Manual on Subsurface Investigations

2nd Edition • September 2022

AASHTO

Table of Contents

List of Tables

List of Figures

Abstract

The primary purpose of geotechnical subsurface investigations in transportation projects is to collect data that will help transportation engineers and planners identify, assess, and address risks associated with subsurface conditions; select appropriate design parameters; and monitor performance during construction and operation phases of a project's life cycle. The results of the research performed for NCHRP Project 21-10 have resulted in a complete revision and update to the 1988 American Association of State Highway Transportation Officials (AASHTO) *Manual on Subsurface Investigation* that reflects the changes in the approaches and methods used for geotechnical site characterization that the geotechnical community has developed and adopted in the past 30 years. The updated manual provides information and guidelines to help geoprofessionals plan and execute a sound geotechnical site investigation program; use the results to develop a ground model for planning, design, construction, and asset management phases of a project; and report and document the results in a manner that facilitates peer review, communication with stakeholders, and potential future uses.

Summary

Subsurface investigation plays a critical role in all phases of transportation project development—planning, design, construction, and operations—as it provides information that is needed to ensure public safety and to make cost-effective decisions. For the past 30 years, transportation engineers and planners have relied on the AASHTO *Manual on Subsurface Investigation* (1988) to provide guidance on best practices for planning and conducting geotechnical subsurface investigations. However, in the past 30 years, significant advances have occurred in the geophysical, *in situ*, and laboratory methods used by geoprofessionals to conduct subsurface investigations. There are also new design approaches (e.g., load and resistance factor design, or LRFD) and project delivery methods (e.g., design–build) that impact subsurface investigations.

These changes in geotechnical practices, design approaches, and project delivery methods warrant an update to the AASHTO *Manual on Subsurface Investigations* to reflect the current state of the practice. The objective of the efforts to update the 1988 manual was to develop a concise, comprehensive document that will be invaluable for planning, executing, and using subsurface investigations and geotechnical characterizations for planning, designing, constructing, maintaining, and managing assets of transportation facilities.

The organization of the updated AASHTO *Manual on Subsurface Investigations* is described in Chapter 1.

The results of the research performed for NCHRP Project 21-10 have resulted in a complete revision and update to the 1988 AASHTO *Manual on Subsurface Investigation*. The updated manual defines a reasonable minimum standard of practice for modern geotechnical site investigations and will enable geoprofessionals to develop cost-effective geotechnical design and construction solutions while optimizing project life-cycle costs, ensuring public safety and environmental sustainability, minimizing contract disputes and cost overruns, and accelerating construction.

Chapter 1
Introduction

1.1 Purpose

The primary purpose of geotechnical subsurface investigations in transportation projects is to collect data that will help transportation engineers and planners identify, assess, and address risks associated with subsurface conditions; select appropriate design parameters; and monitor performance during construction and operation phases of an asset's life cycle. Geotechnical risks generally pose the greatest risk to transportation projects because adverse subsurface conditions can have significant impacts on public safety, project schedules, life-cycle costs, and environmental sustainability. A sound subsurface investigation program can mitigate these risks and yield significant dividends for state transportation agencies in terms of cost savings and timely completion of projects. Thus, it is prudent for transportation agencies to include geotechnical investigations as a part of their project development process.

This manual provides information and guidelines to help geoprofessionals (i.e., geotechnical engineers, geological engineers, geologists, and engineering geologists) plan and execute a sound geotechnical site investigation program; use the results to develop a ground model for planning, design, construction, and asset management phases of a project; and report and document the results in a manner that facilitates peer review, communication with stakeholders, and potential future uses.

1.2 Organization of the Manual

The organization of the manual mirrors how the subsurface investigations are typically performed:

- Planning the investigation (Chapters 2 and 3)
- Executing the investigation (Chapters 4 through 8)
- Reporting and presenting the results of the investigation (Chapter 9)

Supplemental information is presented in appendixes that are broadly grouped into three categories—investigative, administrative, and interpretive. Appendixes A through C contain information regarding investigations that are not typically conducted as part of the routine subsurface investigations but are conducted during either construction or operation to monitor performance and assess the condition of existing geotechnical features. Appendixes D through H contain information pertaining to administration functions, such as geotechnical data management, quality assurance/quality control (QA/QC), and best practices for health and safety. Appendixes I and J contain example relationships of soil and rock, respectively, that can be used to assist in interpreting results from investigations. The following is a synopsis of the content included in each of the chapters and appendixes.

