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CHAPTER 4 – LABORATORY TESTING

4.1 INTRODUCTION

This chapter provides minimum requirements, guidelines, recommendations, and considerations for planning laboratory testing programs. This chapter also provides guidance and considerations for selecting soil and rock samples for laboratory testing, and discusses requirements for presenting the laboratory test results. A summary of the most commonly used geotechnical tests is also provided, and detailed recommendations and guidance are provided for some of the more complex tests.

Proper preparation and execution of a laboratory testing program is a critical and necessary part of the geotechnical design process. It will provide soil and/or rock properties needed to perform geotechnical analyses and develop appropriate geotechnical recommendations. It must be understood that all projects are unique, and similar to the subsurface exploration, the laboratory testing program must be carefully analyzed and planned for the specific needs of the project. Simply using the minimum requirements included in this section is not adequate for most situations. For other than very simple and highly favorable conditions, such an approach will likely result in an inadequate design due to insufficient information.

4.1.1 Purpose

A laboratory testing program is performed to supplement visual observations made during the subsurface exploration. A properly planned and executed laboratory testing program will more definitively estimate the engineering characteristics of the soil and rock, and help predict how the soil and rock will behave during construction and the service life of the roadway, structure, etc. The value of adequate laboratory testing cannot be underestimated or overlooked. An appropriate level of laboratory testing provides a number of substantial benefits, especially relative to the minimal cost of the testing, such as follows:

- Drastically increases the level of knowledge and understanding of subsurface conditions.
- Provides a significantly higher level of confidence in proposed designs.
- Reduces the risk of construction problems, delays, claims, and/or failures.
- Reduces the risk of potential failures and service interruptions post construction.
- Substantially increases the potential quality and longevity of the finished product.
- Has the potential to significantly reduce construction and maintenance costs.

The laboratory test results, along with the information obtained from the subsurface exploration, are needed to select the soil and rock parameters used for geotechnical analyses and design. Relying solely on field observations/descriptions and Standard Penetration Testing (SPT) is not sufficient for most projects. Field descriptions of soil and rock samples are only approximations, and therefore will not always be accurate. Also, SPT can only be used for some
types of granular soil, and only provides an estimate of density/consistency. SPT does not directly measure shear strength, can only be used to correlate strength and density from published information, and is only applicable for particular soil types. Furthermore, engineering properties such as consolidation and shear strength can only be determined from laboratory testing, particularly for fine-grained soils.

The appropriate laboratory testing data provides a higher level of confidence in the soil and rock parameters used for geotechnical analyses compared to only using field observations. This confidence better ensures that the geotechnical design recommendations are appropriate and safe for the proposed construction, while not being overly conservative and unnecessarily costly. The time and cost to perform laboratory testing during the design phase is significantly less than the time and cost associated with a problem during or after construction due to a design based on erroneous soil and/or rock information. Additionally, the use of data from a laboratory test is far more superior, and will provide much more reliable results, compared to situations where back analysis is used to determine soil and rock parameters or provide designs in lieu of laboratory testing. Back analysis is a tool that has limited applicability, must be used in an appropriate manner consistent with actual conditions, and is best used (where appropriate) as a supplemental check to help confirm a design developed using the most suitable level of laboratory testing.

4.1.2 Reasons Laboratory Testing Is Performed

Laboratory testing of soil and rock samples collected during the subsurface exploration is performed for a number of reasons. The following sections discuss these reasons in detail.

4.1.2.1 Verification of Field Soil Descriptions

Subsurface exploration (drilling) observation and preparation of Inspector’s Field Logs must be performed by Certified Drilling Inspectors per Publication 222, Chapter 3.1. The preparation of Inspector’s Field Logs requires the Certified Drilling Inspector to visually describe soil samples obtained from the borings. Although the Certified Drilling Inspector must be proficient at describing soil samples, it is important to verify some of these field descriptions with laboratory testing. Laboratory classification testing provides a level of confidence in the Inspector’s Field Log. When field descriptions generally agree with laboratory classification testing, field descriptions can typically be used with a high level of confidence. Conversely, if field descriptions and laboratory classification testing do not agree reasonably well, then there is reason for concern and results in a low level of confidence in the Inspector’s Field Log. If field descriptions and laboratory classification test results vary significantly, all samples collected during the subsurface exploration must be reviewed by the PGM who must make revisions as appropriate. Note the distinction between the terms description and classification. A soil description is based on visual observations and simple field tests (e.g., rolling soil threads, squeezing/crushing dried soil balls with fingers, etc.), whereas a classification is determined from laboratory testing (e.g., gradation, Atterberg limits, etc.).

Note that it is important to provide the laboratory classification results to the drilling inspector who prepared the Inspector’s Field Logs. Comparing field descriptions to laboratory
classifications is an excellent way for drilling inspectors to improve their field description skills/abilities.

4.1.2.2 Determination of Material Properties

Field descriptions of soil and rock samples provide only a general indication of material properties. For example, field descriptions can:

- Distinguish moisture content as being dry, damp, moist or wet.
- Roughly estimate the percentage of gravel, sand, and fine-grained (silt and clay) particles.
- Predict whether a soil sample is non-plastic or has low, medium, or high plastic fines.
- Roughly estimate soil relative density based on SPT-N_60 or consistency based on pocket penetrometer and Torvane field tests.
- Qualitatively estimate rock hardness and degree of weathering.

Although these general material property descriptions are useful, it is beneficial and necessary to obtain specific material property values for some of the soil and rock samples. Specific material property values can only be obtained by laboratory testing. These specific values not only verify field descriptions, but they help to establish soil parameters and more accurately perform geotechnical analyses.

4.1.2.3 Estimation of Engineering Properties

Engineering properties of soil (such as consolidation and shear strength) and of rock (such as unconfined compressive strength) are sometimes needed to perform geotechnical analyses. Evaluate and assign these properties as accurately as possible because these values will have a significant impact on the geotechnical recommendations. These properties cannot be estimated with an appropriate level of confidence without the use of laboratory testing, particularly when working with fine-grained soils.

4.1.2.4 Comparison with In-Situ Testing

In-situ testing, such as a Cone Penetrometer Test (CPT), vane shear, or pressuremeter tests may be performed during the subsurface exploration to estimate engineering properties of the soil. Although in-situ testing can be a very effective technique to estimate engineering properties, it must be performed carefully and correctly to obtain representative results. However, even when in-situ testing is performed correctly, circumstances may exist that yield erroneous results not representative of the actual conditions. Therefore, if in-situ testing is used to estimate engineering properties, laboratory testing should typically be performed to compare the results with the in-situ test results. Note that SPT is an in-situ test; however, this test only provides an indication of relative density/consistency and does not directly measure density, strength, etc.
4.1.2.5 Chemical Analysis

With the exception of field resistivity testing, chemical analyses of soil and bedrock can only be done in the laboratory. Soil pH, resistivity, sulfate and chloride testing is typically always needed if deep foundations are proposed to support a structure, and these tests can and should be done in the laboratory. Acid bearing potential of bedrock, and in some cases soil, is needed for projects where acid producing materials may be exposed in cuts/excavations. Chemical analyses of water should also be performed for structures that convey flow from rivers, streams, creeks, etc.

4.1.2.6 Selecting Resistance/Safety Factors

Laboratory shear strength testing of soil may have an effect on the geotechnical resistance/safety factors used for design. For example, the resistance factor used for spread footing foundations bearing on soil is dependent upon whether the soil shear strength parameters used in the analyses are based on laboratory test data or presumptive/assumed values. If laboratory shear strength test data is used, a higher resistance factor is permitted compared to the resistance factor used with presumptive/assumed shear strength parameters. Similarly, when slope stability analyses are done, shear strength parameters based on laboratory test results typically allow for a lower safety factor compared to when presumptive strength values are used. Consequently, higher resistance factors and lower safety factors associated with laboratory testing often result in more economical designs compared to when laboratory testing is not completed.

4.2 DEVELOPMENT OF A LABORATORY PROGRAM

Prior to planning the laboratory testing program, several tasks discussed in Chapter 2 of this publication must be completed. These include: review of plans, profiles and cross-sections; review of available geotechnical data; and field reconnaissance. As also previously discussed, the proposed laboratory testing program must be documented in the “Subsurface Exploration Planning Submission”. Requirements for this report are included in Chapter 1 of this publication. This report must be reviewed and approved by the DGE prior to performing the laboratory testing, and any modifications to the originally approved laboratory testing program must be approved by the DGE prior to testing.

Exact laboratory testing requirements cannot be specified in this publication due to the multiple variables associated with a project, including: size of project, complexity of project, design elements (e.g., roadway, pavement, structure), type(s) of strata, thickness of strata, consistency of strata, and others. Some basic requirements are provided herein, along with guidelines and considerations that should be helpful for developing a laboratory testing program tailored to the specific project.

Laboratory testing is required when borings are performed for a project during the Preliminary and Final Design Phases unless otherwise approved by the DGE. At a minimum, moisture content and classification tests (i.e., gradation and liquid/plastic indices) must be performed to verify field descriptions. The number of tests performed and the need to perform
other type(s) of tests will be dependent upon the size of the project, the proposed construction, and the complexity of the subsurface conditions.

If borings are performed during the Alternatives Analysis Phase of a project, a very limited laboratory testing program will most likely be sufficient. The Alternatives Analysis Phase laboratory test program should include a limited number of laboratory classification tests. Other testing (e.g., corrosion, rock strength, acid-base accounting, etc.) should be performed if it will be helpful to evaluate the proposed alignment alternatives. Laboratory testing during the Preliminary and Final Design Phases will be more comprehensive in order to help perform geotechnical analyses and provide recommendations.

The laboratory testing program must be developed at the same time the subsurface exploration program is developed. Similar to the subsurface exploration program, the laboratory testing program is developed using available information, which at a minimum should include: plans, profiles and sections of proposed construction; published soils and geologic information; and field reconnaissance observations. The proposed laboratory testing program must be presented in the “Subsurface Exploration Planning Submission”. Indicate the type(s) and numbers of test proposed, and discuss the purpose and benefit of each type of test.

Keep in mind that, in many cases, the proposed laboratory testing program presented in the “Subsurface Exploration Planning Submission” will be developed with no to minimal site specific subsurface information. Therefore, once the test borings are drilled, the proposed laboratory testing program may have to be modified if the actual subsurface conditions vary from those that were anticipated. Any changes to the proposed laboratory testing program must be discussed and approved by the DGE.

Another reason the laboratory testing program must be developed with the subsurface exploration program is to ensure that the appropriate number and type(s) of samples are collected during the subsurface exploration. For example, if CBR and/or moisture density relation testing is proposed, collection of bulk samples must be included in the subsurface exploration program. If consolidation or shear strength testing is proposed, collection of undisturbed samples (i.e., Shelby tubes) must be included in the subsurface exploration program.

4.3 GUIDELINES FOR SELECTING LABORATORY TESTS AND SOIL AND ROCK SAMPLES

As discussed above, the laboratory testing program is initially developed during the planning of the subsurface exploration program, and then modified as needed based on the actual subsurface conditions encountered by the subsurface exploration (i.e., test borings and test pits). Below are some guidelines and considerations that can be used to develop the initial laboratory testing program, to modify the program as needed once the site specific subsurface conditions are determined, and to select the appropriate soil and rock samples for laboratory testing.

1. Plot the boring information on the roadway profile, structure elevation view, etc. to help understand soil/rock stratification. In addition to field descriptions, look for similarities in color and density/consistency to help group possible stratum that have
slightly different field descriptions. Include on the subsurface profile the proposed roadway grade and/or bottom of structure footing elevations to approximate their relationship to the soil/rock strata. Preferably these profiles should be developed by the drilling inspector or office personnel as borings are completed so samples for laboratory testing can be selected by the PGM and retrieved as quickly as possible.

2. Consider the proposed construction and the anticipated geotechnical analyses and recommendations that will be needed. Perform testing needed to appropriately select the soil and rock parameters needed for the geotechnical analyses that are anticipated to be performed.

3. Test soil samples from the various strata to adequately verify field descriptions and identify necessary soil index and engineering properties. When approximately four or fewer split-barrel samples are collected in a stratum, combine all of the samples to perform laboratory testing. The combining of soil samples will often make it easier to update the Final Engineer’s Log with the results compared to just testing a few of the samples. Additionally, since there will be some variation among individual samples obtained from a stratum, it is best practice to combine as many samples as possible/practical for laboratory testing in order to attain representative results for the stratum.

4. For structure foundations, concentrate laboratory testing on soil stratum/samples that are significant to the geotechnical design. For proposed spread footings bearing on soil, concentrate the soil testing within the zone of influence of footing stresses, which is approximately two times the footing width beneath the footing. Shear strength testing should almost always be performed when spread footings on soil are proposed. For spread footings bearing on bedrock and end/point bearing piles driven to bedrock, soil testing will typically not be critical, although classification testing to verify field descriptions is still necessary, and corrosion testing will be needed in most cases when deep foundations are proposed. For proposed friction piles, laboratory testing including, at a minimum, classification and shear strength, is critical. If temporary shoring is anticipated, ensure sufficient soil classification and/or rock compressive strength tests are performed for selection of temporary shoring parameters. In some cases, soil shear strength testing may also be appropriate for selection of temporary shoring parameters.

5. For roadway design, concentrate laboratory testing on soil stratum/samples that are significant to the geotechnical design. Test pavement subgrade soils, soils within the zone of influence of embankment stresses, soils in proposed cut slopes, and soils that will be excavated and reused to construct embankments. Minimal testing to no testing is typically required on excavated material that will be wasted off site. An exception to this would be if wasted material needs to be tested for acid bearing potential.

6. Minimal testing to no testing should typically be performed on samples collected within a few feet of ground surface or at depths beyond the influence of embankment
or footing stresses. Structure footings are typically placed several feet below ground surface for frost protection, and soils within a few feet of ground surface are usually stripped/removed or compacted prior to embankment placement; therefore, these soils are typically not critical to the geotechnical design.

7. More testing is typically required on fine-grained soils compared to coarse-grained soil. Coarse-grained samples are generally more accurately described in the field, and their behavior is more predictable than fine-grained soil. Fine-grained soils are often less favorable for construction compared to coarse grain soils; therefore, it is important to have a good understanding of the gradation and plasticity of fine-grained strata. Additionally, shear strength and consolidation testing of fine-grained soils are often needed to estimate these engineering properties since presumptive values are very unreliable.

