Development of P-Y Curves for Analysis of Laterally Loaded Piles in Montana

by

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A proposal prepared for the Montana Department of Transportation

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PROBLEM STATEMENT

The response of a laterally loaded pile depends on the lateral stiffness of the soil, the pile stiffness, and the interaction between the pile and the surrounding soil. A laterally loaded pile can be analyzed using different methods; among which, the p-y method, a method of intermediate complexity and reasonable accuracy, has been widely accepted by the geotechnical engineering community. In the p-y method, the soil reaction is replaced with a series of independent nonlinear springs, and the nonlinear behavior of the soil is represented by the p-y curves and relating the soil reaction and pile deflection at points along the pile length. The p-y curves are developed based on a relatively small amount of data in specific soil conditions; therefore, their accuracy depends on the data from which the curve was developed which may or may not correlate well with soils in Montana. Consequently, the applicability of these procedures to different soil conditions is uncertain and may lead to un-conservative or over-conservative designs.

BACKGROUND SUMMARY AND SIGNIFICANCE OF WORK

Introduction

Pile foundations supporting highway bridges are subjected to lateral loads as well as vertical, gravity loads. Thus, in the design of pile foundations, both lateral and vertical loads must be considered to prevent failure or excessive lateral deflection of piles.

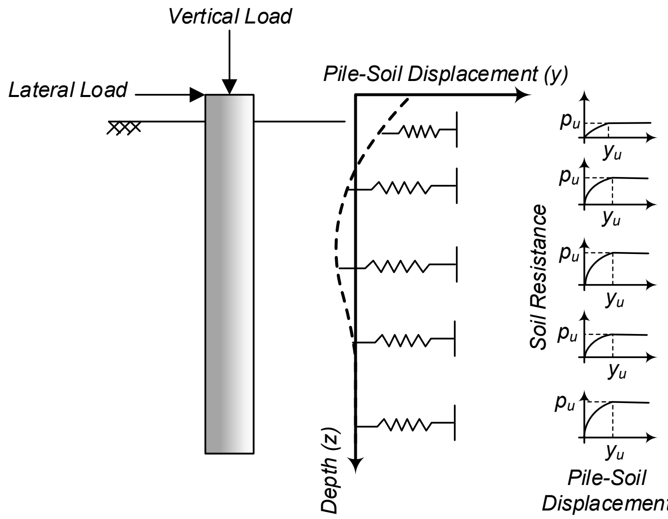

Fig. 1. P-y curve analysis

The analytical approaches developed for evaluating pile response to lateral loading vary from the most simplified approach of limit equilibrium to more complicated methods including finite element or continuum approaches. The analytical method should be able to account for different pile head conditions (e.g., fixed or free to rotate) and consider different combinations of vertical and lateral loading as well as applied moments at the top of the pile. Responses of particular interest include load-deflection behavior at the top of the pile, the deflected shape of the pile, and the variation of shear and bending moment along the length of the pile. Among these methods, the discrete load transfer approach or p-y curve analysis (Fig. 1) has been accepted as an accurate and reliable method to evaluate the response of a single pile subjected to lateral loads. The p-y curves are typically derived from full-scale tests with continuum effect implicitly incorporated (Wallace et al. 2001).

The response of laterally loaded piles has been studied using full-scale field tests (e.g., Kramer 1991; Christensen 2006), model-scale centrifuge tests (e.g., Barton et al. 1994; Brant and Ling 2007; Logan and Hoe 2007; Sawada and Takemura 2014; Haouari and Bouafia 2020), and numerical analyses (e.g., Elhakim et al. 2016; Haouari and Bouafia 2020). Previous experimental and numerical studies demonstrate that the accuracy of p-y methods depends directly on the accuracy with which the p-y curves represent the ability of soil to resist lateral pile deflections (Ashour et al. 1998, Kramer 1991). As shown in Fig. 1, the nonlinear reaction of soil along the depth of the pile is modeled using a series of discrete springs (p-y curves) (Reese et al. 1974; Reese et al. 1975). P-y curves are characterized by three portions: 1) an initial linear (straight) portion with the modulus of the *p-y* curve being dependent on the soil elastic modulus, E_s, 2) the nonlinear portion, and 3) and a constant (straight-line) portion featuring the ultimate failure after reaching the ultimate soil resistance, p_{ult}. The nonlinear portion of the curve is related to the pile dimensions (e.g., pile bending stiffness and pile cross-sectional shape) and soil properties and is derived empirically from full-scale/centrifuge lateral load tests (Wallace et al. 2001). In addition to soil type and pile dimension, pile-head fixity and pile-head embedment influences the resulting p-y curves.

While there are several studies pertaining to p-y curve analysis of laterally loaded piles that will be beneficial in the development of this study, there is a lack of information on the applicability of existing p-y curve criteria to Montana soil conditions. The proposed research project will investigate the applicability of the available p-y curves to soil conditions encountered in Montana. We plan to first identify available methods for the development of p-y curves and evaluate their applicability to soil conditions encountered in Montana. The results from a series of model-scale, instrumented centrifuge experiments on piles embedded in prioritized soils collected from different regions of Montana are coupled with numerical simulations to understand the behavior of a single pile laterally loaded in different prioritized soil conditions. The results will be used to develop p-y curves for analysis of laterally loaded piles in Montana.

BENEFITS AND BUSINESS CASE

The benefits of the research are to identify available methods for the development of p-y curves and to determine which is the most appropriate for the soil conditions encountered in Montana. The results of this research will lead to more accurate prediction of pile response and less conservative design of pile foundations and improve the economy of pile foundations without compromising safety.

OBJECTIVES

The general purpose of the research proposed here is to identify available methods for the development of p-y curves and to evaluate their applicability to soil conditions encountered in Montana. The results of this research lead to more accurate prediction of pile response and less conservative design of pile foundation and improve the economy of pile foundations without compromising safety. The research proposed here will be accomplished with the following steps: 1) review the current methods for analysis of laterally loaded piles, from the most common methods (e.g., p-y method) to the most complex; 2) review and prioritize soil conditions in Montana for which laterally loaded pile behavior is not well known, and evaluate the applicability of p-y curves to Montana soil conditions; 3) perform a series of model-scale, instrumented centrifuge experiments on piles embedded in prioritized soils collected from different regions of Montana in the centrifuge facility at the University of New Hampshire to develop a data set capable of gaining insight into the characteristics of p-y resistance in Montana soil conditions; 4) couple the experimental results with numerical simulations to understand the behavior of a single pile laterally loaded in different prioritized soil conditions and develop p-y curves for analysis of laterally loaded piles in Montana; 5) use the findings from previous tasks in this research to re-evaluate the performance of a laterally loaded pile from a project site located on Interstate 15 in Lewis and Clark County, MT and validate the findings of the new research.

