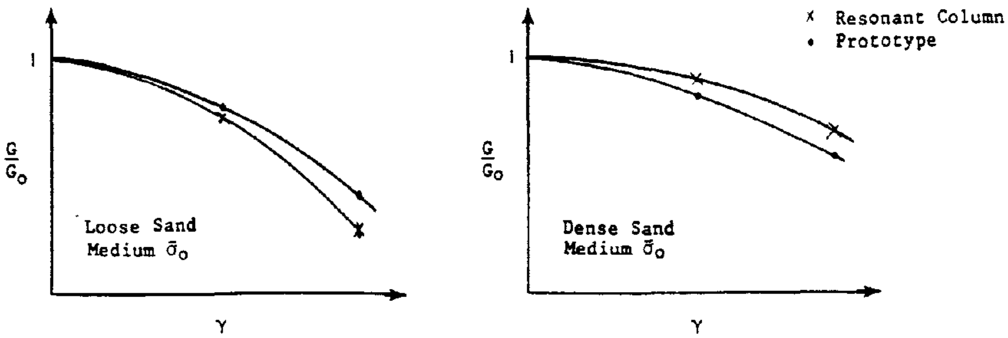


Figure 10: Selected Expected Results - Dynamic Shear Modulus Laboratory Research Study

In general, we do not expect excessive differences between properties determined from results of prototype tests and those determined from results of resonant column tests, nor do we expect excessive scatter in properties obtained using the prototype testing system. We may observe greater differences and greater scatter when testing sands having higher relative densities at higher confining pressures. This may occur because the inner cylinder may be rotationally more flexible relative to the test soil under these conditions (see Phase I Final Report, Supplementary Theoretical Feasibility Study, pp. 63-69). Also, we expect better agreement between properties obtained from prototype tests and properties obtained from resonant column tests when using the refined analysis procedure to infer soil properties from results of prototype tests than when using the intermediate analysis procedure.

Several aspects of the dynamic shear modulus research study will be addressed in the review and discussion of the study. We will address the repeatability of test results and the agreement between properties obtained using the prototype testing system and properties obtained using resonant column apparatus. The relationships of repeatability and agreement to test conditions and level of soil-probe interaction analysis used will be addressed along with potential steps for improving agreement and repeatability. We will identify any limitations of the prototype testing procedure observed during testing and discuss potential improvements. Possible limitations may include mechanical, excitation, measurement, and analysis limitations. We will also discuss any difficulties encountered and possible resolutions. Possible difficulties include mechanical, excitation, measurement, and analysis difficulties.

Our research should lead to two main conclusions: a conclusion concerning the effectiveness of the prototype testing system for determining dynamic shear moduli and a conclusion concerning future research and development needs. The conclusions will relate directly to the objectives of Phase II research. The conclusion concerning the effectiveness of the prototype system will be based on the agreement between properties obtained from prototype tests and properties obtained from resonant column tests, the repeatability of results from prototype tests, and any observed limitations or difficulties encountered when using the proposed testing procedure. The conclusion concerning future research and development needs will be based on the identification of areas in which meaningful improvements are possible.

Conduct Degradation and Liquefaction Characteristics Laboratory Research Study--In this subsection, we discuss the steps planned for the degradation and liquefaction characteristics laboratory research study. We present and discuss expected results and discuss aspects of this study which will be reviewed to develop conclusions.

The degradation and liquefaction characteristics study will be conducted using the general procedure described in the subsection entitled Procedures, pp. 25-26. Basically, degradation and liquefaction characteristics determined from tests conducted for a range of test conditions using the laboratory research prototype testing system will be compared to degradation and liquefaction characteristics determined from tests conducted under comparable conditions using laboratory cyclic simple shear apparatus or, if arrangements can be made, cyclic torsional shear apparatus. Comparative results will be obtained by cyclic simple shear or cyclic torsional shear tests because these tests provide results which are in reasonable agreement with results from large scale tests (33), allow the simulation of the normal state of stress developed in normally consolidated, horizontally layered deposits, and simulate a state of simple shear directly. In addition, the cyclic simple shear test is readily available. The cyclic torsional shear test (41), which is not as readily available as the cyclic simple shear test, avoids some of the nonuniformities which may develop within a sample during a cyclic simple shear test.

A broad range of soil conditions will be considered. Relative densities will be varied from low to high. This will provide a broad range of degradation and liquefaction characteristics. This will also allow us to study the effects of disturbance due to penetration of the probe over a broad range of disturbances, since, as stated in the discussion of the dynamic shear modulus study, penetration of the probe into a test bed having high relative density is expected to dilate the test soil while penetration into a test bed having low relative density is expected to densify the test soil. In contrast to the dynamic shear modulus study, confining pressure will not be varied. Unlike a dynamic shear modulus test, which can be conducted at successively higher loads without excessively disturbing the test soil, normally a degradation and liquefaction characteristics test can be conducted meaningfully only at a single load level. After a single test at a specified load level, the test soil will have been altered significantly. Thus, a large testing program would be required to vary load level, relative density, and confining pressure. Testing at a single value of confining pressure, we will be able to capture the range of the basic behaviors of the testing system. The basic behaviors, expected to range between behavior when testing a highly liquefiable sand and when testing a nonliquefiable sand (see Fig. 3), are not expected to vary greatly with confining pressure. We will consider the intermediate, representative level of confining pressure corresponding to that used in a series of large scale tests (33). This will enable us to effectively compare results from our tests with results from the large scale tests. Similar to the dynamic shear modulus tests, we will impose a normal state of stress in the test bed corresponding to that developed in normally consolidated, horizontally layered deposits. This is a practical as well as a simple state of stress. The test bed will be fully saturated so that degradation and liquefaction can be induced in the test soil when testing in the constant pressure mode (see Technical Approach, p. 16).

A broad range of loading conditions, required to provide the information of interest, will be considered. Load amplitude, designated as applied shear stress ratio (applied shear stress amplitude, τ, divided by the initial effective vertical stress, $\bar{\sigma}_{vi}$), will be varied from low to high.

The proposed testing program is designed to determine the repeatability of tests and to cover adequately the range of cyclic degradation and liquefaction characteristics of interest. However, first we will conduct preliminary tests using the laboratory prototype testing system to establish the most effective testing mode, constant volume or constant pressure (see Technical Approach, p. 17), and to determine the most effective excitation frequency. The main testing program for the comparative tests will be the same as that for the prototype tests. As indicated in Table 2, the program includes twelve tests which will be carried out for the extremes of soil conditions to

REPEATABILITY TESTS

Number of Tests	Relative Density	Stress Ratio
3	low	low
3	high	low
3	low	high
3	high	high

REMAINING TESTS

Number of Tests	Relative Density	Stress Ratio
1	high	medium
1	medium	low
1	medium	medium
1	medium	high
1	low	medium

Table 2: Testing Program - Degradation and Liquefaction Characteristics Study

determine repeatability. Five additional tests will be carried out for intermediate soil conditions to adequately cover the range of cyclic degradation and liquefaction characteristics of interest.

Several parameters will be studied: the cyclic degradation of shear modulus, the buildup in excess porewater pressure, and the cyclic increase in strain amplitude. For the comparisons, results from prototype tests will be converted to equivalent undrained simple shear results. A simple, but effective, single-degree-of-freedom system (SDOF) model will be constructed for this purpose. A somewhat similar conversion was made in the Phase I studies (see Phase I Final Report, Degradation and Liquefaction Characteristics of Sands and Silts, p. 53). Basically, appropriate parameters will be inferred from prototype test results using the soil-probe interaction analysis procedures. These parameters will then be used in the SDOF model to give equivalent undrained simple shear results.

The expected character of test results is shown in Figs. 11, 12, and 13. Figure 11 presents the expected relationship between the ratio of the current degraded secant shear modulus, G_{SN}, to the undegraded secant shear modulus determined from the first cycle of loading, G_{S1}, and the number of cycles of loading, N. Figure 12(a) presents the expected relationship between the excess porewater pressure ratio (excess porewater pressure, u, divided by the initial effective vertical stress) and the number of cycles of loading, and Fig. 12(b) presents the expected relationship between the applied shear stress ratio and the number of cycles of loading for the test soil to develop either initial liquefaction (effective vertical stress = 0) or a shear failure (applied shear stress ≥ degraded shear strength). Figure 13(a) presents the expected relationship between the shear strain amplitude, γ_A, and the number of cycles of loading and Fig. 13(b) presents the expected relationship between the applied shear stress ratio and the number of cycles of loading required for the test soil to develop a strain amplitude of 0.5%. All expected results are presented for bounding conditions. Expected results are not presented in Fig. 13(a) for conditions under which dilation will have a significant effect since we will not have the capability to accurately model dilation during Phase II. Other forms of presentation will be considered.

