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Web-Based Tool to Advance Geotechnical Data Interchange and Reliability-Based Site Characterization

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13. Abstract

The Louisiana Department of Transportation and Development (DOTD) continues to improve its geotechnical data management policies and expand its use of digital data for geotechnical design. New advanced data-rich techniques and methodologies have been developed for geotechnical site characterization, including those recommended by the Advanced Geotechnical Methods in Exploration (A-GaME) program of the Federal Highway Administration (FHWA). Specifically, this research focused on the development and implementation of a web-based platform to efficiently visualize and interpret geotechnical data and help facilitate project delivery. The web-based platform can incorporate geotechnical data from DOTD's OpenGround dataset, gINT files from consultants, and/or Data Interchange for Geotechnical and Geoenvironmental Specialists (DIGGS) data files for

analysis based on the American Association of State Highway Transportation Officials (AASHTO) Section 10 and FHWA Geotechnical Engineering Circular No. 5 (GEC-5) updates.

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Implementation Statement

This research developed a standardized digital data transfer solution that enables the interoperability of geotechnical data between DOTD and its retainer contract holders (consultants). This solution is an implementation of DIGGS, a robust, extensible data transfer interchange supported by FHWA, multiple state DOTs, the United States Army Corps of Engineers (USACE), and others in the geotechnical community.

The digital platform implemented through this research provides a method to generate design profiles and develop statistical parameters based on statistical variability, which is expected to become the basis of future Load Resistance Factored Design (LRFD) code. These statistical parameters are tedious to generate without knowledge of computer programming; as a result, they may pose difficulty for DOTD staff and its consultants when the LRFD code is updated. This research facilitates a smooth transition to updated versions of LRFD, which is the design standard.

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Introduction

Over the past decades, the Louisiana Transportation Research Center (LTRC) conducted multiple phases of geotechnical database research to facilitate geotechnical data management practice for the Louisiana Department of Transportation and Development (DOTD) [1] [2] [3] [4]. The recent Phase IV project identified and converted existing data into Bentley's geotechnical data management system, HoleBASE/OpenGround Cloud (OpenGround). This framework is primarily for internal use, and while it may provide features for DOTD's consultants to use, DOTD has not fully unlocked them at this time.

In the past, DOTD used Bentley's previous geotechnical software, gINT, to manage and transfer geotechnical data between DOTD and its consultants. A previous LTRC research project standardized the gINT file format and libraries to facilitate data interchange between the Department and its consultants. Bentley and DOTD are moving away from gINT as part of a transition to OpenGround, but DOTD still uses gINT files as a vehicle for data interchange with some of its consultants. There is a need for a long-term data interchange standard to take over in the absence of gINT and/or when consultants choose not to use OpenGround in the future. Seequent, the Bentley Subsurface Company, announced that support for existing gINT users will be extended until December 31, 2028 [5].

In recent years, an open-source, standardized digital data format called Data Interchange for Geotechnical and Geoenvironmental Specialists (DIGGS) has been developed and gained momentum. This format is supported by the Federal Highway Administration (FHWA) and the American Society of Civil Engineers (ASCE) Geo-Institute. DIGGS will facilitate the interoperability of geotechnical data within an organization or between multiple organizations [6]. DOTD geotechnical database efforts have followed DIGGS logic, and DOTD has provided preliminary support for developing a web-based DIGGS tool, primarily as proof-of-concept. This tool demonstrates the capabilities of DIGGS by allowing users to import DIGGS files and plot geotechnical data in a web browser. This tool has been demonstrated at various regional and national conferences and has received great interest from the geotechnical community. However, there was no framework to permanently host, develop, and support the tool, so it remained a proof-of-concept. This project will expand and formalize the prototype tool and add additional functionalities for all DOTD projects.

Currently, the American Association of State Highway Transportation Officials' (AASHTO) Load Resistance Factored Design (LRFD) code is undergoing a major update to focus on reliability and data variability. Geotechnical site characterization for appropriate resistance factors needs to account for the variability of soil across an entire project. With this update, the methodologies required to perform site characterization in accordance with the updated code will become computationally more difficult. New tools will be needed to help engineers perform and review the required calculations. A web-based tool using DIGGS and other existing DOTD formats (e.g., gINT, HoleBASE, and OpenGround) will greatly help the Department and its consultants adopt the upcoming design changes to remain in compliance with LRFD code.

Literature Review

Geotechnical engineering practice involves the proper selection of engineering parameters and design methods, coupled with a heavy dose of engineering judgment. How engineers and consultants identify the most appropriate design parameters and methodologies often starts with the interpretation of data collected during initial geotechnical site characterization. Geotechnical site characterization has improved over the years, but remains challenging due to the spatial variability of subsurface conditions. In Louisiana, the Mississippi River Flood Plain and its alluvial deposits create a spatial complexity over approximately one-fifth of the state. As advanced data-rich exploration techniques are developed for site characterization, and as advanced design and analysis methodologies are implemented, there are opportunities for the profession to advance further. Models used for geotechnical site characterization must capture critical factors that impact financial and safety risks in typical transportation infrastructure construction projects.

A web-based platform can provide innovative techniques to automate and optimize the process of interpreting and characterizing geotechnical site conditions. Specifically, a platform that allows engineers to interactively visualize, efficiently evaluate, and rapidly interpret statistical measures of the geotechnical data will facilitate designers in developing appropriate soil design models. A web-based platform can also incorporate multiple types of geotechnical and geoenvironmental data for visualization and interpretation. Typical data types that could be captured and utilized on a platform include laboratory-test data from soil borings, cone penetration testing (CPT), field vane shear test (VST) data, Light Detection and Ranging (LiDAR) data, geophysical testing data, instrumentation data, and deep foundation field load testing data.

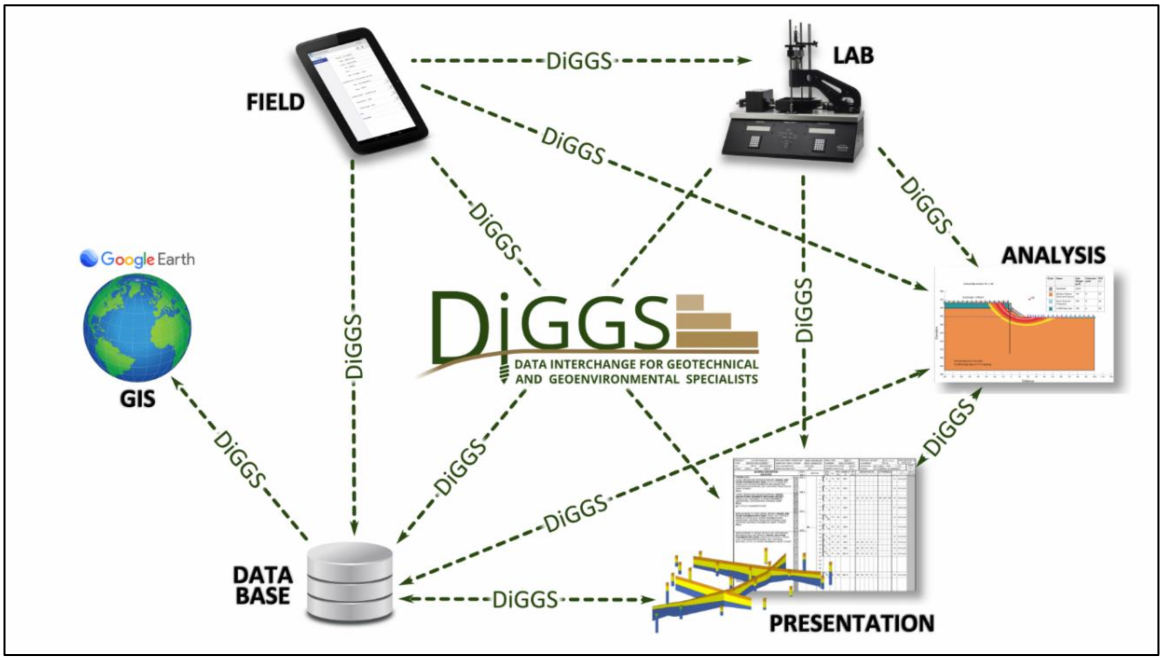
A platform that incorporates and automates geotechnical site characterization methods based on data statistics, as well as certain deep foundation design methods, would aid in implementing FHWA's existing GEC-5 design guidelines.

DOTD and its researchers developed a web-based platform prototype to address site variability in projects over the years. DOTD implemented the prototype platform using a few large-scale highway design and bridge construction projects, including the I-10 Calcasieu River Bridge Project in Lake Charles, LA.

A major goal of this research was to expand and facilitate the evaluation of site variability and the quantification of uncertainty in site conditions across Louisiana for normal

Geotechnical Design section production activities. Methodologies for geotechnical site characterization, subsequent design and analysis activities, and overall project delivery are expected to evolve. Achieving this goal requires improving current practice and incorporating efficient geotechnical data management strategies. Upcoming changes to AASHTO Section 10 will also require specific statistical calculations of the coefficient of variation prior to determining the applicable resistance factor for LRFD.

Figure 1. ASCE Geo-Institute—DIGGS



This project will develop innovative practices to improve geotechnical data management, highlighting the use of a digital toolkit package and services to visualize and interpret geotechnical data to facilitate project delivery. Data Interchange for Geotechnical and Geoenvironmental Specialists (DIGGS) has been implemented in this data management practice to support standardized geotechnical data exchange. Figure 1 shows an overview of the DIGGS logic [6]. Louisiana DOTD will continue its previous efforts [4] to implement DIGGS within its data management and design workflows. Format and nomenclature can vary from software to software, even within an agency. DIGGS will aid in normalizing data across those platforms to ensure precision, continuity, and quality are maintained.

DIGGS is an open-source, extensible, and standardized digital format that facilitates geotechnical data management and interoperability. Its implementation can significantly improve the quality of geotechnical data deliverables as digital assets. Techniques are now available to generate DIGGS files and validate them against their schema and Schematron ruleset. Once this transition to efficient geotechnical data management is complete, engineers and data owners will be able to manage, visualize, and interpret geotechnical and geoenvironmental data reliably and efficiently.

This project demonstrated how geotechnical engineers and consultants can develop reliable soil design models that accurately reflect subsurface stratigraphy and characterization using efficient data management practices. Existing geotechnical workflows can be optimized and partially automated using a web-based platform. Several case histories will show how to visualize and interpret dense geotechnical data sets (e.g., CPT and boring data) efficiently [7] [8]. In conjunction with previous LTRC geotechnical database efforts, the ultimate goal of efficient geotechnical data management is to help engineers and project managers visualize and manage data effectively while optimizing tedious, time-consuming project tasks. This shift will enable engineers and scientists to focus more on developing and evaluating reliable engineering solutions to complex problems. Ultimately, long-term costs will decrease, and project delivery will improve with the implementation of these techniques. Few would argue that we now live in a world of data, even Big Data. Many geotechnical engineers now recognize that leveraging this data can lead to Digital Transformation (DX) in our practice, a transformation that is evolving geotechnical engineering in exciting ways [7]. DX can leverage data to improve design quality and efficiency while reducing uncertainties and costs.

For over 30 years, organizations have used tools like Bentley's geotechnical software, gINT, to manage geotechnical data, boring logs, CPT records, and lab test results. DOTD enhanced geotechnical efforts and increased efficiencies with gINT through previous LTRC geotechnical database research projects [1] [2] [3] [4]. In the LTRC Geotechnical Database—Phase II project, DOTD began the shift to digital data [2]. In Phase IV, DOTD implemented Bentley's newer geotechnical software, OpenGround Cloud (OpenGround). This opened even more digital avenues and features. Researchers, the DOTD Geotechnical Administrator, and consultants have worked toward DIGGS implementation over the years. Combining DIGGS and OpenGround opened new ways to store, share, and analyze geotechnical digital data.

This project will show how current workflows using gINT, OpenGround, or other data platforms can evolve seamlessly into DX, often without major changes to existing processes.

Site Variability

The importance of evaluating variability and uncertainty in geotechnical engineering design has long been recognized by researchers. Over the past three decades, many multinational efforts have been undertaken to develop reliability-based design (RBD) methodologies. Since the beginning of his career, Terzaghi emphasized the unpredictability and uncertainty that are inherent in design in practice [9]. Previous studies [10] [11] [12] [13] [14] [15] [16] [17] [18] [19] [20], along with many other researchers, have contributed to advancing knowledge in geotechnical engineering by evaluating variability and uncertainty and implementing reliability-based design methodologies. This report discusses previous works on geotechnical engineering variability and uncertainty analysis. We also discuss methods for applying reliability analysis to calibrate Load Resistance Factored Design (LRFD) and alternative design methodologies that should account for variability and uncertainty.

There are a number of factors that change features from one location to another, both horizontally and vertically, within the same site. These factors include subsurface deposition, weathering, and the physical environment [21] [22]. Before delving into the history of site variability investigation in geotechnical engineering, it is essential to discuss the numerous mathematical methodologies used in this field. The phenomenon of variation in geotechnical soil characteristics is difficult to describe, as it arises from a wide range of unknown factors. The four fundamental factors that contribute to geotechnical uncertainty and affect soil behavior are: the geographical variability of the soil deposit (both horizontally and vertically), random measurement errors, statistical error, and model bias.

The differences in geologic deposits continuously modify the in-situ soil properties, which vary from location to location. These deposits are the first source of uncertainty. In-situ fluctuations in soil properties are caused by several factors, including the random mixture of different soil types and compositions, as well as variations in water content, density, and stress levels over time. Second, when we attempt to measure soil properties, there are inevitably measurement errors, typically due to either operator or equipment variations. These variations can occur from one test to the next. Equipment errors can be caused by calibration, setup, or loading issues. Operator error often occurs when the individual has discretion in reading or taking measurements, or during sample preparation and handling. There is a possibility that the combination of these two sources constitutes data scatter [23] [24].

Variability is the primary source of uncertainty in geotechnical engineering analyses. Many aspects of geotechnical engineering, particularly the characterization of soil properties, are characterized by high uncertainty. Geotechnical properties are subject to two categories of uncertainty: aleatory and epistemic [25] [26] [27]. The property's intrinsic randomization is indicated by aleatory uncertainty, a result of spatial variability (i.e., soil characteristics). Epistemic uncertainty is generated by a lack of knowledge and/or defects in measurement or calculation. This could be systematic inaccuracy induced by factors such as the quantity of available data, modeling errors, and measurement techniques of material properties.

The subsequent source of uncertainty is human error. However, it is rarely used in uncertainty assessments because it is difficult to clearly separate its effect on probability from effects already included in the collected aleatory uncertainty data [28]. It is imperative to probabilistically illustrate the soil profile, as the functionality of geotechnical structures is contingent upon the local boundaries of characteristics within a subsurface soil profile [29]. Probabilistic classification of soil profiles enables evaluation of geotechnical information on subsurface conditions at a specific site, prediction of how a geotechnical structure will perform, and estimation of the probability of failure [30]. Baecher initially identified two primary sources of variability in rock mass attributes identified during site investigations: inherent spatial variation and sampling and testing errors. In 1982, Baecher conducted site characterization on rock masses. Based on formal inference and statistical reasoning, he proposed a method for managing a significant quantity of uncertainty in rock mass joints [31] [32] [33] and concluded that the sources of uncertainties include:

- geological uncertainty resulting from site formations, geometry, and previous history;
- model uncertainty caused by physical model offerings;
- parametric uncertainty arising from spatial variability, measurement error, and estimation bias; and
- uncertainty arising from omissions or overlooking geological details [33] [34] [23]

The uncertainty in soil/rock parameters is categorized into two categories [35]:

- data scatter, which encompasses true spatial variation and random testing errors; and
- systematic error, which includes statistical error and measurement bias

The primary source of measurement bias is sample disturbance, while statistical error is primarily caused by the use of a limited number of measurements. Building on earlier work, in 2005, Baecher and Christian [23] applied Hacking’s terminology [36] to explain that geotechnical uncertainty comes from two primary sources: natural variability and limited knowledge. As earlier, Baecher and Christian classified the uncertainty into natural variability (i.e., aleatory uncertainty), or the change in soil properties across space and time, and epistemic uncertainty (i.e., knowledge uncertainty), which arises from limited data, understanding, or information. In geotechnical design, Baecher and Christian emphasize that effective decision-making should address both types of uncertainty. Phoon and Kulhawy [24] [37] [38] evaluated three primary categories of uncertainty:

- inherent variability;
- model uncertainty; and
- measurement error during the evaluation of geotechnical variability

The coefficient of variation (COV) and scale of fluctuation are employed to depict the inherent variability in a homogeneous random field model [38]. Kulhawy and Phoon also consider the transformation model uncertainty, which is distinct from the model uncertainty discussed in prior research. This uncertainty is the result of the application of empirical models or correlation models to convert indirect measurements into the necessary design parameters [37]. Equipment, procedural/operator, and random testing effects all contribute to measurement error during the measurement procedure [24].

Unlike most previous researchers, Griffiths and Fenton [39] focused on aleatory uncertainty, or the natural variability of soil. Their work centers on applying random field finite element models to reliability-based design and analyzing the spatial variability of soil parameters. In 2010, they incorporated Vanmarcke’s random field theory [40], which uses the correlation structure of one-dimensional random processes through a variance function and fluctuation scale. The construction of models is facilitated by the random field theory. Griffiths and Fenton's reliability analysis is predicated on the examination of soil spatial variability. To accurately represent soil information at a specific location, Griffiths and Fenton [39] employed a positive correlation between soil parameters measured at close proximity.

In reliability-based design, Fenton and Griffith have also devised the random finite element method (RFEM) by integrating Monte Carlo simulation methodologies with random field theory and the finite element approach [39]. In order to establish spatial correlation structures that could be employed to draw conclusions about other locations with comparable soil engineering properties, Fenton conducted research on quantifying soil qualities [41]. To characterize the spatial variability of tip resistance, Fenton employed the fractal model to analyze the tip resistance measurements from cone penetration tests (CPT) and developed a global correlation model [42]. Onyejekwe [43] conducted research with the objective of statistically characterizing the variability of geotechnical factors in order to increase the adoption of reliability-based design (RBD) by geotechnical engineers. In order to characterize geotechnical characteristics in this investigation, the coefficient of variation (COV) and the first and second statistical moments were employed. Additionally, their fluctuation scales and probability distributions were computed. Onyejekwe [43] discovered that the Semivariogram Function (SVF) is more appropriate for estimating the scale of variation from widely dispersed, discontinuous, irregular data obtained from laboratory testing than the Autocorrelation Function (ACF). In his research, a framework was proposed that integrates the spatial averaging effect of parameters processed from discontinuous and irregular data that is extensively disseminated, using the scale of fluctuation and variance reduction factor.

The Florida Department of Transportation (FDOT), Federal Highway Administration (FHWA), and American Association of State Highway Transportation Officials (AASHTO) employ a constant LRFD design for deep foundations, which is dependent on redundancy but independent of pile or shaft dimension, per McVay [44]. Additionally, McVay [44] observed that soil properties are frequently spatially associated and vary from one location to another. The pile resistance variability (CV_R) will not be identical for both skin friction and end bearing, as both require spatial averaging of soil qualities across the pile or shaft surface (CV_q = pile surface variability). Even though the LRFD resistance factor is determined by the dimensions of the pile, McVay [44] noted that soil or rock variability is also a factor. The CV_R, the spatial correlation, and CV_q are inconsistent at any given location.

AASHTO provides resistance factors for a variety of techniques, types of foundations, and levels of proper validation, such as load testing, in the contemporary design of reliability analysis for deep foundations [45]. The resistance factor (ϕ) values are calibrated using databases of anticipated versus measured resistances and are based on defined target reliability. This calibration has the disadvantage of failing to account for variable degrees of design parameter variability across different design sites. McVay [44] stated that the present study proposes a design methodology based on reliability and applicable to a variety of deep foundation analyses. This methodology takes into consideration the site-specific spatial variability. Stochastic modeling employs geostatistical parameters to quantify the associated uncertainty and represent site heterogeneity. Geostatistics offers a predetermined framework for assessing the regional variability of ground parameters and their influence on the uncertainty of design resistance.

