Use of Finite Element Analysis for the Estimate of Freezing & Maintenance Phase of Indirect & Direct Artificial Ground Freezing of Proposed Frozen Silt Mat, an Alternative of Timber Mat

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Abstract –

The use of heavy cranes has increased with the impact of modernized modular construction, which in turn has led to heavier modules, with weights often measured in hundreds of tons. As a result, the criticality of such lifts depends primarily upon the ground support health. The traditional approach is to make use of timber/steel mats for ground stability. The use of frozen silt (water and silt frozen mixture) as an alternative to this or to reduce the number of layers of timber mats is a novel technology that is explored in this work. For projects where this technology could be applicable, heavy construction companies will be able to avoid extensive ground preparation and reclamation by adopting this approach. The mechanical properties of frozen silt are comparable to timber mats (Coastal Douglas-fir), but are dependent upon the temperature constraint. This contribution encompasses the use of artificial ground freezing for the preparation of frozen silt matting for ground support. The required mat surface temperature is considered as −10 °C, based on the competitive mechanical properties for its practical use. The freezing process is investigated using Finite Element Analysis (FEA). Simulation is performed to obtain the bottom-up estimate of ground freezing using indirect freezing (brine chillers) and direct freezing (liquid nitrogen) for both the freezing phase and maintenance phase. The simulation is executed under three ambient temperatures (10 °C, 5 °C and 0 °C) in order to make it realistic. The results from these simulations can establish a baseline for cost estimation for the alternative crane matting solution in the form of frozen silt mat.

Keywords –

Artificial Ground Freezing, Brine Chillers, Liquid Nitrogen, Crane Mats, FEA, ANSYS Simulation

1 Introduction

Traditionally, the heavy construction industry has relied upon using cranes to build the structures needed in the field since the elements constituting these structures are generally voluminous and heavy. With off-site construction becoming the paradigm of choice for project delivery, complete projects are delivered in the form of modules, which, over the years, have become heavier as an increasing number of components are added to the skeletal modular structure during fabrication. As a result, high-capacity cranes have emerged as the fundamental equipment for the assembly of modularized power plants and refineries. Of course, as the weight of the lifting system (crane + payload) has become heavier, ground-bearing capacity analysis cannot be ignored, since failure of the ground can result in loss of life and property. Today, the traditional approach to improving the capacity of the ground proceeds in two phases: (i) ground preparation, which consists of excavating a given depth of ground that is replaced by a layer (or a mix of layers) of construction aggregates compacted; and/or (ii) addition of one, two or three layers of timber mats. This setup allows the total load of the lifting system to be appropriately distributed. With the adoption of the modular construction paradigm, the demand for crane mats has been augmented. According to market research, in 2014, the total annual mat demand in Canada was in the range of 450,000–750,000, while annual mat production in North America in 2014 was approximately 300,000–600,000, and the number of mats produced in Canada in 2014 was approximately 20,000–25,000. The matting industry increased 200% from 2009 to 2014 [6]. Nevertheless, a study by OSHA reported that, from 2000 to 2009 in the United States, approximately 12% of fatalities on construction sites were associated with crane work. A total of 587 lives were lost as a result of 571 accidents from crane work during that period, of which 105 were crane operators, 375 were riggers, and eight were signal people. It is estimated that approximately 50 deaths were caused by "Crane Tipped Over", which is directly associated with poor ground support [22]. Interestingly, ground support technology has been largely overlooked by practitioners despite the cost and environmental impact associated with current ground capacity improvement methods. In this respect, with increasing environmental awareness, choosing a technology for a given purpose needs not only to be cost-effective but also to have a low impact on the environment. Using the same characteristics, frozen soil has properties similar to the supporting structural material [1]. Considering the mechanical properties of frozen silt (water and silt frozen mixture), the novelty of using frozen silt for crane matting is a novel idea which transcends traditional constraints and helps to minimize environmental impact. The mechanical properties of frozen silt are comparable to timber matting (Coastal Douglas-fir), but are dependent upon the temperature constraint (i.e., the mechanical properties of frozen silt with the surface temperature below −10°C are comparable to Coastal Douglas-Fir). To achieve this temperature, artificial ground freezing can be used. The earliest documented application of artificial ground freezing was in a mine shaft near Swansea, South Wales, in 1862. Later, this freezing method was patented by F. H. Poetsch, in 1883 with some major improvements [18]. In 1884, excavation of a tunnel in Stockholm was aided with a frozen stabilized arch [2]. In practical usage, there are two types of ground freezing methods: indirect freezing (brine chiller) and direct freezing (liquid nitrogen). In this contribution, the Fluid Flow (Fluent) module of ANSYS (17.1) is used to estimate the usage of indirect and direct freezing for the preparation of frozen silt matting. A model of the proposed frozen mat with freezing pipes is generated and uploaded in ANSYS module. The mat model is placed on the ground to create a real case scenario. We thus create a basis for the practical and onsite application of ground freezing methods for frozen silt mat preparation. Constructed on energy equations and viscosity constraints for heat transfer between mat, ground, and air, ANSYS simulation provides the graphical representation of mat freezing with respect to time lapse. To make it realistic, the simulation is performed under three ambient temperatures (10 °C, 5 °C and 0 °C). The simulation of indirect freezing is performed by taking constant fluid flow of brine, whereas for direct freezing, three different fluid velocities are assigned. The idea is to simulate the weather condition of the north-western part of Canada. The freezing phase and the maintenance phase for the frozen silt mat are analyzed to obtain the cooling requirement in figures (numbers). For indirect freezing, the cooling requirement is in the form of the temperature difference between inlet and outlet of freezing pipes, flow of brine, and, for direct freezing, the amount of liquid nitrogen used for the freezing of the mat. The results indicate how much energy drainage is required to convert silt into frozen silt under the same boundary conditions but at different ambient temperature and different flow velocities of the cooling agent. The results are found to be favourable and comparable to the actual artificial ground freezing. The results from these simulations provide a baseline for the cost estimation for the alternative crane matting solution in the form of capital, operational, and opportunity costs for this novel alternative to the use of timber matting ground support. Based on these results, a value proposition of using frozen silt mat can be generated with better SWOT (Strength, Weakness, Opportunities & Threats) figures.

