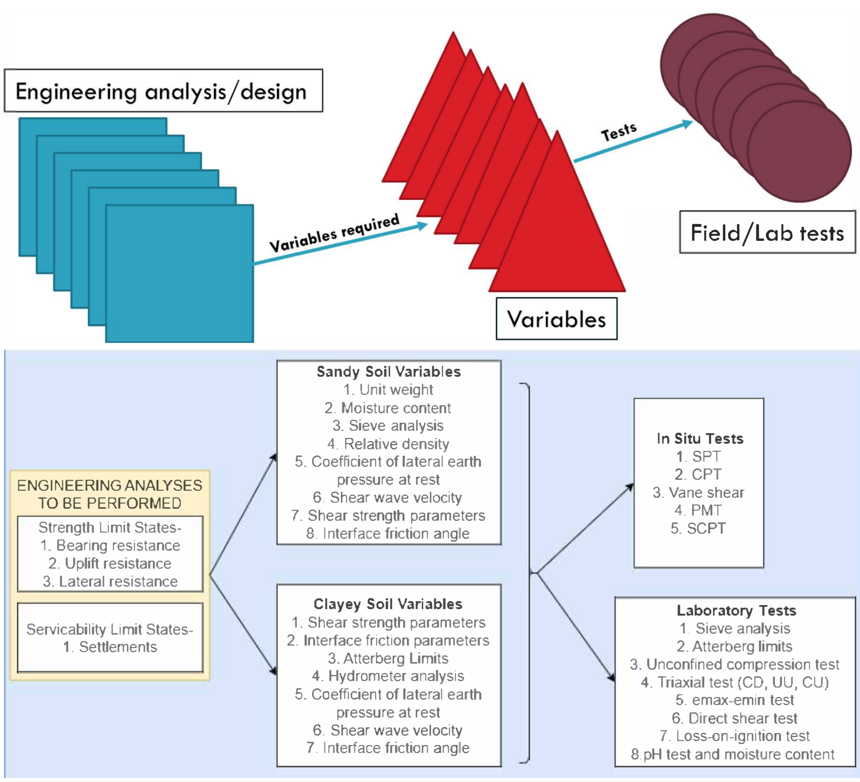
JOINT TRANSPORTATION RESEARCH PROGRAM

INDIANA DEPARTMENT OF TRANSPORTATION
AND PURDUE UNIVERSITY

GIS-Based Geotechnical Database for Collaborative GIS



Rameez Ali Raja, Vidushi Toshniwal, Rodrigo Salgado

SPR-4616 • Report Number: FHWA/IN/JTRP-2023/14 • DOI: 10.5703/1288284317637

RECOMMENDED CITATION

Raja, R. A., Toshniwal, V., & Salgado, R. (2023). *GIS-based geotechnical database for collaborative GIS* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2023/14). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284317637

AUTHORS

Rameez Ali Raja
Graduate Research Assistant
Lyles School of Civil Engineering
Purdue University

Vidushi Toshniwal
Graduate Research Assistant
Lyles School of Civil Engineering
Purdue University

Rodrigo Salgado, PhD
Charles Pankow Professor of Civil Engineering
Lyles School of Civil Engineering
Purdue University
(765) 494-5030
rodrigo@purdue.edu
Corresponding Author

JOINT TRANSPORTATION RESEARCH PROGRAM

The Joint Transportation Research Program serves as a vehicle for INDOT collaboration with higher education institutions and industry in Indiana to facilitate innovation that results in continuous improvement in the planning, design, construction, operation, management and economic efficiency of the Indiana transportation infrastructure. https://engineering.purdue.edu/JTRP/index_html

Published reports of the Joint Transportation Research Program are available at http://docs.lib.purdue.edu/jtrp/.

NOTICE

ACKNOWLEDGEMENT

The work presented in this paper was funded by the Joint Transportation Research Program (JTRP) administered by the Indiana Department of Transportation (INDOT) and Purdue University through contract SPR-4616. The support of the Indiana Department of Transportation (INDOT) and the Federal Highway Administration (FHWA) are gratefully acknowledged. The authors are very grateful for the support received from the project advisor, Boonam Shin, the business owner, Athar Khan, and in particular, the support received from the Study Advisory Committee members (Sung Min Yoon, Peter Becker, Irfan Alvi, Derek Fuller, and Christa Phelps) is much appreciated. The authors are thankful to graduate student Daniel Goldstein Fridman for his comments on early draft of the report.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/IN/JTRP-2023/14		

4. Title and Subtitle GIS-Based Geotechnical Database for Collaborative GIS	**5. Report Date** May 2023 **6. Performing Organization Code**
7. Author(s) Rameez Ali Raja, Vidushi Toshniwal, and Rodrigo Salgado	**8. Performing Organization Report No.** FHWA/IN/JTRP-2023/14
9. Performing Organization Name and Address Joint Transportation Research Program Hall for Discovery and Learning Research (DLR), Suite 204 207 S. Martin Jischke Drive West Lafayette, IN 47907	**10. Work Unit No.** **11. Contract or Grant No.** SPR-4616
12. Sponsoring Agency Name and Address Indiana Department of Transportation (SPR) State Office Building 100 North Senate Avenue Indianapolis, IN 46204	**13. Type of Report and Period Covered** Final Report **14. Sponsoring Agency Code**

15. Supplementary Notes

Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract

INDOT spends at least 8 million dollars annually on geotechnical site investigations, not including the amounts spent by contractors. The laborious and costly job of data collection in geotechnical practice requires the efficient storing and organizing of this valuable data to develop correlations and trends in spatially varying geotechnical data. INDOT currently uses gINT software for managing geotechnical data and ArcGIS for storing boring logs and geotechnical reports. The INDOT geotechnical office is pursuing means to improve the efficiency of their operations by developing a GIS-based geotechnical database for secure storage, easy retrieval, and flexible sharing of geotechnical data to enhance decision making. SPR-4616 is the first step towards the development of a geotechnical data management system in which important decisions on the components and structure of the database were made. The report presents a detailed conceptual layout for the development of a geotechnical database following an object-oriented programming approach. The report discusses in detail the geotechnical applications, the field, laboratory, and verification tests that will be included in the database. The geotechnical variables required to perform the engineering analysis in designing specific applications are logically linked with the geotechnical tests from which they are obtained. Lastly, a detailed layout of the proposed database structure and a user workflow example is provided in the report and can serve as a guide during the development of the database system.

17. Key Words	18. Distribution Statement
GIS, geotechnical database, data management, geotechnical tests	No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	28	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

EXECUTIVE SUMMARY

Introduction

Geotechnical reports contain valuable project information, including borehole data; laboratory, field, and verification test data; engineering analyses; and geotechnical design. These reports are traditionally stored either in hard copy or portable document format forms, which creates issues with the storage, accessibility, and distribution of this valuable information. A preferred and advantageous way to organize these reports is by using a database system. The INDOT geotechnical office is planning to develop relational geotechnical database software. The aim of this project is to lay out the conceptual basis for the development of an object-oriented relational geotechnical database for INDOT. This report presents the scope of the geotechnical applications that will be included in the database. A complete inventory of geotechnical tests performed by INDOT was developed, and the variables required for performing design checks of selected geotechnical applications are linked to the geotechnical tests from which they are obtained. Finally, a proposed structure of the database is presented followed by a user workflow example.

Findings

INDOT is currently using gINT software to manage geotechnical data and ArcGIS to store bore log information and geotechnical reports. An alternative under consideration is the development of a custom integrated geotechnical database that (1) is capable of storing geotechnical data obtained from site investigations, and (2) has the functionality to analyze the information efficiently to make the related design decisions. The potential users of the database are geotechnical, pavement, and bridge engineers who may need to search and access existing geotechnical information for future engineering design.

Implementation

This report presents the conceptual basis for organizing a database that provides geotechnical information in a very clear, logical, and efficient manner. The layout of the proposed database was thoroughly thought out, so that the data entry and query interaction operations function effectively. It is recommended to start the development of geotechnical database in order of priority, such as the applications most frequently used by INDOT.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1 Background

Civil engineering projects rely on geotechnical reports, which are formulated based on geotechnical data obtained from site investigations, which include both *in situ* and laboratory testing performed on either remolded or undisturbed samples. The geotechnical reports are prepared on a project-by-project basis, and thus an abundance of geotechnical data is gathered from a site investigation planned specifically for a project. These reports are mostly submitted in the form of a hard copy and, in some cases, electronically in the form of portable document format (PDF). Storage, archiving, and transferability of geotechnical reports submitted in hard copy is challenging and time consuming. Hard copies of the submitted geotechnical reports are placed in their respective project files, which are generally disposed of after a certain time period. When the reports are submitted electronically, this is done in the form of file types that are proprietary and display information pertinent to the focus of each company, or otherwise not easily amenable to electronic processing. However, as the number of files increases, it becomes more advantageous to place all the geotechnical data at one location and use a database system to manage the reports. An electronic database system provides several advantages over the conventional reporting system by allowing the users to store, query, access and distribute geotechnical reports and related documents in a convenient manner.

INDOT spends at least 8 million dollars annually on geotechnical site investigations, not including amounts spent by contractors as part of contracts. The laborious job of data collection in geotechnical practice dictates the need to efficiently store and organize the valuable data to develop correlations and trends in spatially varying geotechnical data. The INDOT geotechnical office is pursuing means to improve the efficiency of their operations by developing a geotechnical database for secure storage, easy retrieval, and flexible sharing of geotechnical data to enhance their decision-making. It is intended to reduce the need to perform investigations when the data already exists and would also serve as a tool for effective engineering analysis based on which design decisions can be made. This one-year project was envisioned as the first step towards the development of a geotechnical data management system.

1.2 Project Overview

The current research aimed at laying out the conceptual basis for the development of an object-oriented, relational geotechnical database that best fit the current needs of INDOT geotechnical office. In this project, important decisions such as the types of geotechnical applications, field and laboratory tests, and variables required for engineering analysis that will be covered by the database were made.

1.3 Report Structure

Section 1 introduces the project and its scope.

Section 2 presents an overview of the different geotechnical applications that will be covered by the database.

Section 3 presents the details of different laboratory and field tests performed by INDOT.

Section 4 presents different geotechnical variables that are obtained from geotechnical testing and their linkages with the design of selected applications.

Section 5 presents the proposed structure of the database and an interactive user workflow example.

2. APPLICATIONS COVERED BY THE DATABASE

A comprehensive list of services that the INDOT geotechnical office provides in support of civil engineering projects was formulated to finalize the scope of the applications that will be covered in the database. The applications shortlisted for inclusion in the database are discussed below.

2.1 Foundation Design

2.1.1 Shallow Foundation Design

Shallow foundations are preferred when a competent soil layer, which can support the applied loads without undergoing excessive settlement, exists at a shallow depth. They are cost effective option as they require excavation to shallow depths and are also easy to construct. Depending on how dense or stiff the underlying soil layer is, shallow foundations can support not only building structures but can also be used to support bridges. The different types of shallow foundations include spread footings, isolated footings, mat footings, and strap footings. The selection of an appropriate type of footing depends on site conditions, supporting soil properties, applied loads and the type of structure that is to be supported. Shallow foundations are proportioned and designed in accordance with the Load Resistance Factor Design (LRFD) framework as prescribed by AASHTO (2020), such that they perform satisfactorily under all applicable limit states. Design of foundations at ultimate limit states include consideration of the nominal bearing resistance, overturning or excessive loss of contact, and overall stability of the structure and its part. Foundation design at the service limit state shall consider all foundation movements (vertical, horizontal, and rotation) based upon structure tolerance to total and differential movements. The geotechnical investigation planned for a shallow foundation design should identify the properties and behavior of the soil and/or rock, the groundwater conditions, and other subsurface conditions that might affect the foundation design and performance. SPT and/or CPT results are generally used to obtain the foundation design parameters through correlations with shear strength and compressibility. Laboratory testing is carried out to supplement the data obtained from the field testing to refine the design properties by assessing the index properties, shear strength, and compressibility of soils. The information about the depth of groundwater table is critical in performing constructability evaluations and is obtained from the field instrumentation (piezometers) and *in situ* tests (pump tests).

