Comprehensive Field Load Test and Geotechnical Investigation Program for Development of LRFD Recommendations of Driven Piles on Intermediate GeoMaterials

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A pooled fund study proposal submitted to funding agencies

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BACKGROUND STATEMENT

The AASHTO LRFD Bridge Design Specifications (2014) provide comprehensive design and construction guidelines for piles driven in soil. In addition, many transportation agencies in the United States have performed their respective local Load and Resistance Factor Design (LRFD) calibrations for piles in soil (e.g., Ng et al., 2012). 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 LRFD strength limit, 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, soft rock, also known as intermediate GeoMaterial (IGM), 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, AASHTO (2014) 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. For example, a site investigation is performed at every bridge project in Wyoming to determine its subsurface profile and geomaterial properties. SPT is the most commonly used in-situ field test. At the same borehole for the SPT test, a drivepoint penetration test is performed by driving a 2-inch diameter steel drivepoint into the ground to determine the depth of a bearing layer where the drivepoint hammer blow count exceeds 100 blows per 4-inch penetration. However, limited test results are available to describe the rock characteristics and engineering properties. Research was conducted by Mokwa and Brooks (2008) to investigate pile resistance driven into IGM in Montana. Because of the current practice for geotechnical investigation, they recognized difficulties with obtaining representative samples for the IGM and representative field values for pile resistance estimations. These difficulties resulted in high variability between back-calculated pile resistances and dependent variables, such as rock compressive strength and pile length.

Reliable static analysis methods have not been developed to estimate the pile resistance on IGM. AASHTO (2014) suggests that piles driven on soft rock shall be treated in the same manner as soil. However, a recent 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. The calculated resistance biases (i.e., ratio of measured to estimated resistances) varied from 2 to 21 (Ng and Sullivan 2017a). On the other hand, piles driven on hard rock shall be governed by the structural limit state by considering the smallest value based on any applicable buckling failure modes (AASHTO 2014). However, the Wyoming based research found that these 15 test piles were all governed by the geotechnical limit state. The pile load tests conducted by Long (2016) found a significant scatter, but a general trend between tip resistance and modified SPT N-value. He recommended several empirical equations in terms of the modified SPT N-value for predicting pile resistances from IGM. It is important to note that these equations were specifically developed based on the test results obtained at the Green Bay sites in Wisconsin.

The resistances of piles driven on rock are normally determined using dynamic analysis or static load test methods during construction. This limitation could lead to many construction challenges (Mokwa and Brooks 2008). AASHTO (2014) recommends that piles shall be driven based on locally developed criteria to prevent pile damage. Dynamic analysis methods should be used to evaluate pile drivability, control pile driving, and detect pile damage. Experiences 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 required driving resistance was established using the LRFD methodologies for IGM (Long and Horsfall 2017). To overcome this issue, they reduced the required driving resistance and increased the resistance factor. They acknowledged that there are still unknowns with both the design and construction of steel H-piles for IGM. In Wyoming, pile driving will be terminated when a target nominal pile resistance is achieved at the planned depth as determined from 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 and in some bridge projects experiencing relatively high load demand and soft rock bearing. If pile performance cannot be achieved at the end of driving (EOD), a pile restrike will be performed at 24 hours after the EOD to determine a potential increase in the pile resistance. A refusal blow count of 120 blows per foot is used to prevent overstressing and damage to the pile. A static load test is normally not performed to verify the resistances estimated by the dynamic analysis methods. 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).

Research is being conducted in Wyoming to develop locally calibrated LRFD procedures for piles driven on soft rocks using 35 historical and usable pile test results collected in Wyoming since 1970. All piles are steel H-section with pile lengths varying from 20 to 139 ft. Dynamic load tests using PDA/CAPWAP were performed on 33 test piles, and static load tests were performed on the remaining two test piles. Restrikes at 24-hour periods were performed on some test piles. The bearing layers included stiff sand with gravel, sandstone, shale, claystone, and siltstone. SPT N-values were generally available to describe the geomaterials while rock parameters, such as uniaxial compressive strength and rock quality designation, were limited to some layers. The research tasks include literature review, electronic database development, pile resistance estimation, predictive method development, resistance factor calibration, geomaterial classification, and LRFD recommendations. New field investigations and pile load tests are not within the scope of work for this current project.

PROBLEM STATEMENT

Due to the high variability of rock-bearing layers, it is indispensable to identify, sample, and quantify engineering parameters of representative IGM materials for design and construction of driven piles. However, of the 35 Wyoming usable test pile data sets, only 11 sites have uniaxial compressive strength (UCS) results and six sites have rock quality designation (RQD) values. No triaxial test was performed to quantify the intrinsic strength parameters of IGM. In addition, multiple uniaxial compressive tests were not performed at each IGM layer to account for the variability of measured engineering parameters. The insufficient test results and natural variability of IGM 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 a low LRFD resistance factor, and eventually increase the construction cost. IGM characteristics and properties are usually not available for the pile resistance estimation during the design state as similarly acknowledged by Hannigan et al. (2006). Thus, it will be beneficial to establish a catalog of representative IGM properties and unit pile resistances through this comprehensive research program to facilitate the pile resistance estimation. Analyses should be performed to account for IGM variability and optimize the geotechnical investigation.

Recent research in Wyoming has confirmed that pile resistances are greatly underestimated by existing static analysis methods. If the current design practice continues to follow the AASHTO (2014) recommendation of treating piles driven on IGM in the same manner as soil, construction issues associated with the large discrepancy between estimated and measured pile resistances cannot be resolved. Construction issues could include longer pile lengths, overstressed or damaged piles during hard driving, more unacceptable piles, increase in the demand for additional construction controls and pile restrikes, and larger pile caps. These issues will increase construction duration, variation order, and operational cost. In addition, these construction issues could adversely lead to the use of a higher design safety to offset the challenge in construction management since foundation construction is the critical path of a bridge project (Mokwa and Brooks 2008). To address this problem in the current Wyoming study, one of the research tasks is to calibrate the existing static analysis methods to improve the accuracy of pile resistance estimation. However, the lack of measured strength properties of IGM and limited pile load test results could create challenges in developing reliable predictive methods.