8. Projects with horizontal/uniform subsurface profiles will typically require less laboratory testing compared to non-uniform profiles.

9. Shear strength testing should typically be performed when spread footings bearing on soil or friction piles are proposed, and when slope stability is a concern.

10. Consolidation testing should be performed when embankments are proposed to be placed on fine-grained, compressible soil, and the compressible stratum is within the stress influence of the embankment. It should also be performed when pile downdrag is a concern. Typically, soil must be saturated (i.e., below groundwater) and very soft to stiff consistency (i.e., N-value less than or equal to 15 blows per foot) to be prone to significant consolidation settlement.

11. The number of tests, particularly shear strength and consolidation, performed for a project will be dependent upon project specific conditions. Performing just one of these tests can be problematic because the validity of the results cannot be compared to other test results. If two tests are performed, and the results vary significantly, it may be difficult to determine which result is representative. Three or more tests are useful for comparison of test results and selection of design parameters, however, this number of tests may not be appropriate for all projects. For example, on small, less complex projects, performing just one test may be appropriate. Consider a single span bridge replacement project where the subsurface conditions are uniform, and shear strength testing is performed on remolded granular soil for spread footing design. One shear strength test may be appropriate because the test result can be compared to internal angle of friction correlations with SPT to determine the reasonableness of the test results. Conversely, for a new, multi-span bridge where spread footings and friction piles are being considered, three or more shear strength tests would more likely be appropriate.

12. California Bearing Ratio (CBR) and moisture-density testing should be performed when pavement design is required, and the pavement subgrade material is known (i.e., in-situ subgrade or embankments constructed with on-site excavated soils).
CBR testing is not appropriate for projects where the pavement subgrade material is not known, such as a project with embankments constructed from an unknown borrow source. CBR testing is also not appropriate for projects where the proposed pavement section is selected based on matching the existing pavement section.

13. Unconfined compressive strength testing of rock should be performed for foundations bearing on bedrock, including: spread footings, drilled shafts and micropiles. Unconfined compressive strength testing of rock should also be performed for linear type retaining walls socketed into bedrock and when rock anchors are proposed. This testing should also be considered for proposed rock cuts to help evaluate rock excavation.

14. Slake Durability testing should be considered for shallow and deep foundations founded on, and rock cuts or excavations within, claystone, shale and similar weak rocks to estimate qualitatively the durability of weak, non-durable rocks.

15. Acid-Base Accounting testing should be performed on rock and/or soil that are located within formations known to contain acid producing soil/rock, and on samples identified in the field that show signs of acid producing minerals.

4.4 DISTURBED, UNDISTURBED AND REMOLED SOIL SAMPLES

Laboratory testing can be performed using disturbed and undisturbed soil samples collected from the subsurface exploration. Additionally, for tests that require the soil sample to be a specific size/shape for the testing apparatus, samples remolded from disturbed samples can be used, if appropriate. Determining which type of sample to use for various tests will depend on numerous factors, including: test to be performed, soil type, field/construction condition being modeled by the test, and types of samples collected during the subsurface exploration.

4.4.1 Disturbed Soil Samples

Disturbed soil samples, which include samples collected from a split-barrel sampler, augers, and test pits, are best suited for laboratory index tests. Index tests include natural water content, gradation, liquid and plastic limits, and others, which are listed in Section 4.8.4. Disturbed soil samples are more economical to collect compared to undisturbed samples; therefore, they should generally be used for tests that do not require an undisturbed sample. Additionally, SPT’s performed while collecting split-barrel samples provide an indication of density/consistency, and this complementary information is not obtained while collecting undisturbed samples. Disturbed soil samples cannot be used for consolidation testing, and should only be used for shear strength testing under the proper circumstances (see discussion below on remolded samples).
4.4.2 Undisturbed Soil Samples

Undisturbed soil samples are required when conducting performance tests (i.e., consolidation tests, and some shear strength and permeability tests). Undisturbed samples should be used anytime the goal of the testing is to simulate the in-situ or natural, in-place soil conditions. Undisturbed samples can be used to test soil index properties; however, unless these index tests are performed in conjunction with performance tests, disturbed samples should generally be used because it is more economical.

Undisturbed samples are typically collected with a Shelby tube sampler. Shelby tube samplers can generally be used in fine-grained soils that are very soft to stiff (i.e., SPT N-values less than 15 blows per foot). If soil conditions do not permit sample collection with a Shelby tube sampler (e.g., stiff/dense, high gravel content, etc.), relatively undisturbed samples can be obtained with either a Pitcher or Denison tube sampler. A detailed discussion of these various tube samplers is included in Chapter 3 of this publication.

When undisturbed samples are collected, it is best practice to obtain samples in addition to what is believed to be needed for testing. The quality of undisturbed samples cannot be determined until the sample is extruded in the laboratory, so additional samples should be available in case sample quality is found to be poor upon extrusion. Also, if test results appear to be erroneous or suspect, additional samples should be on hand so more testing can be performed.

4.4.3 Remolded Soil Samples

Some geotechnical tests, including shear strength and permeability, require the soil sample be a specific size/shape for the testing apparatus (i.e., direct shear box, triaxial or permeameter cell). Undisturbed soil samples from tube samplers are typically ideal for these tests. However, when it is not possible to collect an undisturbed tube sample, or when it is desired to test the properties of disturbed/compacted soil (i.e., not the in-situ properties) samples remolded from disturbed soil samples can be used.

This remolding process cannot necessarily simulate the in-situ soil condition (i.e., density/consistency and soil structure), particularly for fine-grained soil. For example, residual soils may contain relic rock structure that increases the shear strength of the in-situ soil, and this relic rock structure cannot be duplicated with a remolded sample. Alternatively, glacial deposits may contain varves that reduce the shear strength of the in-situ soil, and these varves cannot be duplicated with a remolded sample.

Samples remolded from disturbed samples are appropriate for shear strength testing of granular soil. Granular soil can generally be remolded to closely simulate in-situ conditions. Additionally, it is typically not possible to obtain undisturbed samples of granular soil due to lack of cohesion. Samples remolded from disturbed samples are also appropriate for shear strength testing of soil that will be placed and compacted during construction (e.g., embankment fill, select fill, etc.). Since relic structure, varves, etc. will not exist in the compacted fill, the remolded laboratory samples will most likely be representative of the field conditions.
4.5 LABORATORY TESTING PRECAUTIONS

Precautions must be taken when performing laboratory testing to help ensure that the test results are representative of the in-situ conditions. These precautions must be taken in the field while collecting, packaging, and transporting the samples, and in the laboratory while storing, handling and testing the samples.

4.5.1 Collecting Samples

The correct tools (e.g., split-barrel sampler, Shelby tube, core barrel, etc.) and sampling procedures, as indicated throughout Publication 222, Subchapter 5E, must be used when collecting both disturbed and undisturbed soil and rock samples. The drilling inspector must verify the depths at which the samples are being collected. Sampling depth can easily be determined by measuring the length of drill tools/rods placed in the boring and subtracting the length of drill rod “stick up” above ground surface. Additionally, it is critical that the boring is cleaned (e.g., free of disturbed material) prior to sampling to ensure that the sample collected is representative of the material at the reported depth.

4.5.2 Sample Volume and Number of Samples

Ensure that an adequate volume or numbers of samples are collected during the subsurface exploration, particularly undisturbed and bulk soil samples, such that both the needs for core box record and all potential laboratory testing are satisfied. Relative to undisturbed samples, multiple sample increments should be collected beyond those that are anticipated to be needed for testing. When extruded in the laboratory, undisturbed samples may be found to be damaged or inadequate for testing, so obtaining additional samples may be needed for testing. Also, sometimes laboratory test results appear erroneous or may not be as expected. In these cases, additional testing, and therefore additional samples, will be needed. The cost of obtaining additional samples during the subsurface exploration far outweighs the cost of remobilizing drilling equipment to obtain additional samples, or the potential costs and problems associated with performing design without the necessary information.

4.5.3 Packaging Samples

Packaging soil and rock samples properly is very important in ensuring representative laboratory test results. Procedures indicated in Publication 222, Section 215 must be followed. All samples must be clearly and accurately labeled to ensure the proper samples are tested. Disturbed soil samples must be kept in sealed jars to retain the natural moisture content. Ensure that the jar top and lid are clean to provide a good seal, and do not overfill jars. When bulk soil samples are collected, place a representative sample in a sealed jar within the bag for moisture content testing. Shelby tubes and other undisturbed soil samples must be properly capped, sealed with wax and taped to help secure the sample within the tube and retain the natural moisture content.

Depending upon the type of rock, core samples may have to be “specially” packaged. Fine-grained rocks, like claystone, mudstone, shale, siltstone, etc. should be wrapped in moist
paper towels and plastic wrap to retain the natural moisture and prevent deterioration prior to laboratory testing. Rock samples should be transported with care to prevent breakage, and bubble wrap or other cushioning material should be considered for protection. Once the rock core is removed from the boring, the natural confining stress is removed, and the core may break along weakly cemented joints. Wrapping the core in moist towels, plastic wrap, bubble wrap, tape, etc. can help to prevent this breakage prior to laboratory testing.

4.5.4 Storing Samples

Storing samples properly is also important to obtain quality laboratory test results. Soil and rock core samples should be stored in a location to prevent freezing or exposure to extreme heat. If jar samples freeze, the jars may break which will affect the natural moisture content and may “contaminate” the soil and prevent testing. Similarly, if rock core samples freeze, moisture within the sample may cause the core to break. Undisturbed soil samples are extremely sensitive and must also be stored in an upright position (i.e., same orientation as in the ground), ideally in a Shelby tube box, and protected from vibration, dropping, rolling, etc. The drilling inspector should take possession of undisturbed samples immediately after the driller has preserved the sample, and deliver to the laboratory as soon as possible. Undisturbed samples must not be stored in a vehicle. Alternatively, temporarily store these samples in a secure location on site or off site (i.e., office, home, hotel/motel room, etc.).

There is no exact time limit for how long samples can be successfully stored prior laboratory testing. The acceptable length of storage time will be dependent upon sample type, the testing to be performed, and how the sample is preserved/stored. Samples should be tested as soon as practically possible, and in particular, undisturbed samples, samples that are tested for natural moisture content, and “weak” rock samples. Soil and rock samples to be laboratory tested should be selected while the borings are being performed or immediately after they are drilled, and promptly delivered to the laboratory for testing.

The Publication FHWA-NHI-01-031, “Subsurface Investigations – Geotechnical Site Characterization” does not recommend long term storage of soil samples in Shelby tubes. Soil can cause the tubes to corrode, which leads to adhesion of the soil to the tube. This adhesion can make it difficult to extrude the sample, and microscopic failures in the soil can develop during extrusion. If undisturbed testing is done on these samples, the results may be erroneous. This FHWA publication also indicates that research has shown that undisturbed samples stored more than 15 days can experience significant changes in strength characteristics and result in unreliable test results.

4.5.5 Visually Review Samples before Testing

Avoid preparing laboratory test work orders/requests based solely on the boring logs. The PGM should visually inspect the samples selected for laboratory testing prior to laboratory testing to ensure that field descriptions appear accurate and revisions to the laboratory test work order/request are not needed. This should prevent unnecessary testing, and ensure that the testing needed for the geotechnical design is performed in a timely manner. If laboratory testing is being done off-site, and the PGM cannot visually inspect the samples, the PGM should discuss
the testing with the laboratory testing manager to verify that the laboratory work order/request appears reasonable. Additionally, when testing is performed on a soil sample from a Shelby tube, the PGM should inspect the sample after extrusion to direct the laboratory on which part(s) of the sample to use for testing. If testing is being performed off-site, digital photographs of the extruded sample can be used by the PGM to direct the laboratory testing.

4.5.6 Selecting Samples from Shelby Tubes

As previously discussed in Chapter 3, Shelby tubes are the most common method in Pennsylvania to obtain undisturbed soil samples to preserve the in-situ nature of the soil to the best extent possible and to estimate in-situ soil properties. When testing samples extruded from Shelby tubes, be sure to select representative portions of the sample for testing. Sometimes the material recovered in the tube will not be consistent throughout the full length of the recovered sample, and often times the tendency is to select the “worst” (e.g., softest, weakest, etc.) portion of the tube for testing. This approach is reasonable if the portion of the sample selected is representative of the majority of the tube. It is not reasonable/appropriate to test a portion of the sample that is unrepresentative of the majority of the tube and apply the test results to an entire soil stratum. Doing this can result in overly conservative and costly design recommendations. If it is believed that the localized “worst” portion of the tube is critical to the design (for instance, if it represents the failure plane of a landslide), consult with the DGE to determine if additional testing is necessary.

4.6 VERIFICATION OF LABORATORY TEST RESULTS

It is critical that the PGM review the laboratory test results immediately as they become available to ensure that they are consistent with expectations. If the results are not consistent with expectations, if they vary significantly between what are believed to be similar materials, or if the results appear not to be representative due to sample disturbance, laboratory error, etc., the PGM must determine if additional testing is required. This determination must be made quickly so that additional samples can be selected for testing, and the testing can be performed without adversely impacting the design schedule. If additional laboratory budget is needed to perform the testing, the PGM must have approval from the DGE prior to performing the testing. Ideally, sufficient samples, and in particular undisturbed and bulk samples, should be collected during the subsurface exploration to permit “unforeseen”, additional testing. If additional drilling is needed to obtain the necessary samples for testing, the DGE must also approve of this work before it is performed.

4.6.1 Example Projects

As previously indicated, exact testing requirements cannot be specified in this publication due to the multiple variables of a project. Keeping this in mind, below are examples of typical Department roadway and bridge construction projects, and what a laboratory test program may consist of based on the conditions indicated.
Example 1

Box culvert replacement with no roadway widening or vertical profile change: box culvert is 75 feet long, new box is approximately same size as existing, wing walls are 15 feet long and new pavement will match existing. Assume three borings were drilled (one at inlet, one near mid length and one at outlet) and one pavement core.

Subsurface conditions: Subsurface conditions will generally have little impact on this design/construction since it is a replacement with no profile increase or widening (i.e., no to minimal increase in load on the foundation). A relatively simple laboratory testing program is appropriate and may include:

- Four each – natural water content, sieve/gradation and liquid and plastic limits (i.e., classification)
- One soil corrosion series (pH, resistivity, sulfate and chloride)
- One water corrosion series (pH, conductivity/resistivity, sulfate and chloride)

Note: Shear strength testing typically is not needed for box culverts since bearing resistance rarely controls the design. Consolidation testing of saturated, cohesive soil may be needed if the culvert increases the load on the foundation, such as, if the culvert is constructed for a new roadway alignment or a roadway widening, or if the profile grade of an existing roadway is being raised considerably.

