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Project Title

Development of LRFD Recommendations of Driven Piles on Intermediate Geomaterials

University

University of Wyoming

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Research Needs

Due to a relatively shallow bedrock stratigraphy in the Rock Mountain region and some states in the Appalachian region, pile foundations are often driven on and into rock to support structures like bridges. To attain the increasing demand in capacity from structures and satisfy the Load and Resistance Factor Design (LRFD) strength limit state, the pile foundation would have to rely on the resistance contributed from the rock-bearing layer. However, this rock-bearing layer usually has high natural variability and is not fully characterized to determine its engineering parameters. Furthermore, intermediate GeoMaterial (IGM), also known as soft rock, is a transitional geomaterial between soil and hard rock, which is not well defined for the design and construction of driven piles. This variability creates challenges in identifying, sampling, and quantifying engineering parameters representative of IGM materials (Long and Horsfall 2017). In fact, the American Association of State Highway and Transportation Officials (AASHTO) (2017) acknowledges that there are currently no acceptable approaches to differentiate soft from hard rocks for the design of driven piles. Local experience with driving piles on soft rocks shall be applied to define its quality. However, limited test results are available to describe the characteristics and engineering properties of IGM (Adhikari et al. 2019).

Reliable static analysis methods have not been developed to estimate the pile resistance on IGM.

AASHTO (2017) suggests that piles driven on soft rock shall be treated in the same manner as soil. However, a past research study based on 15 steel H-piles driven on IGM in Wyoming concluded that static analysis methods originally developed for soil, provided inconsistent and conservative geotechnical resistance estimations (Ng and Sullivan 2017a). The pile load tests conducted by Long (2016) found a significant scatter between estimated and measured pile resistances. The limitation on the estimation of pile resistances creates challenges during the pile design stage.

The resistances of piles driven on IGMs are currently determined using dynamic analysis or static load test methods during construction. AASHTO (2017) recommends that piles shall be driven based on locally developed criteria to prevent pile damage. Lessons gained from the Wisconsin Department of Transportation (WisDOT) revealed that steel H-piles have been found to either run longer than the design length or be damaged during driving when a higher pile driving criterion was established (Long and Horsfall 2017). They acknowledged that there are still unknowns with both the design and construction of steel H-piles on IGM. In Wyoming, pile driving will be terminated when a target nominal pile resistance is achieved at the planned depth as determined using the Wave Equation Analysis Method (WEAP) on all production piles. The Pile Driving Analyzer (PDA), with subsequent signal matching analysis using the CAse Pile Wave Analysis Program (CAPWAP), is used as a construction control method on about only 2% of the production piles. PA/CAPWAP tests are recommended in some bridge projects experiencing relatively high load demand and soft rock bearing. For bridge projects with piles driven on IGM in Wyoming from 2012 and 2015, the performance of some production piles was considered unacceptable in accordance with the LRFD strength limit state recommended by AASHTO (Ng and Sullivan 2017b).

These limitations exaggerate the uncertainty of the subsurface condition, the discrepancy between estimated and measured pile resistances, and the difficulty in establishing criteria to differentiate IGM from hard rocks. These factors reduce the accuracy of pile resistance estimation, result in lower LRFD resistance factors, and eventually increase the construction cost.

Research Objectives

This research project is proposed to accomplish the following four objectives:

1) Develop advanced static analysis methods for pile resistance estimation on IGM;
2) Validate and improve the accuracy of dynamic analysis methods;
3) Develop LRFD resistance factors for piles on IGM; and
4) Recommend changes and improvements to current pile design and construction practices.