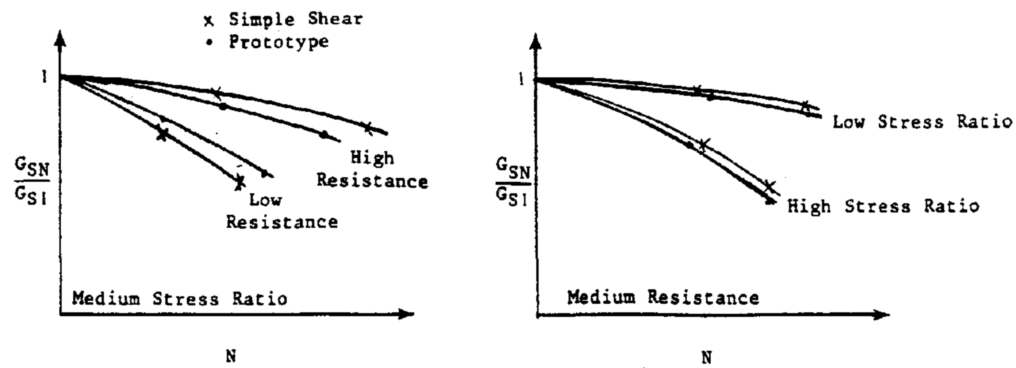
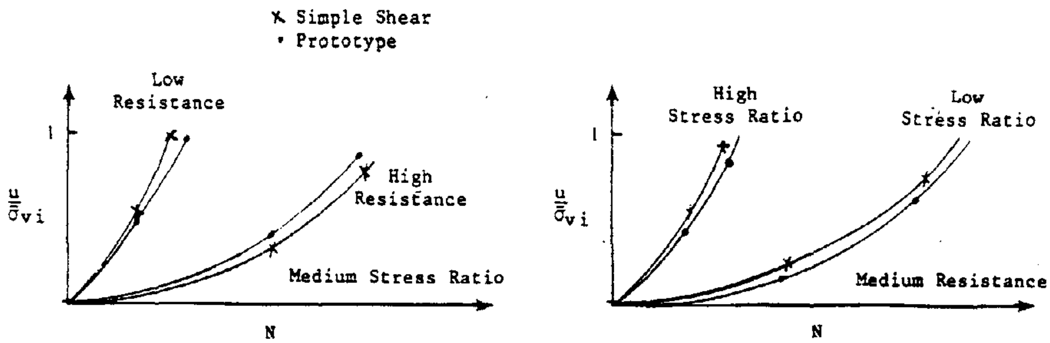
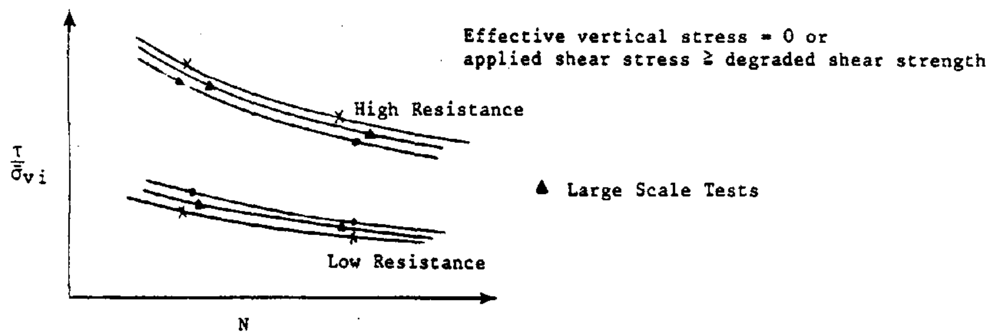


Figure 11: Selected Expected Results - Degradation and Liquefaction Characteristics Laboratory Research Study

As shown in Fig. 11, we expect the ratio of the degraded shear modulus to the undegraded shear modulus to decrease with an increase in the number of cycles of loading. We expect more rapid decreases when testing more easily degradable sands and when testing at higher applied shear stress ratios. Similar to the dynamic shear modulus study, differences between results obtained using the prototype testing system and results obtained from cyclic simple shear or cyclic torsional shear tests may arise from several sources. Figure 11 indicates the nature of the differences which may occur as a result of disturbance to the test soil due to the penetration of the probe of the prototype testing system into the test soil. When testing a dense sand (high resistance to degradation and liquefaction), which would be expected to dilate as a result of penetration, we would expect to underestimate the resistance of the sand to cyclic degradation. When testing a loose sand (low resistance to degradation and liquefaction), which would be expected to densify as a result of penetration, we would expect to overestimate the resistance of the sand to cyclic degradation.



(a) Excess Porewater Pressure Ratio vs Number of Cycles of Loading



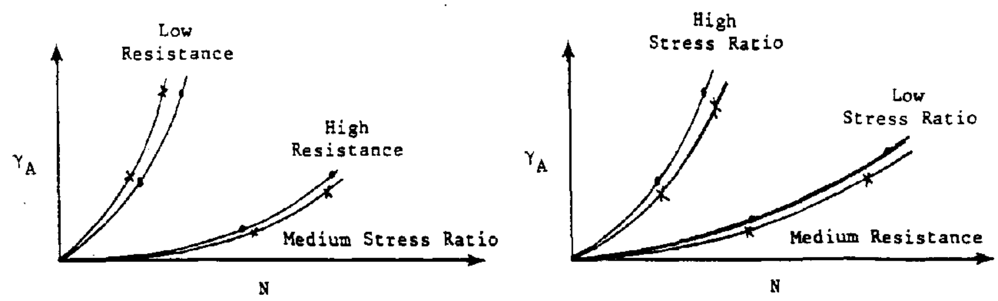
(b) Shear Stress Ratio vs Number of Cycles of Loading to Initial Liquefaction or Shear Failure

Figure 12: Selected Expected Results - Degradation and Liquefaction Characteristics Laboratory Research Study

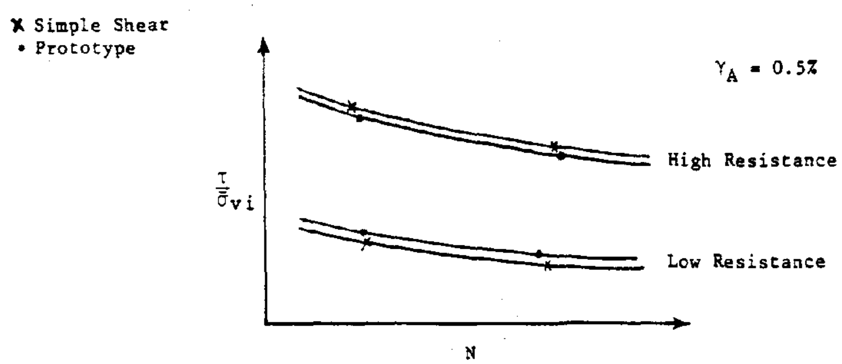
As shown in Fig. 12, we expect an increase in the excess porewater pressure ratio with an increase in the number of cycles of loading. We expect a more rapid increase when testing sands with lower resistance to degradation and liquefaction and when testing at higher applied shear stress ratios. Again, we expect some differences between results obtained using the prototype testing system and results obtained from cyclic simple shear or cyclic torsional shear tests. Due to the nature of the expected penetration-induced disturbance, which has been previously discussed, when testing with the prototype system, we expect to overestimate the increase in excess porewater pressure ratio when testing dense sands and to underestimate this increase when testing loose sands. As shown in Fig. 12(b), as a result of penetration-induced disturbances, we expect the number of cycles of loading required to cause initial liquefaction or shear failure to be underestimated when testing a dense sand using the prototype testing system and overestimated when testing a loose sand.

As shown in Fig. 13, we expect the shear strain amplitude to increase with an increase in the number of cycles of loading. We expect more rapid increases when testing soils less resistant to degradation and liquefaction and when testing at higher applied shear stress ratios. Again, we expect some differences between results from prototype tests and results from cyclic simple shear or cyclic torsional shear tests. Figure 13 indicates the nature of the differences which may occur due to penetration-induced disturbances. Due to penetration-induced dilation, we expect to overestimate the increase in shear strain amplitude when testing dense sands with the prototype system. Due to penetration-induced densification, we expect to underestimate the increase in shear strain amplitude when testing loose sands with the prototype system. As shown in Fig. 13(b), as a result of penetration-induced disturbances, we expect the number of cycles of loading required for the test soil to develop a shear strain amplitude of 0.5% to be underestimated when testing a dense sand and to be overestimated when testing a loose sand.

In general, we do not expect excessive differences between properties obtained from prototype tests and properties obtained from cyclic simple shear or cyclic torsional shear tests, nor do we expect excessive scatter in results obtained using the prototype



(a) Shear Strain Amplitude vs Number of Cycles of Loading



(b) Shear Stress Ratio vs Number of Cycles of Loading to $\gamma_A = 0.5\%$

Figure 13: Selected Expected Results - Degradation and Liquefaction Characteristics Laboratory Research Study

testing system. We may observe greater differences and greater scatter when testing denser sands at lower stress ratios. This may occur because the inner cylinder may be rotationally more flexible relative to the test soil under these conditions (see Phase I Final Report, <u>Supplementary Theoretical Feasibility Study</u>, pp. 63-69). Also, we expect better agreement between properties obtained from prototype tests and properties obtained from cyclic simple shear or cyclic torsional shear tests when using the refined analysis procedure to infer soil properties from results of prototype tests than when using the intermediate analysis procedure.