RESEARCH PLAN

To achieve the research goals, the work is grouped into eleven major tasks (Fig. 2):

Initial Stage

0) *Task 0: Project management and TP meeting #1*,

Research Stage

1) *Task 1: Review the current methods for analysis of laterally loaded piles*, from the most common methods (e.g., p-y method) to the most complex, and evaluate the applicability of p-y curves to Montana soil conditions; and *TP meeting #2*,
2) *Task 2: Review and prioritize soil conditions in Montana for which laterally loaded pile behavior is not well known (e.g., Lake Missoula Silt, Intermediate Geomaterial (IGM), Dense Gravel) with Assistance from TP (including engineers from both geotechnical and bridge sections)*; and *TP meeting #3,*
3) *Task 3: Model-Scale Instrumented Centrifuge Experiments in the Centrifuge Facility at the University of New Hampshire (UNH)*; and *TP meeting #4*: Perform a series of model-scale, instrumented centrifuge experiments on piles embedded in prioritized soils (identified in Task 2) collected from different regions of Montana in the centrifuge facility at the University of New Hampshire to develop a data set capable of gaining insight into the characteristics of p-y resistance in Montana soil conditions,
4) *Task 4: P-Y Curve Analysis and Numerical Modeling*: Couple the experimental results with numerical simulations to understand the behavior of a single pile laterally loaded in different prioritized soil conditions and develop p-y curves for analysis of laterally loaded *piles in Montana,*
5) *Task 5: P-Y Curves Development; and TP meeting #5*,
6) *Task 6: Use the findings from previous tasks in this research to re-interpret and re-evaluate the performance of a laterally loaded pile from a project site located on Interstate 15 in Lewis and Clark County, MT and validate the findings of the new research*. The interpretation/evaluation process involves three main steps: 1) detailed analysis of the pile deformation measured during the lateral load test, 2) interpret the load-deformation data within the framework of existing p-y curve criteria, and 3) evaluate the existing p-y criteria to determine whether they are capable of representing the behavior observed during the lateral load test.

Final Stage

7) *Task 7: Draft Final Report*.
8) *Task 8: TP Meeting #6*.
9) *Tasks 9 to 11: Final Reports and Dissemination of Results*.

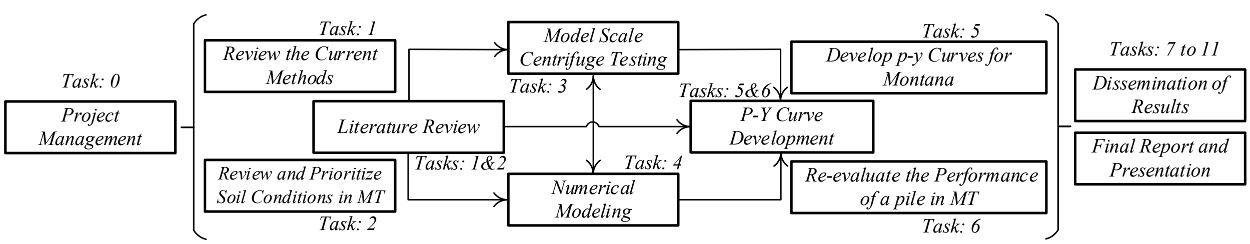

Fig. 2. Project outline: Tasks, and activities

Task 0: Project Management; and TP Meeting #1

The Principal Investigator on this project will be Dr. Mohammad Khosravi. PI Khosravi will lead the overall direction of the project and serve as the primary point of contact between the Montana State University (MSU) research team and the Montana Department of Transportation (MDT) Project Manager. During the course of the project, the research team will submit quarterly progress reports to describe the status of the project with respect to timeline and budget. The project team will also submit task reports upon completion of specific tasks, and a project summary report and a final report upon completion of the project.

Task 0.1. TP Meeting #1: kick-off meeting: The project will begin with a kick-off meeting with the researchers and MDT to ensure everyone is informed of the contractual obligations and to clarify any technical issues and concerns.

Time Frame: *By May 2022*
Responsible Party: *PI and TP*
Deliverable: *TP meeting attendance, TP meeting presentation, TP meeting minutes and notes*.
TP Action: *Review and understand project research problem statement, research question, the limits of the research, and the project schedule. Advise PI's regarding related professional practices, standards, methods and context for the project*.

Task 1: Review Current Methods for Analysis of Laterally Loaded Piles; and TP Meeting #2

Task 1.1. Literature Review: As this research moves ahead, it is essential to be aware and take advantage of any work completed to date by other investigators/organizations. There is a large amount of literature available on this subject that can be reviewed, summarized, and synthesized to extract information relevant to the challenges faced by MDT. In order to understand MDT's perceptions and identify the most common methods of analyses used by MDT, a questionnaire will be designed and submitted to MDT. The results of the survey will be used to narrow down the literature review to those methods used by MDT for analysis of laterally loaded piles, from the most common methods (e.g., p-y method) to the most complex methods. This review will include sources from the Transportation Research Board, State Departments of Transportation, universities, and national and international journals. Meetings with the TP will be conducted to help determine the benchmarks and practices for the design of piles under lateral load. A presentation will be prepared and presented at the end of this task and submitted to MDT for review. This task will include:

- A definition of the problem and research question,
- A theoretical context,
- Methods that may be used to answer the research question with a focus on Montana soil conditions, and,
- Data resources, including availability and quality.

Task 1.2. TP Meeting #2: TP Meeting to discuss the results of Task 1.

Time Frame: *May 2022 – Nov 2022.*
Responsible Party: *PI*
Deliverable: *TP meeting presentation, TP meeting minutes and notes, and submission of progress reports every three months*.
TP Action: *Attend the meeting, discuss with PI, and if necessary direct them to make changes to*

project documents.

Task 2: Review and Prioritize Soil Conditions in Montana; and TP Meeting #3

The objective of this task is to review the applicability of existing p-y curves to Montana soil conditions.