Prediction of Ultimate Pile Resistance

The ultimate axial resistance (Q_u) of a driven pile consists of the end bearing resistance (Q_b) and the skin frictional resistance (Q_s). The ultimate pile resistance can be calculated using the following equation:

$$Q_u = Q_b + Q_s = q_b . A_b + \sum_{i=1}^{n} f_i A_{si} \qquad [1]$$

where,
q_b is the unit tip bearing resistance;
A_b is the cross-section area of the pile tip;
f_i is the average unit skin friction of the soil layer i;
A_{si} is the area of the pile shaft area interfacing with layer i; and
n is the number of soil layers along the pile shaft.

In clayey stratigraphies, shaft frictional resistance often dominates, whereas in sandy stratigraphies, end bearing resistance can contribute more than 50% of the ultimate pile resistance. Since Louisiana soils are primarily clay and silty clay deposits, the Q_s is dominant in the total Q_u compared to the Q_b.

Static Methods

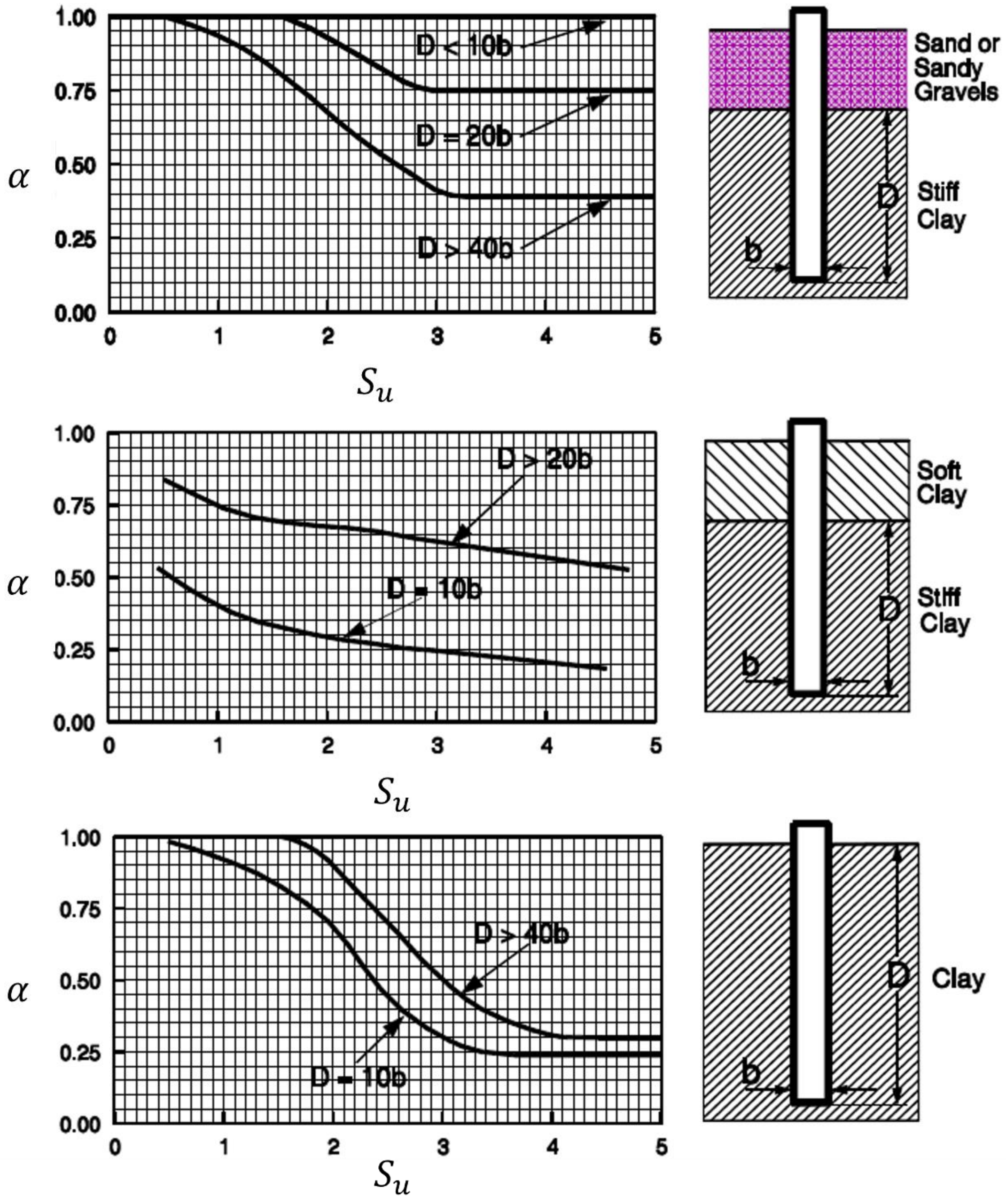
α-Tomlinson Method—The α method is based on total stress analysis. For a soil with an angle of internal friction, $\Phi = 0$, or in total stress analysis, the ultimate skin resistance per unit area of the pile can be calculated as follows [46]:

$$f = \alpha \ S_u \qquad [1]$$

where,
α is an empirical adhesion coefficient, and
S_u is the undrained shear strength.

In this research study, α values suggested by Tomlinson are used [47]. Figure 2 shows α values versus the Undrained Shear Strength (S_u).

Figure 2. Variation of α versus S_u for different soil layering



The Q_s is as follows:

$$Q_s = \int_0^L f\, C_d dz \qquad [2]$$

where,
L is length of the pile in contact with soil, and
C_d is the effective perimeter of the pile.

The Q_b is calculated as follows:

$$Q_b = A_b\, S_u\, N_c \qquad [3]$$

where,
A_b is the cross-sectional area of the pile, and
an N_c of 9 is used in this study as recommended by FHWA [46].

Nordlund Method—In sand, the pile tip resistance (Q_b) can be calculated as:

$$Q_b = A_b . \overline{q} . \alpha . N_q^{'} \qquad [4]$$

where,
q-bar is the effective vertical stress at tip level;
α is a dimensionless correction factor; and
N_q' is a bearing resistance factor varying with Φ.

In this research, the values proposed by Thurman are used for calculation [48]. The Q_s was evaluated using the equation proposed by Nordlund in this research as follows [49] [50]:

$$Q_s = \int_0^L K_\delta\, C_f \overline{P_D} \sin(\delta) . C_d dz \qquad [5]$$

where,
K_δ is a coefficient of lateral stress;
C_f is a correction factor;
P_D-bar is the effective overburden pressure;
δ is the pile-soil friction angle; and
C_d is the effective pile perimeter.

The relationships between the bearing resistance factor and the friction angle, as well as the coefficient of lateral stress and the correction factors, can be found in the Hannigan et al. [46] study.

LRFD

Engineers frequently neglect to acknowledge the spatial variability of geotechnical data, which can lead to potential hazards in foundation design. The uncomplicated assessment of the mean boring measurements within an area or layer alone is not a suitable metric of spatial variability, since it neglects uncertainty, variance, and coefficient of variation. The spatial variability of a site is significantly influenced by differences in nine soil parameters, which, in turn, lead to commensurate variations in the axial capacities of deep foundations. In geotechnical engineering, correlations and empirical relationships are often used to quickly and cost-effectively estimate one parameter from another, more easily obtained, provided the chosen correlations are appropriate. In probabilistic analysis, the quantification of the relationship between various soil attributes enables a more effective assessment of the parametric uncertainty of the design and an indication of the degree of independence between parameters [51] [52] [53]. Uzielli et al. [53] posited that the relationship between various soil properties is influenced to varying degrees by the type of soil, the experimental method used to derive the quantitative parameter value, and the soil homogeneity. Numerous relationships among soil characteristics have already been published. More than fifty of these links were demonstrated by Kulhawy and Mayne [54] in their investigation.

The data at each layer or zone must be presented in histogram form after the site is divided accordingly to verify that the data are statistically stationary. The histogram enables the engineer to observe the frequency ranges of the data, as well as its distribution (i.e., mean and mode). The presence of multiple peaks or modes in the histogram can also be used to ascertain the existence of multiple distributions within the zone or stratum. The histogram should be accompanied by the mean and variance of the data set (e.g., q_i).

$$\mu = \frac{1}{n}\sum_{i=1}^{n} q_i \qquad [6]$$

$$\sigma^2 = \frac{1}{n-1}\sum_{i=1}^{n}(q_i - \mu)^2 \qquad [7]$$

where,
μ = mean soil property trend;
n = number of data points;
q = data values; and
σ = standard deviation.

Equation 8 represents the sample variance of measured soil property data and is used to quantify variability within the observed dataset. However, for LRFD calibration, total uncertainty also includes measurement error, transformation/model uncertainty, and statistical uncertainty associated with limited sampling. The standard deviation can be normalized with respect to the mean soil property trend, μ, in order to enhance the utility of the Coefficient of Variation (COV), a dimensionless measure of inherent soil variability.

$$\text{COV}=\frac{\sigma}{\mu} \qquad [8]$$

The dataset's mean is denoted by μ, while the number of data points is denoted by n. The data values are denoted by q_i, and the standard deviation is denoted by σ. COV, a dimensionless number, denotes the dispersion or distribution of data around the mean. The optimal Probability Density Functions (PDF) to represent the observed data should be chosen by an engineer based on the distribution of the histogram (normal, log-normal) and summary statistics. Significant differences between the mode (most common) and the arithmetic mean are due to the wide range of values and the absence of negative outcomes for most soil characteristics (e.g., strength, modulus). These characteristics are best described by log-normal distributions. The distribution of data is considerably dataset-dependent, with the type of soil having a significant impact on the second-moment statistics (e.g., mean, standard deviation, COV, and probability distribution) according to the previous studies. Local circumstances are often inadequately represented by values from the literature, which may result in failure to achieve efficient, cost-effective outcomes. Consequently, it is necessary to establish second-moment statistics that are specific to each site.

The geotechnical regional variability of the parameters is not accounted for by the second-moment-based approaches for uncertainty characterization of geotechnical parameters previously discussed. It is widely recognized that geotechnical parameters exhibit depth-dependent and lateral relationships. They exhibit spatial variation, with a greater propensity for close neighbors to share similar values than distant neighbors. This is the reason why second-moment statistics alone would not be adequate to characterize the uncertainty in geotechnical parameters [28] [25] [53]. Clark [55] defines geostatistics as a system that is both spatial and random, maintaining a consistent level of quality from one location to another. Stationarity of data is necessary for geostatistical analysis. Data is considered stationary when the following conditions are satisfied:

- The data does not exhibit any trend;
- the variance remains constant as the distance increases;
- seasonal variations are absent; and
- irregular fluctuations are absent from the data.

Stationarity is more critical in time series analysis than in geostatistics. In the fields of geostatistics and random field theory, it is customary to eliminate a low-order polynomial trend in order to transform a nonstationary dataset into a stationary one [30] [53]. To establish spatial variability from measured data, engineers must evaluate the correlation between data sets separated by varying distances, accounting for a variety of factors. One of the most critical fundamental parameters utilized is the covariance (h) between data values q_i and q_j that are separated by a distance h:

$$C(h) = \frac{1}{n}\sum_{i.j=1}^{n}(q_i - \mu)(q_j - \mu) \qquad [9]$$

where,
μ = mean soil property trend;
n = number of data points; and
q_i and q_j = data pairing values.

Where the data pairings (separated by distance h) are denoted as q_i and q_j, respectively, and n is the total number of data pairs, the variance of completely correlated data is equivalent to C(h) (i.e., $q_i = q_j$). If there is no correlation, C(h) is equal to 0. The correlation coefficient is a dimensionless representation of the correlation between the data.

$$\rho(h) = \frac{C(h)}{\sigma^2} \qquad [10]$$

The limits of 0 and 1 ($0 < (h) < 1$) represent no correlation and perfect correlation, respectively. The semivariogram (h) is another essential component of geostatistics, and it is defined as:

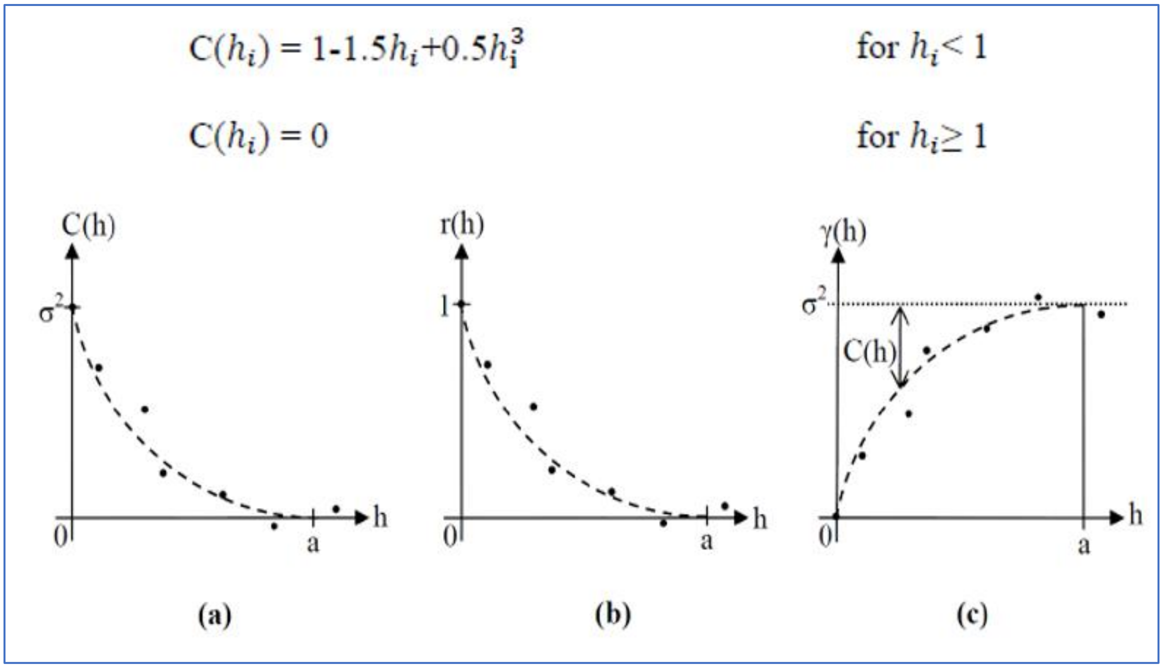
$$\gamma(h) = \frac{1}{2n}\sum(q_i - q_j)^2 \qquad [11]$$

The variance of data σ^2 can be used to extract the covariance C(h) from the semivariogram $\gamma(h)$.

$$\gamma(h) = \sigma^2 - C(h) \qquad [12]$$

Figure 3 illustrates typical examples of C(h), r(h), and $\gamma(h)$, each of which indicates a decreasing correlation as h increases. The data pairings become uncorrelated when the correlation function reaches zero at a distance of h = a, which is called the range. The variogram's upper value, or sill, is achieved using $\mu = \frac{1}{n}\sum_{i=1}^{n} q_i$ [6, where (h=a)= $\sigma^2[C(h)=0]$. A diverse array of theoretical models can be employed to predict the spatial covariance function. Models are classified into four categories: spherical, exponential, Gaussian, and circular [24]. The spherical model is the most frequently employed of these models and is defined as follows:

Figure 3. (a) Spatial covariance function C(h); (b) Spatial correlation function ρ(h); and (c) Variogram γ(h) [44]



The spatial autocorrelation of the measured sample points is depicted in the semivariogram. Once the locations have been mapped, a model is applied to each combination. These models are frequently described by a limited number of properties.

Range—The model of a semivariogram is observed to stabilize at a specific distance. The model begins to flatten out at a certain distance, which is known as the range. Spatial autocorrelation is present between sample locations that are separated by distances less than the range, but it is not present between locations that are farther apart than the range. The physical meaning of the range is that pairings of points that are separated by a certain distance or more are not spatially connected.

Sill—The sill is a representation of the value that the semivariogram model achieves within the semivariogram range (i.e., the y-axis value). A partial sill is equivalent to a complete sill, but it lacks the nugget.

Nugget—In theory, the semivariogram value is 0 when the separation distance is 0 (lag = 0). The nugget effect, which is a value greater than 0 at an infinitesimally small separation distance, is frequently observed in the semivariogram, on the other hand. For instance, the nugget is 2 if the semivariogram model intercepts the y-axis at 2. The measurement error is inherent in the measuring apparatus and is responsible for the nugget effect. Spatial scales of natural phenomena exhibit a wide range of variation. The nugget effect will be observed as a variation at microscales that are smaller than the sample distances. It is imperative to familiarize oneself with the various aspects of geographic variation prior to commencing data collection.

The reduction factor, α, is determined by the ranges obtained from semivariogram analyses [44]. This factor is then used to calculate the spatial coefficient of variation ($COV_{R,spatial}$) of the field measurements (e.g., CPT-qt, SPT-N, S_u) as a function of COV_q using the following equation:

$$\mathrm{COV}_{\mathrm{R,spatial}} = \sqrt{\alpha}\,\mathrm{COV}_{\mathrm{q}} \qquad [13]$$

The coefficient of variation in the sample data q is denoted as $COV_q = \sigma/m$. The generalized expression for COV_R can be expressed as follows for the purpose of pile foundation design [44]:

$$\mathrm{COV}_{\mathrm{R,spatial}} = \frac{\sqrt{\pi^2 D^2 \sum_{j=1}^{n_L} L_{Lj}^2 \alpha_{Lj} \sigma_{Lj}^2 + \sigma_{EB}^2}}{\pi D \sum_{j=1}^{n_L} L_{Lj} m_{Lj} + m_{EB}} \qquad [14]$$

where,
D = pile diameter;
L_{Lj} = the known (deterministic) length intervals of the shaft;
m_{Lj} = the expected values of f_{sLj} (and hence q) in each layer;
m_{EB} = the value (expected) of end bearing resistance;
α_{Lj} = the α for each layer;
σ_{Lj}^2 = the variance in q for each layer; and
σ_{EB}^2 = the variance in end bearing resistance.