Several aspects of the degradation and liquefaction characteristics study will be addressed in the review and discussion of the study. As with the dynamic shear modulus study, we will address the repeatability of prototype test results and the agreement between the properties obtained from prototype tests and the properties obtained from cyclic simple shear or cyclic torsional shear tests. The relationships of repeatability and agreement to test conditions and level of soil-probe interaction analysis used will be addressed along with potential steps for improving agreement and repeatability. We will identify any limitations of the prototype testing procedure observed during testing and discuss potential improvements. Possible limitations may include mechanical, excitation, measurement, and analysis limitations. We will also discuss any difficulties encountered and possible resolutions. Possible difficulties include mechanical, excitation, measurement, and analysis difficulties.

Our research should lead to two main conclusions: a conclusion concerning the effectiveness of the prototype testing system for determining cyclic degradation and liquefaction characteristics and a conclusion concerning future research and development needs. The conclusions will relate directly to the objectives of Phase II research. The conclusion concerning the effectiveness of the prototype system will be based on the agreement between properties obtained from prototype tests and properties obtained from cyclic simple shear or cyclic torsional shear tests, the repeatability of results from prototype tests, and any observed limitations or difficulties encountered when using the proposed testing procedure. The conclusion concerning future research and development needs will be based on the identification of areas in which meaningful improvements are possible.

Subtasks of Task IV

As indicated in Fig. 6, for Task IV we will document the work completed during Phase II. All aspects of Phase II work will be presented and discussed in detail in a comprehensive final report. Most important aspects of the research will be summarized in two planned publications.

There are two subtasks under Task IV: 1) Prepare Final Report and 2) Prepare Publications. These subtasks are discussed in detail in the following subsections.

Prepare Final Report--This subtask involves the documentation of all Phase II work. We will present and discuss, in detail, existing methods, the proposed method, the objectives of Phase II research, research procedures, tests and test results, and conclusions. We will also identify and discuss possible future work. We will attach to our final report any reports prepared by subcontractors. These reports may include a report on the design and construction of the prototype testing system, a report on the comparative dynamic shear modulus tests, and a report on the comparative cyclic degradation and liquefaction characteristics tests.

Prepare Publications--This subtask involves summarizing the most important aspects of Phase II research in two technical publications. One publication will summarize aspects of the dynamic shear modulus study and the other publication will summarize aspects of the cyclic degradation and liquefaction characteristics study. Each publication will include presentations and discussions of the testing system, prototype and comparative tests, actual comparisons, and conclusions.

REFERENCES

1. Anderson, D.G. and Espana, C., "Evaluation of In Situ Testing Methods for High-Amplitude Dynamic Property Determination," prepared by Fugro, Inc., Long Beach, California, for the Electric Power Research Institute, EPRI NP-920, November, 1978.

2. Arulmoli, K., Arulanandan, K., and Seed, H.B., "A New Method for Evaluating Liquefaction Potential," Journal of Geotechnical Engineering, Proc. ASCE, Vol. 111, No. 1, Jan., 1985, pp. 95-114.

3. Briaud, J.-L., Lytton, R.L., and Hung, J.-T., "Obtaining Moduli from Cyclic Pressuremeter Tests," Journal of Geotechnical Engineering, Proc. ASCE, Vol. 109, No. 5, May, 1983, pp. 657-665.

4. Briaud, J.-L. and Meyer, B., "In Situ Tests and Their Application in Offshore Design," Proceedings of the Conference on Geotechnical Practice in Offshore Engineering, ASCE Specialty Conference, Univ. of Texas, Austin, Texas, April 27-29, 1983, pp. 244-266.

5. Castro, G., Shields, D.R., and France, J.W., "Field Index Test for Estimating Liquefaction Potential," Report No. NSF/CEE-82122, prepared by Geotechnical Engineers, Inc., Winchester, MA, for the National Science Foundation, Mar., 1982.

6. Clough, R.W. and Penzien, J., Dynamics of Structures, McGraw-Hill, Inc., New York, 1975.

7. Crandall, S.H., Dahl, N.C., and Lardner, T.J., An Introduction to the Mechanics of Solids, McGraw-Hill, Inc., New York, 1972.

8. Davidson, J.L. and Boghrat, A., "Displacements and Strains Around Probes in Sand," Geotechnical Practice in Offshore Engineering, ASCE Specialty Conference, University of Texas, Austin, Texas, April 27-29, 1983, pp. 181-202.

9. De Alba, P., Baldwin, K., Janoo, V., Roe, G., and Celikkol, B., "Elastic-Wave Velocities and Liquefaction Potential," Geotechnical Testing Journal, GTJODJ, Vol. 7, No. 2, June, 1984, pp. 77-87.

10. De Domenico, U.S. Patent 4,353,247, Awarded 1982.

11. Dobry, R., Stokoe, K.H., Ladd, R.S., and Youd, T.L., "Liquefaction Susceptibility from S-Wave Velocity," ASCE Convention and Exposition, Preprint No. 81-544-1, October 26-31, 1981.

12. Esashi, Y., Yoshida, Y., and Nishi, K., "An Exploratory Method for Dynamic Properties of Ground Through Borehole Wall," Sixth World Conference on Earthquake Engineering, Vol. 6, New Delhi, India, Jan., 1977, pp. 147-152.

13. Finn, W.D.L., "Soil Liquefaction: Recent Developments in Practice," Soil Dynamics and Earthquake Engineering, Proceedings, 2nd International Conference on Soil Dynamics and Earthquake Engineering, on board the ocean liner Queen Elizabeth 2, sailing from New York to Southampton, June/July, 1985, pp. 1-43.

14. Finn, W.D.L., "Dynamic Response Analyses of Saturated Sands," Soil Mechanics-Transient and Cyclic Loads, John Wiley and Sons, New York, 1982, pp. 105-131.

15. Finn, W.D.L., Bhatia, S.K., and Pickering, D.J., "The Cyclic Simple Shear Test," Soil Mechanics-Transient and Cyclic Loads, John Wiley and Sons, New York, 1982, pp. 583-607.

16. Hardin, B.O., U.S. Patent 3,643,498, Awarded 1971.

17. Hardin, B.O. and Drnevich, V.P., "Shear Modulus and Damping in Soils: Design Equations and Curves," Journal of the Soil Mechanics and Foundations Division, Proc. ASCE, Vol. 98, No. SM7, July, 1972, pp. 667-692.

18. Henke, R., "Numerical Procedure for Predicting the Torsional Dynamic Response of Solid Media," dissertation presented to the University of Michigan, Ann Arbor, MI, in partial fulfillment of the requirements for the degree of Doctor of Philosophy, 1980.

19. Henke, R., Richart, F.E., Jr., and Woods, R.D., "Nonlinear Torsional Dynamic Response of a Footing," Journal of Geotechnical Engineering, Proc. ASCE, Vol. 109, No. 1, January, 1983, pp. 72-88.

20. Henke, R. and Wylie, E.B., "Torsional Dynamic Response of Solid Media," Journal of the Engineering Mechanics Division, Proc. ASCE, Vol. 108, No. EM1, Feb., 1982, pp. 73-94.

21. Henke, R., Wylie, E.B., and Richart, F.E., Jr., "Torsional Dynamic Response of Solid Systems," Journal of the Engineering Mechanics Division, Proc. ASCE, Vol. 108, No. EM6, December, 1982, pp. 1067-1085.

22. Idriss, I.M., Dobry, R., and Singh, R.D., "Nonlinear Behavior of Soft Clays During Cyclic Loading," Journal of the Geotechnical Engineering Division, Proc. ASCE, Vol. 104, No. GT12, December, 1978, pp. 1427-1447.

23. Idriss, I.M., Dobry, R., Singh, R.D., and Doyle, E.H., "Behavior of Soft Clays under Earthquake Loading Conditions," Proceedings, Offshore Technology Conference, OTC 2671, Dallas, Texas, 1976.

24. Martin, G.R., Finn, W.D.L., and Seed, H.B., "Fundamentals of Liquefaction under Cyclic Loading," Journal of the Geotechnical Engineering Division, Proc. ASCE, Vol. 101, No. GT5, May, 1975, pp. 423-437.

25. Martin, G.R., Lam, I.P., McCaskie, S.L., and Tsai, C.-F., "A Parametric Study of an Effective Stress Liquefaction Model," International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, University of Missouri-Rolla, 1981, pp. 699-705.

26. Mulilis, J.P., Chan, C.K., and Seed, H.B., "The Effects of Method of Sample Preparation on the Cyclic Stress-Strain Behavior of Sands," Earthquake Engineering Research Center, Report No. EERC 75-18, College of Engineering, University of California, Berkeley, CA, July, 1975.