Task 2.1. Review and Prioritize Soil Conditions: The soil conditions encountered in Montana are reviewed and compared with the soil conditions for which the existing methods can reliably predict p-y behavior. Soil conditions for which existing p-y curve are not available are identified and recommendations towards development p-y curve criteria for such soils are presented. And finally, procedures for the performance of model-scale centrifuge experiments are discussed. These parameters will be later used for parametric study using our validated numerical model (Task 4) and in the design of the model-scale centrifuge experiments in UNH (Task 3). MSU will reach out to MDT for any available soil samples from different locations in Montana.

Task 2.2. TP Meeting #3: TP Meeting to discuss the results of Task 1 and 2.

A report will be completed and at the end of this task and submitted to MDT for review. The literature review will be updated for the Final Report (Task 7).

Time Frame: *Nov 2022 – April 2023: Task 1 report will be sent to the TP at the end of April 2023.*
Responsible Party: *PI*
Deliverable: *Tasks 1&2 report and submission of progress reports every three months, TP meeting presentation, TP meeting minutes and notes*.
TP Action: *Review of progress reports; Advise PI if necessary; Provide soil samples from different locations in Montana for soil testing; Review the materials to ensure they have met the specifications recommended by MDT; Schedule TP Meeting #3.*

Task 3: Model-Scale Instrumented Centrifuge Experiments in the Centrifuge Facility at the University of New Hampshire (UNH); and TP Meeting #4

Task 3.1. Geotechnical index testing: This task includes a series of lab experiments to characterize the index properties of the collected soils which includes: (1) dry sieve analysis (ASTM D6913-04) and hydrometer analysis (ASTM D422-63, 2014), (2) specific gravity (ASTM D854-14), (3) Atterberg limit tests (ASTM D4318 - 17e1), and (4) maximum and minimum void ratio test (ASTM D4254-00, 2000). The experiments will be conducted by a graduate student in the geotechnical engineering lab at MSU.

Task 3.2. Assessing strength properties using triaxial testing: This task includes a series of consolidated undrained monotonic triaxial compression (CU) tests to characterize the strength properties of the collected soils. The triaxial tests will be performed using two TruePath automated stress path triaxial systems in the Geotechnical Engineering lab at MSU. The soil specimens will be compacted in cylindrical molds. Compaction will be performed in five lifts with moist soil distributed evenly throughout the mold for each layer. The amount of soil required for each lift will be determined based on the desired dry density (void ratio). To prevent excessive compaction of lower layers, Ladd's (1978) compaction method will be used. The experiments will be conducted by a graduate student in the geotechnical engineering lab at MSU.

Task 3.3. Centrifuge experiments in the centrifuge facility at UNH: Once the soil characteristics are established and the initial geotechnical tests are complete, a set of model-scaled centrifuge experiments on piles embedded in prioritized soils collected from different regions of Montana will be performed. The experiments will be performed using the 1-m-radius Genisco centrifuge at UNH (Fig. 3) to develop a data set capable of gaining insight into the characteristics of p-y resistance in Montana soil conditions. A 5 g-ton Genisco centrifuge at UNH is suitable for seismic soil models, slope stability evaluation, seepage mechanisms and contaminant transport study, soil-structure interaction problems. The graduate student working on the project will be sent to UNH for three months to perform the centrifuge experiments.

Fig. 3. Schematic of testing apparatus, and tubing configuration

Task 3.3.1. Model design and construction: Fig. 4 depicts a 2D schematic of the tentative design of the testing setup, and specimen configuration. The experiments will be conducted under saturated and unsaturated conditions. Unsaturated testing will be performed using capillary rise method (Komolafe et al. 2021). In this method, an unsaturated soil layer is induced by in-flight free drainage of an initially saturated specimen. This method allows capillary rise to generate an unsaturated soil layer above the location of the groundwater table. The water level is lowered in the specimen to a target elevation during centrifugation by opening and closing miniature solenoid valves for a calibrated period. The depth of the groundwater table is monitored using an array of pore pressure sensors throughout the soil profile until equilibrium conditions are reached. Drained water is collected into drainage tanks located below the in-flight shake table.

Soil models are instrumented with advanced measurement sensors including LVDTs, pore water pressure sensors, moisture content probes, and cameras, all being monitored and controlled through a remote data acquisition system (DAQ). Structural elements will be instrumented with strain gages. The in-flight static lateral loading tests are conducted with state-of-the-art electric actuators. A report will be completed at the end of this task and submitted to MDT for review.

Task 3.4. TP Meeting #4: Mid-project TP Meeting to discuss results of Task 2 and 3.

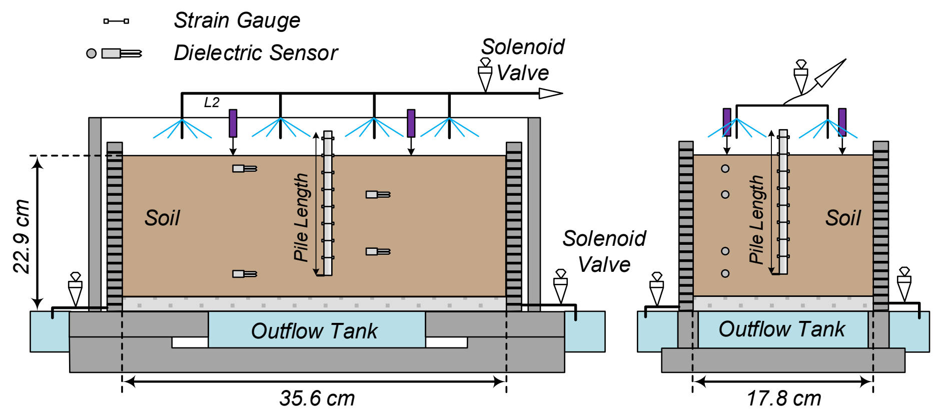

Fig. 4. Schematic of testing apparatus, pile testing configuration and infiltration setup (redrawn from Ghayoomi et al. 2018; Mirshekari and Ghayoomi 2017)

Time Frame: *May 2023 – April 2024: Task 3 report will be sent to the TP at the end of April 2024.*

Deliverable: *Task 3 report: model-scale instrumented centrifuge testing of piles under lateral loading, and submission of progress reports every three months, TP meeting attendance, TP meeting presentation, TP meeting minutes and notes*.

