A Feasibility Study of Road Culvert / Bridge Deck Deicing Using Geothermal Energy

by

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A proposal prepared for the

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Date: 06/01/2020

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PROBLEM STATEMENT

Adverse winter weather conditions have a significant impact on the safety, operation, and maintenance of transportation infrastructure. Snow accumulation on roads and bridges reduces their capacity, decreases safety and increases travel delays. Ice accumulation in and around culverts may adversely affect fish movement and causes flooding and extensive economic losses. Ice accumulation can also lead to propagation of the freezing front into the soil around the culvert and increase the risk of frost heave in the frost susceptible subsoil in road sections adjacent to the culvert. Therefore, deicing bridge decks and culverts is a major maintenance concern in areas with extreme cold weather. Reduction of ice and snow on bridges also leads to safer roadways and enhances winter traffic mobility. The most common deicing solution for bridge decks is the use of salts and other debonding chemicals. However, salt is ineffective for snow melting or de-icing for temperatures below -9.4°C. Long-term use of salts and deicing chemicals also increases the maintenance and repair cost for reinforced concrete (RC) bridges. It accelerates the corrosion of the steel reinforcement used in reinforced concrete, reduces the available reinforcement area over time, and could result in the collapse of RC bridge decks and concrete culverts. The removal of problematic culvert ice is usually accomplished by the application of heat or other mechanical means to remove the ice after it has developed. The proposed research program will investigate the feasibility of the use of a ground-coupled system that utilizes heat energy harvested from the ground as an alternative for deicing bridges and culverts. In addition, if the bridge deck/culvert temperature is greater than 0°C during the operation of the system, the deicing system could also be used for anti-icing in winter. The ground-coupled system relies on circulating fluid through pipes, placed underground (either vertically or horizontally), to utilize the natural heat retained by the earth.

BACKGROUND SUMMARY

Introduction

Snow accumulation on roads and bridges reduces their capacity, decreases safety, and increases travel delays. Ice accumulation in culverts causes flooding and associated economic losses when they remain blocked with ice after spring runoff begins. Ice accumulation can also lead to propagation of the freezing front into the frost susceptible subsoil around the culvert and increase the risk of frost heave in road sections adjacent to the culvert. Therefore, deicing bridge decks and culverts remains a major safety and maintenance concern in areas with extreme cold weather.

The common deicing solution for bridge decks in Montana is the use of salts and other debonding chemicals such as Magnesium and Sodium Chlorides. However, the solutions are ineffective for snow melting or de-icing for temperatures below -12 degrees Celsius (10 degrees Fahrenheit). The effective working temperatures for magnesium chloride and sodium chloride are -12 degrees Celsius (10 degrees Fahrenheit) and -9.4 degrees Celsius (15 degrees Fahrenheit), respectively. Long-term use of salts and deicing chemicals also increases the maintenance and repair cost for reinforced concrete (RC) bridges. It accelerates the corrosion of the steel reinforcement used in reinforced concrete, reduces the available reinforcement area over time, and could result in the collapse of RC bridge decks (Virmani et al., 1983, 1984; Baboian, 1992; Yunovich et al., 2003; White et al., 2005; Granata and Hartt, 2009, Naito et al., 2010). Based on the recent report published by AASHTO (2008), bridge deterioration is the one of the major national infrastructure concerns. The annual direct cost of corrosion in bridges is in the range of $6 to $10 billion (Koch et al., 2002). Including indirect costs, the total cost can be as much as 10 times higher than what was reported by Koch et al., (2002) (Yunovich et al., 2003). Cyclic stressing and straining of bridges in the summer can also be problematic and lead to accelerated deterioration.

The removal of problematic culvert ice after it has developed is usually accomplished by the application of heat or other mechanical means. Electric heating cables have been used in Alaska and other locations to thaw holes through ice-filled culverts (Carey, 1984). The cables are usually installed in the fall, removed in the spring, and can be connected to a local power supply or on-site generators. Alternatively, steam de-icing (Fig. 1) can be used to melt holes through the ice to allow drainage to proceed. These methods are labor intensive and expensive and require frequent monitoring of high-risk culverts.

Fig. 1. Culvert de-icing using hot, glycol filled hoses is Saskatchewan, (www.canadianundergroundinfrastructure.com)

Recently, new materials and innovative techniques have gained attention as desirable alternatives to current methods of removing ice and snow from transportation infrastructure. Several approaches for heated pavements systems have been proposed including electrically heated pavement and hydronically heated pavement. Electrically heated pavement can be utilized wherever electricity is readily available. However, the high voltage required for electrically heated pavement and the high operation cost of using electricity to heat pavement deters wide use of this technology (Fliegel, et al., 2010). Hydronic heating systems utilize heated fluid carried by pipes embedded in the pavement to warm the pavement through conduction. Hydronic heating systems are typically closed loop systems where, after the fluid releases heat into the pavement, it returns to the heat source to be sent through the pipes again (Lund et al., 2016). The fluid can be heated by a variety of sources from a boiler burning fossil fuels to more environmentally friendly options including geothermal piles/wells and waste heat from industries (Minsk, 1999). The great potential for the environmental, social and economic benefits of utilizing shallow geothermal energy has made the use of geothermal piles quite popular in different parts of the world. Seasonal variation of ground temperature is minimal at a depth approximately 20-30 ft below the ground surface (Kusuda and Achenback, 1965). Shallow geothermal vertical or horizontal loops below that depth are, thus, good alternatives for harvesting geothermal energy through heat exchange with the ground.

A conceptual schematic of a ground-source bridge deck deicing system is shown in Fig. 2. Heat is transported to and from the ground through heat exchanger tubes by circulating fluid through a closed loop system embedded within the ground. The heat carrier fluid is then circulated through the tubes embedded under the pavement surface. The capacity of a hydronically heated pavement system to melt snow and ice depends on the materials and design of the system such as fluid temperature, soil and concrete conductivity, pipe depth and pipe spacing. Higher fluid temperatures, greater concrete conductivity, shallower pipe depth and more compact pipe spacing are desirable for improved performance. The harvested energy from the ground can be used to de-ice bridge decks and culverts in the winter. It can also reduce the temperature fluctuation on the surface of the bridge deck, thermal stresses within the concrete bridge decks, and therefore reduce the size of the thermal expansion joint.

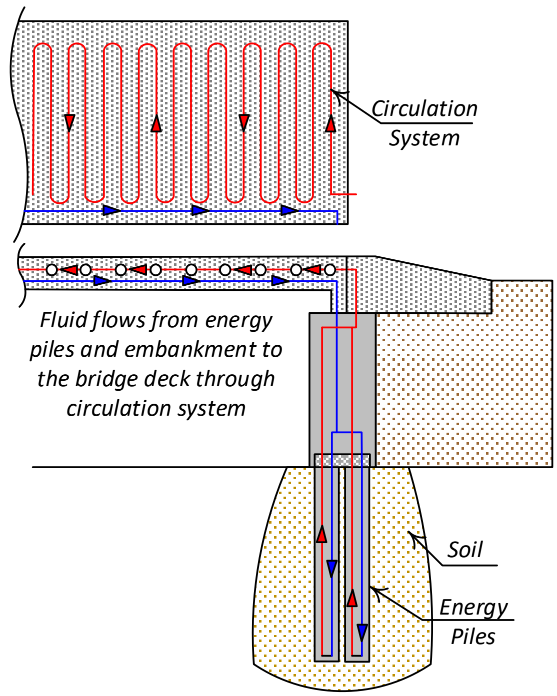

Fig. 2. Schematic of Ground Source Heat Pump (GSHP) for bridge deck deicing (redrawn after Bowers and Olgun 2014).

Background and Previous Studies

The use of ground source heat pump (GSHP) systems as an alternative for deicing bridges have been studied using full-scale pilot tests (e.g. Morita, 2000; Morita, 2005; Eugster and Schatzmann, 2002), model-scale field tests (e.g. Minsk, 1999; Liu et al., 2007; Bowers and Olgun, 2014; Yu et al, 2020), and numerical analyses (e.g. Bowers and Olgun, 2014). Pilot projects for geothermal snow melting and/or geothermal de-icing have been built all over the world (e.g., Japan, and Switzerland). SERSO is a well-known and well-documented geothermal installation in Switzerland meant to prevent ice-formation on a highway bridge surface. SERSO is one of the longest running hydronic geothermal bridge deck deicing projects (Eugster and Schatzmann, 2002; Eugster, 2007). In this project, the temperature of the circulating fluid was regulated using an auxiliary heat pump system, which adjusts the fluid temperature for changes in the ambient air temperature. The results of this study suggested that the energy demand for bridge deck deicing depends on ambient air temperature and varies from 30 MWh to more than 100 MWh. The typical energy demand per unit area to de-ice the deck is in the range of 100 W/m^2 (Eugster, 2007). Another successful bridge deck de-icing pilot study using geothermal energy was built in Japan (Morita and Tago, 2005). The bridge was heated using an underground tank of water. The water in the tank was heated using geothermal energy. Warm fluid was circulated from the tank through the embedded tubes in the bridge decks when the outside temperature was lower than 0.5°C. The system was successful at de-icing the bridge deck without using an auxiliary heat pump system. One of the unique aspects of this project was the ability to thermally recharge the ground during the summer and warm days. The extra thermal energy produced during warm periods was returned to the ground to increase the water temperature in the tank, and was then used during cold periods for deicing. In the US, a few full-scale pilot projects for geothermal road and bridge deck heating have been constructed, some in combination with heat pumps, and some using seasonal heat storage (Minsk, 1999; Spitler and Ramamoorthy, 2000). In these projects, the fluid was circulated through the below ground heat exchanger in 4-in-diameter vertical geothermal boreholes with a depth of 176 ft. The fluid was then circulated through the horizontal loops near the pavement surface. The harvested energy from the ground was sufficient to prevent snow accumulation without the use of an auxiliary heating system.