1.2.1 Planning the Investigation

Chapter 2 describes the two types of uncertainty related to subsurface conditions—natural variability and knowledge uncertainty—and summarizes the nature of the technical and financial risks associated with a subsurface investigation that inadequately recognizes and addresses these uncertainties. General strategies for conducting a sound subsurface investigation program are also provided. Special considerations for subsurface investigations performed for the AASHTO LRFD bridge design and design–building projects are also discussed.

Chapter 3 presents processes for developing the scope for the subsurface investigations related to planning, designing, constructing, and operating transportation facilities, including the following:

- Identifying the types of data required to address the anticipated geotechnical risks and performance issues
- Determining the required appropriate type of data
- Selecting the most appropriate investigation equipment for the anticipated site conditions
- Selecting the appropriate scope for geophysical testing and the appropriate geophysical methods
- Selecting the appropriate scope for *in situ* testing and the appropriate *in situ* tests
- Selecting the appropriate sampling equipment and borehole advancing methods for the anticipated subsurface conditions
- Selecting the appropriate type of measurements to evaluate groundwater conditions
- Selecting the appropriate scope for laboratory testing and the appropriate laboratory tests

1.2.2 Executing the Investigation

Chapter 4 provides an overview of surface and borehole geophysical methods based on measuring, analyzing, and interpreting seismic, electrical, electromagnetic, gravitational, and magnetic fields. Geophysical methods are often useful during the initial phases of a site investigation program to efficiently gain an understanding of the overall subsurface conditions, including stratigraphy and the location and size of potential anomalies. The locations of subsequent borings and soundings can then be optimized to investigate areas of concern identified from the geophysical surveys. Geophysical methods are also useful to estimate some engineering properties of subsurface materials directly.

Chapter 5 provides information on the variety of equipment, methods, and procedures available for drilling and sampling soil and rock to obtained disturbed and undisturbed samples:

- Field equipment
- Methods for advancing boreholes
- Soil sampling

- Rock coring methods
- Logging borings
- Boring closure

Chapter 6 includes information to aid geoprofessionals with evaluating the different *in situ* geotechnical tests commonly used for characterizing soil and rock and with selecting the appropriate *in situ* test(s) for an investigation. *In situ* tests can efficiently collect abundant data to help define subsurface stratigraphy, evaluate vertical and horizontal variability, and obtain geotechnical engineering parameters for analysis and design. The *in situ* tests presented in Chapter 6 for soils include the standard penetration test (SPT), cone penetration test (CPT), flat-plate dilatometer test (DMT), vane shear, and pressuremeter; and the *in situ* tests for rock are the plate load test (PLT, also known as plate jacking test), flat jacking test (FJT), rock dilatometer test, large-field direct shear (DS) test, rock borehole shear test, and borehole cameras.

Chapter 7 describes the methods available to perform a comprehensive hydrogeologic characterization to gather information on (1) geology and hydrogeology, (2) aquifer characteristics, (3) aquitard characteristics, and (4) the direction and gradient of groundwater flow. Methods for establishing groundwater levels and measuring pressure heads (e.g., monitoring wells, piezometers) and estimating aquifer characteristics (e.g., pumping tests, slug tests, packer tests) are presented.

Chapter 8 presents the laboratory testing methods commonly used to characterize soil and rock. The chapter provides references for pertinent AASHTO, ASTM International (ASTM), and other applicable standards for each of the tests discussed. The following topics are presented:

- QA (e.g., sample identification and tracking; transportation, storage, and handling of samples; assessment of sample disturbance)
- Index tests (e.g., particle size distribution, Atterberg limits, moisture content)
- Soil classification
- Performance tests on soil (e.g., compaction, hydraulic conductivity, one-dimensional [1D] consolidation, shear strength, dynamic properties)
- Performance tests for pavement design (e.g., resilient modulus, California Bearing Ratio [CBR])
- Tests on rock (e.g., slake durability, compressive strength, elastic moduli)

1.2.3 Reporting and Presenting the Results of the Investigation

Chapter 9 provides background on the characterization of geotechnical data as either factual or interpretative and typical uses of geotechnical information. The chapter also includes some guidance on compiling, preparing, and presenting geotechnical information. The following are specific topics presented:

- Presentation of factual information
- Presentation of interpretative information
- Geotechnical reports for conventional (i.e., design–bid–build) and alternative (design–build) project delivery methods
- Contractual implications of geotechnical reports

1.2.4 Supplemental Investigative Information

Appendix A contains the following information regarding geotechnical instrumentation to assist geoprofessionals in evaluating the potential effectiveness of an instrumentation program:

- Identifying potential failure modes where instrumentation may add significant value
- Making a preliminary selection of the appropriate types of instrumentation
- Acquiring a conceptual understanding of the steps involved in developing an instrumentation plan
- Evaluating, presenting, and managing the data obtained from instrumentation

Appendix B provides guidelines for implementing a geotechnical instrumentation program for embankments, deep foundations, excavations in soil and rock, dewatering, earth-retaining structures, tunnels, and grouting. Appendix B also highlights how geotechnical instrumentation can be used to resolve legal disputes and manage geotechnical assets.

Appendix C provides guidelines for characterizing the integrity of the existing bridge foundation elements (condition assessment) and assessing their load-carrying capacity.

1.2.5 Supplemental Administrative Information

Appendix D introduces basic geotechnical data management concepts and then advances to providing guidance for developing and implementing a standardized geotechnical data management system. The following aspects of geotechnical data management systems are presented and described:

- Introduction
- Basic features
- Implementation guidelines
- Software requirements
- Data sources
- Business process considerations
- Data interchange for geotechnical and geoenvironmental specialist (DIGGS).

Appendix E establishes QA guidelines to define an agency's standards and quality management protocols during the subsurface investigation to ensure delivery of consistent and competent subsurface investigation products and services. The topics presented include the following:

- QA/QC policy
- Roles and responsibilities
- QA/QC plan
- Prequalification and verification
- Policies and procedures
- Standards

- Geotechnical data management
- Performance monitoring

Appendix F provides guidelines for planning and executing a subsurface investigation following commonly accepted safe operating practices to protect human health and the environment. The topics discussed include the following:

- General health and safety guidelines
- Responsibilities
- Administrative requirements
- Site inspection
- Development of a health and safety plan
- On-site activities

Appendix G provides guidelines and best practices for contracting subsurface investigation services. The topics presented include the following:

- Prequalification of private engineering firms
- Development of scope of work
- QA/QC practices
- Contract administration

Appendix H summarizes the resources available to assist geoprofessionals plan and execute subsurface investigations, analyze and interpret subsurface investigation data, present subsurface information, and manage subsurface investigations. The following topics are presented:

- Technical manuals and reports
- Geotechnical websites
- Available training resources
- References

1.2.6 Supplemental Interpretive Information: Interpreting the Results of the Investigation

Appendix I provides guidance for interpreting soil properties derived from geophysical, *in situ*, and laboratory testing methods. The emphasis is on parameters commonly used in highway analysis and design:

- Soil classification
- Preconsolidation stress or effective yield stress (i.e., stress history)
- Effective-stress and total-stress shear strength parameters
- Lateral stress state
- Modulus

- Coefficient of consolidation
- Hydraulic conductivity

Appendix J provides guidance for interpreting the engineering properties of intact rock and rock masses. The specific topics presented include the following:

- Intact rock classification
- Intact rock properties (e.g., uniaxial compressive strength, shear strength)
- Rock mass classification (e.g., rock mass rating [RMR], Geological Strength Index [GSI])
- Rock mass properties (e.g., shear strength, foundation capacity)

1.3 Data Management and Data Interchange for Geotechnical and Geoenvironmental Specialists (DIGGS)

Geotechnical site characterization for roadways and highway transportation features has been traditionally performed using invasive methods, usually borehole drilling, as part of the preliminary design process for specific projects. Site exploration usually takes place after project scoping and prior to final design such that any favorable or unfavorable discoveries that differ from design assumptions can be accommodated.

Today, additional information is more widely available to supplement site characterization efforts; this information can be at the project, regional, or statewide scale. Information from previous site exploration programs for existing structures may be available in whole or in part. In addition, local soils and geological maps, well borings, regional hydrogeological maps, aerial photography, and LiDAR surveys are now more widely available and easier to access than they have been historically. Some of this information is in the form of immediately usable electronic data that can be processed and used as input for mapping, analysis, visualization, statistical study, and predictive modeling. Each additional resource can provide useful information for identifying and managing geotechnical risks. The increasing value of historic data, within transportation agencies, and data from additional data sources is rapidly becoming more appreciated as processes and systems are becoming more interconnected and geotechnical data sets are becoming more appreciated as a type of big data.