For $n_L = 1$ (single layer) and $m_{EB} = \sigma_{EB^2} = 0$ (no end bearing),

$$\mathrm{COV}_{\mathrm{R,spatial}} = \frac{\sqrt{\pi^2 D^2 \sum_{j=1}^{n_L} L_{Lj}^2 \alpha_{Lj} \sigma_{Lj}^2 + \sigma_{EB}^2}}{\pi D \sum_{j=1}^{n_L} L_{Lj} m_{Lj} + m_{EB}} \qquad [15]$$

and this is reduced to:

$$\mathrm{COV}_{\mathrm{R,spatial}} = \sqrt{\alpha}\,\mathrm{COV}_{\mathrm{q}} \qquad [16]$$

[13

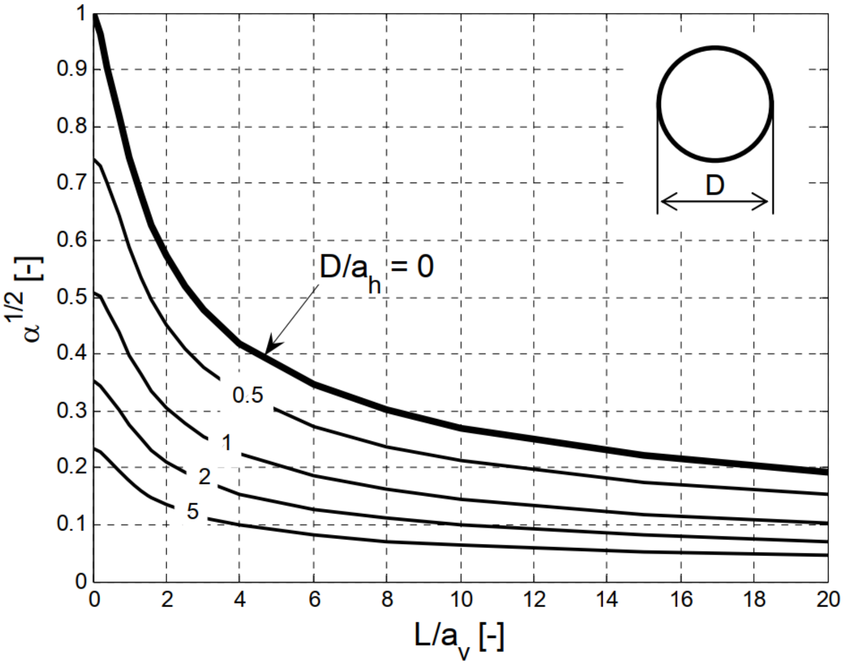
In this equation, the reduction factor, α, is a function of $(\frac{L}{av}, \frac{D}{ah})$, where *L* and *D* are the pile length and diameter, respectively, and a_v and a_h are the correlation ranges in the vertical and horizontal dimensions, respectively. The value of $\frac{D}{a_h}$ is typically approaching zero because the horizontal correlation is much larger than the pile diameter. In this case study, it is presumed that $\frac{D}{a_h}$ is approximately 0. In order to ascertain the value of α for the spherical model, [21] developed the subsequent equation:

$$\alpha = 1 - \frac{L}{2\,a_v} + \frac{L^3}{20\,a_v^3} \qquad \text{For } 0 \leq \frac{L}{a_v} \leq 1 \qquad [17]$$

$$\alpha = 1 - \frac{3\,a_v}{4\,L} + \frac{a_v^2}{5\,L^2} \qquad \text{For } \frac{L}{a_v} \geq 1 \qquad [18]$$

If we wish to take into account both $\frac{L}{a_v}$ and $\frac{D}{a_h}$, we must employ Figure 4 provided by McVay [44]. The subsequent section provides a comprehensive examination of the horizontal and vertical semivariograms. Figure 4 illustrates the results of McVay's [44] numerical integration in terms of $\alpha^{1/2}$, utilizing the square root for improved graphical representation and future convenience as a function of the dimensionless variables $\frac{L}{a_v}$ and $\frac{D}{a_h}$.

Figure 4. Integrating $\alpha^{1/2}$ as a function of $\frac{L}{a_v}$ and $\frac{D}{a_h}$ for piles for the spherical model [44]



The Modified First Order Second Moment Method (MFOSM) calibration equation proposed by McVay [44] can be used to calculate the Resistance Factor, ϕ in the equation below, for pile design according to the LRFD method, once the value of spatial COVR is defined:

$$\phi = \frac{\lambda_R \left(\gamma_D \frac{Q_D}{Q_L} + \gamma_L\right) \sqrt{\frac{1 + COV_Q^2}{1 + COV_R^2}}}{\left(\lambda_{QD} \frac{Q_D}{Q_L} + \lambda_{QL}\right) \exp\left(\beta_T \sqrt{\ln(1 + COV_R^2)\left(1 + COV_Q^2\right)}\right)} \qquad [19]$$

where,
λ_R = the resistance bias factor;
Q_D = the dead load;
Q_L = the live load;
β_T = the target reliability index;
γ_D and γ_L = the dead load factor and live load factors, respectively;
λ_{QD} = the dead load bias factor (measured divided by predicted);
λ_{QL} = the live load bias factor;
COV_{QD}= the inert load;
COV_{QL} = the live load; and
Q_D/Q_L = the ratio of dead and live burden (assumed to be 3 in this study).

The Resistance Bias Factor, λ_R, is contingent upon the design method employed for pile foundations. The LCPC procedure [56] can be used to design piles from CPT data, for example. The LCPC is a direct pile-CPT method that has demonstrated one of the highest levels of performance among pile-CPT methods for estimating the ultimate pile resistance in Louisiana [57]. In the LCPC method, the λ_R and COVR are 1.04 and 0.31, respectively, based on site-specific load test data from DOTD. The static analysis method recommended by the Federal Highway Administration [58] will be used in the design of piles based on soil borings and laboratory experiments. FHWA suggests using the Nordlund method for sand layers based on SPT results, and the α-Tomlinson method for clay layers based on undrained shear strength, S_u. The Nordlund method (λR = 1.02 and COVR, method = 0.48) and the α-Tomlinson method (λR = 0.87 and COVR, method = 0.48) have values of 0.87 and 0.48, respectively [59]. The coefficients of variation of resistance, COVR, that were previously presented for the various design methods (i.e., COVR = 0.31, 0.48, or 0.48) do not account for the impact of site variability, which considers the site with low variability the same as the site with high variability. This should be taken into account. The λ_R can be determined by the following:

$$\lambda_R = \frac{\sum \lambda_{Ri}}{N} \quad [20]$$

where,
N is the number of sites, and
λ_{Ri} is the resistance bias factor for each site.

McVay et al. [44] introduced the coefficient of variation of the random loads, COV_Q, using the following equation:

$$COV_Q = \sqrt{\frac{\frac{{Q_D}^2}{{Q_L}^2}{\lambda_{QD}}^2 COV_{QD}^2 + {\lambda_{QL}}^2 COV_{QL}^2}{\frac{{Q_D}^2}{{Q_L}^2}{\lambda_{QD}}^2 + 2\frac{Q_D}{Q_L}\lambda_{QD}\lambda_{QL} + {\lambda_{QL}}^2}} \qquad [21]$$

where,

COV_{QD} and COV_{QL} are the COV values for the inert load and live load, respectively.

The dimensionless parameters in:

$$\phi = \frac{\lambda_R\left(\gamma_D\frac{Q_D}{Q_L} + \gamma_L\right)\sqrt{\frac{1 + COV_Q^2}{1 + COV_R^2}}}{\left(\lambda_{QD}\frac{Q_D}{Q_L} + \lambda_{QL}\right)\exp\left(\beta_T\sqrt{\ln(1 + COV_R^2)\,(1 + COV_Q^2)}\right)} \qquad [22]$$

and

$$COV_Q = \sqrt{\frac{\frac{{Q_D}^2}{{Q_L}^2}{\lambda_{QD}}^2 COV_{QD}^2 + {\lambda_{QL}}^2 COV_{QL}^2}{\frac{{Q_D}^2}{{Q_L}^2}{\lambda_{QD}}^2 + 2\frac{Q_D}{Q_L}\lambda_{QD}\lambda_{QL} + {\lambda_{QL}}^2}} \qquad [23]$$

can be defined as follows, according to FHWA [60]: γ_L=1.75; λ_{QL}=1.15; COV_{QL}=0.18; γ_D=1.25; λ_{QD}=1.08; COV_{QD}=0.128.

According to AASHTO LRFD Bridge Design Specifications (C10.5.5.3.2), resistance factors are valid only when the prediction method does not exhibit unconservative bias; therefore, the bias factors used in this study are selected in accordance with established recommendations, such as those of Paikowsky et al. [59].

Over the past decade, LTRC has conducted numerous investigations on geotechnical site variability and its role in LRFD calibration for foundations, embankments, and slope stability. LTRC Final Report FHWA/LA.22/673 [61] quantified spatial, measurement, statistical, and model-bias variability using an integrated program of laboratory testing, in-box testing, and extensive in-situ testing (e.g., CPT, SPT, DCP, LFWD, and Geogauge) across Louisiana soils. The study characterized vertical and horizontal correlation lengths, COV, and reduction factors using semivariogram analysis, second-moment statistics, and Bayesian updating. These results directly supported the recalibration of LRFD resistance factors for shallow and deep foundations by explicitly incorporating spatial variability, operator versus specimen effects, and site-specific bias updates using two-level Bayesian methods. Complementing this effort, Moradi et al. [62] introduced a Bayesian neural network framework for predicting CPT tip resistance at sparse sites, benchmarking modern probabilistic and machine-learning approaches to improve subsurface characterization where CPT coverage is limited. This work demonstrated that Bayesian and geostatistical tools (e.g., BNN, EBK, IDW) can substantially reduce uncertainty in q_t prediction and improve estimation of mean bias, COV, and reliability-consistent input parameters for LRFD. Together, LTRC's variability research and the emerging Bayesian/ML approaches form a technical foundation for upcoming AASHTO updates that seek to integrate site variability more explicitly into resistance-factor calibration, improve regional bias models, and modernize geotechnical data usage through probabilistic methods. Table 1 summarizes the ranking of direct pile axial capacity prediction methods derived from cone penetration test (CPT) data.

Table 1. Direct design methods ranking based on different criteria from Louisiana 80 static pile load test data [63]

	Best fit calculation			Arithmetic calculations Qp/Qm			Cumulative probability			Overall rank	
Pile capacity method	Q_{fit}/Q_m	R^2	R1	Mean	COV	R2	Q_p/Q_m at P_{50}	Q_p/Q_m at P_{90}	R3	RI	Final rank
LCPC	1.03	0.74	1	1.07	0.39	3	0.99	1.45	1	5	1
ERTC3	1.04	0.73	1	1.08	0.35	3	1.01	1.41	1	5	1
Probabilistic	0.97	0.78	4	1.03	0.33	1	0.99	1.42	1	6	3
UF	1.03	0.82	1	1.04	0.35	1	0.95	1.45	4	6	3
Philipponnat	1.03	0.79	1	1.02	0.37	3	0.93	1.42	4	8	5
De Ruiter	0.98	0.77	4	0.95	0.36	3	0.87	1.24	4	11	6
CPT2000	1.17	0.79	6	1.11	0.34	6	1.08	1.56	4	16	7
UWA	1.19	0.82	6	1.17	0.31	6	1.09	1.60	4	16	7
Schmertmann	1.20	0.77	6	1.21	0.35	6	1.18	1.58	9	21	9
German	1.03	0.67	4	1.02	0.44	9	0.88	1.52	9	22	10
Eurocode7	1.22	0.74	6	1.17	0.48	10	1.02	1.87	9	25	11
Price and Wardle	0.84	0.79	9	0.83	0.34	9	0.78	1.21	9	27	12
Static	1.16	0.60	9	1.26	0.40	10	1.17	1.71	9	28	13
NGI05	1.28	0.72	11	1.24	0.45	10	1.10	1.96	14	35	14
Tumay Fakhroo	1.29	0.69	11	1.36	0.35	10	1.26	2.02	15	36	15
Fugro	1.44	0.75	13	1.34	0.45	10	1.15	2.14	15	38	16
Purdue	1.45	0.60	13	1.29	0.56	14	1.02	2.36	19	38	18
Aoki	0.83	0.64	9	0.77	0.51	16	0.65	1.27	15	40	18
ICP	1.49	0.74	13	1.33	0.45	10	1.22	2.12	19	42	19
Penpile	0.54	0.85	13	0.59	0.28	15	0.57	0.77	15	43	20
Zhou	1.49	0.85	13	1.68	0.28	17	1.60	2.20	21	51	21
Togliani	1.70	0.81	18	1.83	0.30	18	1.79	2.45	22	58	22

Objective

Web-Based Visualization and Data Analysis

A web-based platform has been implemented by DOTD for several large highway and bridge design and construction projects. These larger projects benefited from the ability to interactively visualize and interpret data from soil borings, CPTs, geophysical data, and conventional field survey data. This project standardizes the visualization process for all DOTD geotechnical design projects.

GEC-5

Demonstrate how geotechnical engineers and consultants can efficiently quantify the uncertainty of site conditions and develop soil design models based on the statistical analysis of soil boring data. The uncertainty model can be interactively evaluated based on the methods presented in FHWA's Geotechnical Engineering Circular (GEC) No. 5—Geotechnical Site Characterization, along with recent revisions to AASHTO Section 10.

DIGGS

Demonstrate how Data Interchange for Geotechnical and Geoenvironmental Specialists (DIGGS) can be implemented into the web-based platform for standardized geotechnical data exchange. The implementation of DIGGS will efficiently increase the quality of geotechnical data deliverables as a digital asset. Other benefits of implementing DIGGS in geotechnical data management include the ability to develop software tools that consume standardized data, such as visualizations and improvements to the DOTD geotechnical design process.

Scope

The Louisiana Department of Transportation and Development (DOTD) continues to improve its geotechnical data management policies and expand its use of digital data for geotechnical design. New advanced data-rich techniques and methodologies were developed for geotechnical site characterization, including those recommended by the Advanced Geotechnical Methods in Exploration (A-GaME) program of the Federal Highway Administration (FHWA).

Specifically, this research focused on the development and implementation of a web-based platform to efficiently visualize and interpret geotechnical data and help facilitate project delivery. The web-based platform incorporates geotechnical data from DOTD's OpenGround dataset, gINT files from consultants, and/or Data Interchange for Geotechnical and Geoenvironmental Specialists (DIGGS) data files for analysis based on anticipated changes to American Association of State Highway Transportation Officials (AASHTO) Section 10 and FHWA Geotechnical Engineering Circular No. 5 updates.

Methodology

The original tasks for the project were as follows:

Task 1—Literature Review. The team will conduct a comprehensive literature review on relevant published works internally and externally.

Task 2—Develop Test, Optimize, and Finalize Prototype Platform

- Finalize a prototype web-based platform capable of consuming DIGGSml files to perform the following functions: interactively select soil borings, create a composite soil stratigraphy, plot soil properties and derived parameters vs. elevation, and develop design profiles.
- Implement security features to allow other stakeholders (e.g., consultants, LTRC, etc.) to access the tool to provide a centralized, repeatable, and standardized method to develop the statistical parameters needed for future Load Resistance Factored Design (LRFD) revisions.
- Find a long-term hosting solution for the web-based tool. LTRC hosts other research-developed tools and software. There will be a developmental site, then long-term hosting via LTRC.

Task 3—DIGGS Implementation

- Develop a standardized DIGGS dictionary based on the current gINT format for DOTD projects.
- Develop a conversion tool for DOTD geotechnical data (gINT files) to benefit DOTD and its retainer contract consultants to ensure data is transferred appropriately into DOTD's current standard Open Ground Cloud.
- Test the module internally at LTRC and DOTD and through conversions with consultants. The file conversions will work for various geotechnical software, as gINT is sun-setting, assuming appropriate data dictionaries are established and implemented with each software.

Task 4—LRFD Module. On the web-based platform, automate the statistical analyses process that will be implemented in the next version of the LRFD design specifications. This specification is being drafted and is expected to utilize concepts detailed in FHWA GEC No.

5. The intent of this module will be to standardize the selection of resistance factors and the evaluation of data variability.

Task 5—Recommend and Implement Strategies. Recommend steps to continue the efforts developed in the research to realize efficiencies (e.g., time, data, productivity, etc.) within the Department. Implementation strategies will be developed with the Project Review Committee (PRC) and guided by the researchers and stakeholders to the end users. Recommendations for best practices that meet Section 67 needs will be at the forefront.

Task 6—Document the Research Effort. Prepare a final report to document the entire research effort. The final report will include data, a discussion of results, and recommendations for future efforts and implementation ideas generated by the study.

Task 7—Process through Editing. The report will be processed through the LTRC editorial process to refine the content, grammar, and format according to LTRC guidelines and Section 508 accessibility requirements. Revisions will be made with the help of the authors, and the report will be resubmitted for publishing.

Software

The research team used a variety of software to expand and facilitate this project and contribute to DOTD efforts to link geotechnical data with a GIS-based platform, adding additional functionality to the created software.

- An **application programming interface (API)** facilitates communication between computers or computer programs. Serving as a software interface, it allows one software to access services provided by another. At the start of this project, DOTD requested a prototype protocol to directly retrieve geotechnical data from OpenGround via API, integrating it into the web-based platform developed for visualization and analysis.
- **Python** is a high-level, interpreted programming language created by Guido van Rossum in 1991. With an emphasis on code readability and object-oriented design, Python provides developers with an efficient toolset. In this project, Python handled the back-end operations of the web-based platform, performing data analytics and processing complex computations derived from user inputs collected via the front-end.
- **JavaScript**, developed by Brendan Eich in 1995, is a programming language primarily used to make websites interactive. In 2025, 98.9% of sites relied on JavaScript for client-

side functions. In this project, JavaScript managed front-end tasks, enabling user interactions and displaying back-end results through web-based visualizations.

- **Bentley Systems (Bentley)** is an infrastructure engineering software company. They state: "Bentley's commitment extends beyond delivering the most comprehensive and integrated software paired with exceptional service, training, and 24/7 technical support. For over 39 years, Bentley has served the engineers and other professionals responsible for designing, constructing, and operating sustainable infrastructure, essential to the quality of life for everyone, everywhere" [64].
- **gINT**. gINT is a geotechnical software developed in 1986 that Bentley acquired in 2009. gINT is a common software for managing geotechnical data. The software is being sunset by Bentley, with the end of product support slated for December 31, 2028. Bentley has pushed this date back at least twice during this LTRC project.
- **OpenGround Cloud (OpenGround).** OpenGround is Bentley's rebranded release of HoleBASE. This cloud version enables smart, cloud-based management of geotechnical data. The software has mapping capabilities and can generate boring logs from digital data. Cloud storage enables faster calculations and connectivity across DOTD HQ, district offices, and consultants.
- **Data Interchange for Geotechnical and Geo-Environmental Specialists (DIGGS).** DIGGS is a transfer protocol. It allows each piece of data to be connected to key metadata such as test reference, geographic location, geologic references, etc. By using a common and robust transfer protocol, the end use (e.g., interpretation, storage, presentation) is separated from data transfer [6]. The DIGGS project involves the development of a Geography Markup Language (GML, an Extensible Markup Language [XML]-based) geospatial standard schema for the transfer of geotechnical and geoenvironmental data within an organization or between multiple organizations. DIGGS can work with existing software, hardware, databases, and data storage facilities to easily transfer and share data [6]. Widespread adoption of DIGGS is also a goal of the Federal Highway Administration (FHWA) and the American Society of Civil Engineers (ASCE) Geo-Institute. The implementation of DIGGS is a DOTD geotechnical goal.
- **Microsoft Power BI (Power BI).** They state: "Power BI is an interactive data visualization software product developed by Microsoft with a primary focus on business intelligence. It is part of the Microsoft Power Platform. Power BI is a collection of software services, apps, and connectors that work together to turn disparate data sources into coherent, visually immersive, and interactive insights. Data may be input by reading

directly from a database, webpage, or structured files such as spreadsheets, CSV, XML, and JSON" [65].

