Engineering Assessment of Drive Point Data for Improving the Prediction of Geomaterial Properties and Design & Construction of Pile Foundations

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BACKGROUND STATEMENT

Highway projects require site investigation (SI) to determine subsurface information for engineering designs and constructions. The subsurface information may include geological profile, geomaterial properties, groundwater, bedrock, and any potential subsurface problems. Some common purposes of the SI include 1) the identification of construction materials, 2) design and construction of highway infrastructure, 3) geomaterial sampling and characterization, 4) planning for the construction technique, and 5) determination of potential subsurface concerns. Due to geological uncertainty and inherent variability of natural soil and rock materials, site characterization typically represents a large share of the geological/geotechnical engineering budget (Coduto et al., 2011). SI typically consists of four main parts: 1) antecedent investigation, 2) field investigation, 3) laboratory testing, and 4) technical reporting. Antecedent investigation provides the basis for subsequent field investigation, and field investigation allows in-situ testing and geomaterial/groundwater sampling for laboratory testing. The SI can lead to the largest source of uncertainties in the design and construction of pile foundations (Oluwatuyi et al., 2023). The most cost-effective SI approach suggested by Handy (1980) is the one with a variability consistent with the variability of the subsurface profile. That is, a few precise tests for a uniform deposit and more tests for an erratic deposit.

The current field investigation practice of the WYDOT Geology Program involves driving a 1¾-inch hollow steel rod with a 2-inch conical tip known as the drive point (DP), which is shown in Figure 1(a). Although ASTM standard is not available, the current DP has been implemented by the Geology Program as part of the SI since the 1960s, and different hammer types with varying efficiencies have been used for driving the DP over decades. In the past 10 years, the DP driving has been conducted using a 140-lb automatic hammer mounted on a drill rig and a hammer stroke height of 30 inches. The automatic hammers of the WYDOT Geology Program are calibrated periodically, and the hammers have efficiencies of more than 90% (Hannigan and Klesney 2017). DP blow count is recorded every one-foot penetration of DP as tabulated in Figure 1(d). The DP blow counts provide a “continuous” profile of the relative denseness of the subsurface, and driving refusal can vary between 30 to 400 blows per foot. The WYDOT Geology Program has been using DP in every SI except for gravel pits and rock quarries. The DP blow count helps geologists and geotechnical engineers to: 1) better understand the subsurface profile through the relative denseness, 2) make a better decision during the field investigation regarding locations or depths of in-situ testing and sampling, 3) identify in-situ test methods, and 4) select drilling methods required to successfully complete a test hole. On the other hand, the DP measurements are not intended for determining rock rippability, soil types, rock lithology, nor bearing capacity of geomaterials. For a project site, DP is often conducted first to understand the subsurface profile and condition before drilling more boreholes, conducting Standard Penetration Test (SPT) shown in Figure 1(b), and collecting undisturbed soil samples using a thin-wall Shelby Tube shown in Figure 1(c). Although borehole drilling can provide a continuous log of the lithology, it can be hard on determining pile refusal depths, settlement zones, and other subsurface problems. SPT is often conducted at every 5 ft and can only provide a discrete snapshot of subsurface conditions. In addition, Shelby-tube sampling is often conducted at the mid-depth of a

soil layer for a length of 1 to 2 ft. Although the Cone Penetration Test (CPT) provides a continuous measurement of soil properties, a smaller conical tip of CPT is not suitable for a typical subsurface with boulders, cobbles, and hard gravelly layers in Wyoming.