TP Action: *Review of progress reports; Review the model design and advise PI if necessary; Provide available data from currently instrumented piles testing.*

Task 4: P-Y Curve Analysis and Numerical Modeling

The experimental results (e.g., those extracted from model-scale experiments) will be coupled with and used to calibrate a numerical model. Numerical simulations of laterally loaded piles will be performed using FLAC software (Itasca 2016). FLAC is a finite difference program and can be used with a built-in programming language called FISH to quickly run iterations of a model for reliability analyses. The calibrated model will be used to expand the applicability of p-y approach to different conditions (e.g., different pile types and dimensions, pile-head fixity, and pile-head embedment) using a family of p-y curves developed based on numerical analyses. The numerical p-y curves are compared and validated against traditional p-y curves for different soils as well as those obtained from centrifuge experiments.

At the early stages of the project, before any experiments are performed, the available experimental/field data available in the literature that may be relevant to this project will be used to develop preliminary numerical simulations. Once the lab and model-scale experiments are performed, we will further calibrate and refine our numerical model by selecting the appropriate model values that best capture the observed behavior. The calibrated model will then be used to run "numerical experiments" which will incorporate simulations with a variety of conditions.

Although listed as Task 4, numerical modeling will be a cornerstone of this project, and closely linked with all phases, including design of the model-scale testing experiments, aiding in the interpretation of experimental results, and extrapolation of experimental findings to the wider range of conditions needed to develop p-y curves. Numerical modeling will begin early on in the project and occur throughout.

Time Frame: *May 2022 – Oct 2024: Task 4 report will be sent to the TP at the end of Oct 2024.*

Responsible Party: *PI*
Deliverable: *Task 4 report: Numerical modeling, and submission of progress reports every three months*.
TP Action: *Review of Task 4 report and progress reports; Advise PI if necessary.*

Task 5: P-Y Curves Development; and TP Meeting #5.

Task 5.1. P-Y Curves Development: Following review of the experimental and numerical data, and discussions with the technical panel, appropriate p-y curves will be developed to capture the pile response under lateral loading. The p-y curves will be implemented within LPile so that the typical MDT engineer can easily use them for a given pile and soil condition and evaluate demands on piles. LPile, one of the common computer programs for analyzing piles under lateral loading using the p-y method, allows users to input their own lateral load-transfer (p-y) curves for specified soil layers. A report will be completed and at the end of this task and submitted to MDT for review.

Task 5.2. TP Meeting #5: TP Meeting to discuss results of Tasks 4 and 5.

Time Frame: *Nov 2024 – April 2025: Task 4 report will be sent to the TP at the end of Nov 2024*
Responsible Party: *PI, assisted by the TP.*
Deliverable: *TP Meeting Presentation, TP meeting minutes and notes, Progress reports approximately every three months*.
TP Action: *Attend the meeting, discuss with PI, and if necessary direct them to make changes to project documents.*

Task 6: Use the Findings from Previous Tasks in this Research to Re-interpret and Re-evaluate the Performance of a Laterally Loaded Pile from a Project Site Located on Interstate 15 in Lewis and Clark County, MT and Validate the Findings of the New Research

The results of model-scale experiments and numerical simulations will be used to re-evaluate the performance of a laterally loaded pile from a project site located on Interstate 15 in Lewis and Clark County, MT and validate the findings of the new research. The pile was a 16-inch pipe pile with conical tip and a nominal manufacturer's wall thickness of 0.5 inch. The site consisted of interbedded sand, gravel, and volcanic ash with varying amounts of silt and clay extending to depths on the order of 21 to 35 feet below natural grade, and cobbles and boulders in volcanic ash matrix extending to depths on the order of 66 to 92 feet below natural ground. A report will be completed at the end of this task and submitted to MDT for review. The interpretation/evaluation process involves three main steps: 1) detailed analysis of the pile deformation measured during the lateral load test, 2) interpret the load-deformation data within the framework of existing p-y curve criteria, and 3) evaluate the existing p-y criteria to determine whether they are capable of representing the behavior observed during the lateral load test.

Time Frame: *May 2025 – Oct 2025: Tasks 5& 6 report will be sent to the TP at the end of Oct 2025.*
Responsible Party: *PIs, assisted by the TP.*
Deliverable: *Tasks 5 & 6 report: P-Y curves development*.
TP Action: *Review and advise.*

Task 7: Draft Final Report

The dissemination of the results will be achieved through a final report documenting research methodology, findings, and recommendations in a publication-ready Draft Final Report within the prescribed MDT report format. Contents will include: an updated abstract, acknowledgement, disclaimer, introduction, Updated Lit Review (Tasks 1 and 2), geotechnical and model-scale centrifuge test results (Task 3), summary of numerical modeling and recommended p-y curves for the design of laterally loaded piles (Tasks 4, 5, and 6), discussion of results, conclusions, and potential for future research, application, or technology transfer, and other sections as appropriate.

Time Frame: *Nov 2025 – Feb 2026: The first draft of the final report will be sent to the TP at the end of Dec 2025.*
Responsible Party: *PIs, assisted by the TP.*
Deliverable: *Draft Final Report using MDT's report template*.
TP Action: *Review and advise.*

Task 8: TP Meeting #6

This TP meeting will occur after the review of the first draft final report is provided to the researchers and include a review of the Draft Final Report. The TP will offer advice on the content and clarity of these work products. The TP will also advise on post research implementation.

Time Frame: *Feb 2026*
Responsible Party: *PIs, assisted by the TP*
Deliverable: *TP meeting presentation, TP meeting minutes and notes*.
TP Action: *TP review of Draft Final Report. If necessary, direct PI to make changes to project documents.*

Task 9: Draft Implementation and Performance Measures Reports

The implementation report will include implementation summary, the researcher's recommendations and an MDT response to each recommendation. Performance measures report will concisely document the value of the research.

Time Frame: *April 2026*
Responsible Party: *PIs, assisted by the TP*
Deliverable: *Draft Implementation and Performance Measures Reports using MDT's report template*.
TP Action: *Review and advise.*

Task 10: Draft Project Summary Report

The summary will concisely document research methodology, findings, recommendations, and any limitations on the use of the findings.

Time Frame: *April 2026*
Responsible Party: *PIs, assisted by the TP*
Deliverable: *Draft Project Summary Report using MDT's report template*.
TP Action: *Review and advise.*

Task 11: Final Report, Webinar, Presentation, and Dissemination of Results

Draft Final Report will be edited to incorporate edits identified by the TP. A final presentation will also be made to MDT in Helena where the implementation potential of the results and future direction of the project can be discussed. The research team will also prepare journal and conference manuscripts for publication and presentation at engineering venues such as the Transportation Research Board's Annual Meeting, American Society of Civil Engineers and Geotechnical Engineering Institute's (ASCE/GI) Geo-Congress.