2 Research Methodology

2.1 Frozen Silt Mat Proposed Design

The first step is to provide a preliminary conceptual design for the frozen silt mat. Based on the data available, a conceptual silt mat design is initiated in this section for ANSYS heat transfer simulation. As per the dimensions of the mat (3.6449 m × 2.4384 m × 0.2032 m), eight frozen silt mats are proposed to be used for a Manitowoc 18000 Crawler Crane (see Figure 1). For analysis purposes, only the crawler crane is selected. The aim of the research presented in this paper, is to perform the simulation for the freezing process of silt mats until the surface temperature reaches or drops below −10°C.

Figure 1 shows the placement of the proposed four frozen silt mats under one track of a crawler crane. For the freezing purpose, conceptually, 10 freezing pipes are used. In the proposed layout, the pipes are placed evenly inside the soil perpendicular to the length of the mat but parallel to the crawler track. It is assumed that each pipe crosses all four mats under one crawler track. The cooling agent enters one end of these pipes and exits from the other end. For insulation purposes, the soil, cost-effective insulation on site, itself can be used as the mat cushion (insulation), where the thickness of the mat is increased to create a mat cushion (insulation) (see Figure 2).

The four silt mats combine to form one long frozen silt mat with mat cushion (insulation). The length of the whole mat (consisting of four frozen silt mats) is considered to be approximately 10.5 m, with a width of 4 m. The proposed height (0.303 m) of the mat exceeds the practical normal mat height (0.203 m). The extra height provides the mat cushion which functions as insulation. If this insulation is not provided, the surface temperature of the mat drops rapidly. A freezing temperature of −10 °C throughout the mat is required (including the mat surface). 2″ steel pipe schedule 40 is used for the freeze pipes. These steel pipes work as a conducting material to transfer heat from the silt to the cooling agent (either brine or liquid nitrogen).