Example 2

Two-span bridge replacement with minor approach embankment widening: bridge spans a roadway (pier in the median); existing foundations are unknown; 50 feet of minor approach embankment widening on each side of the bridge; 15-foot high approach embankments; 5-foot (max.) widening on each side of embankment; and new pavement to match existing pavement section. Assume eight borings were drilled (two borings for each substructure and one boring on each side of bridge at toe of existing fill in proposed embankment widening area) and two pavement cores were obtained.

Subsurface conditions: Assume borings indicate relatively uniform conditions across the site, including: shallow bedrock (less than 10 feet below median grade), loose to medium dense granular overburden soil, and medium to very stiff sandy and gravelly clay embankments. Proposed foundations include abutments (stub or integral) on H-piles and pier spread footing bearing on bedrock.

Since the subsurface conditions are generally uniform and consist of granular soil, and the foundations are not complex, a relatively simple laboratory testing program is appropriate and may include:

- Eight each - natural water content, sieve/gradation and liquid and plastic limits (i.e., classification)
- Two soil corrosion series (pH, resistivity, sulfate and chloride) from abutment borings
- Five bedrock unconfined compressive strength tests from pier borings, or 20 point load breaks if unconfined compressive strength tests cannot be performed

**Testing justification:** Water content tests should generally be performed to compliment other testing. The eight classification tests should be adequate to verify field descriptions. Soil corrosion test results will be used for abutment pile design, and bedrock strength testing will be used for pier foundation design. Since soils are granular and foundations do not attain axial resistance from the soil, soil strength testing is not needed. Additionally, embankment height and widening is minimal so stability analysis is not needed.

**Example 3**

Same bridge project as **Example 2** above except subsurface conditions consist of thick (50 feet or more), predominantly granular overburden overlying bedrock. Proposed foundations alternatives include abutments (stub or integral) on friction or end/point bearing piles, and pier on spread footing on soil or piles (friction or end/point bearing).

Compared to **Example 2** above, the subsurface is slightly more complex since bedrock is deep, and the foundations are more complex since friction piles and a spread footing on soil are being considered. Consequently, more laboratory testing will be required and it may include:

- Twelve each - natural water content, sieve/gradation and liquid and plastic limits (i.e., classification)
- Two soil corrosion series (pH, resistivity, sulfate and chloride)
- Three shear strength tests (direct shear or triaxial shear)

**Testing justification:** Water content tests should generally be performed to compliment other testing. The twelve classification tests should be adequate to verify field descriptions. Soil corrosion test results will be used for pile design. Shear strength testing of soil is needed since friction piles and a spread footing on soil are being considered.

**Notes:**

1. If soft, saturated cohesive soil is present, consolidation testing is most likely not needed since minimal increased load will be placed on the soil since this is a bridge replacement project with minimal embankment widening. The presence of this soil in the subsurface will most likely require point/end bearing piles driven to bedrock in lieu of friction piles or spread footings. Consequently, shear strength testing will not be needed.
2. If bridge spans a waterway (e.g., stream, creek, river, etc.), water corrosion testing (pH, conductivity/resistivity, sulfate and chloride) is needed.
Example 4

Two-span bridge replacement/realignment: bridge replaces an existing structure, but on a new alignment; bridge spans a roadway (pier in the median); existing foundations are unknown; 200 feet of approach embankment realignment on each side of the bridge; 15-foot high approach embankments; and new pavement to match existing pavement section. Assume eight borings were drilled (two borings for each substructure and one boring on each side of bridge beneath the proposed approach embankment) and two pavement cores were obtained.

Testing for this scenario would be similar to that discussed in Example 3 above. However, due to the realigned embankments, consolidation testing would most likely be required if soft, saturated cohesive soil is present since these areas were not previously loaded by embankment.

4.7 PRESENTATION OF LABORATORY TEST RESULTS

It is important that laboratory test results are presented and documented adequately and consistently in boring logs, reports, plans, profiles, cross-sections and contract documents. Proper presentation and documentation provides a permanent record of the laboratory testing, allows the designer and reviewer(s) to better understand the laboratory test results and how they influence geotechnical analyses and recommendations, and gives contractors additional soil/rock information for consideration during bidding/planning of work.

The following are requirements for the presentation/documentation of laboratory test results in various documents. The requirements must be followed unless directed otherwise by the District Geotechnical Engineer (DGE).

4.7.1 Final Engineer’s Log

Laboratory AASHTO and USCS classification symbols must be shown on the Final Engineer’s Log. As indicated in Publication 222, Chapter 3.6.3, field estimated USCS and AASHTO symbols are denoted on the boring log with lower case letters. When laboratory classification testing is performed, the Final Engineer’s Log must indicate which strata were tested by using upper case letters for these symbols.

4.7.1.1 Overview of Final Engineer’s Log

One of the main goals of the Final Engineer’s Log is to identify the strata (i.e., soil and rock layers) beneath a project site, and it is important to keep in mind that within each stratum of soil and rock there will typically be some degree of variation. For example, a soil stratum may be comprised primarily of lean clay with sand and gravel. The amount/percentage of clay, sand and gravel in each split-barrel sample obtained from this stratum will vary, but this does not mean each individual sample is its own unique stratum. Similarly, the color of the individual split-barrel samples may have some variation, and the plasticity of the samples will vary somewhat, but again this does not mean each sample is its own unique stratum. Therefore, although detailed information should be presented on the Final Engineer’s Log, do not lose sight of the overall goal and purpose of the log. A Final Engineer’s Log that denotes numerous, thin
soil strata that have only slight variations is not the intent of the log, is typically not useful, and often creates unnecessary work due to the complexity of the log.

Unlike previous versions of the Final Engineer’s Log, the current log does not include an entry for a field AASHTO and USCS symbol for each split-barrel soil sample that is collected in a boring. Instead, these symbols are only shown for each soil stratum identified/described, and each soil stratum will typically include two or more split-barrel samples. Additionally, the method to describe soil in Publication 222, Chapter 3.6.3 for field descriptions is adapted from the Burmister Soil Description System and it is not related to the AASHTO or USCS classification system. Therefore, multiple AASHTO and USCS symbols can apply to the same field description. For example, a soil stratum field described as CLAY and SILT, would most likely include AASHTO symbols A-6 and A-7-6, but could also include A-4, A-5 and A-7-5. Similarly, the USCS symbol associated with this field description would most likely be CL, but it could also include ML. Therefore, when preparing the Inspector’s Field Log, keep in mind that it is expected/acceptable to have some variation in the soil within each stratum, and this can include variation in the AASHTO and/or USCS symbols. Furthermore, when field and laboratory AASHTO and USCS classification symbols do not agree, it is not acceptable to simply add a stratum to the log for the samples that were tested and keep the stratum that was described in the field for the samples that were not tested. It is the PGM’s responsibility to review all of the information (i.e., field and laboratory) and decide how to appropriately incorporate the laboratory information on the Final Engineer’s Log. Several examples of updating a boring log with laboratory test results are provided below.

4.7.1.2 Incorporating Laboratory Classifications onto the Final Engineer’s Log

As discussed above, laboratory AASHTO and USCS symbols must be shown on the Final Engineer’s Log in capital letters. A laboratory classification is more precise than a field description, and in order to clearly present the subsurface conditions, the field description on the Final Engineer’s Log must at least closely resemble the laboratory classification. If they do not closely resemble one another, the PGM must investigate the discrepancy and make revisions as appropriate. There are several scenarios that may occur with respect to the Final Engineer’s Log and laboratory classification test results. Some of these examples and guidelines for handling them are discussed below, and a brief discussion is also included in Publication 222, Chapter 3.6.2 under the fifth bullet.

Example 1

Assume four consecutive split-barrel samples are collected from a test boring, the samples are similar, and this stratum is field described as F SAND and CLAY, some silt (a-6/sc). This field description would indicate that there could be approximately equal amounts of fine SAND and CLAY since the descriptor “and” (i.e., content ≥ 35% per Publication 222, Chapter 3.6.3(a)) was used. These are the only four samples collected from this stratum, the samples are combined to perform one laboratory classification test, and the test indicates that the combined samples classify as they were described in the field (approximately equal amounts of sand and clay). Since the field and laboratory symbols are the same, change the lower case AASHTO and USCS letters to capital letters, and where applicable add the group number, on the Final Engineer’s Log.
(i.e., A-6(8)/SC). Note that gINT will automatically update the AASHTO and USCS symbols on the Final Engineer’s Log once the laboratory test results are entered into gINT. Also note that the field description may need to be changed depending upon the relative amounts of the various constituents.

**Example 2**

Assume the same situation as above, except the USCS laboratory classification is CL instead of SC. Similar to above the AASHTO and USCS symbols from the laboratory test results (i.e., A-6(8)/CL) must be shown on the Final Engineer’s Log in capital letters. Since the laboratory gradation analysis indicates there is considerably more clay than sand, the field description must be changed to be consistent with the laboratory classification (i.e., CLAY, some fine Sand, some Silt).

**Example 3**

Assume eight consecutive split-barrel samples are collected from a test boring, the samples are similar, and this stratum is field described as CLAY, little SAND (a-7-6/ch). The middle four of the eight samples are combined to perform one laboratory classification test, and the test indicates that the combined samples classify as A-6/CL. The laboratory test results must be reviewed to determine how to appropriately modify the Final Engineer’s log. A change in the field/visual description on the Final Engineer’s Log may be required. If the field description is inconsistent with the laboratory classification, then the description on the Final Engineer’s Log must be modified to be consistent with the laboratory classification. Furthermore, if the field/visual description for adjacent materials that were not laboratory classified is the same as the laboratory classified material, then the field/visual description of the non-laboratory classified material must be changed to a field/visual description (i.e., lower case letters) consistent with the laboratory classified material. No change is required if the field/visual description for adjacent differs from the field/visual description of the laboratory classified materials such that the original classifications of the adjacent materials are more representative of the field/visual description.

**4.7.2 Geotechnical Engineering Reports**

Laboratory test results must be thoroughly documented in all geotechnical engineering submissions/reports as indicated in Chapter 1.

**4.7.3 Soil Profile for Roadway Plans**

Laboratory test results must be graphically presented on the roadway profile according to DM-3, Chapter 5.

**4.7.4 Drafted Structure Borings**

As indicated in DM-4, Section 1.9.4, the information on the Final Engineer’s Log must be presented on the Drafted Structure Borings in the structure plans. The Drafted
Structure Borings must also include the laboratory test result summary tables for soil and rock core.

4.8 GEOTECHNICAL SOIL, ROCK AND WATER LABORATORY TESTS

The following sections provide information and guidance for various geotechnical soil, rock, and water laboratory tests.

4.8.1 AASHTO Materials Reference Laboratory (AMRL)

Laboratory testing must be performed by an AASHTO Materials Reference Laboratory (AMRL) accredited laboratory. It should be noted that AMRL certifies/assesses laboratories for specific tests, not the laboratory in its entirety. Therefore, when selecting a laboratory for testing services, ensure that the laboratory is accredited for each individual test that is proposed. Note that most geotechnical related laboratory tests are accredited by AMRL, but not all tests. In cases where AMRL does not certify a specific test proposed, any reputable laboratory may be used to perform these test. A summary of geotechnical laboratory tests is included in Section 4.8.4, and the summary indicates whether or not each test is accredited by AMRL. A listing of laboratories with their respective accredited test methods, and other information about AMRL can be found on the AMRL website.

4.8.2 Laboratory Test Methods – PTM, AASHTO, AND ASTM

Laboratory testing must be performed in accordance with a standard test method. In many cases there are numerous test methods for individual tests, including: Pennsylvania Test Method (PTM), AASHTO Test Method, and ASTM Test Method. Where more than one standard is available for a test, PennDOT Test Methods (PTMs) take precedence and must be used. Current PTMs can be found in Publication 19.

AASHTO Test Methods must be used for all other tests, but if an AASHTO Test Method does not exist, ASTM Test Methods must be used. For the rare cases where a PTM, AASHTO or ASTM test method does not exist, the PGM should recommend a test method to the DGE and obtain approval from the DGE prior to performing the test. The DGE should notify the CGE so that consideration can be given as to whether it is necessary or appropriate to adopt or create a standard test method.

4.8.3 Water Testing

Chemical testing of water should be performed when structures and/or foundations are in contact with bodies of water (e.g., streams, rivers, ponds, lakes, etc.) to determine if the water is corrosive to concrete and/or steel. For example:

- bridge substructures located in the water or within the floodplain of the stream/river/etc.
- retaining walls located along a body of water or within a floodplain
- box and arch culverts (large enough to have S-#)
Chemical testing of groundwater may be prudent or necessary in some situations. In addition, chemical testing of soil samples above and/or below the groundwater may be required for identifying potentially corrosive environments.

4.8.4 Summary of Geotechnical Laboratory Tests

Laboratory tests can be classified as either index tests or performance tests. Index tests provide information that can be used to assess or estimate the general engineering behavior of the soil or rock. For example, index tests can indicate whether a soil is cohesionless or cohesive, or if it is susceptible to consolidation settlement. Soil index tests do not directly measure strength or compressibility, but they can be used in conjunction with correlations to estimate strength and compressibility. Index tests include: natural moisture content, gradation, liquid and plastic limits, unit weight, specific gravity, organic content, chemical analyses, point load strength and slake durability. Performance tests provide a direct measurement of engineering properties, including shear strength, consolidation and permeability. These tests include direct shear, triaxial shear, soil unconfined compressive strength, consolidation, permeability and rock unconfined compressive strength. Index tests are often performed before or in conjunction with performance tests, and index tests are generally less costly to perform than performance tests. Refer to Chapter 10 for Acid Bearing Rock tests and sample size requirements for Fizz Rating, Neutralization Potential, and Total Sulfur rock tests. A detailed summary of the most commonly performed index and performance tests is provided below.

4.8.4.1 Natural Water (Moisture) Content of Soil

**Purpose:** To estimate the natural (in-situ) water content of soil.

**Uses:** Compare the in-situ water content to the liquid and plastic moisture contents (i.e., Atterberg limits). Also compare the optimum moisture content from moisture-density testing to the in-situ moisture content. This will help determine the effort needed for compaction (i.e., will drying or wetting of soil be required for compaction, or is soil naturally at optimum water content).