Time Frame: *May 2026 – June 2026*
Responsible Party: *PIs*
Deliverable: *Final Report*.
TP Action: *Review of Final Report. Provide formal acceptance of Final Report.*

MDT AND TECHNICAL PANEL INVOLVEMENT

- The following items are respectfully requested of MDT staff during this project:
- Material Testing Specifications: MDT will provide information on specifications, approved products, and the product approval process for testing materials (soil and concrete) in Montana.
- Pile Lateral Testing Data: Meetings with the TP and engineering staff will be conducted to discuss the available data. In addition to the results of a laterally loaded pile from a project site located on Interstate 15 in Lewis and Clark County, MT, MDT will provide the results of any laterally loaded pile test conducted in the next five years.
- Interviews: MDT will ensure the availability of supervisors and engineering staff for personal interviews with the Principal Investigators. MDT's preferred design methodology and material specifications will be reviewed to make sure the remaining tasks will produce results that are consistent with existing MDT's approaches. Before planning any interview, a questionnaire will be designed by MSU with assistance from MDT staff and technical panel and submitted to MDT to understand MDT's perceptions and identify the most common methods of analyses used by MDT.
- Material Testing: MSU will also reach out to MDT for any available soil samples from different locations in Montana for our geotechnical/centrifuge testing. MDT will ensure the materials (e.g., concrete) have met the specifications recommended by MDT. Our objective is to collect the available data in MDT's inventory. These parameters will be later used for parametric study using our validated numerical model and design the model scale experiments.
- Data Collection: The focus of this proposal is to evaluate the feasibility of this technology for state of Montana. Available data from instrumented laterally loaded pile would help us immensely in our study. These parameters will be later used for parametric study using our validated numerical model (Task 4) and in the design of the model scale experiments in NHU (Task 3). MSU will also reach out to MDT for available soil samples from different locations in Montana for our centrifuge testing. MSU will work with MDT staff and technical panel to collect available data from currently instrumented laterally loaded piles. The PI will send his PhD student to help the MDT staff collect the information and convert the paper copies to soft copies.
- Review: General assistance will be sought from MDT personnel throughout the various phases of this project. Of specific importance will be the review of the technical task reports, and involvement in periodic web-based meetings to discuss various aspects of this project. The final report will also be reviewed by the Technical Panel for this project.

PRODUCTS

The following products will be produced as a result of the proposed research:

1) Tasks 1&2 report: Literature Review
2) Task 3 report: model-scale instrumented centrifuge testing of piles under lateral loading
3) Task 4 report: Numerical modeling
4) Tasks 5 and 6 report: P-Y curves development
5) Quarterly progress reports
6) Final report, including an implementation plan and cost/benefit analysis
7) Project summary report
8) Implementation report
9) Performance measures report
10) Final presentation and poster
11) Journal and/or conference publications and presentations
12) Project webinar

Note: All products (presentations, task reports) will be prepared according to Section 508 (ADA) compliance.

IMPLEMENTATION

In the final report, first, the soil conditions encountered in Montana will be briefly reviewed and the applicability of existing p-y curves to Montana soil conditions will be discussed. The final report will also include recommendations toward development of p-y curve criteria for soil conditions for which existing p-y curves criteria are not available. The results of this research would be readily implemented by the Geotechnical Section of MDT once completed since the Geotechnical Section already uses p-y curve data in the designs of piles. The final report would identify the most applicable pile designs methods and the most accurate p-y curve data to support those designs. And this research would develop a dataset that could be further refined with subsequent lateral load test results from future construction projects.

SCHEDULE

Table 1 illustrates the scheduling of the major research tasks on a quarterly basis.

Table 1. Project Time Schedule

Research Task	Time Schedule																																																
	Year 1												Year 2												Year 3												Year 4												Y5
	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	A	M	J
Task #0: Project Management																																																	
Task #0.1 - TP Meeting #1: kick-off meeting																																																	
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Task #1.1: Literature Review																																																	
Task #1.2 - TP Meeting #2																																																	
Deliverable: Presentation and Quarterly progress reports							P																																										
Task #2: Review and Prioritize Soil Conditions in Montana																																																	
Task #2.1: Literature Review																																																	
Task #2.2 - TP Meeting #3																																																	
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Task #3.2 - Model testing at the University of New Hampshire																																																	
Task #3.3 - Laboratory data analysis																																																	
Task #3.4 - TP Meeting #4																																																	
Deliverable: Task 2 report and quarterly progress reports																								TR																									
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Task #4.2 - Synthesis of laboratory and numerical findings																																																	
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- *TR: Task Reports*
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- *IPR: Implementation and Performance Measures Reports*
- *FR: Final Report*
- *PSR: Project Summary Report*

BUDGET

The requested project budget is $246,089. Schedule, budget, and staffing plans are based on state fiscal year proportioning, as shown in Tables 2 to 5.

PI Khosravi is requesting three summer months one for each year with the total of $------- (including benefits). PI's effort allocation throughout the project is 40% centrifuge testing, 40% numerical modeling, and 20% field data analysis.

The proposal requests twelve-month support ($24,330 for Year 1, $25,060 for Year 2, and $25,810 for Year 3) and full-year tuition ($5,566) for one Ph.D. for Years 1, 2, and 3, and two-month summer support for one master student for Years 1 and 2 at Montana State University. Master and Ph.D. students' efforts will include design and develop construction methods and perform centrifuge testing of the soils. The Ph.D.'s effort will also include analysis centrifuge test data and numerical modeling. These two graduate students will work in close coordination with each other and the PI.

Indirect costs are computed at a university-wide rate as a percentage of direct costs. The IDC rate for state research is 25% of all direct costs.

Expendable supplies needed for this project include the cost for: 1) obtaining the testing material to be used in the geotechnical laboratory tests, model-scale test (e.g., soil, sensors, strain gages, etc.) as well as miscellaneous laboratory and computer supplies. Testing materials are budgeted $2,000 for Y1, $6,000 for Y2, and $1,000 for Y3 with the total of $9,000. 2) conducting centrifuge experiments at the university of New Hampshire with the total of $40,000. In summary the total Material and Supplies and equipment budget of $49,000 includes centrifuge experiments, testing material, and miscellaneous laboratory supplies.

