Numerical Modeling of the Test Pit for Falling Weight Deflectometer Calibration

by

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A proposal prepared for the

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PROBLEM STATEMENT

Evaluation of pavements is commonly conducted using the deflection data from Falling Weight Deflectometers (FWDs) tests. The reliability of these evaluations is highly dependent on the accuracy of the measured deflections. Therefore, to ensure the desired accuracy of measured deflections, FWDs undergo annual calibration and monthly relative calibrations. These calibrations are conducted according to AASHTO R32-11. The calibration tests are conducted on an indoor test pit made of a concrete slab underlaid by a base and a soft subgrade.

The calibration facility operated by the Montana Department of Transportation (MDT) has used a 12 ft wide, 15 ft long, and 5 in thick slab overlying a 6-in sandy base and a 4-ft thick clay subgrade (R32 design, Figure 1). The measured deflections during calibration tests conducted by MDT on this test pit met the deflection requirements laid out by AASHTO R32-11 for a few years, after which the test area needed to be replaced. Because rebuilding the test area is both costly and time-consuming, the MDT was interested in a new setup design that could operate over longer periods. MDT designed an alternative to the R32 design, using geofoam instead of the clay layer as the soft subgrade (Figure 2).

Figure 1. Schematic as-built cross-section of the MDT's original testing area (not to scale).

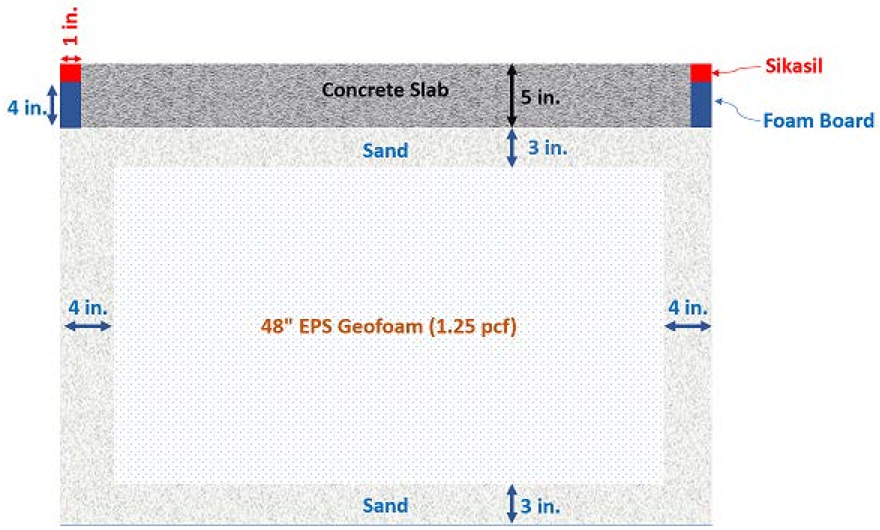

Figure 2. Schematic as-built cross-section of the MDT's preliminary alternative testing area (not to scale).

The alternative calibration test pit (geofoam test pit) was designed based on elastic response analyses. The designed test area was constructed, and several FWD calibration tests were conducted. The new setup did not meet the AASHTO R32-11 deflection requirements. The purpose of this study is to use dynamic response analyses to investigate the possibility of using geofoam instead of the clay layer in the test pit. If the results of the investigation revealed that geofoam can in fact be used, the next goal of this study will be to modify the preliminary alternative design and provide recommendations to improve the performance of the test area to where it meets the AASHTO R32-11 deflection requirements.

BACKGROUND SUMMARY

Management of pavement systems, at the project or network level, relies on the structural evaluation of pavements which entails approximating the remaining pavement life, estimating load-supporting capacity, and calculating the required thickness of structural overlays. Deflection data from Falling Weight Deflectometers (FWDs) are the basis of such evaluations (Irwin et al., 2011). For example, one of the key inputs in deterministic physical models used in pavement structural analyses is the moduli of elasticity of the pavement layers (Irwin et al., 1988). The pavement deflection measured from FWD tests is used to back-calculate the layers' moduli. The reliability of the back-calculated moduli, and any analyses conducted based on those moduli, directly depends on the accuracy of the measured deflections. Annual calibration and monthly relative calibrations of the FWDs are therefore necessary to ensure the desired accuracy of the measured deflections. These calibrations are conducted according to AASHTO R32-11 to establish calibration factors for correcting FWD measurements.

AASHTO R32-11 requires the calibration facility to be an indoor space with a constant temperature between 50 and 100°F, heated, but not necessarily air-conditioned. The calibration tests are conducted on a concrete slab with a smooth and crack-free surface. The concrete slab does not have to be isolated from the surrounding floor provided that the deflection characteristics and other requirements for the facility are met. The suggested dimensions for the concrete slab by AASHTO R32-11 are 12 ft by 15 ft (with an 8 ft wide clear zone around the perimeter).

The required deflections in the concrete slab, i.e., 0.012 in or more due to a 16,000-lb load, is generally achieved by using a 5 in thick Portland cement concrete slab underlaid by 8 in of open-graded crushed aggregate base and relatively weak subgrade (subgrade modulus < 12,000 psi when the bedrock is deeper than 25 ft., and subgrade modulus < 7500 psi when the bedrock is between 10 to 25 ft deep, and areas with bedrocks located shallower than 10 ft are not recommended).