Model-scaled field tests have been used to investigate the performance of GSHP systems for bridge deck deicing. Liu et al. (2003, 2007) and Bowers and Olgun (2014, 2015) built small-scale bridge decks with an embedded hydronic heating system. The GSHP system utilized a vertical closed-loop ground source heat exchanger and a heat pump for fluid circulation in the bridge deck. Both systems successfully kept the deck snow-free during mild and moderate winter storms. The system was not able to keep the deck completely free from snow/ice during severe winter storms, but it was able to keep the surface temperature of the deck above 0^{o}C. Bowers and Olgun (2014) also successfully examined the possibility of thermal recharge of the ground by injecting thermal energy into the ground.

Two-dimensional (2D) and three-dimensional (3D) numerical simulations have been used to examine the long-term performance of the GSHP systems (e.g. Lazzari, 2010; Abdelaziz et al., 2014; Bowers, 2016; Ghasemi-Fare and Basu, 2016). Lazzari (2010) used 2-dimensional finite element models to examine the performance of borehole heat exchanger (BHE) fields over 50 years of operations. In their 2D analyses, they used sine waves to represent the energy demand profiles, and considered four different cases: 1) a single BHE surrounded by homogenous, infinite ground, 2) a single line of infinite BHEs, 3) two staggered lines of BHEs, and 4) a square field of infinite BHEs. The authors concluded that long-term performance is negatively affected for every case except that of a single BHE, and especially for a square field of infinite BHEs. Bowers (2016) also used 2D analysis to examine different injection and extraction scenarios that would improve system performance for a shallow geothermal energy (SGE) system over two years of operation. They found that the average ground temperature within the vicinity of the BHEs depends on the rate of injected vs. extracted energies as well as which boreholes are utilized.

Numerical simulations have been also used to examine the optimization of a borehole heat exchanger (BHE) grid over different years of operation. De Paly et al. (2012) used 2D numerical analysis to examine the optimization of a BHE grid through an uneven distribution of heating loads over 30 years of operation. In their study, a finite line source analytical model was employed to represent the BHEs, and a 2-dimensional cross section of the borehole grid was considered. A similar model was used by Beck et al. (2013) to optimize a system, but primarily through geometric rearrangement. The authors used a single-layer homogeneous subsurface and developed an optimum geometric configuration for two different scenarios: one with the uneven load distribution, and one without it. Bowers (2016) developed a three-dimensional model using COMSOL Multiphysics™ for vertical heat exchangers to investigate different heat injection and extraction scenarios in the context of shallow geothermal energy (SGE) systems efficiency. The model was based on the modeling approach developed and calibrated by Ozudogru et al. (2014). The model included the entire borehole-soil system and utilized several components including: fluid circulation pipes, a 1-dimensional line element through the middle of the fluid circulation pipes upon which fluid flow is determined, and the thermal grout and the soil surrounding the energy pile. To decrease the computational time, they utilized several simplifications in modeling fluid flow, symmetry, and domain discretization. Based on their conclusion, if the energy is first extracted from the perimeter boreholes, and then from the interior boreholes, the energy loss that occurs in the geothermal footprint area minimizes.

Ghasemi-Fare and Basu (2016) used finite difference analysis to investigate thermal performance of geothermal piles with a single U-shaped circulation tube. Based on their analyses, the capacity of a hydronic heated system to melt snow and ice depends on: 1) the initial temperature difference, θ ($\theta = T_{inlet} - T_{initial}$), 2) the thermal properties of soil and concrete, and 3) design parameters of the circulation system (e.g. radius of circulation tube, tube depth, and tube spacing). Their study showed that higher fluid temperatures, greater concrete and soil conductivity, shallower tube depth and more compact tube spacing are desirable for improved performance. It was also concluded that ambient temperature and temperature differences between the ground and fluid circulated to the ground, and ground water level highly affects the efficiency of the GSHP systems. For some areas in Montana where the ground water level is close to the surface, the GSHP system is expected to be more efficient.

The proposed research project will investigate the feasibility of the use of a ground-coupled system that utilizes heat energy harvested from the ground as an alternative for deicing/anti-icing bridges and culverts. We will also numerically investigate other possible benefits of GSHP systems such as using the geothermal heat/cooling to assist with curing bridge decks which could be a large benefit to MDT besides the de-icing/anti-icing potential. We will use thermal properties of the concrete slurry and use the calibrated numerical model to assess the effect of thermal properties of the concrete slurry on temperature distribution around the pipe as well as heat transfer through the pipe during the curing process. In this study, the use of bio-mediated soil improvement, such as MICP, and higher thermally conductive concrete to improve the efficiency of GSHP systems will also be investigated.

BENEFITS AND BUSINESS CASE

Adverse winter weather conditions have a significant impact on the safety, operation, and maintenance of transportation infrastructure. The results of this research are expected to provide benefits in each of these areas. Traffic safety will improve with the reduction of snow and ice accumulation on bridges. Improving highway safety has been an utmost priority for MDT and is critical for progress towards the Vision Zero goals embraced by the agency. The proposed research is expected to help MDT move towards this goal on high-risk bridges in Montana by reducing snow and ice accumulation on the bridge deck. Flooding events associated with ice-clogged culverts will be eliminated, resulting in a reduction of property loss and risk of human danger. Traffic operations will improve by the improvement of driving conditions and capacity of bridges free of snow and ice. Maintenance of transportation infrastructure will benefit by eliminating the need for deicing solutions, which chemically attack concrete and corrode steel reinforcement, reducing frost heave in soils above culverts, and eliminating the need to apply heat or other mechanical means to remove ice in culvers once it has formed. The development of improved winter culvert maintenance techniques supports the 2021 Biennium Maintenance Program goal to provide consistent levels of winter maintenance service and to optimize MDT resources. Ultimately this research is intended to improve the maintenance services that contribute to safe and reliable transportation infrastructure.

OBJECTIVES

The goal of the proposed work is to leverage laboratory experiments and numerical modeling to: 1) investigate the feasibility of the use of a ground-coupled system that utilizes heat energy harvested from the ground as an alternative for deicing bridges and road culverts (with both internal and external heating systems), 2) study the use of bio-mediated soil improvement, such as Microbially-Induced Calcite Precipitation (MICP), and higher thermal conductive concrete to improve the efficiency of ground source heat pump systems, and 3) define important design requirements and operational considerations. The subtasks to achieve these research objectives are threefold. First, a series of model-scale, instrumented experiments on both culvert and bridge deck systems will be performed in the Subzero Research Lab (SRL) at Montana State University to investigate snow and ice accumulation, and the efficacy of geothermal energy as a deicing alternative. The experiments will incorporate environmental field data from a site in Montana where icing and maintenance are known to be a problem. Second, the model-scale experimental results coupled with numerical simulations will be used to quantify and optimize heat transfer within the experimental concrete bridge deck and culvert. Third, the results from experiments and numerical simulations will be used to design a geothermal bridge deck/culvert heating system for future field pilot studies. We will also perform geochemical and geotechnical laboratory experiments to investigate the effect of bio-cementation on soil thermal conductivity and temperature gradients in soil.

RESEARCH PLAN

To achieve the research goals, the work is grouped into eleven major tasks (Fig. 3):

Initial Stage

0) Task 0: Project Management,
1) Task 1: Literature Review,

Research Stage

2) Task 2: Geotechnical and geochemical testing and analysis,
3) Task 3: Model-scale instrumented experiments on both culvert and bridge deck systems in MSU's Subzero Research Laboratory (SRL),
4) Task 4: Numerical modeling,
5) Task 5: TP Meeting #3.
6) Task 6: Pilot test design, and

Final Stage

7) Task 7: Draft Final Report.
8) Task 8: TP Meeting #4.
9) Tasks 9 to 11: Final Reports and Dissemination of Results.

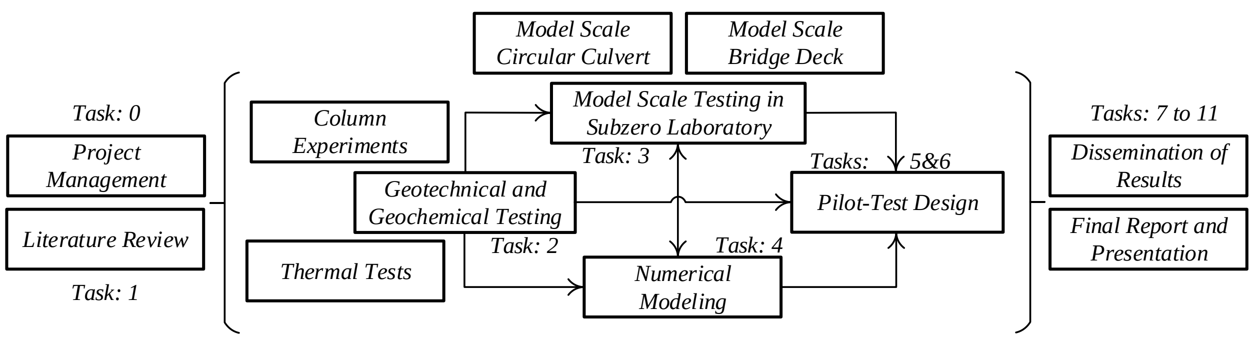

Fig. 3. Project outline: Tasks, and activities

Task 0: Project Management

The Principal Investigators on this project will be Dr. Mohammad Khosravi, Dr. Kathryn Plymesser, and Dr. Steve Perkins. 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 July 2020*
Responsible Party: *PIs, 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: 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. A comprehensive literature review will be conducted to evaluate the state-of-the-practice and recent advances in Ground Source Heat Pump (GSHP) systems with a focus on Montana climate/conditions. Various types of bridges and culverts will be surveyed for the feasibility study. Meetings with the TP will be conducted to identify the most common type of bridges and culverts in the state of Montana for our experiments and modeling. The type of culvert is going to affect its tubing configuration and location. MDT's preferred design methodology and material specifications will be reviewed so that the remaining tasks will produce materials that are consistent with existing approaches where applicable. GSHP systems rely on electricity to operate a compressor and pump to facilitate the heat transfer from the earth to the system. Various power sources for the GSHP systems (electricity for urban area v.s. solar energy for remote areas) will be discussed. This review will include sources from the Transportation Research Board, State Departments of Transportation, Universities, and national and international journals. 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). 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 climate/conditions; and,
- Data resources, including availability and quality.