The PI is requesting travel funds for: 1) PI and the graduate student to attend a national conference during the last year of the project and present findings of this research. Attendance cost is budgeted as an average of $1,900 per person for the PI and $1,300 for students (airfare $500, conference fee $800 for the PI and $200 for the student, lodging and meals for 4 days $600) with the total amount of $3,200; 2) four trips to MDT to attend Technical Panel Meetings and presents the results of the research with a total of $800, 3) the graduate student to travel to the University of New Hampshire to conduct the centrifuge experiments (airfare $800, accommodations for three months $1,500) with a total amount of $2,300.

Total Direct and Indirect Costs

Direct Costs: SFY 22: $8,035.6; SFY 23: $48,213.2; SFY 24: $48,213.3; SFY 25: $48,213.3; SFY 26: $44,195.5

Indirect Costs: SFY 22: $2,008.9; SFY 23: $12,053.3; SFY 24: $12,053.3; SFY 25: $12,053.3; SFY 26: $11,048.9

Total Costs: $246,088.8

Table 2. Budget summary by State Fiscal Year

Item	State Fiscal Year 2022	2023	2024	2025	2026	Total Cost
Salaries						
Benefits	$611.8	$3,670.9	$3,670.9	$3,670.9	$3,365.0	**$14,989.4**
In-State Travel	$32.7	$195.9	$195.9	$195.9	$179.6	**$800.0**
Out-of-State Travel	$261.2	$1,567.3	$1,567.3	$1,567.3	$1,436.7	**$6,400.0**
Supplies	$2,000.0	$12,000.0	$12,000.0	$12,000.0	$11,000.0	**$49,000.0**
Tution	$795.1	$4,770.9	$4,770.9	$4,770.9	$4,373.3	**$19,481.0**
Equipment Purchase	$0.0	$0.0	$0.0	$0.0	$0.0	**$0.0**
Laboratory Fees	$0.0	$0.0	$0.0	$0.0	$0.0	**$0.0**
Subcontracts	$0.0	$0.0	$0.0	$0.0	$0.0	**$0.0**
Total Direct Costs	$8,035.6	$48,213.3	$48,213.3	$48,213.3	$44,195.5	**$196,871.0**
Indirect Costs (25%)	$2,008.9	$12,053.3	$12,053.3	$12,053.3	$11,048.9	**$49,217.8**
Total Project Cost	$10,044.4	$60,266.6	$60,266.6	$60,266.6	$55,244.4	**$246,088.8**

Table 3. Task, meeting, and deliverable cost breakout

Item	Labor	Material	Travel	Award	Total
Project management	$2,240	$0	$200	-	$2,440
Task 0, Kickoff Meeting	$2,240	$0	$200	-	$2,440
Task 1, Review Current Methods for Analysis of Laterally Loaded Piles	$15,200	$0	$0	-	$15,200
Deliverable, TP meeting presentation and quarterly progress reports	$0	$0	$0	-	
Task 2, Review and Prioritize Soil Conditions in Montana	$16,500	$3,000	$0	-	$19,500
Deliverable, Tasks 1&2 report and quarterly progress reports	$0	$0	$0	-	
Task 3, Model-Scale Instrumented Centrifuge Experiments	$25,320	$46,000	$3,200	-	$74,520
Deliverable, Task 3 report and quarterly progress reports	$0	$0	$0	-	
Task 4, P-Y Curve Analysis and Numerical Modeling	$23,370	$0	$1,600	-	$24,970
Deliverable, Task 4 report and quarterly progress reports	$0	$0	$0	-	
Task 5, P-Y Curves Development; and TP meeting #4	$14,080	$0	$1,600	-	$15,680
Deliverable, TP meeting presentation and quarterly progress reports	$0	$0	$0	-	
Task 6, Re-evaluate the Performance of a Laterally Loaded Pile in Montana	$14,080	$0	$200	-	$14,280
Deliverable, Tasks 5 & 6 report and quarterly progress reports	$0	$0	$0	-	
Task 7, 9, 10 and 11: Final Report and Presentation	$8,160	$0	$200	-	$8,360
Deliverable, Draft Final Report	$0	$0	$0	-	
Tasks 5 and 8: TP Meetings #3 & 4	$0	$0	$0	-	$0
Award (Tuition)	-	-	-	$19,481	$19,481
Total	**$121,190**	**$49,000**	**$7,200**	**$19,481**	**$196,871**

Table 4. List and itemize all out-of-state travel

Out of State Travel					
Assumption			*Number*	*Unit*	*Total*
Airfare	*2 trips for 2 persons + 1 trip for 1 person*		*3*	*$ 600.0*	*$ 1,800.0*
Hotel	*2 trips for 2 persons + 1 trip for 1 person*	*2 nights*	*2*	*$ 650.0*	*$ 1,300.0*
Meals	*2 trips for 2 persons + 1 trip for 1 person*	*2 days*	*2*	*$ 50.0*	*$ 100.0*
Airfare	*1 trip for one person*		*1*	*$ 800.0*	*$ 800.0*
Accommodation	*3 months*		*3*	*$ 500.0*	*$ 1,500.0*
Total					*$ 5,500.0*

Table 5. Labor expenses

Person	Role	Kickoff Meeting	Task 1	2	3	4	5	6	7	Total	Hourly Rate	Total Wages	Hourly Benefit Rate	Total Benefits	Total Cost
Mohammad Khosravi	Principal Investigator	80	100	100	120	120	80	80	60	740	$	$	$	$	$
PhD Student	Researcher	0	600	600	1000	1000	600	600	300	4700	$16.00	$71,440	$0.80	$3,760	$75,200
Master Student	Researcher	0	0	100	200	50	0	0	0	350	$13.00	$4,323	$0.65	$228	$4,550
Business Mgr.	Budget Assistance	0	0	0	0	0	0	0	0	0	$0.00	$0	$0.00	$0	$0
Admin Staff	Admin. Support	0	0	0	0	0	0	0	0	0	$0.00	$0	$0.00	$0	$0
Total		**80**	**700**	**800**	**1320**	**1170**	**680**	**680**	**360**	**5790**		**$101,870**		**$19,320**	**$121,190**

Indirect Cost @ 25%	$49,218
Total Labor Cost	$170,408
Tuition Fees	$19,481
Direct Expenses	
In-State Travel	$800
Out of State Travel	$6,400
Expendable Supplies	$49,000
Total Project Cost	$246,089

STAFFING

The Principal Investigators on this project will be Dr. Mohammad Khosravi (MK). MK will lead the overall direction of the project and will be the point of contact with MDT. MK will lead the overall direction of the project and will be responsible for conducting the geotechnical lab testing, centrifuge testing, and numerical modeling. The Principal Investigator will be responsible for ensuring that the objectives of the study are accomplished, executing the project tasks, and preparing the final report. The research team is well qualified, experienced and available to conduct this research and to deliver quality finished products to MDT in a timely and efficient manner. The level of effort proposed for principal and professional members of the research team will not be changed without the written consent of MDT. The following paragraphs describe some of the qualifications and experience of key project personnel in addition to each person's role in this study.

