# Chapter 6 - Engineering Properties of Soil and Rock

## Chapter Contents

# 6.1 General

The purpose of this chapter is to identify appropriate methods of geotechnical soil and rock property assessment to establish engineering parameters for geotechnical design. Geotechnical soil and rock design parameters should be based on the results of a complete geotechnical investigation, which includes in-situ field-testing and a laboratory-testing program. The Geotechnical Engineer determines which geotechnical soil and rock design parameters are critical to project design and prepare a laboratory testing program. Chapter 3 provides guidance on how to plan a geotechnical investigation.

The detailed measurement and interpretation of soil and rock properties should be consistent with the guidelines provided in Loehr et al. (2016). The focus of geotechnical design property assessment and final selection should be on the individual geologic strata identified at the project site. A geologic stratum is characterized as having the same geologic depositional history, stress history, and general similarities throughout the stratum in terms of density, source material, and hydrogeology. It is recognized that the properties of a given geologic stratum at a project site are likely to vary significantly from point to point within the stratum. In some cases, a measured property value may be closer in magnitude to the measured property value of an adjacent geologic stratum rather than the measured properties at another point within the same stratum. However, soil and rock properties for design should not be averaged across multiple strata. It should be recognized that some properties (e.g., undrained shear strength in normally consolidated clays) may vary as a predictable function of a stratum dimension (e.g., depth below the top of the stratum). When the property within the stratum varies in this manner the design parameters should be developed taking this variation into account.

# 6.2 Influence of Existing and Future Conditions on Soil and Rock Properties

Geotechnical soil properties used for design are not intrinsic to soil type. They vary depending on factors, including in-situ soil stresses, groundwater level, seepage forces, and the rate/direction of foundation loading. Prior to evaluating geotechnical soil properties, it is important to determine how existing site conditions will change over the life of the project. For example, future construction (e.g. new embankments) may place new surcharge loads on the soil profile. It is also necessary to determine how geotechnical soil properties within the geologic strata will change over the design life of the project. Over time, normally consolidated clays can gain strength with increased effective soil stresses, over-consolidated clays in cut slopes may lose strength, and embankments composed of weak rock may lose strength.

# 6.3 Methods of Determining Soil and Rock Properties

Geotechnical soil and rock properties of geologic strata are typically determined using one or more of the following methods:

- In-situ testing data from the field exploration program;
- Laboratory testing; and
- Back analysis based on site performance data.

The most common in-situ test methods are the Standard Penetration Test (SPT), Shear Wave Velocity ($V_s$),and Cone Penetration Test (CPT) with or without shear wave velocity and/or porewater pressure. Other in-situ tests, such as the Pressuremeter, Flat Dilatometer, and Vane Shear are used less frequently. In-situ tests for rock, including Borehole Dilatometer, Borehole Jack, Plate Load Test, and Vane Shear Test, are rarely performed.

A variety of laboratory tests to directly measure specific soil and rock engineering properties are discussed in Loehr et al. (2016).

Laboratory geotechnical soil and rock-testing programs may utilize soil and rock engineering index tests with established empirical correlations to estimate preliminary engineering properties of soil and rock. However, final geotechnical designs should be based on direct measurement of specific soil and rock engineering properties as discussed in Loehr et al. (2016).

The observational method, or use of back analysis, may be helpful to estimate the approximate engineering properties of soil or rock units based on measurement of with slope failures, embankment settlement, or settlement of existing structures.

- **Landslides or slope failures:** With landslides or slope failures, the process generally starts with determining the geometry of the failure and then determining the soil/rock parameters or subsurface conditions that cause the safety factor to approach 1.0. Often the determination of the back-calculated properties is aided by correlations with index tests or experience on other projects.
- **Embankment settlement:** For embankment settlement, a range of soil properties is generally determined based on laboratory performance testing on undisturbed samples. Monitoring of fill settlement and pore pressure in the soil during construction allows the soil properties and prediction of the rate of future settlement to be refined.
- **Structure settlement:** For structures such as bridges that experience unacceptable settlement or retaining walls that have excessive deflection, the engineering properties of the soils can sometimes be determined if the magnitudes of the loads are known. As with slope stability analysis, the geometry of the subsurface soil must be adequately known, including the history of the groundwater level at the site.