Time Frame: *June 2020 – Nov 2020: Task 1 report will be sent to the TP at the end of Nov 2020.*
Responsible Party: *PI and Co-PIs*
Deliverable: *Task 1 report: literature review, and submission of progress reports every three months*.
TP Action: *Read Draft Literature Review, discuss with PI and Co-PIs, and if necessary direct them to make changes to project documents; Provide MDT's preferred design methodology and material specifications.*

Task 2: Geotechnical and Geochemical Testing and Analysis

The objective of the geotechnical and geochemical experiments is to assess the mechanical and thermal properties of soil and concrete to be used in this study. The current mix design and the chemical admixtures used by MDT will be used for concrete. We will first collect the available data on thermal properties of soil and concrete from the available literature to establish our range of parameters. In addition to data collected from literature, a series of lab experiments will be conducted to characterize the thermal properties of two different soils, sand and silt. 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 SRL (Task 3). MSU will also reach out to MDT for any available soil samples from different locations in Montana for our thermal testing.

The results will be used to select soil material for model scale testing in the Subzero Research Lab. We will also investigate the use of bio-mediated soil improvement, such as MICP, and higher thermally conductive concrete to improve the efficiency of GSHP systems. PI Khosravi has a master student working on thermo-hydro-mechanical properties of the bio-cemented soils. Therefore, thermal testing of bio-cemented soil in this project is limited to thermal conductivity measurement, which could later be used as a parameter in our numerical simulation to investigate the possible effect of bio-cementation on efficiency of GSHP system. A report will be completed at the end of this task and submitted to MDT for review.

Task 2.1. Thermo-Mechanical (TM) Experiments: A series of lab element tests will be conducted to estimate the thermal behavior of the soil and concrete materials recommended by MDT. Previous studies have indicated that thermal properties (e.g. specific heat) of soil and concrete depend on moisture content, therefore, the specific heat and density will be measured at various levels of moisture content. To determine the thermal conductivity of the concrete and soil, a thermal conductivity test setup similar to the ASTM D5334 test will be developed. Thermal experiments will involve applying one-directional heat flow using a needle probe and measuring the temperature rise over a specified period of time. Fourier's law can be used to calculate thermal conductivity of the material inside the testing system (soil and concrete will be tested). In this study, the use of bio-mediated soil improvement, such as MICP, and higher thermally conductive concrete to improve the efficiency of GSHP systems will also be investigated. Previous studies have indicated that if the soil particles are cemented together by bio-cementation, the thermal contact is significantly improved due to precipitation of calcite crystals in the contact areas between the soil particles and formation of 'thermal bridges' (Venuleo et al., 2016). Microbially-Induced Calcite Precipitation (MICP) treatment of sand could lead to a significant increase in soil thermal conductivity of up to 250% (Venuleo et al., 2016). Based on particle-organism size compatibility and particle size relationships (Fig. 4), silt and sand are believed to meet the ideal particle-organism size compatibility. Silt and sand also provide a sufficient concentration of particle-particle contacts per unit volume so that when cemented the global shear/thermal behavior would be notably altered.

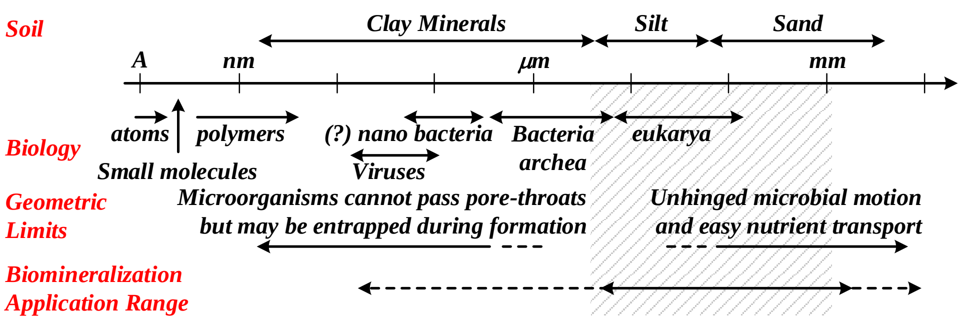

Fig. 4. Microorganism-pore throat size relationship (Mitchell and Santamarina 2005)
*Negative control

As the experiments progress, the data collected and analyzed in Task 2 will be used to couple the model-scale testing (Task 3) and numerical model (Task 4) and guide the design of the pilot test for Task 6. Additional specimens may be prepared for TM testing as the results of the TM experiments inform the development of the injection strategies and changes to the specimen preparation.

Time Frame: *Dec 2020 – May 2021: Task 2 report will be sent to the TP at the end of May 2021.*
Responsible Party: *PI and Co-PIs*
Deliverable: *Task 2 report: Geotechnical and geochemical testing and analysis, and submission of progress reports every three months*.
TP Action: *Review of progress reports; Advise PI if necessary; Provide any available soil samples from different locations in Montana for soil thermal testing; Review the materials to ensure they have met the specifications recommended by MDT; Schedule TP Meeting #2; (It should be noted that MSU will not ask for new traffic control or drilling data. Our objective is to collect the available data in MDT's inventory.)*

Task 3: Model-Scale Instrumented Experiments in MSU's Subzero Lab

Once the soil characteristics are established and the initial geochemical and geotechnical tests are complete, a set of scaled culvert and bridge deck experiments will be performed in the Subzero Research Lab at MSU to investigate snow and ice accumulation, and the efficacy of geothermal energy as a deicing alternative. The experiments will incorporate environmental field data from a site in Montana where icing and maintenance are known to be a problem. A report will be completed and at the end of this task and submitted to MDT for review.

Task 3.1. Model design and construction: Fig. 5 depicts schematics of the tentative design of the testing setup, and specimen configuration. The experiments include three main components: 1) Bridge Deck and Culvert Model, 2) Fluid Circulation System, and 3) Heat Source.

Bridge Deck and Culvert Model: The main objectives in determining the proper design for the bridge deck and culvert are to: 1) replicate a typical bridge deck/culvert design that is used in Montana, and 2) test different deicing system configurations. The size of the model scale should be large enough such that boundary effects do not control the behavior of the system. The results of the preliminary numerical simulations (Task 3) will be used to design the model-scale experiments. The physical models will be constructed in two to three sections that can be operated independently from each other. Each section will be identical except for the circulation tube spacing, and concrete mixture.

As recommended by the technical panel, we will design our experiments on bridge based on the cross-section of typical "urban" area bridges. For culvert, PIs will study different cross sections/materials (e.g. concrete, galvanized steel, aluminum) in ***Task 1: literature review***, and will closely work with MDT personnel to identify the most common type of the culverts in the state of Montana for our experiments and modeling. The type of culvert is going to affect its tubing configuration and location.

A series of thermistors will be located throughout the experimental bridge slab and culvert. For the experimental bridge deck, the sensors will be placed in four locations in the cross section, and three locations in plan view. In the bridge deck's cross-section, the sensors will be placed at the top, the level of the circulation tube, the middle of the deck, and the bottom. In the plan view for both the bridge deck and culvert, the sensors will be placed on a circulation tube, between two circulation tubes, and in the radius of a bend in the circulation tube. Thermal imaging studies will also be performed using a FLUKE TIR2FT-20 camera to check the heat distribution of the heated slab/culvert.

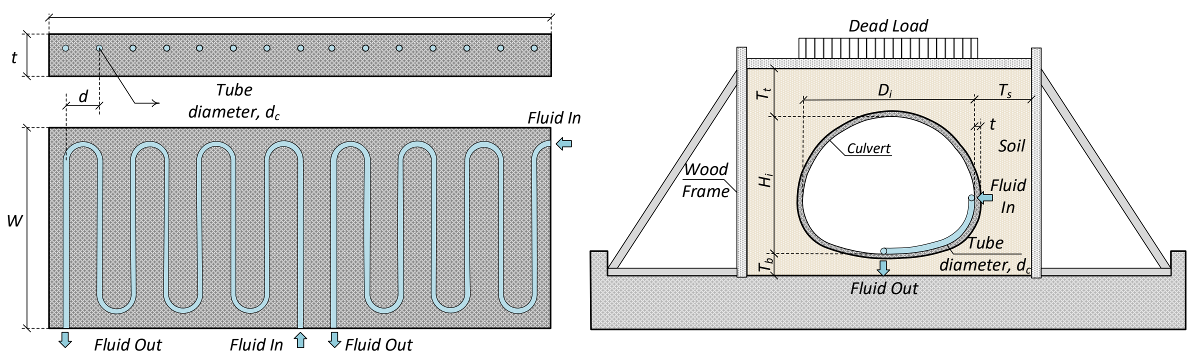

Fig. 5. Schematic of testing apparatus, and tubing configuration

Fluid Circulation System: The circulation system will contain tubing, circulation pumps, and flowmeters. For the circulation system, we will use tubing materials with high durability (e.g. a cross-linked polyethylene (PEX) tubing) to supply warm fluid flow to the bridge deck/culvert. PEX tubing material conforms to the ASTM Standard Specification for Cross-linked Polyethylene (PEX) Hot- and Cold-Water Distribution Systems (ASTM Standard, F877-18a) and is National Sanitation Foundation (NSF) certified for radiant heating. One-inch piping will be used, unless specific sections require ¾" piping. Flowmeters will be used to measure the flow rate of the fluid. Typical circulation fluid for the bridge deck deicing tests is a mix of water, antifreeze (Propylene Glycol), and refrigerant. Previous studies have used 40% glycol by volume, and water (Bowers, 2016). Water alone is used during the thermal recharge tests in the summer. A fill tank will be used as a reservoir for removing air from the system and to add antifreeze to the fluid.