**Soil Types:** All

**Soil Sample Types:** Disturbed (jars and bags) and undisturbed. Samples must be in an air tight jar/bag/tube to retain the natural water content.

**AMRL Certification Required:** Yes

**AASHTO Test Method:**

T 265 – “Standard Method of Test for Laboratory Determination of Moisture Content of Soils”.

**ASTM Test Method:**


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4.8.4.2 Sieve/Gradation Analysis of Soil

**Purpose:** To estimate the distribution/gradation of particle sizes in soils. Sieve analyses provide gradation of only gravel and sand particles (i.e., larger than No. 200 sieve). Gradation of fines (silt and clay) is determined by hydrometer analysis discussed below.

**Uses:** Required for laboratory classification of soils. Provide verification of field description and detailed breakdown of particle sizes.

**Soil Types:** All

**Soil Sample Types:** Disturbed (jars and bags) and undisturbed.

**AMRL Certification Required:** Yes

**AASHTO Test Method:**
T 88 “Standard Method of Test for Particle Size Analysis of Soils”.

**ASTM Test Method:**
D 422 “Standard Test Method for Particle-Size Analysis of Soils”.

**Minimum Sample Size (1 jar = 300 grams):**
- Max. particle size of 9.5 mm (0.375-inch): 500 grams
- Max. particle size of 25 mm (1-inch): 2,000 grams
- Max. particle size of 50 mm (2-inch): 4,000 grams
- Max. particle size of 75 mm (3-inch): 5,000 grams (11 lbs.)

**Approximate Cost:** $75 (2015)

**Companion Testing (R=Required, S=Suggested):** Natural water content (S), Hydrometer (S) - particularly when fines content is greater than approximately 30%.
4.8.4.3 Hydrometer Analysis

**Purpose:** To estimate the distribution/gradation of silt and clay particles (i.e., finer than No. 200 sieve). Note that this test is not needed to classify soils (USCS or AASHTO).

**Uses:** When combined with sieve analysis it provides a complete gradation of the soil. Provides D50 value for scour calculations for fine-grained soils. Needed when geotextile or aggregate filter design is required. Used for design of subgrade stabilization and ground improvement techniques when cement, flyash, etc. are proposed to be mixed with soil.

**Soil Types:** Soils containing approximately 25% or more fines (i.e., silt and clay).

**Soil Sample Types:** Disturbed (jars and bags) and undisturbed.

**AMRL Certification Required:** Yes

**AASHTO Test Method:**
T 88 “Standard Method of Test for Particle Size Analysis of Soils”.

**ASTM Test Method:**
D 422 “Standard Test Method for Particle-Size Analysis of Soils”.

**Minimum Sample Size (1 jar = 300 grams):** Approximately 100 grams of material passing the No. 10 (2 mm) sieve.

**Approximate Cost:** $75 (2015)

**Companion Testing (R=Required, S=Suggested):** Natural water content (S), Sieve/Gradation (S) – particularly when gravel/sand content is greater than approximately 30%., Liquid and Plastic Limits (S)

4.8.4.4 Liquid and Plastic Limits (Atterberg Limits)

**Purpose:** To estimate the liquid limit, plastic limit, and plasticity index of soil.

**Uses:** Required, in addition to sieve analysis, to classify soil (AASHTO and USCS). Limits can also be compared with in-situ moisture content.

**Soil Types:** All soils except clean sands and gravels (i.e., less than approximately 5% passing No. 200 sieve).

**Soil Sample Types:** Disturbed (jars and bags) and undisturbed.

**AMRL Certification Required:** Yes
AASHTO Standard Test Method:
T 89 “Standard Method of Test for Determining the Liquid Limit of Soils”.
T 90 “Standard Method of Test for Determining the Plastic Limit and Plasticity Index of Soils”.

ASTM Test Method:

Minimum Sample Size (1 jar = 300 grams): 100 grams of material passing the No. 40 (0.425 mm) sieve.

Approximate Cost: $75 (2015)

Companion Testing (R=Required, S=Suggested): Natural water content (S), Sieve/Gradation (S), Hydrometer (S)

4.8.4.5 Laboratory Classification of Soil (AASHTO and USCS)

Purpose: To classify soil in accordance with a standardized system.

Uses: Soil classification along with other field and laboratory test results can be used to estimate engineering parameters of soil.

Soil Types: All

Soil Sample Types: Disturbed (jars and bags) and undisturbed.

AMRL Certification Required: Yes (D2487 only)

AASHTO Test Method:
M 145 “Standard Method of Test for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes”. There is currently no AMRL certification required for this test.

ASTM Test Methods:
D 3282 “Standard Practice for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes (AASHTO)”. There is currently no AMRL certification required for this test.

D 2487 “Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)”.

Approximate Cost: Typically no charge when Sieve/Gradation Analysis and Liquid and Plastic Limits are performed. (2015)

Companion Testing (R=Required, S=Suggested): Sieve/Gradation (R), Atterberg Limits (R), Natural water content (S), Hydrometer (S) - particularly when fines content is greater than approximately 30%.

4.8.4.6 Density (Unit Weight) of Intact Soil Sample

Purpose: To estimate the in-situ total unit weight or density of the soil sample. Also can determine in-situ dry unit weight if natural water content testing is performed.

Uses: Use directly in calculations where unit weight of soil is needed.

Soil Types: Soils with adequate cohesion to maintain form when removed from sampler and transported to laboratory.

Soil Sample Types: Undisturbed samples. Also can use split-spoon samples and hand excavated (block) samples if they maintain their form. Samples must be in an air tight container to retain the natural water content of the soil. Not appropriate for non-plastic silts, clean sands and gravels, or sands and gravels with a non plastic matrix.

AMRL Certification Required: There is currently no AMRL certification required.

ASTM Test Method:
D 7263 “Standard Test Methods for Laboratory Determination of Density (Unit Weight) of Soil Specimens”.

Minimum Sample Size (1 jar = 300 grams): One jar with piece of sample from split-barrel sampler, part of undisturbed sample (Shelby tube), or a block/cube of reasonable size (say three cubic inches minimum).

Approximate Cost: $50 (2015)

Companion Testing (R=Required, S=Suggested): None.

4.8.4.7 Specific Gravity

Purpose: To estimate specific gravity of soil solids.

Uses: Calculation of weight-volume relationships, including void ratio for consolidation settlement calculations. Note that specific gravity values of soil solids typically has little variation; therefore, specific gravity testing is generally not performed. However, the specific gravity of peat, highly organic soil, and soil with unusual solid minerals can vary more considerably and testing may be prudent.
Soil Types: Fine gravel (maximum particle size of 4.75 mm), sand, silt and clay. Coarse gravel can be tested but not typically useful for geotechnical purposes.

Soil Sample Types: Disturbed (jars and bags) and undisturbed.

AMRL Certification Required: Yes

AASHTO Test Methods:
T 100 “Standard Method of Test for Specific Gravity of Soils” (for maximum particle size of 4.75 mm (No. 4 sieve)).
T 85 “Standard Method of Test for Specific Gravity and Absorption of Coarse Aggregate” (for particles larger than 4.75 mm (No. 4 sieve)).

ASTM Test Method:
D 854 “Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer” (for maximum particle size of 4.75 mm (No. 4 sieve)).
C 127 “Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate”.

Minimum Sample Size (1 jar = 300 grams): 100 grams (maximum particle size of 4.75 mm (No. 4 sieve)).


Companion Testing (R=Required, S=Suggested): None.

4.8.4.8 Organic Content

Purpose: To estimate the organic content of soil.

Uses: Confirm field identification of organic soils. Quantify the amount/percent of organic material in the soil sample.

Soil Types: Peat, organic muck, and soils containing: vegetative matter that has not decayed/decomposed; fresh plant materials such as wood, roots, or grass; or carbonaceous materials such as coal. Samples must be in an air tight container to retain the natural water content of the soil.

Soil Sample Types: Disturbed (jars and bags) and undisturbed.

AMRL Certification Required: Yes (T 267 and D 2974 only)
AASHTO Test Method:
T 267 “Standard Method of Test for Determination of Organic Content in Soils by Loss on Ignition”.

T 194 “Standard Method of Test for Determination of Organic Matter in Soils by Wet Combustion” (This method is only used for suitability of a soil for plant growth.) There is currently no AMRL certification required for this test. However, when determining organic content of soils for engineering purposes, AASHTO T 267 must be used.

ASTM Test Method:

Minimum Sample Size (1 jar = 300 grams): 100 grams (material passing the 2.00 mm (No. 10) sieve).

Approximate Cost: $115 (2015)

Companion Testing (R=Required, S=Suggested): Natural water content (S).

4.8.4.9 Moisture-Density Relationship (Compaction)

Purpose: To estimate the maximum dry weight density, optimum moisture content and relationship between moisture content and density (i.e., compaction curve).

Uses: Verify that field compaction requirements (moisture content and density) are achieved. Estimate in-place unit weight/density of soils placed during construction to prepare remolded samples for laboratory testing, like strength tests and permeability.

Soil Types: Gravel, sand, silt and clay.

Soil Sample Types: Disturbed - Bulk/bag samples.

AMRL Certification Required: Yes

PTM:
106 “The Moisture-Density Relations of Soil (using a 2.5 kg (5.5 lb.) Rammer and a 305 mm (12-inch) Drop)”. This method is referred to as Standard Compaction. Note that PTM 106 includes Methods A and B; Method B should always be used.

AASHTO Test Method:
T 99 “Standard Method of Test for Moisture-Density Relations of Soil using a 2.5-kg (5.5-lb) Rammer and a 305-mm (12-in.) Drop”. This method is referred to as Standard Compaction.
T 180 “Standard Method of Test for Moisture-Density Relations of Soil using a 4.54-kg (10-lb) Rammer and a 457-mm (18-in.) Drop”. This method is referred to as Modified Compaction.

**ASTM Test Method:**

D 698 “Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft³ (600 kN-m/m³))”. This method is referred to as Standard Compaction.

D 1557 “Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft³ (2,700 kN-m/m³))”. This method is referred to as Modified Compaction.

**Minimum Sample Size:** 50 lbs. Note that per the PTM a minimum of 12 lbs. is needed for the test. The 12 lbs. is only material finer than ¾-inch; therefore, additional material is needed if the sample contains particles larger than ¾-inch. Additionally, the 12 lb. minimum is based on reuse of sample during the test. As discussed in PTM 106, reuse is not recommended where the soil material is fragile or where the soil is heavy-textured clayey material that is difficult to incorporate water. Consequently, when possible a 50 lb. sample shall be obtained to account for particles greater than ¾-inch and to eliminate the need to reuse sample for the test.

**Approximate Cost (includes 3 molds):** $200 (2015)

**Companion Testing (R=Required, S=Suggested):** Sieve/Gradation (R), Natural water content (S), Atterberg Limits (S), Hydrometer (S) - particularly when fines content is greater than approximately 30%.

**Information Needed by Laboratory (supplied by customer):**
Specify Method B of PTM 106.

4.8.4.10 California Bearing Ratio (CBR)

**Purpose:** To estimate the California Bearing Ratio (CBR) of soil.

**Uses:** Required for pavement design when subgrade materials are known.

**Soil Types:** Gravel, sand, silt and clay.

**Soil Sample Types:** Disturbed - Bulk/bag samples.

**AMRL Certification Required:** Yes

**AASHTO Test Method:**

T 193 “Standard Method of Test for the California Bearing Ratio”.

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ASTM Test Method:
D 1883 “Standard Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils”.

Minimum Sample Size: 75 lbs.

Approximate Cost (includes 3 molds): $550 (2015)

Companion Testing (R=Required, S=Suggested): Compaction (R), Sieve/Gradation (R), Natural water content (S), Atterberg Limits (S), Hydrometer (S) - particularly when fines content is greater than approximately 30%.

Information Needed by Laboratory (supplied by customer):
1. Specify water content or range of water content and dry density. Normally maximum dry density and optimum moisture content are used.
2. Specify special surcharge weights if different than the test minimum of 10 lbs. The weight is intended to represent the load from the pavement section (i.e., subbase, base course and wearing course).

4.8.4.11 Consolidation

Purpose: To estimate consolidation settlement properties of soil.

Uses: Provides information necessary to estimate/predict magnitude and time rate of consolidation settlement.

Soil Types: Saturated cohesive soils.

Soil Sample Types: Typically undisturbed; remolded samples are rarely used.

AMRL Certification Required: Yes

AASHTO Test Method:
T 216 “Standard Method of Test for One-Dimensional Consolidation Properties of Soils”.

ASTM Test Method:
D 2435 “Standard Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading”.

Minimum Sample Size: 4-inch tube sample (assume one Shelby tube).

Approximate Cost (includes Shelby tube extrusion cost): $700 (2015)
Companion Testing (R=Required, S=Suggested): Specific Gravity (R), Shelby tube sample extrusion (R), Sieve/Gradation (S), Atterberg limits (S), Hydrometer (S). Natural water content and unit weight are determined as part of this test.

Information Needed by Laboratory (supplied by customer):
1. Specify the load cycle. Typical cycle is 0.25, 0.5, 1, 2, 4, 8, 16, 32, 8, 2, 0.25 tsf. Some labs may not be capable of applying 32 tsf load, which is acceptable in most cases.
2. Specify Method A or B. Method A is typically used and requires each load be held for 24 hours. Method B allows load duration to be reduced to the time it takes for completion of primary consolidation. This method can be considered for soils with low plasticity index, particularly when test results are needed quickly.
3. If remolded samples are used, specify density and water content.

4.8.4.12 Direct Shear

Purpose: To estimate the drained/effective peak shear strength of soil. See Section 4.9.4 for detailed discussion.

Uses: Provides shear strength information (internal friction angle and cohesion) needed for slope stability analysis, foundation design (bearing resistance, friction and end bearing (soil) piles and drilled shaft, etc.) and retaining wall design.

Soil Types: Typically sands and fine-grained soils. Dependent upon size of testing apparatus. See detailed discussion of direct shear testing.

Soil Sample Types: Disturbed (jars and bags) and undisturbed. Sample type preference is dependent upon design application. See detailed discussion of direct shear testing.

