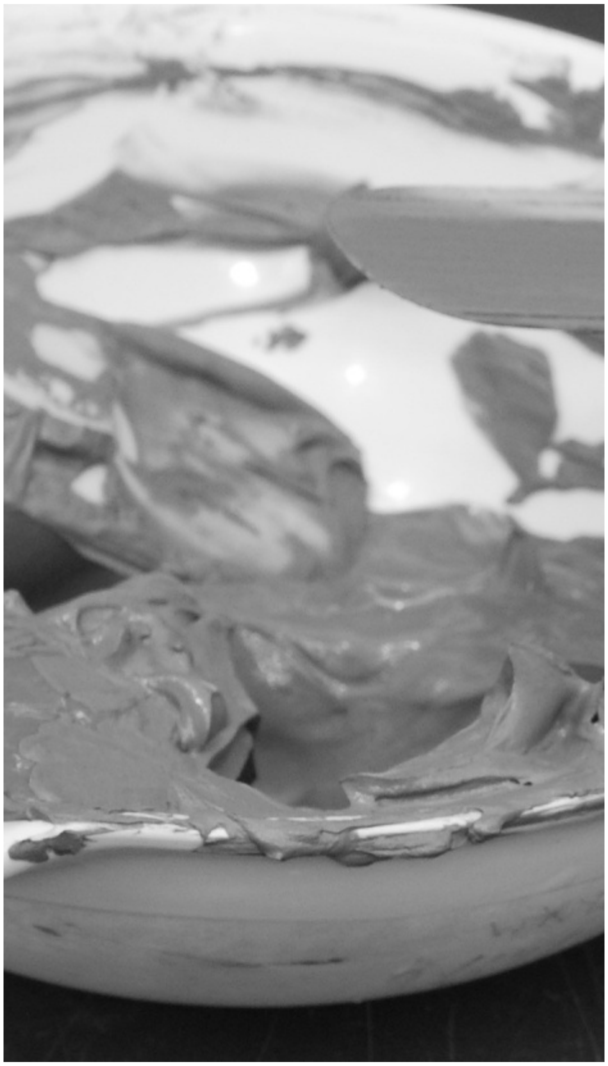
Part I



Chapter 1

Background Information for Part I

SCOPE

Experimental investigation requires an appreciation for more than the individual test method. In order to perform the tests effectively, interpret the measurements properly, and understand the results, background information is required on a variety of general topics. This chapter provides general information important to the overall operation of a laboratory, evaluation of a test method and test result, and handling of disturbed materials. Some of the individual topics are ASTM International, Interlaboratory Test Programs, Precision and Bias, Sampling, Bulk Material Processing, and Test Documentation.

The tests covered in Part I are normally performed on disturbed material and are used to characterize the nature of soils. There are a vast number of specific tests used to characterize particles, the pore fluid, and also the combination of both. Part I contains a variety of the most essential test methods used in geotechnical engineering to quantify the properties of a particular soil as well as providing exposure to a range of experimental techniques. The test methods in Part I are:

- Phase Relations
- Specific Gravity
- Maximum Density, Minimum Density

- Calcite Equivalent
- pH, Salinity
- Organic Content
- Grain Size Analysis
- Atterberg Limits
- Soil Classification and Description

These tests are generally referred to as index and physical property tests. These tests are performed in large numbers for most projects because they provide an economical method to quantify the spatial distribution of material types for the site investigation. The results of these tests are also useful in combination with empirical correlations to make first estimates of engineering properties.

LABORATORY SAFETY

Laboratories have numerous elements that can cause injury, even if an individual is merely present in a laboratory as opposed to actively engaged in testing. Some of the most significant dangers for a typical geotechnical laboratory are listed here. Significant applies to either most harmful or most common. Most of these dangers are entirely preventable with education, some preparation, and common sense. The most dangerous items are listed first. Unlimited supply means that once an event initiates, someone must intervene to stop it. Sometimes a person besides the afflicted individual has to step in, such as with electrocution. Limited supply means that once an event initiates it only occurs once, such as a mass falling from a bench onto someone's toe.

- Electricity (equipment, power supplies, transducers)—unlimited supply, no warning, could result in death. Observe appropriate electrical shut off and lock off procedures. Allow only professionals to perform electrical work. Dispose of equipment with damaged electrical cords rather than attempting to repair them. Do not expose electricity to water, and use Ground Fault Interrupters (GFIs) when working near water. Master proper grounding techniques.
- Fire (Bunsen burner, oven, electrical)—unlimited supply, some warning, could result in death, injury, and significant loss of property. Do not allow burnable objects or flammable liquids near Bunsen burners. Do not place flammable substances in the oven. Dispose of equipment with damaged electrical cords rather than attempting to repair them. Review evacuation procedures and post them in a visible, designated place in the laboratory.
- Chemical reaction (acids mixed with water, mercury, explosions)—large supply, little warning, could result in death or illness. Proper training and personal protection is essential when working with or around any chemicals in a laboratory. Procedures for storage, manipulation, mixing, and disposal must be addressed. Mercury was once used in laboratories (such as in thermometers and mercury pressure pots) but is slowly being replaced with other, less harmful methods.
- Blood (HIV, hepatitis)—contact could result in illness or death. Proper personal protection measures, such as gloves, are required, as well as preventing the other accidents described herein.
- Pressure (triaxial cells, containers under vacuum)—air can have a large supply, little warning, could result in significant injury. Open valves under pressure or vacuum carefully. Inspect containing devices for any defects, such as cracks, which will cause explosion or implosion at a smaller pressure than specified by the manufacturer.
- Power tools and machinery (motors, gears, circular saw, drill)—can have large supply if no safety shutoff, could result in significant injury and release of

blood. Proper procedures, protective gear, and attire are required, as well as common sense.

- Heat (oven racks, tares)—limited supply, could result in burn. Use protective gloves specifically designed for heat, as well as tongs to manipulate hot objects. Arrange procedures so that reaches are not required over or near an open flame.
- Sharp objects (razor blades, broken glass)—limited supply, dangers should be obvious, could result in injury and release of blood. Dispose of sharp objects using a sharps container.
- Mass (heavy pieces of equipment that fall)—limited supply but dangers can blend into background, could result in injury. Do not store heavy or breakable objects up high.
- Tripping, slipping, and falling hazards—limited supply but can blend into background, could result in injury. Do not stretch when trying to reach objects on shelves; instead, reposition to avoid overextension. Maintain a clear path in the laboratories. Put tools, equipment, and boxes away when finished. Clean up spills immediately and put up signage to indicate wet floors when necessary.
- Particulates (silica dust, cement dust)—unlimited supply, could result in serious long-term illness. Use dust masks when working with dry soils and cement. Note that other considerations may be required, such as ventilation.
- Noise (sieve shaker, compressor, compaction hammer)—unlimited supply, could result in damage in the long-term. Use ear protection when presence is absolutely required near a noisy object, such as a compressor. A better solution is to have this type of equipment enclosed in a sound barrier or placed in another designated room away from people. Note that other considerations may be required for the machinery, such as ventilation.

Laboratories require safety training to prevent accidents from happening, and to provide instruction on how to minimize damage should these events occur. Proper attire must be insisted upon. The laboratory must also provide safety equipment, such as eye protection; ear protection; latex, vinyl, or other gloves; and dust masks. A designated chair of authority is essential to facilitating an effective laboratory safety program.