Heat source: A tank of water will be used to simulate warm fluids provided from a GSHP system. Fluid will be pumped from the tank to the hydronic loop system. The water tank will be equipped with a heating/cooling system to allow for temperature control. For depths greater than 9.1 m (30 feet) below ground surface, the soil temperature is relatively constant and corresponds roughly to the water temperature measured in groundwater wells which are usually 9-15 m (30-50 feet) deep (Virginia Department of Mines Minerals and Energy 2012). This is referred to as the "mean earth temperature." Fig. 6 shows the mean earth temperature contours across the US. In Montana, the mean earth temperature ranges from 6.1°C (43°F) in the east to 10°C (50°F) in the south. The minimum water tank temperature used for lab testing will therefore be 6.1°C (43°F).

Task 3.2. Model testing in Subzero Research Lab (SRL): The scaled culvert and bridge deck experiments will be performed in the Subzero Research Lab at MSU. MSU's Subzero Research Laboratory (SRL) is a state-of-the-art, 2700 ft^2 laboratory space, consisting of 7 purpose-built walk-in cold rooms, a wet-chemistry laboratory, and a dedicated cryostage microscopy laboratory. These unique cold rooms include 2 environmental chambers with relative humidity, temperature gradient, and solar radiation controls, a Class 1000 cold clean room, a reinforced structural testing chamber, a cold hydrodynamics chamber, a dedicated -30°C storage room for field-collected ice and snow samples, a -10°C materials characterization and machine shop equipped with a biological microtome, bandsaw, cross-polarized stereographic microscope, and a X-ray computed microtomography system with 5-micron resolution.

The scaled culvert and bridge deck experiments will be conducted in one of the cold rooms in SRL with a temperature range of -40°C to 10°C (± 1°C), and a spatial uniformity of ±2°C. The experiments will incorporate environmental field data from a site in Montana where icing and maintenance are known to be a problem. A significant portion of the deicing systems' operating time is spent in 'pre-heating' mode (Schnurr and Falk, 1973; Liu and Spitler, 2004; ASHRAE, 2013). Therefore, bridge deck/culvert and weather properties first be evaluated in the absence of snow and ice to assess the basic performance of deicing systems, and investigate how long it takes the bridge deck/culvert to reach the desired temperature. The experiments will be performed during three different types of winter storms defined by ambient air temperature and snow/ice accumulation: 1) mild winter storm, 2) moderate winter storm, and 3) severe winter storm. There are two main performance metrics: 1) The amount of energy required from the ground during these storms to deice the deck/culvert, and 2) the temperature of the deck/culvert. The amount of energy imparted to the deck/culvert can be calculated by multiplying the volumetric heat capacity of the circulation fluid by the volumetric flow rate and the temperature difference between the inlet and outlet (Bowers, 2016). The surface temperature of the deck/culvert must be above 0^oC in order for the system to melt the falling precipitation on the bridge deck and preventing the accumulation of ice in the culvert.

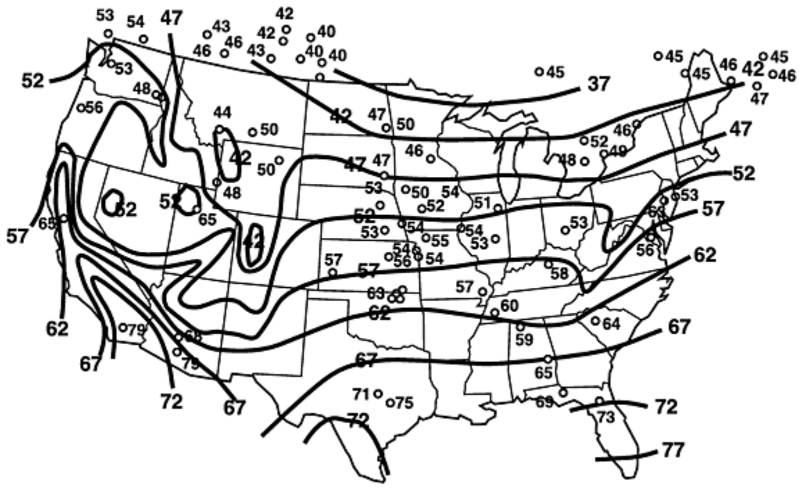

Fig. 6. Mean annual earth temperature observations at individual stations (in degrees of Fahrenheit), superimposed on well-water temperature contours. (Virginia Department of Mines Minerals and Energy, 2012)

Task 3.3. Laboratory data analysis: The results from model-scale experiments, and geotechnical and geochemical tests will be used to: 1) understand snow and ice accumulation, and the efficacy of geothermal energy as a deicing alternative, and 2) confirm thermal modeling assumptions used in Task 4. The results from experiments (Task 3) and numerical simulations (Task 4) will be used to design a geothermal bridge deck/culvert heating system for future field pilot studies.

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

Time Frame: *June 2021 – May 2022: Task 3 report will be sent to the TP at the end of May 2022.*
Responsible Party: *PIs*
Deliverable: *Task 3 report: model-scale instrumented experiments on both culvert and bridge deck systems in MSU's SRL, 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 bridge decks and culverts (Note: MSU won't ask for any new instrumentation during this study.).*

Task 4: Numerical modeling

Bridge deck/culvert heating and deicing is a complex process. It involves different heat transfer components including convection, wind, thermal radiation, solar radiation, and conduction through concrete. It also includes heat flux from snow/ice melt, evaporation, and water flow. Therefore, the potential using of geothermal energy under different local conditions with different ambient temperatures and ground water levels must be considered in the design phase. The experimental results (e.g. those extracted from model-scale experiments) will be coupled with and used to calibrate a numerical model that can then be used to generalize the findings of the small-scale experiments. The numerical modeling will utilize finite element modeling to: 1) further explore the heat transfer mechanism of the geothermal heat pump systems attached to a pavement/culvert surface, and 2) predict the energy harvested from the ground and energy required to de-ice the surface for different ground conditions in Montana. 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 design guidelines. Numerical modeling will begin early on in the project and occur throughout. Drs. Plymesser and Khosravi will be primarily responsible for this aspect of the project. A report will be completed and at the end of this task and submitted to MDT for review.

The model will be created using COMSOL Multiphysics™, a finite element simulation environment (COMSOL, 2015). COMSOL is an interactive environment for modeling and simulating scientific and engineering problems. The numerical model used for validation will be configured after the experimental bridge deck/culvert deicing systems described previously are completed. The bridge deck and culvert systems consist of concrete, rebar, and circulation tubes. Previous studies have suggested not to model the rebar directly, but to use a zoned weighted average approach to increase the model efficiency (Bowers, 2016). The circulation loops will be modeled using 'pseudo-pipe' elements rather than a solid domain. Based on Ozudogru et al. (2014), integrating pipe flow as a 1D linear source element produces two main coupling errors: 1) the temperature field of the slab is coupled directly at that element whereas it should be coupled at a distance equal to pipe's outer radius, and 2) the volumetric heat capacity of the pipes is neglected. The bridge deck model, therefore, will consist of three different material domains: the pseudo-pipe domain, the concrete-rebar domain, and the concrete domain. For the culvert, two additional components, soil domain and water domain, will be included in the culvert model. Temperature sensors installed in the cross-section of the slab, culvert, and the soil in the physical models will be used to define the initial temperatures of the slab/culvert at different locations in the simulation.

At the early stages of the project, before any experiments are performed, the available experimental data available in the literature that may be relevant to this project will be used to develop preliminary numerical simulations. For example, data from Bowers (Virginia Tech): Ground-Source Bridge Deck Deicing and Integrated Shallow Geothermal Energy Harvesting Systems, will be used at the early stages of the project to calibrate the model as the experiments are being conducted. 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. This will provide detailed insight into the mechanisms involved, such as the formation and accumulation of ice. Comprehensive parametric analyses of a GSHP system will be performed to examine the optimization of a borehole heat exchanger (BHE) grid over different years of operation.

Time Frame: *June 2020 – Nov 2022: Task 4 report will be sent to the TP at the end of Nov 2022.*
Responsible Party: *PI and Co-PIs*
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: TP Meeting #3

A summary of the results of model-scale experiments and numerical simulations (Tasks 1 to 4) will be presented by the PIs to decide on how to proceed to the pilot study.

Time Frame: *Dec 2022*
Responsible Party: *PIs, assisted by the TP*
Deliverable: *Presentation, TP meeting attendance, TP meeting minutes and notes*.
TP Action: *TP review of previous reports and decide on whether to proceed to the pilot study.*

Task 6: Pilot-Test Design for the Next Phase of Study

The results of model-scale experiments and numerical simulations will be used to design a larger, and more definitive future study. To design our pilot study, we will incorporate environmental field data from a site in Montana where icing and maintenance are known to be a problem. ***It should be noted that this phase of the study only includes the design of a pilot study which may or may not be pursued in the future depending on the outcomes of the current feasibility study***. The bridge deck and/or roadway culvert pilot study will be designed based on the life cost analysis and energy required to anti-ice/de-ice the surface. The pilot study would include: 1) an energy pile/well used to harvest thermal energy from the ground, and 2) prototype bridge deck/culvert with a design similar to the bridge deck test performed by Bowers and Olgun (2015) (Fig. 7). An overview of the project will be provided with detailed discussions on the findings and recommendations. The pilot test design will include recommendations for the ground-source bridge deck de-icing technology, operational principles, and the key design parameters. PIs will closely work with MDT personnel to identify a potential location for field application of the proposed GSHP system for future research. A report will be completed at the end of this task and submitted to MDT for review. The data report will also include an economic feasibility study to determine the cost effectiveness of different snow melting methods including chemical methods (e.g. using salt and other chemical debonding) and GSHP system using both geothermal energy piles and geothermal energy wells. In a geothermal energy pile, the heat exchanger is integrated in structure foundation which could result in relatively lower cost comparing with traditional geothermal system.

