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LABORATORY INVESTIGATIONS OF SOILS FOR ENGINEERING ANALYSIS AND DESIGN OF NUCLEAR POWER PLANTS

A. INTRODUCTION

Paragraph 100.10(c) and Appendix A, "Seismic and Geologic Site Criteria for Nuclear Power Plants," to 10 CFR Part 100, "Reactor Site Criteria," establishes requirements for conducting site investigations for nuclear power plants to permit an evaluation of the site and provide information needed for seismic response analyses and engineering design. Requirements include the development of information relevant to the static and dynamic engineering properties of soil and rock materials of the site.

Safety-related site characteristics are identified in detail in Regulatory Guide 1.70, "Standard Format and Content of Safety Analysis Reports for Nuclear Power Plants." Regulatory Guide 4.7, "General Site Suitability Criteria for Nuclear Power Stations," discusses site characteristics that affect site suitability. Regulatory Guide 1.132, "Site Investigations for Foundations of Nuclear Power Plants," discusses programs of field studies, exploratory borings, and sampling needed to provide geotechnical data for site evaluation and engineering analysis and design.

This guide describes laboratory investigations and testing practices acceptable for determining soil and rock properties and characteristics needed for engineering analysis and design for foundations and earthworks for nuclear power plants.

Criteria for planning and performing laboratory tests are given in the regulatory position. Terms printed in *italics* are defined in Appendix A. Appendix B is a tabulation of laboratory test methods for soil and rock. References are given in Appendix C.

B. DISCUSSION

1. *General*

In the course of site investigations and analyses for nuclear power plant facilities, a laboratory testing program is required to identify and classify soils and rocks and to evaluate their physical and engineering properties. The NRC staff reviews the information obtained from the site investigations and laboratory tests and considers the safety aspects of the application of the data to the design and construction of nuclear plants. Consideration of public safety imposes particularly stringent requirements on the design and construction of nuclear power plant facilities. Therefore, it is essential that all phases of a site investigation program and associated field and laboratory testing be carefully planned and carried out to ensure that soil and rock properties are realistically estimated.

The course of site and laboratory investigations will depend on actual site conditions, the nature of problems encountered or suspected at the site, and design requirements for foundations and earthworks. Specific testing requirements and details of testing procedures will depend on the nature of the soils and rocks encountered. It is normally desirable to follow testing procedures that are generally known and accepted since they are easily reproduced. Also, the effects of standard procedures on test results are better understood. In some cases, depending on the nature of the soil or rock material, it may be more appropriate and desirable to modify existing standard procedure or to use alternative procedures. Such practice is acceptable; however, it is important that test procedures be fully described so that the test may be reproduced and the results verified.

In most cases, the state of the art of laboratory testing of soils is reflected in existing standards, and, where appropriate, this guide will discuss and reference such standards. However, for some of the more complex geotechnical problems, such as those involving the dynamic response and behavior of soils, the state of the art of laboratory testing is changing and established standard procedures do not exist. Where there are no standards, this guide will describe laboratory testing practices presently used and discuss the importance of some of the procedures used in these tests. Continuing research and advances in the state of the art of dynamic soil testing and subsequent revisions to this guide are expected.

2. *Laboratory Facilities*

A laboratory for soil or rock testing should have a firm, solid floor and should be free of vibrations due to traffic and machinery. Temperature control of the entire laboratory is desirable but is essential for areas in which triaxial, simple shear, resonant column, consolidation, or permeability tests are conducted. Separate areas, and preferably separate rooms, are desirable for dust- and vibration-producing activities such as sieve analyses, compaction tests, and sample processing. Samples are normally tested on arrival from the field. If storage is required, consideration should be given to storing samples in a separate room with the relative humidity maintained at or near 100% (a *humid room*).

3. *Laboratory Equipment*

a. *Apparatus*

When standard laboratory testing procedures are used, the test apparatus should conform to the published specifications. Where testing apparatus do not satisfy published specifications, a complete description of the essential characteristics of the apparatus is needed, with appropriate references to published papers, reports, or monographs. In order to ensure that essential characteristics (such as dimensions, mating of parts, piston friction, and fluid seals) are not significantly altered by wear, handling, corrosion, dirt, or deterioration of materials, all testing apparatus should be regularly inspected and maintained.

b. *Calibration*

All test apparatus and instruments used for quantity measurement should be calibrated against certified calibration standards before being put into service. Calibrations can be verified at regular intervals thereafter. The necessary frequency for recalibration varies according to the susceptibility of the apparatus to change and the required precision of measurement. Physical length or volume measuring apparatus such as metallic tapes, rules, pycnometers, or graduates need not be calibrated unless altered by visible wear or damage. Weights and other equipment used as standards to calibrate test instruments are normally recalibrated periodically by an external agency with equipment directly traceable to the U.S. Bureau of Standards. Metallic weights used for production may be subject to significant alteration by wear or corrosion over long periods and should be periodically checked against the calibrated standards.

It is advisable to recalibrate balances or scales at least annually and to check them against known weights on at least a quarterly basis. The zero should be checked at each weighing. Balances or scales used in the field should also be periodically checked against known weights at each field location.

In general, calibrating instruments for measuring forces, pressures, temperatures, electrical quantities, and length against certified standards annually is sufficient. More frequent calibration may be necessary in cases where instruments are subject to heavy use and to change by drift or wear.

Additional discussion of calibration procedures is given by the Corps of Engineers (Ref. 1).

c. *Reagents and Water*

Guidelines for suitable chemical reagents, distilled water, and apparatus for chemical analyses can be found in standards of the American Public Health Association (Ref. 2). Water for use in soil or rock testing may be distilled or demineralized by ion-exchange processes. Ordinary distillation does not remove ammonia or carbon dioxide, and ion-exchange demineralization does not remove organic colloids. Therefore, special precautions are required where these substances may be present and may interfere with tests. Tap water may be used where specified by standard methods or where chemical analyses show that it does not contain impurities in sufficient amounts to interfere with tests. Consideration should be given to the use of water taken from a specific site in laboratory tests on samples from environments where the water chemistry is such that the use of distilled water in tests would yield nonrepresentative results; e.g., samples from acidic water environments may behave differently when tested with distilled water than when tested with water found in the actual environment of the samples. When saturation of samples is required for testing, it is best to de-air water since dissolved gases or air can make it impossible to obtain full saturation in test specimens. A procedure for de-airing water is given by the Corps of Engineers (Ref. 3). Suitable commercial de-airing devices may be used.