AMRL Certification Required: Yes

AASHTO Test Method:
T 236 “Standard Method of Test for Direct Shear Test of Soils under Consolidated Drained Conditions”. **RESIDUAL VALUES ARE OBTAINED FROM THE RESIDUAL STRENGTH PORTION OF THE STRESS-STRAIN PLOT OF THE DIRECT SHEAR TEST. IT IS NECESSARY TO RUN THE DIRECT SHEAR TEST WITH SUFFICIENT DISPLACEMENT TO ASSURE RESIDUAL SHEAR HAS BEEN OBSERVED.**

ASTM Test Method:
D 3080 “Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions”.

Minimum Sample Size (1 jar = 300 grams): Dependent upon size of testing apparatus. See detailed discussion of direct shear testing. Generally a 6-inch tube sample (assume one Shelby tube) or 1,000 grams.
Approximate Cost (includes required 3 normal loads): $500 (2015).

Companion Testing (R=Required, S=Suggested): Sieve/Gradation (R), Specific Gravity (R), Shelby tube sample extrusion, remolding sample, or block sample preparation (R), Atterberg limits (S), Hydrometer (S), Compaction (S) if remolded samples are being used. Natural water content and unit weight are determined as part of this test.

Information Needed by Laboratory (supplied by customer):
1. Specify normal loads. Commonly 4, 8, and 12 ksf are used.
2. If remolded samples are used, specify density and water content.

4.8.4.13 Residual Direct Shear

Purpose: To estimate the residual shear strength of soil.

Uses: Provides residual shear strength estimate along weak plane(s) within soil deposit, such as along a slope stability/landslide failure plane (active or inactive) or along thin varves. This test is useful for slope stability analysis of in-situ soils and landslide remediation design.

Soil Types: Cohesive soils (clay, silty clay, and clayey silt).

Soil Sample Types: Disturbed (jars and bags) and undisturbed. Sample type preference is dependent upon design application. See detailed discussion of direct shear testing.

AMRL Certification Required: There is currently no AMRL certification required.

Test Method:
Neither AASHTO nor ASTM has a test method for residual direct shear. The United States Army Corps of Engineers EM 1110-2-1906, Appendix IX A is not approved for use by the Department. RESIDUAL VALUES ARE OBTAINED FROM THE RESIDUAL STRENGTH PORTION OF THE STRESS-STRAIN PLOT OF THE NORMAL DIRECT SHEAR TEST (T 236). IT IS NECESSARY TO RUN THE DIRECT SHEAR TEST WITH SUFFICIENT DISPLACEMENT TO ASSURE RESIDUAL SHEAR HAS BEEN OBSERVED.

Approximate Cost: No additional cost. See Section 4.8.4.12 for additional information.

4.8.4.14 Triaxial Compression (Shear) – Unconsolidated, Undrained (UU)

Purpose: To estimate the undrained shear strength (i.e., cohesion) of cohesive soil.

Uses: Provides shear strength parameter for total stress (i.e., short term) stability analysis. Represents field conditions where load is applied rapidly (i.e., embankment construction or loading of a spread footing) and the foundation soil does not have
adequate time to drain (i.e., pore water pressure does not dissipate), and therefore does not consolidate.

Soil Types: Cohesive soils (clay, silty clay, and clayey silt).

Soil Sample Types: Typically undisturbed, but can use disturbed (bag).

AMRL Certification Required: Yes

AASHTO Test Method:
T 296 “Standard Method of Test for Unconsolidated, Undrained Compressive Strength of Cohesive Soils in Triaxial Compression”.

ASTM Test Method:
D 2850 “Standard Test Method for Unconsolidated Undrained Triaxial Compression Test on Cohesive Soils”.

Minimum Sample Size: 24-inch sample (1 tube). Usually two tubes are required since full recovery is not always achieved and some portion of tube may not be suitable for testing (i.e., disturbance at top, piece(s) of gravel, thin layer of soil within the tube not representative of stratum to be tested, etc.). If using disturbed/remolded samples, 25 lbs.

Approximate Cost (includes 3 required confining loads): $600 (2015).

Companion Testing (R=Required, S=Suggested): Specific gravity (R), Shelby tube sample extrusion, remolding sample, or block sample preparation (R), Sieve/Gradation (S), Atterberg limits (S), Hydrometer (S), Compaction (S) if remolded samples are being used. Natural water content and unit weight are determined as part of this test.

Information Needed by Laboratory (supplied by customer):
1. Specify chamber (consolidation) pressure.
2. If remolded samples are used, specify density and water content.

4.8.4.15 Triaxial Compression (Shear) – Consolidated, Undrained (CU) with or without pore pressure measurement

Purpose: To estimate the total shear strength of cohesive soil. If pore pressure measurements are taken during the test, effective shear strength can also be estimated.

Uses: Provides shear strength parameter for total stress (i.e., short term) stability analysis, similar to the UU test. However, unlike the UU test, the CU test is performed by consolidating the sample prior to applying the shear stress. The CU test can be used to represent conditions in the field where load has been applied and foundation soils have had time to consolidate but excess pore water pressure is still present. It also represents conditions of previous consolidation, like glaciation, but excess pore pressure due to newly applied loads. By also measuring pore pressure during testing, the CU test can be
used to represent conditions in the field where load has been applied and foundation soils have consolidated and excess pore water pressure has dissipated (i.e., long-term conditions).

**Soil Types**: Cohesive soils (clay, silty clay, and clayey silt).

**Soil Sample Types**: Typically undisturbed, but can use disturbed (bag).

**AMRL Certification Required**: Yes

**AASHTO Test Method**: T 297 “Standard Method of Test for Consolidated, Undrained Triaxial Compression Test on Cohesive Soils”.


**Minimum Sample Size**: 24-inch sample (one tube). Usually two tubes required since full recovery is not always achieved and some portion of tube may not be suitable for testing (i.e., disturbance at top, piece(s) of gravel, thin layer of soil within the tube not representative of stratum to be tested, etc.). If using disturbed/remolded samples, 25 lbs.

**Approximate Cost (includes 3 required confining loads)**: $1,000 (2015) for no pore pressure measurement. $1,600 (2015) for pore pressure measurement.

**Companion Testing (R=Required, S=Suggested)**: Specific gravity (R), Shelby tube sample extrusion, remolding sample, or block sample preparation (R), Sieve/Gradation (S), Atterberg limits (S), Hydrometer (S), Compaction (S) if remolded samples are being used. Natural water content and unit weight are determined as part of this test.

**Information Needed by Laboratory (supplied by customer)**:
1. Specify chamber (consolidation) pressure.
2. If remolded samples are used, specify density and water content.

4.8.4.16 Triaxial Compression (Shear) – Consolidated, Drained (CD)

**Purpose**: To estimate the effective shear strength of cohesive soil.

**Uses**: This test is performed by allowing drainage (i.e., no excess pore pressure) and consolidation while the shearing stress is applied. Since cohesive soil generally drains very slowly, the shear stress must be applied at a very low rate. Consequently, the test takes considerable time to conduct, is costly and is therefore rarely performed. In lieu of this test, the triaxial CU test with pore water pressure measurements is typically performed to estimate effective (i.e., drained or long term strength) shear strength.
Soil Types: Cohesive soils (clay, silty clay, and clayey silt).

Soil Sample Types: Typically undisturbed, but can use disturbed (bag).

AMRL Certification Required: There is currently no AMRL certification required.

Test Method:
Neither AASHTO nor ASTM has a test method for CD triaxial testing. The United States Army Corps of Engineers EM 1110-2-1906, Appendix X can be used.

Minimum Sample Size: 24-inch sample (one tube). Usually two tubes required since full recovery is not always achieved and some portion of tube may not be suitable for testing (i.e., disturbance at top, piece(s) of gravel, thin layer of soil within the tube not representative of stratum to be tested, etc.). If using disturbed/remolded samples 25 lbs.

Approximate Cost: Laboratories generally provide a price quote based on a project by project basis since this test is rarely performed because it is extremely time consuming and costly. (2015)

Companion Testing (R=Required, S=Suggested): Specific gravity (R), Shelby tube sample extrusion, remolding sample, or block sample preparation (R), Sieve/Gradation (S), Atterberg limits (S), Hydrometer (S), Compaction (S) if remolded samples are being used. Natural water content and unit weight are determined as part of this test.

Information Needed by Laboratory (supplied by customer):
1. Specify chamber (consolidation) pressure.
2. If remolded samples are used, specify density and water content.

4.8.4.17 Unconfined Compression (Soil)

Purpose: To estimate the unconfined compressive strength of cohesive soil.

Uses: Provides an estimate of the undrained shear strength (i.e., cohesion).

Soil Types: Cohesive soils (clay, silty clay, and clayey silt).

Soil Sample Types: Typically undisturbed, but can use disturbed (bag).

AMRL Certification Required: Yes

AASHTO Test Method:
T 208 “Standard Method of Test for Unconfined Compressive Strength of Cohesive Soil”.
ASTM Test Method:
D 2166 “Standard Test Method for Unconfined Compressive Strength of Cohesive Soil”.

Minimum Sample Size: Six-inch piece of tube sample per test (typically, three samples). If using disturbed/remolded sample, 10 lbs.

Approximate Cost (per test): $110 (2015)

Companion Testing (R=Required, S=Suggested): Shelby tube sample extrusion, remolding sample, or block sample preparation (R), Sieve/Gradation (S), Atterberg limits (S), Hydrometer (S). Natural water content and unit weight are determined as part of this test.

Information Needed by Laboratory (supplied by customer):
If remolded samples are used specify density and water content.

4.8.4.18 Unconfined Compression (Rock)

Purpose: To estimate the unconfined compressive strength of bedrock.

Uses: Provides estimate of bedrock strength needed for design of spread footings, drilled shafts, micropiles, rock anchors, etc. Provides an indication of the ease/difficulty and equipment needed to excavate bedrock for roadway cuts, spread footings, drilled shafts, etc. This test is preferred over Point Load tests if required sample size is available.

Rock Types: All

Rock Sample Types: Cylindrical Core

AMRL Certification Required: Yes

ASTM Test Method:
D 7012 “Standard Test Method for Unconfined Compressive Strength of Intact Rock Core Specimens”, Method C.

Minimum Sample Size (per test/break): 1.875-inch minimum diameter and length to diameter ratio of 2 to 2.5. Includes NW and HW conventional rock core, and NX, NQ, HQ and HQ3 wireline rock core.

Approximate Cost (per break): $40 (2015)

Companion Testing (R=Required, S=Suggested): None.

4.8.4.19 Point Load

Purpose: To estimate point load strength index of bedrock.
Uses: Provides point load strength index of bedrock which allows calculation of unconfined compressive strength. This test is not a direct measure of unconfined compression test, and should typically only be used in place of D 7012 if the sample size requirement of D 7012 cannot be met.

Rock Types: All.

Rock Sample Types: Cores (preferred), blocks or irregular lumps.

AMRL Certification Required: Yes

ASTM Test Method:
D 5731, “Standard Test Method for Determination of the Point Load Strength Index of Rock and Application to Rock Strength Classifications”.

Minimum Sample Size (per break): For core a diameter of 1.2 to 3.3 inches, but +/- 2-inch is preferred, and length greater than 0.3 times the diameter. See specification for details on size requirements for core (diametral and axial), block and irregular samples. A minimum of 10 samples is required for core or block tests, and a minimum of 20 irregular lump samples is required.

Approximate Cost (per break): $20 (2015)

Companion Testing (R=Required, S=Suggested): None.

4.8.4.20 Slake Durability

Purpose: To estimate the slake durability index of shale or other similar bedrock.

Uses: Provides a qualitative indication to the slaking potential of bedrock for design of foundations bearing on rock (spread footing, drilled shafts, piles, etc.) and rock cuts. There is no accepted durability index reference value for various rocks; therefore, the test results must be used with engineering judgment, past experience, etc.

Rock Types: Slake prone rocks – shale, claystone, etc.

Rock Sample Types: Rock cores or rock blocks

AMRL Certification Required: Yes

ASTM Test Method:
D 4644 “Standard Test Method for Slake Durability of Shales and Similar Weak Rocks”.
Minimum Sample Size: Ten, roughly equi-dimensional fragments weighing 40 to 60 grams each (total sample weight 450 to 550 g, about 1 lb.). Retain natural moisture of samples prior to testing.

Approximate Cost: $250 (2015)

Companion Testing (R=Required, S=Suggested): None.

4.8.4.21 Resistivity (Soil)

Purpose: To estimate the resistivity of soil in the laboratory.

Uses: Provides an indication of the corrosion potential of soils to steel, typically with respect to foundation design (i.e., steel piles and concrete reinforcement).

Soil Types: All, but only coarse sand (2 mm) and finer particles are used in test.

Soil Sample Types: Disturbed (jars and bags) and undisturbed.

AMRL Certification Required: Yes

AASHTO Test Method:
T 288 “Standard Method of Test for Determining Minimum Laboratory Soil Resistivity”.

Minimum Sample Size (1 jar = 300 grams): 1,500 grams (max. particle size of 2 mm).

Approximate Cost: $35 (2015)

Companion Testing (R=Required, S=Suggested): pH (R), Sulfate (S), Chloride (S)

4.8.4.22 pH (Soil)

Purpose: To estimate the pH of soil.

Uses: Provides an indication of the corrosion potential of soils to steel, typically with respect to foundation design (i.e., steel piles and concrete reinforcement).

Soil Types: All, but only coarse sand (2 mm) and finer particles are used in test.

Soil Sample Types: Disturbed (jars and bags) and undisturbed.

AMRL Certification Required: Yes

AASHTO Test Method:
T 289 “Standard Method of Test for Determining pH of Soil for Use in Corrosion Testing”.

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Minimum Sample Size (1 jar = 300 grams): 100 grams (max. particle size of 2 mm).

Approximate Cost: $35 (2015)

Companion Testing (R=Required, S=Suggested): Resistivity (R), Sulfate (S), Chloride (S)

4.8.4.23 Sulfate Ion (Soil)

Purpose: To estimate water-soluble sulfate in soil.

Uses: Provides an indication of the corrosion potential of soil on concrete (footings, piles, drilled shafts, etc.).

Soil Types: All, but only coarse sand (2 mm) and finer particles are used in test.

Soil Sample Types: Disturbed (jars and bags) and undisturbed.

AMRL Certification Required: There is currently no AMRL certification required.

AASHTO Test Method:
T 290 “Standard Method of Test for Determining Water-Soluble Sulfate Ion Content in Soil”.

ASTM Test Method:
C 1580 “Standard Test Method for Water-Soluble Sulfate in Soil”.

Minimum Sample Size (1 jar = 300 grams): 250 grams (max. particle size of 2 mm).