Pile resistances are determined and pile performances are evaluated using dynamic analysis methods during construction. However, it is important to note that dynamic analysis methods are not a proof load test, and an expensive static load test is usually not performed to verify the resistance estimated by dynamic analysis methods. The Wyoming research found that pile construction control using WEAP produced a higher uncertainty than that based on PDA/CAPWAP (Ng and Sullivan 2017c). WEAP tends to slightly overestimate the total pile resistance and shaft resistance but underestimate the end bearing (Ng and Sullivan 2017a). Furthermore, for those projects with relatively high load demand and soft rock bearing, test results showed that 77% of the production piles did not satisfy the LRFD strength limit state when WEAP was used as the only construction control method at the EOD. When PDA/CAPWAP was included as a construction control method at EOD, 52% of the production piles were considered unacceptable. Almost all piles satisfied the LRFD limit state when 24-hour restrikes were performed and PDA/CAPWAP was used to verify the pile performance at the beginning of restrike (BOR) (Ng and Sullivan 2017b). In some cases, the factored pile resistance estimated by CAPWAP was marginally higher than the factored load. It is uncertain at this moment whether the pile resistance estimated CAPWAP is reliable because of the indeterminate nature of the signal matching technique that produces non-unique pile resistance by CAPWAP (Ng and Sritharan 2013a) or the absence of a static load test to verify the CAPWAP result. Due to relatively high average number of hammer blow counts of 138 and 157 blows per foot at the EOD and BOR events, respectively, it is believed that pile resistance could not be fully mobilized and thereby underestimated. Hence, a static load test program is proposed in this research proposal to verify the pile resistance determined by the dynamic analysis methods and to determine if a higher pile resistance could be attained for cost saving purposes.

RELATIONSHIP TO U.S. DOT STRATEGIC GOALS

The project outcomes will address the following U.S. DOT strategic goals.

1) *State of Good Repair* – The static load test program will determine representative IGM properties, validate the dynamic analysis methods and improve pile performance. The full life cycle cost and additional construction cost caused by aforementioned construction issues will be reduced.
2) *Safety* – The research will account for the variability of IGM layers, improve the reliability of predictive methods, and satisfy the LRFD strength limit state in accordance with the recommended target safety margin.

3) *Economic Competiveness* – Improving the accuracy of predictive methods and optimizing the geotechnical investigation will minimize existing 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.
4) *Environmental Sustainability* – The research outcomes will indirectly reduce redundant geotechnical investigations, unnecessary pile materials, and additional driving efforts that use non-renewable natural resources during construction, such as fossil fuels.

GOAL AND OBJECTIVES

The overall goal of the proposed research project is to develop LRFD recommendations for driven piles on IGM. Recognizing the design and construction challenges of piles driven on IGM, the research project is proposed to accomplish the following objectives:

1) Determine representative engineering properties of soil and IGM;
2) Evaluate the variability of soil and IGM properties;
3) Recommend best geotechnical investigation practices for IGM;
4) Develop advanced static analysis methods for pile resistance estimation on IGM;
5) Validate and improve the accuracy of dynamic analysis methods;
6) Investigate pile setup and/or relaxation;
7) Develop LRFD resistance factors for piles on IGM; and
8) Recommend changes and improvements to current pile design and construction practices.

STATEMENT OF WORK

The research program was established based on the aforementioned research goals and objectives. The research objectives will be achieved by completing two phases and fourteen major tasks.

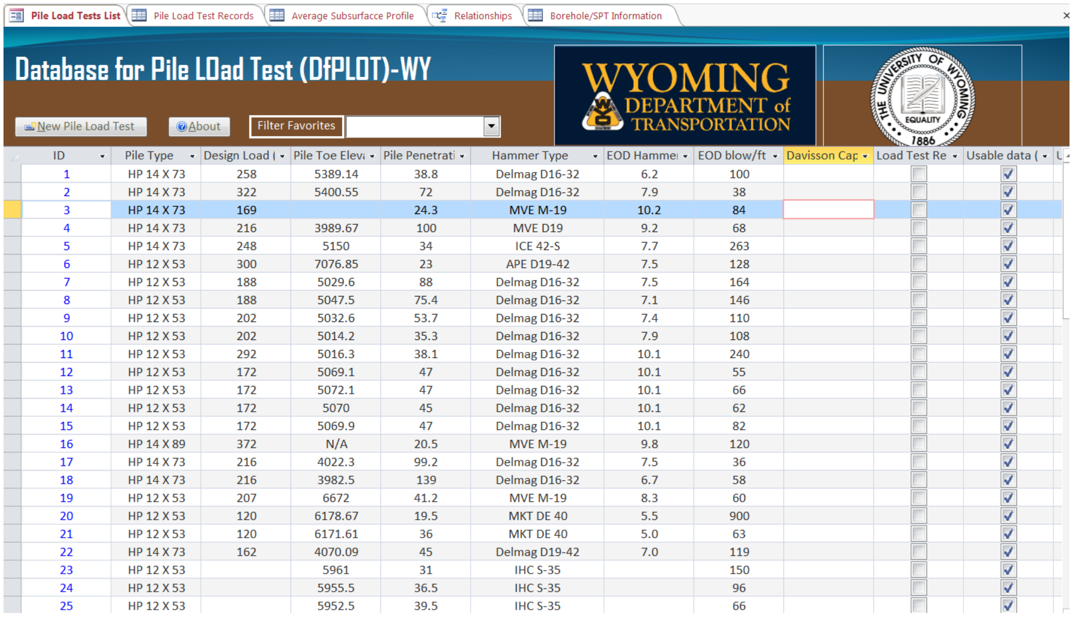
PHASE I: Data Collection, Geotechnical Investigation and Pile Load Test Program

Task I-1: Historical Pile Data Collection (UW & CU)

High quality and usable data containing subsurface, pile, hammer, installation, and load test information will be identified and collected from sponsored state DOTs. Besides the 35 usable Wyoming test results, a summary of over 100 pile test results has been provided by the Colorado Department of Transportation (CDOT) to the principal investigators (PIs). In addition, current research studies conducted in Colorado by Dr. Chang of the University of Colorado Denver (CU) will be included to expand the usable database. Details of these pile results will be acquired from CDOT. In addition, pile test results of bridge projects completed after 2015 will be collected by Dr. Ng of the University of Wyoming (UW) from WYDOT. These pile load tests will be evaluated to identify their usability, added to an electronic database in Task I-2, and included for subsequent analyses in Phase II.