# 6.4 In-Situ Field Testing

Methods, standards, and typical applications regarding in-situ field tests, such as the Standard Penetration Test (SPT) and Electronic Piezocone Penetrometer Test (CPTu), are provided in

Loehr et al. (2016) and ASTM D5778 (ASTM, 2020), D3441 (ASTM, 2018), and D7400 (ASTM, 2019a).

In general, correlations between SPT N-values and geotechnical soil properties (i.e., soil peak friction angle, in-place density, etc.) should only be used for granular, cohesionless soils (Sand or Gravel). However, Gravel particles can plug the sampler, resulting in higher blow counts and over-estimation of soil friction angles. SPT N-values are not recommended to determine geotechnical soil properties of Silt or Clay soils. See Chapter 7 for more information regarding the use of N-values for liquefaction analysis.

SPT N-values should be corrected for hammer efficiency in accordance with section 5.6.2 of Loehr et al. (2016).

ODOT requires that drilling contractors provide all automatic hammer or safety hammers that have energy measurement data. This data must have been calibrated within the last year for each drill rig used on a project performed at the time of drilling of a boring. Hammer efficiency should be supplied with the boring log.

The following values for energy ratios (ER) may be assumed if hammer specific data are not available:

- ER = 60% for conventional drop hammer using rope and cathead
- ER = 80% for automatic trip hammer

Hammer efficiency (ER) for specific hammer systems used in local practice may be used in lieu of the values provided. If used, specific hammer system efficiencies shall be developed in general accordance with *ASTM D-4633* Standard Test Method for Energy Measurement for Dynamic Penetrometers (ASTM, 2016).

Corrections for rod length, hole size, and use of a liner may also be made, if appropriate. In general, these are only significant in unusual cases or where there is significant variation from standard procedures. These corrections may be significant for evaluation of liquefaction. Information on these additional corrections may be found in: "*Proceedings of the NCEER Workshop on Evaluation of Liquefaction Resistance of Soils*"; *Publication Number: MCEER-97-0022*; T.L. Youd, I.M. Idriss (1997) and in "Cetin, K., Seed, R., et al.

N-values are also affected by overburden pressure. The effect should be corrected for if the design method or correlation being used is applicable. N-values corrected for both overburden and the efficiency of the field procedures used shall be designated as $N_{1,60}$ as stated in Loehr et al. (2016) .

Methods, standards, and typical applications regarding in-situ field tests regarding field measurement of permeability is presented in Loehr et al. (2016), and ASTM D 4043 (ASTM, 2017). If in-situ test methods are utilized to determine hydraulic conductivity, one or more of the following methods should be used:

- Well pumping tests
- Packer permeability tests
- Seepage Tests
- Slug tests

- Piezocone tests

# 6.5 Laboratory Testing of Soil and Rock

The primary purpose of laboratory testing is to measure physical soil and rock properties utilizing standard repeatable procedures to analyze soil or rock behavior under proposed ground loading conditions. Laboratory test data are also used to check field soil and rock classifications from the subsurface field exploration program. Details regarding specific types of laboratory tests and their use are provided in Loehr et al. (2016).

Improper storage, transportation, or handling of in-situ soil and rock samples can significantly alter their laboratory-tested geotechnical engineering properties. Quality control (QA) requirements are provided in Mayne, et al. (2002). Laboratories conducting geotechnical testing shall be appropriately accredited by ODOT and compliant with all rules, for qualifying testers, calibrating and verifications of testing equipment.

# 6.6 Engineering Properties of Soil

Laboratory soil testing is used to estimate strength, stress\strain, compressibility, and permeability characteristics. See Loehr et al. (2016) and Section 10, AASHTO LRFD for specific guidance and requirements regarding laboratory testing.

Soil strength tests shall be performed on high quality, relatively undisturbed in-situ specimens. However, it is difficult and frequently impossible to sample, transport, extrude and set-up testing for granular, cohesionless soils (Sand or Gravel) without excessively disturbing or completely obliterating the soil specimen.

Disturbed soil strength testing can be used to provide approximate strength data for back-analysis of existing slopes. It also provides strength data for final stability design and construction quality assurance of fill placement for highway earthwork and embankment materials.

Strength testing of compacted backfill generally yields good results, considering that the soil placement method, in-situ density and moisture content, can all be accurately recreated in the laboratory with a high degree of reliability.

Strength values of disturbed or remolded specimens may be used for evaluating residual shear strength of in situ soils or compacted fills.