Any person entering a laboratory must be made aware of the dangers lurking. In addition, it must be impressed upon persons working in the laboratory that organization and cleanliness are paramount to preventing unnecessary injuries.

TERMINOLOGY

Terminology is a source of confusion in any profession. Imprecise language can lead to misinterpretation and cause errors. Definitions of several very important material conditions terms follow, along with a discussion of appropriate and intended use. These terms are generally consistent with those found in the ASTM D653 Standard Terminology Relating to Soil, Rock, and Contained Fluids. ASTM International is discussed in the next section.

In situ

"In situ" describes rock or soil as it occurs in the ground. This applies to water content, density, stress, temperature, chemical composition, and all other conditions that comprise the importance characteristics of the material.

Sample versus Specimen

Throughout this text, soil will be discussed in terms of both samples and specimens. The two terms are frequently misused in practice. In reality, the two refer to different entities. A sample is a portion of material selected and obtained from the ground or other source by some specified process. Ideally, the sample is representative of the whole. A specimen is a subset of a sample and is the specific soil prepared for and used for a test. A specimen is generally manipulated or altered due to the test process.

Undisturbed versus Intact

"Undisturbed" is a very specific condition that signifies the in situ state of the soil. Literally taken, the adjective encompasses everything from temperature to stress to strain to chemistry. In concept, it can be used to describe samples or specimens, but as a practical matter it is impossible to remove material from the ground without causing some measurable disturbance. "Intact" is the preferred adjective to sample or specimen to signify that the material has been collected using state of the practice methods to preserve its in situ conditions commensurate with the testing to be performed. Describing material as "intact" acknowledges the fact that some disturbance has occurred during the sampling operation. This level of disturbance will depend on the method used to obtain the sample and the level of care used in the sampling operation.

Remolded versus Reconstituted

"Remolded" signifies modifying soil by shear distortion (such as kneading) to a limiting destructured condition without significantly changing the water content and density. A remolded sample is completely uniform and has no preferential particle structure. The mechanical properties at this limiting state are dependent on water content and void ratio. This is a terminal condition and from a practical perspective the completeness of remolding will depend on the method used to remold the material. "Reconstituted" describes soil that has been formed in the laboratory to prescribed conditions by a specified procedure. The fabric, uniformity, and properties of a reconstituted sample will depend on the method and specific details used to make the sample.

STANDARDIZATION

Commercial testing is not an arbitrary process. At the very least, each test method must have a specific procedure, defined characteristics of the equipment, and method of preparing the material. This is essential for a number of reasons. It provides consistency over time. It allows comparison of results from different materials. But most importantly, it allows others to perform the test with the expectation of obtaining similar results. There are many levels of formalization for this information. It may reside in an individual's laboratory notebook, be an informal document for a company laboratory, or be a formalized document available to the general public. Obviously, the level of effort, scrutiny, and value increase with the level of availability and formalization.

There are several standardization organizations, including the International Standardization Office (ISO), American Association of State Highway and Transportation Officials (AASHTO), British Standards (BS), and ASTM International (ASTM). The authors both do extensive volunteer work for ASTM and that experience is heavily represented in this book.

ASTM is a not-for-profit volunteer standardization organization, formerly known as American Society for Testing and Materials. ASTM documents are referred to as "standards" to accentuate the fact that they are products of the consensus balloting process. ASTM produces standard test methods, guides, practices, specifications, classifications, and terminology documents. The criteria for each of these terms as given in ASTM documentation (2008) is presented below:

> **standard**, *n*—as used in ASTM International, a document that has been developed and established within the consensus principles of the Society and that meets the approval requirements of ASTM procedures and regulations.
>
> DISCUSSION—The term "standard" serves in ASTM International as a nominative adjective in the title of documents, such as test methods or specifications, to connote specified consensus and approval. The various types of standard documents are based on the needs and usages as prescribed by the technical committees of the Society.
>
> **classification**, *n*—a systematic arrangement or division of materials, products, systems, or services into groups based on similar characteristics such as origin, composition, properties, or use.

guide, *n*—a compendium of information or series of options that does not recommend a specific course of action.

DISCUSSION—A guide increases the awareness of information and approaches in a given subject area.

practice, *n*—a definitive set of instructions for performing one or more specific operations that does not produce a test result.

DISCUSSION—Examples of practices include, but are not limited to, application, assessment, cleaning, collection, decontamination, inspection, installation, preparation, sampling, screening, and training.

specification, *n*—an explicit set of requirements to be satisfied by a material, product, system, or service.

DISCUSSION—Examples of specifications include, but are not limited to, requirements for physical, mechanical, or chemical properties, and safety, quality, or performance criteria. A specification identifies the test methods for determining whether each of the requirements is satisfied.

terminology standard, *n*—a document comprising definitions of terms; explanations of symbols, abbreviations, or acronyms.

test method, *n*—a definitive procedure that produces a test result.

DISCUSSION—Examples of test methods include, but are not limited to, identification, measurement, and evaluation of one or more qualities, characteristics, or properties. A precision and bias statement shall be reported at the end of a test method.

ASTM does not write the documents, but rather manages the development process and distribution of the resulting products. This is a very important distinction. The information contained in the document is generated by, and is approved by, the volunteer membership through a consensus process. It is essential to recognize that the very nature of the consensus process results in the standard establishing minimum requirements to perform the test method. An expert in the method will be able to make improvements to the method.

ASTM has over 200 Main Committees, including Steel, Concrete, and Soil and Rock. Main Committees are generally divided by technical interest but a particular profession may have interest in several committees. Each Main Committee is divided into subcommittees according to technical or administrative specialization.

ASTM has over 30,000 members, who are volunteers from practice, government, research, and academia. ASTM is an all-inclusive organization. ASTM has no particular membership qualification requirements and everyone with professional interest in a discipline is encouraged to join. Within each committee, there are specific requirements on the distribution of member types that have a vote as well as the restriction that each organization is limited to one vote. This is done so that manufacturers cannot sway the operation of the committees for financial gain.

Committee D18 is the Soil and Rock committee. It is divided into twenty technical subcommittees and seven administrative subcommittees. The committee meets twice per year for three days to conduct business in concurrent meetings of the subcommittees followed by a final Main Committee wrap-up.

ASTM mandates that every standard stays up to date. Each standard is reviewed every five years and placed on a subcommittee ballot. If any negative votes are cast and found persuasive by the subcommittee with jurisdiction, that negative vote must be accommodated. Comments must be considered as well, and if any technical changes are made to the document, it must be sent back to subcommittee ballot. Once the document makes it through subcommittee balloting without persuasive negatives and without technical changes, the item is put on a Main Committee ballot. Similarly, the document must proceed through the process at the Main Committee level without persuasive negatives or any required technical changes. The item is then published with any editorial changes resulting from the process. Any technical changes or persuasive negatives require that the item be sent back to subcommittee-level balloting. If successful ballot action has not been completed at both levels after seven years, the standard is removed from publication.

Each standard has a template format with required sections. This makes the tandard easy to use once familiar with the format but it also makes for uninteresting reading.