Research Methods

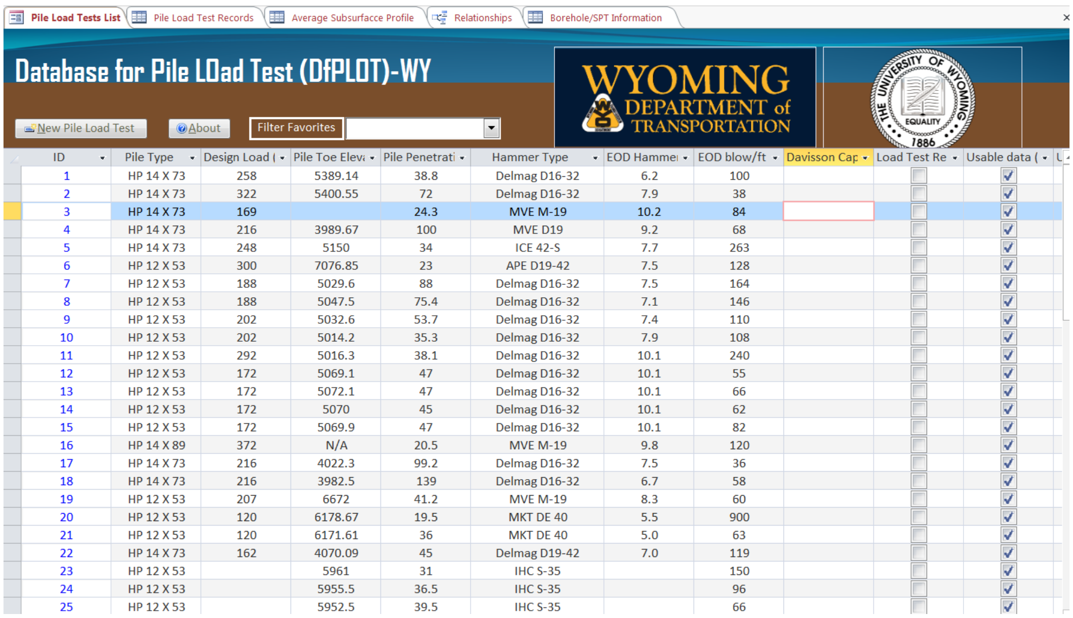
The research program was established based on the aforementioned research objectives. The research objectives will be achieved by seven major tasks.

Task 1: Pile Data Collection

High quality and usable data containing subsurface, pile, hammer, installation, and load test information will be identified and collected from seven DOTs: WYDOT, CDOT, KDOT, IADOT, ITD, MDT and NDDOT. These pile load test data will be evaluated to identify their usability, added to an electronic database developed in Task 2, and included for subsequent analyses described in Tasks 3 through 6.

Task 2: Electronic Database

All usable pile data will be compiled and stored in an electronic database similarly developed for WYDOT using Microsoft Office Access™ as shown in Figure 1. This electronic database enables the delivery of an organized storage facility shrouded beneath an appealing user-friendly interface. This database has the capability of performing efficient filtering, sorting, and querying procedures on the amassed pile data set. This electronic database will allow for the efficient performance of reference and analysis procedures on the comprehensive dataset.



ID	Pile Type	Design Load (	Pile Toe Elev	Pile Penetrati	Hammer Type	EOD Hamme	EOD blow/ft	Davisson Cap	Load Test Re	Usable data (
1	HP 14 X 73	258	5389.14	38.8	Delmag D16-32	6.2	100			✓
2	HP 14 X 73	322	5400.55	72	Delmag D16-32	7.9	38			✓
3	HP 14 X 73	169		24.3	MVE M-19	10.2	84			✓
4	HP 14 X 73	216	3989.67	100	MVE D19	9.2	68			✓
5	HP 14 X 73	248	5150	34	ICE 42-S	7.7	263			✓
6	HP 12 X 53	300	7076.85	23	APE D19-42	7.5	128			✓
7	HP 12 X 53	188	5029.6	88	Delmag D16-32	7.5	164			✓
8	HP 12 X 53	188	5047.5	75.4	Delmag D16-32	7.1	146			✓
9	HP 12 X 53	202	5032.6	53.7	Delmag D16-32	7.4	110			✓
10	HP 12 X 53	202	5014.2	35.3	Delmag D16-32	7.9	108			✓
11	HP 12 X 53	292	5016.3	38.1	Delmag D16-32	10.1	240			✓
12	HP 12 X 53	172	5069.1	47	Delmag D16-32	10.1	55			✓
13	HP 12 X 53	172	5072.1	47	Delmag D16-32	10.1	66			✓
14	HP 12 X 53	172	5070	45	Delmag D16-32	10.1	62			✓
15	HP 12 X 53	172	5069.9	47	Delmag D16-32	10.1	82			✓
16	HP 14 X 89	372	N/A	20.5	MVE M-19	9.8	120			✓
17	HP 14 X 73	216	4022.3	99.2	Delmag D16-32	7.5	36			✓
18	HP 14 X 73	216	3982.5	139	Delmag D16-32	6.7	58			✓
19	HP 12 X 53	207	6672	41.2	MVE M-19	8.3	60			✓
20	HP 12 X 53	120	6178.67	19.5	MKT DE 40	5.5	900			✓
21	HP 12 X 53	120	6171.61	36	MKT DE 40	5.0	63			✓
22	HP 14 X 73	162	4070.09	45	Delmag D19-42	7.0	119			✓
23	HP 12 X 53		5961	31	IHC S-35		150			✓
24	HP 12 X 53		5955.5	36.5	IHC S-35		96			✓
25	HP 12 X 53		5952.5	39.5	IHC S-35		66			✓