Fig. 7. Prototype bridge deck test performed by Bowers and Olgun (2015)

Time Frame: *Jan 2023 – April 2023: Task 6 report will be sent to the TP at the end of April 2023.*
Responsible Party: *PIs, assisted by the TP*
Deliverable: *Task 6 report: Pilot test design including an implementation plan and cost/benefit analysis*.
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 (Task 1), geotechnical and geochemical laboratory and Subzero Research Lab model scale test results (Tasks 2 and 3), summary of numerical modeling and design guidelines for a pilot study for the next phase of the study (Tasks 4 and 5), discussion of results, conclusions, and potential for future research, application, or technology transfer, and other sections as appropriate.

Time Frame: *May 2023 – Aug 2023: The first draft of the final report will be sent to the TP at the end of June 2023.*
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 #4

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: *Aug 2023*
Responsible Party: *PIs, assisted by the TP*
Deliverable: *TP meeting attendance, 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: *Sept 2023*
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: *Oct 2023*
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 and future direction of the use of a ground-coupled system that utilizes heat energy harvested from the ground as an alternative for deicing bridges and road culverts 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: *Oct 2023 - Nov 2023*
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.
- Historical Data: Meetings with the TP, maintenance personnel, and engineering staff will be conducted to discuss the available data. MDT will provide past qualitative and/or quantitative data related to bridge deck/culvert surface temperature, ambient temperature, and soil temperature. Copies (or scans) of records of historical use, laboratory test results, construction documents, and field observations/data should be available to the research team. The PI will send his PhD student to help the MDT staff collect the information, and convert the paper copies to soft copies if needed.
- Interviews: MDT will ensure the availability of maintenance personnel, supervisors and engineering staff for personal interviews with the Principal Investigators. Various types of bridges and culverts will be surveyed for the feasibility study. Meetings with the TP, maintenance personnel, supervisors and engineering staff will be conducted to identify the most common type of bridges and culverts in the state of Montana for our experiments and modeling. The type of culvert is going to affect its tubing configuration and location. 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.
- Material Testing: One of the objectives of the lab testing program is to characterize the range of Thermo-Hydro-Mechanical properties of soils collected from different sites in Montana. We will first collect the available data on thermal properties of soil from literature to establish our range of parameters. These parameters will be later used for parametric study using our validated numerical model and design the model scale experiments. MSU will also reach out to MDT for any available soil samples from different locations in Montana for our thermal testing. MDT will ensure the materials (e.g. concrete) have met the specifications recommended by MDT. MSU will not ask for new traffic control or drilling data. Our objective is to collect the available data in MDT's inventory.
- Data Collection: The focus of this proposal is to evaluate the feasibility of this technology for state of Montana. Available data from instrumented bridges and culverts would help us immensely in our study. We will first collect the available data on thermal properties of soil and concrete from the available literature to establish our range of parameters. In addition to data collected from literature, a series of lab experiments will be conducted to characterize the thermal properties of two different soils, sand and slit. 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 SRL (Task 3). MSU will also reach out to MDT and local construction companies for available soil samples from different locations in Montana for our thermal testing. MSU will work with MDT staff and technical panel to collect available data from currently instrumented bridge decks and culverts. MSU won't ask for any new instrumentation during this study. 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) Task 1 report: Literature Review,
2) Task 2 report: Geotechnical and geochemical testing and analysis,
3) Task 3 report: model-scale instrumented experiments on both culvert and bridge deck systems in MSU's SRL,
4) Task 4 report: Numerical modeling,
5) Task 6 report: Pilot test design including an implementation plan and cost/benefit analysis
6) Quarterly progress reports
7) Final report, including an implementation plan and cost/benefit analysis
8) Project summary report
9) Implementation report
10) Performance measures report
11) Final presentation and poster
12) Journal and/or conference publications and presentations
13) Project webinar

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

IMPLEMENTATION

The final report for this project will include material detailing the design requirements and operational considerations for the use of geothermal energy in Montana as it relates to bridge decks and roadway culverts. This information will be used to design a bridge deck and/or roadway culvert pilot study for an existing site within MDT's network. The pilot study will be identified and designed in cooperation with the applicable MDT districts and departments. The pilot study may be designed at the end of this project with construction taking place thereafter. It is anticipated that the pilot study will be monitored for one winter season after construction. Full implementation of the project findings will be dependent on the outcome of the pilot study.

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																	
	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
Task #0: Project Management																																										
Task #0.1 - TP Meeting #1: kick-off meeting																																										
Deliverable: TP meeting attendance, presentation, minutes and notes																																										
Task #1: Literature Review																																										
Task 1 report: Literature Review																																										
Deliverable: Task 1 report and quarterly progress reports						TR																																				
Task #2: Geotechnical and Geochemical Testing and Analysis																																										
Task #2.1 - Thermo-Mechanical (TM) Experiments of Soils and Concretes																																										
Deliverable: Task 2 report and quarterly progress reports												TR																														
Task #3: Model-Scale Experiments in MSU's Subzero Lab																																										
Task #3.1 - Model design and construction																																										
Task #3.2 - Model testing in Subzero Research Lab (SRL)																																										
Task #3.3 - Laboratory data analysis																																										
Task #3.4 - TP Meeting #2																																										
Deliverable: Task 3 report and quarterly progress reports																								TR																		
Task #4: Numerical Modeling																																										
Model development and validation																																										
Synthesis of laboratory and numerical findings																																										
Deliverable: Task 4 report and quarterly progress reports																														TR												
Task #5: TP Meeting #3																																										
Deliverable: TP meeting attendance, presentation, minutes and notes																																										
Task #6: Pilot-Test Design																																										
Pilot test design																																										
Deliverable: Task 6 report																																			TR							
Quarterly Progress Reports																																										
Deliverable: Quarterly Progress Reports		PR			PR			PR			PR			PR			PR			PR			PR			PR			PR			PR			PR							
Task #7: Draft Final Report																																										
Deliverable: Draft Final Report																																					FR					
Task #8: TP Meeting #4																																										
Deliverable: TP meeting attendance, presentation, minutes and notes																																										
Task #9: Draft Implementation and Performance Measures Reports																																										
Deliverable: Implementation and Performance Measures Reports																																								IPR		
Task #10: Draft Project Summary Report																																										
Deliverable: Project Summary Report																																									SR	
Task #11: Final Report, Webinar, and Presentation																																										
Deliverable: Final Report and Presentation																																									W	FR

- *TR: Task Reports*
- *PR: Quarterly Progress Reports*
- *IPR: Implementation and Performance Measures Reports*
- *FR: Final Report*
- *SR: Summary Report*
- *W: Webinar*

BUDGET

The requested project budget is $210,701. Schedule, budget, and staffing plans are based on state fiscal year proportioning, as shown in Tables 2 to 5.

PI Khosravi is requesting three half-summer months one for each year with the total of $--,--- (including benefits), Co-PI Dr. Plymesser is requesting three half-summer months for each year with the total of $--,--- (including benefits), and Co-PI Dr. Perkins is requesting two half-summer months for years 2 and 3 with the total of $--,--- (including benefits). In summary the total budget for Senior Project Personnel Salaries and Wages is $--,---. PI and Co-PIs' effort allocation throughout the project is 20% lab testing, 40% model-scale testing in SRL, and 40% numerical modeling.

The proposal requests twelve-month support ($20,400) and full-year tuition ($7,277) 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 student's efforts will include geothermal testing of the untreated and bio-treated soils, design and develop construction methods and prepare/assemble the model-scale test setups. The Ph.D.'s effort will include preliminary laboratory testing of the untreated and bio-treated soils, thermos-mechanical analysis of untreated and bio-treated soils and numerical modeling, 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 and Co-PIs.

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 obtaining the testing material to be used in the geochemical and geotechnical laboratory tests, model-scale test in SRL (e.g. soil, rebar, concrete, sensors, strain gages, etc) as well as miscellaneous laboratory and computer supplies. Testing materials are budgeted each year for $5,000 for Y1, $12,000 for Y2 and $5,900 for Y3. In summary the total Material and Supplies budget of $22,900 includes testing material and miscellaneous laboratory supplies.

In-state travel funds will be used to travel between Bozeman, MT and Helena, MT to meet with the technical panel (two trips per task). The PIs are also requesting travel funds for two members of the research team (either PIs or their graduate students) 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 $1,600 per person (airfare $900, and lodging and meals days $700) with the total amount of $3,200.