4. *Handling and Storage of Samples*

Improper handling and storage of soil and rock samples can result in damage or alteration that could affect the results of laboratory tests. *Undisturbed soil samples*, whether in blocks or tubes, require the most stringent protective measures. It is important to transport and handle undisturbed samples so as to minimize disturbance of the *soil structure*. To avoid disturbance of tube samples of granular soils, they may be hand carried or transported and stored vertically. Padded containers or racks are recommended for use in transportation and storage of samples. Close inspection of moisture seals upon receipt of the samples at the laboratory is necessary to ensure that the seals are intact and that the samples have been protected against changes in water content. Seals should be renewed if needed. The natural water content of rock samples and soil blocks may be preserved by sealing them in styrofoam or cheesecloth and wax at the site prior to transporting.

Even the most careful treatment of samples cannot prevent slow structural and chemical changes with time. These changes usually result in a decrease of both shear strength and the value of preconsolidation stress. It is therefore best to test samples as soon as possible after receipt, perferably within two weeks. Longer storage periods may be acceptable for materials whose properties are less susceptible to change with time. Samples that have been stored for long periods may be suitable for visual inspection but should not be considered to have the characteristics of undisturbed samples. A discussion of the effects of storage and extrusion on undisturbed samples is given by Arman and McManis (Ref. 4).

Special handling for preserving undisturbed samples of sand that are free draining may consist of partially draining or partially draining and freezing the samples at the site. However, some believe freezing will produce disturbances to the soil structure even in free-draining soils. If sand samples are frozen they should be well drained (but not permitted to dry) since freezing of saturated or near-saturated samples produces disturbances from expansion of freezing water. Soils that are not free draining cannot be frozen without disturbance. Also, it is important to protect frozen samples from thawing and from wide fluctuations of temperature below the freezing point.

Bulk and disturbed samples of soil do not require any special care in or protection from mechanical disturbance. Samples to be used for fluid content determinations and shale samples to be used for tests of mechanical properties need to be protected against change in water content. Rock samples with soil-like properties such as soft shales or weakly indurated sandstones can be transported, handled, and stored as soils.

Criteria regarding sample handling and storage are given in regulatory position 2.

5. *Selection and Preparation of Test Specimens*

a. *Undisturbed Samples*

The selection of soil and rock specimens for laboratory testing requires careful examination of boring records and available samples. It is important that test specimens be representative of the soil or rock unit to be tested and be accurately described to permit establishment of the soil profile. Average test values of material properties need to be identified as well as the range of values identifying their variability. This requires the testing of not only the most *representative samples*, but also of those with extreme properties and those representative of critical zones. Guidelines for spacing of borings and frequency of sampling are given in Regulatory Guide 1.132. Additional boring and sampling may be required when laboratory examination of the samples reveals an inadequate number or distribution of suitable samples to meet testing requirements.

Undisturbed tube samples of soils should be examined for evidence of disturbance. General criteria for selecting undisturbed samples for testing are given by Hvorslev (Ref. 5) and are stated in regulatory position 3.

Hvorslev describes procedures for examining cut surfaces of soil samples. Portions of the tube samples may be examined by these procedures while other portions are used for testing. A desirable alternative is the use of radiography, which can be used to examine samples for distortion of strata, gaps, voids, and shear zones and which leaves the samples intact. It is also useful for delineating the boundaries of soil zones with different properties and thus aids in subdividing samples and selecting test specimens. Procedures for examination by X-radiography are given by Krinitzky (Ref. 6).

A serious source of damage to undisturbed soil samples is the extrusion of the samples from the sample tubes. One method that may minimize this damage in the removal of samples from thin-wall tubes is to split the tube longitudinally by milling. An alternative may be to saw the tube transversely into segments of sufficient length to extrude a single test specimen from each and trim off the ends. The fact that milling may cause disturbance and changes in the void ratio in some soils, particularly in loose sand, is an important consideration in the assessment of the best way to remove samples from tubes. Dressing the cut tube edges before extruding samples from the tube sections reduces disturbance of the sample. Reuse of thin-walled sample tubes that have not been cut is not recommended if they have been damaged during retrieving or extruding samples.

Trimming and shaping of test specimens of soils require great care to prevent disturbance and changes in water content. Frozen samples can be prepared under conditions that will prevent premature thawing. Details of procedures depend on the nature of the test and the specimen. Procedures for preparing soil specimens for testing are described by the Corps of Engineers (Ref. 3). Methods of preparation of rock specimens for testing are described by Obert and Duvall (Ref. 7) and in ASTM standards (Refs. 8, 9).

b. *Reconstituted or Remolded Samples*

High-quality undisturbed samples are preferred for all tests of strength and dynamic response of in situ materials, whether cohesive or cohesionless. However, in some instances, reconstituted or remolded samples must be used when representative undisturbed samples cannot be obtained. Remolded samples are also used as representative of compacted fill or backfill material for new construction. Undisturbed samples of earth fill are taken for confirmatory testing during construction. Undisturbed samples are also taken in the testing and reevaluation of existing

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structures. Reconstituted specimens representative of in situ material should be molded to the in situ density and moisture content as determined from actual field measurements. Regulatory Guide 1.132 discusses methods of determining the in situ density of cohesionless soils. Samples representative of fill material should be molded to the range of densities and water contents expected or obtained under field conditions.

In preparing remolded specimens, care should be taken to avoid mixing granular soils of different gradation. Such a mixture may exhibit behavior that is entirely different from that of its separate components, even though the density is closely reproduced. Scalping (the removal of the coarse fraction of a sample) is also known to influence test results particularly in dynamic testing, but the nature of the influence is not well understood. Therefore, scalping should be avoided whenever possible.

6. *Laboratory Testing Program*

All soils and rocks sampled at the site need to be identified and classified. This requires index and classification tests and water content and density determinations. Additional classification tests may also include grain size analyses, mineralogical analyses, organic content determinations, and other types of testing as appropriate to the soil and rock types and water conditions encountered.

Test requirements beyond those for identification and classification are determined by consideration of the nature and distribution of the soil and rock materials at the site, material properties, design loading conditions, and potential problems. Common tests required of foundation and embankment materials include drained and undrained shear strength, consolidation and swelling characteristics, compaction, relative density, and permeability.

In addition to the usual geotechnical engineering considerations, the investigation and evaluation of sites for nuclear power plants require an evaluation of the site response to earthquake loading as well as other dynamic loading conditions. Such analyses include the evaluation of wave propagation characteristics of subsurface materials with interaction effects of structures, the analysis of the potential for soil *liquefaction*, settlement under dynamic loading, and the analysis of the effects of earthquake loading on the stability of slopes and embankments.

The basic parameters required as input for dynamic response analyses of soils include total mass density, relative density, Poisson's ratio, the static soil strength, initial stress conditions, shear and compressional wave velocities, and the dynamic shear modulus and *damping* ratio. The variation of strength, moduli, and damping with strain is also needed for such analyses.