2.1.2 Deep Foundation Design

Deep foundations are used to safely transfer structural loads to deeper rock or firm soil layers. They are the preferred foundation type for a project site where loose sands or soft clays exist at shallow depth and cannot provide adequate bearing capacity to support the applied loads. Piles are the most common type of deep foundation. They are made of concrete, steel, timber, or polymers and they can efficiently transfer the applied loads through skin friction and end bearing. Depending on the method of installation, piles are classified as full-displacement piles, partial-displacement piles, and non-displacement piles. Full-displacement pile installation does not require any prior soil removal and is installed either by driving or jacking. Nondisplacement piles, on the other hand, are installed *in* situ by first removing a volume of soil from the ground by drilling and then filling the resulting cylindrical void left in the ground with concrete. Partial displacement piles lie between these two extremes and are mostly installed using different types of auger or drilling tool. The selection of pile type and its installation method is determined by the required bearing capacity, pile length, soil conditions, and economic consideration. The pile types commonly used by INDOT are steel pipe piles, steel H-piles, and drilled shafts. Piles are proportioned and designed in accordance with the Load and Resistance Factor Design (LRFD) framework as prescribed by AASHTO (2020). Engineering analyses are required to assess the pile base resistance and pile shaft resistance. The analyses will include loading from the superstructure, but also downdrag loading if applicable. The design based on these analyses aims to prevent excessive foundation movement and to assure stability. Geotechnical information required for performing engineering analysis of deep foundations includes the details of subsurface profile, location of groundwater table, rock type and strength, shear strength, the compressibility parameters of soils, horizontal earth pressure coefficients, and soil-pile interface friction parameters. For drilled shafts, the assessment of groundwater seepage, need for dewatering, and protection against caving are key factors to avoid any constructability issues. In the case of driven piles, it is important to identify the presence of very hard layers or the presence of boulders as they can cause drivability issues. Pile foundations may cause damage to the nearby structures due to vibrations and ground heaving during pile driving.

2.2 Retaining Wall Design

Retaining walls are earth retention structures used for the purpose of creating space and providing the support required to build on ground which is unstable otherwise. They are also employed in projects in which existing facilities are to be widened or replaced, such as bridge abutments. There are different types of retaining walls, each requiring different materials, equipment, and construction procedures. Gravity walls, cantilever walls, and mechanically stabilized earth (MSE) walls are common types of walls. Project requirements dictate the type and extensiveness of the field and laboratory testing to establish properties for the retaining wall design. The design, constructability, and performance criteria are assessed by determination of *in situ* and backfill material properties, wall geometry, active and passive earth pressures acting on the wall, applied surcharge loads, backslope and toe slope of the embankment. The Load Resistance Factor Design (LRFD) framework as prescribed by AASHTO (2020) is used for designing retaining walls. External stability checks (sliding, overturning, settlement, bearing capacity and global stability) are generally performed for all types of retaining walls while additional internal stability analysis (reinforcement tensile strength, reinforcement pullout capacity, reinforcement-wall connection strength, and sliding along reinforcement-soil interface) is required for MSE walls.

2.3 Slope Stability Analysis

The stability of a slope is of critical importance in geotechnical engineering as any natural or artificial slope failure can severely damage any infrastructure of which it is part or that is near it. Human casualties are not rare. A slope stability failure occurs when the available shear strength between the moving and stable soil mass is insufficient to prevent sliding. The slope stability analysis is performed by geotechnical and foundation engineers to ensure the stability of cut and fill slopes, embankment stability, global stability of retaining walls, stability of foundation works carried out on sloping ground, and assessment of stability due to landslides and liquefaction. Limit equilibrium, limit analysis, finite element analysis, finite difference analysis, and material point method analyses are the main types of analysis performed for assessing the stability of a slope. Of all these, the limit equilibrium method remains the most commonly used method to assess slope stability with the aid of computer programs. Since the analysis techniques are sensitive to the input data, a detailed assessment of soil and/or rock stratigraphy is critical in obtaining material properties and behavior for slope stability analysis. Piezometric data at multiple locations and depths, within and below the slope, is also required to obtain an accurate groundwater profile to check for potential seepage or piping failure. The different input parameters needed to perform a slope stability analysis are the soil unit weights, undrained shear strength, critical-state friction angle, and minimum residual friction angle.

2.4 Ground Improvement

Ground improvement techniques are employed to enhance constructability or structure performance under operational loads. Ground improvement can be broadly classified into four categories: replacement, drainage, densification, and admixture stabilization. Many ground improvement techniques have been developed and applied when construction occurs in problematic soils, such as soft clays, highly organic soils, or loose sand deposits below the water table, which may be subject to liquefaction. Geotechnical parameters such as strength, compressibility, and permeability of the soil should be evaluated first to understand the problem and then recommend a suitable ground improvement method. The choice of the method is based on the site-specific conditions and project needs. The common ground improvement techniques used by INDOT are vibro-compaction, vibro-replacement, stone columns, geosynthetics, grouting, and wick (PVD) drains.

2.5 Pavement Design

In pavement works, geotechnical input parameters are required in designing a new roadway alignment and in pavement rehabilitation projects. Comprehensive subsurface investigation and laboratory testing is necessary to ascertain the strength of the subgrade. The resilient modulus is used to define the stiffness of the subgrade soil, which characterizes the soil support provided by the subgrade. Geotechnical recommendations on suitable soil stabilization techniques are also required if the natural soils at the site are unsuitable for the planned pavement structure. Reason for unsuitability include soils with inadequate strength, inappropriate gradation, or with potential to swell. Subgrade stability must be considered both in the short and long term: the subgrade should adequately support the heavy equipment during construction and should also support the roadway during its design life. Depth of groundwater table, drainage and climatic conditions are also assessed to properly design the stormwater management system and determine the shrinkage/swelling factors. In addition, the *in situ* classification of the soils ensures that the slopes of cuts and fills are stable while executing the earthwork.

3. FIELD, LABORATORY, AND VERIFICATION TESTS PERFORMED BY INDOT

In this section, we discuss the inventory that we compiled of the geotechnical tests that are performed by the INDOT geotechnical office. We categorize the geotechnical tests into field, laboratory, and verification tests. Table 3.1, Table 3.2, and Table 3.3 provide a consolidated list of these tests along with their respective standards. We briefly discuss below the tests and the geotechnical design parameters obtained from each test.

3.1 Field Tests

The field tests are performed during site investigation to characterize the subsurface profile and obtain soil parameters (e.g., relative density, moisture content, and shear strength) *in situ*. Field tests performed by INDOT are discussed in this section.

3.1.1 Standard Penetration Test (SPT)

The standard penetration test is performed in accordance with AASHTO T 206 (2022) and ASTM D 1586 (2022) and is best suited for sandy ("cohesionless") soils. In this test the number N_{SPT} of blows required to drive a split-barrel sampler into the ground at specified intervals is recorded. The split-barrel sampler is also used to collect disturbed samples during the test for the purpose of identification and laboratory testing. The test is typically performed at 1.5 m (5 ft) depth intervals or when a significant change of materials is observed during drilling, unless otherwise specified. SPT test results and identification information are used in subsurface exploration for a wide range of geotechnical applications. The obtained N_{SPT} values for the blow counts are corrected for hammer efficiency, rod length, borehole diameter, and sampling method. The N_{SPT} values are correlated with different soil parameters such as unit weight γ, relative density D_R, friction angle ϕ, and undrained compressive strength q_u. Correlations also exist to relate the N_{SPT} values with the cone resistance q_c obtained from the CPT test.

3.1.2 Cone Penetration Test (CPT)

The cone penetration test is performed in accordance with ASTM D 5778 (2020). In this test an electronic probe is pushed into the soil while continuously recording the measurements for tip resistance q_c, sleeve friction f_s and pore water pressures u. The standard cone penetration rate should not exceed 2 cm/s. The continuous nature of CPT results provides a detailed stratigraphic profile which also serves as a guide for selective sampling. CPT data can be used to interpret subsurface stratigraphy, and, through use of site specific correlations, the results can provide data on engineering properties of soils intended for use in design and construction of earthworks and foundations. The q_c values are correlated with different soil parameters such as D_R, ϕ, and small-strain shear modulus G_0.

3.1.3 Seismic Cone Penetration Test (SCPT)

The test is performed in accordance with ASTM D 7400 (2019) to determine compression (P) and shear (S) wave velocity profiles in geotechnical earthquake engineering investigations. Since certain counties in

TABLE 3.1
Summary of the field tests performed by INDOT

Test	Standard	Variables
Standard penetration test (SPT)	AASHTO T 206, ASTM D 1586	N_{SPT}
Cone penetration test (CPT)	ASTM D 5778	q_c, f_s, u
Seismic cone penetration test (SCPT)	ASTM D 7400	v_s
Dynamic cone penetrometer test (DCPT)	ITM 509	Blow counts
Light weight deflectometer (LWD)	ITM 508, ASTM E 2583	E_d
Falling weight deflectometer (FWD)	ASTM D 4694	E
Pocket penetrometer (PP)	ASTM WK 27337	q_u
Dilatometer test (DMT)	ASTM D 6635	Lateral stress and stiffness
Pressuremeter test (PMT)	ASTM D 4719	E_M
Plate load test (PLT)	ASTM D 1194	q_{ult}, w
Vane shear test	AASHTO T 223, ASTM D 2573	s_u
One-point proctor moisture and density relation	ITM 512	*in situ* wc, $\gamma_{d,max}$

TABLE 3.2
Summary of the laboratory tests performed by INDOT

Test	Standard	Variables
Sieve analysis and hydrometer test	AASHTO T 88	D_{50}, C_U, C_C
Atterberg limits	AASHTO T 89, AASHTO T 90	LL, PL, PI, LLR
Moisture content determination	AASHTO T 265	wc (%)
Unit weight determination	AASHTO T 233	γ_m
Specific gravity test	AASHTO T 100	G_s
Constant and falling head test	AASHTO T 215	K
Standard and modified proctor test	AASHTO T 99, AASHTO T 180	OMC, $\gamma_{d,max}$
One-dimensional consolidation test	AASHTO T 216	e, C_c, C_s, c_v, C_α
Triaxial compression tests	AASHTO T 296, AASHTO T 297, ASTM D 7181	ϕ_c, c, s_u
Direct shear test	AASHTO T 236	c, ϕ_c
Ring shear test	ASTM D 6467	c, ϕ_r, $\phi_{r,min}$
Unconfined compressive strength test	AASHTO T 208	q_u
Uniaxial compressive strength of rocks	ASTM D 7012	q_u, E, v
Point load strength index of rocks	ASTM D 5731	I_s
Subgrade resilient modulus	AASHTO T 307	MR
pH test	AASHTO T 289	pH
Loss-on-ignition test	AASHTO T 267	OC (%)
Expansive index of soils	ASTM D 4829	EI
Corrosion test	AASHTO T 288, T 289, T 290, T 291	pH, resistivity, *Su* (%), and *Cl* (%)
Slake durability index	ASTM D 4644	I_d
Jar slake test	ITM 511	I_j

Indiana fall within the seismic zones, this test is routinely performed by INDOT. During the test, travel times of the seismic waves are analyzed, and seismic velocity is calculated. The P-wave and S-wave velocities are directly related to the important geotechnical elastic constants such as Poisson's ratio v, shear modulus G, bulk modulus K, and Young's modulus E. These parameters are used in analysis of soil behavior under both static and dynamic loads. The shear wave velocity determined in this test is also used in the liquefaction assessment of the soils.