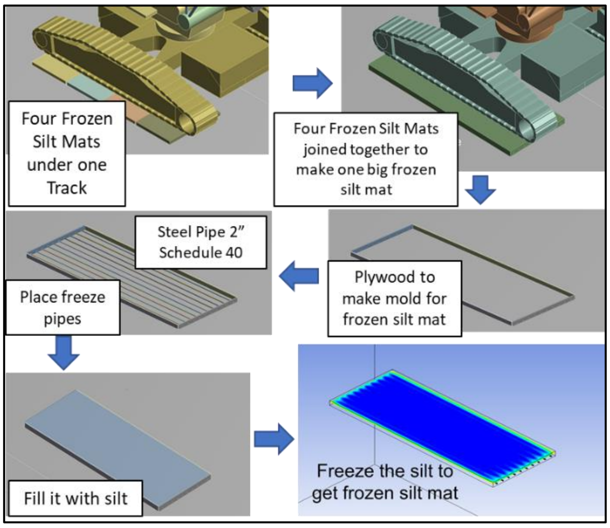

Figure 1: Proposed Frozen Silt Mat configuration

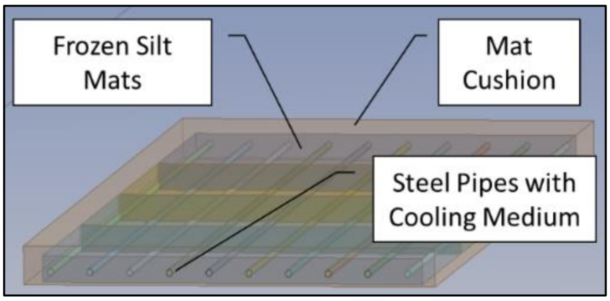

Figure 2. Mat Cushion for insulation

2.2 Mechanical Properties of Frozen Silt Mat

Mats made of frozen silt can sustain the Ground Bearing Pressure (based on the comparable mechanical properties of timber matting) if the mat temperature is below −10 °C. The mechanical properties of the frozen silt mat, it should be noted, are considered from the research done by Yang et al. (2015), and by Wilson (1982) [20][21]. The value of Young's modulus ranges from 0.7 GN/m^2 to 16.5 GN/m^2 with the temperature ranging from 0 °C to −10 °C. The dry density is found to vary from 320 kg/m^3 to 941 kg/m^3, while the water/moisture content varies from 62% to 225% [21]. Based on the above data, the compressive strength of the frozen silt varies from 1.7 MPa to 7.1 MPa [21]. For the purpose of comparison, the surface temperature of frozen silt mat is considered as −10 °C. Table 1 shows the comparison between the mechanical properties of Coastal Douglas-Fir and the proposed frozen silt mat. As can be seen, the properties of the frozen silt are found to be comparable with the timber mat made of Coastal Douglas-Fir.

Table 1. Linear mechanical properties for comparison

		Units	Coastal Douglas -Fir	Frozen Silt
1	Young's Modulus	MPa	13,400[a]	10,000[b, d]
2	Poisson's Ratio		0.449[c]	0.3[e]
3	Tensile Yield Strength	MPa	2.3[a]	5.1[d]
4	Compressive Yield Strength	MPa	5.0[a]	5.0[d]
5	Tensile Ultimate Strength	MPa	5.0[a]	5.1[d]

Sources: Data adapted from

a) Kretschmann, David. E. 2010. "Mechanical Properties of Wood, Chapter 5." In Wood Handbook, 5.1-46. U.S. Dept. of Agriculture, Forest Service, Forest Products Laboratory.
b) Wilson, Charles Ralph. 1982. "Dynamic Properties of Naturally Frozen Fairbanks Silt." Master of Science Thesis in Civil Engineering. Corvallis: Oregon State University, April 22.
c) Green, David W., Jerrold E. Winandy, and David E. Kretschmann. 1999. "Mechanical Properties of Wood." In Wood Handbook, 4.1-45. U.S. Dept. of Agriculture, Forest Service, Forest Products Laboratory.
d) Yang, Zhaohui (Joey), Benjamin Still, and Ziaoxuan Ge. 2015. "Mechanical properties of seasonally frozen and permafrost soils at high strain rate." Cold Region Science and Technology 113: 12-19. doi:doi.org/10.1016/j.coldregions.2015.02.008
e) Andersland, Orlando B., and Branko Ladanyi. 2004. Frozen Ground Engineering. New Jersey: Wiley