7. *Testing Procedures for Determining Static Soil Properties*

a. *Soil Testing*

WASH-1301 (Ref. 39) describes the methods commonly employed in determining the classification and engineering properties of soils and rocks. It places into perspective the various aspects of classification and engineering properties as they pertain to geotechnical investigations for nuclear plants.

Whenever possible, laboratory testing should be carried out according to generally accepted published procedures. Such published procedures include those of the standards of the American Society for Testing and Materials (ASTM), the American Association of State Highway and Transportation Officials (AASHTO, formerly AASHO), and those established by U.S. Government agencies such as the U.S. Army Corps of Engineers, the Bureau of Reclamation, and the Soil Conservation Service. Others include widely known and accepted tests, monographs, and journals describing test procedures and publications of similar character and standing. Laboratory procedures for some of the more common tests are included in Appendix B together with references to selected literature. Criteria regarding testing procedures are stated in regulatory positions 1 and 5.

The U.S. Army Engineer Manual EM 1110-2-1906, "Laboratory Soil Testing" (Ref. 3) and ASTM standards (Refs. 8, 9) give detailed procedures that are widely accepted for many index and engineering property tests of soils. These include:

Water Content	Permeability
Unit Weights	Consolidation
Void Ratio	Direct Shear Test
Porosity	Triaxial Compression Tests
Saturation	
Atterberg Limits	Unconfined Compression Tests
Specific Gravity	
Grain Size Analysis	Relative Density
Compaction	

In addition to the Corps of Engineers Manual, there is a two-volume monograph entitled *Methods of Soil Analysis* (Ref. 10) sponsored jointly by the American Society of Agronomy and the American Society for Testing and Materials that provides accepted procedures for determining some engineering properties and a wide variety of tests for physical, chemical, and microbiological properties of soils. Both the Corps of Engineers Manual and this monograph provide valuable discussions of common problems, precautionary measures, calibration procedures, and control of errors in testing soils.

Where cohesive soils are used in water-retention structures, or are otherwise used to control water movement, it is essential that the *dispersion* characteristics and erodibility of the soil be evaluated by suit-

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able tests of samples remolded to the same density and water content used for design. Acceptable testing methods are described by Sherard et al. (Ref. 11) and Perry (Ref. 12).

b. *Tests of Groundwater or Surface Waters.* The requirements for testing of groundwater and surface water depend on the nature of potential problems identified at the site. Acid water, for example, may cause the degradation of carbonate rocks and concrete foundations. Standard methods of testing water for physical, chemical, radioactive, and microbiological properties are described in Reference 2. This reference also describes methods of testing polluted water, wastewaters, effluents, bottom sediments, and sludges. Standard testing methods can be used unless special problems are encountered that require modifications or alternative methods.

8. *Testing Procedures for Determining Dynamic Soil Properties and Soil Behavior*

a. *General*

Some laboratory investigations and testing procedures for determining dynamic soil properties and soil behavior are listed, with references, in Appendix B. Test methods and analyses relevant to determining the dynamic response of soils are discussed by Shannon and Wilson and Agbabian-Jacobsen Associates (Refs. 13, 14). Silver discusses laboratory procedures for conducting cyclic triaxial tests in Reference 30. Criteria regarding some of the procedures used in dynamic soil testing are given in regulatory position 4.

It is important that the laboratory tests represent field conditions as closely as practical to ensure a realistic assessment of soil properties. Before dynamic tests are performed, the initial state of stress in the soil is normally determined, and a series of static consolidated-drained and consolidated-undrained triaxial compression tests are made to determine static strength. The dynamic testing program includes tests to determine the soil parameters needed as input for reference analyses and soil structure interaction studies as well as testing to determine the dynamic strength characteristics and liquefaction potential of soils. Criteria regarding the range of consolidation stress ratios and confining pressures that are appropriate for both static and dynamic testing are given in regulatory position 4.

b. *Testing to Determine the Dynamic Shear Modulus, Damping, and Poisson's Ratio*

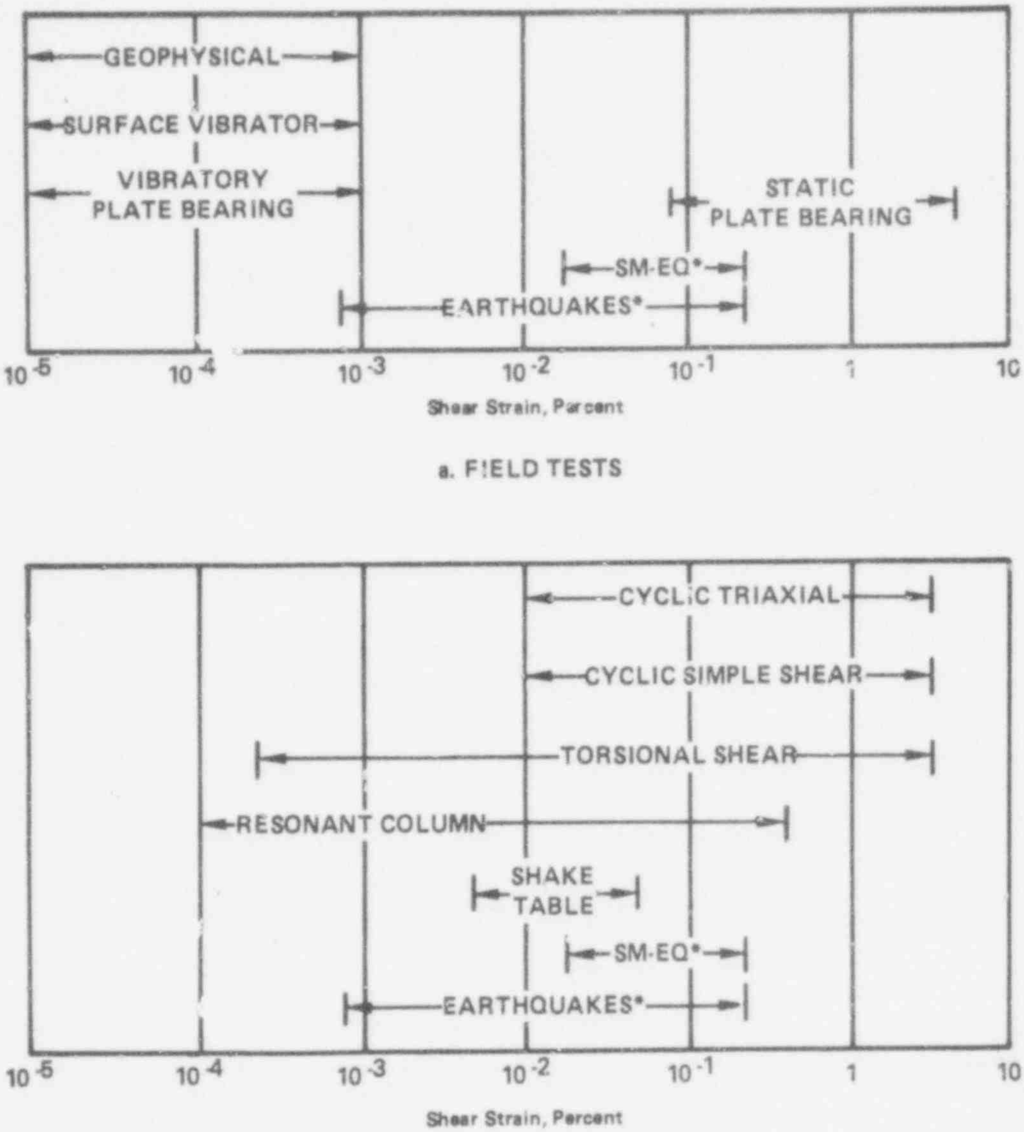
The dynamic shear modulus and damping values in soils are strain dependent; it is therefore important to determine these properties using several different testing methods to cover various ranges of applied strain. Figure 1 shows the level or range of strain applicable to each test procedure.