3.1.4 Dynamic Cone Penetrometer Test (DCPT)

The test is performed in accordance with ITM 509 (INDOT, 2022a) and is used to estimate the strength of the *in situ* soil. This test is performed by driving a metal cone into the ground by repeatedly striking it with a hammer of standard weight dropped from a fixed height. The use of DCPT fundamentally started with pavement applications where it was used as a proxy test for the determination of the California Bearing Ratio (CBR). However, considering the portability of the apparatus it is also used as a verification test to check compaction standards. The DCPT blow count measured during the test can be correlated with *in situ* D_R, γ, resilient modulus MR, and bearing capacity of the soils.

3.1.5 Light Weight Deflectometer (LWD)

The test is performed in accordance with ITM 508 (INDOT, 2019a) and ASTM E 2583 (2020) and is used

TABLE 3.3
Summary of the verification tests performed by INDOT

Test	Standard	Variables
Static pile load test (SPLT)	ASTM D 1143	Load-settlement curve, load-transfer curves, limit unit shaft resistance vs. depth plot, limit shaft capacity, ultimate base capacity, ultimate load capacity
Dynamic pile load test (DPLT)	ASTM D 4945	Estimated pile load-carrying capacity, estimated shaft resistance, estimated base resistance, driving/restrike records, parameters used to describe pile-soil static and dynamic stress-strain response, pile set
Pile integrity test	ASTM D 5882	Discontinuity, consistency, interpreted pile length, pile diameter vs depth plot, velocity signals
Pile lateral load test	ASTM D 3966	Flexural stiffness, lateral deflection, bending moment, shear force, load and displacement at failure, soil resistance
Proofrolling	INDOT Standard Specification, Section 203.26	Subgrade deformation and standard acceptance testing
Light weight deflectometer (LWD)	ITM 508, ASTM E 2583	E_d
Falling weight deflectometer (FWD)	ASTM D 4694	E
Dynamic cone penetrometer test (DCPT)	ITM 509	Penetration index, blow count for 6 in. or 12 in. of penetration

as a quick non-destructive method for determining the stiffness of the subgrade and unbound base layers, granular layers, and backfilling materials. In this test the deflection of the paved and unpaved pavement surfaces is measured under the falling weights to estimate the soil modulus. The deflections are correlated to pavement performance and *in situ* material parameters of the pavement layers. INDOT uses this test for sands, aggregates, and chemically modified soils. The test data is useful for quality assurance of compacted layers, structural evaluation of load-carrying capacity and determination of thickness requirements for highway and airfield pavements.

3.1.6 Falling Weight Deflectometer (FWD)

The test is performed in accordance with ASTM D 4694 (2020). The falling weight deflectometer is used to simulate deflection of a pavement surface in response to an impulse load applied by a fast-moving truck. The resulting deflections are measured at the center of the applied load and at various distances away from the load. Knowing the thickness of individual pavement layers the deflection can be related to the stiffness of the pavement using various computational methods. The measured deflections are an indicator of pavement performance and could be used to determine the modulus of pavement layers and subgrade soils. The result of this test could be used to evaluate structural load-carrying capacity and determine overlay thickness requirements for highway and airfield pavements.

3.1.7 Pocket Penetrometer Test (PP)

This test is performed in accordance with ASTM WK 27337 (2010) and is used to determine consistency, shear strength, and approximate unconfined compressive strength of soils. This lightweight, hand-held, and direct reading penetration device consists of a calibrated spring and 0.25-in.-diameter piston encased inside a metal casing. INDOT uses pocket penetrometer only as a supplementary test to more precise strength determinations.

3.1.8 Dilatometer Test (DMT)

This test is performed in accordance with ASTM D 6635 (2001) and is used to determine the strength and deformation characteristics of fine-grained soils. The main part of the flat dilatometer consists of a flat stainless thin steel blade with a circular expandable steel membrane of 60-mm diameter on one side. The test involves driving the steel blade into the ground, inflate the steel membrane and measure the corresponding pressure and deformation. The corrected DMT pressures readings are used to estimate the *in situ* lateral stress and lateral soil stiffness.

3.1.9 Pressuremeter Test (PMT)

The pressuremeter test is performed in accordance with ASTM D 4719 (2020). In principle the pressuremeter test is performed by applying pressure to the side walls of a borehole and observing the corresponding deformations. In this test, a cylindrical probe is lowered into a pre-drilled borehole and then pressure within it is increased by inflating a flexible membrane in the lateral direction in about 10 increments. For each increment, the change in volume of the measuring cell is recorded until the volume is equal to twice its initial deflated volume. The test is best used for dense sands, hard clays, and weathered rock. The limit pressure is obtained through which soil shear strength could be estimated using cylindrical cavity expansion analysis. The results of this test are used to estimate the soil stiffness, strength, and at-rest horizontal earth pressure, which are used in the design of foundation.

3.1.10 Plate Load Test (PLT)

The test is performed in accordance with ASTM D 1194 (2003). In this test, the plate is placed at the desired depth and loaded incrementally. The settlement for each load increment is measured to plot the corresponding load-settlement curve. The test gives information about the soil up to the depth of about two diameters of the bearing plate. It is performed to evaluate the load-settlement curve and estimate the ultimate bearing capacity of a soil that will be used in the design of foundations. In pavement design applications the plate load test is normally used to measure the short-term settlement of pavement subgrade.

3.1.11 Vane Shear Test

The vane shear test is performed in accordance with ASTM D 2573 (2018) and AASHTO T 223 (1996). The test is performed in soft, saturated clayey ("cohesive") soils to estimate their undrained shear strength s_u. The test is relatively simple, quick, and provides a cost-effective way of estimating the soil shear strength. The vane shear test apparatus consists of a four-blade stainless steel vane attached to a steel rod that is pushed into the ground. The vane is then rotated at a slow rate of 6° per minute until a maximum torque is reached and the vane rotates rapidly for several revolutions. The peak torque measured is related to the peak undrained shear strength. This test method is used extensively in a variety of geotechnical explorations for total stress analysis of saturated fine-grained clays and silts.

3.1.12 One-Point Proctor Moisture and Density Relation

The test is performed in accordance with ITM 512 (INDOT, 2019b) and is used to obtain the corrected maximum dry density and optimum moisture for compaction control in cohesive soils. The standard provides relationships for density-moisture and Atterberg limits to estimate maximum dry density and optimum moisture content. The test is used to ensure quality control during compaction.

3.2 Laboratory Tests

Field testing is complemented by laboratory testing to ensure that soil properties selected for design are realistic. The laboratory tests performed by INDOT on disturbed and undisturbed soil samples obtained from the field are discussed below.

3.2.1 Sieve and Hydrometer Analysis

A combination of sieve analysis and hydrometer analysis is performed to obtain the grain size distribution curve for the soil samples. Sieve analysis is performed in accordance with AASHTO T 88 (2020) for quantitative determination of the distribution of particle sizes present in the soil sample. The test is coupled with the hydrometer analysis to obtain the full gradation curve for a soil when more than 20% of the soil sample passing the No. 200 sieve in sieve analysis.

3.2.2 Atterberg Limits and Plasticity Index

This test is performed to check the consistency of fine-grained soils by determining the Atterberg limits. The liquid limit (LL) is determined in accordance with AASHTO T 89 (2022), while the plastic limit (PL) and the plasticity index (PI) are determined in accordance with the AASHTO T 90 (2020). These limits describe the water content at which the behavior of the fine-grained soil changes from a "solid" state to a "liquid" state. The Atterberg limits are correlated with the soil's engineering behavior properties, such as strength, compressibility, permeability, and density–moisture relationships.

3.2.3 Liquid Limit Ratio Test (LLR)

The liquid limit ratio (LLR) of the soil is defined as the ratio of the liquid limit of the soil obtained after the loss on ignition test AASHTO T 267 (1986) to the liquid limit of the natural soil. The values obtained for the liquid limit ratio are related to the organic content present in the soil.

3.2.4 Moisture Content Determination

This test is performed in accordance with AASHTO T 265 (2015) and is used to determine moisture content of soil samples. If the content of fines (< 0.075 mm) is less than 35% then this test may not be required. The moisture content is an important soil property which is related to the soil shear strength, compressibility, and other engineering properties.

3.2.5 Unit Weight Determination

This test is performed in accordance with procedures outlined in AASHTO T 233 (2022). This test is intended to determine the density of natural or compacted soil by measuring the weight and volume of undisturbed samples.

3.2.6 Specific Gravity Test

The specific gravity of the solids G_s is the ratio of the unit weight γ_s of the solids to the unit weight γ_w of water. This test is performed in accordance with AASHTO T 100 (2022) and provides useful relationships between void ratio, degree of saturation, and water content. For most soils the value of G_s is of the order of 2.6–2.7.

3.2.7 Constant Head and Falling Head Hydraulic Conductivity Test

This test is performed in accordance with AASHTO T 215 (2022) to obtain the hydraulic conductivity *K*, defined as the ratio of the specific discharge to the hydraulic gradient. The test is performed on an undisturbed sample and is used to determine the drainage properties of the soil. The constant head permeability test is used to determine the permeability of water through granular (cohesionless) soils in a steady-state condition. The test is recommended for soils with $K > 1 \times 10^{-3}$ cm/sec. The falling head permeability test is used to determine the permeability of fine-grained soils with intermediate and low permeability such as silts and clays. A temperature correction may need to be incorporated into the calculations as the hydraulic conductivity obtained through this standard, for which the standard temperature is 68°F.

3.2.8 Standard Proctor Test

The standard proctor test is performed in accordance with AASHTO T 99 (2022). This test is used to determine the optimum moisture content (OMC) and maximum dry density ($\gamma_{d,max}$) of a soil. It provides the curve for standard moisture density relations. A minimum of 4 points with at least 2 on each side of the curve are required. These values of OMC and $\gamma_{d,max}$ obtained from the test are used as a guideline to set the compaction standards in the field.

3.2.9 Modified Proctor Test

The test is similar to the standard proctor test and is performed in accordance with AASHTO T 180 (2020). The main difference between the two tests is the amount of compaction effort: it is higher for the modified proctor test because of the use of a heavier hammer with an increased drop height. A direct consequence of this increased compaction effort is the greater compaction energy, which results in higher unit weights at a lower moisture content. When specifying compaction standards, there is a need to clearly indicate whether the standard or the modified proctor test was used to obtain the maximum dry density values.

3.2.10 One-Dimensional Consolidation Test

The one-dimensional consolidation (or oedometer test) is performed in accordance with AASHTO T 216 (2007). Consolidation is defined as a process in which water is slowly forced out of the soil under the application of external loads, leading to a reduction in the void ratio of the soil. The test is called one-dimensional because, during the test, the soil sample is restrained laterally by a metal ring, and pressure increments are applied axially. The rate of consolidation is indicative of soil compressibility and hydraulic conductivity. Another factor evaluated by the consolidation test is the amount of swelling or rebound that can occur when the load is removed. This test provides important parameters that are used in the estimation of settlements of foundations and embankments.