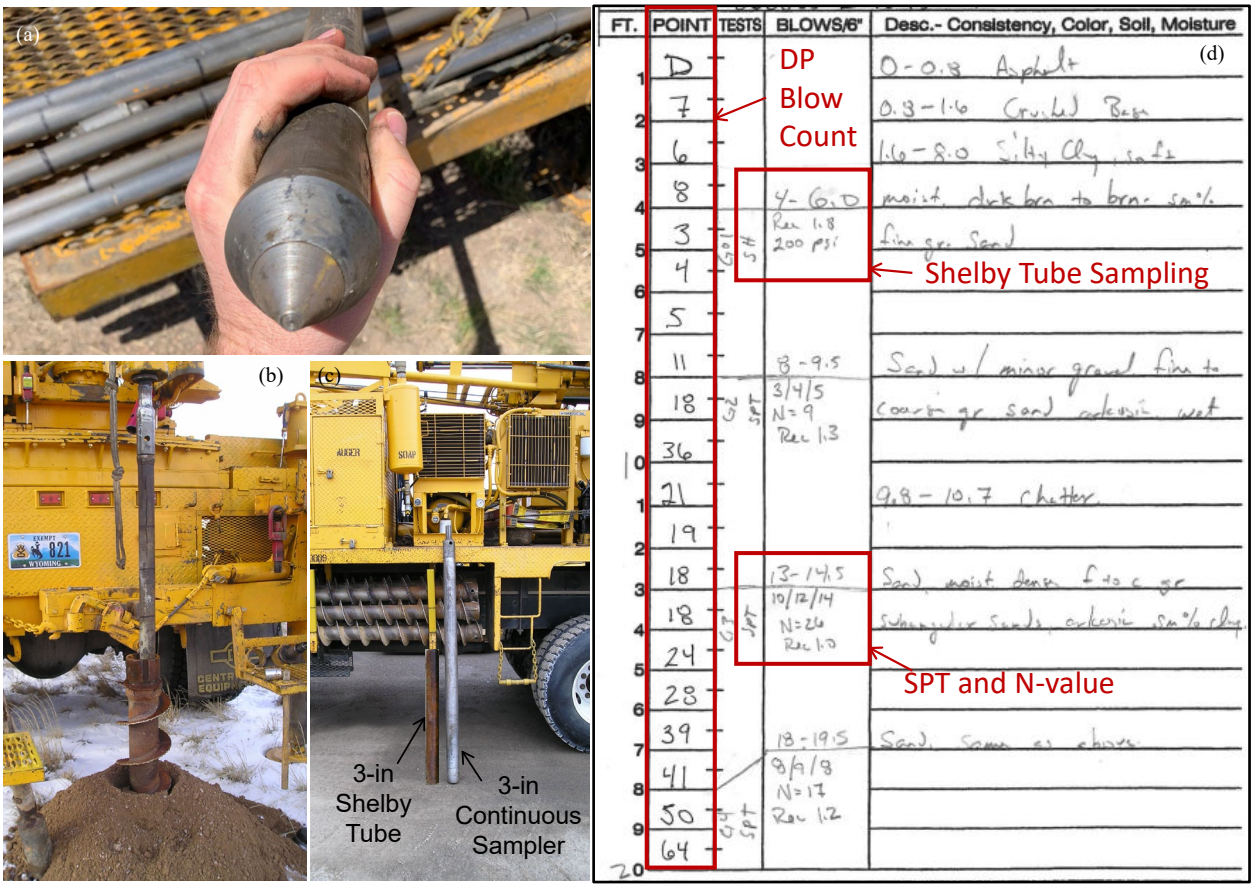

Figure 1. Graphical illustration of (a) a steel drive point, (b) SPT with a split spoon sampler, (c) soil sampling using a Shelby tube and continuous sampler, and (d) an example of a borelog sheet.

DP measurements in terms of penetration and hammer blow count have been utilized by the Geology Program to predict driven pile penetration and other engineering applications. Using 77 historical test data of HP 10×42 piles collected in the 80s and early, 95% confidence limits were obtained for the linear relationship between DP penetration and HP 10×42 pile penetration below bedrock datum defined as elevation at SPT N-value of 100 blows/ft (Figure 2). It is believed that the SPT tests were conducted using a safety hammer with a hammer efficiency of 60%. Likewise, a design chart for predicting soil strength based on hammer blow count was originally developed by the Texas Department of Transportation (TxDOT) based on a 3-inch cone penetrometer using 170-lb hammer with 2-ft dropping height. It is believed that the safety hammer was used in the development of this chart. This design chart was later adapted by WYDOT for the 2-inch DP as shown in Figure 3. Based upon experiences from using DP over the years, the Geology Program developed a quick reference of utilizing DP blow count for various engineering applications as indicted in Table 1.