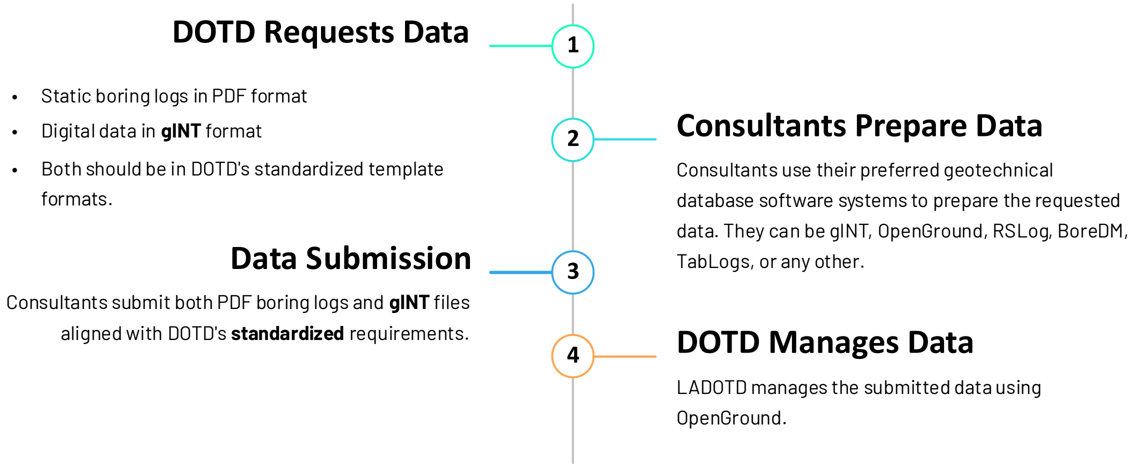
- **RAPID CPT.** RAPID CPT is a gINT add-in that makes analyzing CPT Geotechnical data simple. RAPID CPT encapsulates the entire CPT analysis procedure into a single location, a gINT project. RAPID CPT allows one to import raw text files from nearly any CPT manufacturer, whether in English or metric units [66].
- **Office of Technology Services (OTS).** The Louisiana Division of Administration's Office of Technology Services envisions an effective and efficient state government through information technology support, advancement, and innovation. OTS's mission is to establish competitive, cost-effective technology systems and services while acting as the sole centralized customer for the acquisition, billing, and recordkeeping of those technology services. OTS promotes integrity, quality, and efficiency in state government administration, IT standards, and policy implementation by providing state agencies with exemplary technology systems and services [67].

Discussion of Results

DOTD's Existing Workflows with Geotechnical Data

Currently, DOTD requests geotechnical data from consultants in two formats: static boring logs in PDF, and the associated digital data in gINT. Consultants use their preferred software systems, such as gINT, OpenGround, RSLog, BoreDM, TabLogs, or other borehole data management platforms, to prepare the deliverables. As gINT sunsets, other options will be needed for geotechnical data management. DOTD chose KeyLAB and OpenGround as its path forward and intends to remain software-agnostic (see Phase IV [4]) moving forward. The intent is that DIGGS and other tools should allow for the interaction and transfer of geotechnical digital data. Regardless, all submissions must conform to DOTD's standardized requirements, ensuring both consistency and usability. DOTD manages all geotechnical data through OpenGround, which serves as the central data management system. Figure 5 shows the major geotechnical data flow at DOTD.

Figure 5. Current geotechnical data flow at DOTD [68]



- Static boring logs in PDF format
- Digital data in **gINT** format
- Both should be in DOTD's standardized template formats.

Consultants use their preferred geotechnical database software systems to prepare the requested data. They can be gINT, OpenGround, RSLog, BoreDM, TabLogs, or any other.

Consultants submit both PDF boring logs and **gINT** files aligned with DOTD's **standardized** requirements.

LADOTD manages the submitted data using OpenGround.

Internally, the Geotechnical Unit at DOTD uses OpenGround plugins to export data into Excel or Power BI for site planning, characterization, and design analysis. While some repetitive tasks can be automated and completed quickly, advanced automation, geospatial analysis, and collaboration remain limited due to the constraints of Excel and Power BI.

For design and construction projects delivered by consultants, DOTD typically shares gINT files, allowing external teams to conduct their own analyses using their preferred workflows.

One of the most time-consuming and challenging steps in this process is developing soil design models and selecting design parameters. If soil strength parameters are underestimated, the project may incur unnecessarily high construction costs. Conversely, if parameters are overestimated, the design may lack sufficient reliability against failure.

Currently, the approaches used to develop soil models and parameters can be subjective, difficult to quantify, and inconsistent across agencies and consultants, making evaluation difficult. While DOTD continues to refine its state-level design specifications, the agency is working toward a more consistent, standardized workflow, aligned with FHWA and AASHTO national standards, that can be applied across both internal DOTD projects and external consultant-delivered projects.

The Sunset of gINT

Bentley Systems, through its Seequent subsidiary, has announced that gINT will reach the end of its supported life on December 31, 2028, with new license sales ending in 2027. While existing users will continue to receive limited support until that date, the software's legacy architecture makes it increasingly difficult to maintain compatibility with modern systems and evolving security requirements. Bentley is transitioning its geotechnical data management strategy to OpenGround, a cloud-based platform designed for real-time collaboration and integration across infrastructure design workflows.

At the same time, several other commercial solutions are emerging in the marketplace, such as RSLog, TabLogs, BoreDM, and others that are expected to mature in the coming years. This evolving landscape highlights not only the need to evaluate specific replacement platforms but also the importance of developing and implementing software-agnostic strategies for geotechnical digital data deliverables. By standardizing data structures and workflows independently of any single vendor, agencies and consultants can better ensure long-term accessibility, interoperability, and reliability of subsurface information to support engineering design and construction. In this regard, adoption of open data exchange standards such as DIGGS (Data Interchange for Geotechnical and Geoenvironmental Specialists) can add significant value by enabling consistent, vendor-neutral data sharing across organizations and projects, thereby future-proofing digital geotechnical workflows.

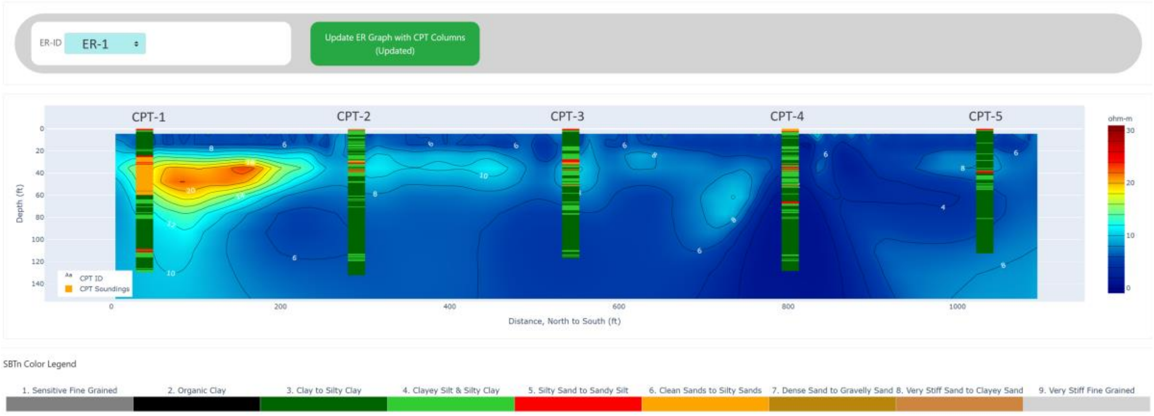
Web-Based Prototypes in DOTD's Deep Foundation Projects

To establish a standardized, software-agnostic framework that supports engineering design and construction in DOTD projects, the Geotechnical Unit at DOTD previously partnered with a retainer contractor to develop and test web-based prototypes across several production projects. These prototypes introduced innovative techniques to automate and optimize geotechnical site characterization and design analysis.

The tools enabled engineers to interactively visualize, efficiently evaluate, and rapidly interpret statistical measures of geotechnical data, ultimately facilitating the development of more reliable soil design models. They were designed to integrate and process diverse data types, including laboratory testing data from soil borings, Cone Penetration Test (CPT) results, field Vane Shear Test (VST) data, LiDAR datasets, geophysical testing data, instrumentation outputs, and deep foundation field load testing results.

The implementation of advanced site characterization methods, including cone penetration testing, seismic and electrical geophysics, etc., can augment the parameter selection process. However, it is typically tedious and time-consuming to combine data from different investigation sources for data visualization and interpretation. A web-based prototype was previously implemented, including features to visualize the geospatial locations of different geotechnical exploration features (e.g., lines and points) on an interactive map. In this prototype, users could efficiently and interactively select any combination of exploration methods to visualize and interpret the data. For example, Figure 6 shows a screenshot of an interactively generated figure that combines a 2-D electrical resistivity survey with nearby cone penetration testing soundings.

Figure 6. Interactive electrical resistivity survey profile with CPT soundings to evaluate the spatial variability of a project design site [69]

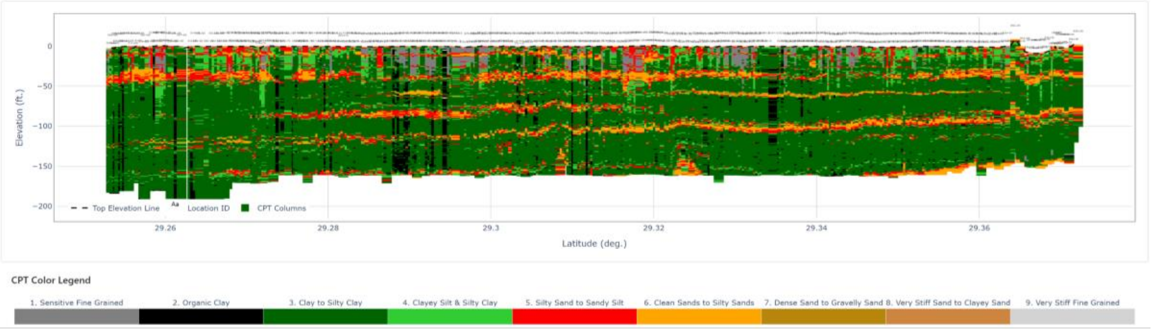


ER-ID: ER-1

In Figure 6, CPT soundings are interpreted and visualized with the normalized soil behavior types using Robertson's method [70]. The electrical resistivity surveys typically show comparatively high resistivity values for silt and sands, depicted as warm (orange to red) colors in the contour plot. Clays typically have lower resistivity values, which are represented by cool (blue) colors in the contour plot. In CPTs, the same warm colors represent silt- and sand-like materials, while green colors represent clay-like materials. As this case shows, the continuous electrical resistivity survey data closely matches the discrete CPT columns, demonstrating that data from multiple site characterization methods can effectively help engineers and designers to better understand the variability of subsurface stratigraphy. In cases where multiple site characterization methods do not agree, additional tests and interpretation may be required to assess the data quality of each method and identify the cause of the discrepancy. In any case, this prototype provides an efficient means to visualize and evaluate the data from multiple site characterization methods.

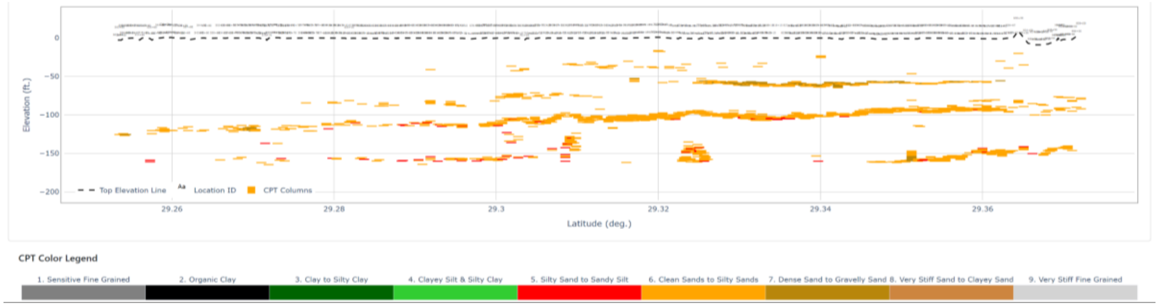
Additionally, another prototype efficiently visualized and interpreted data from a large amount of CPT soundings to generate continuous subsurface stratigraphy. Figure 7 shows a screenshot of an interactive cross-section profile that includes more than 300 CPTs, totaling approximately 1 million data points. Typically, such a plot would be tedious to generate using standard geotechnical data management software due to the sheer amount of data, but plots are easily accomplished with the DOTD GeoData-eXplorer (GDX-plorer).

Figure 7. Soil stratigraphy profile with more than 300 CPT soundings to evaluate the spatial variability of the design site [71]



The CPT soundings are interpreted and visualized with the normalized soil behavior types using Robertson's method [70]. Further, the result is not just a static image; all data are digitally embedded to allow interactive manipulation to further understand the subsurface stratigraphy. Figure 8 shows the same cross-section profile as Figure 7, with a user-defined data filter to identify and visualize critical silt and sand layers for specific design purposes.

Figure 8. CPT stratigraphy profile with user-defined rules to identify and visualize critical soil design layers [71]



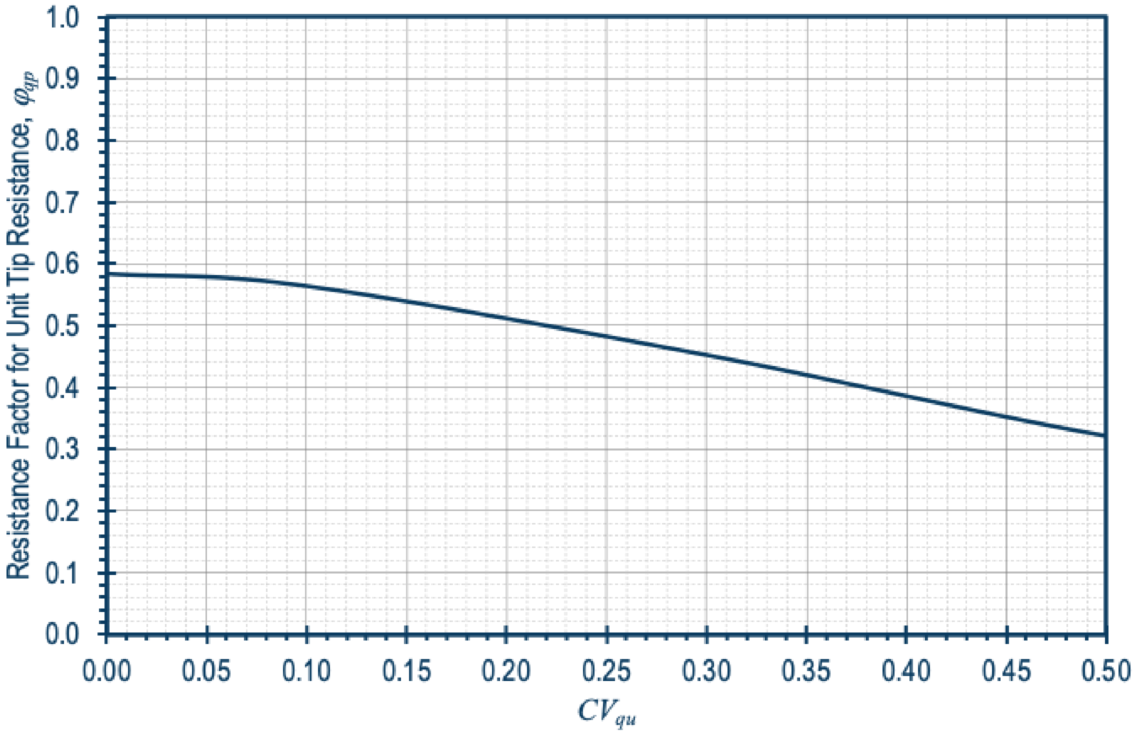
Beyond data integration, the platform also automated aspects of site characterization using statistical methods and incorporated deep foundation design procedures aligned with FHWA guidelines, including GEC-5, GEC-10, and GEC-12. Together, these capabilities demonstrated the potential of web-based solutions to deliver a standardized, software-agnostic framework that streamlines complex data processing and design analysis, while fostering clearer collaboration between owners and designers.

AASHTO Updates to LRFD Design Specifications

A major rewrite of Section 10 of the AASHTO LRFD Bridge Design Specifications is in progress. This update is designed to fundamentally change how geotechnical uncertainty is handled in bridge foundation design. The primary motivation for this significant update is to address a long-standing issue: the current code does not explicitly quantify or account for the uncertainty inherent in site characterization and the resulting design parameters. This can lead to inconsistencies; for example, if two engineers investigate the same site and arrive at different design parameters, the current code does not provide a clear framework to determine which characterization is more reliable or has less uncertainty. The goal of the rewrite is to create a methodical and objective framework that formally incorporates the reliability of various subsurface investigation techniques directly into the design process.

The new approach is quantitative and moves away from subjective assessments, drawing on concepts from FHWA's GEC-5. This marks a significant shift in practice, as most resistance factors will no longer be single, fixed values pulled from a table. Instead, they will be determined from curves that are a function of the Coefficient of Variation (COV), a statistical measure of variability calculated for site-specific design parameters. The quality and extent of a site investigation directly affect this COV; for instance, using more measurements or higher-quality sampling techniques will reduce the calculated COV. Figure 9 shows an example relationship between the resistance factor for unit tip resistance and the COV from compressive shear strength measurement [72]. The new specification aims for a target COV of 0.30 or less, as this is expected to produce designs with reliability that meet or exceed the LRFD specifications' target reliability. This new method directly connects the quality and quantity of one's site investigation data to the safety factors used in the final design.

Figure 9. Example relationship between the resistance factor for unit tip resistance and COV for compressive shear strength measurement [72]



To support this new framework, several sections are being completely rewritten, including 10.4 (Soil and Rock Properties Site Characterization), 10.5 (Limit States and Resistance Factors), and 10.9 (Micropiles). As part of this reorganization, resistance factor tables are being moved from Section 10.5 into the articles for their specific foundation types (e.g., Spread Footings, Driven Piles). The rewrite also consolidates repetitive articles and incorporates recent research, including NCHRP findings on downdrag and FHWA research on large-diameter open-end piles (LDOEPs).

The AASHTO update also introduces new terminology to provide clearer, more consistent language for applying these concepts. Key new terms include Design Area, which defines a site zone where design parameters are relatively consistent, and a distinction between Direct Measurement and Indirect Measurement. Direct Measurement evaluates a property without needing a transformation, whereas Indirect Measurement requires a correlation to estimate a design parameter (e.g., using SPT N-values to estimate a friction angle). Perhaps the most important new concept is the Critical Design Parameter, which has a significant influence on the design for a specific limit state. This is context-dependent; for example, the strength of a thin, soft clay seam might be a critical parameter for a shallow footing found above it but not for a deep foundation element that extends well past it.

The rollout of these changes has followed a structured timeline. A draft of the updated Section 10 was presented at the Committee on Bridges and Structures (COBS) Annual Meeting in June 2024. The implementation timeframe has not yet been determined, but the ballot item was sent for review in March 2026.

A New Unified Web-Based Framework

Overview

Based on the promising results from the implementation of prototypes in several large bridge and highway design and construction projects, DOTD's Geotechnical Unit has concluded that the development of a unified, web-based, software-agnostic framework is both feasible and strategically valuable. This framework is envisioned as a centralized platform accessible to both internal DOTD staff and external stakeholders, enabling streamlined data workflows, reducing redundancy, and enhancing collaboration across projects. It will also incorporate the latest AASHTO LRFD Design Specification updates and support DIGGS implementation, ensuring compliance with national standards and alignment with best practices in geotechnical engineering.

While earlier prototypes successfully demonstrated advanced capabilities for visualizing and analyzing CPT, geophysical, and other categories of geotechnical data, soil borings with associated laboratory testing results have been identified as the priority for the initial rollout. These datasets form the foundation of nearly all geotechnical design projects and thus provide the most practical and impactful starting point. By focusing first on this essential dataset, DOTD can deliver immediate value while simultaneously building a scalable foundation that supports future expansion.

A defining feature of the platform is its modular and highly customizable architecture. This design allows for the incremental integration of additional geotechnical data categories and advanced analytical features as needs evolve. Future modules may encompass CPT interpretation, geophysical survey integration, in-situ testing data, and real-time monitoring from construction sites. This progressive expansion ensures that the platform can adapt to DOTD's evolving requirements while incorporating emerging technologies and analytical methodologies.