2.3 ANSYS Methodology

This research on frozen silt mats can be divided into two parts with respect to Finite Element Analysis (FEA):

a. heat transfer to/from proposed frozen silt mat;
b. usage of a cooling agent for the freezing of proposed silt mat for cost comparison.

ANSYS Workbench (version 17.1) is used for this research. For thermal simulation, it should be noted, "Fluid Flow (Fluent)" solver is available in ANSYS to simulate the computational fluid dynamics (CFD) and thermal variation. The whole process is divided into 5 steps. Step 1 (Geometry Build): In this step, the geometry of the object or structure is drafted or imported from a 3D AutoCAD file. Here the lower the number of geometry parts is, the faster the ANSYS fluid flow solver can analyze and implement the mesh. As the number of parts of a geometry increases, the time required by the ANSYS solution increases exponentially. Step 2 (Generate Mesh): In this step, the model is uploaded to ANSYS Fluid Flow (Fluent) solver "Mesh". This includes meshing of the model to small elements for FEA. The type and conditions of meshing are described later in this section, where, the smaller the meshing element is, the better it is considered to be. However, the accuracy and precision must be monitored to make it workable. It is also preferable to give each surface a separately named selection. (These name selections make step 4 easier.) Step 3 (Apply Boundary Conditions): In this step, the previously determined energy equations are applied to the geometry, and thermal/viscous properties of the fluids are assigned. The interference between different body surfaces is also assigned in this step, as well as cell zone conditions. Finally, the inlet and outlet temperature and fluid velocity are assigned accordingly. Step 4 (Obtain Solution): After obtaining the geometry and assigning the required boundary conditions, the solution to the problem is initiated. The solution depends upon the solution initialization, the number of time steps, the duration of time steps, and the maximum iterations per time step. Step 5 (Display Results): The final step is to obtain the results, where fluid dynamics is the basis of these results. Heat transfer with respect to time is obtained in this step. The results can be shown in the form of graphs, colour variation, or various charts and sheets. The data can be exported to different file formats as necessary for further investigation.

2.4 Thermal Properties

For the thermal analysis, the thermal properties of the material for ANSYS simulation are tabulated in Table 2. The heat transfer occurs in the following manner: (a) heat transfer from the pipes to the cooling agent through conduction and convection, where the thermal properties and the viscosity of the cooling agent cover the estimation for heat rejection from the geometry (frozen silt mat, pipes, air, ground); (b) heat transfer from the mat to the pipes through conduction; (c) heat transfer from ground to the freezing mat, where, during the mat freezing process, the soil under the mat also is frozen with the passage of time and later functions as insulation; and (d) heat transfer from the air to the silt mat in the form of convection (2 $W/m^2 \cdot K$, assumption) and radiation (external emissivity 0.98, assumption) [4][19].

Table 2. Thermal properties of materials involved in frozen silt mat thermal process ANSYS analysis.

Density (kg/m^3)	C_p ($j/kg \cdot °C$)	Thermal Conductivity ($W/m \cdot K$)	Viscosity (Poise)
	Steel		
7,500	500	43	0
	Frozen Silt (120%)		
1,100[a]	1,360[a]	1[a]	0
	Ice		
900	2,090	0.08	0
	$CaCl_2$ (30%)		
1,318[b]	2,650[b]	0.5[c]	0.221[c]
	Liquid Nitrogen (−150°C)		
808.5[d]	2,040[e]	0.1396[e]	0.00068[f]

Sources: Data adapted from

a) Andersland, Orlando B., and Branko Ladanyi. 2004. Frozen Ground Engineering. New Jersey: Wiley.
b) OXYChem. 2018. "Calcium Chloride - A Guide to Physical Properties." OXYChem Publisher.
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f) Grevendonk, W., W. Herreman, and A. De Bock. 1970. "Measurement on the Viscosity of Liquid Nitrogen." Physica (Elsevier B.V.) 46 (4): 600-604.