Standards are used extensively in all types of laboratory testing from very simple manual classification procedures to complicated engineering tests. In short, standardization provides a means of maintaining consistency of testing equipment and test methods across testing organizations. ASTM standards are the reference standards wherever possible in this textbook.

ASTM International publishes their standards in over seventy-five volumes. The volumes can be obtained individually or as various sets, and are published in three formats: print, compact disc, or online subscriptions. Libraries and organizations may have full sets of the ASTM volumes. Individual members are able to choose one volume a year as part of their membership fee. Annual membership dues are relatively small as compared to other professional organizations. Standards under the jurisdiction of D18 the Soil and Rock Committee are published in two volumes: 04.08 and 04.09.

ASTM also offers student memberships and has an educational program where professors can choose up to ten standards to use as part of their curriculum. This package is made available to students for a nominal fee. For more information, refer to ASTM's web site at www.astm.org. Navigate to the "ASTM Campus" area for student memberships, and educational products and programs.

EVALUATION OF TEST METHODS

How good is a test result? This is a very important question and one that has been very difficult to answer relative to testing geo-materials. Conventional wisdom holds that the natural variability of geo-materials is so large that any two results using the same method are "just as likely to be different because of material variability as due to the variation in performing the test." This line of thinking has had a serious negative impact on the advancement of quality testing. Within the last two decades there have been several attempts to improve the quality of testing. However, the cost of testing, the number of test methods, and the variability of geo-materials make this a difficult task.

Several terms are used to express the quality of a measurement such as accuracy, bias, precision, and uncertainty. ASTM has chosen to quantify the goodness of a test method in terms of two quantities: precision and bias. In fact, Precision and Bias is a mandatory section of every ASTM test method. Precision and bias are two separate measures that replace what one might typically consider "accuracy." Bias quantifies the difference between a measured quantity and the *true* value. Precision quantifies the scatter in measurements around an average value. Refer to Figure 1.1 for a schematic depiction of precision and bias.

Precision is especially useful in testing geo-materials because one can quantify the variability in measuring a rather arbitrary quantity. A good example of these concepts is the liquid limit test. The liquid limit is defined by the test method and is not

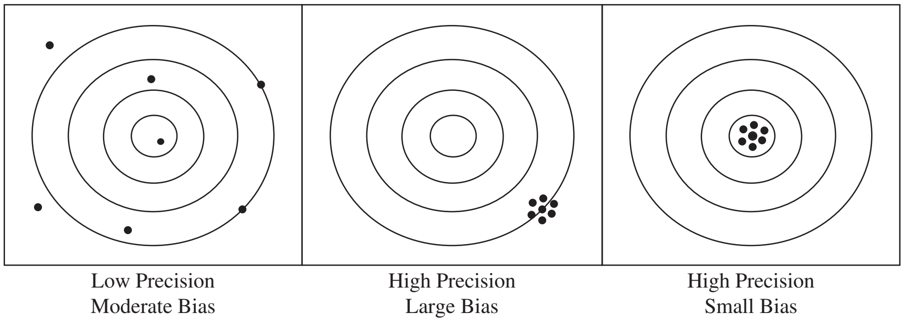


Figure 1.1 Schematic depiction of precision and bias. (Adapted from Germaine and Ladd, 1988).

an absolute quantity. Therefore, there can not be bias for this test result. On the other hand, we could run many tests and compute the standard deviation of the results. This would be a measure of the scatter in the test method or the precision.

The framework (or standard method) for determining the quality of an ASTM test method is prescribed by E691 Standard Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method. ASTM E691 defines the process that must be followed to develop a numerical precision statement for a specific test method. The practice also specifies the minimum requirements for the process to be valid. At least six independent laboratories must return results of triplicate testing on a single material. In addition, the test program should include ruggedness testing. Since standard test methods are normally written as generally as possible, there will be a range of acceptable parameters that satisfy the method specification. The test program must include the range of conditions, procedures, and equipment allowed in the standard test method. Finally, the test program should include a range of soils. One can easily see the practical difficulty in performing an all-inclusive program.

Either a round robin testing program or an interlaboratory testing program can be used to obtain the necessary test results to develop the numerical precision statement. A round robin program uses one specimen which is sent around to the laboratories participating in the program. Each laboratory performs the three test measurements and then sends the specimen to the next laboratory. Round robin testing programs are appropriate for nondestructive test methods. The use of one specimen eliminates scatter associated with specimen variability.

If the testing alters or destroys the specimen, such as in most geotechnical testing, a round robin program would not be appropriate. An interlaboratory test program uses a uniform source material and distributes a different sample to each laboratory. The source material must be homogenized by blending and then pretested prior to distribution. The laboratory then prepares the test specimen and performs the three tests. This method is used most frequently in soils testing. Interlaboratory test programs add a component of variability due to the fact that each sample is unique.

An important component of variability in the test results arises from individual interpretation of the standard test method. For this reason, each laboratory participating in the program is reviewed by the team conducting the study to be confident that the testing is conducted in accordance with the method.

PRECISION AND BIAS STATEMENTS

Once the interlaboratory test program is complete and the results are returned, they are analyzed by the team conducting the study. The test documentation is first reviewed to be sure the assigned procedures were followed and the data set is complete.

Statistics are performed on the final data set to develop the repeatability and reproducibility statements for the test method. “Repeatability” is a measure of the variability of independent test results using the same method on identical specimens in the same laboratory by the same operator with the same equipment within short intervals of time. “Reproducibility” is a measure of the variability of independent test results using the same method on identical specimens, but in different laboratories, different operators, and different equipment.

Using basically the same terminology as E691, the statistics are calculated as follows. The average of the test results are calculated for each laboratory using Equation 1.1:

$$\bar{x}_j = \sum_{i=1}^{n} x_{i,j} / n \tag{1.1}$$

Where:

$\bar{x}_j$ = the average of the test results for one laboratory
$x_{i,j}$ = the individual test results for one laboratory, j
n = the number of test results for one laboratory

The standard deviation is calculated using Equation 1.2:

$$s_j = \sqrt{\sum_{i-1}^{n} (x_{i,j} - \bar{x}_j)^2 / (n-1)} \tag{1.2}$$

Where:

s_j = standard deviation of the test results for one laboratory

Both the average and the standard deviation calculations are those used in most calculators. However, since some will use “n” in the denominator of the standard deviation calculation in place of “$n-1$,” it must be verified that the calculator is using the correct denominator shown above.

The results for each laboratory are then used to calculate the average and standard deviation of the results for all laboratories. The average value for all laboratories is calculated using Equation 1.3:

$$\bar{\bar{x}} = \sum_{j=1}^{p} \bar{x}_j / p \tag{1.3}$$

Where:

$\bar{\bar{x}}_j$ = the average of the test results for one material
p = the number of participating laboratories

The standard deviation of the average of the test results for one material is calculated using Equation 1.4:

$$s_{\bar{x}} = \sqrt{\sum_{j=1}^{p} (\bar{x}_j - \bar{\bar{x}})^2 / (p-1)} \tag{1.4}$$

Where:

$s_{\bar{x}}$ = standard deviation of the average results of all participating laboratories

The repeatability standard deviation and the reproducibility standard deviation are calculated as Equation 1.5 and Equation 1.6, respectively:

$$s_r = \sqrt{\sum_{j=1}^{p} {s_j}^2 / p} \tag{1.5}$$

Where:

s_r = repeatability standard deviation

$$s_R = \sqrt{(s_{\bar{x}})^2 + (s_r)^2 (n-1) / n} \tag{1.6}$$

Where:

s_R = reproducibility standard deviation (minimum value of s_r)

Finally, the 95 percent repeatability and reproducibility limits are calculated using Equation 1.7 and Equation 1.8, respectively:

$$r = 2.8 \cdot s_r \tag{1.7}$$

$$R = 2.8 \cdot s_R \tag{1.8}$$

Where:

r = 95 percent repeatability limit
R = 95 percent reproducibility limit

E691 also provides for the removal of outlier results. These outliers are removed from the data set prior to performing the final statistics to obtain the precision statement.