Task I-2: Expand Electronic Database (UW)

All usable pile data will be compiled and stored in the electronic database currently developed for WYDOT using Microsoft Office Access^{TM} 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 Eleva	Pile Penetrati	Hammer Type	EOD Hamme	EOD blow/ft	Davisson Cap	Load Test Re	Usable data (	U
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 currently developed electronic database for WYDOT.

Task I-3: Identify Bridge Projects for Field Test Program (UW, CU and DOTs)

In consultation with the funding agencies and sponsored DOTs, a minimum of 10 bridge project sites will be selected to yield a minimum 10 pile load tests. These tests will be subjected to comprehensive geotechnical investigation and the pile load test program described in subsequent tasks. These test locations will be at bridge projects undertaken by the state DOTs. Piles driven on IGM shall be expected in these selected projects. Various IGMs, overburden soil materials, load demands, and other factors, such as contractual and construction issues, field test costs, and design challenges will be considered in the selection of bridge projects.

Task I-4: Detailed Geotechnical Investigation (UW, CU & DOTs)

The subsurface profile at each test site will be characterized using both in-situ and laboratory tests. The in-situ tests include boring, Standard Penetration Tests (SPT), drivepoint penetration tests, soil and rock sampling, and determination of RQDs. In addition, modified SPT tests will be conducted in the IGM to record the SPT hammer counts as a function of penetration (Long 2016). To evaluate the vertical variability of soil and IGM in Phase II, a minimum of two SPT tests will be performed in each main geomaterial layer. Sufficient disturbed and undisturbed soil samples shall be collected from each main layer for standard soil characterization (i.e., gradation, Atterberg limits, in-situ moisture content, in-situ unit weight), unconfined compression tests for cohesive soil, and a set of either triaxial tests for cohesive soil or direct shear tests for cohesionless soil. A minimum 10-ft coring of IGM should be conducted to determine a range of RQDs and to collect sufficient IGM samples for laboratory testing. A minimum of one uniaxial compressive test and three triaxial tests should be performed on IGM samples to determine relevant mechanical properties. The laboratory soil tests will be conducted by the respective DOTs, and the laboratory tests on IGM samples will be conducted at UW. To evaluate the horizontal variability of soil and IGM in Phase II, a minimum of three geotechnical investigations (i.e., three boreholes) will be performed at each test pile location over the area of the abutment or pier. The aforementioned SPT, drivepoint penetration test, sampling, and laboratory test requirements will be followed at each borehole location.

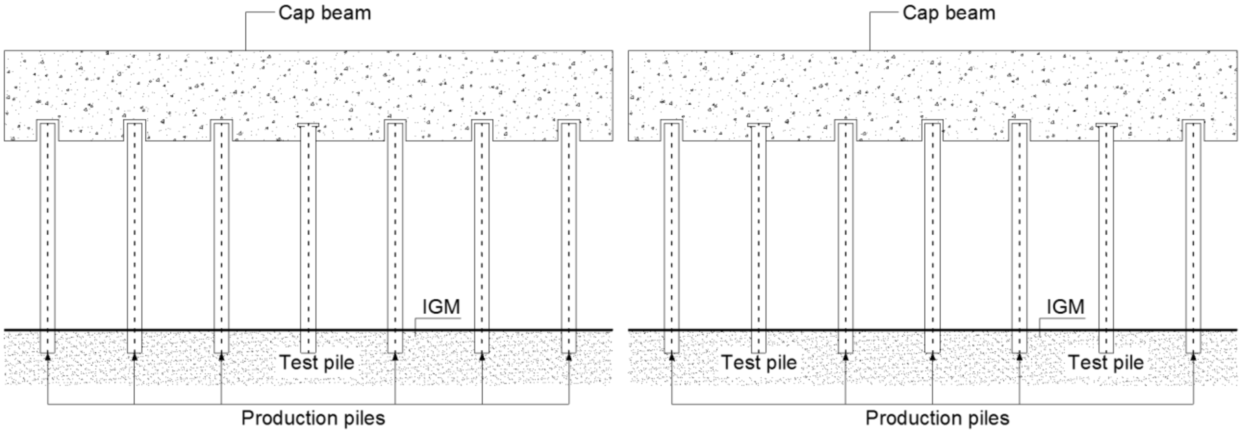
Task I-5: CDOT-CU Innovative Static Pile Load Tests (CU, CDOT, DOTs, & UW)

A two-year study on "Innovative Pilecap Beam Static Load Test (PBSLT)" sponsored by the CDOT was recently completed by the research team led by Dr. Chang of CU through a large-scale model test program. The objectives of this research are to develop a cost-effective PBSLT for evaluation of static pile capacity and to determine an optimal number of piles for a bridge abutment or pier. The proposed PBSLT method will minimize any construction delays caused by the static load test and reduce the overall cost of the proposed load test program.