27. Richart, F.E., Jr., "Some Effects of Dynamic Soil Properties on Soil-Structure Interaction," Journal of the Geotechnical Engineering Division, Proc. ASCE, Vol. 101, No. GT12, December, 1975, pp. 1193-1240.

28. Richart, F.E., Jr., Hall, J.R., Jr., and Woods, R.D., Vibrations of Soils and Foundations, Prentice-Hall, Englewood Cliffs, NJ, 1970.

29. Robertson, P.K., Campanella, R.G., Gillespie, D., and Rice, A., "Seismic CPT to Measure In-Situ Shear Wave Velocity," Measurement and Use of Shear Wave Velocity for Evaluating Dynamic Soil Properties, Proceedings, ASCE Convention, Denver, Colorado, May 1, 1985, pp. 34-48.

30. Sasaki, Y. and Koga, Y., "Vibratory Cone Penetrometer to Assess the Liquefaction Potential of the Ground," Wind and Seismic Effects, Proceedings, 14th Joint Panel Conference of U.S.-Japan Cooperative Program in Natural Resources, National Bureau of Standards Special Publication 651, April, 1983, pp. 541-555.

31. Seed, H.B., "Evaluation of Soil Liquefaction Effects on Level Ground During Earthquakes," State-of-the-Art Paper, Liquefaction Problems in Geotechnical Engineering, Preprint 2752, ASCE Annual Convention, Sept. 27-Oct. 1, 1976, Philadelphia, PA, pp. 1-104.

32. Seed, H.B. and Idriss, I.M., Ground Motions and Soil Liquefaction During Earthquakes, Earthquake Engineering Research Institute Monograph, 1982.

33. Shannon and Wilson, Inc., and Agbabian Associates, "Determination of Soil Liquefaction Characteristics by Large-Scale Laboratory Tests, "Report No. NUREG-0027, prepared by Shannon and Wilson, Inc., Seattle, Washington, and Agbabian Associates, El Segundo, California, for the U.S. Nuclear Regulatory Commission, Washington, D.C., May, 1975.

34. Sidey, R., Marti, J., Rodriguez, L., and White, D., "Borehole Shear Device Feasibility and Preliminary Studies," Report prepared by Dames and Moore, Los Angeles, CA, for the Air Force Weapons Laboratory, Kirtland Air Force Base, NM, Aug., 1980.

35. Sowers, G.B. and Sowers, G.F., Introductory Soil Mechanics and Foundations, The Macmillan Company, New York, 1970.

36. Stokoe, K.H., II, Arnold, E.J., Hoar, R.J., Shirley, D.J., and Anderson, D.G., "Development of a Bottom-Hole Device for Offshore Shear Wave Velocity Measurement," Proceedings, Offshore Technology Conference, OTC 3210, Houston, TX, May, 1978, pp. 1367-1380.

37. Stokoe, K.H., II, and Nazarian, S., "Use of Rayleigh Waves in Liquefaction Studies," Measurement and Use of Shear Wave Velocity for Evaluating Dynamic Soil Properties, Proceedings, ASCE Convention, Denver, Colorado, May 1, 1985, pp. 1-17.

38. Streeter, V.L., Wylie, E.B., and Richart, F.E., Jr., "Soil Motion Computations by Characteristics Method," Journal of the Geotechnical Engineering Division, Proc. ASCE, Vol. 100, No. GT3, March, 1974, pp. 247-263.

39. Terzaghi, K. and Peck, R.B., Soil Mechanics in Engineering Practice, John Wiley and Sons, Inc., New York, 1967.

40. Walters, S., "Superautomation - A View from the Factory Floor," Mechanical Engineering, Vol. 107, Number 1, January, 1985, pp. 44-53.

41. Woods, R.D., "Measurement of Dynamic Soil Properties," Proceedings of the ASCE Geotechnical Engineering Division Specialty Conference, Volume 1, Pasadena, CA, June 19-21, 1978.

42. Wiegel, R.L., Editor, Earthquake Engineering, Prentice-Hall, Englewood Cliffs, New Jersey, 1970.

43. Wylie, E.B., "Fluid Transients in Two Spatial Dimensions," Presented at ASME Pressure Vessels Conference, Orlando, Florida, June, 1982.

44. Wylie, E.B. and Henke, R., "Nonlinear Soil Dynamics by Characteristics Method," Proceedings of the 2nd U.S. National Conference on Earthquake Engineering, Earthquake Engineering Research Institute, Stanford University, Stanford, CA, 1979, pp. 563-572.

APPENDIX B

In this appendix, we provide copies of two publications (11) (12) related to the project discussed herein. Each publication was presented at a conference and was included in the proceedings of the corresponding conference.

We also provide copies of abstracts for two publications (13) (14) related to the project discussed herein. Each abstract was submitted to a conference to be held in 1991.

IN SITU TESTING METHOD FOR OBTAINING CYCLIC AND DYNAMIC SOIL PROPERTIES

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INTRODUCTION

This paper introduces a concept for an in situ geotechnical testing system for directly estimating in situ cyclic and dynamic soil properties. The use of the system and its theoretical feasibility are demonstrated.

The testing system is intended to reduce uncertainty and potential for error in estimates of liquefaction resistance, degradation characteristics, the dynamic shear modulus, and its variation with shear strain. This will allow the benefits of the potentially powerful cyclic and dynamic soil-structure-equipment system analysis procedures, developed over the past two decades, to be realized to a greater degree. The result should be greater safety, economy, and reliability of soil-structure-equipment systems constructed to resist earthquakes, vibrations, wave loadings, and blasts.

TERMINOLOGY AND SYMBOLS

Under large cyclic shearing loads, saturated soils may undergo degradation (decrease in shearing stiffness). As shown in Fig. 1, under a cyclic shear stress loading of uniform amplitude, degradation of an element is observed as an increase in the amplitude of the resulting cyclic shear strain with an increase in the number of cycles. Loose sands will generally degrade severely while dense sands degrade only mildly. The loose sands may eventually undergo liquefaction (unrestrained deformation). Because of the restraining effects of dilation, dense sands will show only limited deformations. Clays also usually develop only limited deformations.

The following symbols are used repetitively: C_T=torsional viscous damping coefficient, G_o=low amplitude dynamic shear modulus, I=mass moment of inertia, K_T=torsional spring constant, T=torque applied to inner cylinder, t=time, u=excess

pore water pressure, γ =shear strain, Θ =rotation of inner cylinder, $\bar{\sigma}_{vi}$=initial effective vertical stress, τ =shear stress, τ_A=shear stress amplitude, and τ_m=shear strength.

EXISTING METHODS

A number of advances have been made in the active area of laboratory and in situ testing for determining cyclic and dynamic soil properties (Woods, 1978); however, there is still need for further advancement.

Laboratory testing is attractive because cyclic and dynamic loads are applied, detailed information required by analyses is directly obtained, and such testing is applicable to all soils. However, in situ conditions are disturbed, possibly leading to considerable uncertainty and potential for error.

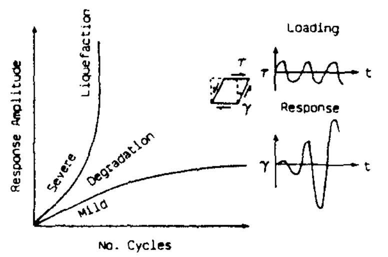

Figure 1: Degradation and Liquefaction

In situ testing overcomes, to a degree, the shortcomings of laboratory testing since, generally, in situ conditions are better preserved. However, in situ testing gives rise to other problems which can lead to considerable uncertainty and potential for error. For example, in penetration tests, which are used to indirectly determine liquefaction resistance by correlation, cyclic earthquake-type loads are not applied and these tests do not readily provide the detailed information needed for analyses. Also, correlations are not available for all soils of interest. New approaches for determining liquefaction resistance, also indirect, include electrical methods (Arulmoli, et al., 1981) and shear wave velocity methods (Dobry, et al., 1981). No in situ procedures for directly determining either cyclic degradation characteristics or the variation in dynamic shear modulus with shear strain, to our knowledge, are in common use. A number of in situ methods are used to determine the low amplitude dynamic shear modulus (Woods, 1978). Additionally, new methods have been developed (Stokoe, et al., 1978; the Oyo Corporation in Japan - no known reference; Hardin, 1971). Our system is expected to provide an alternative.

DESCRIPTION OF TESTING SYSTEM

Basically, the testing system (patent pending) is intended to directly provide the accurate and detailed descriptions of in situ cyclic and dynamic shear stress-strain behavior needed for cyclic and dynamic analyses. The most attractive features of laboratory and in situ testing are to be combined, while

minimizing shortcomings. Cyclic and dynamic shearing loads are to be applied in situ to an element of soil below the base of a single borehole and considerable effort will be directed toward minimizing disturbances to in situ conditions. Also, the procedure is not intended to rely on correlations and, therefore, is expected to apply to all soils of interest.