2.5 Freezing Methods

A standard soil freezing installation involves a refrigeration source, a distribution system, and cooling pipes for freezing of the soil (called "freeze pipes") [14]. The distribution system circulates the cooling agent (coolant for the freezing of the soil) from the refrigeration source to the freeze pipes, which extract the heat from the soil. In general, there are two main types of cooling agents: brine solution (indirect freezing) and liquid nitrogen (direct freezing).

In indirect freezing, one- or two-stage refrigeration plants are the most commonly used refrigeration sources. They are powered by diesel or electric engines. Usually, chilled calcium chloride ($CaCl_2$) is used as a cooling agent to freeze the ground. The cooling agent is pumped through the freeze pipes, and, after withdrawing heat, returns to the unit (see Figure 3). The whole process occurs in three phases. The first phase is known as the **freezing phase**. The temperature of the brine solution increases by approximately 1°C to 2°C during this process. In this phase, the ground is frozen to achieve the required strength. The next step is to maintain the temperature of the frozen soil. This is known as the **maintenance phase**. The energy drainage required to freeze the ground, it should be noted, is greater than the energy drainage required to sustain the frozen ground [12].The final phase, known as the thaw phase, is to terminate the freezing project. In this phase, the ground is left to thaw [9].

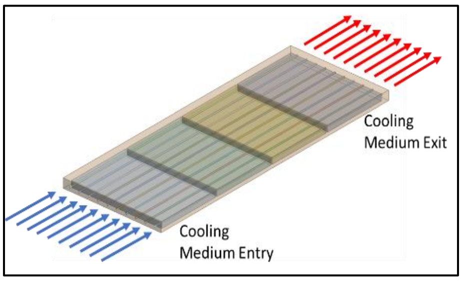

Figure 3. Cooling agent flow through mat

In direct freezing, as indicated by its name, the soil is directly cooled by the freezing agent. Primarily liquid nitrogen is used to freeze the ground in this process. It also involves three phases: the freezing phase, the maintenance phase, and the thaw phase. The coolant is supplied directly from the storage tank, and the soil/silt around each freeze pipe freezes radially. The amount of nitrogen required for the freezing is maintained by means of a temperature-sensing valve. As the valve opens, nitrogen escapes into the atmosphere at a rate that is not dangerous to the environment.

2.6 Heat Transfer Analysis Method

The data from the mat strength analysis provide the basis for the heat transfer analysis. For heat transfer analysis, ANSYS Fluid Flow (Fluent) solver is used to simulate the cooling of frozen silt mat in order to convert silt into frozen silt mat (solid). The process is summarized in the following steps:

Step 1: The mat dimensions obtained from the mat strength analysis are used to propose the design of the frozen silt mat. The freeze pipes are added to the frozen silt mat for the purpose of freezing the soil around the freeze pipes, resulting in a solid frozen silt mat. The proposed design of the mat with the addition of freeze pipes is uploaded in ANSYS Flow (Fluent) Geometry Module, and the proposed mat is placed on the soil model. The parameters of soil and the frozen silt mat are considered equal, with the exception of the differences in the internal temperature of the frozen silt after cooling and the ambient temperature of the loose soil.

Step 2: One end of the pipe is considered an inlet for the cooling agent, while the other end is the outlet for the cooling agent. For indirect freezing, $CaCl_2$ is used as the cooling agent. The velocity and temperature of the cooling agent are adjusted to obtain the heat transfer. For direct freezing, the flow of liquid nitrogen is used to monitor the freezing of the mat. The temperature of the cooling agent is adjusted as per the cooling parameters.