A minimum of 10 pile load tests will be performed at 10 project sites identified in Task I-3. A Grade 50 steel H-pile will be instrumented with strain gauges on both web surfaces along the pile length. The test pile will be adequately instrumented so that the resistance provided by the shaft friction from each main soil layer and end bearing generated during a static load test can be separated. These gauges and cables will be protected from damage during pile installation. The test pile will be driven on or into the IGM layer, and hammer blow counts will be recorded. During the driving process, pile accelerations and strains will be collected using the PDA. The nominal pile resistance can be estimated using the PDA data with subsequent signal matching analyses using CAPWAP in Phase II. Based on the authors' experiences, nominal pile resistances estimated by the PDA-CAPWAP agreed well with the static load capacity within some precisions (Chang et al., 2011). To determine the change in pile resistances, pile restrikes will be performed at one hour and one day after the EOD. If time permits and the pile hammer is available, additional restrikes will be performed prior to the static load test.

The static load test will be performed on the test pile using the proposed PBSLT Scheme One as illustrated in Figure 2 and/or PBSLT Scheme Two as illustrated in Figure 3. Scheme One-1, as shown in Figure 2(a), has one test pile with the pile head casted in the beam. The production piles will have their pile heads housed in beam cavities at an overhead selected spacing between the pile heads and top of cavities. Under increasing bridge dead load during the girder and deck placement, the test pile settles and causes decreasing overhead spacing until all production pile heads become in contact with the top of cavities. These production piles begin to share the bridge dead load and, eventually, traffic live load, and settle with the test pile. Performances of all or selected piles will be monitored using the instrumented strain gauges designed for a long-time monitoring of the pile performances. Scheme One-2, shown in Figure 2(b), has two test piles. This is an alternative Scheme One to enhance the stability of the cap beam during the girder and deck placement.

Prior to cap beam casting, the nominal resistance of the test pile will be verified using PDA-CAPWAP with signal matching. If the nominal resistance of the test pile significantly exceeds the plan specified load demand, we could follow up with testing 100% of the production piles to obtain pile resistances at both EOD and BOR. Hence, a higher resistance factor of 0.75, increased from 0.65 in accordance with the AASHTO (2014), could be recommended for future pile designs. Adopting the 24-hour restrike, the pile resistance could be increased, say 10%, to the pile resistance determined at the EOD. The incorporation of pile setup discussed in Task II-3 would probably reduce the number of piles as specified in the contract plan and save the overall project cost. However, to realize the cost saving from the planned number of piles, the pile head/cap beam will need to be redesigned using a newly developed software known as "Cap Beam Pro" (Nghiem et al., 2017). The coding effort is near completion, and it can be used to produce a design cap beam expeditiously. If the test pile does not reach its ultimate capacity, either Chin's method (1970) or Davisson's method (1972) will be used to estimate the ultimate pile capacity.



(a) Scheme One-1 (b) Scheme One-2

Figure 2. A schematic drawing of the proposed PBSLT Scheme One for (a) one test pile, and (b) two test piles.

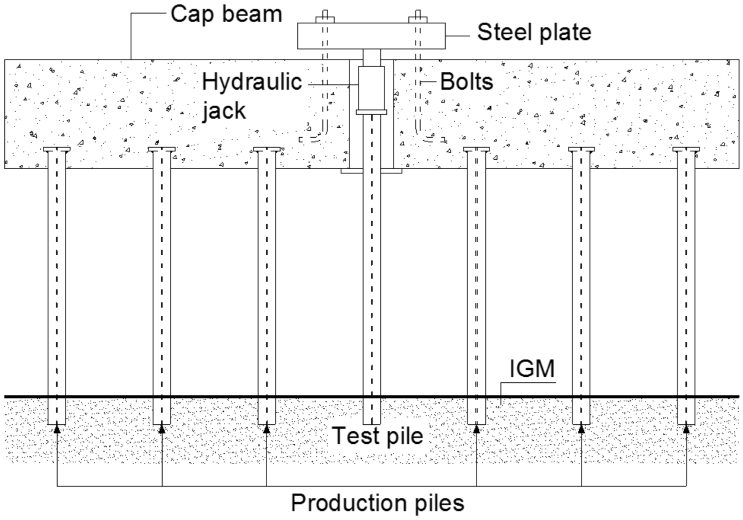


Figure 3. A schematic drawing of the proposed PBSLT Scheme Two.

Scheme Two, as shown in Figure 3, has one test pile in the middle of pilecap beam along with the production piles. All production pile heads are casted in pilecap beam with a cavity position at the center to house the test pile. The static load test will be conducted on the test pile in accordance with the ASTM D1143 (2013). According to the Wyoming historical data, the maximum nominal total resistance of a test pile on IGM was about 550 kips as determined using CAPWAP at a 24-hour restrike. A loading system with a minimum capacity of 1,100 kips will be designed to load the test pile to its ultimate capacity defined by Davisson’s criterion (1972). A concrete anchor using a bolt connection system will be provided from the pilecap beam to the loading system. This connection will allow recycling of the loading system for the next static load test. A cavity between the test pile and the pilecap beam will be created to allow an independent test pile displacement from the pilecap beam and to avoid contact between them. Steel plates will be placed on top of the test pile and followed by a minimum 300-ton hydraulic jack, and load cell. The hydraulic jack will be connected to an electrical pump, which will extend and retrieve the jack during the loading and unloading stages, respectively. When a vertical load is applied on the test pile, an equal and opposite vertical load will exert upward on the main loading system, which will be resisted by the bolt connection. The vertical load will eventually be transferred to the production piles through the pilecap beam and resisted by the shaft friction along the production piles. The applied load will be measured by the load cell, and the pile top displacements will be measured by two displacement transducers mounted on the test pile from two independent reference beams. During the static load test, the strains along the test pile will be measured using the strain gauges at each load increment and decrement. Upon completion of the static load test, the loading system will be removed, the test pile will be cut below the top surface of the pilecap beam, the embedded concrete anchor bolts will be cut off, and the cavity will be sealed with a high strength concrete mix.

In both schemes, all test piles are initially installed with strain gauges for a long-term monitoring. This, if successful, can provide information about the long-term performance of the pile and for warning of potential impending failures.