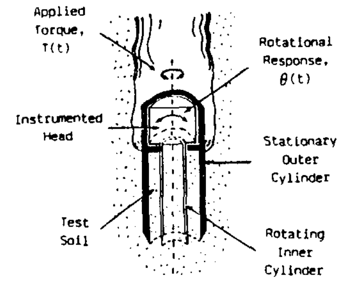

Figure 2: Probe in Borehole Setting (Main Elements Only)

Figure 2 shows, schematically, the probe of the testing system, consisting of two concentric, thin-walled cylinders, penetrated below the base of a borehole. The test soil is the well-defined annular element between the two cylinders. A selected cyclic or impulsive torque will be applied to the inner cylinder. In response, the cylinder will rotate in a manner which is expected to depend on the shearing properties of the test soil. Both the torque and rotation will be measured by transducers in the instrumented head. The shear stress-strain distributions that develop within the test soil, while not complex, will be nonuniform; thus, soil properties will be inferred by modeling tests analytically (soil-probe interaction analysis). Properties will be iteratively assumed until computed and measured results agree acceptably. The final assumed properties are expected to closely represent the in situ properties.

The concept consists of several features to preserve effects of in situ conditions. For example, as shown in Fig. 3, the upper portion of the rotating inner cylinder will be shielded to minimize effects of disturbances near the base of the borehole. The rigid vertical cylinder walls are intended to help preserve in situ lateral stresses, while an annular piston system, shown in Fig. 3, will reapply the vertical stress which existed prior to removal of soil from the borehole. Also, the influence of the soil within the inner cylinder on the motion of this cylinder will be minimized.

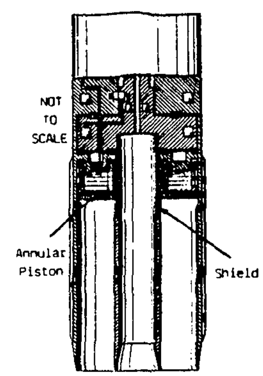

Figure 3: Detailed Schematic Diagram of Probe (Patent Pending)

For accuracy, a descriptive soil-probe interaction analysis will be used to infer in situ properties.

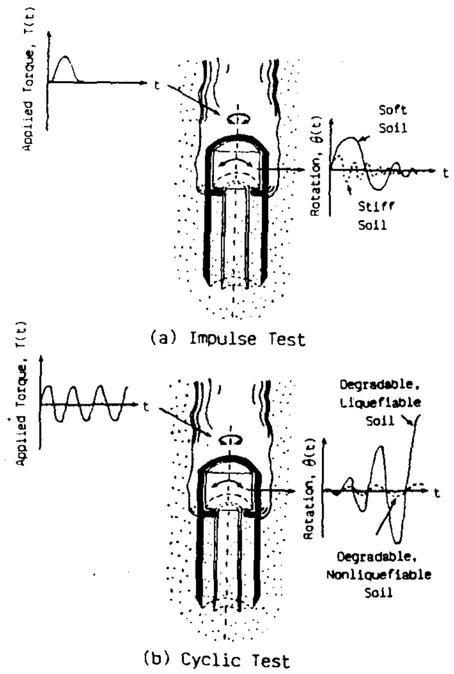

Figure 4: Example Testing Sequence

Henke, Wylie, and Richart (1982) describe an applicable continuum analysis procedure capable of simulating the torsional, dynamic behavior of an axisymmetric soil-rigid body system. This procedure treats the soil as a nonlinear, inelastic continuum and should allow accurate determination of dynamic shear moduli. To be able to determine degradation and liquefaction characteristics, we plan to extend the soil modeling to describe degradation, liquefaction, and the flow of pore water. Finn (1982) and Idriss, et al. (1978) discuss appropriate modeling. The soil modeling in the soil-probe interaction analysis will be almost identical to that used in commonly applied cyclic and dynamic analyses; therefore, the properties required by these analyses will be provided directly, minimizing intermediate interpretation.

Figure 4 shows an example testing sequence. First, impulse tests may be conducted to determine dynamic shear moduli. Then, a higher amplitude cyclic test could be conducted to determine liquefaction and/or degradation characteristics. As shown in Fig. 4, the response of the inner cylinder to each excitation is expected to be strongly related to soil characteristics. A number of variations on tests and also on testing systems should be possible.

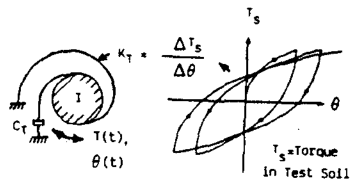

Figure 5: Simple Nonlinear, Inelastic, Degrading Model of Soil-Probe System

THEORETICAL FEASIBILITY STUDY

To determine the theoretical feasibility of the testing system, we analytically simulated impulse and cyclic tests considering expected variations in the soil properties of interest. If the predicted behavior of the testing system was found to be

sensitive to a soil property in a clear, physically reasonable manner, then we concluded that this soil property could be reasonably inferred from the behavior, and therefore, that the testing system is a theoretically feasible means for determining this property.

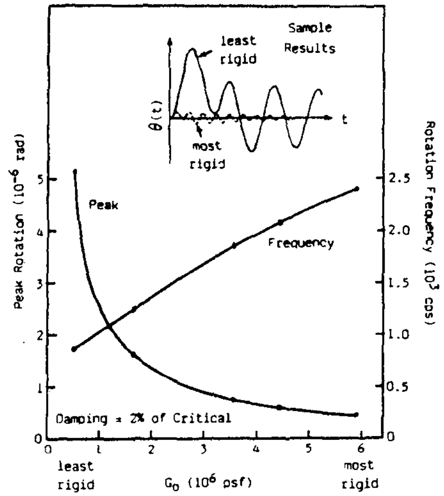

Figure 6: Predicted Measured Parameters - Low Amplitude Impulse Test

Analytical simulations

Our analytical model, shown in Fig. 5, was a simple single-degree-of-freedom system. The mass moment of inertia represented the effectively rotating mass and the dashpot represented viscous damping. The torsional spring modeled the nonlinear, inelastic, degrading torque-rotation characteristics of the test soil. Spring characteristics were derived mainly from the shear stress-strain model of the test soil. The nondegrading, nonlinear, inelastic stress-strain behavior expected during impulse tests was described using Ramberg-Osgood equations (Richart, 1975). Cyclic tests, during which degradation is expected, were modeled using a clay degradation model (Idriss, et al., 1978) and a sand degradation/liquefaction model (Finn, 1982).

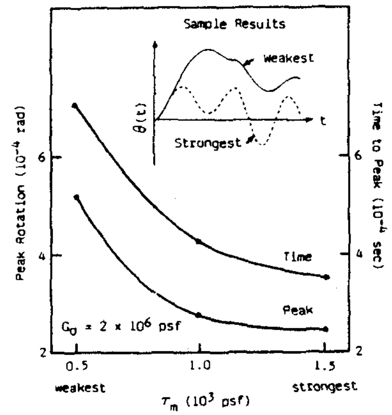

Figure 7: Predicted Measured Parameters - High Amplitude Impulse Test

To simulate impulse tests, we numerically solved the equation of motion for the single-degree-of-freedom system. In simulating cyclic tests, we assumed inertia forces to be negligible and the response was computed only on a half-cycle basis.

The simulations involved several significant simplifications or assumptions: a lumped parameter system; a linear, axisymmetric, horizontal displacement distribution in the test soil in horizontal planes;

uniform behavior in the vertical direction; independence in the behavior of the soil with respect to the planes on which shear stresses develop; and no slippage. Also, effects of dilation were not fully taken into account and we did not model the flow of pore water. Thus, the simple model is expected to give only qualitatively accurate results. However, the accuracy is judged appropriate for establishing feasibility.

Presentation and discussion of results and conclusions

All tests were simulated assuming a probe with dimensions approximately compatible with commonly used drilling equipment. The inner radius of the outer cylinder was 1.5 in. The outer radius of the inner cylinder was 0.5 in and its active length (height of test soil) was 8 in.

Impulse tests The soil conditions considered ranged from saturated, loose to dry, dense sand deposits. Values for G_o and τ_m were calculated (Hardin and Drnevich, 1972). Ramberg-Osgood shape parameters were chosen to give stress-strain curve shapes that closely match experimental data for sands (Richart, 1975). Viscous damping was estimated as 2% of critical damping (Richart, Hall, and Woods, 1970). Long duration, rectangular, impulsive torque loadings having a low amplitude of 0.015 ft-lb, which induced linear stress-strain behavior, and a high amplitude of 2.7 ft-lb, which induced nonlinear behavior, were considered. A mass moment of inertia of 0.00028 lb-ft-sec^2 was estimated.