The core workflows envisioned for the initial implementation include:

- **Data Importing and Exporting**—Seamless integration with existing digital data deliverable with gINT, as well as OpenGround through Application Programming Interface (API) connections, enabling efficient data transfer, improved interoperability, and compatibility with external platforms.
- **Geospatial Visualization**—Interactive mapping and site characterization tools to support planning, site selection, and evaluation of geotechnical conditions.
- **Borehole Data Visualization**—Intuitive representation of soil lithology, laboratory testing results, and SPT data, improving analysis, reporting, and communication.
- **2-D Cross-Sectional Profiles**—Dynamic visualization of soil lithology layers to facilitate clearer interpretation of subsurface conditions.
- **Interactive Statistical Analysis**—Integrated statistical tools consistent with FHWA GEC-5 and the latest AASHTO updates, enabling statistical evaluation of geotechnical parameters.
- **Design Stratigraphy Development**—Tools to construct design stratigraphy models and compile soil parameter design tables to support engineering design workflows.
- **Resistance Factor Identification**—Automated workflows for calculating resistance factors based on statistical analyses, consistent with AASHTO LRFD requirements.
- **Export of Analysis Results**—Streamlined output generation to facilitate peer review, quality assurance, and formal project submittals.

By following this phased, modular approach, DOTD ensures that the GDX-plorer platform will not only meet current project needs but also provide a robust and adaptable foundation for future innovation. Over time, this framework will evolve into a comprehensive statewide system capable of integrating diverse geotechnical datasets, supporting advanced analyses, and enhancing decision-making across all phases of geotechnical design, construction, and asset management.

Authorized users can access this web-based platform through any modern web browser, regardless of location or time, with no installation required on their local computer. Figure 10 displays the web user interface after login.

Figure 10. User interface of the new web-based platform after login

Data Importing and Exporting

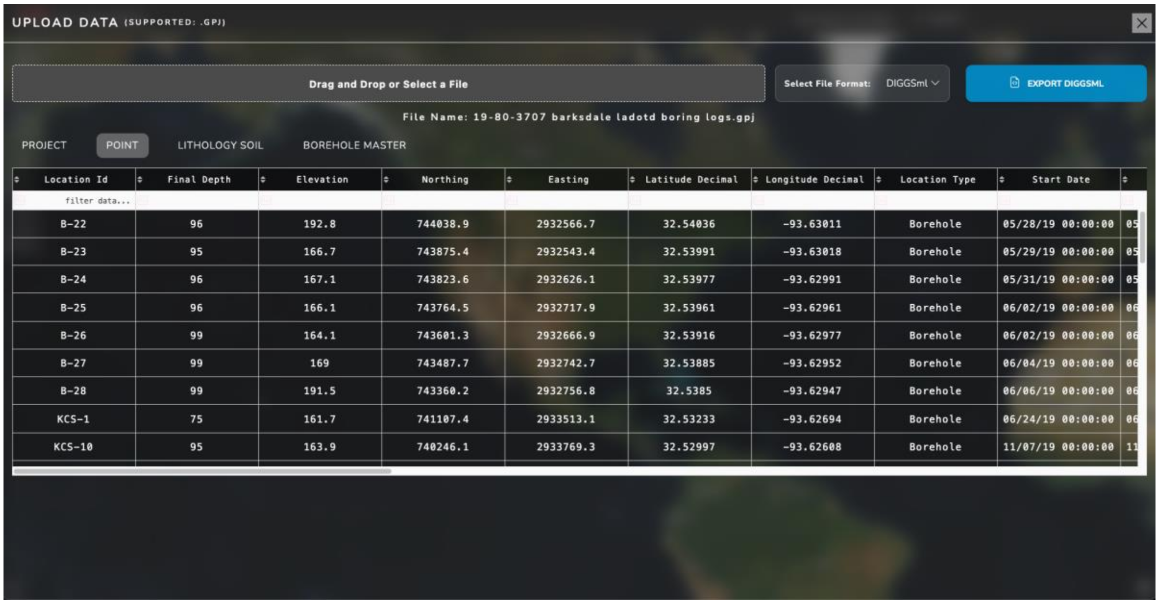
DOTD previously developed a standardized gINT template through an LTRC research initiative [2], which has since become the Department's standard format for geotechnical data submission. Today, most of DOTD's contractors use this template to provide digital geotechnical data alongside PDF boring logs as part of their routine project deliverables. For decades, gINT has served as the gold standard for generating PDF boring logs; however, the underlying digital data stored in gINT files are not readily usable by design engineers for direct geotechnical analysis, research, or correlations across a project or all DOTD projects.

In practice, geotechnical engineers typically export gINT data to Excel spreadsheets for analysis. This process is time-consuming and requires manual effort because the gINT database stores data across multiple relational tables, which translate into multiple worksheet tabs when exported. This fragmented structure often creates inefficiencies for engineers who need a consolidated dataset for analysis.

To address these challenges, the unified web-based platform includes a gINT importing module. With this module, users can quickly upload any gINT data file that complies with DOTD's standardized template. The platform automatically processes the file and populates all relevant soil boring information and laboratory test results within a modern web browser.

Once loaded, the data can be used seamlessly for visualization, statistical analysis, and design workflows without requiring intermediate manual steps. Figure 11 illustrates the data importing and exporting interface with a gINT data file that has been successfully loaded.

Figure 11. Data importing and exporting interface of the web-based platform with a gINT data file successfully loaded



Select File Format: DIGGSml

File Name: 19-80-3707 barksdale ladotd boring logs.gpj

Location Id	Final Depth	Elevation	Northing	Easting	Latitude Decimal	Longitude Decimal	Location Type	Start Date
B-22	96	192.8	744038.9	2932566.7	32.54036	-93.63011	Borehole	05/28/19 00:00:00
B-23	95	166.7	743875.4	2932543.4	32.53991	-93.63018	Borehole	05/29/19 00:00:00
B-24	96	167.1	743823.6	2932626.1	32.53977	-93.62991	Borehole	05/31/19 00:00:00
B-25	96	166.1	743764.5	2932717.9	32.53961	-93.62961	Borehole	06/02/19 00:00:00
B-26	99	164.1	743601.3	2932666.9	32.53916	-93.62977	Borehole	06/02/19 00:00:00
B-27	99	169	743487.7	2932742.7	32.53885	-93.62952	Borehole	06/04/19 00:00:00
B-28	99	191.5	743360.2	2932756.8	32.5385	-93.62947	Borehole	06/06/19 00:00:00
KCS-1	75	161.7	741107.4	2933513.1	32.53233	-93.62694	Borehole	06/24/19 00:00:00
KCS-10	95	163.9	740246.1	2933769.3	32.52997	-93.62608	Borehole	11/07/19 00:00:00

For performance and security, all uploaded data are temporarily cached on a remote cloud server to support computation and analysis. Results are then delivered to the client browser for visualization and interaction. Importantly, no project data are stored permanently in the cloud, ensuring confidentiality and compliance with DOTD's data management policies.

The platform also provides flexible exporting options:

- Data can be exported into a streamlined Excel spreadsheet with a more user-friendly structure than the raw Excel exports generated by gINT. This optimized structure enables engineers to conduct analyses more efficiently.
- Data can also be exported as DIGGSml files, providing interoperability with other DIGGS-compliant software. This capability makes the platform future-ready by enabling seamless data exchange across agencies, consultants, and other digital engineering platforms. Figure 12 shows a sample screenshot of the DIGGSml file exported from the platform.

Figure 12. Sample screenshot of the DIGGSml file exported from the web-based platform

```xml
<?xml version="1.0" ?>
<Diggs xmlns:gml="http://www.opengis.net/gml/3.2" xmlns="http://diggsml.org/schema-dev" xmlns:diggs="http://diggsml.org/schema-dev" xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xmlns:xlink="http://www.w3.org/1999/xlink"
xmlns:g3.3="http://www.opengis.net/gml/3.3/ce" xmlns:glr="http://www.opengis.net/gml/3.3/lr" xmlns:glrov="http://www.opengis.net/gml/3.3/lrov" xmlns:witsml="http://www.witsml.org/schemas/131" xsi:schemaLocation="http://diggsml.org/schema-dev
https://diggsml.org/schema-dev/Diggs.xsd" gml:id="DGS_14C0DA915A7D">
  <documentInformation>
    <DocumentInformation gml:id="DGS_683920B731C7">
      <creationDate>2025-09-04</creationDate>
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        <BusinessAssociate gml:id="BA_144EBA07F9E5">
          <gml:name>DOTD GD Xplorer</gml:name>
        </BusinessAssociate>
      </author>
      <disclaimer>See disclaimer at LTRC's website</disclaimer>
      <auditTrail>
        <Remark>
          <content>Generated by DOTD GD Xplorer</content>
          <remarkDateTime>2025-09-04</remarkDateTime>
        </Remark>
      </auditTrail>
    </DocumentInformation>
  </documentInformation>
  <project>
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      <gml:name>I-220/I-20 Interchange Improvement</gml:name>
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            </BusinessAssociate>
          </businessAssociate>
        </Role>
      </role>
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          <gml:description>Project area in Shreveport, LA</gml:description>
        </Locality>
      </locality>
    </Project>
  </project>
  <samplingFeature>
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      <gml:name>B-22</gml:name>
      <internalIdentifier codeSpace="DOTD_GD_Xplorer">B-22</internalIdentifier>
      <status>FINAL</status>
      <remark>
        <Remark>
          <content>Hammer Efficiency: 74%</content>
          <remarkDateTime>2025-09-04</remarkDateTime>
        </Remark>
      </remark>
      <investigationTarget>Natural Ground</investigationTarget>
      <projectRef xlink:href="#Project_H.003370"/>
      <locality>
        <Locality gml:id="LOC_1EB155D5F57B">
          <gml:description>Borehole B-22 location</gml:description>
          <station>93260.32</station>
          <offset uom="ft">26.65</offset>
          <offsetDirection>L</offsetDirection>
        </Locality>
```

Through these importing and exporting capabilities, the platform transforms gINT data from static archival records into actionable datasets that can be directly leveraged in modern web-based workflows, supporting both current and future geotechnical data management practices.

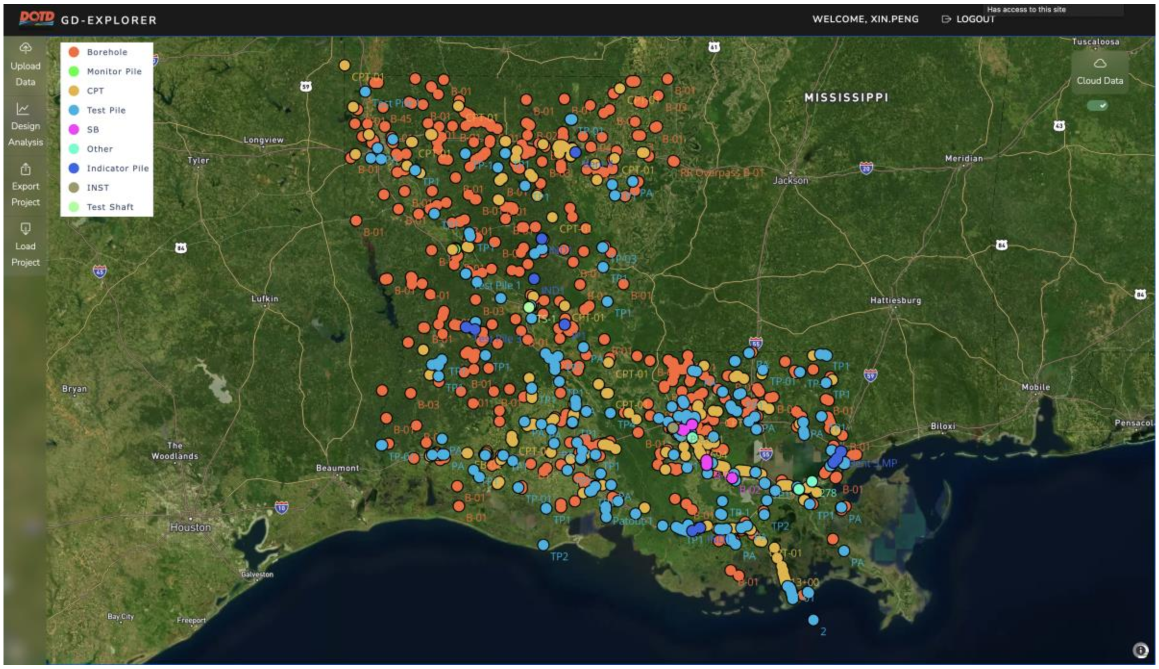
API Integration

As previously discussed, DOTD's Geotechnical Unit currently relies on OpenGround to manage geotechnical data from production projects conducted by internal crews and external consultants. Internally, OpenGround plugins are primarily used to export data into Excel or Power BI for tasks such as site planning, characterization, and preliminary design analysis. While these tools enable some degree of automation for repetitive tasks, they remain limited in their ability to support advanced automation, geospatial analysis, and collaborative workflows.

To address these limitations, the API capabilities offered by OpenGround are being leveraged and integrated into the GDX-plorer platform. This approach provides a scalable and flexible long-term solution for data management, analysis, and visualization. As part of this research effort, a feasibility study and preliminary framework for OpenGround API integration were completed. The results demonstrate that the OpenGround API is fully compatible with the platform, enabling seamless data interchange between the OpenGround Cloud database managed by DOTD and the web-based environment for advanced analysis and visualization.

Figure 13 illustrates this capability, showing an interactive map within the platform populated with geotechnical point features loaded directly from the OpenGround Cloud database via an API connection. At the time of capture, the platform successfully retrieved more than 4,900 point locations, including over 2,700 soil borings, 1,300 CPTs, and 760 monitoring and test piles. This demonstrates the platform's ability to dynamically scale and handle large, diverse datasets.

Figure 13. Screenshot of the interactive map within the platform populated with geotechnical point features loaded directly from the OpenGround



While the API connection can access nearly all data stored in OpenGround, the current project focuses on borehole data and associated laboratory testing results, as these form the foundation of geotechnical design analysis. Accordingly, the platform currently emphasizes querying and analyzing borehole-related datasets. Future project phases may extend functionality to include CPT data, pile testing records, and other deep foundation datasets.

At present, the platform has successfully imported and managed more than 26,000 lithology layers and 58,000 soil samples with laboratory testing results from OpenGround. These datasets can now be leveraged for interactive visualization, statistical evaluation, and design workflows in a modern web-based environment, capabilities that extend far beyond the constraints of Excel or Power BI.

Site Selection

As discussed in the previous sections, the current version of the unified GDX-plorer platform can load geotechnical data directly from gINT files using the standardized DOTD gINT template or the OpenGround API connection. Figure 14 illustrates a screenshot of borehole locations loaded from a gINT file for a DOTD project.

Figure 14. 3-D interactive map view displaying deep soil boring locations imported from a gINT file onto the web-based platform

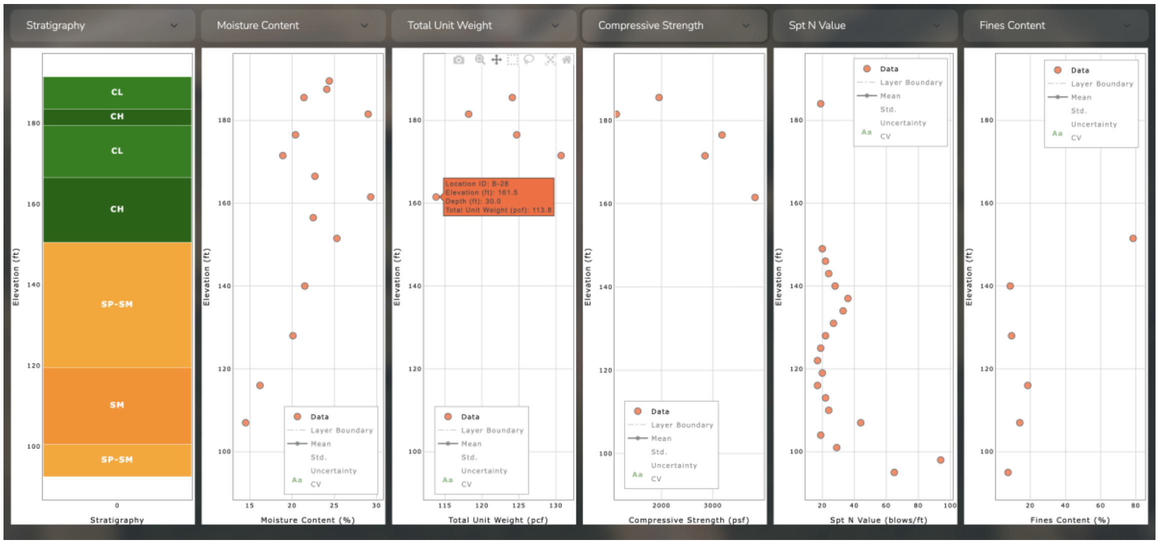
Once the borehole locations are loaded into the platform, engineers can efficiently group soil borings using interactive tools such as lasso select or box select. This functionality enables the rapid evaluation of subsurface conditions for site characterization and design-driven site selection. By integrating these selection tools with the platform's data visualization and design features, engineers can analyze soil lithology and laboratory test results to develop conceptual soil models with simplified stratigraphy and corresponding geotechnical design parameters from the selected borings. This approach facilitates the identification of spatial patterns, supports assessment of potential geotechnical risks, and enables data-driven decision-making regarding project site suitability.

Data Visualization

In addition to the geospatial view of geotechnical features on the interactive project map, engineers can select either a single boring or a group of borings for more detailed subsurface evaluation. To support this process, the platform implements a suite of interactive data visualization tools that provide engineers with a clearer, more efficient way to explore geotechnical datasets.

One key feature is the ability to generate interactive data profile charts plotted along elevation, displaying soil stratigraphy alongside corresponding laboratory test results and SPT data. Figure 15 shows an example of these charts generated for a single soil boring selected from the interactive map. The layout is intentionally designed to mimic the content of a typical DOTD PDF boring log submittal, while providing a far more dynamic and flexible user experience within a web browser.

Figure 15. Interactive data profile charts plotted along elevation for a single soil boring selected from the interactive map



Location ID: B-28
Elevation (ft): 161.5
Depth (ft): 30.0
Total Unit Weight (pcf): 113.8

On the far left, the stratigraphy chart presents lithology layers by elevation, with each layer color-coded and labeled with the corresponding Unified Soil Classification System (USCS) classification. In the example shown, green shades represent lean and fat clays, while yellow shades represent sand deposits. Adjacent to the stratigraphy chart are a series of integrated property charts, displaying profiles for key soil parameters such as moisture content (%), total unit weight (pcf), unconfined compressive strength (psf), SPT N-values (blows/ft.), and fines content (%).

Beyond these fundamental properties, engineers can also visualize additional datasets, including undrained shear strength (psf), dry unit weight (pcf), liquid limit, plastic limit, plasticity index, liquidity index, and other derived soil parameters. Indirect measurements and correlations, such as N_{60} (blows/ft.), $N_{1,60}$ (blows/ft.), and SPT-based friction angles (°) calculated using different correlation methods, can also be plotted. These correlations and their analytical applications will be discussed in greater detail in later sections.