Approximate Cost: $35 (2015)

Companion Testing (R=Required, S=Suggested): Resistivity (R), pH (R), Chloride (R)

4.8.4.24 Chloride Ion (Soil)

Purpose: To estimate water-soluble chloride in soil.

Uses: Provides an indication of the corrosion potential of soil on concrete (footings, piles, drilled shafts, etc.).

Soil Types: All, but only coarse sand (2 mm) and finer particles are used in test.

Soil Sample Types: Disturbed (jars and bags) and undisturbed.

AMRL Certification Required: There is currently no AMRL certification required.
AASHTO Test Method:
T 291 “Standard Method of Test for Determining Water-Soluble Chloride Ion Content in Soil”.
Minimum Sample Size (1 jar = 300 grams): 250 grams (max. particle size of 2 mm).
Approximate Cost: $35 (2015)
Companion Testing (R=Required, S=Suggested): Resistivity (R), pH (R), Sulfate (R)

4.8.4.25 Hydraulic Conductivity (Permeability) (Soil)

Purpose: To estimate the soil’s ability to transmit water through pore spaces or fractures when submitted to a hydraulic gradient.
Uses: Provides an indication of the permeability of water through soil.
Soil Types: All, refer to ASTM D 2434 for high permeability soils.
Soil Sample Types: Disturbed (jars and bags) and undisturbed.
AMRL Certification Required: Yes

ASTM Test Method:
Minimum Sample Size: Determined per method, soil type, and/or testing laboratory.
Approximate Cost: $540 (2015)
Companion Testing (R=Required, S=Suggested): pH (S), Sulfate (S), Chloride (S)

Information Needed by Laboratory (supplied by customer):
If remolded samples are used specify density and water content.

4.8.4.26 Conductivity/Resistivity (Water)

Purpose: To estimate conductivity/resistivity of water. Resistivity is the inverse of conductivity.
Uses: Provides an indication of the corrosion potential of water on steel, typically with respect to foundation design (i.e., steel piles and concrete reinforcement).

Water Sample Types: Streams/Creeks/Rivers/etc., Ponds/Lakes/etc., and ground water.
AMRL Certification Required: There is currently no AMRL certification required.

ASTM Test Method:
D 1125 “Standard Test Methods for Electrical Conductivity and Resistivity of Water” (Method A). Note that results from this test method are reported in Siemens/cm. Conversion to ohm-cm is done by taking the inverse of the Siemens value (i.e., 0.00005 siemens/cm equals 20,000 ohm-cm).

Minimum Sample Size: Determined by testing agency.

Approximate Cost: $35 (2015)

Companion Testing (R=Required, S=Suggested): pH (R), Sulfate (S), Chloride (S)

4.8.4.27 pH (Water)

Purpose: To estimate pH of water.

Uses: Provides an indication of the corrosion potential of water to steel, typically with respect to foundation design (i.e., steel piles and concrete reinforcement).

Water Sample Types: Streams/Creeks/Rivers/etc., Ponds/Lakes/etc., and ground water.

AMRL Certification Required: There is currently no AMRL certification required.

ASTM Test Method:
D 1293 “Standard Test Methods for pH of Water”.

Minimum Sample Size: Determined by testing agency.

Approximate Cost: $35 (2015)

Companion Testing (R=Required, S=Suggested): Resistivity (R), Sulfate (S), Chloride (S)

4.8.4.28 Sulfate (Water)

Purpose: To estimate water-soluble chloride in soil.

Uses: Provides an indication of the corrosion potential of water on concrete (footings, piles, drilled shafts, etc.).

Water Sample Types: Streams/Creeks/Rivers/etc., Ponds/Lakes/etc., and ground water.

AMRL Certification Required: There is currently no AMRL certification required.
ASTM Test Method:
D 516 “Standard Test Method for Sulfate Ion in Water”.

Minimum Sample Size: Determined by testing agency.

Approximate Cost: $35 (2015)

Companion Testing (R=Required, S=Suggested): Resistivity (R), pH (R), Sulfate (R)

4.8.4.29 Chloride (Water)

Purpose: To estimate water-soluble chloride in water.

Uses: Provides an indication of the corrosion potential of water on concrete (footings, piles, drilled shafts, etc.).

Water Sample Types: Streams/Creeks/Rivers/etc., Ponds/Lakes/etc., and ground water.

AMRL Certification Required: There is currently no AMRL certification required.

ASTM Test Method:
D 512 “Standard Test Method for Chloride Ion in Water”.

Minimum Sample Size: Determined by testing agency.

Approximate Cost: $35 (2015)

Companion Testing (R=Required, S=Suggested): Resistivity (R), pH (R), Sulfate (R)

4.9 GEOTECHNICAL TEST CONSIDERATIONS

This section discusses issues concerning some of the more complex laboratory tests involving soils. It focuses on considerations involving strength testing, consolidation, and moisture density relationships.

4.9.1 Moisture Density, PTM 106

The Moisture Density Test, which is often referred to as a Compaction Test, is performed to establish a relationship between water content and unit weight of the soil (i.e., compaction curve). Ultimately, the test yields the maximum dry density (i.e., unit weight) and the water content (i.e., optimum water content) at which this maximum density occurs.

The Moisture Density test is performed for several reasons. Commonly, the test is performed for construction quality control purposes. The values obtained from the laboratory tests are compared with density and water content values measured during construction with a nuclear density gauge or sand cone to ensure the project specifications are met. The test is also
performed to support other laboratory tests, including California Bearing Ratio (CBR), or when remolded samples are used for testing (i.e., strength testing and permeability). The Moisture Density test provides an estimate of the moisture and density that the soil will be compacted to during construction, and these values can be used to remold samples for laboratory testing which simulate field conditions.

The compaction effort used on the soil in the laboratory test is intended to simulate the compaction effort used on the soil in the field during construction. PTM 106, which is a slight modification to AASHTO T 99 (Standard Compaction), is typically used to simulate field compaction for embankment, subgrade and foundation design and construction. However, in some cases it may be necessary to require a higher compactive effort during construction. In these situations consideration should be given to performing the laboratory testing in accordance with AASHTO T 180, which is referred to as the Modified Compaction test.

4.9.2 California Bearing Ratio AASHTO, T 193

A key input for the design of bituminous and concrete pavement is the subgrade strength (i.e., resilient modulus, \(M_r\)). The resilient modulus value used has a critical effect on the design of economical, durable pavement sections; therefore, it is imperative that soil subgrade samples be collected appropriately and tested properly so that a representative resilient modulus value is used. Guidance is provided below for the sampling and testing of subgrade soil for pavement design.

In accordance with Publication 242, the resilient modulus value for Department projects is estimated through a correlation with the California Bearing Ratio (CBR). The CBR is determined in accordance with laboratory test AASHTO T 193-10, and the resilient modulus is calculated by multiplying the CBR by 1,500. Note that at this time the laboratory test method for determining the resilient modulus directly (i.e., AASHTO T 307) cannot be used on Department projects per Publication 242.

Soil samples for CBR testing should be collected on all projects where pavement design is required, unless in-situ test methods for determining resilient modulus are approved for use (e.g., dynamic cone penetrometer (DCP) or falling weight deflectometer (FWD)). Where new pavement sections will simply match existing sections, such as some widening projects and on small projects (i.e., less than 500 feet of continuous paving on divided highways, less than 1,000 feet of continuous paving on undivided highways, and less than 1,000 feet of total roadway approach paving for bridges) pavement design is not needed, and CBR testing should not be performed.

Per the AASHTO test method 75 pounds of material is needed to perform the CBR test. However, if the soil sample has oversize particles (i.e., material larger than the \(\frac{3}{4}\)-inch sieve), obtain an additional sample so that the oversize material can be replaced with finer grained material per the test method.

Similar to most geotechnical testing, the appropriate number of CBR tests performed is dependent upon several factors, including the size of the project and the variability of the
subgrade materials. Below are some guidelines to help determine the appropriate number of tests for a project; however, each project is unique and must be considered individually:

- A minimum of one test per subgrade soil type should be performed on projects for local and collector roads with less than approximately 2,500 feet of paving.
- A minimum of three tests per subgrade soil type should be performed on projects for local and collector roads with more than approximately 2,500 feet of paving.
- A minimum of three tests per subgrade soil type should be performed on projects for interstate and arterial roads.
- Two tests per subgrade soil type are generally not recommended because if the test results vary considerably, it is difficult to determine which test is representative. If multiple tests are performed, a minimum of three is recommended.
- Fine-grained soils generally will have a lower CBR value compared to coarse-grained soils; therefore, testing should be performed on fine-grained soils when encountered, unless they are in an isolated area and will be treated/stabilized. When both fine and coarse-grained subgrade soils are encountered on a project, it may not be necessary to test the coarse-grained material, assuming a single CBR value will be used to design the pavement for the entire project. However, coarse-grained soils containing fines (i.e., sm, sc, gm, gc, etc.) should be tested since the fine-grained portion of these soils often controls the behavior of the soil.

As per AASHTO T 193-10, the test method is primarily intended for, but not limited to, evaluating the strength of cohesive materials having maximum particle sizes less than ¾-inch. Gradation of materials having maximum particle sizes greater than ¾-inch is modified so that the material used for tests passes the ¾-inch sieve. The percentage by weight of materials retained on the ¾-inch sieve are replaced with material passing the ¾-inch sieve and retained on the No. 4 sieve. CBR results for materials having substantial percentages of particles retained on the No. 4 sieve are more variable than for finer materials. Because of this, it is recommended to consider performing additional tests when the materials encountered are anticipated to contain significant percentages of particles retained on the No. 4 sieve.

Although AASHTO T 193-10 allows for testing material in an unsoaked condition, all samples for Department projects must be soaked prior to penetration unless otherwise directed by the Department. During soaking a surcharge weight (i.e., 10 pound weight, minimum) is applied to simulate the intensity of loading from the pavement. Based on the equation below, a 10-pound weight is equivalent to approximately 4-inches of pavement. Additional weight may be applied in increments of five (5) pounds for thicker pavement if approved by the District Pavement Engineer. Note that the CBR value for the same soil will likely increase as the surcharge weight is increased.

To use a surcharge weight greater than the 10-pound minimum, the pavement design engineer must estimate the thickness of the proposed pavement prior to laboratory testing, and must direct the laboratory accordingly. The surcharge weight for the proposed pavement can be estimated using the following equation:

\[ W_s = (h_p \gamma_p)A_m \]
where:

\[ W_s = \text{weight of surcharge (ft.)} \]
\[ h_p = \text{height of bituminous or plain cement concrete pavement (not including subbase) (ft.)} \]
\[ \gamma_p = \text{unit weight of pavement (lbs./ft.}^3\text{)} \]
\[ A_m = \text{area of CBR mold (ft.}^2\text{)} \]

It is generally recommended to only consider the bituminous or cement concrete portion of the pavement section, and not the subbase, when calculating the surcharge weight. Including the subbase in the surcharge weight calculation can result in very high, and possibly unrealistic, surcharge weights. The typical pavement (bituminous or cement) has a unit weight of approximately 150 pounds per cubic foot, and the area of a 6-inch diameter CBR mold is approximately 0.2 square feet.

After the samples have soaked, they are penetrated with a piston, and a plot of load versus penetration is constructed from the test results. The CBR is calculated in percent by dividing the load required to penetrate the samples 0.1 and 0.2 inch by the standard load of 1,000 and 1,500 psi, respectively. The CBR is generally selected at 0.10-inch penetration. However, if the CBR at 0.20-inch penetration is greater, the test must be rerun. It is not acceptable to simply use the CBR at 0.20-inch penetration. If the results of the rerun test are similar to the original test, and the CBR at 0.20-inch penetration is greater than at 0.10-inch, the CBR at 0.20-inch penetration should be used.

For projects where several CBR tests are performed on similar soil types, judgment must be used to determine the appropriate CBR value to use for pavement design. It is generally not appropriate to use the average CBR value unless all of the values are relatively close. If there is a high or low value that appears to be an anomaly, it may be appropriate to disregard this value and average the remaining similar values to determine the design CBR value. When there is a significant range in the CBR values, using an average value would likely result in an inadequately designed pavement section or an excessively thick pavement section over the majority of the project alignment. In most cases, it is prudent to use a value toward the low end of the range of test results. If the lowest value appears to be an anomaly or is only representative of an isolated area of the project, it may be economical to perform subgrade improvement in the area where the low value was obtained and use a higher CBR value for the pavement design to better model the overall project conditions. Note that per Publication 242, undercutting and/or stabilizing the subgrade may be required where the CBR value is less than five. Additionally, Publication 242 requires that recommended design CBR values greater than 10 be approved by the Chief Geotechnical Engineer. Refer to Publication 242 for additional details regarding determination of an appropriate CBR value for design.

4.9.3 Consolidation, AASHTO T 216

Consolidation testing is done to estimate consolidation (not immediate) settlement characteristics of fine-grained, typically cohesive, saturated soils. When saturated, cohesive soil is loaded by an embankment, spread footing foundation, etc., the load is initially carried by the water trapped in the void space of a soil mass. This results in excess porewater pressure in the
soil. Since the water in the voids is under pressure, the water is forced out of the voids. The time for drainage to occur is dependent upon the permeability of the soil, the thickness of the layer, and the presence of drainage layers (i.e., higher permeability soil like sand or gravel layers, or manmade inclusions like wick or sand drains). Once the excess porewater pressure in the soil mass dissipates, the load is carried fully by the soil particles. This process is referred to as primary consolidation. Since granular soils have high permeability, they drain quickly when loaded and consolidation settlement is not applicable.

Consolidation testing should be performed on cohesive, saturated foundation (in-situ) soils that will be subjected to vertical loads, such as from an embankment or a structure foundation. Since structure foundations underlain by cohesive soil typically utilize deep foundations in lieu of spread footings, consolidation testing may not be needed for structure foundation design. However, where approach embankments or other vertical loads may cause settlement of the soil surrounding a deep foundation, consolidation testing may be needed for foundation design to help estimate if downdrag may occur.

Since this test is typically performed on foundation soil (i.e., in-situ and not a proposed embankment) undisturbed soil samples, such as from a thin-walled sampler (Shelby tube), must be used to perform the test. Remolded samples cannot be used to estimate in-situ consolidation settlement characteristics. If consolidation properties of a proposed embankment are needed, which is very rare in the transportation industry, a remolded sample would be appropriate to use.