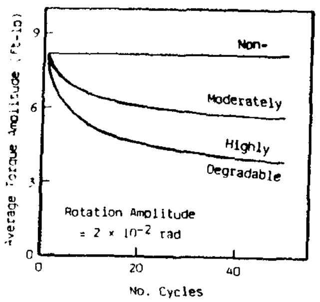

Figure 8: Predicted Measured Parameter - Cyclic Test, Clay

Figures 6 and 7 present results. Figure 6, which demonstrates low amplitude behavior, gives selected parameters of the oscillating response of the inner cylinder as functions of the low amplitude dynamic shear modulus. Figure 7, which demonstrates high amplitude behavior, gives selected response parameters as functions of shear strength, assuming a selected low amplitude dynamic shear modulus and shear stress-strain curve shape.

The results indicate that the behavior of the testing system will be sensitive to the dynamic shear modulus and its variation with shear strain. For example, Fig. 6 shows that, for the low amplitude loading, the frequency of oscillation will be about 3 times greater in the most rigid sand than in the least rigid sand while the peak rotation will be about 10 times less. For the high amplitude loading, Fig. 7 shows that the peak rotation will be about 2 times less and the time to this peak will be about 2 times shorter in the strongest sand than in the weakest sand.

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These results are physically reasonable. For a given low amplitude loading, one would expect the peak rotation to be greater and the oscillation frequency less in a less rigid soil. Additionally, for a given low amplitude dynamic shear modulus and shear stress-strain curve shape, at higher amplitudes of loading one would expect a decrease in the peak rotation and the time to this peak with an increase in strength. Thus, we concluded that the proposed testing procedure is a theoretically feasible means for determining the dynamic shear modulus and its variation with shear strain.

Cyclic tests - clay degradation characteristics The range of soil conditions was established by varying the degradability of the test soil while maintaining the nonlinear, undegraded shear stress-strain behavior. We modeled, for a depth of 50 ft, a highly degradable soil (average degradation parameter curve in Fig. 12 of Idriss, et al., 1978), a moderately degradable soil (½ degradation parameter curve used for highly degradable soil), and a nondegradable soil. Values for G_o and τ_m were calculated (Hardin and Drnevich, 1972). Ramberg-Osgood parameters were chosen to give stress-strain curve shapes that closely match experimental data for clays (Richart, 1975). We considered a cyclic excitation of uniform rotation amplitude.

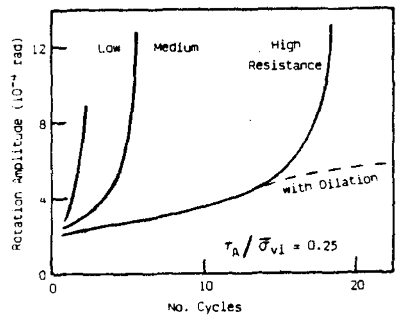


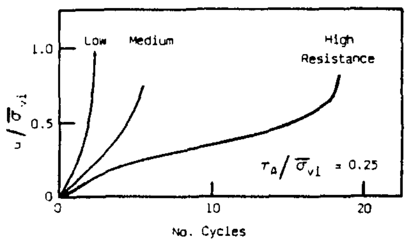
Figure 9: Predicted Measured Parameter - Cyclic Test, Sand

Results are presented in Fig. 8, which gives the average amplitude of the cyclic torque developed by cyclically rotating the inner cylinder with an amplitude of 0.02 rad (induces cyclic shear strains having amplitudes of about 3% along the wall of the inner cylinder) as a function of the number of cycles of loading for the various levels of degradability.

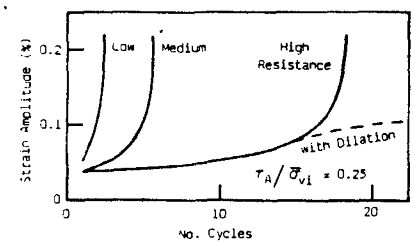
The results indicate that the behavior of the testing system will be sensitive to the degradation characteristics of a clay. Figure 8 shows that after 50 cycles, the amplitude of the cyclic torque developed will be reduced by about 50% in the highly degradable clay and 30% in the moderately degradable clay.

These results are physically reasonable. One would expect the torque amplitude, for a given rotation amplitude, to show more of a decrease with a more degradable clay. Thus, we concluded that the proposed testing procedure is a theoretically feasible means for determining the degradation characteristics of a clay.

<u>Cyclic tests - sand degradation and liquefaction characteristics</u> The range of soil conditions was established by varying the degradation and liquefaction characteristics of the test soil and also, in a consistent manner, the undegraded, nonlinear shear stress-strain characteristics. The test soil, considered at a depth of 25 ft, was assumed to have high, medium, and low resistance to degradation and liquefaction. Values for the parameters describing degradation and liquefaction characteristics were obtained from Martin, et al. (1981). Values for G_0 were calculated (Hardin and Drnevich, 1972). Values for γ_m were estimated such that the low, medium, and high resistance models show cyclic behavior similar to that of freshly deposited Monterey No. 0 test sand (Seed, 1976) at relative densities of about 54%, 75%, and 90%, respectively. We considered a cyclic excitation of uniform torque amplitude. Two failure modes could be predicted: 1) excess pore water pressure equal to the initial vertical effective stress and 2) shear failure (applied stress exceeds degraded strength).



(a) Excess Pore Water Pressures



(b) Shear Strains

Figure 10: Predicted Derived Information - Cyclic Test, Sand

Figure 9 presents, for a medium shear stress ratio ($\tau_A/\bar{\sigma}_{vi}$) of 0.25, the amplitude of the cyclic rotation of the inner cylinder as a function of the number of cycles of loading for the low, medium, and high resistance soils. The actual behavior expected with dilation taking place is indicated.

The results indicate that the behavior of the testing system will be sensitive to the degradation and liquefaction characteristics of a sand. For example, Fig. 9 shows that it will take about 7 times as many cycles of loading for the inner cylinder to reach a rotation amplitude of 0.0008 rad in the high resistance sand as in the low resistance sand.

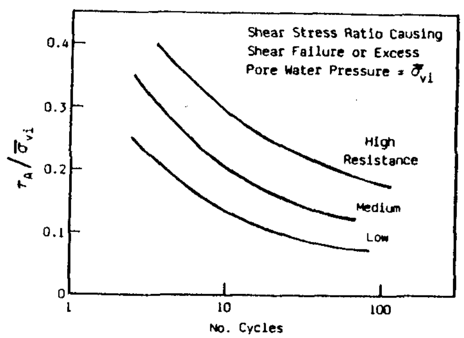


Figure 11: Predicted Derived Information - Cyclic Test, Sand

These results are physically reasonable. The amplitude of the cyclic rotation would be expected to increase more rapidly in soils less resistant to liquefaction and degradation. Thus, we concluded that the proposed testing system is a theoretically feasible means for determining the degradation and liquefaction characteristics of a sand.

Figures 10 and 11 show, for demonstrative purposes, information that may be derived from measured data by soil-probe interaction analysis. Figure 10(a) shows the buildup in excess pore water pressure as a function of the number of cycles of loading at a medium shear stress ratio for the various soil conditions and Figure 10(b) similarly shows shear strain amplitude. Figure 11 shows the shear stress ratio required to cause shear failure or the excess pore water pressure to equal the initial vertical effective stress as a function of the number of cycles of loading for the various soil conditions.

SUMMARY AND CONCLUSIONS

A concept has been introduced for an in situ geotechnical testing system for obtaining certain in situ cyclic and dynamic soil properties. The system is intended to reduce uncertainty and potential for error in estimates of these properties. An analytical study designed to demonstrate use of the system and determine its theoretical feasibility was presented. We concluded that the testing system is a theoretically feasible means for determining in situ cyclic and dynamic soil properties.

ACKNOWLEDGMENT

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REFERENCES

Arulmoli, K., Arulanandan, K., and Seed, H.B. (1981) "A New Method for Evaluating Liquefaction Potential In Situ," ASCE Conv. and Exp.

Dobry, R., Stokoe, K.H., Ladd, R.S., and Youd, T.L. (1981) "Liquefaction Susceptibility from S-Wave Velocity," ASCE Conv. and Exp.

Finn, W.D.L. (1982) "Dynamic Response Analyses of Saturated Sands," <u>Soil Mech.-Trans. and Cyclic Loads</u>, J. Wiley and Sons, NY.

Hardin, B.O. (1971) U.S. Patent 3,643,498.

Hardin, B.O. and Drnevich, V.P. (1972) "Shear Modulus and Damping in Soils: Design Equations and Curves," <u>J. Soil Mech. and Found. Div.</u>, ASCE, Vol. 98, SM7.

Henke, R., Wylie, E.B., and Richart, F.E., Jr. (1982) "Torsional Dynamic Response of Solid Systems," J. of the Eng. Mech. Div., ASCE, Vol. 108, EM6.

Idriss, I.M., Dobry, R., and Singh, R.D. (1978) "Nonlinear Behavior of Soft Clays During Cyclic Loading," J. of the Geotech. Eng. Div., ASCE, Vol. 104, GT12.

Martin, G.R., Lam, I.P., McCaskie, S.L., and Tsai, C. (1981) "A Parametric Study of an Effective Stress Liquefaction Model," Int. Conf. on Recent Advances in Geotech. Earthquake Eng. and Soil Dynamics, Univ. of Missouri-Rolla.