3.2.11 Triaxial Test

A triaxial test is used to determine the shear strength parameters of a soil. There are three types of triaxial tests according to the possibility of drainage during the consolidation or shearing stages of the test: unconsolidated undrained (UU), consolidated undrained (CU), and consolidated drained (CD). These tests are performed in accordance with AASHTO T 296 (2010), AASHTO T 297 (1994), and ASTM D 7181 (2020), respectively. The test is performed in two stages. The first stage is the consolidation stage (although the soil may or may not undergo volume change, depending on whether water is allowed to drain from or come into the sample); the second is the shearing stage. Tests in which drainage is allowed during the consolidation stage are referred to as consolidated or C tests; when drainage is prevented, they are known as unconsolidated or U tests. Tests in which drainage is allowed during the shearing stage are known as drained (D); otherwise, tests are referred to as undrained (U). The undrained shear strength s_u of clay determined from the UU test results is commonly used in foundation design, earth pressure calculations, and embankment stability analysis. In CU test, total stresses and pore-water pressures are typically measured, allowing the calculation of effective stresses through the shearing stage of the test. Axial deformation is also measured. The loading path in a triaxial test can be further categorized as TXC (triaxial compression) or TXE (triaxial extension). In a TXC test, the sample is compressed axially while the radial pressure is kept constant. In contrast, in a TXE test, the sample is pulled or extended axially while the radial pressure is kept constant.

3.2.12 Direct Shear Test

This test is performed in accordance with AASHTO T 236 (2008). The test consists of determining the consolidated drained shear strength parameters of soil using a shear box by measuring the shear stress required to shear the sample along the horizontal plane separating the upper and lower halves of the box. The test can be performed on undisturbed or remolded soil samples. This test is used to obtain information about the shear resistance of soils to calculate the soil's bearing capacity, slope stability, lateral earth pressures on retaining structures, or to perform pavement designs.

3.2.13 Ring Shear Test

The test is performed in accordance with ASTM D 6467 (2022a). Ring shear tests are the recommended method for developing the baseline values for drained residual strength because of the ability of the ring shear device to apply large shear displacements without any reversal in the direction of shear. This allows for complete particle orientation along the shearing plane, and a more accurate measurement of the drained residual strength than would be achieved in traditional direct shear or triaxial tests. Generally, three or more normal stresses are applied to a test specimen to determine the drained residual failure envelope.

3.2.14 Unconfined Compressive Strength Test

This test is performed in accordance with AASHTO T 208 (2015) and is used to determine the unconfined compressive strength of clayey ("cohesive") soils in undisturbed, remolded, or compacted states. The sample is loaded, at a constant rate, to the load at which it fails, or the load corresponds to 15% strain, whichever occurs first. This test method provides an approximate value of the strength of cohesive soils in terms of total stresses. The shear strength of a clayey sample is given by half of the unconfined compressive strength measured.

3.2.15 Uniaxial Compression Test of Rock

This test is performed in accordance with ASTM D 7012 (2023), Method C, and is used to determine the uniaxial compressive strength of a rock specimen. The results of test are also used to estimate both the elastic modulus and the Poisson's ratio of an intact rock core.

3.2.16 Point Load Strength Index of Rocks

The test is performed in accordance with ASTM D 5731 (2016). Point load testing is used to determine rock strength indexes to classify the rock strength. It is used to estimate the unconfined compressive strength of rock using index-to-strength conversion factors. The strength index I_S of a rock is also used to assess the degradation potential of shale.

3.2.17 Resilient Modulus

The resilient modulus (MR) of subgrade soil is determined in accordance with AASHTO T 307 (1999). The resilient modulus is a measure of the stiffness of the soil and is an important parameter in the pavement design procedure to predict undesirable pavement behaviors such as cracking and rutting. The test can be performed either on remolded soils from the embankment fill or on Shelby tube samples from the subgrade soil.

3.2.18 pH Test

The test is performed in accordance with AASHTO T 289 (1991) and on soil samples prepared in accordance with AASHTO T 87 (2004). The pH test measures soil acidity or alkalinity and is commonly used to supplement soil resistivity measurements in corrosion testing. The prepared soil samples are mixed with distilled water to create a soil-water suspension, which is then stirred and allowed to settle for a period. After the settling period, a pH meter is used to measure the pH of the soil-water suspension.

3.2.19 Loss on Ignition Test

This test is performed in accordance with AASHTO T 267 (1986). This method determines the quantitative oxidation of organic matter in soils and gives a valid estimate of organic content. Soils with high organic content such as peat and those containing relatively undecayed or undecomposed vegetative matter or fresh plant materials have low shear strength and high moisture content. They are also susceptible to settlement due to decomposition/decaying of the organic matter over time.

3.2.20 Expansive Index of Soils

The test is done in accordance with ASTM D 4829 (2021) and allows for determination of expansion potential of soils when inundated with distilled water. The method measures the expansion index (EI) of the soil, which provides an indication of its swelling potential. The EI value is used by engineers and other professional to determine the suitability of soil for construction projects. It is used to determine design requirements for foundations, site selection, and material selection to mitigate the potential for damage to structures caused by soil movement.

3.2.21 Corrosion or Electrochemical Classification Tests

Corrosivity testing is used to help predict the likelihood of corrosion or degradation of a material (metal or concrete) in contact with ground. INDOT Standard Specifications (INDOT, 2022) require that the structural backfill also be tested for corrosion potential. Different parameters that define the corrosion potential of the soil are pH values (AASHTO T 289, 1991), organic content (AASHTO T 267, 1986), resistivity values (AASHTO T 288, 2012), *Su* (%) (AASHTO T 290, 1995), and *Cl* (%) (AASHTO T 291, 1994). The corrosion potential of a soil is critical in assessing the design life of an underground structure and is useful in decisions as to whether any coating or cathodic protection measure is required.

3.2.22 Slake Durability Test

The test is performed in accordance with ASTM D 4644 (2016). The main purpose of the test is to evaluate the weathering resistance of shales and other weak rocks. The test method is used to estimate qualitatively the durability of weak rocks through weakening and disintegration resulting from a standard two cycles of wetting and drying. A quantitative durability index I_d value is then assigned to the tested rock.

3.2.23 Jar Slake Test

This test is performed in accordance with ITM 511 (INDOT, 2013). It is used to determine the reaction of weak rock material to water during a certain time period. A quantitative jar slake index I_j value is then assigned to the tested rock. The index I_j has implications on the porosity, grains, interactions, and density of the weak rock.

3.3 Verification Tests

The verification tests performed by INDOT to comply with their quality control procedures relevant to different geotechnical applications are discussed below.

3.3.1 Static Pile Load Test (SPLT)

The test is performed in accordance with ASTM D 1143 (1994). Static load tests are performed during the test phase of each contract to verify the design assumptions and the load carrying capacity of piles. During the test, a static load is applied on the test pile using a hydraulic jack and measured using a load cell. A reaction frame sufficient to take the pile load test to the desired load or settlements must be designed. Loads are applied in increments and each increment is held for a predetermined time interval. The pile response to the applied load is measured throughout the test to determine the pile capacity and ultimate failure load.

3.3.2 Static Pile Lateral Load Test

This test is performed in accordance with ASTM D 3966 (2022). This test measures the lateral deflection of an individual pile or group of piles when subjected to static lateral loading. The test results provide a relationship between the static lateral load applied to a deep foundation and the resulting lateral movement. The results could be useful to assess the distribution of lateral resistance along the element and the long-term load-deflection behavior. The test results could be analyzed to evaluate pile-soil interaction properties such as coefficient of horizontal subgrade reaction to estimate bending stresses and flexural stiffness.

3.3.3 Dynamic Pile Load Test (DPLT)

This test is performed in accordance with ASTM D 4945 (2017). Sensors (strain gauges and accelerometers) are attached directly to the pile. Readings from these sensors allow measurement of velocity and stress due to each hammer blow, from which shaft resistance and base resistance can calculated using suitable relationships for energy dissipation along the pile-soil interface. The test also allows evaluation of the shape and integrity of the foundation element.

3.3.4 Pile Integrity Test

The pile integrity test is performed in accordance with ASTM D 5882 (2016). This non-destructive, low-strain pile testing method is used for the assessment of the integrity of piles and reveals potential pile defects, such as major cracks, necking, soil inclusions or voids. In this test the velocity induced on the pile by an impact device is measured. The impact device is usually applied axially and perpendicularly to the pile head surface. During the test, the accelerometer attached to the test pile measures a plot of acceleration versus time that can be integrated to produce a plot of velocity versus time. This plot reveals any significant changes in cross-section that may exist along the pile shaft. If major defects exist, test results may be interpreted to estimate their magnitude and location. The test results help determine pile integrity and continuity; consistency of pile materials and pile cross-sectional area; and length.

3.3.5 Proof Rolling

Proof rolling is performed in accordance with INDOT Standard Specifications 2022, Section 203.26 (INDOT, 2022b). The test results are used to check the subgrade compaction and to locate soft areas. The deformation of subgrade is measured during the test by driving a dump truck weighing at least 15 tons at a maximum speed of 2 mph over designated areas of the soil surface. Proof rolling has the potential to reveal issues with subgrade drainage. There is no ASTM standard for this procedure.

3.3.6 Light Weight Deflectometer (LWD)

The LWD test described above under the field tests is also used by INDOT as a verification test.

3.3.7 Falling Weight Deflectometer (FWD)

The FWD test described above under the field tests is also used by INDOT as a verification test.

3.3.8 Dynamic Cone Penetration Test (DCPT)

The DCPT test described above under the field tests is also used by INDOT as a verification test.

4. VARIABLES TO BE INCLUDED IN THE DATABASE AND METHODS OF INTERPRETATION

This section presents the geotechnical design parameters that are obtained as result of the site investigation through various field and laboratory tests. We discuss these variables below by providing their relationships with the engineering analysis of geotechnical applications discussed in Section 2 and provide a consolidated list of all the variables in Table 4.1.

TABLE 4.1
List of geotechnical variables to be included in the database

Symbol	Quantity represented
A	Cross-sectional area
A_b	Area of pile base
A_{si}	Pile shaft area interfacing with layer i
B	Foundation width/diameter
b	Width of MSE wall reinforcement
Cl (%)	Chloride content
C_α	Secondary compression index
C_C	Coefficient of curvature
C_c	Compression index
C_s	Swelling index
C_U	Coefficient of uniformity
c	Cohesive intercept
c_v	Coefficient of consolidation
D	Embedment depth
DD	Ultimate downdrag load
D_R	Relative density
D_{50}	Mean particle size
E	Young's modulus
EI	Expansive index
E_c	Strip thickness corrected for corrosion
E_d	Dynamic elastic modulus
E_M	Menard pressuremeter modulus
E	Load eccentricity
e_{max}	Maximum void ratio
e_{min}	Minimum void ratio
e_0	Initial void ratio
F^*	Pullout friction factor
FS	Factor of safety
f_s	Sleeve friction
f_y	Yield stress of steel
GWT	Groundwater table
NGWT	No groundwater table
G_s	Specific gravity
H	Height of retaining wall/ slope
I	Moment of inertia
IFR	Incremental filling ratio
I_c	Collapse potential
I_d	Slake durability index
I_e	Collapse index
I_j	Jar slake index
I_s	Point load strength index
K	Hydraulic conductivity
k	Coefficient of subgrade reaction
K_0	Coefficient of lateral earth pressure at-rest
L	Foundation length
LF	Load factor
LL	Liquid limit
LLR	Liquid limit ratio
L_d	Length of PVD
L_r	Length of reinforcement
MR	Resilient modulus
M_{yield}	Yield stress of pile material
N_{SPT}	SPT blow count
OC (%)	Organic content
OCR	Overconsolidation ratio
OMC	Optimum moisture content
PI	Plasticity index
PL	Plastic limit
p_c	Soil compressive resistance
p_L	Limit unit lateral resistance
p_s	Soil shear resistance
Q_{ann}	Annulus capacity
Q_{plug}	Soil plug capacity
q_b	Design bearing pressure
$q_{b,ult}$	Ultimate unit base resistance
q_c	Cone resistance
q_{sL}	Limit unit shaft resistance
q_u	Unconfined compressive strength
q_{ult}	Ultimate unit bearing capacity
q_w	Discharge capacity of PVD
q_0	Surcharge
RF	Resistance factor
RR	Recovery ratio
RMR	Rock mass rating
RQD	Rock quality designation
R_c	Coverage ratio
r_s	Radius of smear zone
Su (%)	Sulfate content
s_h	Horizontal spacing between reinforcement/ PVDs
s_u	Undrained shear strength
s_v	Vertical spacing between reinforcement/ PVDs
T	Time factor
T_{ult}	Ultimate tensile strength
t	Thickness of reinforcement
u	Pore water pressure
v_s	Shear wave velocity
wc (%)	Water content
w	Settlement
w_{tol}	Tolerable settlement
y	Lateral deflection
Z	Depth of the soil layer
β_i	Slope inclination with horizontal
δ	Interface friction angle
γ	Soil unit weight
$\gamma_{d,max}$	Maximum dry unit weight
γ_{fn}	Unit weight of foundation soil
γ_m	Moist unit weight of soil
γ_{rf}	Unit weight of reinforced fill
γ_{rt}	Unit weight of retained backfill
v	Poisson's ratio
ϕ_c	Critical-state friction angle
ϕ_{fn}	Friction angle of foundation soil
ϕ_r	Residual friction angle
$\phi_{r,min}$	Minimum residual friction angle
ϕ_{rf}	Friction angle of reinforced fill
ϕ_{rt}	Friction angle of retained backfill
σ'_v	Vertical effective stress