Because soil samples from Shelby tubes are typically used to perform this test, it is important to reiterate the importance of properly obtaining, preserving, transporting and storing undisturbed samples. The consolidation test is one of the most “sensitive” tests with respect to sample quality. Sample disturbance will most likely affect the test results, and the test results may not be representative of the in-situ conditions. It is not necessarily obvious when sample disturbance has affected the test results. An indication of sample disturbance is when there is no distinct break in the slope of the plotted laboratory consolidation curve (void ratio versus log of pressure) between recompression and virgin compression. However, this lack of break in slope is sometimes seen in low plasticity soils so it is not an absolute sign of sample disturbance.

In addition to properly obtaining, preserving, transporting and storing undisturbed samples, it is critical that testing of undisturbed samples be performed as soon as possible after obtaining the sample. In addition to losing natural moisture, soil samples inside Shelby tubes often swell over time. This swelling makes it very difficult to extrude the sample from the tube without significantly disturbing the sample. If the testing cannot be performed within a few weeks of obtaining the sample, the sample should be extruded from the tube and stored in an airtight container to retain the natural water content until it can be tested.

The consolidation test determines several parameters, including: preconsolidation pressure \( P_c \), virgin compression index \( C_{vc} \), recompression index \( C_r \), sometimes referred to as swelling or rebound index \( C_s \), and the coefficient of consolidation \( c_v \). The preconsolidation pressure \( P_c \) is possibly the most valuable parameter determined by the test. The preconsolidation pressure represents the magnitude of the maximum stress (i.e., effective overburden pressure) that the soil has experienced since it was deposited. The stress history of a
soil deposit can be affected by numerous things, including glaciation, erosion, desiccation, groundwater fluctuation, and more. Once the preconsolidation pressure is known, it can be compared to the present day effective overburden pressure to determine if the soil is normally consolidated or overconsolidated. The magnitude of consolidation settlement can be estimated by using the appropriate equation and the $C_c$ and/or $C_r$ values obtained from the test results, and the time rate of settlement can be estimated using the coefficient of consolidation ($c_v$).

4.9.4 Direct Shear, AASHTO T 236

The direct shear test is done to estimate the peak shear strength of soil. This test is performed slowly to ensure that the soil sample is consolidated and drained (i.e., no excess pore water pressure) during the test. This test is intended to represent the long term strength of the soil. It models soil conditions after construction/loading has taken place and the soil has had a chance to fully consolidate/drain (i.e., no excess pore water pressure). Consequently, this strength state is often referred to as the S (slow) strength. These test results can be used directly in slope stability analysis and foundation design (spread footings bearing on soil, friction piles, lateral earth pressure, etc.).

The direct shear test is performed by placing the soil sample in the direct shear box, which can be either square or circular. The shear box consists of two halves to allow them, and the soil sample, to move horizontally independent of each other and develop a shear/failure plane. A normal (vertical) stress selected by the engineer is applied to the sample. After the soil sample has consolidated/drained due to the applied normal stress, the halves of the box are slowly displaced horizontally from one another causing shearing. Shearing occurs at a constant rate while shear resistance and horizontal displacement are measured. Shearing continues until a decrease in shearing resistance is measured, which signifies a shear failure (i.e., excessive horizontal movement) of the sample.

Typically, three test specimens are sheared at increasing normal stresses to estimate the shear strength of the soil. Mohr-Coulomb failure envelopes can be drawn from the test results by plotting effective normal stress on the x-axis and shear stress on the y-axis. The effective friction angle can be calculated by using the inverse tangent of the failure (shear) stress divided by the normal stress. The “line” defining the effective shear strength of the soil will typically pass through the origin (i.e., 0, 0), which indicates no cohesion (i.e., $c=0$) in the sample. This is typical for most soils. Only cemented sands and some overconsolidated clays appear to have true effective cohesion ($c'$) (Sabatini, 2002). If cohesion is indicated by the test results, and the samples are not cemented sands or overconsolidated clays, the samples were likely sheared too quickly to allow drainage of pore water during the test. Cohesion indicated by the test is often ignored, possibly conservatively, when performing slope stability analyses or foundation design. If cohesion is indicated by the direct shear test results but does not appear to be appropriate for the soil type, consideration should be given to performing additional direct shear tests.

Normal (vertical) stresses used for the test must be selected by the engineer and supplied to laboratory. Values of 4 ksf, 8 ksf, and 12 ksf are commonly used and are generally acceptable for most project conditions. The normal stresses used for the test should be selected to bracket the range of actual stresses anticipated at the project site. For example, assume a bridge pier...
founded on a spread footing bearing on soil is being considered during design, and direct shear testing is performed to estimate the soil shear strength in order to calculate bearing resistance. The estimated stress from the footing on the foundation soil is approximately 6 ksf; therefore, the commonly used values of 4, 8 and 12 ksf would be appropriate to use in the test for this situation. However, assume an embankment 100 feet high is proposed, and direct shear testing is being done to estimate the shear strength of the foundation soil for slope stability analysis. Assuming an embankment unit weight of 120 pcf, the estimated stress on the foundation soil is 12 ksf (i.e., 100 feet x 120 pcf). Since the estimated stress in the field is 12 ksf, one of the normal stresses used in the laboratory should exceed 12 ksf. Possible normal stresses of 6 ksf, 10 ksf, and 14 ksf could be considered for this situation. Note that the effective overburden stress at the depth of the soil stratum being tested also needs to be added to the proposed embankment load when selecting laboratory normal stresses.

Direct shear testing can be performed on all soil types (granular, fine-grained, cohesionless and cohesive), but there are limitations on maximum soil particle size that can be used. The maximum permissible particle size is based on the size of the shear box that is used. Per the AASHTO test standard:

- The minimum width/diameter (square/circular box) of the shear box is 2.0-inches.
- The minimum thickness is 0.5-inch.
- The minimum diameter/width to thickness ratio is 2:1.
- The maximum particle size in the soil sample must be less than Six times the thickness of the shear box.

As an example, for a shear box with the minimum thickness of 0.5 inch, the maximum soil particle size that can be used in the test is 0.5-inch divided by 6, or 0.083-inch (2.1 mm), which is approximately equivalent to the No. 10 sieve opening.

The Department’s Geotechnical Material and Testing Laboratory has the capability to perform direct shear testing. The Department’s direct shear equipment includes a shear box that is 2.5 inches in diameter and 1-inch high. This size shear box is fairly typical of most labs. These dimensions meet the AASHTO requirements for minimum width/diameter, thickness, and diameter/width to thickness ratio. Based on AASHTO criteria, a soil sample with a maximum particle size of 0.17-inch (4.3 mm or approximately No. 4 sieve) can be used in this shear box. Shear boxes 12-inches wide by 6-inches thick and even larger exist, but they are not commonly found.

Disturbed soil samples used to remold samples for direct shear testing may contain particles that are larger (i.e., oversize) than that permitted by the AASHTO standard. These oversize particles must be removed prior to remolding the test samples. A few approaches can be taken for this situation. One approach is to simply remove/scalp all the oversize particles from the sample and test only the remaining portion of the sample. This approach will most likely yield a conservative/low shear strength value since the oversize particle sizes, which typically improve shear strength, were not used in the test. In this case consideration can be given to using a higher design shear strength value than was obtained from the laboratory test.
The other approach to deal with oversize particles is to replace the oversize particles with an equivalent amount (by weight) of coarse material that meets the AASHTO criteria. For example, if the maximum particle size permitted by the AASHTO standard is 4.3 mm, particles larger than this are removed from the sample, and an equivalent weight of particles that meet the AASHTO standards (say No. 4 to No. 10 material) is added to the sample. This approach is not provided in the AASHTO standard, but the US Army Corps of Engineers provides direction for this approach in “Laboratory Soils Testing”, EM 1110-2-1906, dated November 30, 1970. This approach is included in Section 4.8.4.16. Note that triaxial shear test samples are typically much larger than direct shear test samples, and therefore, are permitted to have larger particle sizes.

**NOTE TO REVIEWERS OF THIS CT: A PTM FOR DIRECT SHEAR IS CURRENTLY UNDER DEVELOPMENT. THIS PTM WILL INCLUDE, BUT IS NOT LIMITED TO, COARSE PARTICLE SUBSTITUTION, SAMPLE PREPARATION AND COMPACION, AND SHEARING RATES. ONCE RESOLVED AND IMPLEMENTED, THIS SECTION WILL BE MODIFIED TO INCLUDE THIS PTM IN A FUTURE CT**

Undisturbed and remolded soil samples can be used for direct shear testing, but it is important to use the appropriate type of sample for the conditions being analyzed. Undisturbed soil samples should be used when direct shear testing is performed to estimate the in-situ strength of soil. In-situ soil strength is needed to:

- Analyze slope stability of an embankment foundation or a soil cut.
- Estimate bearing resistance for a spread footing supported on soil.
- Estimate the frictional resistance of a deep foundation.
- Estimate lateral earth pressure on retaining structures.

In-situ soils often times have characteristics or properties that cannot be replicated with remolded samples. For example, in-situ soils may be cemented or have residual/relic rock structure that provides strength to the soil mass. Conversely, the in-situ soil may contain thin, weak varves that decrease the soil mass strength. If a remolded sample is used to represent the in-situ soil, the strength indicated by the test result may be lower or higher than the in-situ strength, and sometimes significantly. However, when in-situ soils are cohesionless and undisturbed samples cannot be obtained, the use of remolded samples for direct shear testing for the above conditions will most likely be appropriate.

In addition to using remolded samples when Shelby tubes are not able to obtain a sample, remolded samples should also be used when the shear strength of proposed fill materials is needed. For example, assume a roadway project consists of cuts and fills/embankments, and the material from the cuts will be used construct the fills/embankments. If slope stability analyses of the proposed embankments are needed, then remolded samples should be used to estimate the shear strength of the embankment material. Similarly, in order to estimate the shear strength of a soil that will be used to construct a geosynthetic reinforced slope, the use of remolded samples is appropriate to perform the direct shear tests. Remolded samples are appropriate for these and similar conditions since they represent/model proposed field conditions. Remolded samples should be compacted to the same requirements anticipated for construction. For example, if the construction specifications require the soil embankment to be compacted to 95 percent of the
maximum dry weight density and to within 2 percent of the optimum water content, then the remolded sample for testing should be compacted to these same specifications.

4.9.5 Residual Direct Shear

This test is performed to determine the residual shear strength of a soil. Residual shear strength is used in situations where there has been sufficient strain (e.g. slope failure) such that the material in question is past peak shear strength values. Residual shear strength is generally associated with fine-grained plastic soils. Residual and peak strengths are usually the same or very close for granular cohesionless materials. Residual shear strength values are generally not used for the design of newly constructed earth structures, but rather for analysis of failed slopes or when mitigation of a failed slope involves adding resistance without reworking (removing and recompacting) the failed material. An example where residual shear strength parameters would be used for design would be when a wall is constructed in front of or intercepting the failure surface.

Neither AASHTO nor ASTM has a test method for residual direct shear. The United States Army Corps of Engineers EM 1110-2-1906, Appendix IX A, has a method that is often cited or referenced. This residual direct shear method is performed by repeatedly reversing the direction of shear until the residual (i.e., minimum) shear strength is obtained. Similar to the peak direct shear test, the residual direct shear test is performed slowly to ensure that the soil sample is consolidated and drained (i.e., no excess pore water pressure) during the test. This test is intended to represent or model the strength along a weak plane within the soil mass. This weak plane could be the result of past movement (e.g., sliding failure) or deposition (e.g., varves).

The United States Army Corps of Engineers EM 1110-2-1906, Appendix IX A method is not approved for use by the Department. There is concern that the method does not accurately model field conditions (i.e., continuous shear with large deformation in one direction). By repeatedly reversing the shear direction, there will be a realignment of particles with each direction reversal. As a result, orientation of particles parallel to the direction of shear may not be achieved as with large strain shear.

To determine residual shear strength parameters, the Department uses AASHTO T 236 “Standard Method of Test for Direct Shear Test of Soils under Consolidated Drained Conditions”. Residual values are obtained from the residual strength portion of the stress-strain plot of the direct shear test. It is necessary to run the direct shear test with sufficient displacement to assure residual shear has been observed (no change in shearing stress with continued displacement after peak shear stress been observed).

In situations where there is insufficient travel of the shear box to fully develop residual shear strength when using the standard AASHTO T 236 test method, the sample can be reversed back to the original position and then re-sheared. Realignment of particles in the reversal may result in some recovery of sample shear strength; however, it should be limited and should also be overcome with minimal strain. Additional shearing in the same direction (as the original shearing of the sample) will provide residual shear strength values. It is important that the
sample reversal and re-shearing be conducted at the same strain rate as the original shearing to determine peak shear strength values.

4.9.6 Triaxial Shear, AASHTO T 296 and AASHTO T 297

The triaxial shear strength test can be used to estimate the strength of soil for various loading conditions, including:

- Unconsolidated-undrained
- Consolidated-undrained
- Consolidated-drained

Triaxial tests are primarily for fine-grained, cohesive soil with relatively low permeability. Coarse-grained soils and relatively high permeability soils that drain rapidly when load is applied are not appropriate for triaxial testing. Cohesive, fine-grained samples can contain coarse-grained particles; however, there are limitations on maximum particle size. Undisturbed and remolded samples can be used for this test.

The maximum acceptable particle size for use in the triaxial shear test is determined by the size of the triaxial cell used for the test. Per the AASHTO standard, the maximum acceptable particle size must be smaller than one sixth of the test sample diameter. Additionally, the test sample must be cylindrical, have a minimum diameter of 1.3 inches (33 mm) and have a height to diameter ratio between 2 and 2.5. Typical triaxial equipment found in laboratories can test samples up to 2.8 inches in diameter, which is the sample diameter obtained from a standard Shelby tube. Per the AASHTO standard, the minimum sample height for this diameter is 5.6 inches. Additionally, for this diameter, a maximum particle size of 0.5-inch (i.e., 2.8 inches divided by 6) can be used. This 0.5-inch (12-mm) particle is almost three times larger than the particle size permitted in a typical 1-inch high direct shear box. As discussed in Section 4.9.4, there are guidelines for testing samples that have particle sizes larger than those permitted by the AASHTO test standard.