Richart, F.E., Jr. (1975) "Some Effects of Dynamic Soil Properties on Soil-Structure Interaction," J. of the Geotech. Eng. Div., ASCE, Vol. 101, GT12.

Richart, F.E., Jr., Hall, J.R., Jr., and Woods, R.D. (1970) Vibrations of Soils and Foundations, Prentice-Hall, NJ.

Seed, H.B. (1976) "Evaluation of Soil Liquefaction Effects on Level Ground During Earthquakes," Liq. Problems in Geotech. Eng., ASCE Annual Conv., Phila., PA.

Stokoe, K.H., Arnold, E.J., Hoar, R.J., Shirley, D.J., and Anderson, D.G. (1978) "Development of a Bottom-Hole Device for Offshore Shear Wave Velocity Measurement," Proc. Offshore Tech. Conf., Houston, TX.

Woods, R.D. (1978) "Measurement of Dynamic Soil Properties," Proc. ASCE Geotech. Eng. Div. Spec. Conf., Vol. 1, Pasadena, CA.

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Laboratory Prototype of In Situ Cyclic and Dynamic Geotechnical Testing System

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INTRODUCTION

This paper presents selected elements of a laboratory prototype of a new in situ geotechnical testing system. The testing system, currently under construction, is intended to provide improved measures of the in situ nonlinear shear stress-strain characteristics of the upper layers of a soil deposit. Such information is needed for earthquake site response analysis procedures (for example, see Streeter, Wylie, and Richart[1] and Finn, Lee, and Martin[2]) used to predict the behavior of sites during earthquakes. Such procedures are commonly used at the advanced stages of the earthquake resistant design of critical soil-structure-equipment systems (offshore structures, hospitals, dams, etc.). The elements of the testing system described in this paper are elements intended to help preserve in situ conditions.

The proposed in situ testing system is intended to reduce uncertainty and potential for error in analytical predictions of the behavior of sites during earthquakes. Existing methods for determining in situ shear stress-strain characteristics can create excessive uncertainty (Henke and Henke[3]; Henke and Henke[4]). This can severely limit the effectiveness of the costly, potentially powerful analysis procedures used for earthquake resistant design. If successfully developed, the testing system will lead to greater safety, reliability, and economy of critical soil-structure-equipment systems located in seismically

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active areas.

The following sections are presented: In Situ Testing System, Selected Elements, Summary, Future Work, Acknowledgments, and References.

IN SITU TESTING SYSTEM

The proposed testing system is summarized in this section. A complete description, along with a discussion of existing methods and an extensive list of appropriate references, is given by Henke and Henke[3].

The testing system (U.S. Patent No. 4,594,899) is intended to directly provide accurate and detailed descriptions of the in situ shear stress-strain characteristics of a soil deposit. The most attractive features of laboratory testing of soil samples recovered from a site and in situ testing are to be combined, while shortcomings are to be minimized.

Laboratory testing is attractive because earthquake-like cyclic shearing loads are applied, detailed information required for earthquake site response analyses is directly obtained, and such testing is applicable to most soils. In situ conditions, however, may be greatly disturbed, leading to considerable uncertainty and potential for error. In situ testing overcomes, to a degree, this shortcoming since, generally, in situ conditions are better preserved. However, to our knowledge, no in situ methods for directly determining the nonlinear shear stress-strain characteristics needed for earthquake site response analyses are in common use.

With the proposed testing system, earthquake-like cyclic and dynamic shearing loads are to be directly applied in situ, detailed information required for earthquake site response analyses is to be directly obtained, and considerable effort will be directed toward minimizing disturbances to in situ conditions.

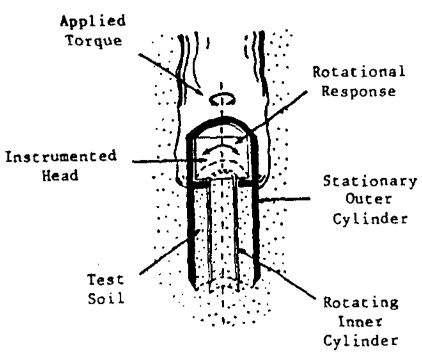

Figure 1: Probe in Borehole Setting (Main Elements Only)

Figure 1 shows, schematically, essential elements of the probe of the testing system. Two concentric, thin-walled

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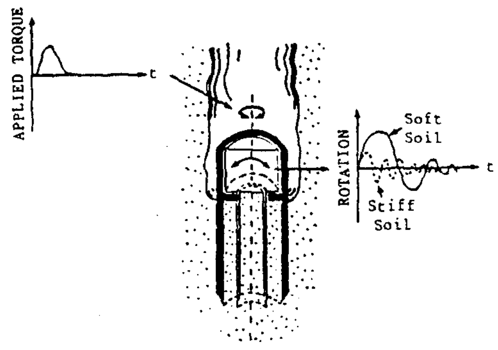
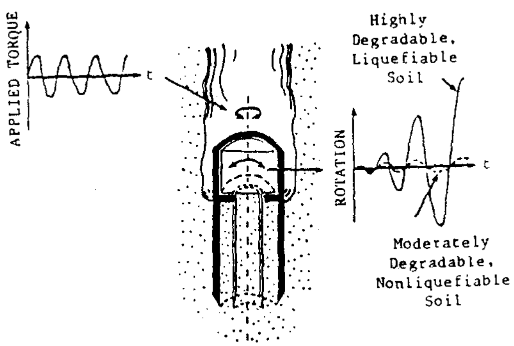
cylinders are shown penetrated below the base of a test borehole. The test soil will be the well-defined annular element of soil between the two cylinders. As shown in Figure 2, a selected impulsive or cyclic torque is to be applied to the inner cylinder/instrumented head assembly. In response, this assembly should rotate in a manner expected to depend strongly on the shear stress-strain characteristics of the test soil. Both the applied torque and the rotational response are to be measured by transducers in the instrumented head. Soil properties will be inferred by modeling tests analytically (soil-probe interaction analysis). This is necessary because torsional shear stress and strain



(a) Impulse Test



(b) Cyclic Test

Figure 2: Possible Testing Sequence

distributions developed within the test soil, while not complex, will be nonuniform. Properties will be iteratively assumed until computed and measured results agree acceptably. The final assumed properties are expected to closely represent the in situ properties.

SELECTED ELEMENTS

Three elements which have been included in the design of a prototype of the proposed in situ testing system will be discussed in this section. The purpose of these elements is to minimize disturbances to in situ conditions. These elements are

1) a vertical pressure system,

2) a shield, and

3) special wall finishes.

The vertical pressure system is designed to recreate, as closely as possible, the state of stress and deformation which existed within the element of test soil prior to the drilling of the test borehole. The vertical pressure system will consist of an annular piston, shown schematically in Figure 3, and a hydraulic pressure system. The piston is to be capable of moving along the length of the annular space between the inner cylinder/shield assembly and the outer cylinder. The hydraulic pressure system is to be capable of applying appropriate pressures to the annular piston. Prior to the penetration of the probe, the annular piston will be advanced to the tip of the probe and pressurized to an appropriate pressure. Generally, this pressure will be such that a pressure equal to the vertical

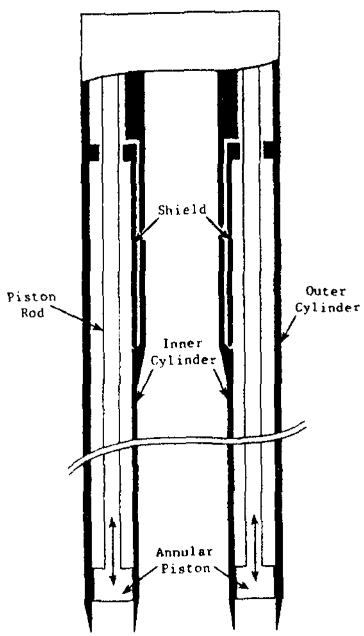


Figure 3: Schematic Diagram of Vertical Pressure System and Shield

pressure due to the weight of soil removed from the borehole must be applied to the base of the piston to initiate significant relative movement between the piston and the cylinders. After placement of the probe at the base of the borehole, a penetration force will be applied to the probe. The cylinders (including the shield) are expected to advance relative to the piston and penetrate into the soil below when the penetration force is such that the pressure developed at the base of the piston equals the pressure required for relative movement between the piston and the cylinders. As will be discussed later, the cylinder walls (including the shield) will be treated to minimize the development of frictional forces in the vertical direction during penetration. Thus, immediately prior to and during the penetration of the cylinders into the test zone, the piston should apply approximately the desired level of vertical pressure to the test soil. The application of this pressure in the manner described is expected to cause the test soil to take on a state of deformation and stress adequately close to that which existed prior to the creation of the borehole.

After penetration has been completed and the penetration force reduced to the level needed to balance the force in the piston system, the vertical pressure system will be set for one of two modes of testing: a constant pressure mode or a constant volume mode.