Task I-6: Reporting (UW & CU)

To update the progress of the research project, quarterly reports will be submitted to funding agencies. At the conclusion of Phase I, a report describing Tasks I-1 to I-5 will be submitted to funding agencies.

PHASE II: Data Interpretation, Pile Resistance Estimation, Statistical Analysis, Cost-Benefit Analysis and Recommendations

Task II-1: Geotechnical and Pile Data Interpretation (UW & CU)

Using the historical data compiled in the electronic database in Task I-2 and new data obtained from the load test program, 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. Test piles with a similar IGM type will be sorted and grouped. Likewise, grouping can be efficiently conducted based on bridge structure, pile size, overburden soil type, location, hammer, and test method. Geotechnical reports and subsurface profiles will be assessed to determine properties of the overburden soils and underlying IGM necessary for pile resistance estimation in Task II-2. Correlation analysis will be conducted to determine relevant geomaterial parameters, such as friction angle, cohesion, unit weight, and rock mass rating. The stratigraphy, geology, and discontinuity of IGM will be described. These characteristics and properties will be summarized for pile resistance estimation in Task II-2 and variability analysis in Task II-4.

Task II-2: Pile Resistance Estimation (UW & CU)

Shaft resistance, end bearing and total resistance of historical and new test 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.

Task II-2-1: Static Analysis Methods (CU)

Using the geotechnical data and pile data collected from Phase I and interpreted in Task II-1, the geotechnical resistances of driven piles from usable data records will be estimated using static analysis methods specified in the AASHTO (2014). These static analysis methods may include 1) α-method by Tomlinson (1987), 2) β-method by Esrig and Kirby (1979), 3) λ-method by Vijayvergiya and Focht (1972), 4) SPT method by Meyerhof (1976), 5) Nordlund (1979) method, and the Federal Highway Administration (FHWA) DRIVEN program. The use of box or flange perimeter for shaft resistance and end bearing estimations will be evaluated for different

IGMs (Chang et al., 2011). Since these static analysis methods were developed based on piles driven in soil materials, the side resistance and end bearing of piles driven on IGM are likely to be underestimated. Using the measured pile resistances obtained from static load tests or the resistance distribution estimated from CAPWAP, static analysis methods will be calibrated by modifying respective empirical coefficients (e.g., adhesion factor (α) defined in the α-method) and incorporating IGM properties (e.g., uniaxial compressive strength). Calibration of selected static analysis methods will be performed using regression analyses to reestablish the relationship of empirical coefficients specifically for piles driven on IGM. If the calibrated static analysis methods do not yield reasonably good estimations, a multivariate regression analysis will be performed to develop an advanced and completely new static analysis method by including significant dependent variables in the pile resistance estimation.

Task II-2-2: Wave Equation Analysis using WEAP (UW)

Using the pile, driving, hammer, and soil information, pile resistances will be estimated using the wave equation analysis method at the EOD and BOR events. Estimated resistances from a bearing graph analysis will be compared with resistances determined from static load tests. If the static load test results are not available, the comparison will be performed with the results obtained from the signal matching analysis using CAPWAP conducted in Task II-2-3.

Task II-2-3: Signal Matching Analysis using PDA/CAPWAP (UW)

Using the PDA data collected from the pile load test program in Phase I, signal matching analysis will be performed using CAPWAP to determine the load distribution along the test pile, shaft resistance, end bearing, and total resistance. Signal matching analysis will be performed by adjusting the load distribution, dynamic soil parameters, and other pile parameters until a reasonable good match quality of less than three can be achieved. The signal matching analysis will be performed at the EOD and each BOR event. The estimated pile resistances from CAPWAP at the last restrike will be compared with results from the static load test to validate the signal matching technique and confirm if the CAPWAP results are underestimated. Assimilating the results from CAPWAP and static load tests, a catalog of representative unit shaft resistances and end bearings of piles driven on IGM will be established to facilitate the pile design procedure.

Task II-3: Pile Setup/Relaxation Investigation (UW & CU)

The pile resistances estimated at the EOD and all BOR events by CAPWAP and measured by the static load tests will be plotted as a function of time to determine pile setup or relaxation. The change in shaft resistances in soil and IGM and end bearing in IGM will be evaluated to determine their contribution to the overall pile setup and relaxation (Ng et al., 2013b). If significant and consistent pile setup is observed on piles driven on IGM, the amount of pile setup will be quantified and incorporated into the LRFD resistance factor development in Task II-5 using the methodologies developed by Yang and Liang (2006) and Ng and Sritharan (2016).

Task II-4: Variability Analysis (UW)

The relative variability of the soil and IGM materials has a significant effect on the capacity and performance of driven piles. This variability could be classified into inherent variability and geological uncertainty. The inherent variability refers to differences in geomaterial parameters from one point to another in space (Phoon and Kulhawy 1999). The geological uncertainty appears in the forms of one geomaterial embedded in another or the inclusion of a small percentage of different material types in a more uniform soil/IGM mass (Deng et al., 2017). To consider both inherent variability and geological uncertainty simultaneously, a coupled Markov chain (CMC) model (Elfeki and Dekking 2001) will first be considered using the collected borehole data obtained from Phase I. While there are a number of geostatistical models that might be used, the CMC model has the following advantages: (1) it is theoretically simple and can handle a number of soil types, (2) it directly incorporates borehole data (even for a small number of boreholes), and (3) it explicitly gives the probability of a soil type occurring at a particular location (Qie et al. 2016). The inherent variability associated with the soil parameters will be obtained through simulation of the random field (Schabenberger and Gotway 2005). Deng et al. (2017) recommend a Cholesky decomposition technique to do this simulation using the midpoint method to discretize the random field. Based on the realizations of the random fields, the pile resistance will be estimated using a finite element method and Monte Carlo simulation (Righetti and Harrop-Williams 1988). The estimated pile resistance will be compared against the measured resistance obtained from the load test program. The process will be repeated to evaluate the effect of the borehole layout scheme, test frequency, and coefficient of variation of significant geomaterial parameters on the reliability of pile resistance estimation.