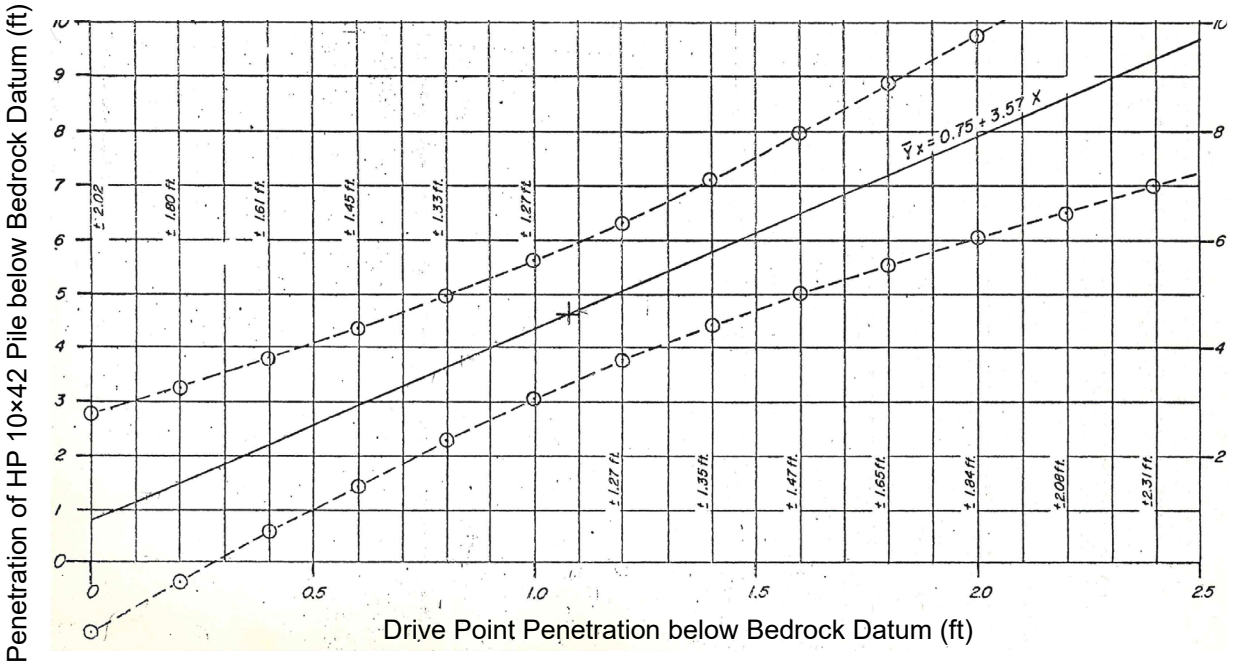

Figure 2. A relationship between drive point penetration and HP10×42 pile penetration below bedrock datum.