Laboratory tests that measure shear modulus include the cyclic simple shear test, the cyclic torsional shear test, and the resonant column test. In addition, the cyclic triaxial test is used to determine the Young's modulus from which the shear modulus may be calculated based on an estimated value for Poisson's ratio. This is an indirect method of estimating the shear modulus, but it is widely used. The resonant column device has been improved to cover a broader range of applied shear strain, and the device is becoming more commonly available. The resonant column and cyclic triaxial tests are also the most commonly used laboratory procedures for determining material damping. Regardless of the methods used in determining the shear modulus and damping characteristics of soils, it is important to use several different techniques and to correlate laboratory data with geophysical data from the field. The range of values selected for design purposes should then be tempered with judgment and experience.

Values of Poisson's ratio may be obtained in the laboratory by (1) monitoring both axial and radial strains in the cyclic triaxial compression test, (2) comparing data from cyclic triaxial and cyclic simple shear tests, or (3) comparing response in the axial mode with that in the torsional mode in the resonant column test. Care should be taken that data compared are from tests with approximately equal strain levels. Laboratory determination of Poisson's ratio is difficult, and it is sometimes preferable to determine values based on field measurement of shear and compression wave velocity in situ. Also, in some cases there may be laboratory or field test data available for similar soils that should be evaluated in estimating values of Poisson's ratio. Under dynamic or undrained conditions, Poisson's ratio for fully saturated soils normally will have a value approaching 0.5 because of the influence of the water, whereas soils of low saturation usually have lower values.

c. *Testing to Determine Dynamic Shear Resistance and Liquefaction Potential*

The shear and other deformation behavior of soils subjected to seismic or other dynamic loads may be determined by a testing program including both monotonic (static) and cyclic load tests. Appropriate static tests include consolidated-undrained triaxial tests with pore pressure measurements. These tests may include isotropically and anisotropically consolidated specimens, with a range of confining pressures and *consolidation stress ratios* appropriate to the field conditions. The effect of cyclic loading is evaluated by a program of *stress- or strain-controlled cyclic loading tests*. Equipment available for conducting such tests include the cyclic triaxial, cyclic simple shear, and cyclic torsional shear devices. However, the cyclic triaxial device is more commonly available. It is important that the scope of the dynamic testing program



a. FIELD TESTS

b. LABORATORY TESTS

*Note: Range of shear strain denoted as "Earthquakes" represents an extreme range for most earthquakes. "SM-EQ" denotes strains induced by strong motion earthquakes.

Figure 1. Field and Laboratory Tests Showing Approximate Strain Ranges. (Adapted From Reference 13).

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be sufficient to determine the degree to which shearing resistance is affected by cyclic loading.

d. *Special Considerations in Performing Dynamic Soil Testing*

In planning, performing, and interpreting dynamic laboratory tests, consideration should be given to (1) the condition of undisturbed test specimens and the degree to which the structure of the soil has been preserved, (2) the method of reconstituting remolded samples, (3) the consolidation and saturation of the specimens prior to testing, (4) the applied confining pressures and the applied axial deviator stress or stress ratio, (5) the wave form of cyclic loading, (6) the frequency of loading, and (7) the duration of confining pressure application. The time effect of loading is particularly important for cohesive soils. All of these factors and parameters will have an important influence on test results and their interpretation. For example:

(1) The method of reconstituting samples has a strong effect on dynamic test results, and it is important to consider this effect in the interpretation of test data as well as in planning the test program. Mulilis, Chan, and Seed (Ref. 15) discuss the effect of method of sample preparation on the results of cyclic loading tests.

(2) Square-wave loading produces more severe conditions than sinusoidal loading and consequently may produce an apparently lower *cyclic shear strength* or greater susceptibility to liquefaction. At the other extreme, triangular wave loading produces less severe conditions than sinusoidal loading and consequently may produce an apparently higher cyclic shear strength or lower susceptibility to liquefaction.

(3) Information available at the present time indicates that the dynamic behavior of soils is relatively insensitive to the frequency of applied cyclic loading within the range of 0.5 to 2 Hz. It is therefore common practice to carry out laboratory cyclic tests at a frequency in the neighborhood of 1 Hz.

C. REGULATORY POSITION

1. *General Requirements for a Laboratory Testing Program*

a. A labroatory testing program needed for determining the properties of subsurface materials at a nuclear power plant site is highly dependent on actual site conditions, material properties, and design requirements for foundations and earthworks. Therefore, a program should be made flexible and tailored to each site and plant design as the site and laboratory investigations proceed and should be under the direction of experienced engineers and geologists that have demonstrated competence in the field of soil and rock mechanics testing and are familiar with the site. Laboratory tests on soil and rock material should be thorough and of documented quality that permits a realistic estimate of soil and rock properties and subsurface conditions.

b. Personnel experienced in laboratory practices for soil testing should be responsible for handling samples, preparing test specimens, testing procedures and operations, and all related documentation.

c. The testing facility should be adequate for the planned testing program. It should be a substantial structure free of traffic and machinery vibration and should be provided with sufficient area to separate activities such as sample preparation, sieve analyses, compaction tests, and physical property tests.