Step 3: The heat transfer rate along the flow of the liquid provides the heat transfer data for estimation purposes, while the cooling administered by the cooling agent is used to determine the freezing refrigeration unit for indirect freezing. For direct freezing, the amount of liquid flow provides the quantity of liquid nitrogen used for the freezing of the mat. The time required for the freezing of the mat surface is also recorded for further analysis.

Step 4: The ambient temperature and the boundary conditions are applied to the model. Prior to this, the geometry is subdivided into smaller elements by applying "meshing". Meshing is carried out to break the whole model into small finite elements for analysis. The time steps and iterations per step are applied to the solver.

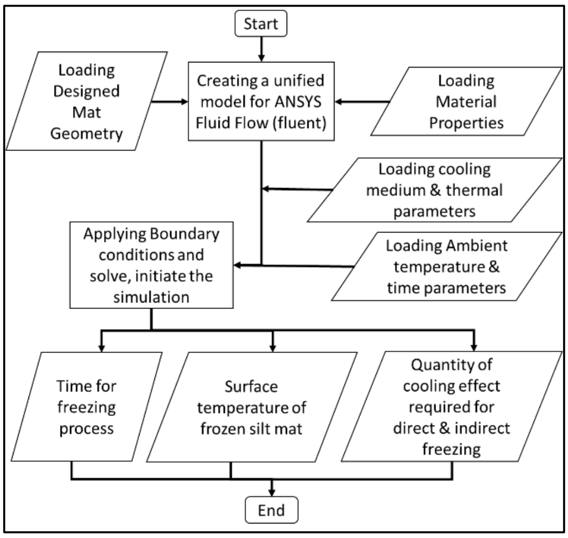

Figure 4. Flowchart for frozen silt mat freezing sequence

Step 5: The solution is uploaded to the results section of the solver, and the heat transfer with respect to time is obtained for the whole system. The surface temperature of the mat is observed and recorded to check the feasibility of the required frozen silt mat temperature. For indirect freezing, there are three main variables obtained from this exercise: the temperature difference between inlet and outlet temperature of cooling medium; the time required for cooling; and the surface temperature of the frozen silt mat. For direct freezing, there are three main variables: the flow of liquid nitrogen; the time required for cooling; and the surface temperature of the mat.

The above-mentioned methodology is presented in the form of a data flowchart in Figure 4.

3 ANSYS Simulation

3.1 Indirect Freezing ($CaCl_2$)

Calcium chloride ($CaCl_2$) is used as a cooling agent, and its velocity is assumed to be 0.29 ft/s (0.088392 m/s). The inlet temperature of $CaCl_2$ at the start of the analysis is the same as the ambient temperature, but it drops gradually until it reaches −30.15 °C. To avoid complexity, it is assumed that the temperature drop is 5 °C over a 24-hour period (gradual). To simplify the model, the heat generated from the crane engine/crawler track is not considered. For data collection, each step is composed of 3,600 seconds, with 200 iterations, and the number of steps as 720. Hence, the total simulation time is 30 days.

The temperature of the mat surface (under the mat cushion) is recorded and plotted against time (days) in Figure 5. As per the simulation, the surface temperature of the frozen silt mat is close to −10 °C with the ambient temperature of 10 °C, and it takes 8 to 9 days to freeze the silt sufficiently to create a frozen silt mat. In the case of 5 °C ambient temperature, it takes less than 7 days to freeze, and, for 0 °C, it is less than 5 days. The surface temperature of the mat (under mat cushion) ranges between −10 °C and −15 °C for case-2 (5 °C) and it is below −15 °C in case-3 (0 °C).

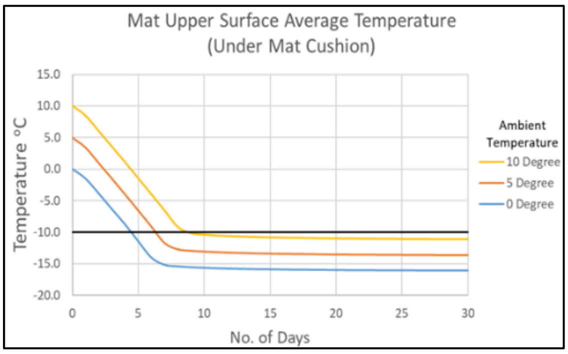

Figure 5. Mat Surface Average Temperature

The heat removal from the proposed frozen silt mat in the simulation is shown in Figure 6. The heat removal value for case-1 (ambient temperature 10 °C) is higher than in the other two case examples. The first part of the graph (the linear part) shows the freezing phase, while the later horizontal line shows the maintenance phase.