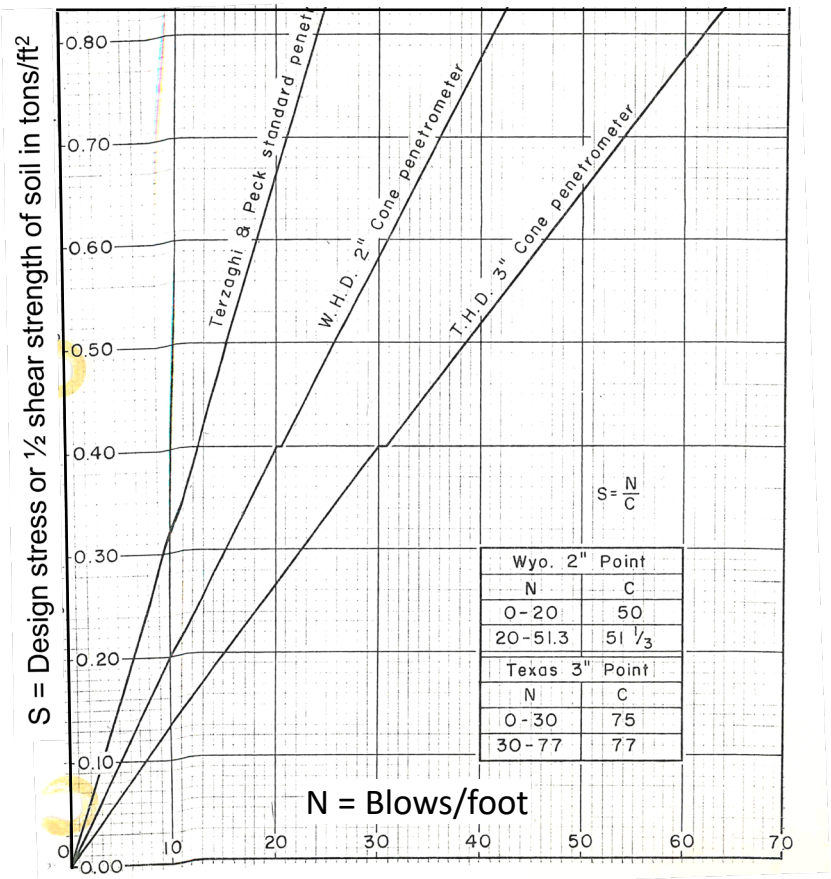

Figure 3. Design chart for predicting design stress and soil shear strength.

Table 1. WYDOT quick reference for various applications of DP blow count

Application	Target Blow Count (bl/ft)	Comments
Settlement	<10	Compressible layers possess blow counts <10 bl/ft. Take a Shelby at the midpoint of the compressible layer as needed.
Shelby Tubes	<12-15	Depends on Rig and Material. If within a compressible layer, take the Shelby in the center, and SPT at contacts. Watch for swings in blow counts.
Scour	<30	Scour can be expected within material possessing less than 30 bl/ft.
Sheet Pile	>30	Two consecutive intervals of >30 bl/ft for sheet pile refusal.
Subgrade	30-50	Two consecutive feet of 30 bl/ft or 1 foot with 50 bl/ft. Intervals of <10-12 bl/ft will not support construction equipment.
Drainage Structures	30-50	Look for soft zones for possible subex. Take SPTs as necessary for bearing values.
Retaining Walls	100 to 400	100 bl/ft if no deep foundation is required. 400 blows if a deep foundation is required.
Structures	400	H-Pile refusal at 400 bl/ft and back-up by N-field values of 100 bl in less than 0.8 ft.
Coring	400	Coreable material is generally found after drive point values of 400 bl/ft, and two consecutive N-field values of 100 bl in less than 0.8 feet.

These design charts and the quick reference demonstrate the importance of DP in the current practice of the Geology Program. The DP method has been implemented by the Geology Program on all 124 bridge projects in 22 WY counties between 2010 and 2022. These amassed DP datasets are valuable in this study for conducting engineering and statistical assessment of the DP measurements and developing recommendations for predicting geomaterial properties and driven pile penetrations.

PROBLEM STATEMENT

Despite the many advantages of using DP during SI and engineering designs, there are some challenges with using the existing DP method. The challenges include the premature DP refusal due to skin friction, outdated DP chart for predicting pile penetration (Figure 2), non-validated DP chart for soil strength (Figure 3), discrepancy in pile penetration predictions, and absence of methods for predicting pile shaft resistance and end bearing using DP.

Skin friction develops along the DP and steel rods as the DP is driven into ground. The skin friction increases when the DP penetration increases, leading to early DP refusal. Using the Curtis Street interchange bridge project in Laramie, Albany County, WY as an example, the DP driving logs shown in Figure 4 indicate that the DP at station 65+20 with approximate 20 ft of fine-grained fill reaches refusal at the elevation of 7,140 ft. In contrast, the adjacent DP at station 65+88 without the fill reaches refusal at a deeper elevation of 7,123 ft. Comparing existing pile tip elevations to the lithology, the DP at station 65+88 provides a comparable pile penetration prediction while the DP at station 65+20 would have underestimated the pile penetration

by 17 ft due skin friction from the fill. Similar observations are noticed with DP at stations 67+40 and 68+12.