Total Direct and Indirect Costs

Direct Costs: FY 1: $32,776; FY 2: $56,187; FY 3: $56,187; FY 4: $23,411

Indirect Costs: FY 1: $8,194; FY 2: $14,047; FY 3: $14,047; FY 4: $5,853

Total Costs: $210,701

Table 2. Budget summary by State Fiscal Year

	State Fiscal Year				**Total Cost**
Item	2020	2021	2022	2023	
Salaries	$20,020	$34,320	$34,320	$14,300	**$102,961**
Benefits	$3,280	$5,623	$5,623	$2,343	**$16,869**
In-State Travel	$156	$267	$267	$111	**$800**
Out-of-State Travel	$622	$1,067	$1,067	$444	**$3,200**
Supplies	$4,453	$7,633	$7,633	$3,181	**$22,900**
Tution	$4,245	$7,277	$7,277	$3,032	**$21,831**
Equipment Purchase	$0	$0	$0	$0	**$0**
Laboratory Fees	$0	$0	$0	$0	**$0**
Subcontracts	$0	$0	$0	$0	**$0**
Total Direct Costs	$32,776	$56,187	$56,187	$23,411	**$168,561**
Indirect Costs (25%)	$8,194	$14,047	$14,047	$5,853	**$42,140**
Total Project Cost	$40,970	$70,234	$70,234	$29,264	**$210,701**

Table 3. Task, meeting, and deliverable cost breakout

Task, Meeting, and Deliverable Cost Breakout			
Item	Labor	Travel	Total
Project management	$5,920	$200	$6,120
Task 0, Kickoff Meeting	$1,880	$200	$2,080
Task 1, Literature Review	$9,770	$0	$9,770
Deliverable, Task 1 report and quarterly progress reports	$0	$0	
Task 2, Geotechnical and Geochemical Testing and Analysis	$23,740	$0	$23,740
Deliverable, Task 2 report and quarterly progress reports	$0	$0	
Task 3, Model-Scale Experiments in MSU's Subzero Lab	$23,240	$1,600	$24,840
Deliverable, Task 3 report and quarterly progress reports	$0	$0	
Task 4, Numerical Modeling	$26,160	$1,600	$27,760
Deliverable, Task 4 report and quarterly progress reports	$0	$0	
Task 6, Pilot-Test Design	$13,440	$0	$13,440
Deliverable, Task 6 report and quarterly progress reports	$0	$0	
Task 7, 9, 10 and 11: Final Report and Presentation	$15,680	$200	$15,880
Deliverable, Draft Final Report	$0	$0	
Tasks 5 and 8: TP Meetings #3 & 4	$0	$200	$200
Total	**$119,830**	**$4,000**	**$123,830**

Table 4. List and itemize all 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*
Rental Car	*3 trips - 2 days per trip*	*0*	*$*	*$*
Meals	*2 trips for 2 persons + 1 trip for 1 person - 2 days*	*2*	*$ 50.0*	*$ 100.0*
Total				*$ 3,200.0*

Table 5. Labor expenses

Person	Role	Kickoff Meeting	Task 1	Task 2	Task 3	Task 4	Task 5	Task 6	Total	Hourly Rate	Total Wages	Hourly Benefit Rate	Total Benefits	Total Cost
Mohammad Khosravi	Principal Investigator	50	40	40	45	40	40	60	315	$ -----	$--------	$--------	$-------	$--------
Katey Plymesser	Co-Principal Investigator	50	40	40	45	40	40	60	315	$ -----	$--------	$--------	$-------	$--------
Steve Perkins	Co-Principal Investigator	30	10	20	20	33	34	55	202	$ -----	$--------	$--------	$-------	$--------
PhD Student	Budget Assistance	0	250	1000	1000	1200	400	300	4150	$16.00	$63,080	$0.80	$3,320	$66,400
Master Student	Admin. Support	0	50	140	60	0	0	0	250	$13.00	$3,088	$0.65	$163	$3,250
Total		**130**	**390**	**1240**	**1170**	**1313**	**514**	**475**	**5232**		**$97,781**		**$22,049**	**$119,830**

Indirect Cost @ 25%	$42,140
Total Labor Cost	$161,970
Tuition Fees	$21,831
Direct Expenses	
In-State Travel	$800
Out of State Travel	$3,200
Expendable Supplies	$22,900
Total Project Cost	$210,701

STAFFING

The Principal Investigators on this project will be Dr. Mohammad Khosravi (MK), Dr. Kathryn Plymesser (KP), and Dr. Steve Perkins (SP). 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 together with Co-PIs Plymesser (KP) and Perkins (SP) will be responsible for conducting the geotechnical and thermal lab testing, model testing in the Subzero Research Lab, and numerical modeling. The Principal Investigators 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.

Co-PI: Kathryn Plymesser, Ph.D., PE

Co-PI Plymesser is an Assistant Professor in the Department of Civil Engineering at Montana State University. PI Plymesser's research focus is ecohydraulics and fish passage engineering with expertise in hydraulic and computation fluid dynamics (CFD) modelling. Current funded projects include a hydraulic assessment of the nature-like fish bypass and the Huntley Irrigation Diversion and the development and testing of scaled fishway designs for low-head dams. She will be primarily involved in the numeric modelling and testing of the culvert deicing system however will help develop and review all deliverables and co-advise the graduate students working on the project.

Co-PI: Steve Perkins, Ph.D., PE

Dr. Perkins will serve in the role of Co-PI on the project. Dr. Perkins has been the PI and Co-PI of numerous projects with MDT over the past 25 years. The majority of these projects have related to geotechnical aspects of pavements, including the role of geosynthetics in roadway performance and design, and characterization of subgrade soils. Several of these projects have included advanced numerical modeling of the mechanical behavior of reinforced pavements, advanced laboratory testing of soils and geosynthetics, and construction of full-scale models.

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. Master student's efforts will include laboratory testing of the untreated and bio-treated soils, design and develop construction methods and prepare/assemble the model-scale test setups. The Ph.D.'s effort will include preliminary laboratory testing of the untreated and bio-treated soils, thermos-mechanical analysis of untreated and bio-treated soils using X-ray CT and numerical modeling, 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 and Co-PIs.

Research Team Hours and Availability

It is anticipated that the proposed work associated with this research project will take 5282 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

			Task								
Person	Role	Kickoff Meeting and Others	1	2	3	4	5	6	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	50	40	40	45	40	40	60	315	6.0%	5.0%
Katey Plymesser	Co-Principal Investigator	50	40	40	45	40	40	60	315	6.0%	5.0%
Steve Perkins	Co-Principal Investigator	30	10	20	20	33	34	55	202	3.8%	3.2%
PhD Student	Lab Testing and Numerical Modeling	0	300	1000	1000	1200	400	300	4200	79.5%	67.3%
Master Student	Lab Testing	0	50	140	60	0	0	0	250	4.7%	4.0%
Total		130	440	1240	1170	1313	514	475	5282	N/A	N/A

The level of current commitments held by Mohammad Khosravi, Katey Plymesser, Steve Perkins, and the 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 FY20	FY21	FY22	FY23
Mohammad Khosravi	Civil Engineering Department	Teaching/Service	50	50	50	50
	Spatial Variability Effect on Slope Stability	Dissertation Advisor	10	10	10	10
	Bio-Cement Material Charactrization	Thesis Advior	10	10	0	0
	Road Culvert / Bridge Deck Deicing	PI	5	10	10	5
		Total Commitments	**75**	**80**	**70**	**65**
Kathryn Plymesser	Civil Engineering Department	Teaching/Service	*55*	*55*	*55*	*55*
	MT DOJ Huntley Diversion Hydraulic Evaluation	Co-PI	*5*	*5*	*0*	*0*
	USGS Scaled Denil Fishway Design and Testing	PI	*10*	*10*	*5*	*0*
	USFWS Passage Guideline Development	PI	*5*	*5*	*0*	*0*
	MDT Culvert/Bridge Deicing	Co-PI	*5*	*5*	*5*	*0*
	Road Culvert / Bridge Deck Deicing	Co-PI	5	10	10	5
		Total Commitments	**85**	**90**	**75**	**60**
Steve Perkins	Civil Engineering Department	Teaching/Service	*60*	*60*	*60*	*60*
	MDT Project: Large-Scale Lab, Geosynthetics	PI	*10*	*0*	*0*	*0*
	Proposed MDT Project: Deicing, Geothermal	Co-PI	*5*	*5*	*5*	*5*
	Road Culvert / Bridge Deck Deicing	Co-PI	5	10	10	5
		Total Commitments	**80**	**75**	**75**	**70**

FACILITIES

1- 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 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.
- *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.
- *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.

The *geosynthetics testing equipment* in the geotechnical lab includes:

- Servo-hydraulic controlled pullout test facility.
- MTS load frame with environmental chamber and its data acquisition system.

2- MSU Center for Biofilm Engineering (CBE):

The CBE moved into the MSU's Engineering/Physical Sciences Building when it was built in 1997. The >20,000 ft^2 facility includes offices and conference rooms for faculty, staff, and students; two computer laboratories; and thirteen fully equipped research laboratories. The full-time CBE Technical Operations Manager oversees the research laboratories, provides one-on-one training for students, ensures safe laboratory practices, and maintains equipment. State-of-the-art instruments and equipment are available for use by all CBE faculty, staff, and students. General use areas include a microbiology lab, a media kitchen, an instrument lab, and an isolated radioactive isotope lab. Facilities of particular note are described below.

MRI Spectrometers: The College of Engineering MR Lab (COE MRL) houses two high field Bruker MRI systems and a low field system:

- A 250 MHz vertical wide bore (89 mm) magnet integrated with a Bruker AVANCE III spectrometer running Bruker imaging software Paravision 6.0.
- A 300 MHz vertical super-wide bore (154 mm) magnet integrated with a Bruker AVANCE III spectrometer running Bruker imaging software Paravision 6.0.
- A 2 MHz Magritek Rock Core Analyzer, bench top spectrometer

Mass Spectrometry Facility: The mass spectrometer facility houses the following equipment:

- An Agilent 1100 series high performance liquid chromatography system with autosampler and fraction collector, an Agilent SL ion trap mass spectrometer, and an Agilent 6890 gas chromatograph with electron capture detector, flame ionization detector, and 5973 inert mass spectrometer.
- An Agilent 7500ce inductively coupled plasma mass spectrometer with autosampler, liquid, and gas chromatographic capabilities.

Microscope Facilities: The microscopy facilities are coordinated by the Microscopy Facilities Manager who maintains the equipment and trains and assists research staff and students in capturing images of in situ biofilms via optical microscopy and fluorescent confocal microscopy. The microscopy facilities include three separate laboratories—the Optical Microscopy Lab, the Confocal Microscopy Lab, and the Microscope Resource Room and Digital Imaging Lab.