Equipment should be initially calibrated when installed as in the case of field facilities and regularly inspected and maintained. A calibration program that is formally documented as part of the laboratory testing program should be provided. The program should ensure that equipment is recalibrated at least annually and continually inspected. Standards traceable to the National Bureau of Standards should be used for recalibration and should be at least four times as accurate as those required of the working instrument.

d. The number of tests required in a laboratory investigation program will depend upon the type of material, the quality of samples, the purpose and relative importance of the test, and the scatter of test data. In general, all soils and rocks sampled at the site should be first identified and classified using appropriate index and classification tests. The Unified Soil Classification System should be used in describing soils and in preparing soil profiles. Further tests required to establish physical and engineering properties should be sufficient to define the range of values for material properties. A sufficient number of tests should be completed to cover the range of values expected under field conditions for such important variables as confining pressure, consolidation ratio, degree of saturation, and density.

e. When applicable, laboratory tests should be carried out according to generally accepted published procedures such as those identified in this guide. Appendix B lists preferred methods for conducting many soil and rock tests.

Standard test procedures that are followed without deviation and performed on standard equipment require documentation by reference only. For tests where there are no standard procedures available or where it is appropriate to use modified or alternative procedures, the details of the test procedures should be documented for evaluation and future referencing. The technical basis for deviating from standard testing procedures should be documented. Use of other than standard equipment, even if it is used with standard testing procedures, should also be documented.

2. *Handling and Storage of Samples*

Undisturbed samples should be transported and handled so as to minimize disturbance of the soil structure by impact or vibration, and they should be protected against changes in water content. Undisturbed sand samples may be partially drained before transporting and storing. Regardless of the methods used for handling and transporting samples, some type of control measure should be made to detect potential disturbance. Moisture seals should be periodically checked and renewed as needed.

Samples should be tested as soon as possible after reaching the laboratory to minimize the effects of structural and chemical changes with time. The duration of storage before testing should be recorded for each sample test. Samples that have been stored for long periods of time should not be considered to have the characteristics of undisturbed samples. Therefore, they should not be tested as undisturbed samples.

3. *Selection and Preparation of Test Specimens*

a. *Undisturbed Samples*

Test specimens should be *representative* of each discrete soil or rock unit to be tested and should be accurately described on the basis of classification tests to permit establishment of the soil and geologic profiles. The best quality and most representative undisturbed samples available should be used in physical and engineering property tests of in situ soils whether cohesive or cohesionless.

Undisturbed tube samples should satisfy the following criteria:

(1) The *specific recovery ratio* should be between 90 and 100 percent; a tube with less recovery may be acceptable if it appears that the sample may have broken off and otherwise appears undisturbed. The actual recovery obtained should be recorded and documented.

(2) On the surface of or in sliced sections of the sample, there should be no visible distortions, planes of failure, pitting, discoloration, or other signs of disturbance that can be attributed to the sampling operation or handling of the sample.

(3) The net length and weight of the sample and the results of other control tests should not have changed during shipment, storage, and handling of the sample.

In addition to the above, samples that have been subjected to violent mechanical shocks or to accidental freezing and thawing should not be considered to be undisturbed even if other evidence of disturbance is absent.

b. *Reconstituted or Remolded Samples*

Where reconstituted specimens must be used to represent in situ materials, as in the case of some sands or gravelly soils, they should be reconstituted to the in situ density and water contents as determined from actual field measurements. Usually, the use of relative density as interpreted from Standard Penetration Tests (SPT) is not sufficiently accurate for determining densities in cohesionless soils. Regulatory Guide 1.132, "Site Investigations for Foundations of Nuclear Power Plants," discusses methods of determination of in situ density in cohesionless soils. Samples prepared as representative of fills such as earth embankments should be remolded to the range of water contents acceptable for fill placement and compacted to densities equivalent to those that will be achieved under field conditions.

Where large particles are present in the material to be tested, the diameter of the test specimen should be at least six times the diameter of the largest particle. Scalping should be avoided whenever possible. In instances where scalping cannot be avoided, the test specimens should be prepared at a density corresponding to the *matrix* density of the material, which is normally lower than the total bulk density. This may be done by replacing oversize particles with an equal percentage, by weight, of material retained on the No. 4 sieve, with a top size not exceeding the maximum allowable sieve size. Scalping procedures should be explained together with reasons for expecting test results to be valid. Experience has shown that reconstituting samples to the matrix density of the material will sometimes give different results. However, it is believed to be a conservative approach. For granular soils, an alternative would be to prepare the sample to a density corresponding to the same relative density as that of the original in situ unscalped material.

4. *Criteria for Testing Procedures*

a. *General*

(1) All representative soil samples prepared for consolidated triaxial compression tests, whether static or dynamic, should be consolidated to a range of consolidation stress ratios appropriate to expected field conditions. Consolidation stress ratio values of 1.0, 1.5, and 2.0 are usually satisfactory but may vary with anticipated soil conditions. Confining pressures should also cover a range of values corresponding to those expected in the field. Pore pressures should be measured in consolidated undrained static and dynamic tests. Sufficient data should be obtained to permit the determination of the nonlinearity of the consolidated drained and consolidated undrained stress-strain relations, as well as the peak and residual shear strengths. Also, testing should be performed on both isotropically and anisotropically consolidated specimens, as necessary, to represent initial stress conditions in the field.

(2) Tests of soils that will be below the water table or will become saturated during plant operation should be performed only on specimens that are essentially 100% saturated, as indicated by Skempton's *B-value*. The minimum acceptable B value is considered to be 0.95.

b. *Cyclic Loading Tests*

(1) It is recommended that the cycle triaxial device be periodically checked by measuring the cyclic strength of some standard sand as that described by Silver et al. (Ref. 28).

(2) The absolute value of the *applied deviator stress* σ_{dp} in the cyclic triaxial tests normally should not exceed the effective ambient confining pressure (σ_3) so that the vertical stress remains compressive. Exceeding the effective confining pressure will result in physical pulling on the end caps in the extension half of the loading cycle and, unless the sample is highly dilative, will cause separation of the cap from the sample. Applied stress ratios of loading $\frac{\sigma_{dp}}{2\sigma_3}$ in the triaxial device should therefore normally be limited to 0.5. A higher ratio may be acceptable if the sample is sufficiently dilative so that the effective stress remains compressive and the end cap does not separate from the sample. These conditions should be thoroughly documented.

(3) Test specimens in cyclic triaxial tests sometimes neck (experience exaggerated reduction in cross sectional area usually near the end cap) during extension. Test results should be considered invalid from the moment that necking begins. Tests in which necking occurs should be identified in the documentation of test results.

(4) The loading function used in the dynamic testing program should be documented. The loading function for cyclic tests should be reasonably representative of field loading conditions. Whatever the form of loading function used, the first half cycle of loading in a cyclic triaxial test should be compressional. The effects of the loading function used on apparent dynamic shear strength should be considered when evaluating test results. The staff will interpret test data based on the loading function used.

(5) Cyclic tests should be carried out with loading frequencies within the range 0.5 to 2 Hz.