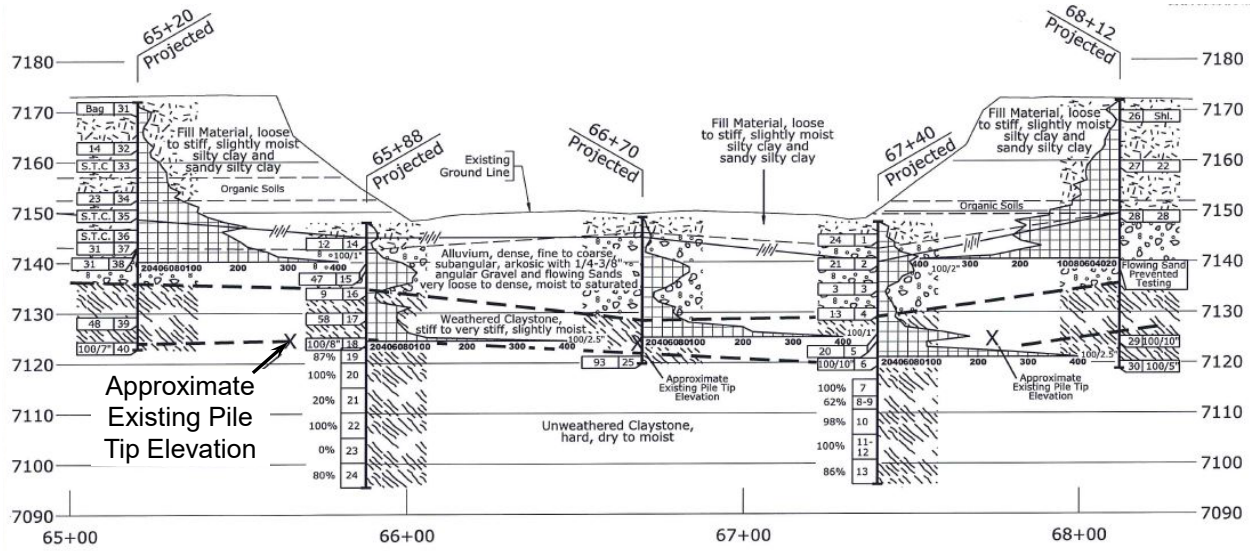

Figure 4. DP driving logs of the Curtis Street interchange bridge project in Laramie, WY.

Pile penetration has been predicted using the DP chart given in Figure 2. However, this chart was developed in the 80s based on a safety hammer system that has lower efficiency than the automatic hammer used in the past 10 years. In addition, this chart was developed based only on HP 10×42 test pile data while HP12 and HP14 steel piles are commonly used in most bridge projects in the past decade. In short, this DP chart does not necessarily represent current design and construction practices.

Likewise, the chart for soil strength prediction given by Figure 3 was developed based on a safety hammer system that yields higher N-values than that based on the automatic hammer currently used by the Geology Program. This difference in N-values will result in underestimation of soil strengths in current WYDOT design practice. In addition, the history of the chart development was not known, and the data used in the development were not available to validate the accuracy and reliability of the chart.

The DP method has been conducted in conjunction with SPT to predict pile tip elevations and bedrock datum. There are some project sites in which DP refusal records are variable, and the DP and SPT data are contradictory. The Hillsdale bridge replacement project east of Cheyenne, WY along I-80 is such an example. For this project, it was challenging to determine the final pile tip elevations as SPT data did not confirm refusal, and DP refusal blow count of 400 blow/ft reached between 5,700 and 5,750 ft, or 50 ft of variability in pile tip elevation. Three to four different mortar beds were encountered and could potentially stop pile penetration prematurely. However, none of these beds were identified from the DP method. As a result, the pile penetration lengths on the westbound were 50 to 60 ft overestimated using the existing static analysis method while DP provided a comparable pile penetration prediction. If DP data would have been considered for final pile elevations, the construction costs could be reduced, and wastage could be avoided.

Unlike the SPT-based methods, DP blow counts have not been utilized for predicting pile shaft resistance and end bearing in geomaterials. This limitation is attributed to absence of prediction equations developed to relate unit pile resistances with the DP blow counts.

LITERATURE REVIEW

It is believed that DP method was developed and has been implemented only by WYDOT in the past decades. The DP method has been recently introduced by Taylor Ree of the Geology Program to the Kansas Department of Transportation (KDOT) to be implemented in their highway projects. Little to no study has been conducted of the DP method. Furthermore, the background and development of DP charts given by Figure 2 and Figure 3 are not known. The DP method is like the SPT test and the Texas Cone Penetrometer (TCP) test.