The calibration facility operated by MDT has used a test pit setup shown in Figure 1. Although the AASHTO's deflection requirements were met using this setup, the short lifetime of the test pit inspired a new more durable test pit design. In their first attempt at designing such a setup, MDT designed an alternative to the R32 design based on elastic response analysis, where they used geofoam instead of the clay subgrade (Figure 2). When tested, the new geofoam test area did not meet the AASHTO R32-11 deflection requirements. Static analyses usually neglect the slab mass and subgrade's damping, despite their importance in the dynamic response of structural elements (Khazanovich, 2000). Three-dimensional dynamic models, on the other hand, are able to incorporate these crucial factors. For example, one such model has been developed by Kuo et al., (2016), and was used to calibrate the back-calculation of pavement layers' stiffnesses. Their model confirmed that subgrade damping and self-weight of the slab, that are ignored in static analyses, have in fact significant effect on the results. According to their findings, boundary conditions are another significant factor in modeling FWD deflections.

The purpose of this study is to use dynamic response analyses to modify the preliminary alternative design and provide recommendations to improve the performance of the test area to where it meets the AASHTO R32-11 deflection requirements.

BENEFITS AND BUSINESS CASE

The findings of this study could be used to build an alternative test pit for FWD calibration with increased service time. The calibration test with the current design only lasts for a few years after which it needs to be removed and replaced. Removing the test pit and replacing it with a new one not only takes time but also cost more than $10,000 each time. Considering the fact that this replacement is required every few years with the current design, the potential new design can save a significant amount of effort, time, and cost for the Montana Department of Transportation. In addition, there are seven other calibration centers in the country operated by private or state agencies. These include centers operated by Foundation Mechanics Inc, CA, Dynatest® in Starke, FL, and those operated by the Departments of Transportation of Colorado (CDOT), Minnesota (MnDOT), Pennsylvania (PennDOT), Texas (TxDOT), and California (Caltrans). The proposed design can also be used at these seven calibration centers to reduce their costs of removing and reconstructing their test pits. The increased durability of the test pits and the consequent reduced-cost of the calibration center's maintenance can eventually decrease the calibration costs of the FWDs for the clients.

It is also worth mentioning that calibrating the FWDs cost MDT $12,000 in 2019 ($5000 for calibrating two FWDs and $7000 for transportation) because their test pit was not functioning. This price was somewhat affected by the global pandemic (COVID19) and the consequent travel restrictions. However, it is estimated that the cost of calibration for MDT without the calibration test pit would be around $7,500 per year. Building the alternative test pit for FWD calibration not only eliminates this yearly expense but also could generate income for MDT when other entities use MDT's calibration site.

Furthermore, the developed model can be used to improve the back-calculation of layers' properties obtained from FWD tests. According to Kuo et al., (2016), current back-calculation procedures are based on static mechanics which usually results in discrepancies within the back-calculated parameters. The common practice among the pavement engineers is to use random empirical multipliers to match the back-calculated parameters to the field measurements (Kuo et al., 2016). The developed model in this study will use dynamic response analyses that could potentially replace the current back-calculation procedures and improve the accuracy of the back-calculated properties.

OBJECTIVES

The main objective of this study is to better understand the dynamic responses of the FWD calibration test pits. The dynamic response can then be used to examine the possibility of using geofoam instead of the clay layer as the relatively weak subgrade in the traditional R32 design. If successful, the new FWD calibration test pit would last longer under serviceable conditions which can save a noteworthy amount of time, effort, and cost. Numerical modeling will be conducted to gain a better understanding of the dynamic behavior of the test pit and to simulate the behavior of both traditional R32 and the new geofoam design. The results will then be used to first determine whether or not the geofoam can be used in place of the clay layer. If geofoam is proven to be applicable, the second objective of the study would be to modify the design of the current geofoam test pit. The modified design will provide practical suggestions regarding the required geometry (e.g., the thickness of each layer) and the mechanical properties of different layers of the test pit so that the new test pit can perform in accordance with AASHTO R32-11 requirements.

RESEARCH PLAN

In this research, a three-dimensional numerical program (FLAC3D or 3DEC, both developed by Itasca Consulting Group, Inc., Minneapolis, Minnesota, USA) will be used to better understand the behavior of layers in the calibration test area under the dynamic loads imposed by the weight drop in FWD calibration tests.

Task 1: Literature review and data collection

The first task of this project is to conduct a thorough literature review and collect all the required data (e.g., mechanical properties of the layers) for the numerical modeling of the test pit. Some of these data will be provided by the MDT staff (D.J. Berg, Pavement Analysis Engineer at MDT). Where the required data is not available, the published data in the literature will be used. Some modifications of the published data might be required to duplicate the observed behavior of the test pit in the numerical models. Such modifications are usually based on experience and engineering judgment. If required for this research, these modifications will be applied after consulting with the experienced MDT and FHWA staff (D.J. Berg, Pavement Analysis Engineer at MDT; John Amestoy, Non-Destructive Testing Supervisor at MDT; Matt Strizich, Asset Management/Materials & Pavement Engineer at FHWA, and Jeff Jackson, Geotechnical and Pavement Bureau Chief at MDT). The results of the literature review and the data to be used in the models will be discussed in the first quarterly meeting with the MDT staff, and after their approval, they will be reported as the “Task 1 report”. We then proceed to the next steps. The literature review will be updated as the project proceeds and the complete version will be included in the final report.