The Optical Microscopy Lab houses two Nikon Eclipse E-800 research microscopes which are used for transmitted light and epi-fluorescent imaging. Both microscopes are equipped with cooled CCD cameras from Photometrics and use Universal Imaging Corporation's MetaVue software (v 7.4.6) for digital image acquisition. Other equipment in the Optical Microscopy Lab includes a Nikon SMZ-1500 barrel zoom stereomicroscope equipped with a color camera, a Leica CM1800 cryostat, a Zeiss Palm Laser Capture Dissection microscope and a dry ice maker. The Confocal Microscopy Lab contains two brand-new (2011) Leica SP5 Confocal Scanning Laser Microscopes (CSLMs).

MSU ICAL Laboratory: The Image and Chemical Analysis Laboratory (ICAL) in the Physics Department at Montana State University is located on the 3rd floor of the EPS Building, adjacent to the Center for Biofilm Engineering. ICAL is a user oriented facility that supports basic and applied research and education in all science and engineering disciplines at MSU. The laboratory provides access to state of the art equipment, professional expertise, and individual training to government and academic institutions and the private sector. Laboratory instrumentation is dedicated to the characterization of materials through high resolution imaging and spectroscopy. ICAL promotes interdisciplinary collaboration between the research, educational and industrial fields. education, and industry, and to strengthen existing cooperation between the physical, biological, and engineering sciences by providing critically needed analytical facilities. These facilities are open to academic researchers.

A critical point dryer, jointly purchased in 2007 by the CBE and the Image & Chemical Analysis Laboratory, is housed in the ICAL lab for the processing of biological samples for electron microscopy. This equipment allows our researchers to remove water from soft samples without distorting the sample.

The ICAL currently contains eleven complementary microanalytical systems:
* Atomic Force Microscope (AFM)
* Field Emission Scanning Electron Microscope (FE SEM)
* Scanning Electron Microscope (SEM)
* Small-Spot X-ray Photoelectron Spectrometer (XPS)
* Time-of-Flight Secondary Ion Mass Spectrometer (ToF-SIMS)
* X-Ray Powder Diffraction Spectrometer (XRD)
* Scanning Auger Electron Microprobe (AUGER)
* Epifluorescence Optical Microscope
* Microplotting System
* Critical Point Drying
* Video Contact Angle System

3- MSU Subzero Research Laboratory (SRL)

MSU's Subzero Research Laboratory (SRL) is a state-of-the-art, 2700 ft^2 laboratory space, consisting of 7 purpose-built walk-in cold rooms, a wet-chemistry laboratory, and a dedicated cryo-stage microscopy laboratory (Fig. 8). It should be noted that all the rooms listed below and their capabilities, including instrumentation, are fully functional and require no additional funding from this project, aside from hourly operational costs. These unique cold rooms include

- 2 environmental chambers with relative humidity, temperature gradient, and solar radiation controls
- a Class 1000 cold clean room
- a reinforced structural testing chamber
- a cold hydrodynamics chamber
- a dedicated -30°C storage room for field-collected ice and snow samples
- a -10°C materials characterization and machine shop equipped with a biological microtome, bandsaw, cross-polarized stereographic microscope, and an X-ray computed microtomography system with 5-micron resolution.

Environmental Chambers: Metamorphism of ice and snow microstructures is made possible with a solar simulation source, a temperature controlled ceiling, and humidity control. Additionally, the base plate used to mount snow samples is temperature controlled and capable of diffusing various gases into the snowpack.

- *Room1*. Temperature: -40°C to 10°C (± 1°C), a spatial uniformity of ±2°C, Ceiling Temperature: -10°C to -50°C, Simulated Solar: 0 to 1200 W/m2, Room Size: 3 m x 4.3 m (10' x 14')
- Room 2. Temperature: -68°C to 60°C (± 1°C). Simulated Solar: 0 to 1200 W/m2, Room Size: 1.8 m x 2 m (6' x 6.5') with exterior glove box mounts.

Class 1000 Cold Clean Room: Decontamination of ice cores and the study of organic and inorganic impurities in snow and ice is made possible with a Class 1000 clean room, which also houses a hooded Class 100 partition. This room provides space for the processing of pristine ice core samples and for conducting microbial related experiments.

Temperature: -20°C to 10°C (± 2°C), a spatial uniformity of ±2°C, Room Size: 3 m x 3.7 m (10' x 12')

Cold Structural Testing: This room contains an integrated "strong floor" with tie downs to test structural materials and elements at low temperatures, explore new materials, test durability of existing materials and explore the manufacture of innovative structural materials to be used in cold environments. This chamber can be used to study the physical, chemical and biological properties as increased pressure transforms snow (firn) to ice in temperate and polar glaciers. The antechamber of this cold chamber also houses a MTS Criterion 43 uniaxial testing system with Environmental Chamber that can test to temperatures as low as -130°C and loads as high as 30kN.

Temperature: -40°C to 10°C (± 2°C), a spatial uniformity of ±2°C, Room Size: 3.7 m x 6 m (12' x 20')

Cold Hydrodynamics Chamber: Primarily used to create dendritic-type snow crystals in bulk, the cold hydrodynamics chamber utilizes a temperature controlled de-ionized water reservoir, which provides a steady flow of water to the chamber. Other applications include the study of wetland and permafrost environments. This room also has a solar simulation source.

Temperature: -25°C to 10°C (± 2°C), a spatial uniformity of ±2 ◦C, Simulated Solar: 0 to 1200 W/m2, Room Size: 3.7 m x 4.3 m (12' x 14')

Cold Specimen Storage Chamber: This unit has a fully redundant refrigeration system with multiple power and compressor backups.

Temperature: -30°C (± 1°C), Room Size: 3 m x 4.3 m (10' x 14')

Materials Characterization & Machine Shop: General specimen preparation is performed with a precision bandsaw, a polarized light table, biological sledge microtome, and a stereographic microscope. For creating parallel surfaces, either a flat mill or the microtome is used. Room also contains a Bruker Skyscan 1173 X-ray computed microtomography system.

Temperature: -30°C to 10°C (± 2°C), a spatial uniformity of ±2 ◦C, Room Size: 4.3 m x 4.9 m (14' x 16')

Cryostage Microscopy Laboratory: At the center of this facility is a Nikon Eclipse 80i epifluorescence microscope. The microscope contains a digital imaging head with dual ports including an internal zoom optical system (0.8 to 2.0x), built-in Siedentopf binocular body, integrated universal epifluorescence system, ports for two detectors and an elextronic shutter.

Objectives: (1) CFI Plan Fluor 4x/0.13NA WD 17.1 mm, (2) CFI Plan Fluor 10x/0.03NA WD 16 mm, (3) CFI Plan Fluor 20x/0.45C ELWD 7.6 mm, (4) CFI Plan Fluor 40x/0.60 ELWD with correction collar 0-2 mm: working distance 2.9 to 5 mm and (5) CFI Plan Fluor 100x/1.3NA WD 0.2 mm oil.

Camera: T-PS24HS PAXcam ARC 20 MPixel w/LINKAM interface.

Cryostages (for up to 1000x magnification in either brightfield or fluorescence mode): (1) Linkam L-MDBCS196 motorized cryobiology pro-stage system, (2) Linkam L-GS120 temperature gradient stage system.

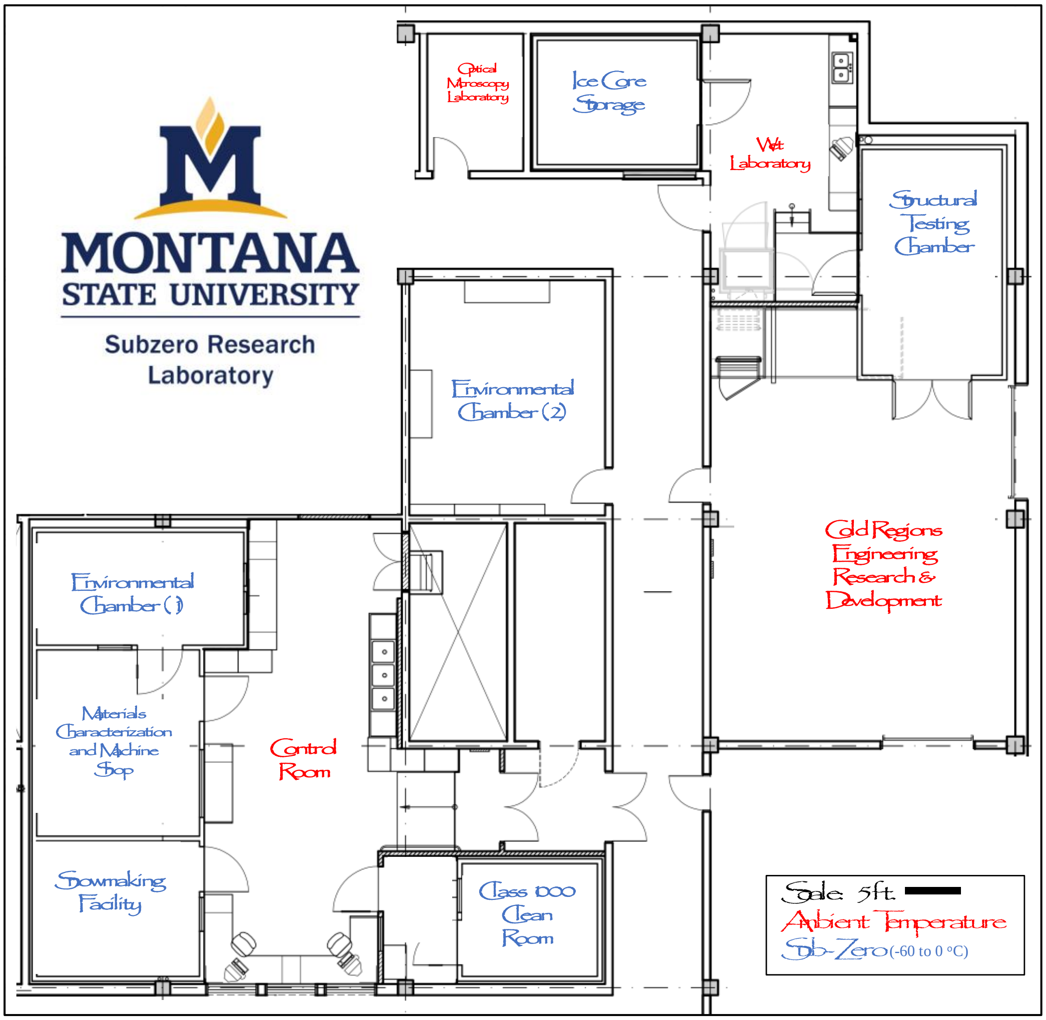

Fig. 8. Subzero Research Lab (SRL)

Relevant Laboratory Equipment: the SRL also includes MTS Criterion 43 w/ Environmental Chamber for conducting tests in temperature range of -80 to 100 °C (Fig. 9)

Fig. 9. MTS Criterion 43 w/ Environmental Chamber

4- 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 numerical analyses, PIs have access to a license for COMSOL Multiphysics^{TM}, a finite element simulation environment (COMSOL, 2015). COMSOL is an interactive environment for modeling and simulating scientific and engineering problems.