It is important to realize that even under the best of circumstances, occasionally a test result will simply be unacceptable.

The final results are referenced in the test method in the form of a precision statement. The details of the interlaboratory study and the results generated are archived by ASTM in the form of a research report.

Precision statements can be extremely useful. Assuming that the measurement errors are random, the precision values can be used to compare two individual measurements. There is a 95 percent probability that the two measurements will be within this range, provided the tests were performed properly. This is essentially the acceptable difference between the measurements. The precision values can be used to compare the results for different laboratories and can be used to evaluate the relative importance of measurements in a single test program.

Bias is defined in ASTM as the difference between the expected test results and a reference value. Bias applies to most manufactured products, but is not relevant for naturally occurring materials such as soil. Therefore, most of the standards in ASTM Soil and Rock Committee will not have numerical bias statements.

LABORATORY ACCREDITATION

Accreditation provides a means for assuring that laboratories meet minimum requirements for testing. There are many individual accreditation programs, each of which has different criteria, levels of inspection, frequency of visits by the accrediting body, proficiency testing requirements, and fees. Specific accreditation may be required by an organization to perform work for a client or to bid on a job. Many accreditation bodies exist that are required to work in certain geographic areas. Trends in the practice are such that eventually a centralized, international body may exist for accreditation. Two nationally recognized accreditation programs are described in this section; however, there are numerous others.

ASTM International does not provide accreditation. It does, however, have a standard titled D3740 Standard Practice for Minimum Requirements for Agencies Engaged in the Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction. The document provides guidance on the basic technical requirements for performing geotechnical testing including record keeping, training, and staff positions. Other agencies that do provide accreditation are described below.

American Association of State Highway and Transportation Officials

The American Association of State Highway and Transportation Officials (AASHTO) operates an accreditation program. The program has several requirements ranging from paying application and site assessment fees, to developing a quality management system that meets the requirements in the AASHTO R18 manual, to an on-site assessment where the AASHTO inspector observes technicians performing tests, and enrollment in the appropriate proficiency testing program. On-site assessments are performed every eighteen to twenty-four months, and must be completed to maintain accreditation.

AASHTO accreditation establishes the ability to run certain tests. The laboratory will receive an AASHTO accreditation certificate listing the specific tests for which it is accredited. In addition, AASHTO accreditation allows the laboratory to choose to be accredited for the AASHTO or ASTM version of a particular test method, or both. AASHTO requires enrollment in their proficiency testing program. The soils proficiency program is managed by the Material Reference Laboratory (AMRL), while for concrete products, the program is run by the Cement and Concrete Reference Laboratory (CCRL).

American Association for Laboratory Accreditation

American Association for Laboratory Accreditation (A2LA) works in a manner very similar to AASHTO with a few exceptions. There is no on-site assessment for A2LA accreditation. The guidance document for the certification is International Organization for Standardization (ISO) 17025 General Requirements for the Competence of Testing and Calibration Laboratories. Finally, the proficiency testing program is not operated by A2LA, but rather the laboratory must choose from an approved list of accredited proficiency testing providers.

PROFICIENCY TESTING

Proficiency testing is a useful tool to evaluate lab procedures, as well as being required as part of some laboratory accreditation programs. Proficiency programs are conducted by an agency that sends out uniform, controlled materials to the participating laboratories at a specified, regular frequency.

Individual details of the proficiency programs vary according to the material of interest and the requirements of the accreditation program. In most cases, the labs perform the required tests and return the results to the managing agency within a specified timeframe. The results of all the participating laboratories are compiled, and the participating laboratories are sent the overall results along with information on where their laboratory fell within the results. Laboratories with outlier results must respond with a report outlining the cause of their poor results. Soils proficiency samples are sent out at a regular frequency.

Laboratories can purchase samples of the reference soils used for the interlaboratory study (ILS) conducted by the ASTM Reference Soils and Testing Program on several test methods. Five-gallon buckets of sand, lean clay, fat clay, and silt can be purchased from Durham Geo Enterprises (Durham Geo web site, 2008). These samples were produced for uniformity testing in the ASTM ILS and are an invaluable resource for teaching students, as well as qualifying technicians in commercial laboratories. The bucket samples come with the summary information and testing results used to develop precision statements for six ASTM test methods. The poorly graded sand bucket samples include the summary analysis sheets for D854 (Specific Gravity), D1140 (Percent Finer than the No. 200 Sieve), D4253 (Maximum Index Density), and D4254 (Minimum Index Density). The silt, lean clay, and fat clay bucket samples include the summary analysis sheets for D854, D1140, D698 (Standard Effort Compaction), and D4318 (Liquid Limit, Plastic Limit, and Plasticity Index).

TECHNICIAN CERTIFICATION

Various regions and agencies have technician certification programs for laboratory and field technicians, as well as a combination of both. The concrete industry has a certification program managed by the ACI (American Concrete Institute).

One national technician certification program that includes soil technicians is National Institute for Certification in Engineering Technologies (NICET). The NICET program was developed by the National Society of Professional Engineers. There are four levels of certification corresponding to levels of skill and responsibility. The individual applies to take a written exam, and if a passing grade is achieved, the individual is given a NICET certification for that level.

UNIT CONVENTION

Hopefully, it is not surprising to find an introductory section focused on the selection and application of units. From a purely academic perspective this is a rather boring topic, but consistency in units has enormous implications for the application of calculations to practice. One of the most public unit-caused mistakes resulted in the Mars Climate Orbiter being lost in space in 1999 (Mishap Investigation Board, 1999). The message is clear: always state the units you are working with, and be sure to use the correct unit conversions in all your calculations.

There are many different systems of units in use around the world and it appears that the United States uses them all. You will find different measures for stress depending on company, region, and country. This is not inherently wrong, but does require more care in documentation of test results.

One should develop good habits relative to calculations and documentation of unit specific information. All equations, tables, and graphs should be properly labeled with the designated units. Conversions between various units will always be necessary. Conversion constants should be carried to at least two more significant digits than the associated measurement. Appendix A contains conversion constants for commonly used parameters in geotechnical practice. A far more general list of conversions can be found online or in various textbooks, such as the *CRC Handbook of Chemistry and Physics* (Lide, 2008).