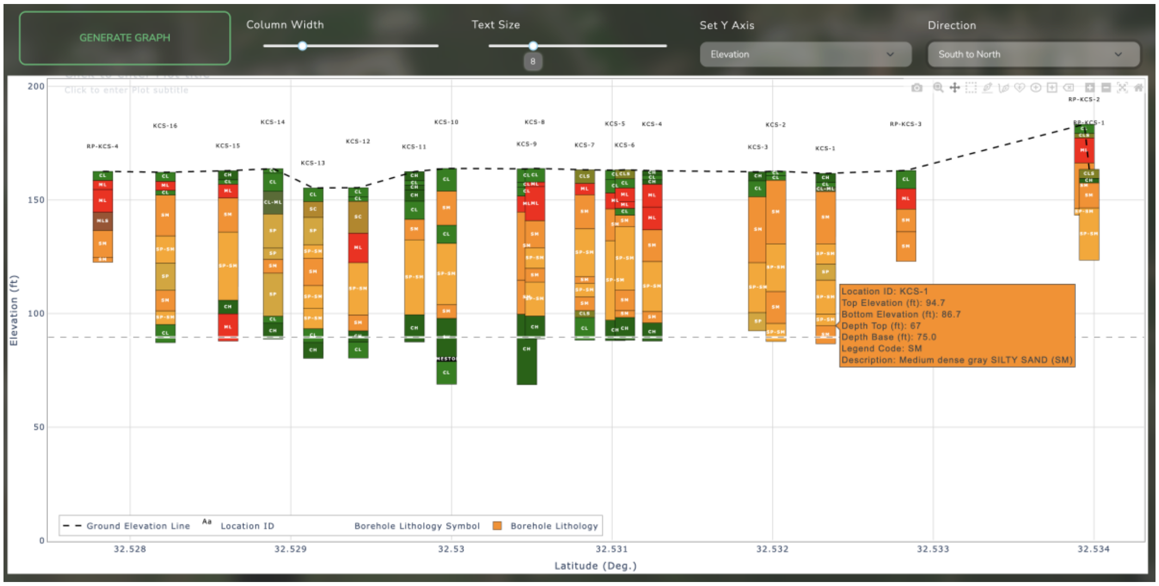
The charts are fully interactive; engineers can hover the mouse over any data point to reveal detailed information, including the exact value, borehole ID, elevation, and depth, as shown in the orange tooltip in Figure 15 for the total unit weight chart. Users can also zoom in, pan across, or dynamically adjust the X- and Y-axis ranges to focus on a specific interval of interest, such as a problematic soil zone within a given depth range. This interactive functionality offers a significant advantage over static PDF boring logs, allowing engineers to more efficiently evaluate data trends, identify anomalies, and refine interpretations.

Several additional statistical visualization components are generated alongside these charts. Although hidden in Figure 15 for clarity, these components are automatically calculated in the background and provide advanced insights into the statistical distribution of soil parameters. Their details and applications will be discussed in the following section.

As discussed earlier, similar profile charts can also be generated dynamically for groups of borings selected from the map. In these cases, the platform aggregates data across multiple locations, allowing engineers to compare soil conditions laterally and identify spatial trends across a project site.

Beyond profile charts, engineers can also generate interactive cross-section or fence-diagram views for groups of borings, as shown in Figure 16. In this example, 20 borings are selected and displayed along a west-to-east alignment. Each lithology layer is color-coded using the same rules as in the profile view, with USCS classification symbols displayed at the center of each layer. This cross-section view is also interactive; hovering over any layer reveals detailed lithology descriptions, borehole ID, and top and bottom elevations and depths, as shown in the yellow tooltip in Figure 16 for Borehole KCS-1.

Figure 16. Interactive cross-section view of 20 borings along a west-to-east alignment



Text Size: 8

Set Y Axis: Elevation

Direction: South to North

Location ID: KCS-1
Top Elevation (ft): 94.7
Bottom Elevation (ft): 86.7
Depth Top (ft): 67
Depth Base (ft): 75.0
Legend Code: SM
Description: Medium dense gray SILTY SAND (SM)

The visualization is highly customizable. Engineers can adjust the borehole column width with the Column Slider, toggle the Y-axis between depth and elevation, and change the alignment direction between west–east and south–north. With these capabilities, generating a cross-section for any group of borings within a project takes only a few seconds, dramatically reducing the time and effort compared to preparing static cross-section figures in PDF format. This interactivity empowers engineers to rapidly evaluate subsurface conditions and make informed design decisions during site characterization and early project phases.

Soil Stratigraphy and Dynamic Data Statistics

Identifying a design site with a group of soil borings and developing a reasonable conceptual soil model for design analysis typically requires creating a composite soil stratigraphy along with corresponding design parameters for each layer. This is often an iterative process that relies on both engineering judgment and systematic evaluation.

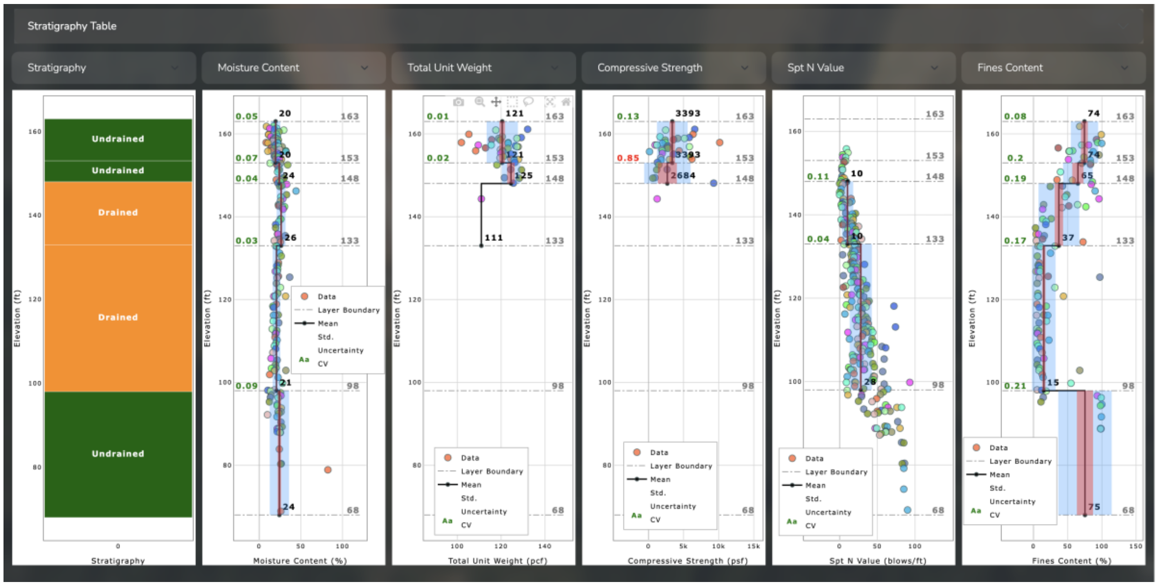
This web-based platform, GDX-plorer, supports this process by providing intuitive features that integrate statistical calculations consistent with FHWA's GEC-5 guidance and the ongoing AASHTO LRFD design specification updates. These tools streamline parameter development while maintaining flexibility for engineering input.

An example workflow for developing design layers and parameters is illustrated in this section. Based on the cross-section profile shown in Figure 16, the soil borings from

Borehole RP-KCS-4 at the south (left) side toward Borehole KCS-4 to the north exhibit a similar stratigraphic trend. Specifically, the major borings indicate clay and silt layers extending from the ground surface down to approximately El. +140 ft., followed by predominantly sand layers between El. +140 ft. and El. +100 ft., then clay and silt layers again below El. +100 ft.

As an initial evaluation, it is reasonable to group these borings into a single preliminary design site for assessing deep foundation strategies. Based on this assumption, engineers can return to the data profile charts to conduct more detailed evaluations and develop a preliminary soil model. From this model, design layers can be defined, and corresponding design parameters can be derived for deep foundation design analysis, as demonstrated in Figure 17.

Figure 17. Data profile charts for a preliminary design site with statistical features



Similar to the single-boring profile charts discussed earlier, the first chart on the left side of Figure 17 is the stratigraphy chart. Since 20 soil borings were selected, this chart integrates all soil samples, automatically aggregates them by USCS classification, and generates a composite stratigraphy. Because undrained and drained soils are the two primary modeling categories in Louisiana, the algorithm automatically classifies the composite soil layers into these two categories. Green shades represent undrained layers, and yellow shades represent drained layers. Sub-layers within each category are determined by the dominant USCS classifications of the soil samples included.

The key steps of the stratigraphy generation process are summarized below:

1. Creates five-foot elevation intervals spanning the minimum to maximum elevations from all samples.
2. Groups all soil samples within each elevation interval.
3. Calculates the percentage of each USCS classification in each interval.
4. Identifies the dominant material type in each elevation range.
5. Combines adjacent elevation intervals with the same dominant material type.
6. Creates continuous layers of the same material type.
7. Calculates the total thickness and percentage of each consolidated layer.

This auto-generated composite stratigraphy serves as a starting point for analysis. Engineers can further refine it using statistical trends and their own engineering judgment.

Adjacent to the stratigraphy chart are a series of property charts that display profiles for key soil parameters, including moisture content (%), total unit weight (pcf), unconfined compressive strength (psf), SPT N-values (blows/ft.), and fines content (%). Within each property chart, six statistical visualization components are dynamically generated:

- **Testing results**—Circular points represent measured values, with each color corresponding to a specific boring.
- **Layer boundaries**—Dark gray dashed horizontal lines indicate the elevation boundaries of composite layers, with elevation values labeled in the top-right corner of each line.
- **Mean values**—Vertical lines showing the average values of test results within each composite layer.
- **Standard deviation bands**—Semi-transparent blue bands representing the mean ± one standard deviation for test results in each layer.
- **Uncertainty bands**—Semi-transparent red bands calculated based on ongoing AASHTO LRFD updates.
- **Coefficient of variation (COV)**—Values displayed at the top-left of boundary lines. As noted in FHWA GEC-5 and AASHTO LRFD updates, geotechnical designs based on soil parameters with COV ≤ 0.3 generally achieve or exceed target reliability. Therefore, COV values greater than 0.3 are automatically highlighted in red (e.g., the “0.85” shown at El. 153 in the compressive strength chart) while acceptable values are shown in green.

Each component can be toggled on or off, giving engineers the flexibility to focus on specific features for subsurface evaluation. This combination of automated statistical processing and interactive visualization allows engineers to efficiently move from raw boring data to defensible design parameters in a transparent, data-driven workflow.

Outlier Selection and Statistic Update

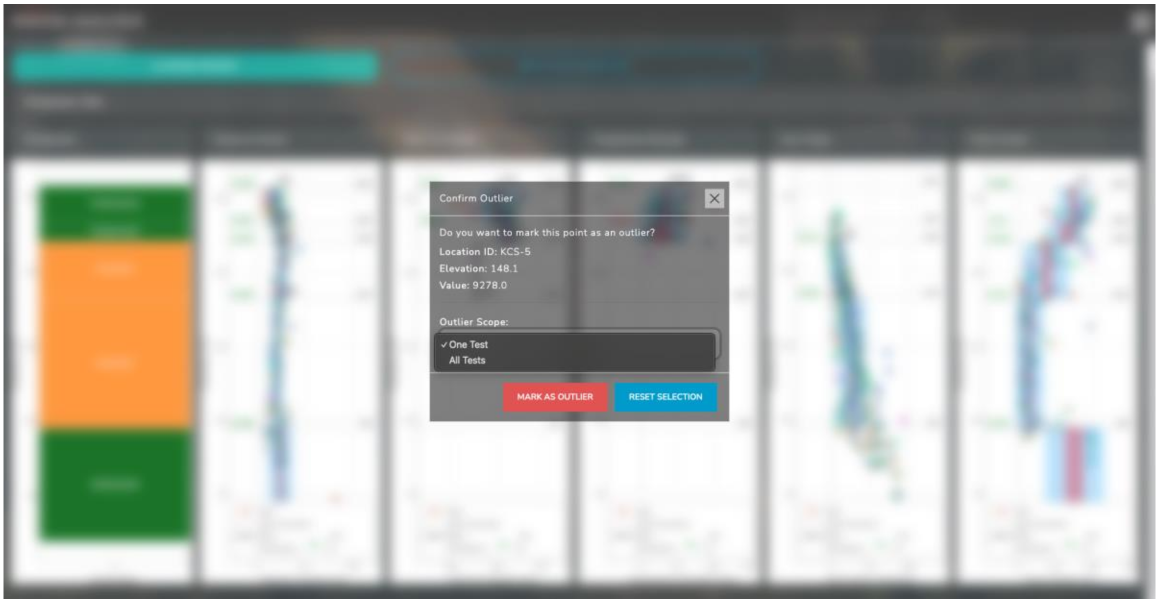
The quality of testing results from soil borings can vary, and in some cases, engineers must rely on their judgment and experience to identify outlier data points. These outliers may need to be excluded when calculating design parameters and related statistics, such as COV values, for each soil design layer. This web-based platform provides an intuitive interface that makes this process straightforward.

For example, in the compressive strength profile shown in Figure 17, one data point at El. +148 ft. records a compressive strength of approximately 9,300 psf, significantly higher than the other values within the undrained layer defined between El. +153 ft. and El. +148 ft. An engineer may take a conservative approach and exclude this point when calculating the mean compressive strength for the layer. Doing so would also reduce the COV value (initially 0.85, as shown in Figure 17), which exceeds the reliability threshold specified in FHWA GEC-5 and the ongoing AASHTO LRFD updates.

To exclude the outlier, the engineer simply clicks the data point in the chart. A pop-up window (see Figure 18) then provides two scoping options:

1. One Test—Excludes only the selected compressive strength test result from its soil sample.
2. All Tests—Excludes all laboratory test results associated with the same soil sample.

Figure 18. Pop-up window providing two scoping options for outlier selection



Do you want to mark this point as an outlier?

Location ID: KCS-5

Elevation: 148.1

Value: 9278.0

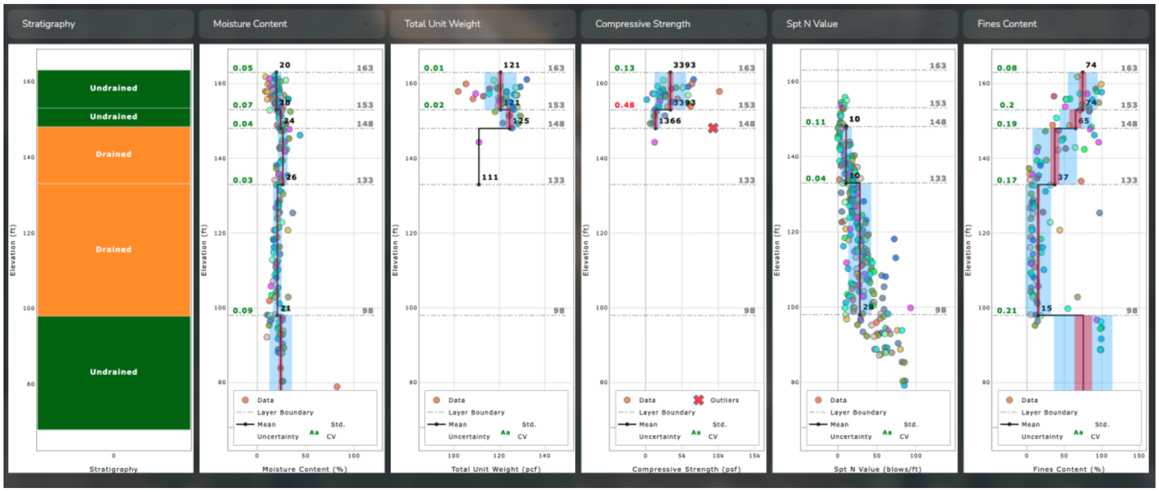
Outlier Scope:

✓ One Test

All Tests

The first method affects only the compressive strength statistics for that layer, whereas the second method affects all property charts associated with that layer. After selecting the desired option and clicking the red “MARK AS OUTLIER” button, the data profile charts automatically update, and excluded points are displayed as red cross markers; see Figure 19. In this example, applying the “One Test” option reduced the mean compressive strength from 2,684 psf (Figure 17) to 1,366 psf and decreased the COV value from 0.85 to 0.48.

Figure 19. Updated data profile charts with an outlier data point excluded



The process can be repeated to exclude additional data points based on engineering judgment. If an excluded point needs to be reinstated, the user can simply click the marker again to remove it from the outlier group.

This outlier selection module not only streamlines the recalculation of statistics with a few clicks but also enhances collaboration by allowing peers to review and refine outlier selections efficiently.

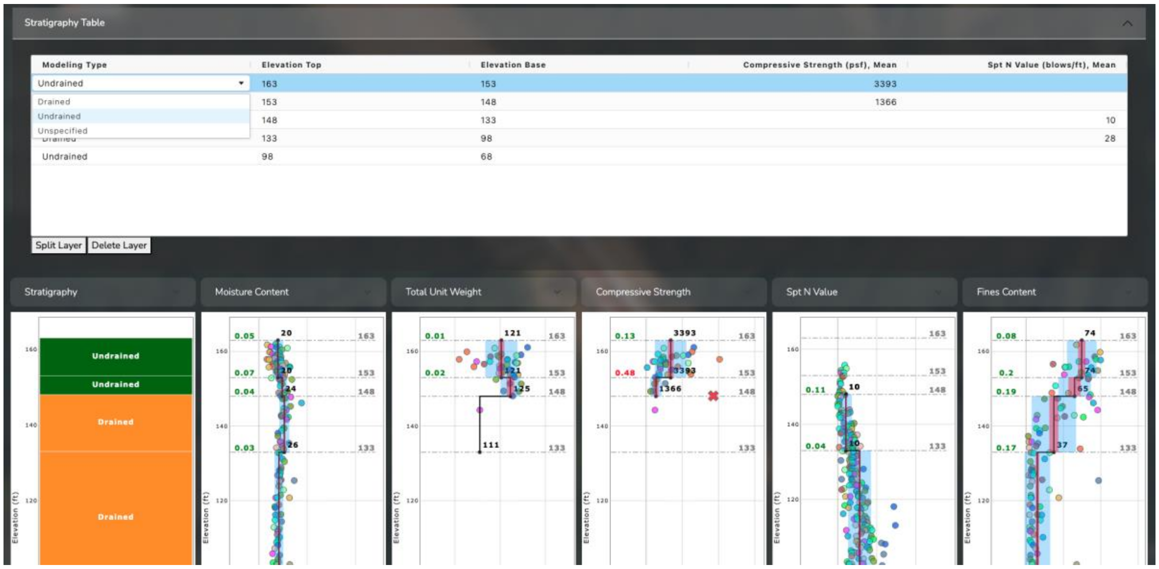
Design Stratigraphy Adjustment and Statistic Update

The layer boundary elevations shown in the data profile charts in Figure 19 are automatically generated following the steps described in the FHWA GEC-5 *Soil Stratigraphy and Dynamic Data Statistics* Section. While this provides a strong starting point, the boundaries may not always align perfectly with engineering experience. To address this, the platform includes intuitive tools that allow engineers to adjust boundary elevations and soil-modeling types (undrained or drained) based on professional judgment.

A stratigraphy table, dynamically generated and displayed above the data profile charts, supports these adjustments. By default, the table is collapsed, but it can be expanded by clicking its title bar, shown in Figure 20. Within the table:

- The Modeling Type and Elevation Base columns are editable by the user.
- The top value in the Elevation Top column is automatically set to the maximum ground elevation among the selected boreholes, and subsequent rows are updated automatically when the Elevation Base is modified.
- Statistical values such as Compressive Strength (psf), Mean, and SPT N Value (blows/ft.) are calculated automatically and correspond directly to the mean trend lines shown in the data profile charts.
- Compressive strength and undrained shear strength are calculated only for “undrained” layers, while SPT N-values, N_{60}, $(N_1)_{60}$, and SPT-based friction angle correlations are calculated only for “drained” layers.