The driving of a 2-inch diameter DP is similar to driving a standard 2-inch split-spoon sampler during the SPT using a 140-lb hammer with a drop height of 30 inches. Recommendations have been developed from past studies to correct SPT hammer blow count per foot penetration known as the N-value for borehole diameter, rod length, hammer efficiency, and overburden pressure (Liao and Whitman 1986). The SPT N-value has been utilized to predict physical properties of sand (Duderstadt 1977), friction angle (Peak et al., 1953), and unconfined compressive strength (Terzaghi and Peck 1967). Many more relationships have been developed to relate the SPT N-value with other soil properties (Kulhawy and Mayne 1990).

The 3-inch TCP test method is commonly used in SI by the TxDOT. The TCP test is conducted by driving a hardened conical point into ground and hard rock by dropping a 170-lb hammer for a height of 2 ft (Vipulanandan et al., 2008). A penetration resistance in terms of blow count is determined by adding the number of hammer blows for the first 6 inches and the second 6 inches of penetration. Relationships between SPT and TCP in cohesive and cohesionless soils were developed by Touma and Reese (1969). The TCP test is routinely used as the primary SI method for predicting the shear strength of soil layers at bridge sites (Hamoudi et al., 1974). Several prediction equations have been developed using statistical approaches to predict soil shear strength based on the TCP N-value.

OBJECTIVES

*The overall **goal** of the proposed research is to improve the performance of transportation infrastructures in Wyoming.* Recognizing the advantages and some challenges with the DP method, this research project is proposed to accomplish three main ***objectives***:

1) Improve the understanding of subsurface profiles and conditions.
2) Scientifically and statistically develop relationships between DP and geomaterial properties.
3) Improve the design and construction of driven piles using the DP method.

The proposed research will generate the following ***output measures***:

1) *Encourage and support innovation*: This proposal will conduct the first scientific investigation of the DP method, so fundamentally sound engineering recommendations can be developed to facilitate implementation of this method.

2) *Acquire and responsibly manage resources*: The engineering development of the DP method will optimize a site investigation plan in each project so an adequate amount of geomaterial sampling, borehole drilling, and in-situ testing can be designed. An optimized SI plan will use less resources including fewer trips for SI, less fuel used by the drill rigs, and less manhours for the SI.
3) *Provide safe, reliable, and effective transportation systems:* The proposed DP method will add value to the site investigation plan and improve confidence in the engineering design and construction, particularly pile foundations.

The proposed research will have the following ***outcome measures***:

1) *SI performances*: The proposed DP method will improve the overall performance and effectiveness of the SI. The proposed DP method will improve the understanding of subsurface conditions and allow for better decisions on subsequent geotechnical testing and geomaterial sampling.
2) *Engineering performances*: Equations will be developed to predict geomaterial properties, strength measures, and pile resistances based on DP data. These outcomes will improve the performance of geotechnical engineering design and construction.

The ***performance measures*** are evaluated from the following: 1) quarterly reports and a final report submitted by the PIs, 2) publication of journals and conference papers, 3) frequent communication and reporting from the research team to the Geology Program and Research Program, and 4) diligent management of the research budget by the PIs and the University of Wyoming (UW) to ensure funds are adequately spent.

STATEMENT OF WORK

The research plan is established based on the research goal, objectives, and measures described in the previous section. The research objectives will be achieved by completing the following four tasks described under the Work Plan in accordance with the Work Schedule.

Work Plan

Task 1: Collection and Review of Site Investigation, Drive Point, and Pile Data

The PIs will be working closely with the Geology Program to collect the site investigation documents (i.e., borelogs and DP drive logs), pile designs, resistance estimations, and test pile reports from dynamic analysis methods and field static load tests. The PIs have been informed that DP data and SI documents are available in all 124 bridge projects completed in 22 WY counties between 2010 and 2022. Furthermore, the WYDOT's Direct Shear Study LRFD Database contains geomaterial properties and DP data for some bridge projects that can be utilized in this study. The collected data will be reviewed, organized, and summarized according to geomaterials, subsurface profiles, DP and pile penetration depths, useable SI data, and foundation types.

Task 2: Data and Statistical Analysis

The DP data collected in Task 1 will be evaluated with respect to penetration depth and skin friction of geometerials determined using static analysis methods. DP data at different depths from adjacent drive logs at the same site for all projects will be

compared based on their respective effective vertical stress, penetration depth, and skin friction. Statistical regression methods will be used during the DP comparison to develop equations to modify the recorded DP hammer count to an equivalent, or "corrected" DP blow count.