The choice of units for a specific project can be a difficult decision. Two absolute rules must be followed. While in the laboratory, one must use the local units of measure to record data. This is an absolute rule even if it results in working with mixed units while in the laboratory. Never make an observation (say in inches), convert to another unit (inches to cm), and then record the result (cm) on a data sheet. This practice encourages confusion, invites round-off errors, and causes outright mistakes. The second rule is always to provide final results (tables, graphs, example calculations, and the like) in the client's units of choice. This is because individuals (the client in this case) develop a sense of comfort (or a feel) with one particular set of units. It is generally good practice to make use of this "engineering judgment" For quality control. As a result, it is common practice to post-process the data from the "lab" units to the "client" units as the last step in the testing process.

A commonly used collection of measurement units comprises a system. Every system has a set of base units and a series of derived units. There are many systems and even variations of systems, leading to a laundry list of terms. The two systems most commonly used in engineering practice today are the SI system and the British system. For the SI system (and limiting attention to geotechnical practice), the base units are meters, kilograms, and seconds. Unfortunately there are two British systems, the absolute and the gravitational. The British Absolute system is based on the foot, pound mass (lbm), and second. The British gravitational system (also called the U.S. Customary System) is based on the foot, slug, and second. All of these systems make use of a unique and consistent collection of terminology.

Past engineering practice has caused problems relative to the specification of force and mass when working with the British systems. Force is a derived unit ($F = ma$). In the absolute system, force is reported in poundals. In the gravitational system, the unit of force is a pound. The situation is exacerbated by the fact that at standard gravity, 1 lbm results in a force of roughly 32 poundals and a mass of 1 slug generates a force of roughly 32 lbf. Since there are about 32 lbm in one slug, it is understandable how pound became interchangeable for mass and force. Making matters even worse, the same casual reference was applied to the kilogram.

In the laboratory, the mass is obtained, not the weight. Weight is a force. In this text, the SI system is used wherever practical. The system is clean, easy to use, and avoids most of the confusion between mass and force.

In geotechnical practice, compression is positive and extension is negative, unless indicated otherwise. This is contrary to the practice in structural engineering.

SIGNIFICANT DIGITS

It is important to report measurements and calculated results to the appropriate significant digit. The individual performing the test calculations is normally in the best position to make the decision as to how many significant digits are appropriate to report for a particular measurement. Reporting too many digits is poor practice because it misleads the user of the results by conveying a false sense of accuracy. On the other hand, at times it can be a challenge to determine the appropriate number of digits to report. In geotechnical testing, five factors must be considered when determining the least significant digit of a number: the mathematical operation, the rules of rounding, the resolution of the measurement, the size of the specimen, and in some cases, the practice associated with the test method.

Determination of the number of significant digits in the result of a specific calculation depends on the mathematical operation. There are several variations on the best practice, and the degree of precision depends on the operation. For addition and subtraction, the final result is reported to the position of the least precise number in the calculation. For multiplication and division, the final result is reported to the same number of significant digits as in the least significant input. Other operations, such as exponentials, logarithms, and trigonometry functions need to be evaluated individually but can be conservatively assumed to be the same as the input. Intermediate calculations are performed using one additional significant digit. Constants can contain two more significant digits than the least significant measurement to be sure the constant does not control the precision of the calculation.

It will often be necessary to round off a calculation to the appropriate significant digit. The most common rules for rounding are to round up if the next digit to the right is above 5 and to round down if the digit to the right is below 5. Uncertainty arises when dealing with situations when the digit to the right is exactly 5. Calculators will round numbers up in this situation, which introduces a systematic bias to all calculations. The more appropriate rule is to round up if the digit to the left of the 5 is odd, and round down if it is even.

The resolution of a measuring device sets one limit on significant digits. When using electronic devices (e.g., a digital scale), the resolution is automatically set as the smallest increment of the display. When using manual devices, the situation is less clear. A pressure gage will have numbered calibration markings and smaller “minor” unnumbered tick marks. The minor tick marks are clearly considered significant numbers. It is often necessary to estimate readings between these minor tick marks. This measurement is an estimate and can be made to the nearest half, fifth, or tenth of a division, depending on the particular device. This estimate is generally recorded as a superscript and should be used with caution in the calculations.

The specimen size also contributes to the significant digit consideration. This is simply a matter of keeping with the calculation rules mentioned in the previous paragraphs. It is an important consideration when working in the laboratory. The size of the specimen and the resolution of the measuring device are both used to determine the significant digits of the result. While this may seem unfair, all other factors being equal, there is a loss of one significant digit in the reported water content if the dry mass of a specimen drops from 100.0 g to 99.9 g. Being aware of such factors can be important when comparing data from different programs.

The final consideration comes for the standard test method. In geotechnical practice, some of the results have prescribed reporting resolutions, independent of the calculations. For example, the Atterberg Limits are reported to the nearest whole number. This seemingly arbitrary rule considers the natural variability of soils as well as application of the result. ASTM D6026 Standard Practice for Using Significant Digits in Geotechnical Data provides a summary of reporting expectations for a number of test methods.

TEST SPECIFICATION

Individual test specification is part of the larger task of a site characterization program. Developing such a program is an advanced skill. Mastering the knowledge required to test the soil is a first step, which this textbook will help to accomplish. However, eventually a geotechnical engineer must specify individual tests in the context of the project as a whole. Designing a site characterization and testing program while balancing project needs, budget, and schedule is a task requiring skill and knowledge. A paper titled “Recommended Practice for Soft Ground Site Characterization: Arthur Casagrande Lecture” written by Charles C. Ladd and Don J. DeGroot (2003, rev. 2004) is an excellent resource providing information and recommendations for testing programs. Analysis-specific testing recommendations are also provided in this paper. Although this paper specifically addresses cohesive soils, many of the principles of planning are similar for granular soils.

There are two general, complementary categories of soil characteristics: index properties and engineering properties.

Index tests are typically less expensive, quick, easy to run, and provide a general indication of behavior. The value of index properties is many-fold: index properties can define an area of interest, delineate significant strata, indicate problem soils where further investigation is needed, and estimate material variability. They can be used to approximate engineering properties using more or less empirical correlations. There is a tremendous amount of data in the literature to establish correlations and trends. The most common index tests are covered in the first part of this book, such as water content, particle size distribution, Atterberg Limits, soil classification, and so on.

Engineering properties, on the other hand, provide numbers for analysis. These tests generally simulate specific boundary conditions, cost more, and take longer to perform. They typically require more sophisticated equipment, and the scale of error is equipment dependent. Engineering testing includes strength, compressibility, hydraulic conductivity, and damping and fatigue behavior, among others. The compaction characteristics of a material fall into an odd category. Compaction is not an index property, nor does it provide numbers for an analysis. However, determining the level of compaction is used as an extremely important quality-control measure.

A properly engineered site characterization program must achieve a balance of index and engineering properties testing. More index tests are usually assigned to characterize the materials at a site. The results are then used to select a typical material or critical condition. These materials or locations are then targeted for detailed engineering testing.

Once a program has been established, individual tests are assigned on specific samples. To avoid a waste of time, resources, and budget, the tests must be consistent with the project objectives, whether that is characterization, determining engineering properties, or a combination of both. Test specification should be done by the project engineer or someone familiar with the project objectives and the technical capabilities of the laboratory. In addition to general test specification, details including, but not limited to, sample location, specimen preparation criteria, stress level, and loading schedule, may need to be provided, depending on test type.

The testing program can not be so rigid as to prevent changes as new information unfolds during the investigation. Rarely does a test program run on “autopilot.” The results must be evaluated as they become available, and rational changes to the program made based on the new findings. As experience develops, the radical changes in a testing program will not occur as often.