The next step in this research is executing the numerical modeling of the test pit which will be conducted in three stages (tasks 2-4) as described below.

Task 2: The first stage of numerical modeling:

In this stage, a model will be developed based on the original design (Figure 1) where the deflection requirements were met during the previous calibration tests. The results of the previous calibration tests, i.e. deflection characteristics of the concrete slab, will be used to validate the model. This is done by comparing the deflections predicted by the model with those measured in the FWD calibration tests. This step is necessary to verify the constitutive models, boundary conditions, and material properties used for different layers in the model. The Mohr-Coulomb constitutive model has been successfully used in FLAC3D to simulate static/dynamic behavior of soils (clays and sands in the calibration test pit) and concrete. The discontinuity between the concrete slab and the sand base layer in the test pit can be modeled using sliding and/or tensile and shear bonding interface in FLAC3D. However, using other constitutive models instead of the Mohr-Coulomb model might be necessary for simulating the test pit behavior due to this discontinuity. This will be investigated in this stage and the appropriate constitutive model will be chosen. Another important factor in the dynamic analysis of materials in FLAC3D is the choice of mechanical properties of the layers, especially the damping properties. The plastic flow used in the numerical implementation of the Mohr-Coulomb model in FLAC3D dissipates considerable energy at high excitation levels. Hence, the selection of additional damping and damping parameters is less critical compared to elastic models in FLAC3D. Generally, the maximum shear strains developed in the model before the plastic flow occurs is used to identify whether or not additional damping is required in the model. If additional damping was deemed required, there are two options in

FLAC3D to specify the appropriate additional mechanical damping, i.e., Rayleigh damping and hysteretic damping. The hysteretic damping is commonly used for soil and rocks as the natural damping of these materials is mainly hysteretic. The Rayleigh damping method will be examined in this study to identify which method better represents the observed behavior of the test pit in the previous calibration tests. If constitutive models other than the Mohr-Coulomb model are chosen, both damping options will be tested and the damping type that better simulates the test pit behavior will be chosen.

As explained before, deflection data from the previous calibration tests conducted by MDT are required for validating the model. This data will be provided by D.J. Berg, Pavement Analysis Engineer at MDT. It has been confirmed that the data from previous calibration tests conducted on the alternative geofoam pad is available and efforts are underway to confirm the availability of the previous calibration tests conducted on the original test pit (with the clay layer instead of the geofoam).

In the unlikely event that the deflections cannot be reproduced using the FLAC3D program, e.g., due to insufficient data, the project will be terminated at this stage and a final report including all the findings of the research up to the point of termination will be provided. If successful, the results of the first stage of modeling (task 2) will be discussed at the second quarterly meeting with the MDT staff, and after their approval, it will be reported as the “Task 2 report”.

Task 3: The second stage of numerical modeling:

After validating the model developed in the first step, the model will be adjusted to simulate the behavior of the preliminary alternative test area (Figure 2). As in the first step, the results of previous calibration tests conducted on this setup will be used to validate the model. Although the deflections measured in these tests did not meet the AASHTO R32-11 deflection requirements, the data can be used to validate the model. In addition to verifying the constitutive model and material properties used for the geofoam layer in the model, this step will also validate the ability of the model to properly simulate the interaction of geofoam and sand layer at their interface. This interaction could be different from the friction/cohesion interaction at the sand-clay interface in the previous design and needs to be verified. Although FLAC3D is capable of modeling a few simple interfaces, more complicated models with more than a few interfaces are better modeled with the 3DEC program. We believe that the geometry of the model is simple enough to be modeled within FLAC3D. If it proves to be difficult to continue modeling with FLAC3D, however, the 3DEC software which is available at Montana Tech will be used for the rest of the project.

Again, if the FLAC3D and 3DEC models were not capable of modeling the preliminary alternative test area, the project will be terminated at this stage and a final report including all the findings of the research up to the point of termination will be provided. If the models were successful, the results of the second stage will be discussed at the third quarterly meeting with the MDT staff, and after their approval, it will be reported as the “Task 3 report”.

Task 4: The third stage of numerical modeling:

After validating the models developed in the previous stages, they will be used to determine whether or not the use of geofoam instead of the clay layer is practically possible. The validated models in previous stages will be utilized to modify the preliminary alternative test area design to achieve deflection amplitudes that are in the acceptable range suggested by AASHTO R32-11.

This is done primarily by either of (or a combination of) three modifications in the design: 1.) keeping the same material used in the preliminary alternative test area while changing the dimensions of each layer, e.g. changing the thickness of the sand layer; 2.) changing the material used in the design, e.g. changing the gradation of the sand layer or using a different type of geofoam with different flexural strength, elastic modulus, and density; 3.) adding or removing a layer in the design. Based on the results of these investigations, other possible modifications might also be suggested/tested in this stage. These investigations will determine whether the geofoam can in fact be used instead of the clay layer. In other words, it will indicate if any configuration can be found to achieve the recommended deflections. If the results indicate that such a configuration cannot be found, the project will be terminated at this stage and a final report including all the findings of the research up to the point of termination will be provided.