Because geologic processes are generally slow, historical geotechnical information at specific project sites are often directly applicable to subsequent reconstruction or expansion projects at the same site or nearby. Frequently, structures are rehabilitated in place, or they are expanded for extra traffic capacity in the same geotechnical conditions as the original structures. Often, previous investigation data provide useful supplemental information or provide additional insight into site stratigraphy or variability. Historic borings, soundings, or other information, such as foundation installation records, may allow scope reduction for a current investigation. At the very least, existing information can be used to develop an appropriate scope for new geotechnical investigations. If borings exist, relatively fast geophysical exploration methods or CPT soundings may be appropriate to provide additional information at reduced cost or in a reduced timeframe. The value of geotechnical data is becoming increasingly recognized and appreciated when compared to the time and cost of new investigations.

The amount and varying formats of additional geotechnical, and related, information present new challenges for geoprofessionals with respect to data quality, organization, exchange, storage, engineering review, and overall data management.

This manual provides guidance on conducting subsurface investigations in terms of planning and executing appropriate testing. Information related to reporting and presenting information can be found in the appendixes.

1.3.1 Data Management

Geotechnical data management is about more than ensuring that field and lab measurements are obtained following proper testing procedures. Measured values become the basis for design and are usually presented in a variety of formats for different purposes through the project life cycle.

Geotechnical and related site exploration information, such as that obtained from regional mapping efforts or historic construction records, has considerable project value. Unexpected geotechnical conditions can easily lead to project delays and cost escalation; because the geotechnical work occurs early in the project construction schedule, these impacts can easily propagate through the construction timeline. It is therefore important to acquire geotechnical data and manage them effectively to ensure that appropriate analysis is conducted, decisions are made, means and methods or performance requirements are established, and the appropriate information is provided to the right people at the right time. It is therefore important to have quality data management practices in place to support the subsurface investigation and reporting process.

Within a typical geotechnical process workflow, once a measurement or test record is acquired it may be used or processed multiple times, and manual intervention, such as the selection of conversion factors, or data entry and reentry into software programs, boring log databases, spreadsheets, and reports, is currently common. In addition to general inefficiency, manual data handling provides opportunities for transcription or other errors. As more data are acquired, particularly larger data sets, such as continuous 1D profiles and 2D and 3D data, there is an increasing demand for system interoperability and seamless data exchange.

1.3.2 DIGGS

The Data Interchange for Geotechnical and Geoenvironmental Specialists (DIGGS) protocol is an open-source, flexible and expandable, extensible markup language (XML) format with accompanying data dictionaries for exchanging geotechnical and environmental data. The American Society of Civil Engineers (ASCE) Geo-Institute currently hosts the DIGGS website and supports the ongoing development of the geotechnical electronic data exchange standard. The XML structure defines the form and content of the data, data attributes, and data relationships. The XML format is used by the software community for data transfer; this format is more flexible than comma separated value (CSV) files, such as the Association of Geotechnical & Geoenvironmental Specialists (AGS) data format. The DIGGS data dictionary explains the meaning of the terms used in the data structure. DIGGS is a data transfer protocol and allows data to be exchanged in a common format, eliminating the barriers associated with both proprietary software (input and output files) and multiple formats used by agencies in their internal data structures (spreadsheets, databases, etc.).

The schema files, which are updated as new processes or tests are included to expand use cases, are developed by the DIGGS development community. Development work began as a Federal Highway Administration (FHWA) Transportation Pooled Fund Study in 2004 and involved 12 state Departments of Transportation, FHWA, U.S. Environmental Protection Agency (EPA), U.S. Army Corps of Engineers, the U.S. Geological Survey (USGS), and the UK Highway Agency. Current development, with an expanded development community, is through an online platform for code development. DIGGS is not yet associated with the Open Geospatial Consortium. More information on the history and development of DIGGS is available online from the Geo-Institute.

In 2020, AASHTO created provisional standard PP 102. This standard adopts the DIGGS format for the purpose of transmitting data, in a defined and consistent format, for efficient data communication among computer software, applications, Geographic Information System (GIS) visualization platforms, and geotechnical data management systems.