PI: Mohammad Khosravi, Ph.D.

PI Khosravi (MK) is an Assistant Professor in the Department of Civil Engineering at Montana State University. PI Khosravi is an experienced physical modeler. His expertise is in geotechnical testing, and performance of natural and man-made soil structures. He has also experience in numerical modeling and its application in geotechnical engineering. He has performed 2D and 3D modeling of soil, and soil-structure interaction using FLAC2D, and 3D for his Ph.D. work at Virginia Tech and post-doctoral research at UC Davis. He has published more than 30 peer reviewed journal and conference papers and is an active member of ASCE and Natural Hazards Engineering Research Infrastructure (NHERI) network.

Research Assistant

The proposal requests twelve-month support and full-year tuition for one full-time Ph.D. graduate student at Montana State University for Years 1, 2, and 3, and two-month summer support for one master student for Years 1, and 2, at Montana State University. The Ph.D.'s effort will include geotechnical testing of soils, design and develop construction methods and prepare/assemble the model-scale test setups, and numerical modeling. Master student's efforts will include geotechnical testing of soils, and also helping the master student prepare/assemble the test setups. These two graduate students will work in close coordination with each other and the PI. These two graduate students will work in close coordination with each other and the PI and Co-PIs.

Research Team Hours and Availability

It is anticipated that the proposed work associated with this research project will take 5790 person hours. The quantity of hours committed to the project by each member of the research team during this time period is shown in Table 6. Key personnel assigned to accomplish the work associated with this project are available throughout the duration of this project.

Table 6. Project staffing

Person	Role	Kickoff Meeting and Others	Task 1	Task 2	Task 3	Task 4	Task 5	Task 6	Task 7	Total	Percent of Time vs. Total Project Hours (total hrs./person/ total project hrs.)	Percent of Time- Annual Basis (total hours/ person/ 2080 hr.)
Mohammad Khosravi	Principal Investigator	80	100	100	120	120	80	80	60	740	12.8%	11.9%
PhD Student	Lab Testing and Numerical Modeling	0	600	600	1000	1000	600	600	300	4700	81.2%	75.3%
Master Student	Lab Testing and Numerical Modeling	0	0	100	200	50	0	0	0	350	6.0%	5.6%
Business Mgr.	Budget Assistance	0	0	0	0	0	0	0	0	0	0.0%	0.0%
Admin Staff	Admin. Support	0	0	0	0	0	0	0	0	0	0.0%	0.0%
Total		80	700	800	1320	1170	680	680	360	5790	N/A	N/A

The level of current commitments held by Mohammad Khosravi and Research Assistants are shown in greater detail in Table 7. Key personnel assigned to accomplish the work associated with this project are available throughout the duration of this project. The level of effort proposed for principal and professional members of the research team will not be changed without written consent of MDT.

Table 7. Commitments of research team

Team Member	Project/Work	Role	Percent Committed FY23	FY24	FY25	FY26
Mohammad Khosravi	Civil Engineering Department	Teaching/Service	50	50	50	50
	Soil-Cement Column Supported Embankment Under Lateral Loading	Dissertation Advisor	10	10	0	0
	Bio-Cement Material Charactrization	Thesis Advior	5	5	0	0
	Aggregate Pier and Load Distribution	Thesis Advior	5	5	0	0
	Road Culvert / Bridge Deck Deicing	PI and Dissertation Advisor	5	10	5	5
		Total Commitments	**75**	**80**	**55**	**55**

FACILITIES

MSU Geotechnical Engineering Lab

The geotechnical engineering lab houses a wide variety of geotechnical, geosynthetics, and materials engineering testing equipment which provides a place to test the mechanical and physical properties of a variety of materials. The *geotechnical engineering testing equipment* includes:

- *Two TruePath Automated Stress Path Systems*: The triaxial system consists of a load frame, two DigiFlow pressure volume actuators (flow pumps), and a high-resolution analog data acquisition system. Specimens can be loaded in variety of modes, including constant rate of deformation, constant rate of loading, or a series of step loads, and under different stress paths. DigiFlow pressure volume actuators (flow pumps) can generate and control pressures up to 2100 kPa and flow rates ranging from 25 mL/min to 0.000025 mL/min. These devices are used for the measurement of one-dimensional consolidation of various geo-materials and mineral mixtures. The system can also be modified to conduct tests under unsaturated condition. The triaxial system is also equipped with a DigiChill system designed for thermal testing of cold specimens under saturated and unsaturated conditions.
- *A thermo-hydro-dynamic Triaxial Testing System:* The Advanced Dynamic Triaxial Testing System (DYNTTS) is a high-end testing apparatus combining a triaxial cell with a dynamic actuator capable of applying load up to 40kN and a dynamic force, deformation and stresses at up to 5Hz. The system is capable of conducting monotonic and dynamic testing of granular materials (soil and snow) under different stress paths, and different thermal (frozen and/or heated) and hydro-mechanical (saturated/unsaturated) conditions. It is possible to apply temperature ranging from -20°C to 80°C, due to the use of oil as confining fluid instead of water.
- *Two automated incremental consolidometer*: The consolidometer system incorporates GeoJacs (automated load actuators) for vertical loading. Testing can be performed under closed loop control of deformation, load, or pressure. These devices are used for the measurement of one-dimensional consolidation of various geo-materials and mineral mixtures.
- *Unconfined Compression Test Device*: Four sets of load frames can be obtained for the unconfined compressive strength evaluation each from two triaxial devices, and two simple shear devices.
- *Two Automated Shearing Systems for Direct, Simple and Residual Shear Testing*: The shearing system incorporates GeoJacs (automated load actuators) for both vertical and horizontal loading. Specimens can be loaded and sheared in a variety of modes, including constant rate of deformation, constant rate of loading, or application of a series of step loads. This device is used for the evaluation of peak and residual shear strength of disturbed and undisturbed soil specimens for reversible drained and undrained loading.
- *Constant and Falling Head Permeability Devices*: The lab has three constant and falling head permeability devices that are currently used to measure permeability of various geo-materials and mineral mixtures.
- *Routine Geotechnical Testing Devices*: The lab has few sets of sieve analysis devices, hydrometer analysis devices with water bath, motorized liquid limit devices, plastic limit devices, shrinkage limit devices, sand cone density meter, rubber balloon density meter, standard and modified proctor compaction devices, and unconfined compression devices.