4.9.6.1 Triaxial Shear (UU), AASHTO T 296

Triaxial shear testing is used to estimate the shear strength of soil for the unconsolidated-undrained (UU) load condition. This strength is often referred to as the Q (i.e., quick) strength. This test provides an estimation of the undrained shear strength or cohesion. The UU test represents the condition in the field where load is applied to foundation soil (e.g., embankment, spread footing, etc.) and the soil does not have adequate time to drain excess pore water pressure and consolidate. Consequently, the load is carried by the water trapped within the voids/pores of the soil mass. UU test results can be used directly in slope stability analysis. Note that similar to the unconfined compression test, there are inherent problems with the UU triaxial test, so this test should not be relied upon solely for estimation of undrained shear strength (Sabatini, 2002).

The UU test is performed by applying a lateral confining stress (chamber pressure) and then applying an axial load without allowing the sample to drain. Normally three samples are sheared, and the chamber pressure is increased for each sample. The chamber pressures must be
specified by the engineer and communicated to the laboratory, and these pressures should “bracket” the soil pressure expected in the field. Common pressures used in laboratories are 10, 20, and 40 psi (i.e., 1,440, 2,880 and 5,760 psf), but these must be checked for specific project needs. A more detailed discussion on selecting pressures for testing is included in Section 4.9.4.

UU test results can be plotted using Mohr-Coulomb failure envelopes. Normal stress is plotted on the x-axis, and shear stress is represented on the y-axis. The ideal test results will yield a single line that is tangent to all of the Mohr-Coulomb envelopes and parallel to the x-axis. The shear strength is equal to the y-intercept (i.e., cohesion), and an internal friction angle of zero is represented by the line parallel to the x-axis (i.e., no slope). Due to possible variations between samples degree of saturation and void ratio, samples may not exhibit constant undrained shear strength at various normal/axial loads. Where this variation is significant, each test should be evaluated individually, and undrained shear strength should be determined for each sample by assuming an internal angle of friction of zero. The range of undrained shear strengths will have to be analyzed, and an appropriate value selected for design. Where the variation is minimal, a best fit line taking all results into account should be appropriate.

As previously indicated UU triaxial testing can be performed on either undisturbed or remolded samples, but it is important to use the appropriate type of sample for the condition being analyzed. UU testing is normally performed to estimate the shear strength of in-situ soil that will be loaded by an embankment or a footing. Therefore, undisturbed samples should be used for this type of UU testing. Since UU testing is not generally performed to estimate the shear strength of compacted fills/embankments, remolded samples are typically not appropriate. However, if undisturbed samples are not available, the use of remolded samples can be considered for testing.

4.9.6.2 Triaxial Shear (CU), AASHTO T 297

Triaxial shear testing is used to estimate the shear strength of soil for the consolidated-undrained (CU) load condition. This strength is often referred to as the R (i.e., rapid) strength. This test provides an estimation of total shear strength. The CU test represents the condition in the field where load is applied to foundation soil (e.g., from an embankment, spread footing, deep foundation, etc.) and the foundation soils have had time to consolidate but excess pore water pressure is still present. This strength condition is also applicable where foundation soils have been consolidated prior to construction loading, such as from glaciation. The CU strength phase occurs between the UU and the CD (consolidated-drained) strength phases. CU test results can be used directly in slope stability analysis and foundation design.

The CU test is performed similarly to the UU test, but the CU test is done by consolidating the sample before shearing. Once consolidated, a lateral confining stress (consolidation pressure) is applied, and then an axial load is applied to shear the sample. Similar to the UU test, the sample is not permitted to drain during testing. Normally three samples are sheared, and the consolidation pressure is increased for each sample. The consolidation pressure, which is the difference between the chamber pressure and the back pressure, must be specified by the engineer and communicated to the laboratory. These pressures should “bracket” the soil pressure expected in the field. Common consolidation pressures used in laboratories are 10, 20,
and 40 psi (i.e., 1,440, 2,880 and 5,760 psf), but these must be checked for specific project needs. A more detailed discussion on selecting pressures for testing is included in Section 4.9.4.

CU test results can be plotted using Mohr-Coulomb failure envelopes. Normal stress is plotted on the x-axis, and shear stress is represented on the y-axis. The ideal test results will yield a single line that is tangent to all of the Mohr-Coulomb envelopes, which is similar to the UU test results. The cohesion portion of the soil shear strength is equal to the value where the line crosses the y-axis. Unlike the UU test results, the CU test results will typically yield a positive-sloped line, indicating that the soil also has a frictional component to its shear strength. Due to possible variations between degree of saturation and void ratio, samples may not exhibit a uniform total shear strength (i.e., single line cannot be drawn tangent to all sample Mohr-Coulomb failure envelopes). Where the variation is minimal, a best fit line taking all results into account should be appropriate. Where the variation is significant, the test results should be reviewed, and additional testing should be performed if necessary.

CU triaxial testing can be performed on either undisturbed or remolded samples, but it is important to use the appropriate type of sample for the condition being analyzed. CU testing is normally performed to estimate the shear strength of in-situ soil that will be loaded by an embankment or a footing. Therefore, undisturbed samples should be used for this type of CU testing. Since CU testing is not generally performed to estimate the shear strength of compacted fills/embankments, remolded samples are typically not appropriate. However, if undisturbed samples are not available, the use of remolded samples can be considered for testing.

4.9.6.3 Triaxial Shear (CU with pore pressure measurement), AASHTO T 297

Triaxial shear testing is used to estimate the shear strength of soil for the consolidated-drained (CD) load condition. This strength is often referred to as the S (i.e., slow) strength. This test provides an estimation of effective shear strength. The CD test represents the condition in the field where load is applied to foundation soil (e.g., from an embankment, spread footing, deep foundation, etc.) and the foundation soils have had time to consolidate and drain (i.e., no excess pore water pressure). The CD strength phase occurs after the CU strength phases. CD test results can be used directly in slope stability analysis and foundation design. Due to the significant length of time required to perform the CD test, a CU test with pore pressure measurement can be performed as an alternative. This test method is much quicker than the CD test and provides not only an estimate of the effective shear stress, but the total shear strength as well.

The CU with pore pressure measurement test is performed the same as the CU test except pore water pressure is measured during the test. This pore pressure measurement allows the estimation of the effective (i.e., drained) shear strength. Although typically more expensive than the “plain” CU test, the CU with pore pressure measurement test is generally preferred since both total and effective shear strength are determined when pore pressure is measured. Note that the CD test can be performed by shearing the sample extremely slowly to allow consolidation and pore pressure dissipation; however, this method is typically not used because it is too time consuming and costly. Additionally, this method only provides effective shear strength and not total shear strength.
CU with pore pressure measurement test results can also be plotted using Mohr-Coulomb failure envelopes. Total shear strength results are plotted the same as discussed in the CU Triaxial Shear discussion above. Effective shear strength results from the test are plotted similarly. These results should yield a shear strength with less, and possibly zero, cohesion, but a higher internal friction angle compared to the total shear strength. Similar to the “plain” CU test, due to possible variations between samples degree of saturation and void ratio, samples may not exhibit a uniform total and/or effective shear strength. Where the variation is minimal, a best fit line taking all results into account should be appropriate. Where the variation is significant, the test results should be reviewed, and additional testing should be performed if necessary.

CU triaxial testing with pore pressure measurement can be performed on either undisturbed or remolded samples, but it is important to use the appropriate type of sample for the condition being analyzed. CU with pore pressure measurement testing is normally performed to estimate the shear strength of in-situ soil that will be loaded by an embankment or a foundation. Therefore, undisturbed samples should normally be used for this testing. Since CU with pore pressure measurement testing is not generally performed to estimate the shear strength of compacted fills/embankments, remolded samples are typically not appropriate. However, if undisturbed samples are not available, the use of remolded samples can be considered for testing.

**4.9.7 Comparison of Direct Shear and Triaxial Shear Testing**

It is often desirable and beneficial to perform shear strength testing using both the direct shear and triaxial shear test methods, but some situations/projects may not warrant both. As previously discussed direct and triaxial shear tests can be performed on both undisturbed samples and remolded samples. The direct shear test can be performed on both granular, although limited particle size, and fine-grained (cohesive and cohesionless) materials. The triaxial shear test can only be performed on soils with sufficient cohesion so samples maintain their shape while unconfined prior to placing in the triaxial cell. Triaxial test samples can contain granular material, and typically can have larger particle sizes compared to direct shear samples.

The direct shear test is a drained (i.e., no excess pore pressure) test, so only drained or effective shear strength can be obtained from this test. The direct shear test cannot be used to estimate undrained or total shear strength. Conversely, the triaxial shear test method can be used to estimate undrained, total, and effective shear strength.

One of the main differences between the direct and triaxial shear test is the orientation of the failure plane produced by the test. The direct shear test forces the soil sample to shear along a horizontal plane (i.e., normal/perpendicular to the axial load) between the two halves of the shear box, whereas the triaxial shear test forces the sample to shear on an inclined plane (i.e., at an angle to the axial load). This difference in failure plane orientation must be considered when naturally occurring weak horizontal planes from varves, ancient failure planes, etc. are present in the soil stratum being tested. The direct shear test can be used to estimate the shear strength along these weak planes, assuming samples with these planes can be obtained. The triaxial shear test would most likely not detect the weakened strength since the failure plane would cut across, and not along, the naturally occurring weakened plane. However, even where weakened planes
are present in the soil, it will often be necessary/beneficial to use the triaxial test method to obtain the “higher end” range of the shear strength for potential failure planes that cut across existing weakened planes.

Some advantages of performing the direct shear test in lieu of the triaxial shear test include:

- estimates both peak and residual shear strength
- typically less expensive and quicker to perform
- less soil sample is needed
- shear strength along existing weakened planes can be estimated
- more common/more laboratories are capable of performing.

Some advantages of performing the triaxial shear test in lieu of the direct shear test include:

- larger test samples are possibly more representative of in-situ conditions
- undrained, total and effective shear strength can be estimated
- typically can accommodate larger particle sizes.

### 4.9.8 Rock Unconfined Compressive Strength

Rock core samples chosen for testing should have a length-to-diameter ratio (L/D) of 2.0 to 2.5. When samples of rock core with the required L/D are not available, samples with an L/D as close to 2.0 may be used and the apparent compressive strength corrected in accordance with the following equation from a previous ASTM standard (ASTM D2938-86):

\[
C = C_a / \left(0.88 + \left(0.24\frac{b}{h}\right)\right)
\]

where:
- \(C\) = computed compressive strength of an equivalent L/D = 2 specimen,
- \(C_a\) = measured compressive strength of the specimen tested,
- \(b\) = test core diameter
- \(h\) = test core height

The use of this correction should be clearly documented as it is not included in the current ASTM.

### 4.9.9 Testing and Monitoring Domestic Water Supplies

Testing and monitoring of domestic water supplies, which include wells and springs, must be considered on projects where blasting will be done for rock excavation in the vicinity of domestic water supplies. Although less commonly done, testing and monitoring should also be considered when other construction activities, including earthwork and pile driving, are planned in the vicinity of domestic water supplies. If a public water supply, such as a well owned by a city, municipality, or private company, is located in the vicinity of a project site, more stringent testing and monitoring may be required. When a public water supply is involved, close
coordination with the well owner and PADEP is required to develop an appropriate and amicable testing and monitoring program.

The effects of blasting and other construction activities on water supplies is dependent upon numerous factors, including: type of construction activity, distance and location of water supply from construction activity, type of water supply (e.g., shallow spring or well, deep well, etc.), well construction (e.g., uncased or shallow cased well, deep cased well, etc.), geology, and regional groundwater flow. These and other factors must be considered when determining which water supplies should be tested and monitored. Typically, water supplies located within approximately 1,000 feet of blasting should be tested and monitored, although some projects may warrant testing water supplies more than 1,000 feet from blasting activities. For construction activities other than blasting, a distance of less than 1,000 feet is likely reasonable, but as previously discussed, this must be determined on a project by project basis.

Water supplies should be tested prior to construction activities to establish baseline information that can be compared to information obtained during and/or after construction. In some cases, testing may be beneficial more than once prior to construction. For example, testing could be done once during wetter seasons and once during dryer seasons. Water supplies should also be tested shortly after construction activities are complete (i.e., within 8 weeks) in the area of the water supply, and tested as needed during construction to address concerns raised with specific water supplies.

The following guidelines are provided to develop the water supply testing and monitoring program:

- The overall intent of the testing and monitoring program is to obtain available water supply information and estimate the quality of water from the water supply.
- Interview the property owner to obtain information about the water supply, including: year constructed, well depth and diameter, casing depth, pump depth, the well yield that was estimated by the driller during construction of well, and any known well issues/problems (e.g., turbidity, yield, contaminants, etc.). The underside of the well cap, if accessible, may contain well information. Note that it is not recommended to measure depth of water inside the well casing due to concerns with possible contamination.
- Collect water samples using sample collection and preservation techniques specified by the testing laboratory.
- Collect water samples prior to treatment system (e.g., softener, disinfection system, etc.)
- Allow water to run approximately 10 to 15 minutes before collecting samples to ensure a representative sample from the water supply is obtained.
- At a minimum perform tests for the following: pH, temperature, specific conductance, turbidity, total coliforms, fecal coliforms/e. coli, nitrate, nitrite, chloride, hardness, iron, and sulfates. pH, temperature, specific conductance and turbidity should be measured in the field, and the other tests are done in the laboratory. Tests for additional parameters may be done based on site specific project conditions.
• Use a PADEP certified laboratory to perform tests.
• Executing the water supply testing and monitoring program requires coordination with the property owner to accommodate their schedule. The interview with the property owner can either be done over the phone or in person.

The consultant scope of work must clearly indicate the anticipated work associated with the testing and monitoring of water supplies, including: number of water supplies to be tested/monitored, number of times each water supply will be tested, specific tests to be performed, and deliverable(s). The deliverable(s) must include the field and laboratory test results. It is also recommended that the deliverable include a brief report/narrative that summarizes the test results, identifies areas of concerns or potential impacts to water supplies from planned construction, and provides recommendations for modifications to the original scope of work (e.g., additional round/phase of testing, testing for additional parameters, etc.). Typically a deliverable is provided after each phase of testing.

Note that the preceding discussion is focused on testing and monitoring for construction activities. Some projects may warrant some level of water supply study during the preliminary or final design phase. For instance, if multiple alignments are being considered, it may be necessary to investigate the number of water supplies that could potentially be impacted by the various alignments. Similarly, the number of water supplies that could be impacted by a project may need to be investigated to estimate the cost of repairing or replacing the impacted supplies. In these instances, identifying the water supplies and interviewing the owner may be sufficient. Water sampling and testing may not be needed.