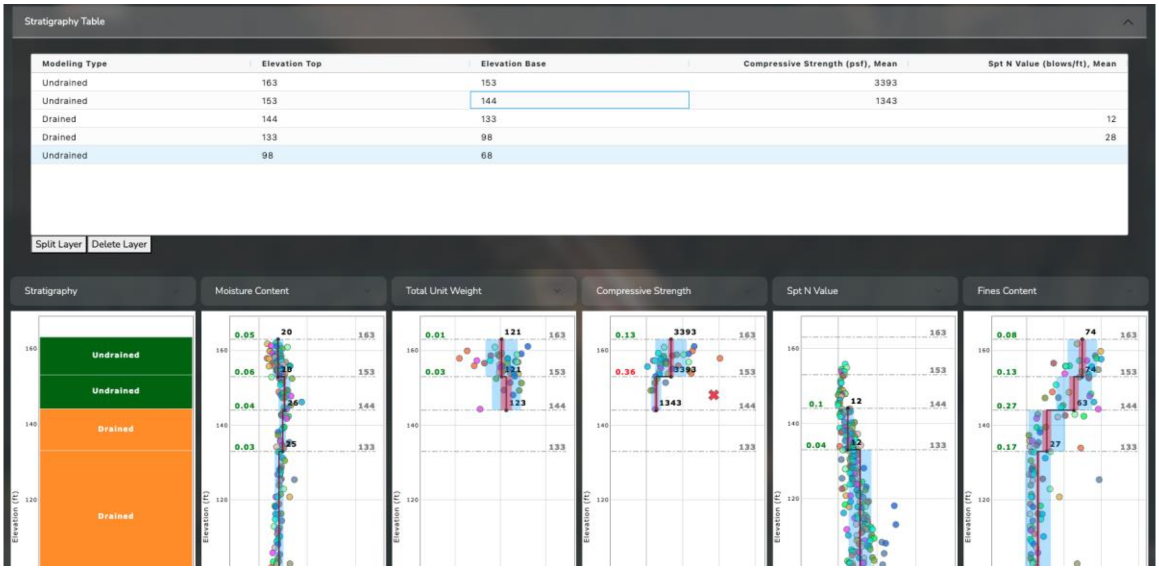
Figure 20. Stratigraphy table, dynamically generated and displayed above the data profile charts



Modeling Type	Elevation Top	Elevation Base	Compressive Strength (psf), Mean	Spt N Value (blows/ft), Mean
Undrained	163	153	3393	
	153	148	1366	
	148	133		10
	133	98		28
Undrained	98	68		

To modify the Modeling Type, users simply double-click the relevant cell and select the desired category from the dropdown menu. Adjusting boundary elevations is equally straightforward; users edit the Elevation Base value, and all associated statistics are updated automatically. For example, extending the bottom boundary of the second undrained layer from El. +148 ft. to El. +144 ft. instantly recalculates the compressive strength mean and COV, reducing them from 1,366 psf to 1,343 psf and from 0.48 to 0.36, respectively; see Figure 21.

Figure 21. Updated stratigraphy table and data profile charts after the adjustment of the bottom boundary elevation of the second undrained layer from the top

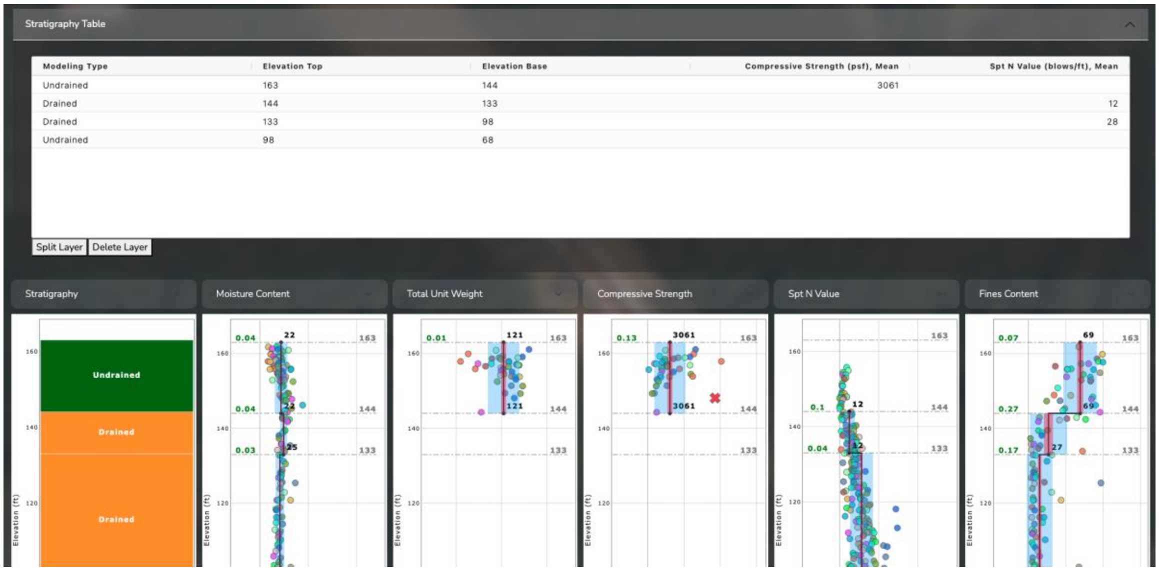


Stratigraphy Table

Modeling Type	Elevation Top	Elevation Base	Compressive Strength (psf), Mean	Spt N Value (blows/ft), Mean
Undrained	163	153	3393	
Undrained	153	144	1343	
Drained	144	133		12
Drained	133	98		28
Undrained	98	68		

Beyond boundary edits, the platform also enables splitting or merging layers within the stratigraphy table. For instance, if the engineer decides to merge the top two undrained layers, they can simply select the second layer and click the "Delete Layer" button beneath the table. The stratigraphy table and data profile charts update automatically; see Figure 22. In this case, the elevated COV value observed in the second undrained layer disappears because the data points are consolidated, and the recalculated COV for the combined layer now meets the FHWA GEC-5 and AASHTO LRFD reliability threshold (COV ≤ 0.3).

Figure 22. Updated stratigraphy table and data profile charts after combining the top two undrained layers



Stratigraphy Table

Modeling Type	Elevation Top	Elevation Base	Compressive Strength (psf), Mean	Spt N Value (blows/ft), Mean
Undrained	163	144	3061	
Drained	144	133		12
Drained	133	98		28
Undrained	98	68		

This design stratigraphy table provides engineers with an efficient, transparent way to refine soil models by combining engineering judgment with real-time statistical validation. The process not only streamlines model adjustments but also ensures that the resulting subsurface models and design parameters are defensible and consistent with FHWA and AASHTO specifications.

SPT-Based Correlations for Friction Angles

According to the updated AASHTO Section 10 guidance, both direct and indirect measurements can be used to establish soil design parameters. Direct measurements come from tests that directly measure the engineering property of interest. For example, the compressive strength data points shown in the previous example (Figure 22) are direct measurements from undrained shear strength tests.

Indirect measurements, by contrast, require transformation of another measured property to estimate the desired parameter. For instance, the friction angles of drained materials are design parameters that are often not measured in laboratory tests for DOTD projects. Instead, they are commonly estimated from SPT blow counts, which were also visualized in Figure 22.

To support this process, the platform implements four correlation methods typically used by DOTD for estimating drained friction angles:

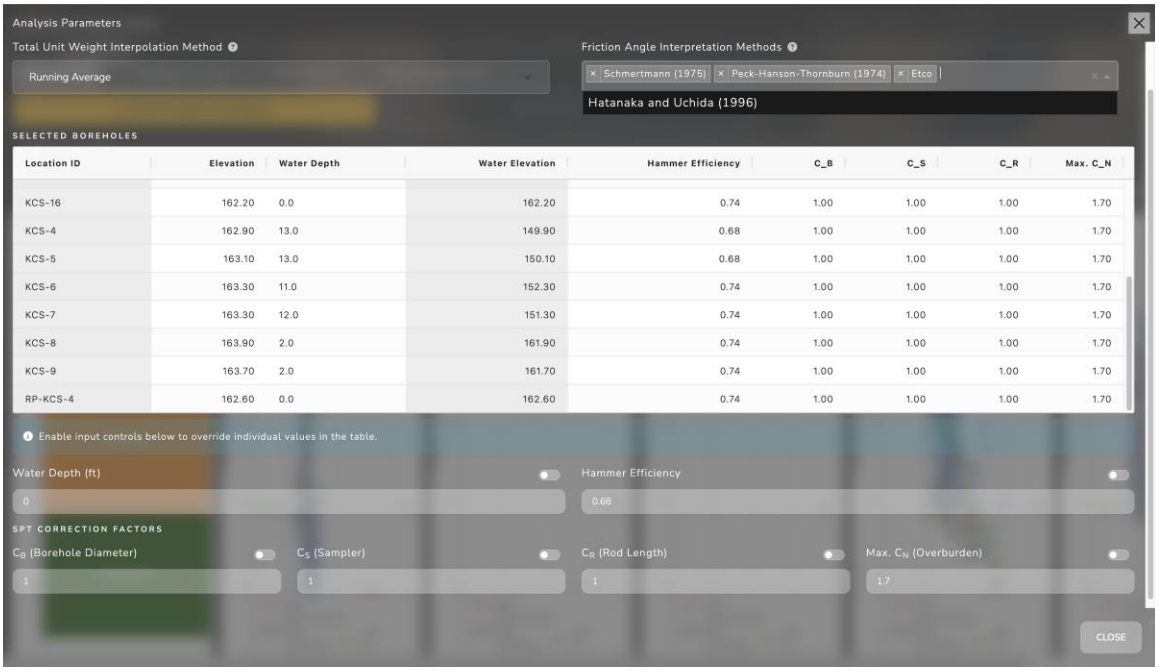
- **Schmertmann (1975)** [73]— based on corrected N_{60} values.
- **Peck, Hanson & Thornburn (1974)** [74]—based on corrected N_{60} values.
- **Hatanaka & Uchida (1996)** [75]—based on normalized, corrected $(N_1)_{60}$ values, accounting for hammer energy, borehole diameter, sampler type, rod length, and overburden pressure.
- **ETCO Engineers (Louisiana)**—based on corrected N_{60} values.

Since the Hatanaka & Uchida (1996) [75] method requires overburden correction, the platform employs a sample-based approach to estimate overburden using total unit weights. This is automatically calculated through a "running average" method that smooths values across elevations as follows:

1. Construct a composite sample table with a row at each sample elevation.
2. Initialize a "running average unit weight" column. If the top row has no data, assign a starter value of 115 pcf.
3. Moving downward:
   - — Continue using the starter value until the first measured unit weight appears.
   - — Replace the starter with this first measured value.
4. Between subsequent measured values:
   - — Carry the last average downward until a new measurement is encountered.
   - — At each new measurement, compute the average of the current running value and the new measured value.
   - — Continue propagating this updated average until the next measurement.
5. Repeat this process until the bottom of the table is reached.
6. Using the completed running average column, compute total overburden pressures at each depth.
7. When water tables are present, use water elevations from the individual selected borings to calculate hydrostatic pressures and determine effective overburden pressures**.**

Figure 23 shows the platform interface where users can specify one or more correlation methods to estimate friction angles for the same group of borings used in the previous design example. The interface also tabulates water elevations, hammer efficiencies, and other correction factors for $(N_1)_{60}$ values by boring, allowing users to review and adjust values as needed. Unified override values can also be applied across borings based on engineering judgment.

Figure 23. User interface where users can specify one or more correlation methods to estimate friction angles for drained layers



Total Unit Weight Interpolation Method: Running Average

Friction Angle Interpretation Methods: Schmertmann (1975), Peck-Hanson-Thornburn (1974), Etco

Hatanaka and Uchida (1996)

Location ID	Elevation	Water Depth	Water Elevation	Hammer Efficiency	C_B	C_S	C_R	Max. C_N
KCS-16	162.20	0.0	162.20	0.74	1.00	1.00	1.00	1.70
KCS-4	162.90	13.0	149.90	0.68	1.00	1.00	1.00	1.70
KCS-5	163.10	13.0	150.10	0.68	1.00	1.00	1.00	1.70
KCS-6	163.30	11.0	152.30	0.74	1.00	1.00	1.00	1.70
KCS-7	163.30	12.0	151.30	0.74	1.00	1.00	1.00	1.70
KCS-8	163.90	2.0	161.90	0.74	1.00	1.00	1.00	1.70
KCS-9	163.70	2.0	161.70	0.74	1.00	1.00	1.00	1.70
RP-KCS-4	162.60	0.0	162.60	0.74	1.00	1.00	1.00	1.70

Enable input controls below to override individual values in the table.

Water Depth (ft): 0

Hammer Efficiency: 0.68

C_B (Borehole Diameter): 1

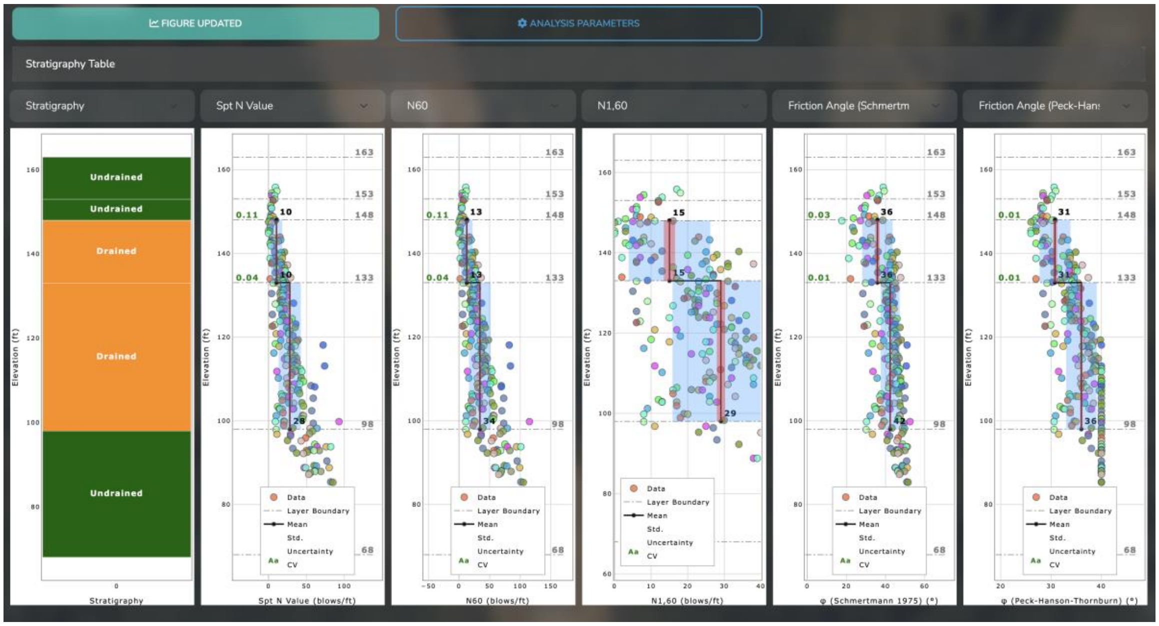
C_S (Sampler): 1

C_R (Rod Length): 1

Max. C_N (Overburden): 1.7

Once correlation method(s) are selected, the platform automatically calculates N_{60}, $(N_1)_{60}$, and the corresponding estimated friction angles. These values are then added as selectable datasets in the interactive profile charts. Engineers can plot them side by side with automatically generated statistics, including COV values for defined drained layers, for direct comparison and evaluation; see Figure 24.

Figure 24. Data profile charts for calculated N_{60}, $(N_1)_{60}$ values, and the corresponding estimated friction angles based on user-selected methods with automatically generated statistics



Selection of Resistance Factors

According to the updated AASHTO Section 10 guidance, the resistance factors applied to critical design parameters vary based on the corresponding COV values within each defined soil design layer.

For example, consider a driven pile designed with a tip elevation located within the cohesive layer between El. +163 ft. and El. +144 ft., as shown in Figure 22. In this case, compressive strength is the critical design parameter used to evaluate tip resistance in the static pile design method. As illustrated in Figure 22, the mean compressive strength within this layer is 3,061 psf, with a COV value of 0.13. The appropriate resistance factor for computing the factored tip resistance should therefore be determined based on this COV value.

The Resistance Factor versus COV curve for calibrated design parameters is provided in AASHTO. Other parameters may be calibrated using local data.

Calibration of transformations using indirect design parameters requires additional steps and knowledge of the uncertainty of the transformation itself. This functionality is not yet integrated into the web-based platform, as additional guidance from FHWA and/or AASHTO is forthcoming. Figure 25 presents the FHWA GEC-5 correlation between unit tip resistance, q_p, and mean uniaxial compressive strength, q_u, based on data from multiple states (Colorado, Kansas, Missouri, Oklahoma, and Texas) [76]. The plotted measurements show a generally increasing trend, indicating that stronger geomaterials exhibit higher tip resistance. The solid regression line represents the best-fit relationship, while the dashed lines illustrate the upper and lower bounds of the recommended design envelope. This empirical framework, adopted in GEC-5, provides a practical basis for estimating pile tip resistance in the absence of site-specific load testing and highlights the inherent variability across regions and material conditions.

Figure 25. Correlation between unit tip resistance, q_p, and mean uniaxial compressive strength, q_u

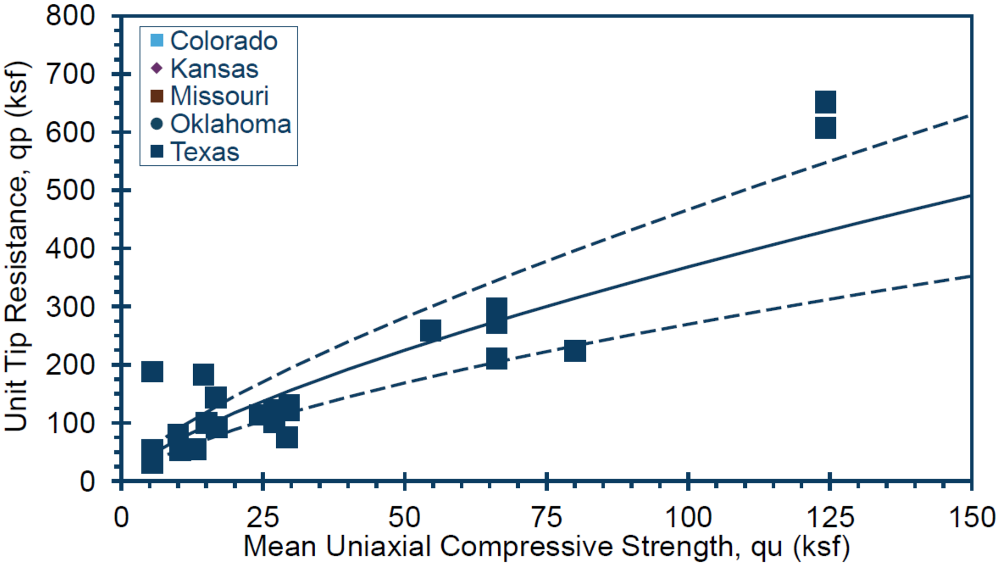
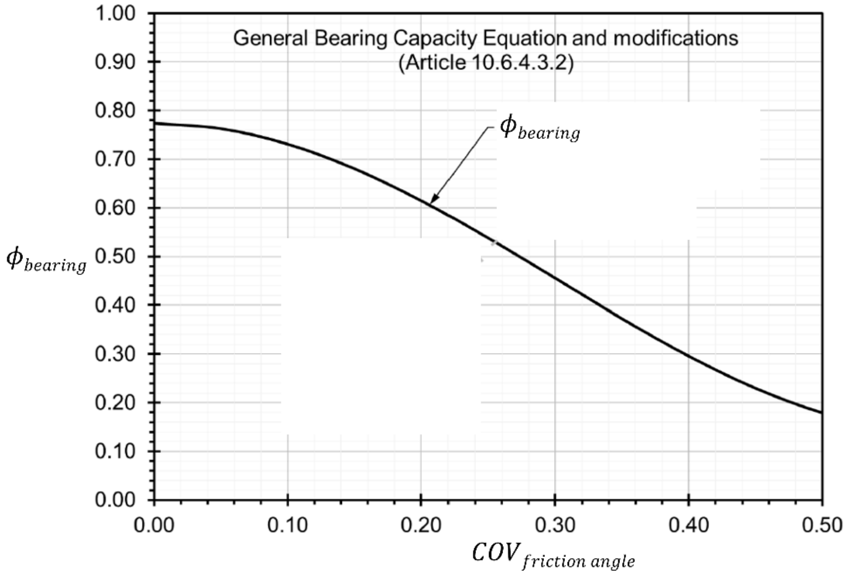