Task II-5: Development of LRFD Resistance Factors (UW)

Using the new results obtained from the pile load test program described in Task I-5, the pile resistance estimated by static and dynamic analysis methods obtained from Task II-3 will be compared with the measured pile resistance from the static load tests. For the historical data, CAPWAP results will be considered as the next best available “measured” resistance if static load tests were not available. 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, such as the First-Order Reliability Method (FORM), First-Order Second Moment (FOSM) method, and/or Monte-Carlo simulation. The reliability methods will ensure that the regionally calibrated resistance factors would satisfy the LRFD framework as required by AASHTO (2014). These reliability methods will account for different uncertainties induced by the parameters, such as variability of IGM and deficiency of a design method, that influence the accuracy of resistance estimations while maintaining a common target reliability index to ensure a prescribed margin of safety. The regional 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 as documented by Paikowsky et al. (2004) and Allen (2005). A reliability index of 2.33 for commonly used redundant pile groups (i.e., a group of five or more piles) suggested by AASHTO (2014) will be used in the calibration. For a non-redundant pile group, a higher reliability index of 3.00 will be used to account for the lower redundancy. The reliability indexes of 2.33 and 3.00 corresponded to approximate failure probabilities of 1 in 100 and 1 in 1000, respectively. To increase the efficiency of LRFD, and to provide better recommendations, resistance factors using different reliability methods will be developed and compared for existing and/or calibrated static analysis methods and dynamic analysis methods. The calibrated resistance factors will be adjusted if necessary to maintain consistency and resolve any anomalies observed among the factors. Finally, a set of resistance factors for both design and construction control methods will be recommended.

Task II-6: Cost-Benefit Analysis (CU)

Using the research outcomes from the aforementioned tasks in Phase II, a cost-benefit analysis (CBA) will be performed to determine the effects of geotechnical investigation procedure, geomaterial variability, predictive methods, and frequency and type of construction control methods on the performance of piles driven on IGM while satisfying the LRFD requirements. The analysis will be systematically performed to compare the benefits and costs of each factor. This task will attempt to provide recommendations for optimizing the geotechnical investigation considering the inherent variability and geological uncertainty, selecting a cost-effective predictive method for the pile resistance estimation, and assigning an adequate set of construction control methods and pile restrikes during pile construction.

Task II-7: Outcomes and Recommendations (UW & CU)

Upon completion of all tasks described in Phases I and II, research outcomes and LRFD recommendations will be established to facilitate the design and construction of driven piles on IGM. The anticipated research outcomes and recommendations are summarized as follows:

1) An electronic database of historical and new pile data.
2) A catalog of representative soil and 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 a static load test procedure for piles on IGM.
6) Recommendation of calibrated static analysis methods for the improved estimation of shaft resistance and end bearing of piles driven in different soil and IGM materials.
7) Recommendation for improving pile resistance estimation by WEAP and CAPWAP.
8) A catalog of dynamic soil parameters for dynamic analysis methods.
9) Recommendation for considering pile setup in pile design and construction.
10) A set of recommended LRFD resistance factors for design and construction control methods as a function of geomaterials.
11) Recommendation of best geotechnical investigation practices for soil and IGM.
12) Recommendation of best design and construction practices for piles driven on IGM.

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

Task II-8: Reporting (UW & CU)

To update the progress of the research project, quarterly reports will be submitted to funding agencies. At the conclusion of Phase II, a final report describing Tasks II-1 to II-7 and the electronic database will be submitted to funding agencies. A final presentation will be given by the research team to funding agencies to facilitate the implementation of LRFD recommendations.

SCHEDULE

The total duration for both phases presented in this proposal is 60 months, tentatively starting from July 1st 2018 to June 30th 2023. A time schedule for all tasks in both phases is summarized in Table 1.

Table 1. Detailed schedule for the proposed research tasks in two phases.

Task	**Task Description**	**2018**		**2019**				**2020**				**2021**				**2022**				**2023**	
		Q3	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**
I-1	Historical Data Collection	🟩	🟩	🟩	🟩	🟩	🟩														
I-2	Electronic Database					🟦	🟦	🟦	🟦							🟦	🟦	🟦	🟦		
I-3	Identify Project Sites	🟨	🟨	🟨	🟨																
I-4	Geotechnical Investigation			🟧	🟧	🟧	🟧														
I-5	Static Pile Load Test				🟧	🟧	🟧	🟧	🟧	🟧											
I-6	Reporting									⬛	⬛										
II-1	Data Interpretation								🟨	🟨	🟨										
II-2	Pile Resistance Estimation									🟥	🟥	🟥	🟥	🟥	🟥						
II-3	Pile Setup/Relaxation														🟩	🟩					
II-4	Variability Analysis						🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦				
II-5	LRFD Resistance Factors															🟫	🟫	🟫			
II-6	Cost-Benefit Analysis																	🟦	🟦		
II-7	Outcome and Recommendations																		🟪	🟪	
II-8	Reporting																		🟥	🟥	🟥

BENEFITS

The proposed research project will have several direct benefits to state DOTs, deep foundations industries and other relevant stakeholders. These anticipated benefits to design and construction of driven piles on IGM are described as follows:

<u>Benefits to Geotechnical Investigation:</u>

1) The inherent variability of geomaterials and geological uncertainty can be considered.
2) The geomaterial heterogeneity will be transparent to design engineers so that they can make appropriate decisions based upon detailed geotechnical investigations.
3) Geotechnical investigations can be optimized to quantify the relevant engineering properties of soil and IGM materials.

<u>Benefits to Pile Design:</u>

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) Pile setup can be incorporated into the design at the EOD to optimize the efficiency of the foundation system.
6) The overall accuracy of geotechnical resistance estimation of driven piles on IGM can be improved.
7) LRFD of piles driven on IGM can be performed using the calibrated resistance factors.
8) Improvements to existing LRFD pile design practices, specifications, and guides.