SAMPLING

Field sampling methods can have a significant impact on the scope of a testing program as well as on the quality of the final results of laboratory testing. The sampling methods to be used for a site investigation must be aligned with the type of soils to be sampled, the field conditions, and the quality of specimen needed for the specific tests. Sampling technology is an extensive topic and beyond the scope of this textbook. A brief discussion of some of the most important (and often overlooked) aspects of sampling is included in this section and in Chapter 11, “Background Information for Part II.” The reader is referred to other literature (such as the U.S. Army Corps of Engineers manual *Geotechnical Investigations: EM 1110-1-1804*) for further information on sampling methods.

Field sampling can be divided into two general categories: disturbed methods and intact methods. As the name implies, disturbed methods are used to collect a quantity of material without particular concern for the condition of the material. Sometimes preservation of the water content is important but the primary concern is to collect a representative sample of the soil found in the field. Intact methods are designed to collect a quantity of material and, at the same time, preserve the in situ conditions to the extent practical. Changes to the in situ conditions (disturbance) will always happen. The magnitude of the disturbance depends on soil condition, sampling method, and expertise.

Intact sampling normally recovers much less material, requires more time, and more specialized sampling tools. When working with intact samples, it is always important to preserve the water content, to limit exposure to vibrations, and to limit the temperature variations. When maintaining moisture is a priority, the samples must be properly sealed immediately upon collection and stored on site at reasonable temperatures. Intact samples should be transported in containers with vibration isolation and under reasonable temperature control. ASTM D4220 Standard Practices for Preserving and Transporting Soil Samples provides a very good description of the technical requirements when working with either intact or disturbed samples.

Disturbed Sampling

A test pit is an excavated hole in the ground. A very shallow test pit can be excavated by hand with a shovel. A backhoe bucket is normally used, however, which has an upper limit of about 8 to 10 m achievable depth, depending on the design of the backhoe. Soil is removed and set aside while the exposed subsurface information (soil strata, saturated interface, buried structures) is recorded, photos taken, and samples obtained from target strata. Usually, grab samples are collected at representative locations and preserved in glass jars, plastic or burlap bags, or plastic buckets. Each sample container must be labeled with project, date, initials, exploration number, depth, and target strata at a minimum. At the completion of these activities, the test pit is backfilled using the backhoe.

Disturbed sampling is very common when evaluating materials for various post-processing operations. Typical examples are borrow pit deposits being using for roadway construction, drainage culverts, sand and aggregate for concrete production, mining operations, and a myriad of industrial applications. Grab samples are generally collected in plastic buckets or even small truckloads. The sampling focus is to collect representative materials with little concern for in situ conditions.

Auger sampling is accomplished by rotating an auger into the ground. Hand augers can be used for shallow soundings (up to about 3 m). Augers attached to a drilling rig can be used up to about 30 meters. Soil is rotated back up to the surface as the auger is rotated to advance the hole. This sampling technique gives only a rough correlation of strata with depth and returns homogenized samples to the surface. Since layers are mixed together, the method has limited suitability for determining stratigraphy. In addition, the larger particles may be pushed aside by the auger rather than traveling up the flights to the surface. The location of the water table can also be approximated with auger methods. Samples are normally much smaller due to the limited access and are stored in glass jars or plastic bags. A typical sample might be 1 to 2 kg.

Split spoon sampling involves attaching the sampler to a drill string (hollow steel rods) and driving the assembly into the ground. This is done intermittently at the bottom of a boring, which is created by augering or wash boring. Split spoon sampling is usually combined with the standard penetration test (SPT) (ASTM D1586 Standard Test Method for Penetration Test and Split-Barrel Sampling of Soils) where a specified mass (63.5 kg [140 lb]) is dropped a standard distance (0.76 m [30 in.]) and the number of drops (blows) is recorded for 6 inches of penetration. The blow counts provide a measure of material consistency in addition to providing a disturbed sample for examination. The sampler is driven a total of 24 inches. The middle two number of blows (number of blows to drive the split spoon sampler 12 inches) are added to give the N-value. Numerous correlations between N-value and soil properties exist. The SPT test and split spoon sample combined provide a valuable profiling tool as well as providing material for classification and index tests. The small inside diameter of the split spoon sampler automatically limits the maximum collectable particle size. Split spoon samples are typically placed in a jar (usually referred to as jar samples) and labeled with project name or number, exploration number, sample number, initials, and date at a minimum. Sometimes other information, such as blow counts and group symbol, are included as well.

Table 1.1 Typical production rates of various disturbed sampling methods

Sampling Method	Samples per day	Coverage	Sample Size
Hand excavation	8 to 10	1 m depth 5 to 10 m spacing	Up to 5 gallon bucket
Test pit	10 to 15	10 m depth 5 to 10 m spacing	Depends on max particle
Borrow pit	10 to 15	1 m depth 5 to 10 m spacing	Depends on max particle
Auger returns	20+	Up to 1.5 m intervals 40 m depth	Up to 2 kg
Split spoon	20+	Up to 1.5 m intervals 40 m depth	Less than 1 kg

Disturbed methods are useful for profiling the deposit, approximately locating the water table and obtaining samples for measuring physical properties and classification of soils. The borehole methods can also be used to advance the hole for in situ tests, observation wells, intact samples, or for installing monitoring instrumentation. The sampling operations are typically fast and relatively cheap. Disturbed methods are especially useful when combined with interspersed intact sampling. Table 1.1 provides an overview of the attributes of the various disturbed sampling methods.

Intact Sampling

Intact samples can be collected near the ground surface or exposed face of an excavation using hand techniques and are referred to as block samples. More commonly, intact samples are collected from boreholes using a variety of specialized sampling tools. Sampling is generally limited to soils that are classified as fine-grained soils with a small maximum particle size. If the deposit contains a few randomly located particles, the maximum size can be nearly as large as the sampler. When the large particles are more persistent, sample quality will suffer as the maximum size approaches 4.75 mm in diameter (No. 4 sieve).

Intact samples are collected to observe in situ layering and to supply material for engineering tests. Characterization and index tests can be performed on intact samples, but the added cost and effort required to collect intact samples are typically only justified when performing engineering tests as well. There are specific techniques involved in controlling the intact sampling operation to preserve these properties.These sampling details, along with processing of intact samples, are addressed in Chapter 11, “Background Information for Part II.”

PROCESSING BULK MATERIAL

Bulk material is considered any sample that arrives at the laboratory as a disturbed sample or portions of intact samples that will be used for index testing. Disturbed samples are normally in loose form and transported by dump truck, 5-gallon bucket, and gallon-size sealable bags. A laboratory usually receives a much larger amount of material than needed for the specified tests. Even if just enough soil is received, it may need to be manipulated so multiple tests can be run on matching samples. Furthermore, many tests have limiting specifications and require specific processing of a fraction of the sample. As a result, materials must be processed prior to testing.

Three generic processing methods are available to manipulate the material. They are blending, splitting, and separating. Each has well-defined objectives and can be performed using a variety of techniques and devices.