If successful, the results of the third stage (task 4) will be discussed at the fourth quarterly meeting with the MDT staff, and after their approval, it will be reported in the draft of the final report.

Task 5: Development of Final Deliverables:

According to the MDT guidelines, a three months period is allocated for the final report comment/revision cycle. After this cycle and receiving all the comments, a “future steps, next phase small scale experiments, and future implementation discussion” meeting will be held with the MDT staff before the final report is submitted. After this meeting, the final report will be prepared and submitted to MDT.

Based on these numerical modeling results, recommendations on the possible changes in the design that could improve the performance of the alternative test area will be provided. If more than one possible approach that could improve the performance of the test area is found, all possibilities will be suggested to the MDT so that other factors, such as the cost difference, can be considered to choose the appropriate design. A project summary report and an implementation report will also be prepared and submitted to the MDT. It is worth mentioning that the results of this study should be tested on small scale models before implementing the results at the MDT’s calibration facility. This will be discussed in more detail in the implementation report. Finally, a performance measures report will be prepared if a B/C and ROI can be calculated.

INTELLECTUAL PROPERTY

Montana Department of Transportation has a master agreement dated August 21, 2020, in place with Montana Technological University and the terms outlined in section 1.4 of the agreement entitled “Ownership and Intellectual Property” will be followed for this study.

MDT AND TECHNICAL PANEL INVOLVEMENT

Developing the models in the first two stages of the numerical modeling (tasks 2 and 3) requires access to the geometrical and mechanical properties of the layers used in the FWD calibration test pits (both R32 and the geofoam designs) and the stratigraphy of the ground underneath the test area including the depth of the bedrock. The mechanical properties include as-built density, moisture content, cohesion, friction angle, dilation, elastic modulus, elastic and dynamic shear modulus, and damping.

Additionally, the deflection data measured during the previous calibration tests conducted on both R32 and the geofoam test pits are required to validated the models developed in the first two stages of model building. Based on the PIs conversations with the MDT staff (see below), we might need to conduct an FWD test on the geofoam test pit to provide critical input to modeling.

The PIs have been in contact with the MDT staff (listed below) regarding this study and confirmed that most of the data mentioned above can be provided by the MDT Staff. Some data regarding the mechanical properties of the layers, however, might not be available, in which case, the published data in the literature will be used. The mentioned MDT staff will lend their experience to the PIs to choose/adjust the published data to be used in the models. The PIs will have Quarterly Progress Meetings with the MDT staff and they will also assist us in reviewing the deliverables.

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406-444-7651

Matt Strizich, P.E.
Asset Management/Materials & Pavement Engineer, FHWA
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Jeff Jackson, P.E.
Geotechnical and Pavement Bureau Chief, MDT
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406-444-3371

PRODUCTS

Project deliverables will include:

1. Monthly progress reports during meetings (virtual because of COVID-19 concerns).
2. Quarterly written progress report.
3. The final report with a cover photo
   The final report will include the results of all the models indicating whether or not geofoam can be used instead of the clay subgrade layer. If the results indicate that the geofoam can be used, the final report will also include recommendations on possible different ways to improve the performance of the test area using geofoam instead of the clay subgrade layer. Schematic 3D drawings of all the possible designs will be included in the report. Suggestions on the possible next steps, including the small-scale experiments before the implementation of the suggested designs in MDT's calibration center, will be incorporated in the final report. Dr. Speece will edit the reports to ensure their quality.
4. Future steps, next phase small scale experiments and future implementation discussion meeting
5. Final presentation
6. Project summary report
7. Implementation Report
   This report summarizes the results after the final Presentation/Implementation Meeting and will include next phase small scale experiments and implementation recommendations
8. Performance Measures Report

IMPLEMENTATION

The results of this study will be three FLAC3D/PFC numerical models in FISH scripting language (FISH is a scripting language embedded within FLAC3D that enables the user to define new variables and functions). These models will determine whether or not the clay subgrade layer in the R32 design can be replaced with geofoam to increase the durability of the test pit. If the results indicate that this replacement is in fact possible, the geometry (e.g., the thickness of each layer) and required mechanical properties of the layers will be reported. If more than one possible configuration is determined, all such configurations will be reported. A schematic 3D drawing of the design will also be provided for each configuration. The results of this study should be experimentally tested using small scale tests before implementing the results at the MDT's calibration facility. Geotechnical and Pavement Bureau of MDT would logically be responsible for applying the research results. The results of this study could affect AASHTO R32-11 standard.