4.1 Shallow Foundation Design

The design of shallow foundations is done in accordance with LRFD Bridge Design Specifications as prescribed by AASHTO (2020), according to which the foundation geometry is proportioned such that the factored resistance is not less than the effects of the factored loads considered for serviceability and ultimate limit states. In the LRFD method, the foundation may be evaluated for a number of load combinations, including those for normal strength and extreme-event loading requirements. Ultimate limit states in foundation design include checks for bearing capacity failure, overturning of the footing, sliding of the footing base, and global (overall) stability of the structure and its parts. Serviceability limit states in foundation design relate to foundation settlement and rotation that are marginally intolerable.

Figure 4.1 shows in schematic form the engineering analysis and design required to prevent shallow foundations from attaining strength and serviceability limit states. The required geotechnical investigation is separated into field and laboratory tests that are performed to obtain the engineering properties and design variables that are required to perform the engineering analysis. The SPT is the most common field test. SPT results are used to design shallow foundations through correlations to shear strength and compressibility. Other field and verification tests that INDOT may perform while designing a shallow foundation are the CPT, pressuremeter test, vane shear test and plate load tests. In the case of shallow foundations bearing on rocks, the strength and consistency of the rock mass is verified by determining the rock quality designation RQD and recovery ratio RR. Index tests such as soil gradation, water content, Atterberg limits, and organic content may also be performed to obtain the input variables for some aspects of foundation design. In addition, these basic laboratory tests also serve as confirmatory tests to verify any classification of soils based on the field tests. Laboratory strength tests are conducted on undisturbed soil samples to assess the shear strength and compressibility parameters of the foundation soil.

4.2 Deep Foundation Design

Designing a deep foundation is a complex process that requires expertise in geotechnical engineering, structural engineering, and construction. It is done in accordance with the load and resistance factor design approach (LRFD) as prescribed in the LRFD Bridge Design Specifications, as prescribed by AASHTO (2020). Foundations must be able to sustain axial and lateral loads without suffering structural damage, failing in bearing capacity, or undergoing excessive settlements or deflections. Subsurface explorations are performed to provide the information needed for the design and construction of foundations. The extent of exploration is based on variability in the subsurface conditions, structure type, and any project requirements that may affect the foundation design or construction. The exploration program should be extensive enough to reveal the nature and types of soil deposits and/or rock formations encountered, the engineering properties of the soils and/or rocks, the potential for liquefaction, and the groundwater conditions. Common types of deep foundations include drilled shafts, driven piles, and micropiles. The capacity of the foundation to support the loads is determined by performing engineering calculations based on soil properties, pile type, and other factors. Individual foundation elements are designed based on load-carrying capacity calculations. Two general types of deep foundations are typically considered: drilled shaft foundations and pile foundations.

4.2.1 Drilled Shaft Foundations

For drilled shaft foundations, it is especially critical that the groundwater regime is well defined at each foundation location because of constructability issues. Drilled shaft foundations are designed against both service and strength limit states. Along the drilled shaft, unit shaft resistance (unit "skin friction") or downdrag loadings are calculated using suitable analyses. The load at the top and the base resistance (calculated using a suitable method of design), along with the pile top and base settlements, are also key variables. Additional database variables may be needed to describe constructability, scour, seepage, and potential for caving.

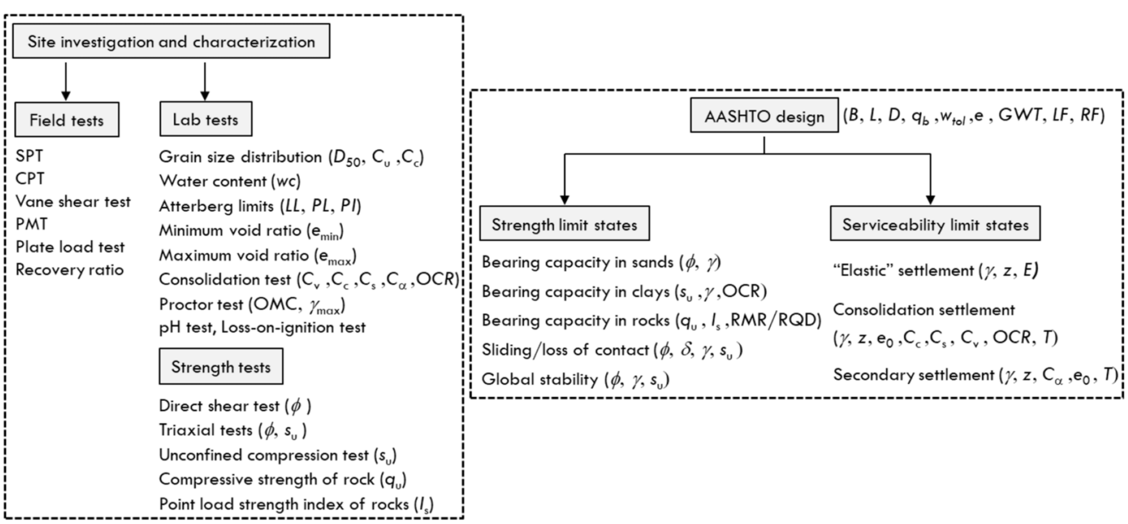


Figure 4.1 Variables required in the engineering analysis and design of shallow foundations and related geotechnical tests.

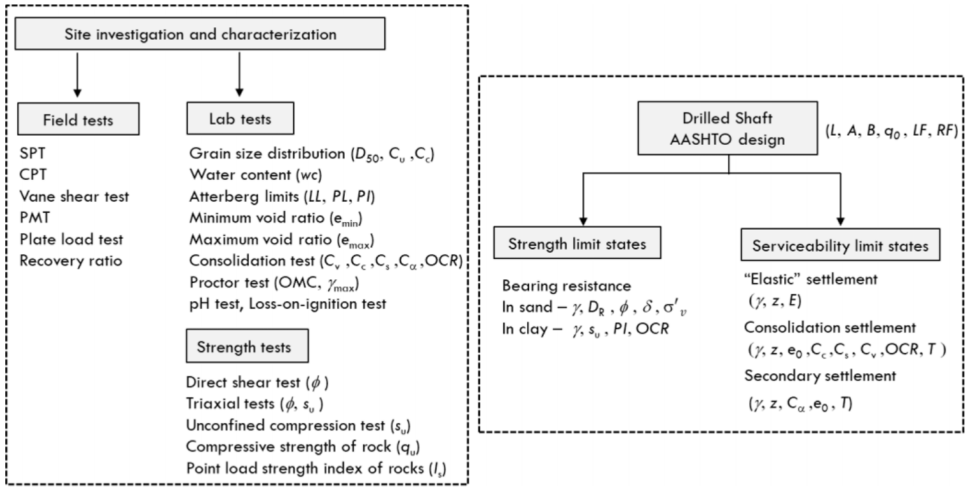


Figure 4.2 Variables required in the engineering analysis and design of drilled shaft foundation and related geotechnical tests performed for deep foundations.

Figure 4.2 describes the site investigation tests and lab tests performed by INDOT and the obtained soil variables and their use in engineering design. Foundation design relies upon the SPT and/or q_c results obtained during the field exploration and also on independent data obtained by visual descriptions of the soil/rock encountered, possibly laboratory tests and general knowledge of local geology.

4.2.2 Driven Pile Foundations

A pile derives its load-carrying capacity from the shear stress that develops along the pile shaft with the surrounding soil—known as the unit shaft resistance—and from the compressive resistance that develops at the contact of the pile base with the underlying soil. Driven piles may be open-ended or closed-ended. The performance of open-ended driven pile foundation depends on the plugging response during pile driving.

Figure 4.3a and Figure 4.3b discuss variables required for limit state design of open-ended and closed-ended steel pipe piles. Engineering analysis of pile foundation is a crucial step in ensuring the stability and safety of the structure. It is necessary to ensure that the foundation does not reach its limit states—serviceability limit states (SLS) and ultimate limit states (ULS). SLS includes excessive deformation or settlement that affects the performance of the structure, and an ULS is reached when a pile foundation is no longer able to support the load of the structure due to bearing capacity failure or excessive settlement. Engineering analyses are performed to evaluate bearing capacity and settlement for pile foundation. It is also essential to consider the effects of downdrag (DD) and scour when designing piles to ensure their stability and safety over time. Downdrag load is the load applied on the pile by soil consolidating around it. Scour, on the other hand, refers to the erosion of soil around the pile due to water flow, which can cause the pile to become unstable. Laterally loaded piles are usually analyzed using the p-y method. In this method, the horizontal soil resistance along the piles is modeled using suitable p-y curves, as shown in Figure 4.3c.

4.3 Retaining Wall Design

The design of retaining walls is done in accordance with AASHTO LRFD Bridge Design Specifications as prescribed by AASHTO (2020). In Figure 4.4 the design of MSE walls is shown as an example for retaining walls as they are designed as any conventional retaining wall but have some additional design considerations to meet the internal stability requirements. Furthermore, in current design practice, MSE walls are an important component of transportation infrastructure that can serve not only as a retaining structure but also as bridge abutments and wing walls. The main components of MSE wall are the retained backfill, reinforced fill, reinforcing elements (e.g., steel strips, steel grids, or planar geosynthetics), wall facing (e.g., precast concrete panels, modular blocks, and welded wire mesh) and foundation soil. MSE walls are designed for external stability (bearing capacity failure, overturning, sliding, and global stability) of the wall as well as internal stability (reinforcement rupture, reinforcement pullout, and reinforcement-facing connection strength) of the reinforced soil mass behind the facing.