Computer Facilities

MSU staff and students have access to workstations connected to the MSU College of Engineering computer network. A student computer laboratory offers state-of-the-art PCs along with scanning and printing services. In addition, the COE maintains computational PCs and a computational cluster for data manipulation, mathematical modeling, and graphic image analysis. For slope stability analyses, PI khosravi is going to buy a license for FLAC2D, Fast Lagrangian Analysis of Continua, out of his startup package. FLAC is a numerical modeling software for advanced geotechnical analysis of soil, rock, groundwater, and ground support in two dimensions. In addition to FLAC2D, GeoSlope or ReSSA which are slope stability software for soil and rock slopes will be used. Both of these platforms can be used for analyzing simple and complex problems for a variety of slip surface shapes (both the rotational and translational stability of slopes), pore-water pressure conditions, soil properties, and loading conditions. The Civil Engineering Department at MSU owns a Research Computing Server called CE-CATS composed of 36 cores (72 hyper-threaded), 256 GB RAM, an Nvidia Quadro P4000 GPU, 4 TB of SSD storage, and 10 TB of HDD storage, which can be used for the numerical simulations.

REFERENCES

ASTM D6913-04 (2004). "Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis." *ASTM International*, West Conshohocken, PA, 2004, www.astm.org.

ASTM D422-63(2007)e2. (2007). "Standard Test Method for Particle-Size Analysis of Soils." (Withdrawn 2016), *ASTM International*, West Conshohocken, PA, 2007, www.astm.org.

ASTM D854-14 (2014). "Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer." *ASTM International*, West Conshohocken, PA, 2014, www.astm.org.

ASTM D4318-17e1. (2017). "Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils." *ASTM International*, West Conshohocken, PA, 2017, www.astm.org.

ASTM D4254-00 (2000). "Standard Test Methods for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density." *ASTM International*, West Conshohocken, PA, 2000, www.astm.org.

Ashour, M., Norris, G., & Pilling, P. (1998). "Lateral loading of a pile in layered soil using the strain wedge model." *Journal of Geotechnical and Geoenvironmental Engineering*, 124(4), 303-315.

Ashour, M., & Norris, G. (2000). "Modeling lateral soil-pile response based on soil-pile interaction." *Journal of Geotechnical and Geoenvironmental Engineering*, 126(5), 420-428.

Barton, Y.O. (1985). "Response of Pile Groups to Lateral Loading in the Centrifuge." *Proceedings of the Application of Centrifuge Modelling to Geotechnical Design*, Editor W. H. Craig, University of Manchester.

Brant, L., & Ling, H. I. (2007). "Centrifuge Modeling of Piles Subjected to Lateral Loads." *Soil Stress-Strain Behavior: Measurement, Modeling and Analysis*. Geotechical Symposium in Roma, Vol. 146, 895–907.

Christensen, D.S. (2006). "Full Scale Static Lateral Load Test of a 9 Pile Group in Sand." *Thesis (M.S.)*, Brigham Young University, Department of Civil and Environmental Engineering.

Elhakim, A. F., Allah El Khouly, M. A., & Awad, R. (2016). "Three dimensional modeling of laterally loaded pile groups resting in sand." *HBRC Journal*, 12:1, 78-87, DOI: 10.1016/j.hbrcj.2014.08.002.

Ghayoomi, M., Ghadirianniari, S., Khosravi, A., & Mirshekari, M. (2018). "Seismic Behavior of Pile-Supported Systems in Unsaturated Sand." *Soil Dynamics and Earthquake Engineering* 112(July 2017): 162–73. https://doi.org/10.1016/j.soildyn.2018.05.014.

Haouari, H., & Bouafia, A. (2020). "A Centrifuge Modelling and Finite Element Analysis of Laterally Loaded Single Piles in Sand with Focus on P–Y Curves." *Periodica Polytechnica Civil Engineering*, 64(4), 1064-1074, 2020. https://doi.org/10.3311/PPci.14472.

Itasca (2016). "FLAC3D, Fast Lagrangian Analysis of Continua in 3D dimensions, User's Guide, Version 5.01." *Itasca Consulting Group*, Inc., Minneapolis, MN.

Kramer, S. L. (1991). "Behavior of piles in full-scale field lateral loading tests." *Report No. WA-RD 215.1*, Washington State Dept. of Transportation, Va.

Komolafe, O. O., & Ghayoomi, M. (2021). "Experimental Design of a Centrifuge Model to Study Laterally Loaded Piles in Unsaturated Sands." *In Proposed Paper*.

Ladd, R.S. (1978). "Preparing test specimens using undercompaction." *Geotechecnical Testing Journal*, 1(1), 16-23.

Mirshekari, M., & Ghayoomi, M. (2017). "Centrifuge Tests to Assess Seismic Site Response of Partially Saturated Sand Layers." *Soil Dynamics and Earthquake Engineering*, 94: 254–65. http://dx.doi.org/10.1016/j.soildyn.2017.01.024.

Reese, L. C., Cox, W. R., & Koop, F. D. (1974). "Analysis of laterally loaded piles in sand." *Proc. Of 6th offshore Tech. Conf*., Houston, TX, Vol. 2, p. 473-483.

Reese, L. C., Cox, W. R., & Koop, F. D. (1975). "Field testing and analysis of laterally loaded piles in stiff clay." 7th Offshore Technology Conference, p. 671-690.

Sawada K, & Takemura J. (2014). "Centrifuge model tests on piled raft foundation in sand subjected to lateral and moment loads. " *Soils and Foundations,* 54(2):126–40.

Wallace, J. W., Fox, P. J., Stewart, J. P., Janoyan, K., Qiu, T., & Lermitte, S. (2001). "Cyclic large deflection testing of shaft bridges: Part I-Background and field test results." Report to California Department of Transportation, University of California, Los Angeles.