SCHEDULE

Table 1. Project Time Schedule

Task	2020		2021												2022
	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec	Jan.
1- Literature review/ collecting data such as properties of the layers used in the model	▨ ◆														
Task 1 report		▨ ⬆													
2- Conducting the first stage of modeling	▨	▨	▨ ◆												
Task 2 report			▨ ⬆												
3- Conducting the second stage of modeling				▨	▨	▨ ◆									
Task 3 report						▨ ⬆									
4- Conducting the third stage of modeling							▨	▨	▨ ◆						
5- Preparing the final deliverables									▨	▨					
Draft of the Final written report										▨ ⬆					
Final report comment/revision cycle											▨	▨	▨ ◈		
The Final written report														▨ ⬆	
Project Summary Report															▨ ⬆
Implementation Report															▨ ⬆
Performance Measures Report															▨ ⬆

◆ Quarterly Progress Meeting/Reports

⬆ Deliverable Due Dates

◈ Future steps, next phase small scale experiments, and future implementation discussion meeting

BUDGET

This project will be funded by the Montana Department of Transportation (MDT) and Montana Technological University (Montana Tech (MT)). The total cost of the project is **$33,210** and is summarized in Table 2. The cost includes all allocated research staff time and other anticipated expenses. Travel has not been included because communication with MDT to be done remotely in response to COVID-19 concerns. Note that the budget includes a 3% escalation factor on wages in the second fiscal year. The budget includes $3,400 for tuition for one semester for the graduate student assigned to work on this project. This requests includes $500 for expendable supply: backup storage (flash), $300; paper/duplicating $125 (@0.10/page); three research laboratory notebooks, $75. These estimates are based on historic usage. Table 3 shows the budget itemized by task and Table 4 shows the state fiscal year budget breakout and includes Montana Tech’s match. The total budget is split between MDT ($26,569) and MT ($6,641) to satisfy the cost share requirement. The cost share is accommodated by Drs. Sadeghiamirshahidi and Speece’s academic year salaries and the contributed indirect costs (IDCs) associated with these salaries.

In summary, the total funding request to MDT for this project is for **$33,210**.

Table 3. Task Budget

	Task Breakout
Item	**Total**
Task 1	$1,758
Task 2	$6,554
Task 3	$8,496
Task 4	$14,430
Task 5	$1,972
Total:	***$33,210***

Table 4. State Fiscal Year (7/1 – 6/30) Breakdown Showing Montana Tech (MT) Match

Item	State Fiscal Year 2021	State Fiscal Year 2021	State Fiscal Year 2022	State Fiscal Year 2022	Total Cost
	MDT	**MT**	**MDT**	**MT**	
Salaries	$10,900	$3,549	$5,41	$701	20,191
Benefits	$766	$887	$648	$175	$2,477
Tuition	$3,400	$0	$0	$0	$3,400
Expendable Supplies	$400	$0	$100	$0	$500
Total Direct Costs	$15,467	$4,436	$5789	$876	$26,568
Indirect Cost – 25%	$3,867	$1,109	$1,447	$219	$6,642
Total Project Cost	***$19,333***	***$5,545***	***$7,237***	***$1,095***	***$33,210***

STAFFING

The research team is comprised of the Principal Investigator (PI) Dr. Mohammadhossein Sadeghiamirshahidi and Co-Principal Investigator (Co-PI) along with one graduate student research assistant. A short biography of the PI and Co-PI are provided below.

Mohammadhossein Sadeghiamirshahidi, Ph.D., is currently an Assistant Professor of Geological Engineering at Montana Tech. He has obtained his BSc and MSc in Mining Engineering and his Ph.D. in Civil (geotechnical) Engineering. He has taught different courses such as soil mechanics and foundation design, advanced soil mechanics, geotechnical engineering lab, senior design, and mechanics of materials. His main research areas include analytical and experimental investigation of geomaterial (sois, rocks, aggregates, and mine tailings) behavior, especially their static and dynamic mechanical properties, geotechnical earthquake engineering (especially liquefaction), and application of biotechnological methods in geotechnical engineering. He has published 17 journal and conference proceedings papers. A resume for the PI is provided at the end of this proposal.

Marvin Andrew Speece, Ph.D., is currently a Professor of Geophysics at Montana Tech. He has taught 26 different courses at Montana Tech: many in applied geophysics. He maintains an active research program in controlled-source seismology and in engineering and environmental geophysics. His recent research touches on the subjects of climate, glaciers and tectonics. His research in Antarctica was featured in a NOVA special: *Secrets beneath the Ice*. He has generated approximately $3.6 million in external funding and published 41 journal articles or book chapters, one book and 13 refereed proceedings papers. In 2002-2003, during a Fulbright sponsored visit to Egypt, Dr. Speece conducted GPR and seismic surveys at numerous archaeological sites including near the pyramids at Giza and the Sphinx. A short resume is provided at the end of the proposal.

Dr. Sadeghiamirshahidi will be responsible for most of the work in the report, including the literature review and initial modeling. He will closely supervise a graduate student during the spring and summer of 2021. The graduate student will complete the modeling with close supervision of Dr. Sadeghiamirshahidi. Dr. Speece will advise the project on the expected seismic response of the model under load, manage the budget, and edit the final report. Table 5 summarizes the person-hours devoted to each task by each member of the research team.

Table 5. Project Staffing

Name of Principal, Professional, Employee, or Support Classification	Role in the Study	Task						Percent of Time vs. Total Project Hours (total hrs./person /total project hrs.)	Percent of Time - Annual Basis (total hours/ person/ 2080 hr.)
		1	2	3	4	5	Total		
Mohammadhossein Sadeghiamirshahidi	Principal Investigator	15	21	15	24	8	83	9%	4%
Marvin A. Speece	Co-Principal Investigator	2	2			8	12	1%	<1%
Graduate Student	Numerical Modelling	0	0	320	520	0	840	90%	40%
TOTAL		17	23	335	544	16	935	N/A	N/A

The PI and Co-PI, Sadeghiamirshahidi and Speece respectively, can commit the time necessary to complete this work in a timely manner. Drs. Sadeghi and Speece currently have ~20% available time for this project. Their commitments include teaching (60%) and service (20%). The level of effort will not change without the written consent of MDT.