Figure 4.4 shows the details of the engineering analysis required in the design of MSE walls. The variables required to perform the design checks are linked with the geotechnical tests from which they are obtained. A thorough classification of the foundation soil, retained soil, and reinforced soil is required as engineering properties of each of these soils to perform various design checks. Considering that INDOT typically uses metallic strips as reinforcement, soil corrosiveness is also analyzed thorough different physiochemical parameters. The values obtained from these

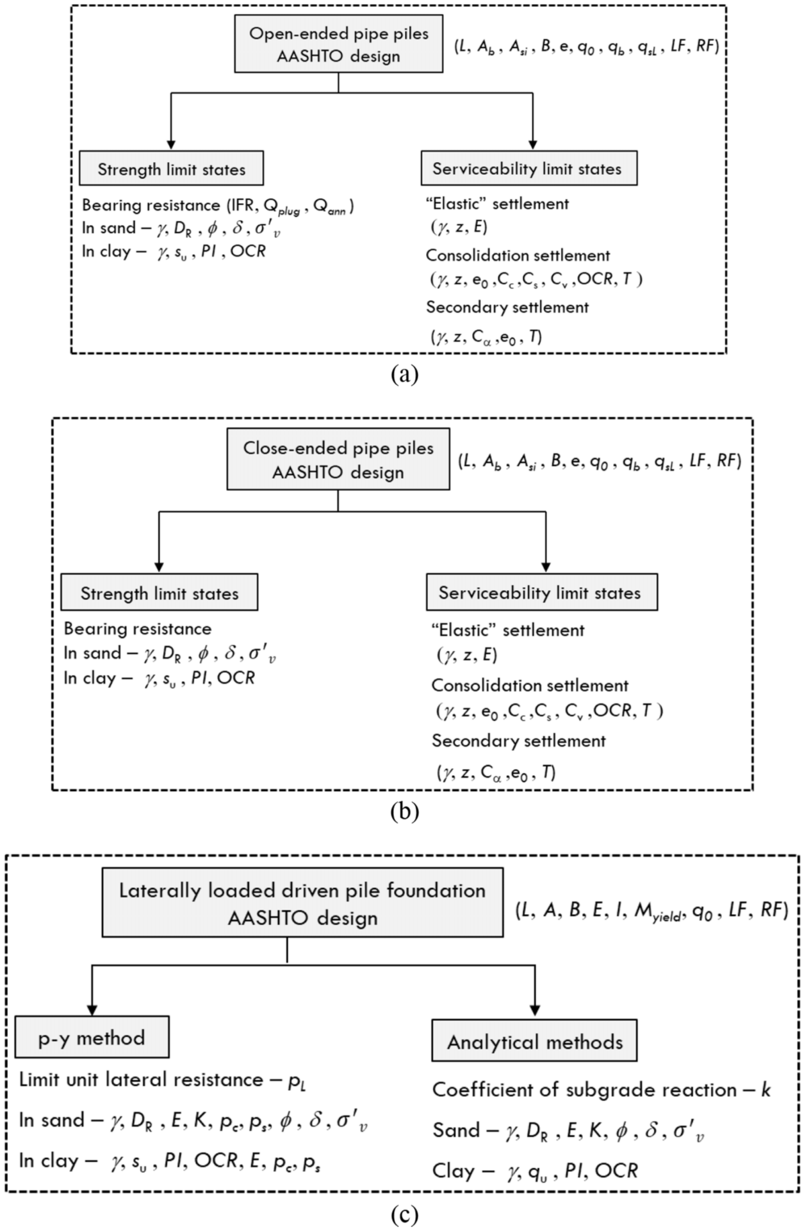


Figure 4.3 Variables required in the engineering analysis of (a) open-ended pipe pile foundation design under axial loads, (b) closed-ended pipe pile foundation design under axial loads, and (c) pile foundation design under lateral loads.

tests are needed to take preventive measure against long-term corrosion and degradation of the reinforcement being exposed to corrosive and contaminated environment.

4.4 Slope Stability

Detailed assessment of soil and rock stratigraphy is critical to the proper assessment of slope stability. The site investigation and laboratory tests carried out for slope stability analysis are listed in Figure 4.5. The key *in situ* tests often used in analysis are the standard penetration test, cone penetration test, and vane shear test. The groundwater regime beneath the slope will also be determined through piezometric data at multiple locations and depths. Selection of soil shear strength parameters used as input to the analysis will vary depending on whether short-term or long-term stability analysis must be performed. For short-term analysis, undrained shear strength parameters are required; for long-term stability analysis, drained shear strength parameters are required.

Slope stability is mostly performed using limit equilibrium methods—modified Bishop, simplified Janbu, or Spencer method being the most common. The factor of safety calculation resulting from the analysis requires that the slope geometry be completely defined, and the soils in the slope adequately characterized. Figure 4.5 shows the field and laboratory tests performed to obtain the soil parameters used in

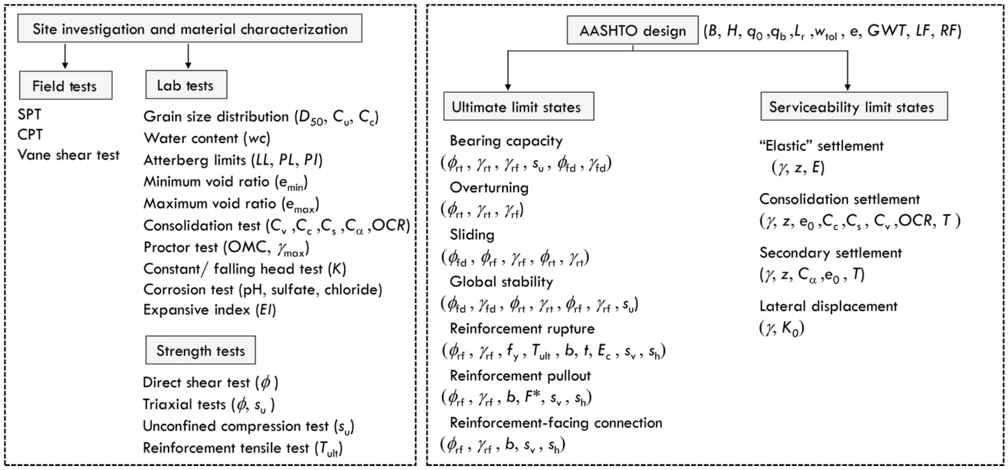


Figure 4.4 Variables required in the engineering analysis of MSE wall design and related geotechnical tests.

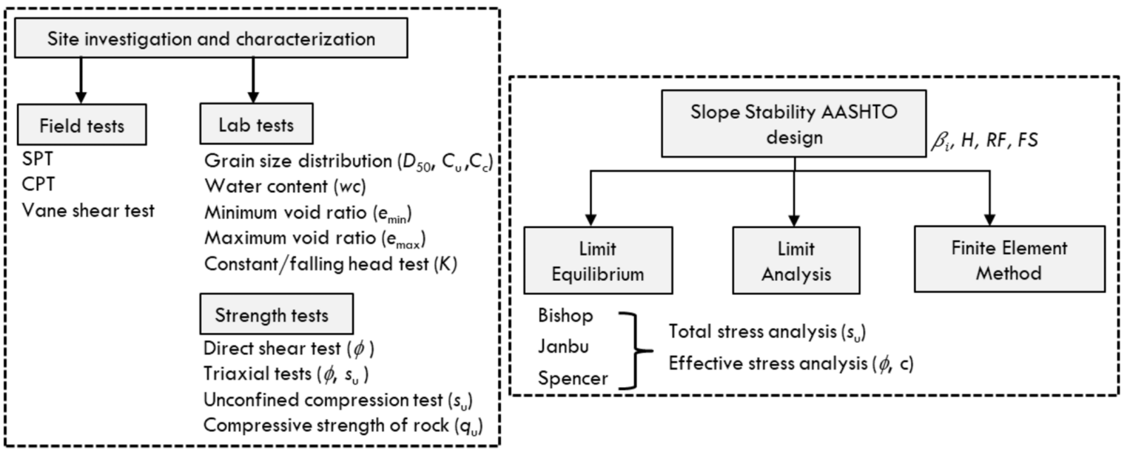


Figure 4.5 Variables required to perform slope stability analysis and related geotechnical tests.

slope stability analysis calculations. The resistance factors and load factors are required to perform the design check specified in LRFD Bridge Design Specifications AASHTO (2020). Slope stability checks may also be done using the finite element method or other more sophisticated methods.

4.5 Ground Improvement

One of the major tasks a geotechnical engineer may have to undertake is to design, evaluate, and implement ground modification schemes for infrastructure projects. Before the start of any construction project, the properties of the soil on site are evaluated to check its suitability for construction. Ground improvement is necessary when poor soil conditions are encountered. Ground improvement is carried out for various objectives, including improving bearing capacity, reducing settlement of soft ground, preventing soil liquefaction, controlling groundwater flow, stabilizing excavations, preventing deformation of surrounding ground, or mitigating erodibility. There are many different ground improvement systems adaptable to a wide array of site conditions, soils, and structure types. In general terms, there are three typical modes of soil improvement: densification, reinforcement, and drainage enhancement. The selection of methods is based on site conditions, improvement objectives, equipment availability, cost, construction period, skills, and past experiences.

Depending on the ground improvement method adopted, there are certain variables that are directly associated with the method. In Figure 4.6, as an example, we show three methods for ground improvement. When wick drains (PVDs) are used as a ground improvement method in a project, variables of interest associated are size, shape, and length of the PVDs, the vertical and horizontal spacing between the PVDs, vertical and horizontal drainage, and the total discharge rate of the PVDs. These details should be included in the database. In addition, pertinent details such as information regarding the smear zones, well resistance, and splicing may also be included in the database.

4.6 Pavement Works

Pavement works include subgrade modification and stabilization to improve the strength and stability of the

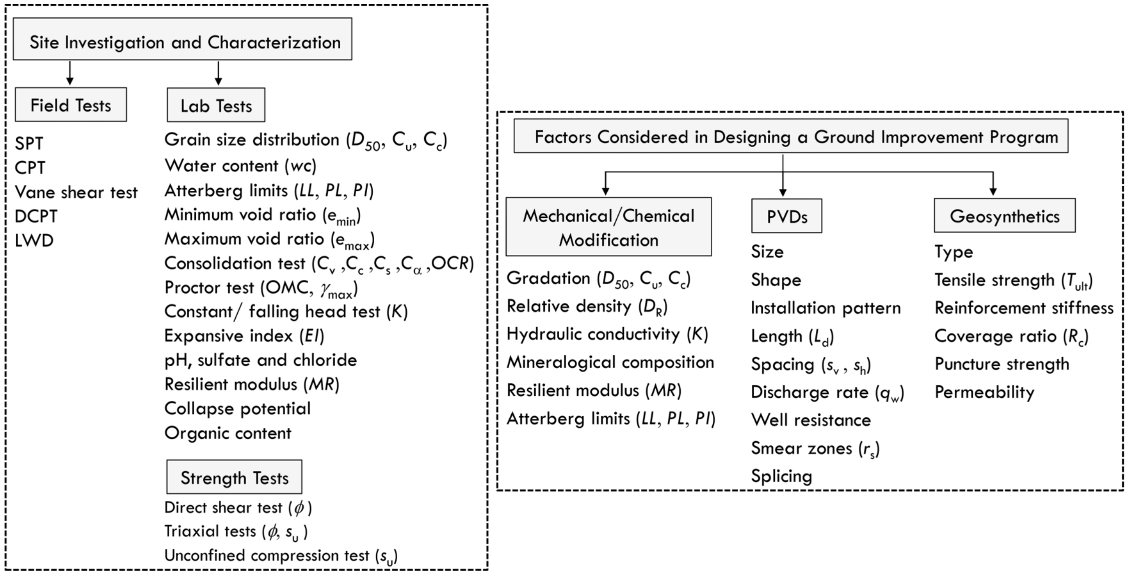


Figure 4.6 Geotechnical tests required to establish the need for ground improvement and variables related to different ground improvement techniques.