Figure 1. The homepage of an electronic pile database for WYDOT.

Task 3: Geotechnical and Pile Data Assessment

Using the pile data collected in Task 1, subsurface profiles will be constructed, pile embedded length and penetration into the IGM will be determined, soil and IGM parameters will be identified, and pile, driving, hammer, restrike and load test information will be interpreted. Technical reports will be reviewed to determine properties of the overburden soils and underlying IGM as well as pile information necessary for pile resistance estimations in Task 4.

Task 4: Pile Resistance Estimations

Shaft resistance, end bearing and total resistance of driven piles will be estimated using static analysis methods and dynamic analysis methods. Advanced static analysis methods will be developed to improve resistance estimation of piles driven on IGM during the design stage. Using the measured pile resistances obtained from static load tests or CAPWAP, a multivariate regression analysis will be performed to develop advanced and new static analysis methods by including significant dependent variables in the pile resistance estimation. The new static analysis methods will be validated using independent pile data obtained from the seven DOTs and literature. Pile resistances will be estimated using WEAP at the EOD and BOR events.

Estimated resistances from a bearing graph analysis will be compared with resistances determined from load tests. Procedures to improve pile resistance estimations using WEAP will be established.

Task 5: Development of LRFD Resistance Factors

Pile resistances estimated by proposed static analysis methods and WEAP in Task 4 will be compared with the measured pile resistance from the load test methods. Resistance bias will be determined for each predictive method. To examine if the resistance biases follow lognormal distributions, a hypothesis test will be used based on the Anderson–Darling (AD) (1952) normality test. LRFD resistance factors will be determined using probability-based reliability methods: the First-Order Reliability Method (FORM), First-Order Second Moment (FOSM) method, and Monte-Carlo simulation. The reliability methods will ensure that the regionally calibrated resistance factors would satisfy the LRFD framework as required by AASHTO (2017). The LRFD resistance factors will be developed based on the assumptions made in the reliability methods such as those recommended numerical values for probabilistic characteristics of loads (Paikowsky et al. 2004; Allen 2005). Reliability indices of 2.33 and 3.00 for a redundant pile group (i.e., a group of five or more piles) and a non-redundant pile group will be used in the calibration. Finally, a set of resistance factors for both design and construction control methods will be recommended.

Task 6: LRFD Recommendations

Upon completion of Tasks 1 through 5, LRFD recommendations will be established to facilitate the design and construction of driven piles on IGM. The LRFD recommendations are summarized as follows:

1) An electronic database of pile data.
2) A catalog of representative IGM properties for pile designs.
3) A catalog of unit shaft resistance and end bearing to facilitate pile designs.
4) An improved classification of geomaterials for piles driven on IGM.
5) Recommendation of calibrated static analysis methods for the improved estimation of shaft resistance and end bearing of piles driven in different IGMs.
6) Recommendation for improving pile resistance estimation by WEAP.
7) A set of recommended LRFD resistance factors for design and construction control methods.
8) Recommended best design and construction practices for piles driven on IGM.

The LRFD recommendations will provide transportation agencies the basis for the establishment of revised guidelines and specifications pertaining to piles driven on IGM.

Task 7: Reporting

To update the progress of the research project, quarterly reports will be submitted to MPC. At the conclusion of the project, a final report describing Tasks 1 to 6 will be submitted to MPC. A final presentation will be given by the research team to MPC and seven DOTs to facilitate the implementation of LRFD recommendations.