During the summer Dr. Sadeghiamirshahidi can commit much of his time to the project. We have budgeted for 28 hours.

FACILITIES

Most of this research will be conducted at Montana Technological University using FLAC3D and/or PFC Suite software developed by Itasca Consulting Group, Inc., Minneapolis, Minnesota, USA. The Department of Geological Engineering at Montana Technological University has a license for these two software suits.

In the case where an FWD test on the geofoam test pit is required, the test will be conducted at MDT’s FWD calibration center.

REFERENCES

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Curriculum Vitae

Mohammadhossein Sadeghiamirshahidi, Ph.D., A.M. ASCE.

- **Education**

Ph.D. Civil (Geotechnical) Engineering, Michigan Technological University, MI, USA
M.S. Mining Engineering, Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran
B.S. Mining Engineering, Yazd Univerity, Yazd, Iran

- **Academic Experience**

August 2019-Present:
Assistant Professor: Department of Geological Engineering, Montana Technological University, Butte, MT.
Summer, 2016
Lecturer: Department of Civil and Environmental Engineering, Michigan Technological University, Houghton, MI.
Spring, 2015 - Spring 2019 (nine semesters):
Graduate Teaching Assistant: Soil mechanics Laboratory, Michigan Technological University, Houghton, MI.
Spring, 2011- Summer, 2014:
Lab Supervisor: Petrology Laboratory, Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran.
Fall, 2009 – Spring, 2011:
Graduate Teaching Assistant: Petrology Lab., Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran

- **Non-Academic Experience (consulting)**

August, 2018 - September, 2018:
Signature Research, Inc., Calumet, MI, Soil analysis (grain size distribution, mechanical sieve and hydrometer), thermal conductivity, Munsell color, soil density) for thermal determination of disturbed ground for rapid runway constructions.

July, 2018 - August, 2018:
Keweenaw Research Center (KRC), Houghton, MI, NATO mobility summit soil database for vehicle mobility test track. Soil analysis included triaxial compression, direct shear, proctor compaction, grain size distribution (sieve and hydrometer), and Atterberg limits.
July, 2017 - September, 2017:
Highland Copper Company, Longueuil, Quebec Canada, Oversaw geotechnical exploration drilling program for the proposed Copperwood Mine site facilities located in Gogebic County, western Upper Peninsula of Michigan. Collection of rotary sonic samples, selection and packaging of soil samples for laboratory testing, analysis of laboratory test results and conducting borehole logging. Conducted bearing capacity and settlement calculations for the design of the mine facilities on

both lacustrine and glacial till clay soil. Report preparation and submittal to G-Mining, Montreal Canada.

June, 2016-September, 2016:

Highland Copper Company, Longueuil, Quebec Canada, Mechanical rock testing of the main ore zone of the Copperwood Mine for mine design and investigating the potential for mechanical mining of the Precambrian age Nonesuch Shale Formation. Conducted uniaxial compressive strength (UCS), Brazilian splitting tensile strength (BTS), and point load index tests. Analysis and compilation of the final report.

June, 2015-September, 2015:

Golder Associates, Lansing, MI, Location and stability assessment of historic 1853 to 1893 underground coal mining, which was discovered to be beneath and adjacent to Interstate I-94 in Jackson, MI. Conducted stability analysis of mine roof spans based on extraction ratios and estimated the rock's RMR and GSI values. Assisted in the preparation and submittal of the final report to Golder.

September, 2013- June, 2014:

Cavosh Madan Consulting Engineers, Tehran, Iran, Economical assessment and feasibility studies of a prospective Iron seam near Sangan Mine during exploration stages.

September, 2011- August, 2013:

Alborz Sharghi Coal Washing Company, Shahrood, Iran, Investigation of the extent of pyrite oxidation at different locations and depths in waste dumps of the Alborz Sharghi Coal Washing Company (with an annual production of 300,000 tons of washed coal) and the environmental consequences of possible Acid Mine Drainage (AMD) production due to the pyrite oxidation.

September, 2007- September, 2009:

Zafar Construction Company, Tehran, Iran, Oversaw the construction of a 10 story (20 units) skyscraper in the business district of Zafar Street, Tehran, Iran.

- **Publications:**
  https://scholar.google.com/citations?user=1rrhWq4AAAAJ&hl=en

Curriculum Vitae

Professor Marvin A. Speece, Ph.D.

Education

Ph.D. Geophysics, University of Wyoming, 1992
M.S. Geology, University of Michigan, 1984
B.S. Geological Sciences, Wright State University, 1982

Academic Experience

Montana Tech, Head/Chair, 2005-2008 & 2013-2020, Full Time.
Montana Tech, Full Professor, 2001-present, Full Time.
Montana Tech, Tenured Associate Professor, 1999-2001, Full Time.
Montana Tech, Associate Professor, 1996-1999, Full Time.
Montana Tech, Assistant Professor, 1992-1996.