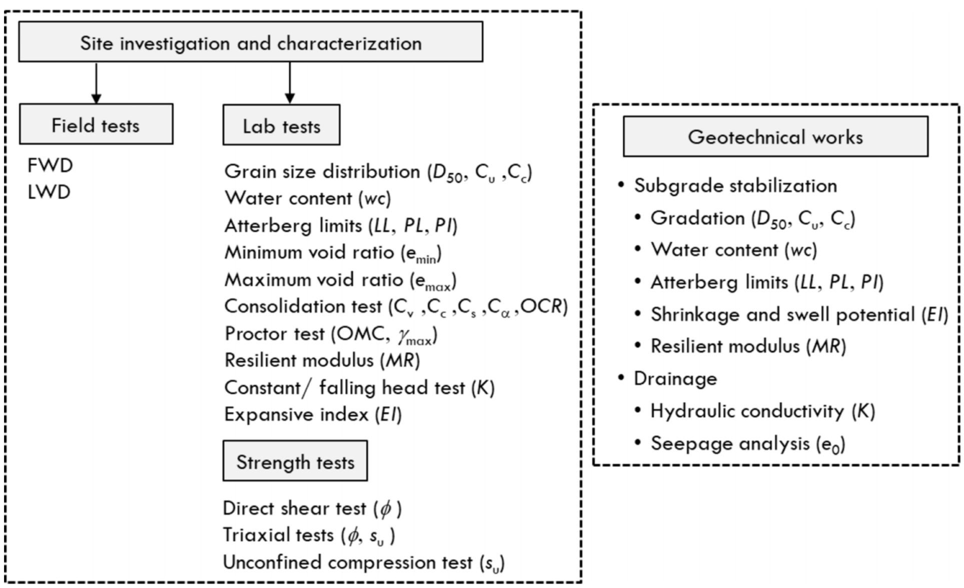


Figure 4.7 Variables required in the pavement design and related geotechnical tests.

subgrade to improve performance and longevity of the pavement structure. Proper characterization and evaluation of the subgrade soil is crucial to ensure the overall stability and durability of pavement structures. The properties of the subgrade soil are also used as input parameters for other pavement layers. The site investigation and laboratory tests carried out by INDOT for the same are listed in Figure 4.7. The FWD and the LWD are the important *in situ* tests. The resilient modulus measures the stiffness of the subgrade and is an important parameter used in the design of pavement structures. Other important lab tests to obtain pavement design input parameters include strength tests, consolidation test to assess the compressibility parameters of soil, hydraulic conductivity, Atterberg limits, minimum and maximum void ratio.

5. PROPOSED DATABASE STRUCTURE AND EXAMPLE

5.1 Database Structure

Figure 5.1 shows the proposed database structure, designed following the object-oriented paradigm. It will be a user-friendly web-based GIS application helpful for engineers using the database. The purpose of the database is to organize the data in a structured manner for easy retrieval of information associated with any design step of any INDOT project. This would allow

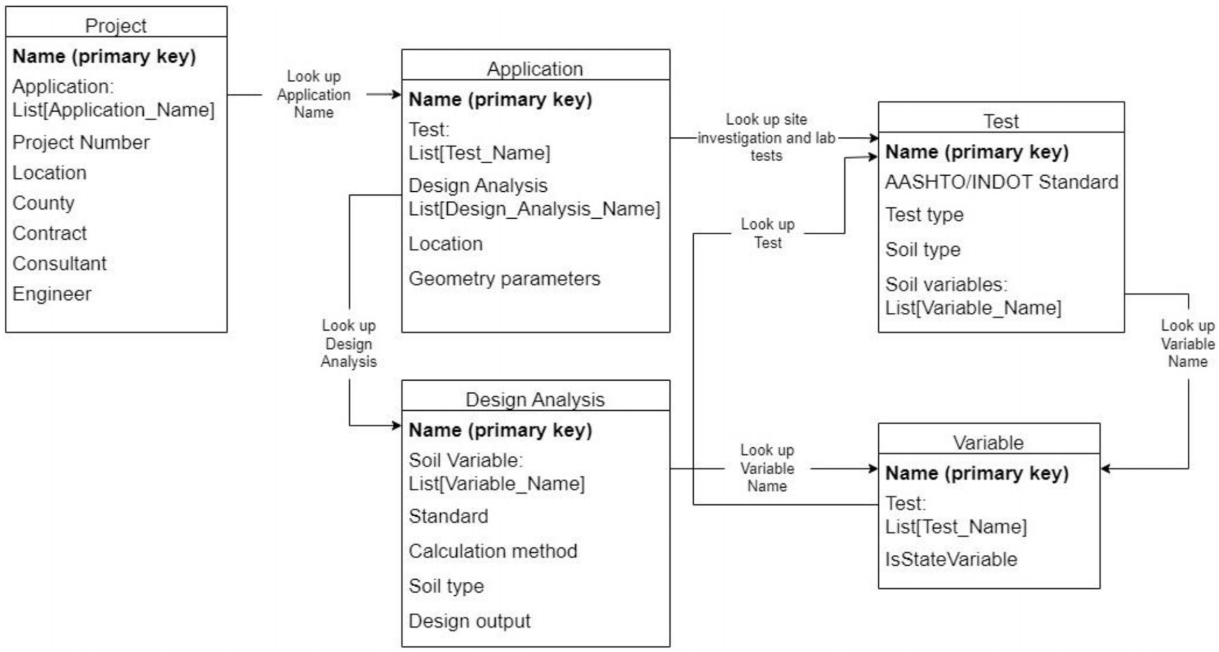


Figure 5.1 Proposed structure of the object-oriented relational database.

for remote access without operating robust GIS software. It is a fully integrated relational database. The database is organized in the form of tables and associated relations between them. Each table in the database corresponds to a separate class and the different entries in the table will be the various objects of the respective class. For example, the applications table is responsible for storing the *Application* class. The fields of the table are the class attributes, and each row of the table is a separate *Application* object. Each table also has a primary key that uniquely identifies an object of that table. This primary key is used to establish relations between tables. For example, the design analysis field in *Application* table holds the list of design checks to be performed. These names can be directly used to query the detailed description in the *Design Analysis* table.

We identified the basic building blocks for identifying the geotechnical applications design in a project as follows: *Project*, *Application*, *Test*, *Variable*, and *Design Analysis*. The *Project* table has fields for project description (project name, number, location, county, contract, consultant, engineer) and the associated applications based on the project scope. The applications field in the project table acts as a foreign key into the *Application* table.

The *Application* table has fields for its description (name, location, geometry), the design analysis to be performed, and the tests required (gives details about site investigation and laboratory tests performed for an application). The test field in the application table acts as a foreign key into the *Test* table and the design analysis field acts as a foreign key into the *Design Analysis* table.

The *Test* table has fields describing a geotechnical test such as test name, test type, test standard and output soil type, and soil variables from the test. The variable field in the *Test* table can be used to query its detailed description from the *Variable* table. This table stores the information related to the soil variables and has corresponding fields—name, identification if it is a state variable or profile variable, and relevant tests. The test field in the *Variable* table also acts as a foreign key into the *Test* table. The variables required would vary depending on the analysis being performed. The soil profile variables would be, for example, ground surface elevation, depth to water table, depth to bedrock, number of soil layers, layer thickness and soil type for each layer. The soil state variables would store the soil properties like void ratio, relative density, unit weight, and hydraulic conductivity. Variables are direct input for design analysis to be performed for any given application.

The *Design Analysis* table has fields describing a design method. These include, for example, name, AASHTO/INDOT standard it follows, soil type it is applicable for, and the soil variables required to perform the analysis. The soil variable field in the design analysis table acts as a foreign key into the *Variable* table to find the description and tests performed to obtain the required soil variable for an engineering analysis. There are complex relationships existing between all the classes but defined rigorously in a logical manner.

One of the ways in which the database will be useful will be when the user is looking for specific type of data in a certain area. This database design will enable the users to make complex queries on the design of geotechnical applications corresponding to a project. See the following examples.

- "Get all variables required for design of shallow foundation for project number 123."
- "Get all variables required for axial load capacity analysis for pile foundations that can be obtained by performing site investigation tests."
- "Get all tests needed to perform settlement checks for deep foundations."

Note that the above queries can give deterministic answers for even incomplete queries by the user. For example, query 1 above did not identify a specific design analysis, and query 3 did not have specified soil variables. We believe this database design will be useful in answering most of the queries made by geotechnical engineers and optimize their time and improve the storage and handling of large amounts of data corresponding to design of various geotechnical applications. The database will reduce the need for performing investigations if the data already exists.

We have conceptualized the database to include different types of geotechnical applications, the corresponding field and laboratory tests that need to be performed along with the applicable variables, and which interpretation method(s) will be used. The database will comprise several classes linked together in a logical manner to input, store or extract information from the database. And hence could allow storing and organizing this information in an efficient way for the later use. That use can consist of planning or designing new structures, or revisiting a completed project to view what was done.

5.2 User Workflow Example

Figure 5.2 shows an example of the proposed user workflow for the database. The selected example is a shallow foundation bearing capacity analysis in which a strip footing is designed for an interior bridge pier. The example corresponds to a completed INDOT project. Figure 5.3 shows the factored resistances obtained using the calculation methods proposed by Terzaghi (1943), Meyerhof (1963), and Vesic (1973), precisely as reported in the geotechnical report of the project. Additional information such as project description, soil properties, footing geometry, and applicable resistance factor is also included in the figure.

Figure 5.2 illustrates how the information from a geotechnical report of a project is organized in different classes or tables according to the proposed database structure. The *Project* table stores project details such as the project name, number, location, and county. The name of the consultant and the engineer responsible for the project are also entered in the same class along with all the geotechnical applications that are part of the project. The applications field in the *Project* table acts as a foreign key into the *Application* table. In Figure 5.2, we present workflow for one of the specific applications of the project i.e., shallow foundation design for an interior pier. The *Application* table has fields that contain information regarding footing elevation, GIS coordinates, borehole information, and footing geometry parameters (footing shape, width, length, and footing embedment depth). The test and design analysis fields in *Application* table act as a foreign key into the *Test* and *Design Analysis* table. The information

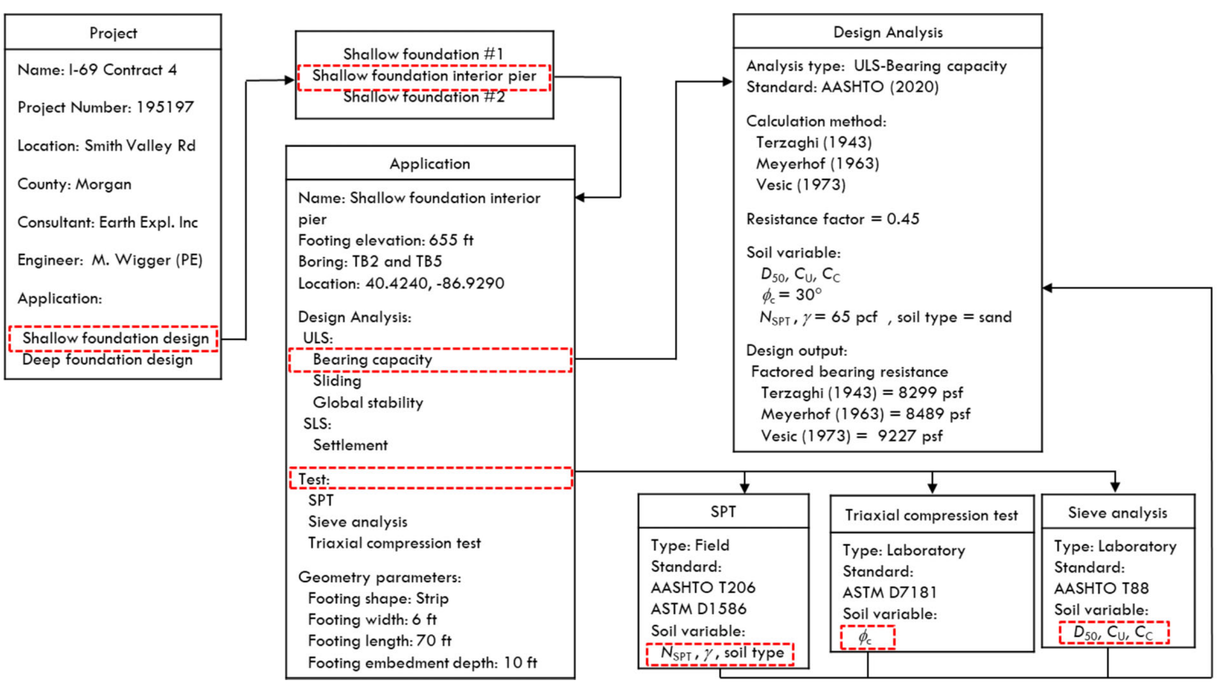


Figure 5.2 User workflow example for bearing capacity analysis of a shallow foundation.