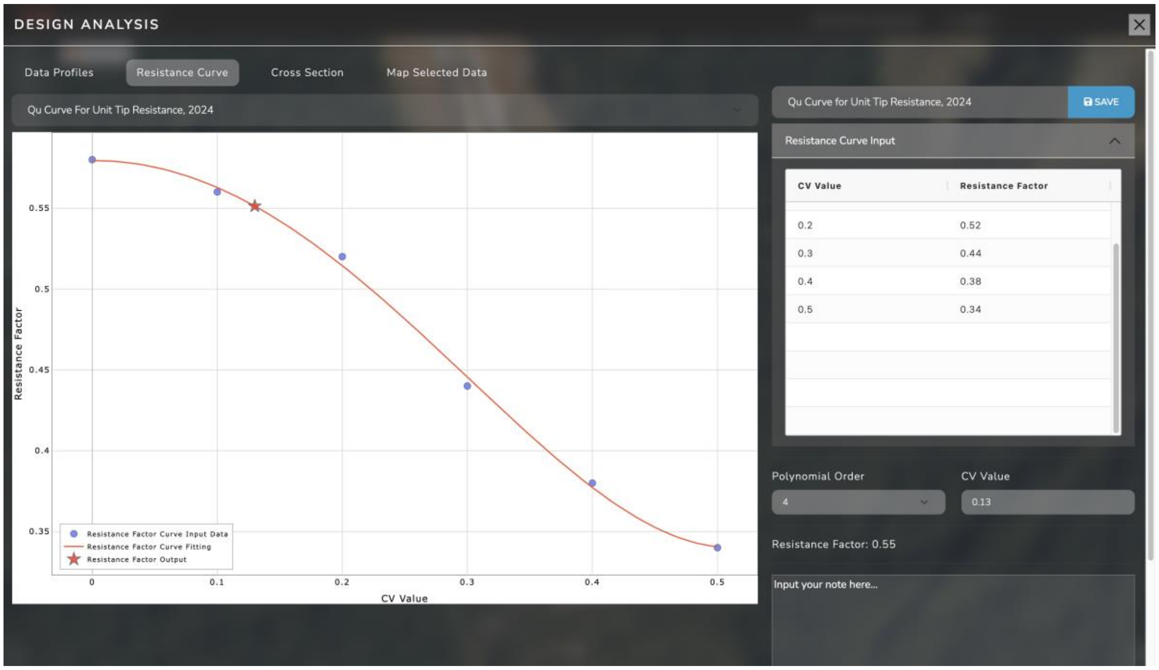
Figure 27. Screenshot of the user interface to estimate the **resistance factors based on the calculated COV values**presents the variation of the bearing resistance factor, as a function of the coefficient of variation of the friction angle, based on the general bearing capacity equation and its modifications outlined in AASHTO LRFD Article 10.6.4.3.2. As shown, ϕ_{bearing} decreases steadily with increasing variability in soil strength, reflecting the reduced reliability associated with higher uncertainty in ϕ. This trend highlights the LRFD approach's emphasis on probabilistic consistency, where resistance factors are calibrated to account for punching shear, slope effects, and soil layering. The curve demonstrates how reliability-based design incorporates geotechnical variability into bearing resistance evaluations.

Figure 26. Variation of the ϕ of the $bearing$ capacity as a function of the COV of the friction angle, based on the general bearing capacity equation and its modifications outlined in AASHTO LRFD Article 10.6.4.3.2



To support this framework, the web-based platform provides functionality for both predefining and customizing resistance factor curves used to estimate resistance factors based on COV values of critical design parameters. A screenshot of this user interface is shown in Figure 27.

Figure 27. Screenshot of the user interface to estimate the resistance factors based on the calculated COV values



Qu Curve For Unit Tip Resistance, 2024

Qu Curve for Unit Tip Resistance, 2024

CV Value	Resistance Factor
0.2	0.52
0.3	0.44
0.4	0.38
0.5	0.34

Polynomial Order: 4

CV Value: 0.13

Resistance Factor: 0.55

Input your note here...

Users can:

- Select any pre-defined resistance factor curve using the dropdown menu above the chart.
- Modify an existing curve by editing the data points in the accompanying data table on the right.
- Fit the curve dynamically by choosing a desired polynomial order based on the updated data points.
- Rename the curve and add notes or comments for documentation and future reference.

Using the previously discussed example shown in Figure 22, the user would select the resistance factor curve for compressive strength (unit tip resistance) and input the COV value of 0.13. Based on the selected resistance factor curve, the platform dynamically calculates the corresponding resistance factor, which in this case is 0.55; see Figure 27.

Project File Exporting and Importing

Because this web-based platform does not store data on cloud servers, it provides functionality to freeze and save all analysis data, including defined resistance factor curves, as a local cached project file. This file can later be reloaded into the platform for continued analysis or peer review.

The saved local file preserves all computed results and configuration settings, effectively serving as a digital deliverable that supports efficient QA/QC review by project owners and stakeholders. This workflow enhances consistency, transparency, and collaboration across the design team.

It is important to note that the local cached file is version-dependent. If substantial updates are made to the platform, such as the addition of new features or analytical modules, the cached file may only be compatible with the specific version of the platform used to create it. The capability to maintain version-independent file compatibility is planned for implementation in a future phase of the project.

Deployment and Security

The DOTD GDX-plorer test environment has been successfully deployed on the Louisiana state infrastructure following all Office of Technology Services (OTS) requirements and security standards. The deployment establishes a secure web-based geospatial data visualization platform that integrates seamlessly with Louisiana's existing enterprise authentication and identity management systems. The application runs on a dedicated Windows Server 2022 machine within the state network and is accessible via the domain name **test.gdxplorer.dotd.la.gov.**

The technical architecture employs containerization technology to isolate the application from the underlying server infrastructure, enhancing both security and maintainability. This approach aligns with modern enterprise deployment practices and provides a clean separation between the application code and the server operating system. The containerized application is managed through industry-standard tools and follows the same deployment patterns used across Louisiana's technology infrastructure.

The server was assigned appropriate network addressing within the state infrastructure and configured with DNS settings that map the user-facing domain name to the server location. To enable secure public access while maintaining the containerized application architecture, Internet Information Services (IIS) was deployed as a reverse proxy layer. This configuration allows IIS to handle incoming web traffic on standard HTTPS ports and securely forward requests to the containerized application, in accordance with established patterns for Louisiana state web applications.

The reverse proxy configuration provides several benefits that align with OTS requirements. All web traffic is routed through IIS, which handles SSL certificate management for encrypted communications, enforces HTTPS-only access, and provides centralized logging for security auditing and compliance purposes. This architecture separates the concerns of web traffic management from application logic, allowing each layer to be maintained and secured independently.

In accordance with OTS security requirements, the application integrates with Louisiana's existing Active Directory Federation Services (ADFS) to provide single sign-on capability. This integration eliminates the need for a separate authentication system and ensures that all user access follows the same security protocols used across state systems. Users access the application with their existing Louisiana state credentials, and authentication is handled entirely by the state's identity infrastructure rather than by the application itself.

The authentication flow follows the SAML protocol, which is the OTS-approved standard for federating authentication between systems. When users attempt to access the application, they are automatically redirected to the Louisiana ADFS login page. After successful authentication, ADFS provides the application with verified user identity information, including email address, full name, and group memberships. The application uses this information to determine appropriate access levels and permissions without ever handling user passwords or credentials directly.

A key aspect of the deployment involves Louisiana's centralized Identity and Access Management (IAM) Portal, which manages user groups and permissions through the Source of Louisiana Authority (SOLA) attribute system. Rather than managing access through traditional Active Directory groups, application access is controlled through formal IAM Access requests that maintain proper audit trails and comply with state information security policies.

Future Enhancements and Expansion of GDX-plorer

During the project development phase, the research team held regular meetings to demonstrate progress and gather feedback regarding GDX-plorer development. Several requests for additional features and modules beyond the project's original scope were received. These items represent potential areas for future enhancement and expansion of the GDX-plorer platform:

- **Enhancement of uncertainty estimation procedures under the revised AASHTO Section 10.** At the time of this project, the AASHTO Section 10 rewrite had not yet been finalized and published. As a result, some information needed to improve the statistical calculation procedures and user workflows within the platform was still unavailable. For example, four transformation equations are currently implemented to estimate the friction angle design parameter from indirect measurements, such as SPT N_{60} or $(N_1)_{60}$ values. However, the current rewrite draft provides uncertainty coefficients C_1, C_2, C_3, and $C_4$for only one method: Hatanaka & Uchida (1996). The draft does not yet provide procedures for determining uncertainty coefficients for other transformation equations or for other design parameters. Consequently, only the uncertainty and coefficient of variation (COV) values associated with the friction angle estimated using the Hatanaka & Uchida 1996 method can currently be calculated in accordance with the updated AASHTO Section 10 provisions, with the corresponding uncertainty coefficients hard-coded in the platform. If users select other transformation equations to estimate the friction angle for a project, the resulting uncertainty and COV values are not fully compliant with the latest draft update. It is anticipated that this limitation may be addressed in the final version of the AASHTO Section 10 rewrite, enabling the development of a more streamlined module within GDX-plorer for uncertainty estimation using any supported transformation equation based on indirect measurements.
- **Support for multiple design sections within a single project view.** The current platform allows users to save different design sections and their corresponding analyzed design parameters as separate, locally cached project files. However, there is a need to allow users to define multiple design sections with different groups of borings within the same web view and save them together as a single locally cached project file. This capability would improve project organization, sharing, and collaboration.
- **Cloud-based management and sharing of user-defined resistance curves.** At present, the platform allows users to define customized resistance curves based on local experience and save them within locally cached project files. However, these user-defined curves cannot be permanently stored in the cloud for broader sharing. A valuable future enhancement would be to allow DOTD administrative users to define and manage resistance curves in the cloud so that they can be shared consistently with the consultant community over time.

- **Automated report generation.** The platform currently provides functionality to download images from interactive charts for engineering reporting. An additional reporting feature that automatically generates a PDF summarizing key input data, analysis procedures, and results in accordance with the latest LRFD updates would further improve the platform's usability.
- **Expanded 2-D cross-section visualization capabilities.** The current 2-D cross-section module allows users to instantly generate interactive fence diagrams showing lithologic layers based on selected borehole locations. A useful enhancement would be the ability to dynamically generate color-coded cross-section profiles for selected soil properties, thereby providing stronger support for subsurface interpretation and design.
- **Migration to the latest DIGGS schema.** At the time of the DIGGS implementation phase of this project, the latest available DIGGS schema was Version 2.6.0. Accordingly, all DIGGS-related features implemented in GDX-plorer were based on the Version 2.6.0 schema. However, DIGGS Version 3.0.0 was released in February 2026, near the end of this project, and includes numerous fixes and enhancements to Version 2.6.0. Because this new release is not backward compatible with Version 2.6.0 and introduces structural changes to several elements, additional effort will be required to migrate the current DIGGS module to the Version 3.0.0 schema.
- **Selective downloads.** The ability to filter the API call that pulls all data from the OGC cloud to the DOTD server. There is a need to pull data directly from our OGC cloud without downloading everything at once.

As discussed in the previous section, GDX-plorer is currently deployed on a test server hosted by OTS and can be securely accessed by Louisiana state employees using their existing state credentials. Following completion of the project, the DOTD Geotechnical Design section will continue to test and use the platform on real production projects. The research team will continue to collect feedback to support future enhancements and expansions of the platform, leveraging emerging technologies and updated specifications.

Once GDX-plorer has been thoroughly tested internally by the DOTD Geotechnical Design section, additional effort will be needed to deploy the platform to a production server hosted by OTS. This deployment will enable DOTD’s consultant community to obtain official access to the platform and use it to perform design analyses in accordance with the latest AASHTO Section 10 updates for DOTD projects.

All of these improvements would further streamline workflows, reduce manual effort, and enhance collaboration, providing DOTD with a single source of truth for geotechnical data that supports more efficient and accurate decision-making across all projects.

Conclusions

This project expanded upon a prototype interface initially developed for large, data-rich projects and produced a functional tool that DOTD can use on any digital project within the Department. The new tool, named GDX-plorer, builds upon DOTD's ongoing efforts to modernize geotechnical data management and support the adoption of advanced techniques recommended through the FHWA A-GaME program. The software provides several benefits to DOTD.

- The software can import and analyze geotechnical data from multiple sources, including DOTD's OpenGround dataset, consultant-provided gINT files, and Data Interchange for DIGGS-compliant data.
- The software streamlines the implementation of updated AASHTO Section 10 calculations and FHWA Geotechnical Engineering Circular No. 5 (GEC-5) procedures through a simple, consistent user interface.
- The software incorporates security features that meet or exceed the requirements of Louisiana OTS, ensuring that sensitive project information is handled in accordance with state standards.
- The software provides DOTD and its consultants with a practical method to characterize sites, evaluate the spatial variability of soil properties, and produce appropriate statistical representations so that resistance factors consistent with AASHTO LRFD methodologies can be selected.
- DOTD and its consultant partners can create, save, and share analysis files, allowing project teams to review and confirm selected resistance factors and maintain consistency across geotechnical evaluations.
- The software embraces DIGGS logic and uses API functionality to link, exchange, and organize geotechnical data efficiently across projects.
- Additionally, the web-based interface developed through this research improves DOTD's ability to visualize and interpret geotechnical datasets, including SPT, laboratory tests, and other in-situ measurements used to evaluate site conditions and support project delivery.

- By integrating these capabilities into a single platform, the tool enhances DOTD's capacity to incorporate site variability, measurement variability, and design updates from AASHTO and FHWA into everyday geotechnical engineering practice.

Together, these capabilities position the DOTD GDX-plorer as a key component of DOTD's transition toward modern, digital geotechnical design workflows and provides a foundation for future updates as AASHTO Section 10 and LRFD guidance continue to evolve.

Recommendations

- DOTD should fully implement the developed platform, GDX-plorer, for Louisiana projects to ensure appropriate site characterization is made and appropriate resistance factors are determined for design calculations.
- As parallel efforts for site characterization with cone penetrometer testing (CPT) are developed, they too should be implemented, and additional resistance factor curves should be added to the GDX-plorer software.
- The DOTD Geotechnical Design section should implement the training procedures and coordinate with consultants to ensure proper flow, QA/QC, and documentation for the new software.
- Other efforts to advance the DOTD Geotechnical Data Management efforts should continue in future research to further advance DOTD and LTRC efforts.
    - Scanning and Digitization (upcoming LTRC Project 26-2GT)
    - Pile load test data
    - CPT-Pile analysis
    - Metadata for previous file versions and upgrades
- Potential enhancements could include the development of intuitive data entry and editing interfaces, enabling users to directly update, validate, and manage a wide range of geotechnical datasets, including deep foundation information.
- All data editing and input processes could be seamlessly connected to the OpenGround Cloud database, ensuring consistency, accessibility, and real-time synchronization across systems.
- These improvements would further streamline workflows, reduce manual effort, and enhance collaboration, providing DOTD with a single source of truth for geotechnical data that supports more efficient and accurate decision-making across all projects.

Acronyms, Abbreviations, and Symbols

Term	**Description**
A-GaME	Advanced Geotechnical Methods in Exploration
AASHTO	American Association of State Highway and Transportation Officials
ACF	Autocorrelation Function
ADFS	Active Directory Federation Services
ALF	Accelerated Load Facility
API	Application Programming Interface
ASCE	American Society of Civil Engineers
BCS_MCMC	Bayesian Compressive Sampling with Markov Chain Monte Carlo
BNN	Bayesian Neural Network
BoreDM	Borehole Data Management System
CBR	California Bearing Ratio
cm	centimeter(s)
COBS	AASHTO Committee on Bridges and Structures
COE	Coefficient of Efficiency
COV	Coefficient of Variation
COV_q	Coefficient of Variation in the Sample Data
COV_{QD}	Inert Load
COV_{QL}	Live Load
COV_R	Spatial Coefficient of Variation
CPT	Cone Penetration Testing
CSV	Comma-Separated Values
CVq	Pile Surface Variability
CV_R	Pile Resistance Variability
DCP	Dynamic Cone Penetrometer
DIGGS	Data Interchange for Geotechnical and Geo-Environmental Specialists
DIGGSml	DIGGS Markup Language (XML-based geotechnical data exchange file format)
DNS	Domain Name System

Term	Description
DOTD	Louisiana Department of Transportation and Development
DX	Digital Transformation
EBK	Empirical Bayesian Kriging
FDOT	Florida Department of Transportation
FS	Factor of Safety
ft.	foot (feet)
GA	Genetic Algorithm
GDX-plorer	DOTD software developed through this research
GEC	Geotechnical Engineering Circular
GEC-10	Geotechnical Engineering Circular No. 10
GEC-12	Geotechnical Engineering Circular No. 12
GEC-5	Geotechnical Engineering Circular No. 5
GEP	Gene Expression Programming
gINT	Bentley Geotechnical Software (sunsetting in 2028)
GIS	Geographic Information System
GML	Geography Markup Language
HQ	DOTD Headquarters
HTTPS	HyperText Transfer Protocol Secure
IAM	Identity Access Management
IDW	Inverse Distance Weighting
IIS	Internet Information Services
in.	inch(es)
JSON	JavaScript Object Notation
KeyLAB	Laboratory information management system for geotechnical data
lb.	pound(s)
LCPC	Laboratoire Central des Ponts et Chaussées
LFWD	Light Falling Weight Deflectometer
LiDAR	Light Detection and Ranging
LRFD	Load Resistance Factored Design
LTRC	Louisiana Transportation Research Center

Term	**Description**
m	meter(s)
MAPE	Mean Absolute Percentage Error
MFOSM	Modified First Order Second Moment (Method)
$(N_1)_{60}$	SPT values corrected for overburden and hammer efficiency
N_{60}	SPT N-value corrected for hammer efficiency
OpenGround	Bentley Geotechnical Database Software, OpenGround Cloud
OTS	Louisiana Office of Technology Services
PDF	Probability Density Function
PI	Performance Index
PRC	Project Review Committee
Q_b	End Bearing Resistance
Q_D	Dead Load
Q_D/Q_L	Ratio of Dead and Live Burden
Q_L	Live Load
Q_s	Shaft (Skin) Resistance
Q_u	Ultimate Pile Resistance
q_u	Unconfined Compressive Strength
q_p	Unit Tip Resistance
q_t	Corrected Cone Tip Resistance
RBD	Reliability-Based Design
RFEM	Random Finite Element Method
RMSE	Root Mean Square Error
RSLog	RockWare Geotechnical Borehole Logging Software
SAML	Security Assertion Markup Language Protocol
Section 67	DOTD Pavement and Geotechnical Design section
SGeMS	Stanford Geostatistical Modeling Software
SOLA	Source of Louisiana Authority
SPT	Standard Penetration Test
SSL	Secure Sockets Layer
S_u	Undrained Shear Strength

Term	**Description**
SVF	Semivariogram Function
TabLogs	Tabular Logging Software for Geotechnical Data
USCS	Unified Soil Classification System
VST	Vane Shear Test (Field Vane Shear Test)
XML	Extensible Markup Language
β_T	Target Reliability Index
γ	Unit Weight
γ_D & γ_L	Dead Load Factor and Live Load Factors
λ_{QD}	Dead Load Bias Factor
λ_{QL}	Live Load Bias Factor
λ_R	Resistance Bias Factor
ϕ	Friction Angle
$(N_1)_{60}$	SPT N-value corrected for overburden and hammer energy

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Appendix

User Manual Information and Instructional Videos are available through DOTD Section 67/ Geotechnical. For access to these tools, please contact Jesse Rauser at jesse.rauser@la.gov.