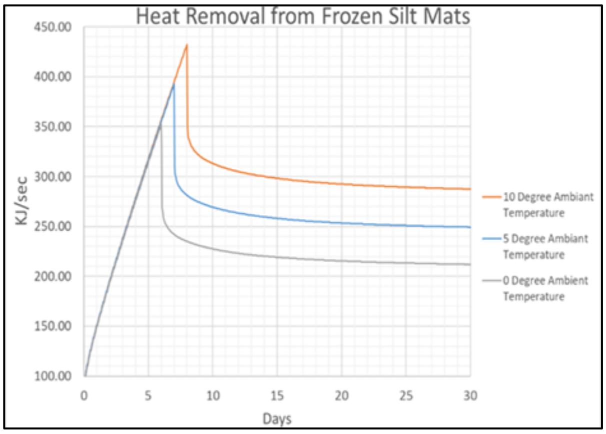

Figure 6. Heat Removal from Frozen Silt Mat

3.2 Direct Freezing (Liquid Nitrogen N_2)

Direct freezing differs from indirect freezing as discussed in section 2.5. The flow of the liquid nitrogen is the main cost driver. For ANSYS simulation purposes, three assumed cases are taken into consideration based on different flow velocities of liquid nitrogen. As per the proposed design of frozen silt mat, there are 10 pipes for each frozen silt mat. The velocity of liquid nitrogen for the outer pipes (pipe 1 and pipe 10) is taken to be constant. The velocity of liquid nitrogen for the inner pipes (pipe 2 to pipe 9) is considered variable with respect to time. Table 3 shows the details of these cases.

Each assumed case is simulated at three different ambient temperatures: 10 °C, 5 °C, and 0 °C. All the remaining parameters are similar to those described in Section 2. The use of liquid nitrogen with respect to the number of days is shown in Figure 7. The flow is found to be maximum for case-1 and minimum for case-3. With every case analyzed under each of the three ambient temperature scenarios, in total nine case examples are simulated for freezing silt mat in ANSYS.

The average surface temperature of the mat decreases rapidly due to the low temperature of liquid nitrogen as compared to brine (the boiling point of nitrogen is −195.8 °C at atmospheric pressure). It is assumed for the ANSYS simulation that the temperature of liquid nitrogen (LN_2) entering the pipe is −150 °C. Due to this low-temperature flow, the temperature of the mat material (silt) decreases rapidly. The graphical representation of the mat surface temperature with respect to time is shown in Figure 8. From this simulation exercise, case-1 is found to perform well at every ambient temperature as compared to case-2 and case-3. The surface of the frozen silt mat reaches −10 °C faster if the use of liquid nitrogen is increased in the form of higher flow (case-1). The surface temperature for case-1 is found to be lower than that for case-2 and case-3.

Table 3. Liquid nitrogen velocity for three cases.

	Case-1	Case-2	Case-3
Outer Pipes	0.005 m/s (0.016 ft/s)	0.004 m/s (0.013 ft/s)	0.003 m/s (0.0098 ft/s)
Inner Pipes 0 to 24 hr	0.005 m/s (0.016 ft/s)	0.004 m/s (0.013 ft/s)	0.003 m/s (0.0098 ft/s)
Inner Pipes 24 to 720 hr	0.005 m/s (0.016 ft/s) linearly decreasing to 0.002 m/s (0.0056 ft/s)	0.004 m/s (0.013 ft/s) linearly decreasing to 0.0015 m/s (0.0049 ft/s)	0.003 m/s (0.0098 ft/s) linearly decreasing to 0.001 m/s (0.0033 ft/s)