DP data sorted according to geomaterial types will be statistically compared against geomaterial properties, such as unconfined compressive strength, undrained shear strength, cohesion, friction angle, and SPT N-value. Linear and nonlinear models of the geomaterial properties will be examined in terms of measured and "corrected" DP, and best models will be selected based on statistical selection criteria. Empirical equations will be proposed based on the best model to predict geomaterial properties using the DP blow count. Furthermore, using the proposed empirical equations, design charts (like Figure 3) will be developed based on the DP blow count to facilitate the determination of soil strength.

The test pile data from dynamic and static load tests will be studied to determine the unit shaft resistances and unit end bearing of each test pile. These unit resistances will be compared against the "corrected" DP blow count for similar geomaterials, such as fine-grained soil, coarse-grained soil, and bedrocks. Statistical methods will be implemented to determine the best models based on statistical selection criteria. Equations based on the best model will be developed through regression analysis to predict unit pile resistances based on the DP blow count to account for different pile types, geomaterial types and properties, and overburden pressure.

The final pile tip elevation or pile penetration will be compared with the measured and "corrected" DP blow count. Regression analysis will be performed to relate pile penetration into hard soil or bedrock datum to DP blow count for different pile types, geomaterial types, and geomaterial properties. Design charts (like Figure 2) will be developed to facilitate the prediction of pile penetration lengths.

Task 3: Development of Recommendations and Deliverables

Upon completion of Tasks 1 and 2, research outcomes and recommendations will be developed to facilitate the SI as well as the design and construction of driven piles. The research outcomes will result in the following recommendations and deliverables in this task:

- Methods will be proposed to correct DP blow count for overburden pressure and skin friction.
- Best models and equations will be developed for predicting geomaterial properties based on DP blow count.
- Design charts will be developed to facilitate the prediction of geomaterial strength parameters.
- Design charts will be developed for predicting pile penetration below bearing datum for different pile types and geomaterials.
- Empirical equations for predicting unit shaft resistance and unit end bearing for different geomaterials and other significant factors will be recommended in terms of DP blow count.

Task 4: Reporting

To update the progress of the research project, short quarterly reports will be submitted to WYDOT Research and Geology Programs. A final report will be prepared integrating all the outcomes obtained from the research tasks and comments given by WYDOT representatives. A final report containing all aspects of the proposed research will be prepared and submitted to WYDOT. Upon request, a technical presentation on the completed project will be given to the WYDOT Research Advisory Committee (RAC) and the Geology Program.

Work Schedule

The projected duration for the research presented in this proposal is 24 months, or eight quarters, tentatively beginning January 2024 through December 2025. The proposed work schedule is shown in Table 2.

Table 2. The detailed schedule proposed for the research tasks

Task		2024				2025			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1	DP, SI, and Pile Data Collection								
2	Data Analysis								
4	Develop Recommendations								
3	Reporting								

BENEFITS

The proposed research project will directly benefit WYDOT, KDOT, civil engineering consultants, contractors, and other relevant stakeholders. The anticipated benefits to design and construction of transportation infrastructures and DOTs are described as follows:

1) The potential for false or early DP refusal can be avoided.
2) The DP blow count can be corrected to improve understanding of the subsurface profile and conditions.
3) The geotechnical SI can be better optimized to quantify the relevant engineering properties of geomaterials, subsurface profiles, and bedrock datum.
4) Any geomaterial heterogeneity and problematic subsurface conditions will be more transparent to geologists and civil engineers so that they can make appropriate decisions on sampling, drilling, and in-situ testing during the SI and laboratory testing on sampled soil and rock materials.
5) The proposed design DP charts will improve the prediction of geomaterial strength properties, pile tip elevation, and pile resistances.
6) The LRFD procedure of driven piles will be improved to yield more reliable and efficient pile designs.
7) The discrepancy between predicted and actual pile tip elevations or pile penetrations will be minimized to reduce cost overrun, lower pile construction cost, avoid construction delay, minimize additional operational cost, reduce the possibility of variation orders, and avoid unnecessary conflicts between contractors and owners.