Non-Academic Experience (consulting last five years)

Big Sky Geophysics, Consultant, Geophysics, 2019-20, Part Time.
City of Dillon Montana, Consultant, Geophysics, 2017. Part Time.
Union Oil Company, Geophysicist, Exploration Geophysics Internship, Summer 1982, Full Time.

Scientific and Professional Societies

Fulbright Association, 2003-present (active-for-life member); *Phi Kappa Phi*, 1989-present (active-for-life member); Society of Exploration Geophysicists, 1981-present; American Geophysical Union, 1987-present; Environmental and Engineering Geophysical Society, 1993-present; Alternate Board Member, Incorporated Research Institutions for Seismology (IRIS), 1999-present.

Honors and Awards

Antarctic Service Medal, 2011; Sigma Xi Lecturer, Montana Tech, 2003, 2006; Fulbright Scholar, Egypt, 2002-03.

Principal Publications/Presentations (last 5 years; *Indicates student first author under Speece’s supervision)

Prudhomme, K. D., Khalil, M. A., Shaw, G. D., Speece, M. A., Zodrow, K. R., and Malloy, T. M., 2019, Integrated geophysical methods to characterize urban subsidence in Butte, Montana, U.S.A.: Journal of Applied Geophysics, 164, 87-105, doi:10.1016/j.jappgeo.2019.03.004.

Khalil, M., Orubu, A., Rutherford, B., Speece, M., Santos, F., Farzamian, M., 2018, Integrated application of 2D resistivity and electromagnetic methods to investigate a metallic-sulfide deposit in Soap Gulch, Montana. A case study: Arabian Journal of Geosciences, 11(23):764, doi:10.1007/s12517-018-4130-1.

Li, M., Zhou, X., Gammons, C. H., Khalil, M., and Speece, M., 2018, Aeromagnetic and spectral expressions of rare earth element deposits in the Gallinas Mountains area, central New Mexico, USA: *Interpretation*, 6(4), 1-52, doi:10.1190/int-2017-0199.1.

Levy, R. H., Harwood, D. M., Florindo, F., Sangiorgi, F., Eagle, R., von Eynatten, H., Gasson, E., Kuhn, G., Tripati, A., DeConto, R., Fielding, C., Field, B., Golledge, N., McKay, R., Naish, T., Olney, M., Pollard, D., Schouten, S., Talarico, F., Warny, S., Willimott, V., and SMS Science Team, 2016, Antarctic Ice Sheet sensitivity to atmospheric CO_2 variations during the early to mid-Miocene: *Proceedings of the National Academy of Sciences of the United States of America*, 113 (13), 3453-3458, doi:10.1073/pnas.1516030113.

*Porter, M. C., Rutherford, B. S., Speece, M. A., and Mosolf, J. G., 2016, Cordilleran Front Range

structural features in Northwest Montana interpreted from vintage seismic reflection data: *Journal of Structural Geology*, 85, 115-129, doi:10.1016/j.jsg.2016.02.011.

*Knatterud, L., Speece, M. A., Mosolf, J., McDonald, C., and Zhou, X., 2015, Using gravity data to decipher the structural setting of the Avon Valley in west-central Montana: *Northwest Geology*, 44, 5.

Norman, E., Shaw, G. D., Pal, R., Speece, M. A., Khalil, M. A, 2019, Quantifying Groundwater and Surface Water Interactions as a Result of Low-Impact Stream Restoration: 2019 Fall Meeting, AGU, Abstract H41K-1858.

*Hadley, R., Speece, M. A., Khalil, M. A., Shaw, G. D., and Pal, R., 2019, Geophysical Survey of Blacktail Creek Beaver Mimicry Site near Butte, Montana: 2019 Fall Meeting, AGU, Abstract NS41B-0809.

*Hadley, R., Speece, M., Khalil, M., Shaw, G., and Pal, R., 2019, Geophysical survey of Blacktail Creek beaver mimicry site near Butte, Montana: *Montana Tech Summer Undergraduate Research Fellowship Poster Symposium Program*, 2.

*Clarke, J. W., Speece, M. A., and Crowley, J., 2018, Boresight calibration of a UAS mounted LiDAR using a 3D photogrammetry model: 2018 Fall Meeting, AGU, Abstract NH23D-0863.

*Clarke, J., Speece, M., and Crowley, J., 2018, 3-D Photogrammetry for LiDAR Calibration: *Montana Tech Summer Undergraduate Research Fellowship Poster Symposium Program*, 2.

MacLaughlin, M., Kammerer, C., Speece, M., and Nesladek, N., 2018, Use of fiber optic systems for distributed monitoring of rock mass strain, temperature, and vibrations: an underground case study: 2018 SME Annual Conference & Expo, Onsite Program, 147-148.

Khalil, M., Orubu, A., and Speece, M., 2017, 2-D and 3-D resistivity imaging to study dewatering of Lolo Creek, Montana, USA: Symposium on the Applications of Geophysics to Engineering and Environmental Problems, library.seg.org/doi/pdf/10.4133/SAGEEP.30-001, 28.

*Wilson, A., Speece, M., and Masters, M., 2017, A ground penetrating radar survey of the unexcavated 24BE2206 site near Dewey, in the Big Hole Valley of Montana, AGU Virtual Poster Showcase, 8.