# 6.7 Engineering Properties of Rock

Engineering properties of rock are generally controlled by the discontinuities within the rock mass and not the properties of the intact material. Therefore, engineering properties for the rock mass must be reduced from the measured properties of the intact pieces to account for "defects" in the rock mass as a whole - specifically considering discontinuities within the rock mass. A combination of laboratory testing of small samples, empirical analysis, and field observations should be employed to determine the engineering properties of rock masses. There should be a greater emphasis placed on visual observations and quantitative descriptions of the rock mass.

Rock properties can be divided into two categories: intact rock properties and rock mass properties.

- **Intact rock**: Intact rock properties are determined from laboratory tests on small samples typically obtained from coring, outcrops, or exposures along existing cuts. Engineering properties typically obtained from laboratory tests include specific gravity, unit weight, point load, and compressive strength.
- **Rock mass properties:** Rock mass properties are determined by visual examination and measurement of discontinuities within the rock mass, and how these discontinuities will affect the behavior of the rock mass when subjected to the proposed construction.

The methodology and related considerations provided by Loehr et al. (2016), should be used to assess the design properties for the intact rock and the rock mass - except fractured rock mass shear strength parameters should be in accordance with Hoek, et al. (2018). This updated method uses a Geological Strength Index (GSI) to characterize rock mass for estimating strength parameters, and has been developed based on re-examination of hundreds of tunnel and slope stability analyses. Hoek, et al. (2018) is considered the most accurate methodology and should be used for estimating fractured rock mass shear strength determination. Note that this method is only to be used for highly fractured rock masses in which the stability of the rock slope is not structurally controlled.

# 6.8 Final Selection of Design Values

The geotechnical designer should review the quality and consistency of the field and laboratory testing data and determine if the results are consistent with expectations based on experience from other projects in the area or in similar soil/rock conditions.

Inconsistencies between laboratory test results should be examined to determine possible causes and develop procedures to correct, exclude, or downplay the significance of any suspect data. Chapter 8 of Loehr et al. (2016) outlines a systematic procedure for analyzing data and resolving these inconsistencies.

Engineering judgment, combined with parametric analyses as needed, will be needed to make the final assessment and determination of each design property. This assessment should include a decision as to whether the final design value selected should reflect the interpreted average value for the property, or a value that is somewhere between the most likely average value and the most conservative estimate of the property. Design property selection should achieve a balance between the desire for design safety, cost effectiveness, and constructability of the design.

Depending on the availability of soil or rock property data and the variability of the geologic strata under consideration, it may not be possible to reliably estimate the average value of the properties needed for design. In such cases, the geotechnical designer may have no choice but to use a more conservative selection of design parameters to mitigate the additional risks created by potential variability or the scarcity of relevant data. Note that for those resistance factors that were determined based on calibration by fitting to allowable stress design, this property selection issue is not relevant, and property selection should be based on the considerations discussed previously.

Processes and examples to make the final determination of properties to be used for design are provided by Loehr et al. (2016).

# 6.9 Development of the Subsurface Profile

The development of design property values should begin and end with the development of the subsurface profile. Test results and boring logs will likely be revisited several times as the data is developed and analyzed before the relation of the subsurface units to each other and their engineering properties are finalized.

The ultimate goal of a subsurface investigation is to develop a working model that depicts major subsurface layers exhibiting distinct engineering characteristics.

The end product is the subsurface profile, a two dimensional depiction of the site stratigraphy. The following steps outline the creation of the subsurface profile:

1. Complete the field and lab work and incorporate the data into the preliminary logs.
2. Lay out the logs relative to their respective field locations and compare and match up the different soil and rock units at adjacent boring locations, if possible. However, caution should be exercised when attempting to connect units in adjacent borings, as the geologic stratigraphy does not always fit into nice neat layers. Field descriptions and engineering properties will aid in the comparisons.
3. Group the subsurface units based on geologic stratigraphy and then associated engineering properties.
4. Create cross sections by plotting borings at their respective elevations and positions horizontal to one another with appropriate scales. If appropriate, two cross sections should be developed that are at right angles to each other so that lateral trends in stratigraphy can be evaluated when a site contains both lateral and transverse extents (i.e. a building or large embankment).
5. Analyze the profile to see how it compares with expected results and knowledge of geologic (depositional) history. Address any anomalies and unexpected results encountered during exploration and testing during the profile development process. Make sure that all of the subsurface features and properties pertinent to design have been addressed.

# 6.10 References

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