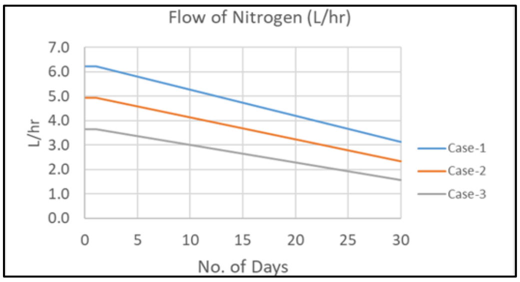

Figure 7: Liquid Nitrogen Total Flow (L/hr)

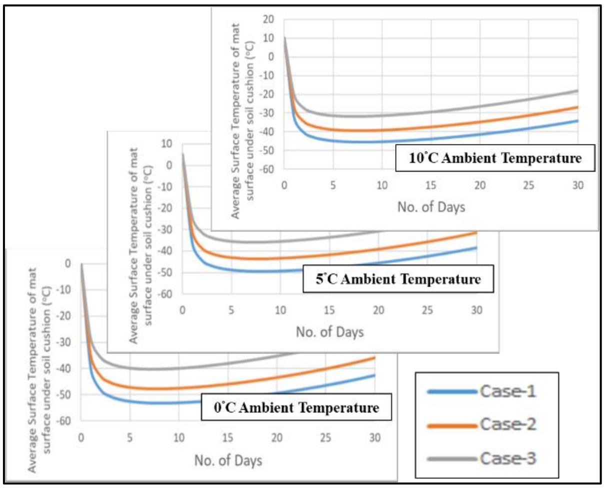

Figure 8: Average Mat Surface Temperature (Direct Freezing - Liquid Nitrogen LN_2)

4 Conclusion

- This research provides a guideline for the freezing process of frozen silt mat. The mechanical properties of frozen silt mat are found to be comparable if the surface temperature is −10 °C or below.
- The results of indirect freezing in the form of the graph representing energy drainage with respect to time are similar to the energy removal graph presented by Newman et al. (2011) [15]. The steep line represents the freezing phase while the horizontal line after the freezing phase represents the maintenance phase to maintain the temperature.
- The results also show that the freezing process in direct freezing is quicker as compared to in indirect freezing. The surface temperature reaches −10 °C in hours in direct freezing, compared to days in indirect freezing.
- This research can be used for estimating the duration of the freezing process for frozen silt mat in cold regions, as less energy drainage will be required. The frozen silt mat can be an environmentally friendly alternative for crane timber mats in some cases, but future study is required in this regard to determine the suitability of this technology.
- ANSYS can be used for the estimation of artificial ground freezing for practical use. The graphical representation of indirect and direct freezing provides a better overview of how moist soil turns into frozen ground as compared to the manual calculations of artificial ground freezing.

5 Recommendation and future aspects of the research

This research indicates that ANSYS can be used to estimate the application of artificial ground freezing methods for the preparation of frozen silt matting. Different fluid flow velocities need to be investigated to obtain a better view and understanding of the mat freezing process. But, before addressing this particular aspect, the stress comparison must be established for the frozen silt mat in accordance with the timber mats (Coastal Douglas-Fir). The physical properties must be verified using ANSYS and later by means of lab/site testing. For frozen silt mats, future research can investigate other soil types (sand, clay, loam, chalky soil, etc.) in order to establish an empirical relationship between mat surface temperature, ambient temperature, soil composition, water content, and different freezing methods. These projected figures further need to be verified by lab/site testing. The variation of Young Modulus with respect to the surface temperature on the strength of frozen silt mat should also be investigated in detail, as well as the impact of density change on freezing methods. Density anomalies of water/ice/frozen silt with respect to ambient temperature, it should be noted, are not incorporated in this research. These anomalies and their impact on the strength of a frozen silt mat can be considered in future research. The use of mesh/reinforced bars/pulp to increase the stability and strength of frozen silt mat also needs to be studied in detail in order to arrive at a better and more progressive value proposition with respect to timber mats, both technically and financially [17].

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