PP 102 defines practice promoting consistency, completeness, and integrity of geotechnical data after data are generated and checked, maintaining data quality. More efficient programming, automation, data management and interchange, and workflow operations related to geotechnical investigations, testing, analyses, reporting, designs, bid-package preparation, and construction and performance monitoring are expected through the use of the standard, resulting in savings of time and cost, and risk reduction by minimizing communication errors associated with data entry or reproduction.

Use of the standard helps provide that geotechnical data can be easily acquired, exchanged, used, validated, stored, and otherwise managed throughout the geotechnical portion of the project, the overall project life cycle, and future projects. Adoption of the standard also provides that inbound data, internal data, and outbound data are uniform, consistent, and available in a consistent format for efficient use in project workflow.

1.3.3 DIGGS, Electronic Design, and Future Workflow Interoperability

Recognizing that future practice is beyond the scope of this document, the DIGGS framework provides both an immediate opportunity for geotechnical practitioners to efficiently exchange information with their colleagues as well as other project and organizational partners and the potential for future interoperability with systems that are currently in development. Although DIGGS is not yet tied to the Open Geospatial Consortium (OGC), integration with other systems is recognized as an important component to standardize the exchange of geospatial information with other platforms such as Building Information Modeling (BIM), and digital as-built information.

As an example of other related markup language use cases, GeoSciML is a model of geologic features commonly depicted in geological mapping. OGC is working on the development of a Model for Underground Data Definition and Integration (MUDDI). Although this effort currently focuses on depicting underground utilities for conflict avoidance and risk reduction, it is also focused on associated above-ground and underground characteristics and the maximum use of data from different data sources. Information on the OGC Underground Infrastructure Pilot: MUDDI Workshop is available online (OGC, n.d.).

Adopting DIGGS for geotechnical data interchange is a step toward more comprehensive data integration with larger project systems (CAD designs, 3D plans, BIM, digital plans, digital as-builts, and geospatial models) where including subsurface characterization can provide increased project value.

1.4 Key Complementary Resources

To complement the information in this manual, geoprofessionals responsible for planning and executing subsurface explorations, and using the results for planning, design, construction, and asset management phases of a project, should consult the following complementary resources that also provide comprehensive information on geotechnical site characterization:

- R 13 (ASTM D420), Conducting Subsurface Investigations
- PP 102, Standard Practice for Digital Interchange of Geotechnical Data
- Article 10.4 of the *AASHTO LRFD Bridge Design Specifications* (AASHTO, 2020)
- Federal Highway Administration Geotechnical Engineering Circular No. 5 on Geotechnical Site Characterization (FHWA, 2017)
- The reference manuals for National Highway Institute (NHI) Course No. 132012 on Soils and Foundations (FHWA, 2006a, 2006b)
- The U.S. Army Corps of Engineers (USACE) Engineer Manual No. 1110-1-1804 on Geotechnical Investigations (USACE, 2001)
- ASCE GI-DIGGS website (ASCE)

1.5 References

AASHTO Materials Standards:

- PP 102, Digital Interchange of Geotechnical Data
- R 13, Conducting Geotechnical Subsurface Investigations

AASHTO. *AASHTO LRFD Bridge Design Specifications*. 9th ed. LRFDBDS-9. American Association of State Highway and Transportation Officials, Washington, DC, Article 10.4, 2020.

ASCE. Geo-Institute. DIGGS. Available from https://geoinstitute.org/index.php/special-projects/diggs.

FHWA. *Soils and Foundations*, Reference Manual – Volume I. NHI-06-088. Federal Highway Administration, U.S. Department of Transportation, Washington, DC, 2006a. Available from https://www.fhwa.dot.gov/engineering/geotech/pubs/nhi06088.pdf.

FHWA. *Soils and Foundations*, Reference Manual – Volume II. NHI-06-089. Federal Highway Administration, U.S. Department of Transportation, Washington, DC, 2006b. Available from https://www.fhwa.dot.gov/engineering/geotech/pubs/nhi06089.pdf.

FHWA. *Geotechnical Site Characterization*. Geotechnical Engineering Circular No. 5. NHI-16-072. Federal Highway Administration, U.S. Department of Transportation, Washington, DC, 2017.

Open Geospatial Consortium (OGC). Underground Infrastructure Pilot: MUDDI Workshop. Available from https://www.ogc.org/projects/initiatives/ugipilot.

USACE. *Geotechnical Investigations.* Engineer Manual 1110-1-1804. U.S. Army Corps of Engineers, Department of Defense, Washington, DC, 2001.