APPLICABLE QUESTIONS

The DP method and existing design charts have been implemented by the Geology Program on many bridge projects. Any improvement to the DP method while not changing the current DP driving procedure not incurring additional operational cost will facilitate the implementation of proposed DP recommendations in future projects. If the useable DP, SI, and pile data from this study are not sufficient to yield valid results and reliable prediction equations, additional field SI on future highway projects can be proposed in a future Phase II study to obtain high quality data.

BUDGET

The cost estimate of $117,936 is requested by UW to complete the research project, and a cost estimate of $4,500 is requested by the WYDOT Geology Program to disseminate the research outcomes. Hence, the total cost request from the WYDOT Research Program is $122,436 (see Table 3). For the UW budget, the fund is requested to support salaries covering 1 month salary for the PI, 0.75 month salary for the co-PI, and 24 months for a graduate research assistant. The total fringe benefit of $9,511 is charged in accordance with the current rates: 1) 40.9% for PI and co-PI, and 2) 1.8% for the graduate research assistant. A travel cost of $850 is included to cover all traveling expenses required to perform the tasks, present the research progress, and provide the final report to WYDOT. Tuition, fees, and health insurance of the graduate student are included with a total amount of $21,143. A travel cost of $3,441 is estimated for disseminating the research outcomes by the PI at a TRB annual meeting. The indirect cost rate of 20% with $19,656 is charged on all direct costs.

Table 3. Detailed budget estimate for the proposed research

Description	Budgeted Amount	Explanatory Note
Direct Cost		
Total Personnel Costs	$ 63,335	
Principal Investigator	$ 12,418	One month
Co-principal Investigator	$ 8,992	¾ month
Graduate Research Assistant	$ 41,925	24 months
Fringe Benefits	$ 9,511	
Research Travel	$ 850	
Materials and Supplies	--	
Tuition, Fees and Health Insurance	$ 21,143	
Technical Transfer		
Conferences/Report Presentation	$ 3,441	
Indirect Costs		
Indirect Costs	$ 19,656	20% indirect rate
In-Kind Match		
Total Cost Requested by UW	$ 117,936	
Total Cost Requested by WYDOT Geology Program	$ 4,500	
TOTAL	$ 122,436	

IMPLEMENTATION

The research outcomes and recommendations will directly benefit WYDOT, especially the Geology Program, as well as other programs in the design and construction of highway infrastructures involving geology, geomaterials, and pile foundations. The research project will help WYDOT to expand the implementation of the DP method. This implementation plan will be performed closely with WYDOT representatives from the Geology Program. The implementation depends on the positive outcomes and the deliverables described in Task 3 from the research work. The final report will highlight the research outcomes and provide recommendations for WYDOT implementation. Recommendations established from this research study will provide the knowledge and technology for using DP in the engineering design and construction for pile foundations. Lessons learned from this research will help WYDOT to adjust and revise its current design procedures and construction practices.

TECHNOLOGY TRANSFER

Technology transfer will be performed closely with WYDOT, especially the Geology Program, throughout the project. The final report will provide recommendations and deliverables on the DP method described in Task 3. The research results and outcomes will be disseminated through peer-reviewed publications and technical presentations at state conferences (e.g., the annual Wyoming Engineering Society meeting) and national conferences (e.g., TRB annual meeting in Washington, D.C).

DATA MANAGEMENT PLAN

The DP, SI, and pile data will be compiled and analyzed to improve the efficiency of conducting the research tasks described in the Work Plan section. The database format will be followed when collecting, summarizing, and presenting the data. Furthermore, the data will be stored in an electronic format to facilitate the data transfer to the WYDOT Geology Program. The pile driving logs will be shared with the research team via the WYDOT *iPDWeb* Construction Management System (CMS). All test data contained in folders under a research directory will be stored in an online file hosting service that offers cloud storage (e.g., Dropbox) and in the existing RAID hard drive storage of the PIs. The online file storage service allows the research team to access data remotely and share the data. The PI at UW will secure all original data. Furthermore, research findings and results will be disseminated in the forms of reports, journal papers, conference papers, and technical presentations that can be widely shared with other researchers and the public, as well as permanently documented by publishers and in conference proceedings. The data acquired and preserved in the context of this proposal will be further governed by UW policies pertaining to intellectual property, record retention, and data management.

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