(6) In cyclic loading tests on soils where the form of a relation between dependent and independent variables (such as cyclic shear stress and number of cycles to a particular strain level or failure) is known or suspected to be nonlinear, the curve expressing the relation should have sufficient data points to accurately define the curve. The range of applied shear or deviator stress values in the cyclic test should sufficiently encompass anticipated field loading conditions to permit the margin of safety to be evaluated. The number of tests required should be increased when the scatter of data is wide and when there are large variations in material gradation or density, quality of samples, or changes and adjustments in test procedures.

5. *Documentation of Test Results*

a. All laboratory test results and soil and rock identifications and descriptions should be documented in detail in a manner that permits independent verification and analysis of data. All test data including seemingly anomalous test results should be included.

b. The degree of variability or scatter in data, the range of extreme values, and selected design values should be clearly shown to permit an independent evaluation of the test results.

c. The scales of all graphs, diagrams, and plots should be so chosen that data may be read directly from these documents with an engineer's scale. The scales should be identified on all such documents.

D. IMPLEMENTATION

This guide will be used by the staff to evaluate the results of laboratory tests on soils and rocks including the adequacy and quality of data provided to define their characteristics and properties needed for engineering analysis and design. The staff will use this guide to evaluate the results of laboratory tests submitted in connection with construction permit applications docketed after December 1, 1978. The staff will also use this guide to evaluate the results of any new tests performed after December 1, 1978, by a person whose construction permit was issued on or before December 1, 1978.

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APPENDIX A

DEFINITIONS

For the convenience of the user, the following terms are presented with their definitions as used in this guide:

Applied deviator stress (σ_{dp}) is the cyclic stress applied to the vertical axis of a sample in a cyclic triaxial test with an ambient confining pressure equal to σ_3. In the compression half of the loading cycle, the vertical stress σ_1 equals $\sigma_3 + \sigma_{dp}$ in the extension half of the loading cycle, $\sigma_1 = \sigma_3 - \sigma_{dp}$.

B-value is a measure of the degree of soil saturation used when preparing samples for testing. It is defined as $B = \frac{\Delta u}{\Delta \sigma_a}$ where Δu is the pore water pressure induced in a soil sample as a result of a given applied increase in ambient pressure $\Delta \sigma_a$.

Consolidation stress ratio is the ratio of the major principal stress to the minor principal stress during consolidation. If the ratio is unity, consolidation is isotropic.

Cyclic strength is the cyclic stress that produces either a failure condition or a specific level of strain measured in extension or compression or both (double amplitude strain) in a given number of cycles.

Damping is the dissipation of strain energy during cyclic loading. The energy dissipated is proportional to the area of the hysteresis loop. (See Reference 32 for relationships between damping terms.)

Dispersion (of soils) refers to a change in soil structure with loss of bonding forces between particles so that the particles tend to assume wider spacing and are relatively easily eroded.

Disturbed sample is a sample whose internal structure has been damaged to such a degree that it does not reasonably approximate that of the material in situ. Such a sample bears a resemblance to an undisturbed sample in having preserved the gross shape given it by a sampling device.

Humid room is a room or chamber in which the relative humidity is maintained at or near 100%. It is used for storage of samples and/or preparation of test specimens.

Inside clearance ratio, C_i, of a sampling device, is defined as:

$$C_i = \frac{D_s - D_e}{D_e}$$

where D_s is the inside diameter of the body of the sample tube or liner and D_e is the diameter of the cutting edge.

Liquefaction refers to a significant loss of shearing resistance in a cohesionless soil, due to an increase in pore pressure under loading. It may be caused by cyclic or monotonic increase in static loading.

Matrix in soil or rock is the assemblage of finer grains in which grains of distinctively larger size are embedded.

Representative sample is a sample that contains (1) approximately the same mineral constituents of the stratum from which it is taken in the same proportions and with the same grain size distribution and (2) is uncontaminated by foreign materials or by chemical alteration.

Specific recovery ratio in the advance of a sample tube is defined as:

$$R_s = \frac{\Delta L}{\Delta H}$$

where ΔL is the increment of length of sample in the tube corresponding to an increment ΔH of sampler advance.

Strain-controlled test is a test in which strains are produced in a specimen with controlled rate or magnitude.

Stress-controlled test is a test in which stresses are applied to a specimen with controlled rate or magnitude.

Soil structure is a complex physical-mechanical property, components of which are the sizes, shapes, and arrangements of the constituent grains and intergranular matter and the bonding and capillary forces acting among the constituents.

Undisturbed sample is a sample obtained and handled in such a way that disturbance of its original structure is minimal so that the sample is suitable for laboratory tests of material properties that depend on in situ soil structure.

APPENDIX B

LABORATORY TEST METHODS FOR SOIL AND ROCK

NAME OF TEST	STANDARD OR PREFERRED METHOD [1]	OTHER REFERENCES	PROPERTIES OR PARAMETERS DETERMINED	REMARKS/SPECIAL EQUIPMENT REQUIREMENTS
		SOILS—INDEX AND CLASSIFICATION TESTS		
Gradation Analysis	ASTM D421 D422 D2217	Refs. 16, 3	Particle size distribution	Methods are applicable to some rocks, after disaggregation.
Percent Fines	ASTM D1140	Refs. 16, 3	Percent of weight of material finer than No. 200 sieve	
Atterberg Limits	ASTM D423 D424 D427	Refs. 16, 3	Plastic limit, liquid limit, plasticity index, shrinkage factors	
Specific Gravity	ASTM D854	Refs. 16, 3	Specific gravity or apparent specific gravity of soil solids	Boiling should not be used for de-airing. Method can be used for rock, after grinding sufficiently fine to eliminate internal voids in the intact rock.
Soil Description	ASTM D2488		Description of soil from visual-manual examination	
Soil Classification	ASTM D2487		Unified soil classification	
X-ray		Ref. 6	Comparative density, macrostructure	Very useful for detection of disturbance due to sampling and for delineation of soil strata in tube samples. Requires X-ray apparatus.
		SOILS—MOISTURE-DENSITY RELATIONS		
Bulk Unit Weight	Ref. 3		Bulk unit weight (bulk density)	Methods are applicable to rocks, with some obvious modifications.
Water Content	ASTM D2216 D2974	Ref. 3	Water content as percent of dry weight	Method is applicable to rock.
Relative Density	Ref. 3	ASTM D2049	Maximum and minimum density of cohesionless soils	Requires vibration table. In vibration table testing, both amplitude and frequency should be adjusted to values that yield greatest density. However, treatment that produces breakage of grains should be avoided and mechanical analyses should be performed as a check on grain breakage.
Compaction	ASTM D698 D1557	Ref. 3	Optimum moisture content-density relations	Method for earth and rock mixtures is given in Ref. 3.
		SOILS—CONSOLIDATION AND PERMEABILITY		
Consolidation	ASTM D2435	Refs. 16, 3	One-dimensional compressibility, permeability of cohesive soil	

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NOTE: 1. ASTM standard methods are given in Reference 8.