BEARING RESISTANCE ANALYSIS

File No.: CJ195197 Date: 12/16/19
Project Name: Smith Valley Road over I-69
Johnson County

Comments: Shallow Foundation Analysis
Interior Pier
Boring Nos.: TB-2, TB-5
Bearing Soil: Gravelly Sand
Footing Elev.: 655

Soil Data: Input below

c = 0 psf
ϕ = 30 degrees
γ_t = 65 pcf

Footing Dimensions		Footing Type		Resistance Factor
Length (L) =	70	1		0.45
Depth (D) =	10		strip = 1, square = 2, round = 3	
Width (B) =	6			

Bearing Capacity Method	Nominal Resistance			Factored Resistance		
Terzaghi (1943)	q_n =	18,443	psf	q_R =	8,299	psf
Meyerhof (1963)	q_n =	18,865	psf	q_R =	8,489	psf
Vesic (1973)	q_n =	20,505	psf	q_R =	9,227	psf
				Average	8,672	psf
				USE	8,500 psf	

Figure 5.3 Bearing capacity analysis of strip footing (extracted from the geotechnical report of the project: Smith Valley Road over I-69).

regarding the field and laboratory tests performed during the project and the geotechnical variables obtained from the tests are stored in *Test* table. The soil variables obtained from the geotechnical tests are used as input to perform the required design analysis. The *Design Analysis* table has fields describing the standard and calculation methods used to perform the engineering analysis and the output obtained from the design analysis. The proposed database structure is designed to separately store the information regarding the design checks for ultimate limit states and serviceability limit states.

In Figure 5.2, an ultimate bearing capacity analysis is performed to check the bearing capacity of a strip footing in sand using LRFD Bridge Design Specifications as prescribed by AASHTO (2020) with a resistance factor of 0.45. The required soil variables are also included in the design analysis table and are linked with the geotechnical tests from which they are obtained. Three different methods (Terzaghi (1943), Meyerhof (1963), and Vesic (1973)) are used to calculate the factored bearing resistance which is stored as the design output in the *Design Analysis table.*

As the information in the database is distributed into several classes that are linked in a logical manner, a database user can easily extract the required information by querying the database. In this form, the user can retrieve desired geotechnical data or use some criteria (county, applications, project ID, work type) to narrow down the search. Such an interface is useful when a user is just looking for a specific type of data available in a certain area. If a future project is planned in the vicinity of a previous project, the existing data stored in the database would be beneficial for the engineer in making any preliminary design decisions and planning a geotechnical investigation.

6. CONCLUSIONS AND RECOMMENDATIONS

The scope of the proposed geotechnical database was discussed in the context of the geotechnical applications, tests, and variables that will be included in the database. In addition, the proposed database structure and user workflow was presented. The proposed database structure is designed following the object-oriented paradigm. It is organized in a manner that enables the user to retrieve specific information related to a particular project in an efficient manner. The database classes include *project*, *application*, *test*, *variable*, and *design analysis*. The associated relations between the classes provide a clear understanding of the data flow. The primary objective of the proposed database is to reduce the need to perform geotechnical investigations when the data already exists. If implemented, this approach will save time, resources, and improve the efficiency of INDOT geotechnical office operations. Moreover, the database can also serve as a tool for effective engineering analysis and decision-making. It can provide significant benefits to geotechnical engineers, geologists, and other professionals who deal with geotechnical data regularly. By providing a centralized location for storing and accessing data, the database can improve collaboration, consistency, and accuracy of geotechnical data, leading towards better design solutions.

While this project has provided the conceptual basis for the design of a geotechnical database system that would provide a user-friendly platform for storing and organizing valuable data, it is recommended that the INDOT geotechnical office consider the development of the database in steps, starting with higher-priority items. It is also recommended that, in the initial phase of the development/implementation process, only major geotechnical applications be included in the database; later, depending on user feedback, the database can be expanded and refined.

REFERENCES

AASHTO. (2020). *AASHTO LRFD bridge design specifications* (9th ed.). American Association of State Highway and Transportation Officials.

AASHTO T 100. (2022). *Standard method of test for specific gravity of soils*. American Association of State Highway and Transportation Officials.

AASHTO T 180. (2020). *Standard method of test for moisture–density relations of soils using a 4.54-kg (10-lb) rammer and a 457-mm (18-in.) drop*. American Association of State Highway and Transportation Officials.

AASHTO T 206. (2022). *Standard method of test for penetration test and split-barrel sampling of soils*. American Association of State Highway and Transportation Officials.

AASHTO T 208. (2015). *Standard method of test for unconfined compressive strength of cohesive soil*. American Association of State Highway and Transportation Officials.

AASHTO T 215. (2022). *Standard method of test for permeability of granular soils (constant head)*. American Association of State Highway and Transportation Officials.

AASHTO T 216. (2007). *Standard method of test for one-dimensional consolidation properties of soils*. American Association of State Highway and Transportation Officials.

AASHTO T 223. (1996). *Standard method of test for field vane shear test in cohesive soil*. American Association of State Highway and Transportation Officials.

AASHTO T 233. (2022). *Standard method of test for density of soil in-place by block, chunk, or core sampling*. American Association of State Highway and Transportation Officials.

AASHTO T 236. (2008). *Standard method of test for direct shear test of soils under consolidated drained conditions*. American Association of State Highway and Transportation Officials.

AASHTO T 265. (2015). *Standard method of test for laboratory determination of moisture content of soils*. American Association of State Highway and Transportation Officials.

AASHTO T 267. (1986). *Standard method of test for determination of organic content in soils by loss on ignition*. American Association of State Highway and Transportation Officials.

AASHTO T 288. (2012). *Standard method of test for determining minimum laboratory soil resistivity*. American Association of State Highway and Transportation Officials.

AASHTO T 289. (1991). *Standard method of test for determining pH of soil for use in corrosion testing*. American Association of State Highway and Transportation Officials.

AASHTO T 290. (1995). *Standard method of test for determining water-soluble sulfate ion content in soil*. American Association of State Highway and Transportation Officials.

AASHTO T 291. (1994). *Standard method of test for determining water-soluble chloride ion content in soil*. American Association of State Highway and Transportation Officials.

AASHTO T 296. (2010). *Standard method of test for unconsolidated, undrained compressive strength of cohesive soils in triaxial compression*. American Association of State Highway and Transportation Officials.

AASHTO T 297. (1994). *Standard method of test for consolidated, undrained triaxial compression test on cohesive soils*. American Association of State Highway and Transportation Officials.

AASHTO T 307. (1999). *Standard method of test for determining the resilient modulus of soils and aggregate materials*. American Association of State Highway and Transportation Officials.

AASHTO T 87. (2004). *Standard method of test for dry preparation of disturbed soil and soil aggregate samples for test*. American Association of State Highway and Transportation Officials.

AASHTO T 88. (2020). *Standard method of test for particle size analysis of soils*. American Association of State Highway and Transportation Officials.

AASHTO T 89. (2022). *Standard method of test for determining the liquid limit of soils*. American Association of State Highway and Transportation Officials.

AASHTO T 90. (2020). *Standard method of test for determining the plastic limit and plasticity index of soils*. American Association of State Highway and Transportation Officials.

AASHTO T 99. (2022). *Standard method of test for moisture–density relations of soils using a 2.5-kg (5.5-lb) rammer and a 305-mm (12-in.) Drop*. American Association of State Highway and Transportation Officials.

ASTM D 1143. (1994). *Standard test method for piles under static axial compressive load*. ASTM International.

ASTM D 1194. (2003). *Standard test method for bearing capacity of soil for static load and spread footings*. ASTM International.

ASTM D 1586. (2022). *Standard test method for standard penetration test (SPT) and split-barrel sampling of soils*. ASTM International.

ASTM D 2573. (2018). *Standard test method for field vane shear test in saturated fine-grained soils*. ASTM International.

ASTM D 3966. (2022). *Standard test methods for deep foundation elements under static lateral load*. ASTM International.

ASTM D 4644. (2016). *Standard test method for slake durability of shales and other similar weak rocks*. ASTM International.

ASTM D 4694. (2020). *Standard test method for deflections with a falling-weight-type impulse load device*. ASTM International.

ASTM D 4719. (2020). *Standard test method for prebored pressuremeter testing in soils*. ASTM International.

ASTM D 4829. (2021). *Standard test method for expansion index of soils*. ASTM International.

ASTM D 4945. (2017). *Standard test method for high-strain dynamic testing of deep foundations*. ASTM International.

ASTM D 5731. (2016). *Standard test method for determination of the point load strength index of rock and application to rock strength classifications*. ASTM International.

ASTM D 5778. (2020). *Standard test method for electronic friction cone and piezocone penetration testing of soils*. ASTM International.

ASTM D 5882. (2016). *Standard test method for low strain impact integrity testing of deep foundations*. ASTM International.

ASTM D 6467. (2022). *Standard test method for torsional ring shear test to determine drained residual shear strength of cohesive soils*. ASTM International.

ASTM D 6635. (2001). *Standard test method for performing the flat plate dilatometer*. ASTM International.

ASTM D 7012. (2023). *Standard test methods for compressive strength and elastic moduli of intact rock core specimens under varying states of stress and temperatures*. ASTM International.

ASTM D 7181. (2020). *Standard test method for consolidated drained triaxial compression test for soils*. ASTM International.

ASTM D 7400. (2019). *Standard test methods for downhole seismic testing*. ASTM International.

ASTM E 2583. (2020). *Standard test method for measuring deflections with a light weight deflectometer*. ASTM International.

ASTM WK 27337. (2010). *New test method for pocket penetrometer test*. ASTM International.

INDOT. (2013). *Jar slake test* (ITM No. 511-13). Indiana Department of Transportation, Division of Materials and Tests.

INDOT. (2019a). *Field determination of deflection using light weight deflectometer* (ITM No. 508-19). Indiana Department of Transportation, Division of Materials and Tests.

INDOT. (2019b). *Field determination of maximum dry density and optimum moisture content of soil* (ITM No. 512). Indiana Department of Transportation, Division of Materials and Tests.

INDOT. (2022a). *Dynamic cone penetrometer test* (ITM No. 509). Indiana Department of Transportation, Division of Materials and Tests.

INDOT. (2022b). *INDOT standard specifications: Section 203.26, Proofrolling*. Indiana Department of Transportation.

Meyerhof, G. G. (1963). Some recent research on the bearing capacity of foundations. *Canadian Geotechnical Journal*, *1*(1), 16–26.

Terzaghi, K. (1943). *Theoretical soil mechanics*. John Wiley & Sons.

Vesic, A. S. (1973). Analysis of ultimate loads of shallow foundations. *Journal of the Soil Mechanics and Foundations Division*, *99*(1), 45–73.

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

Further information about JTRP and its current research program is available at http://www.purdue.edu/jtrp.

About This Report

An open access version of this publication is available online. See the URL in the citation below.

Raja, R. A., Toshniwal, V., & Salgado, R. (2023). *GIS-based geotechnical database for collaborative GIS* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2023/14). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284317637