In the constant pressure mode, the hydraulic pressure on the piston is to be kept constant during testing. This should provide a constant pressure to the upper horizontal surface of the test soil. The piston is to be capable of moving up or down as necessary to maintain a constant pressure on the soil. This mode of testing may be preferable in soils having low permeability. In such soils, porewater pressures induced by testing are not expected to dissipate readily. Any degradation of the cyclic shear stress-strain behavior of the test soil is expected to develop as a result of a reduction in effective confining pressure due to a buildup of porewater pressure.

In the constant volume mode, the position of the piston is to be locked during testing, providing an approximately constant volume for the test soil to occupy. The pressure exerted on the test soil as a result of pressure on the piston should vary as the test soil expands or contracts. This mode of testing may be preferable in soils having high permeability. When testing such soils, because of drainage high porewater pressures are not expected to develop even though significant densification of the test soil may take place. Any degradation of the cyclic shear stress-strain behavior of the test soil is expected to develop as a result of a reduction in effective confining pressure due to

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densification of the test soil under approximately constant volume conditions. This type of degradation is expected to be strongly linked to the type of degradation which would be expected under undrained conditions. Cyclic testing under constant volume conditions is discussed more fully by Finn, Bhatia, and Pickering[5].

The second element intended to help minimize disturbances is the shield, shown schematically in Figure 3. The shield is intended to reduce the effects on test results of disturbances caused by the drilling of the test borehole. The shield will consist of a stationary cylinder which is to shield the upper portion of the annular zone of soil from the torsional excitation to be provided by the inner cylinder. This upper zone is likely to be disturbed by the drilling process and would be expected to have a large effect on test results if unshielded. Thus, the behavior of the relatively undisturbed soil below the shield should dominate test results.

The third element, special wall finishes, will be included to minimize penetration-induced disturbances to the test soil, to help recreate the state of stress and deformation which originally existed within the test soil (discussed previously), and to minimize slip during testing. All cylinder and shield surfaces will be machined to a smooth finish and coated with a low-friction material to minimize penetration-induced disturbances and to help recreate the original state of stress and deformation within the test soil. The inside and outside surfaces of the outer cylinder and the outside surfaces of the inner cylinder and the shield will be grooved longitudinally to minimize slip between the soil and these surfaces during testing without causing excessive disturbance during penetration.

SUMMARY

Elements of a laboratory prototype of a new in situ geotechnical testing system were presented. The system is intended to advance our ability to determine in situ cyclic and dynamic shear stress-strain characteristics. This will improve our ability to predict the behavior of sites during earthquakes. In situ cyclic and dynamic stress-strain characteristics need to be determined accurately and descriptively for earthquake site response analyses. Such analyses are carried out at the advanced stages of the design of critical structures located in seismically active areas. The testing system is to combine the attractive features of both laboratory and in situ testing, while minimizing shortcomings. The elements discussed herein are expected to help minimize disturbances to in situ conditions without compromising testing. Sources of disturbance related to the proposed testing system include the drilling of the test borehole and the penetration of the probe.

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FUTURE WORK

Future work will be directed toward continuing the development of the proposed testing system. At this time, a laboratory prototype of the proposed in situ testing system is being constructed, and several soil-probe interaction analysis procedures are being developed. After the completion of these tasks, we plan to extensively test the prototype under laboratory conditions. If the testing system looks promising after the laboratory tests are completed, the prototype will be modified for field use and field tests will be conducted.

ACKNOWLEDGMENTS

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REFERENCES

1. Streeter, V.L., Wylie, E.B., and Richart, F.E., Jr. (1974), "Soil Motion Computations by Characteristics Method," Journal of the Geotechnical Engineering Division, ASCE, Vol 100, pp. 247-263.

2. Finn, W.D.L., Lee, K.W., and Martin, G.R. (1977), "An Effective Stress Model for Liquefaction," Journal of the Geotechnical Engineering Division, ASCE, Vol 103, pp. 517-533.

3. Henke, W. and Henke, R. (1985), "In Situ Testing Procedure for Obtaining Dynamic and Cyclic Soil Properties," Report prepared for the National Science Foundation by Dynamic In Situ Geotechnical Testing, Inc., Houston, TX.

4. Henke, R. and Henke, W. (1985), "In Situ Testing Method for Obtaining Cyclic and Dynamic Soil Properties," Soil Dynamics and Earthquake Engineering (Ed. Brebbia, C.A., Cakmak, A.S., and Abdel Ghaffar, A.M.), Proceedings of the 2nd Int. Conf. on Soil Dynamics and Earthquake Engineering, held on board the ocean liner Queen Elizabeth 2, sailing from New York to Southampton, pp. 2-47 to 2-56.

5. Finn, W.D.L., Bhatia, S.K., and Pickering, D.J. (1982), "The Cyclic Simple Shear Test," Soil Mechanics-Transient and Cyclic Loads, John Wiley and Sons, New York, pp. 583-607.

ABSTRACT

Cyclic Tests Conducted Using Laboratory Prototype
of In Situ Geotechnical Testing System

by
Wanda Henke and Robert Henke

In this paper, we present and discuss a portion of our first laboratory testing program for a prototype in situ cylindrical shear testing system. The system is to advance our ability to design critical systems to resist earthquakes. It is to provide accurate and detailed information on in situ cyclic and dynamic shear stress vs strain characteristics of soil deposits. The information is to be appropriate for analyses used at the advanced stages of earthquake resistant design to predict the behavior of sites of critical systems during earthquakes.

The cylindrical shear testing system combines attractive features of laboratory and in situ testing while reducing shortcomings. Earthquake-like shear loads are applied to an element of soil in situ by applying cyclic or dynamic torques to a cylindrical probe penetrated carefully below the base of a borehole. Both applied torque and the rotation of the cylinder are measured. Detailed information on in situ cyclic and dynamic shear stress vs strain characteristics, including information on undegraded nonlinearity, degradation, liquefaction, and limiting strains, is provided. Considerable effort is directed toward minimizing disturbances to in situ conditions.

Results are presented for cyclic tests. All tests were conducted on dry ottawa sand prepared to medium dense relative densities of 60 - 63%. The test sand was carefully deposited by raining into a large test chamber and was then subjected to a confining pressure of 10 psi. The tests, conducted on dry sand, were intended to give rise to the main effects of cyclic loading on saturated sand by imposing on the test sand cyclic shearing loads under the condition of relatively constant volume. For each test a cyclic torque of constant amplitude was applied. Results presented include photographs from an oscilloscope and processed test data. These include torque and angular displacement vs time curves, torque vs angular displacement curves, and a plot of torque amplitude vs number of cycles to "initial liquefaction" (herein defined as first loss of torsional stiffness).

Test results indicate that the testing system is promising. Results show that the laboratory prototype gives results typical of those obtained from high quality laboratory cyclic tests conducted on samples of saturated medium dense sand. The angular displacement data show an increase in the amplitude of the angular displacement with an increasing number of cycles of loading at a constant amplitude. The torque vs angular displacement curves show undegraded nonlinearity, cyclic degradation, behavior corresponding to "initial liquefaction" caused by densification at relatively constant volume and restiffening due to dilation, and increases in deformation after "initial liquefaction." The plot of torque amplitude vs number of cycles to "initial liquefaction" shows that as the amplitude of the applied torque increases, the

number of cycles to "initial liquefaction" decreases. From torque and angular displacement data we expect to be able to infer shear stress vs strain curves by analytically simulating tests.

ABSTRACT

Impulse Tests Conducted Using Laboratory Prototype
of In Situ Geotechnical Testing System

by
Wanda Henke and Robert Henke

In this paper, we present and discuss a portion of our first laboratory testing program for a prototype in situ cylindrical shear testing system. The system is to advance our ability to design critical systems to resist earthquakes. It is to provide accurate and detailed information on in situ cyclic and dynamic shear stress vs strain characteristics of soil deposits. The information is to be appropriate for analyses used at the advanced stages of earthquake resistant design to predict the behavior of sites of critical systems during earthquakes.

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Results are presented for impulse tests. All tests were conducted on dry ottawa sand prepared to medium dense relative densities. The test sand was carefully deposited by raining into a large test chamber and was then subjected to a confining pressure of 10 psi. The tests were intended to provide information on linear and nonlinear shear stress vs strain characteristics under dynamic loading conditions. For each test an impulsive torque was applied. Tests were carried out over a range of amplitudes inducing both reasonably linear and highly nonlinear behavior. Results presented include photographs from an oscilloscope, plots of digitized test data, and comparisons between test results and results from analytical simulations of tests. The results include torque and angular acceleration vs time curves, and shear stress vs strain curves for the test soil.

Results from impulse tests indicate that the impulse testing procedure is promising. The dynamic analyses used to simulate tests were found to describe tests effectively. Also, results from analyses indicate that results from impulse tests will be sensitive to the shear stress vs strain characteristics of the test soil.

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