NAME OF TEST	STANDARD OR PREFERRED METHOD[1]	OTHER REFERENCES	PROPERTIES OR PARAMETERS DETERMINED	REMARKS/SPECIAL EQUIPMENT REQUIREMENTS
		Ref. 17	One-dimensional expansion vs. load relation	Method uses conventional consolidometer apparatus.
Permeability	ASTM D2434	Refs. 3, 17	Permeability	Suitable for remolded or compacted soils. For natural, in situ soils, field test should be used.
		SOILS—PHYSICAL AND CHEMICAL PROPERTIES		
Mineralogy	Ref. 19	Ref. 20	Identification of minerals	Applicable to rock. Requires X-ray diffraction apparatus. Differential thermal analysis apparatus may also be used.
Organic Content	Ref. 21	ASTM D2974; Ref. 22	Organic and inorganic carbon content as percent of dry weight	Dry combustion methods (ASTM D2974) are acceptable, but where organic matter content is critical, data so obtained should be verified by wet combustion tests (Ref. 21).
Soluble Salts	Ref. 23		Concentration of soluble salts in soil pore water	
Pinhole Test		Refs. 11, 12	Dispersion tendency in cohesive soils	Significant in evaluation of potential erosion or piping (Ref. 24).
		SOILS—SHEAR STRENGTH AND DEFORMABILITY		
Unconfined Compression	ASTM D2166	Ref. 3	Strength of cohesive soil in uniaxial compression	
Direct Shear, Consolidated-Drained	ASTM D3080	Ref. 3	Cohesion and angle of internal friction under drained conditions	
Triaxial Compression, Unconsolidated-Undrained	ASTM D2850	Refs. 25, 3	Shear strength parameters; Cohesion and angle of internal friction for soils of low permeability	
Triaxial Compression, Consolidated-Undrained		Refs. 3, 25	Shear strength parameters; Cohesion and angle of internal friction for consolidated soil. With pressure measurements, cohesion and friction may be obtained.	Circumferential drains, if used, should be slit to avoid stiffening test specimen.
Triaxial Compression, Consolidated-Drained		Refs. 3, 25	Shear strength parameters; Cohesion and angle of internal friction, for long-term loading conditions	Circumferential drains, if used, should be slit to avoid stiffening test specimen.
Cyclic Triaxial Strain-Controlled [2]		Refs. 26, 13	Young's modulus damping and pore pressure response of cohesionless soils, modulus and damping of cohesive soils	See text, subsection 9(e).
Cyclic Triaxial, Stress Controlled	Ref. 27	Refs. 13, 28	Cyclic strength of cohesive and cohesionless soils	See text, subsection 9(e).

2. Comprehensive single references are not available for most dynamic test procedures. A literature survey is recommended to any laboratory performing such tests.

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NAME OF TEST	STANDARD OR PREFERRED METHOD[1]	OTHER REFERENCES	PROPERTIES OR PARAMENTERS DETERMINED	REMARKS/SPECIAL EQUIPMENT REQUIREMENTS
Cyclic Simple Shear[3]		Refs, 29, 30, 31, 32	Shear modulus and damping values and cyclic strength of cohesive and cohesionless soils	Tests may be run with either stress control or strain control. Two different types of apparatus, NGI and Roscoe devices, are described in Refs. 29 and 31, respectively.
Resonant Column		Ref. 33	Shear modulus and damping in cohesive and cohesionless soils. Some devices can be used with deformations in longitudinal mode to determine Young's modulus. Some devices can be used to determine cyclic strength.	Requires resonant column device.
		ROCKS—ENGINEERING PROPERTIES[3]		
Porosity		Refs. 34, 35	Bulk unit weight, specific gravity, and total porosity (Melcher Method) or effective porosity (Simmons or Washburn-Bunting Method)	Soil testing methods generally applicable with minor modification.
Permeability		Refs. 34, 35	Permeability of intact rock	Laboratory permeability values are not normally representative of in situ permeability of shallow jointed rock masses.
Seismic Velocity	ASTM D2845	Refs. 7, 36	Compressional and shear wave velocities in intact rock	Requires signal generator, transducers, oscilloscope.
Direct Tensil Strength	ASTM D2936	Ref. 7	Uniaxial tensile strength of intact rock	
"Brazilian Test"		Ref. 7	Indirect measure of tensile strength of intact rock	
Modulus of Rupture		Ref. 7	Indirect measure of tensile strength of intact rock	
Unconfined Compression	ASTM D2938	Ref. 7	Young's moduli and unconfined compressive strength of intact rock	
Triaxial Compression (Undrained)	ASTM D2664	Ref. 7	Young's moduli, cohesion friction parameters of failure envelope	
Triaxial Compression with Pore Pressure Measurements		Ref. 37	Young's moduli, cohesion friction parameters of effective stress conditions	
Slake Durability		Ref. 38	Index of resistance to slaking	

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3. Many methods of tests for soil are also applicable to rock. See under listings for soils.

APPENDIX C
REFERENCES

1. U.S. Army Engineer Manual EM 1110-2-1909, *Calibration of the Laboratory Soils ʹesting Equipment*, Washington, D.C., 1970.

2. American Public Health Association, American Water Works Assoᴗiation, and Water Pollution Control Federation, *Standard Methods for the Examination of Water and Wastewater*, 13th ed., New York, 1971.

3. U.S. Army Engineer Manual EM 1110-2-1906, *Laboratory Soils Testing*, Washington, D.C., 1970.

4. A. R. A. Arman and Kenneth L. McManis, "Effects of Storage and Extrusion of Sample Properties," *Soil Specimen Preparation for Laboratory Testing*, ASTM STP 599, American Society for Testing and Materials, 1976.

5. M. J. Hvorslev, *Subsurface Exploration and Sampling of Soils for Civil Engineering Purposes*, U.S. Army Waterways Experiment Station, Vicksburg, Mississippi, 1949.

6. E.L. Krinitzky, *Radiography in the Earth Sciences and Soil Mechanics*, Plenum Press, New York, 1970.

7. Obert, Leonard, and Duvall, *Rock Mechanics and the Design of Structure ʹn Rock*, John Wiley & Sons, Inc., New York, 1967.

8. American Society for Testing and Materials, *Special Procedures for Testing Soil and Rock for Engineering Purposes*, ASTM STP 479 Philadelphia, Pennsylvania, 1970.