<u>Benefits to Pile Construction:</u>

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 or static load test 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 predicted and accepted during construction, especially at the EOD to avoid unnecessary pile restrikes.
5) Pile construction can be accelerated 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.

DELIVERABLES

To update the progress of the research project, short quarterly reports will be submitted to funding agencies and DOTs. Also, a yearly interim report will be submitted at the end of each year to report the research progress. Integrating all the research outcomes obtained from Phases I and II, as well as comments given by representatives from the funding agencies, a draft final report will be prepared. A final report containing all aspects of the proposed research, an executive summary, and a plan for any future works will be prepared and submitted. A technical presentation on the completed project will be given to the funding agencies to facilitate the implementation of LRFD recommendations. To further disseminate the research outcomes, journal/conference papers will be published and technical presentations will be given at regional and/or national conferences.

BUDGET

The detailed budget estimate requested for this proposed research is presented in Table 2. Funds are requested to support wages covering 4 months for Dr. Ng, 2 months for Dr. Wulff, 2.5 months for Dr. Chang and 24 months for Dr. Nghiem. Dr. Ng will be the lead principal investigator to administrate the overall project progress, control the budget, manage the research team, liaison with the funding agencies, prepare reports, and organize research meetings. Dr. Wulff will be responsible for helping the CU team on the regression analysis for the static analysis methods described in Task II-3, conducting the variability analysis described in Task II-4, and calibrating the LRFD resistance factors described in Task II-5. Under the leadership of Dr. Chang, Dr. Nghiem will be responsible for conducting the static load tests described in Task I-5 and collecting pile test data described in Phase I. The UW team will assist the CU team on static load tests. In addition, stipends are requested to support one master graduate assistant for 24 months, three PhD graduate assistants for 36 months each, and undergraduate research assistants for a total 600 hours. The full-time master student and PhD student will be supervised by Dr. Ng of UW, and two half-time PhD students will be supervised by Dr. Chang of CU. Undergraduate students will help in accomplishing tasks described in Phase I and developing the electronic database described in Task I-2. The fringe benefits for each UW employee are charged individually as direct costs in accordance with the current rates: 1) 43.3% for faculty, and 2) 3.9% for the undergraduate and graduate research assistants. The fringe benefits for each CU employee are charged in accordance with the current rates: 1) 29% for faculty, and 2) 1% for the graduate research assistants.

A total domestic travel cost of $59,600 is included to cover all travelling expenses required to perform 10 field pile load tests described in Task I-5, and disseminate research outcomes at national conferences (such as Transportation Research Board annual meeting). The travel expense for conducting the 10 pile load tests is estimated as $47,600. The cost of conducting a field load test at a project site covers all basic travel expenses of the research team to complete the sensor installation, dynamic load tests at the EOD and restrike events, and a static load test. Ten working days have been estimated to complete one field load test per site described in Task I-5. However, it is important to note that longer travel duration may be required depending on the test location and state that can be reached by a ground transport. The travel cost of $4,760 per test site has been estimated based on the following: ground transportation = $430 × 2 teams = $860; conventional hotel rate = $100 × 9 nights × 2 teams = $1,800; and per diem = $42 × 10 days × 5 team members = $2,100. The travel expense for disseminating research outcomes at four national conferences is estimated as $3,000 per conference travel for a total $12,000.

A budget of $80,142 for supplies and materials is included to cover all instrumentations and equipment to perform static load tests on 10 test piles described in Task I-5. Instruments include strain gauges, electric cables, and displacement transducers. Equipment for the static load tests includes hydraulic jack, load cell, electric pump, loading system, concrete anchored bolts, and data acquisition system. In addition, supplies are required for the laboratory triaxial tests on IGM at UW. The list of purchased equipment will be provided to WYDOT as the lead agency for the purpose of inventory management.

Tuition fees of the four graduate students are included under the other direct cost. The tuition fees for a 24-month master student and a 36-month PhD student attending UW are estimated to be $19,568 and $29,352, respectively. Likewise, the tuition fees of two 36-month PhD students attending CU are estimated to be $72,000. The indirect cost of $98,131 at a rate of 20% is charged on all direct costs except all tuition fees and equipment exceeds $5,000. The total cost estimate for this research project is $739,462. This total cost will be spread over in 60 months from July 1st 2018 to June 30th 2023 with $105,938 for year 2018, $145,766 for year 2019, $210,098 for year 2020, $138,773 for year 2021, $117,664 for year 2022, and $21,224 for year 2023.

It is important to note that the budget estimate summarized in Table 2 does not cover 1) the cost of detailed geotechnical investigations except triaxial tests on IGM described in Task I-4, 2) the cost of bridge structures and enlarged pilecap beams to accommodate the static load test described in Task I-5, 3) the construction cost of the test and production piles, 4) the indirect cost associated with possible construction delays due to field load tests, and 4) heavy equipment and operators for installing and dismantling the static load test system and for pile restrikes. However, these costs should be considered as part of the total construction cost of a bridge project. These activities associated with the research should be incorporated into the contract bidding process and construction documents of the bridge project. Since this is a pooled-fund study, the total funding requested from each funding agency is $150,000 or $30,000 per year for five years.

FACILITIES

The research team has the required software programs and equipment to perform the PDA testing as well as dynamic analyses. The Department of Civil and Architectural Engineering at UW and the Department of Civil Engineering at CU have computer, structural, and geotechnical/material laboratories, which are adequate for this research project, especially the triaxial test on IGM. The high-speed computing networks at UW and CU support services for instruction and research. The libraries at UW and CU offer facilities and services that aid in research, teaching, and studying. The libraries have extensive interlibrary loan capabilities that further enhance research activities.