REFERENCES

Abdelaziz, S. L., Ozudogru, T. Y., Olgun, C. G., and Martin, J. R. (2014). "Multilayer finite line source model for vertical heat exchangers." *Geothermics*, 51, 406-416.

American Association of State Highway and Transportation Officials (AASHTO) (2008). "Bridging the Gap: Restoring and Rebuilding the Nation's Bridges." *American Association of State Highway and Transportation Officials*.

ASTM Standard, D5334-14. (2014) "Standard Test Method for Determination of Thermal Conductivity of Soil and Soft Rock by Thermal Needle Probe Procedure." West Conshohocken, PA; ASTM International, 2014. doi: https://doi.org/10.1520/D5334-14

ASTM Standard, F877-18a (2018) "Standard Specification for Cross-linked Polyethylene (PEX) Hot- and Cold-Water Distribution Systems, ASTM International, West Conshohocken, PA, ASTM International, 2018 DOI: 10.1520/F0877-18A www.astm.org.

Baboian, R. (1992). "Synergistic Effects of Acid Deposition and Road Salts on Corrosion." *Corrosion Forms and Control for Infrastructure*, ASTM STP 1137, 17-29.

Beck, M., Bayer, P., de Paly, M., Hecht-Mendez, J., and Zell, A. (2013). "Geometric arrangement and operation mode adjustment in low-enthalpy geothermal borehole fields for heating." Energy, 49(1), 434-443.

Bowers, G.A., and Olgun, G.C. (2014). "Ground-source bridge deck deicing systems using energy foundations", *Geo-Congress*, February 23-26, Atlanta, Georgia.

Bowers, G.A., and Olgun, G.C. (2015). "Experimental investigation of bridge deck deicing using energy piles", *IFCEE*, March 17-21, Atlanta, Georgia, 1628-1637.

Bowers, Jr. (2016). "Ground-Source Bridge Deck Deicing and Integrated Shallow Geothermal Energy Harvesting Systems." *Ph.D. Dissertation*, Virginia Polytechnic Institute and State University.

Carey, K. L. (1984). "Solving Problems of Ice-Blocked Drainage." *Report*, No. CRREL-84-2. Cold Regions Research and Engineering Lab, Hanober, NH.

De Paly, M., Hecht-Mendez, J., Beck, M., Blum, P., Zell, A., and Bayer, P. (2012). "Optimization of energy extraction for closed shallow geothermal systems using linear programming." Geothermics, 43, 57-65.

Eugster, W., Schatzmann, J. (2002) "Harnessing Solar Energy for Winter Road Clearing on Heavily Loaded Expressways", *Procedings XIth PIARC International Winter Road Congress*, Sapporo, Japan, January 2002.

Eugster, W. (2007). "Road and bridge heating using geothermal energy overview and examples", Proceeding European Geothermal Congress, May 30th - Jun 1st, Unterhaching, Germany.

Fliegel, J., Flyer, J., Katz, M., Le, A., Ngo, T., Roberts, K., Santoro, A., Sun, C., and Weyforth, T. (2010). "Design and Evaluation of a Retrofittable Electric Snow Melting System for Pavements", *Gemstone Program Final Report*, Department of civil and Environmental Engineering, University of Maryland, College Park, MD., 118.

Ghasemi-Fare, O. Basu, P. (2016). "Predictive assessment of heat exchange performance of geothermal energy piles", *Renewable Energy*, 86, 1178-1196. doi:10.1016/j.renene.2015.08.078.

Granata, R.D., and Hartt, W.H. (2009). "Integrity of Infrastructure Materials and Structures." *U.S.D.o.T. FHWA*, ed., FHWA, U.S. Department of Transportation, United States, 90p.

Hansson, K., Simunek, J., Mizoguchi, M., Lundin, L.C., and van Genuchten, M.T. (2004). “Water flow and heat transport in frozen soil: Numerical solution and freeze-thaw applications.” Vadose Zone J., 3, 693–704.

Koch, G.H., Brongers, M.P.H., Thompson, N.G., Virmani, Y.P., and Payer, J.H. (2002). "Corrosion Cost and Preventive Strategies in the United States." *FHWA, U.S. Department of Transportation*, United States, 790p.

Kusuda, T., and Achenbach, P.R. (1965). "Earth Temperature and Thermal Diffusivity at Selected Stations in the United States." *ASHRAE Transactions*, 71(1), 61-65.

Lazzari, S. (2010). "Long-term performance of BHE (borehole heat exchanger) fields with negligible groundwater movement." *Energy*, 35(12), 4966-4974.

Liu, X., Rees, S., and Spitler, J. (2003). "Simulation of a Geothermal Bridge Deck Anti-icing System and Experimental Validation." *Proceedings Transportation Research Board 82nd Annual Meeting*. Washington, D.C., January 12-16, 2003.

Liu, X., Rees, S. J., and Spitler, J. D. (2007a). "Modeling snow melting on heated pavement surfaces. Part I: Model development." *Applied Thermal Engineering*, 27(5-6), 1115-1124.

Liu, X., Rees, S. J., and Spitler, J. D. (2007b). "Modeling snow melting on heated pavement surfaces. Part II: Experimental validation." *Applied Thermal Engineering*, 27(5-6), 1125-1131.

Lund, J. W., and Boyd, T. L. (2016). "Direct utilization of geothermal energy 2015 worldwide review." *Geothermics*, 60, 66-93.

Morita, K., and Tago, M. (2005). "Snow-melting on sidewalks with ground-coupled heat pumps in a heavy snowfall city." *Proceedings World Geothermal Congress*, Antalya, Turkey.

Morita, K., and Tago, M. (2005), "Operational Characteristics of the Gaia Snow-melting System in Ninohe, Iwate, Japan," *World Geothermal Congress*, Kyushu-Tohoku, Japan, 2000.

Minsk, D. (1999). "Heated Bridge Technology." *Final Report, Report No. FHWA-RD-99/158*, Federal Highway Administration, Washington, D.C., 1999.

Naito, C., Sause, R., Hodgson, I., Pessiki, S., and Macioce, T. (2010). "Forensic Examination of a Non-Composite Adjacent Precast Prestressed Concrete Box Beam Bridge." *ASCE Journal of Bridge Engineering*, 15(4), 408-418.

Ozudogru, T. Y., Ghasemi-Fare, O., Olgun, C. G., and Basu, P. (2014). "Numerical Modeling of Vertical Geothermal Heat Exchangers Using Finite Difference and Finite Element Techniques." *Geotechnical and Geological Engineering*, 33(2), 291-306.

Ozudogru, T. Y., Olgun, C. G., and Senol, A. (2014). "3D Numerical Modeling of Vertical Geothermal Heat Exchangers." *Geothermics*, 51, 312-324.

Spitler, J., Ramamoorthy, M. (2000). "Bridge Deck Deicing using Geothermal Heat Pumps." *Proceedings of the 4th International Heat Pumps in Cold Climated Conference*, Aylmer, Quebec. August 2000.

Virmani, Y. P., Clear, K. C., and Pasko, T. J. (1983). "Time-To-Corrosion of Reinforcing Steel in Concrete Slabs. Volume 5. Calcium Nitrite Admixture or Epoxy-Coated Reinforcing Bars as Corrosion Protection Systems." *FHWA, U.S. Department of Transportation*, United States, 80p.

Virmani, Y. P., Jones, W. R., and Jones, D. H. (1984). "Steel corrosion in concrete: pH at corrosion sites." *Public Roads*, 48(3), 96-102.

White, D.J., Sritharan, S., Suleiman, M.T., Mekkawy, M.M., and Chulter, S. (2005). "Identification of the Best Practices for Design, Construction, and Repair of Bridge Approach Sections." *Final Report*, *Iowa DOT TR-481*, CTRE Report 02-118.

Yunovich, M., Thompson, N. G., and Virmani, Y. P. (2003). "Life Cycle Cost Analysis for Reinforced Concrete Bridge Decks." *Corrosion NACExpo 2003*, NACE International, San Diego, California, April 2003, Paper No. 03309.

Yu, X., Hurley, T. M., Li, T., Lei, G., Pedarla, A., Puppala, A. J., (2020). "Experimental feasibility study of a new attached hydronic loop design for geothermal heating of bridge decks" *Applied Thermal Engineering*, 164 (5), 114507

Venuleo, S., Laloui, L., Terzis, D., Hueckel, T., and Hassan, M. (2016). "Microbially induced calcite precipitation effect on soil thermal conductivity." *Geotech Lett*., 6(1).

Virginia Department of Mines Minerals and Energy (2012). "Earth Temperature and Site Geology." <http://www.geo4va.vt.edu/indexGeo4VA.htm>.

COMSOL. (2015). "COMSOL MultiphysicsTM Version 5.1: User’s Guide and Reference Manual." *COMSOL Inc*., Burlington, MA.