Independent of the method used to process the bulk sample, consideration must be given to the quantity of material required to maintain a representative sample. This topic is discussed in detail in Chapter 8, “Grain Size Analysis.” One possible criterion is to consider the impact of removing the largest particle from the sample. If the goal was to limit the impact to less than 1 percent, the minimum sample size would be 100 times the mass of the largest particle. Using this criterion leads to the values presented in Table 1.2.

Blending

It is very common for bulk samples to segregate during transport. Vibration is a very effective technique to separate particles by size. Blending is the process of making a sample homogeneous by mixing in a controlled manner. This can be done through hand mixing, V-blenders, tumble mixers, and the like. Fine-grained materials will not segregate during mixing. Blending fine-grained soils is easily performed on dry material (with proper dust control), or on wet materials. When mixing coarse-grained materials, separation of sizes is a significant problem. The best approach is to process the materials when moist (i.e., at a moisture content between 2 and 5 percent). The water provides surface tension, giving the fine particles adhesive forces to stick to the larger particles.

Blending is relatively easy when working with small quantities. Hand mixing can be done on a glass plate with a spatula or even on the floor with a shovel. For large quantities, based on the largest quantity that fits in a mixer, the material must be mixed in portions and in sequential blending operations. Figure 1.2 provides a schematic of this operation for a sample that is four times larger than the available blender. The material is first divided (it does not matter how carefully) into 4 portions labeled 1, 2, 3, and 4. Each of these portions is blended using the appropriate process. Each blended portion is then carefully split into equal quarters labeled a, b, c, and d. The four "a" portions are then combined together and blended in a second operation. Each of the four second blends will now be uniform and equal. Provided the requirements of Table 1.2 are met, and the split following the first blend provides an equal amount to each and every portion for the second blend (and particle size limitations are not violated), the final product will be uniform. The same process can be expanded to much larger samples.

Splitting

Splitting is the process of reducing the sample size while maintaining uniformity. Simply grabbing a sample from the top of a pile or bucket is unlikely to be representative of the whole sample. Random subsampling is difficult to do properly. Each subsample should be much larger than the maximum particle size and the sample should contain at least ten subsamples. Quartering, on the other hand, is a systematic splitting process. It can be performed on both dry and moist materials of virtually any size. Each quartering operation reduces the sample mass by one half. Figure 1.3 provides a schematic of the sequential quartering operation. The material is placed in a pile using reasonable care to maintain uniformity. The pile is split in half and the two portions spread apart. The portions are then split in half in the opposite direction and spread apart. Finally, portions 1

Table 1.2 Minimum required dry sample mass given the largest particle size to maintain uniformity (for 1 percent or 0.1 percent resolution of results).

Largest Particle		Particle Mass	Dry Mass of Sample	
(mm)	(inches)	(Gs = 2.7)	For 1%	For 0.1%
9.5	3/8	1.2 g	120 g	1,200 g
19.1	¾	9.8 g	1,000 g	10 kg
25	1	23 g	2,500 g	25 kg
50	2	186 g	20 kg	200 kg
76	3	625 g	65 kg	650 kg
152	6	5,000 g	500 kg	5,000 kg

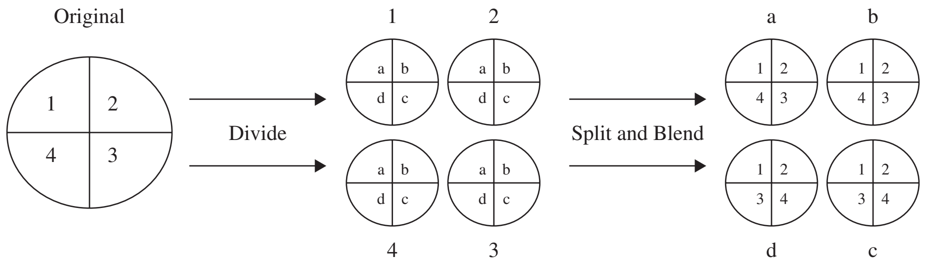


Figure 1.2 Schematic of the blending procedure for large samples.

and 3 (and 2 plus 4) are combined to provide a representative half of the original sample. This method can be repeated over and over to sequentially reduce a sample to the required size. For small samples, the process can be performed on a glass plate using a straight edge. For large samples, use a splitting cloth and shovel.

Another method of splitting a sample is by use of the riffle box. The riffle box also cuts the sample quantity in half for each run through the method. Material is placed in the top of the riffle box and half the material falls to one side of the box on slides, while the second half falls to the opposite side. Containers are supplied with the box to receive the material. Care must be exercised to distribute the material across the top of the box. The sample must be dry or else material will stick to the shoots. The riffle box should only be used with clean, coarse-grained materials. Fines will cause a severe dust problem and will be systematically removed from coarse-grained samples. Figure 1.4 shows the riffle box.

Separating

Separation is the process of dividing the material (usually in two parts) based on specific criteria. For our purposes, the criterion is usually based on particle size, but it could be iron content or specific gravity, as in waste processing, or shape, or hardness. To separate by particle size, a sieve that meets the size criterion is selected, and the sample is passed through the sieve. This yields a coarser fraction and a finer fraction. Sometimes multiple sieves are used in order to isolate a specific size range, such as particles smaller than 25 mm, but greater than 2 mm.

TEST DOCUMENTATION

This is a simple, commonsense topic, but its importance is often overlooked. The only tie between the physical material being tested and the results submitted to a client is the information placed on the data sheets at the time of the test. Data sheets must be filled out accurately and completely with sample and specimen specific information, as well as test station location, initials, and date.

A carefully thought-out data sheet assists with making sure the necessary information is collected and recorded every time. Training on why, where, and when information is required is essential to preventing mistakes. Note that recording superfluous information is costly and can add to confusion. Normally, geotechnical testing is “destructive,” meaning that once the specimen is tested, it is generally unsuitable for retesting. It is, however, good practice to archive specimens at least through the completion of a project.

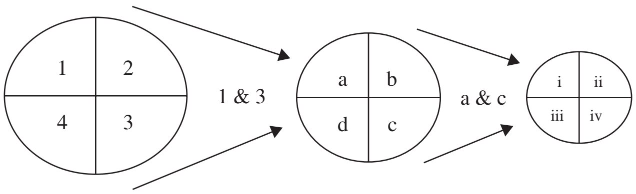


Figure 1.3 Schematic of the sequential quartering procedure.

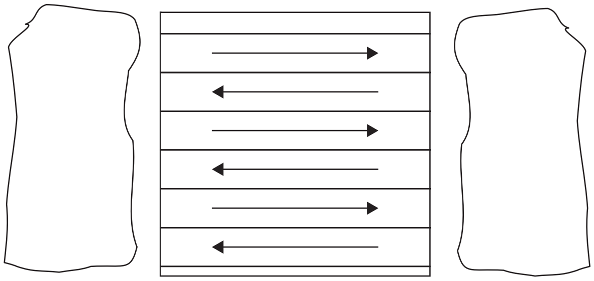


Figure 1.4 Schematic of the riffle box for use with coarse-grained materials.