9. American Society for Testing and Materials, *Annual Book of ASTM Standards: Part 19*, Philadelphia, Pennsylvania.

10. American Society of Agronomy and American Society for Testing and Materials, *Methods of Soil Analysis*. Parts 1 and 2, American Society of Agronomy, Inc., Madison, Wisconsin, 1965.

11. J. L. Sherard, L. P. Dunningan, R. S. Decker, and E. G. Steele, "Pinhole Test for Identifying Dispersive Spills," *Journal of the Geotechnical Engineering Division*, American Society of Civil Engineers, Vol. 102, No. GT 1, 1976, pp. 69-85.

12. E. G. Perry, "Piping in Earth Dams Constructed of Dispersive Clay; Literature Review and Design of Laboratory Tests," Technical Report S-75-15, U.S. Army Waterways Experiment Station, Vicksburg, Mississippi, 1975.

13. Shannon & Wilson, Inc., and Agbabian-Jacobsen Associates, *Soil Behavior Under Earthquake Loading Conditions; State-of-the-Art Evaluation of Soil Characteristics for Seismic Response Analyses*, Report for U.S. Atomic Energy Commission, 1972.

14. Shannon & Wilson, Inc. and Agbabian Associates, *In Situ Impulse Test; An Experimental and Analytical Evaluation of Data Interpretation Procedures*, Report for U.S. Nuclear Regulatory Commission, 1976.

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

16. T. W. Lambe, *Soil Testing for Engineers*, John Wiley & Sons, Inc., New York, 1951.

17. W. G. Holtz, "Suggested Method of Test for One-Dimension Expansion and Uplift Pressure of Clay Soils," *Special Procedures for Testing Soil and Rock for Engineering Purposes*, ASTM STP 479, American Society for Testing and Materials, Philadelphia, Pennsylvania, 1970a, pp. 198-205.

18. W. G. Holtz, "Suggested Method of Test for Permeability of Undisturbed Soil or Rock Specimens," *Special Procedures for Testing Soil and Rock for Engineering Purposes*, ASTM STP 479, American Society for Testing and Materials, Philadelphia, Pennsylvania, 1970b, pp. 150-156.

19. C. M. Warshaw and R. Roy, "Classification and a Scheme for the Identification of Layer Silicates," *Bulletin of the Geological Society of America*, Vol. 72, pp. 1455-1492, 1961.

20. Jack E. Gillott, *Clay in Engineering Geology*, Elsevier, New York, 1968.

21. L. E. Allison, "Wet Combustion Apparatus and Procedure for Organic and Inorganic Carbon in Soil," *Proceedings, Soil Science Society of America*, Vol. 24, pp. 36-40, 1960.

22. N. O. Schmidt, "Suggested Method of Test for Organic Carbon Content of Soil by Wet Combustion," *Special Procedures for Testing Soil and Rock for Engineering Purposes*, American Society for Testing and Materials, STP 479, Philadelphia, Pennsylvania, 1970.

23. Soil Co... ation Service, *Soil Survey Laboratory Methods and Procedures for Collecting Soil Samples*, Soil Survey Investigations Report No. 1, U.S. Soil Conservation Service, Washington, D.C., 1967.

142 148

24. J. L. Sherard, L. P. Dunningan, and R. S. Decker, "Identification and Nature of Dispersive Soils," *Journal of the Geotechnical Engineering Division*, ASCE, Vol. 102, No. GT 4, 1976, pp. 287–301.

25. A. W. Bishop and D. J. Henkel, *The Measurement of Soil Properties in the Triaxial Test*, 2d ed., Edward Arnolds, Ltd., London, 1962.

26. M. L. Silver and T. K. Park, "Testing Procedure Effects on Dynamic Soil Behavior," *Journal of the Geotechnical Engineering Division*, ASCE, Vol. 101, No. GT 10, 1975, pp. 1061–1083.

27. M. L. Silver, "Laboratory Triaxial Testing Procedures to Determine the Cyclic Strength of Soils," NUREG-0031, U.S. Nuclear Regulatory Commission, 1976.

28. M. L. Silver, et al., "Cyclic Triaxial Strength of Standard Test Sand," *Journal of the Geotechnical Engineering Division*, ASCE, Vol. 102, No. GT 5, 1976, pp. 511–523.

29. G. R. Thiers and H. B. Seed, "Cyclic Stress-Strain Characteristics of Clay," *Journal of the Soil Mechanics and Foundations Division*, ASCE, Vol. 94, No. SM 2, 1968, pp. 555–569.

30. M. L. Silver and H. B. Seed, "Deformation Characteristics of Sand Under Cyclic Loading," *Journal of the Soil Mechanics and Foundations Division*, ASCE, Vol. 97, No. SM 8, 1971, pp. 1081–1098.

31. W. D. Liam Finn et al., "Sand Liquefaction in Triaxial and Simple Shear Tests," *Journal of the Soil Mechanics and Foundation Division*, ASCE, Vol. 97, No. SMS, 1971, pp. 639–659.

32. F. E. Richart et al., *Vibrations of Soils and Foundations*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1970.

33. B. O. Hardin, "Suggested Method of Test for Shear Modulus and Damping of Soils by the Resonant Column," *Special Procedures for Testing Soil and Rock for Engineering Purposes*, ASTM STP 479, American Society for Testing and Materials, Philadelphia, Pennsylvania, 1970.

34. Arthur W. Buell, "Porosity and Permeability Analysis," *Subsurface Geologic Methods (A Symposium)*, 1st ed., Colorado School of Mines, Golden, Colorado, 1950, pp. 168–175.

35. George H. Francher, "The Porosity and Permeability of Elastic Sediments and Rocks," *Subsurface Geologic Methods (A Symposium)*, 2nd ed., Colorado School of Mines, Golden, Colorado, 1950, pp. 685–712.

36. A. R. Gregory, "Shear Wave Velocity Measurements of Sedimentary Rock Samples Under Compression," *Proceedings, 5th Symposium on Rock Mechanics*, University of Minnesota, The McMillan Company, New York, 1963, pp. 439–471.

37. W. J. Heck, "Development of Equipment for Studying Pore Pressure Effects in Rock," *Proceedings, Tenth Symposium on Rock Mechanics*, University of Texas at Austin, American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., New York, 1972, pp. 243–266.

38. J. A. Franklin and R. Chandra, "The Slake-Durability Test," *International Journal of Rock Mechanics and Mineral Science*, Volume 9, Pergamon Press, Ltd., London, 1972, pp. 325–341.

39. W. I. Hall, N. M. Newmark, and A. J. Hendren, Jr., "Classification, Engineering Properties, and Field Exploration of Soils, Intact Rock, and In Situ Rock Masses," WASH-1301, U.S. Nuclear Regulatory Commission, Washington, D.C., 1974.

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