IMPLEMENTATION

The aforementioned research outcomes and recommendations will directly benefit funding agencies and state DOTs that involve in the design and construction of bridge pile foundations. The research project will provide improvement to the current geotechnical investigation practices, pile design and construction practices, and LRFD specifications and guidelines pertaining to bridge pile foundations installed on IGM. This implementation plan will be performed in close coordination with the representatives from funding agencies. The final report will include a section specifically highlighting the research outcomes, recommendations, and implementations. A final presentation will be given by the research team on the implementation of research outcomes and recommendations.

TECHNOLOGY TRANSFER

Technology transfer will be performed in close coordination with funding agencies throughout the entire project duration. The final report will provide recommendations for potential revisions to existing LRFD design and construction specifications and guidelines pertaining to geotechnical investigation and piles driven 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 state and national conferences, such as the Transportation Research Board annual meeting. A final presentation will be given to facilitate technology transfer.

Table 2. Detailed budget estimate for the proposed research project

Budget Estimate

Description of Individual Cost	Year 2018	Year 2019	Year 2020	Year 2021	Year 2022	Year 2023	Subtotal
Salary							
Dr. Kam Ng (4 Months)	$ -	$ 9,756	$ 9,756	$ 9,756	$ 9,756	$ -	$ 39,025
Dr. Shaun S. Wulff (2 Months)	$ -	$ 4,459	$ 4,459	$ 4,459	$ 4,459	$ -	$ 17,837
Dr. NY Chang (2.5 Months)	$ -	$ 7,813	$ 7,813	$ 7,813	$ 7,813	$ -	$ 31,250
Dr. Hien Nghiem (24 Months)	$ -	$ 29,167	$ 29,167	$ -	$ -	$ -	$ 58,333
UW MS Graduate Assistant (24 months)	$ -	$ -	$ 16,800	$ 16,800	$ -	$ -	$ 33,600
UW PhD Graduate Assistant (36 months)	$ -	$ -	$ 11,190	$ 22,380	$ 22,380	$ 11,190	$ 67,140
CU PhD Graduate Assistant 1 (36 months)	$ 6,000	$ 12,000	$ 12,000	$ 6,000	$ -	$ -	$ 36,000
CU PhD Graduate Assistant 2 (36 months)	$ -	$ -	$ 6,000	$ 12,000	$ 12,000	$ 6,000	$ 36,000
Undergradaute Assistant (600 hours)	$ 1,000	$ 2,000	$ 1,000	$ -	$ 2,000	$ -	$ 6,000
Fringe							
Dr. Kam Ng (4 Months)	$ -	$ 4,224	$ 4,224	$ 4,224	$ 4,224	$ -	$ 16,898
Dr. Shaun S. Wulff (2 Months)	$ -	$ 1,931	$ 1,931	$ 1,931	$ 1,931	$ -	$ 7,724
Dr. NY Chang (2.5 Months)	$ -	$ 2,266	$ 2,266	$ 2,266	$ 2,266	$ -	$ 9,063
Dr. Hien Nghiem (24 Months)	$ -	$ 8,458	$ 8,458	$ -	$ -	$ -	$ 16,917
UW MS Graduate Assistant (24 months)	$ -	$ -	$ 655	$ 655	$ -	$ -	$ 1,310
UW PhD Graduate Assistant (36 months)	$ -	$ -	$ 436	$ 873	$ 873	$ 436	$ 2,618
CU PhD Graduate Assistant 1 (36 months)	$ 60	$ 120	$ 120	$ 60	$ -	$ -	$ 360
CU PhD Graduate Assistant 2 (36 months)	$ -	$ -	$ 60	$ 120	$ 120	$ 60	$ 360
Undergradaute Assistant (600 hours)	$ 39	$ 78	$ 39	$ -	$ 78	$ -	$ 234
Travel-Domestic	$ -	$ 27,200	$ 20,400	$ -	$ 12,000	$ -	$ 59,600
Supplies/Materials	$ 80,142	$ -	$ -	$ -	$ -	$ -	$ 80,142
Other Direct Costs							
UW MS Graduate Assistant (24 months)	$ -	$ -	$ 9,784	$ 9,784	$ -	$ -	$ 19,568
UW PhD Graduate Assistant (36 months)	$ -	$ -	$ 9,784	$ 9,784	$ 9,784	$ -	$ 29,352
CU PhD Graduate Assistant 1 (36 months)	$ 12,000	$ 12,000	$ 12,000	$ -	$ -	$ -	$ 36,000
CU PhD Graduate Assistant 2 (36 months)	$ -	$ -	$ 12,000	$ 12,000	$ 12,000	$ -	$ 36,000
Total Direct Cost:	$ 99,241	$ 121,472	$ 180,343	$ 120,905	$ 101,684	$ 17,686	$ 641,331
Indirect Costs (20%)	$ 6,697	$ 24,294	$ 29,755	$ 17,867	$ 15,980	$ 3,537	$ 98,131
Total Costs Per Year	**$ 105,938**	**$ 145,766**	**$ 210,098**	**$ 138,773**	**$ 117,664**	**$ 21,224**	$ 739,462
TOTAL ALL COSTS				**$739,462**			
Funding Requested from Each Agency	$ 30,000	$ 30,000	$ 30,000	$ 30,000	$ 30,000		$ 150,000

DATA MANAGEMENT PLAN

The historical pile data obtained in Task I-1 and new pile load data from Tasks I-4 and I-5 will consist of hammer, pile, geomaterial, driving, and load test information. These pile data sets will be collected in an electronic database in Task I-2. The usable pile data can be filtered and queried according to the specified location, hammer, pile, geomaterial, driving, and load test information. Also, all relevant documents, such as geotechnical reports, construction plans and test reports, will be attached in pdf format that can be easily extracted from the database. While developing the pile database, all pile data contained in folders under a research directory will be stored in an online file hosting service that offers cloud storage (e.g., Dropbox) as well as in existing RAID hard drive storage. The online file storage service allows the research team to access data remotely and share the data. All original data will be secured by the PIs. 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 the PI's institution policies pertaining to intellectual property, record retention, and data management.

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