SPREADSHEETS

Commercially available spreadsheet programs (such as Microsoft's Excel©) can be used to develop a framework for data reduction and results presentation. The ancillary web site for this textbook, www.wiley.com/college/germaine, provides an example electronic data sheet, a raw data set, and an example of what the results should look like for that raw data set. The online component of this textbook allows the instructor to have access to the spreadsheet with the formulas; however, it does not allow the student to have access. The reason for this is simple: if the data reduction is provided as a "canned program" the student simply does not learn how to analyze the data. Providing an example of what the results should look like given raw input data allows the student to write the formulas themselves, with assurance that they have developed them correctly if their results match the example set. This method also allows a certain measure of quality control in that a student can usually spot errors in spreadsheet formulas if the results do not match the example.

Numerous data reduction and results presentation software packages are available. Some provide a convenient tool for processing a constant stream of data in a well thought-out and accurate manner. Others are black boxes that do not explain the assumptions and approximations that underlie the output of the programs. Still others have a good, solid framework, but the format of the output cannot be modified for individual facility needs.

Whether using a commercially available data reduction package or an individualized spreadsheet, the user must have a working knowledge of the analysis and applications to various situations. Stated another way, the user cannot simply approach the software as a black box, but rather must understand the workings of the programs. At the very least, the results should be checked by hand calculations.

In all cases, a reliable quality-control (QC) system must be in place. The QC manual provides some of the most common measures to provide quality control. Many QC techniques involve project-specific knowledge or awareness of the laboratory performing the work, such as how samples flow through the lab, to detect and resolve a problem with the testing.

REPORTING TEST RESULTS

The primary responsibility of the laboratory is to perform the test, make the observations, and properly report the factual information to the requesting agency. The laboratory report must include information about the material tested including the project, a description of the material, and the conditions in which the material was delivered to the laboratory.

The report must also include the test information including the name of the test method and revision number, deviations from the published protocol when applicable, and the method used to process the material before testing. It must include laboratory factual information such as the specific device, the person in charge of the test, and the date of testing. Finally, the report provides the test results after performing the appropriate calculations.

Proper reporting should include tabulated and graphical test results, as well as a statement of procedures. The results must be reported to the appropriate resolution for the individual test and should not include engineering interpretation. Engineering interpretation requires the test measurements to be integrated with the context of the application and is the responsibility of the engineer of record. For example, interpretation of a friction angle from test data requires experience and project-specific application only available to the engineer.

Buried behind the report are specimen size requirements, test limitations, procedural deviations, and rules of significant digits. This level of detail is lost by the time the results are reported to the client. It becomes the professional responsibility of the laboratory to take these issues into account when conducting laboratory testing. The end result of testing is best described as a factual (and hopefully objective) laboratory data report.

A laboratory will usually archive data sheets, electronic files, and a summary of calculation methodology within the laboratory for a certain period of time. This information is usually available for a number of years after completion of the project; however, individual companies have their own policies regarding record retention.

TYPICAL VALUES

Each testing chapter of this text has a section titled "Typical Values." This section is included to provide the reader with a sense of magnitude and range in numerical values expected for each test. Some of these values have been obtained from the literature, while others are from unpublished personal consulting or research records. These values are *not* intended to provide numbers for analysis. Properties of soils can vary significantly through a depth profile, across a site, and among geographical locations as well as with specific testing conditions. The typical values provided should be used as a ballpark comparison with the testing results obtained using the procedures described in the associated chapter.

FURTHER READING AND OTHER REFERENCES

Since this textbook is meant to accompany an undergraduate course, the focus is on presenting the information necessary to perform certain tests, as well as some supporting background information to understand the important factors influencing the results. There are other valuable resources available on the topic of testing.

The three-volume series written by K. H. Head, titled *Manual of Soil Laboratory Testing,* has been published with several revised editions for each volume. The three editions are *Volume 1: Soil Classification and Compaction Tests, Volume 2: Permeability, Shear Strength and Compressibility Tests*, and *Volume 3: Effective Stress Tests*. The texts cover most of the same tests discussed in this text, but in much more detail as would be used for a reference by those performing the tests for commercial purposes on a daily basis.

The textbook by T. W. Lambe, *Soil Testing for Engineers,* covers many of the topics of this book. The textbook was intended for use for teaching the subject to students, although numerous engineers carried this reference with them into practice and still have the book on their bookshelves. However, the book was published in 1951, was never updated, and is out of print. Engineering libraries and practicing engineers may have a copy of this valuable resource.

The Naval Facilities Engineering Command (NAVFAC) produces technical documents formerly referred to as "Design Manuals." The three NAVFAC manuals most commonly used in geotechnical work were DM 7.01 (Soil Mechanics), DM 7.02 (Foundations and Earth Structures), and DM 7.3 (Soil Dynamics, Deep Stabilization, and Special Geotechnical Construction). These manuals provide an array of useful information and design procedures, while the sSoil mMechanics volume contains the information relative to geotechnical laboratory testing. The design manuals can be found in numerous places online for free download; however, NAVFAC has revamped their technical document systems. The NAVFAC design documents are now called "Unified Facilities Criteria" or UFC. Refer to NAVFAC's web site and navigate to the "Document Library" for free download of their documents. The geotechnical publications can be found by going to the "Technical" section of the "Document Library," then selecting "Unified Facilities Criteria," "UFC Technical Publications," and finding the list titled "Series 3-200: Civil/Geotechnical/Landscape Architecture."

The U.S. Army Corps of Engineers produces a manual titled *Laboratory Soils Testing,* which can be obtained through their web site at www.usace.army.mil/publications/eng-manuals (Corps of Engineers, 1986). This manual provides a large amount of useful (even if somewhat dated) information on laboratory testing and equipment. The web site has numerous other manuals available for free download as well.

The U.S. Bureau of Reclamation produces a document titled *Earth Manual,* which can be obtained through their web site at http://www.usbr.gov/pmts/writing/earth/earth.pdf (U.S. Bureau of Reclamation, 1998). This manual covers methods of testing, exploration, and construction control.

Numerous soil mechanics textbooks exist. Typically, the textbook used to teach the topic originally is the one used most frequently. For the authors of this text, that book is *Soil Mechanics* by T. W. Lambe and R. V. Whitman. This text is referenced in numerous places in this book.

ASTM International produces standards that include procedures for testing. The ASTM International web site (www.astm.org) allows anyone to browse ASTM standards and view the scope of any standard. The standards can be purchased through ASTM International or accessed in engineering libraries. Engineering schools and companies likely have online access accounts for standards. Individual members pay a rather small annual membership fee and obtain one volume a year, in print, on CD, or online.

The American Association of State Highway and Transportation Officials (AASHTO) produces their own testing and sampling methods and material specifications in the book *Standard Specifications for Transportation and Methods of Sampling and Testing.* Usually, the testing methods are consistent with those produced by ASTM International. The book can be purchased through AASHTO or accessed in engineering libraries.

The Massachusetts Institute of Technology (MIT) has converted many MIT theses to digital form. Although not all theses are available digitally, those that are can be downloaded in .pdf form and viewed by anyone inside or outside of MIT. Only MIT can download the forms that are able to be printed to hardcopy, however. To browse or obtain theses in this way, go to MIT's web site, then navigate to the "Research/Libraries" page, click on "Search Our Collections" and find the entry in the list titled "- theses written by MIT students, electronic" and click on "MIT Theses in DSpace". Alternatively, this can be accessed directly (at least at the time of this writing) at http://dspace.mit.edu/.

Other books and journal articles are referred to as appropriate throughout this text.

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