Expected Outcomes

The proposed research project will have the following expected outcomes on pile design and construction:

Pile Design

1) A catalog of representative soil and IGM engineering properties to facilitate pile design.
2) A catalog of unit shaft resistance and end bearing on IGM to facilitate pile design.
3) Calibrated static analysis methods will be available to yield accurate estimation of geotechnical resistances of piles driven on IGM prior to construction.
4) Classification of soil, IGM, and hard rock can be performed and "correct" predictive methods can be selected accordingly for pile design.
5) The overall accuracy of geotechnical resistance estimation of driven piles on IGM can be improved.
6) LRFD of piles driven on IGM can be performed using the calibrated resistance factors.
7) Improvements to existing LRFD pile design practices, specifications, and guides.

Pile Construction

1) The discrepancy between estimated and measured pile capacities will be minimized.
2) LRFD strength limit state of piles on IGM can be achieved during construction when verifying using dynamic analysis methods.
3) A set of calibrated resistance factors will be available for construction control methods to check against the LRFD strength limit state.
4) Pile performance can be well accepted during construction, especially at the EOD to avoid unnecessary pile restrikes.
5) Challenges with pile acceptance can be alleviated to yield lower pile construction costs, avoiding construction delays, minimizing additional operational costs, reducing the possibility of variation orders, and avoid unnecessary conflicts between contractors and owners.
6) Improvements to existing LRFD pile construction practices, specifications, and guides.

Relevance to Strategic Goals

The project outcomes will address the primary strategic goal of *economic competiveness*. Improving the accuracy of pile resistance estimations will alleviate current design and construction challenges and reduce pile design and construction costs. An efficient foundation system with a higher allowable pile resistance will provide cost savings to the transportation agencies. The secondary strategic goal is related to *Safety*. The research will improve the reliability of predictive methods and satisfy the LRFD strength limit state in accordance with the recommended target safety margin.

Educational Benefits

A graduate student majoring in civil engineering will be supported to assist principal investigators to complete this project. The student will be trained to use statistical methods in the data analysis, WEAP to perform dynamic pile analysis, and reliability methods to calibrate LRFD resistance factors. The bridge foundation projects obtained from DOTs will be incorporated into the student design projects in CE4610 (Foundation Engineering). The properties and behaviors of IGM materials will be presented in a new graduate course on rock mechanics, which will be offered in spring 2022 by the PI, Dr. Ng.

Technology Transfer

To update the progress of the research project, short quarterly reports will be submitted to the MPC. Integrating the outcomes obtained from the research plan, a draft final report will be prepared. A final report, containing all aspects of the proposed research, will be submitted to the MPC. A technical presentation on the completed project will be given to the MPC upon request. To disseminate the research outcomes, journal/conference papers will be published, and technical presentations will be given at regional and/or national conferences.

Technology transfer will be performed in close coordination with seven DOTs that support this study throughout the entire project. The final report will provide the LRFD recommendations for driven piles on IGM. Research activities and outcomes will be summarized in the final report. They will be disseminated through peer-reviewed publications and technical presentations at conferences, such as the Transportation Research Board annual meeting in Washington, D.C.

Work Plan

The work plan consists of seven tasks, and they are explicitly described in the Research Methods section. This section lists the seven proposed tasks and their respective timeline. The total duration for the proposed research is 14 months, tentatively beginning May 2021 through June 2022.

<u>Task 1: Pile Data Collection (Month 1 to Month 3)</u>
Pile data consisted of subsurface, hammer, pile and load test information will be collected from seven DOTs.

<u>Task 2: Electronic Database (Month 4 to Month 6)</u>
Electronic database will be developed to compile and collect usable pile data.

<u>Task 3: Geotechnical and Pile Data Assessment (Month 3 to Month 6)</u>
Geotechnical and pile data will be evaluated for pile resistance estimations in Task 4.

<u>Task 4: Pile Resistance Estimation (Month 7 to Month 11)</u>
Estimated pile resistances will be compared with measured pile resistances from load tests to develop new static analysis methods and improve WEAP procedure.

<u>Task 5: Development of LRFD Resistance Factors (Month 12)</u>
LRFD resistance factors will be calibrated to achieve the target reliability for piles driven on IGMs.

<u>Task 6: LRFD Recommendations (Month 13)</u>
LRFD recommendations on site investigation, pile design and pile construction will be developed.

<u>Task 7: Reporting (Month 14)</u>
Quarterly reports and a final report will be submitted.

Project Cost

Total Project Costs:	$159,045
MPC Funds Requested:	$ 45,646
Matching Funds:	$113,399
Source of Matching Funds:	Wyoming Department of Transportation

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