*Nesladek, N. J., Kammerer, C., Speece, M. A., MacLaughlin, M., Wang, H. F., and Lord, N., 2017, Comparison of Distributed Acoustic Sensing (DAS) from fiber-optic cable to three component geophones in an underground mine: 2017, Fall Meeting, AGU, Abstract S33B-0868.

*Clarke, J., Wilson, A., Masters, M., and Speece, M. 2017, A ground penetrating radar survey of the unexcavated 24BE2206 site near Dewey, in the Big Hole Valley of Montana: *Montana Tech Summer Undergraduate Research Fellowship Poster Symposium Program,* 3.

*Ha, C. D. M., Shepherd, K., Mack, A., Rutherford, B. S., and Speece, M. A., 2016, Geophysical investigation of buried slag at the Parrot tailings site, Butte, Montana: 2016 Fall Meeting, AGU, Abstract NH11A-1705.

Hall, T., Wilson, T. J., Henrys, S., and Speece, M. A., 2016, Sediment volume record of Paleogene-Neogene Transantarctic Mountains erosion and landscape modification, McMurdo Sound region, Antarctica: 2016 Fall Meeting, AGU, Abstract C53C-0725.

Khalil, M. A., Santos, F. M., and Speece, M. A. 2016, A static shift correction for 2-D resistivity data through frequency domain electromagnetic data: Symposium on the Applications of Geophysics to Engineering and Environmental Problems, Abstract 58.

*Rutherford, B. S., Speece, M. A., and Constenius, K. N., 2015, Geophysical evidence for the tectonic evolution of the inverted Belt-Purcell basin, northwestern Montana: 2015 Fall Meeting, AGU, Abstract T13C-3012.

Levy, R. H., Harwood, D. M., Forindo, F., Sangiorgi, F., Eagle, R., von Eynatten, H., Gasson, E., Kuhn, G., Tripati, A., Deconto, R. M., Fielding, C. R., Field, B., Golledge, N. R., Mckay, R. M., Naish, T., Olney. M., Pollard, D., Schouten, S., Talrico, F. M., Warny, S., Willmott, V., and ANDRILL SMS Project Science Team, 2015, Antarctic ice sheet sensitivity to atmospheric CO_2 variations during the Early to Mid-Miocene: 2015 Fall Meeting, AGU, Abstract PP24A-05.

Research (last 5 years)

Ground Penetrating Radar, LIDAR and Thermal Imaging Survey of the Rochester Cemetery, Twin Bridges, Montana: *Analogs*: Montana Tech Undergraduate Research Program Summer Undergraduate Research Fellowship, $3000, with Jason Hogan (student), and Michael Masters, 2020.

Synergic field identification of heavy metal contaminants in mining tailings and exposed sediments using laser-induced breakdown spectroscopy and hyperspectral spectroscopy: NSF-EPSCoR, $50,000, with Xiaobing Zhou (PI), 2020.

Mineral Exploration using Joint Hyperspectral and Laser Induced Breakdown Spectroscopy Techniques: Newmont Mining Corporation, $40,000, with Xiaobing Zhou (PI), 2019.

Improvements in Surface and Groundwater Quantity, Quality, and Ecosystem Function from Implementation of Beaver Dam Analogs: Montana Tech Undergraduate Research Program Summer Undergraduate Research Fellowship, $9,700, with Carly Peach (student), Rachel Hadley (student), Mary Riggs (student), Glenn Shaw, Mohamed Khalil, and Robert Pal, 2019.

A Resistivity Method to Increase the Depth of Investigation: Newmont Mining Corporation, $20,000, with Mohamed Khalil (PI), 2019.

Resistivity and Time Domain Electromagnetic Induction Ground Water Studies near Sidney, Montana: Montana Bureau of Mines and Geology, $16,971, with Mohamed Khalil (PI), 2018.

Boresight Calibration of a UAV LiDAR System using a 3D Photogrammetry Model: Montana Tech Undergraduate Research Program Summer Undergraduate Research Fellowship, $3,800, with Jacob Clarke (student), and Jeremey Crowley, 2018.

Acquisition of Equipment for a Distributed Acoustic Sensing Laboratory at Montana Tech: Newmont Mining Corporation, $20,000, with Khalid Miah (PI), 2017.

A Ground Penetrating Radar Survey of the Unexcavated 24BE2206 Site near Dewey, in the Big Hole Valley of Montana: Montana Tech Undergraduate Research Program Summer Undergraduate Research Fellowship, $4,864, with Andrew Wilson (student), Jacob Clarke (student), and Michael Masters, 2017.

Acquisition of Equipment for a Distributed Acoustic Sensing Laboratory at Montana Tech: Newmont Mining Corporation, $12,000, with Khalid Miah (PI), 2016.

Acquisition of Equipment for a Distributed Acoustic Sensing Laboratory at Montana Tech: Newmont Mining Corporation, $15,000, with Khalid Miah (PI), 2015.

Demonstration of the Ability of Distributed Fiber Optic Sensing Technologies to Enhance Mine Safety through Distributed Monitoring of Ground Deformation, Temperature, and Dynamic Events: CDC-NIOSH, $299,993, with Mary MacLaughlin (PI) and Herbert Wang, 2014-17.