COMPETITIVE FINITE ELEMENT ANALYSIS (ANSYS) FOR THE USE OF ICE & FROZEN SILT AS A SUPPORTING STRUCTURAL MATERIAL, AN ALTERNATIVE TO THE TRADITIONAL CRAWLER CRANE MAT MATERIAL (S355, G40.21 & COASTAL DOUGLAS-FIR)

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Abstract: The construction industry is moving towards modular construction, which has resulted in heavy crane usage. At the same time, new, more sustainable construction methods/materials are being explored. The concept of using ice as a supporting structure is not new. For instance, a British-led classified project during the Second World War, Project Habakkuk, sought to develop an aircraft carrier made of ice. In addition to ice, a soil and water mixture when frozen has strong mechanical properties that can compete with those of timber (Coastal Douglas-fir). This research's contribution is to investigate the competitive finite element analysis (FEA) of ice and frozen silt as a crane mat, considering -10 °C as mat surface temperature based on the competitive mechanical properties for its practical usage. The impact of identical crane loading on the crane mat is monitored using ANSYS (FEA platform) using five matting materials (S355, G40.21, Coastal Douglas-fir, ice, and frozen silt) with five linear and one non-linear mechanical properties. The graphical results in the form of normal stresses and ground deflection along the crane superstructure slew, provides a perceptual mapping for the utilization of ice or frozen silt against traditional materials (i.e., steel and wood). The resulting graphical representation shows that the compressive stresses under the mat are non-uniform in nature. Moreover, the findings are favorable as the behavior of frozen silt is on par with that of Coastal Douglas-fir. The results of these simulations will provide a starting point for the estimation of the ground freezing process.

1   INTRODUCTION

The construction industry has become modernized with the advent of modularization. Modules are prefabricated offsite and later transferred to the site for onsite installation. The whole sequence is dependent on mobile crane work. The surge in demand for crane work has caused an increase in the number of crane accidents, which in return has increased the number of fatalities. According to the Occupational Safety and Health Administration (OSHA), USA, from 1997 to 2003, 'Crane Tip Over' accounted for approximately 11% of crane accidents connected with onsite mobile crane operation. Moreover, approximately 84% of crane and derrick fatalities were of the workers involved in crane operations (crane operators, signal mans, riggers etc.) (Beaver, et al. 2006). The major player in 'Crane Tip Over' is poor ground support for crane work. The remedy is to prepare the ground for the crane work, or to use crane mats to overcome low soil bearing capacity. The competitive advantage of the crane mat is that it is reusable, which makes it superior to ground preparation. The mats for cranes are usually made of steel

or timber. Their major use is to provide ground support for the heavy equipment used in construction and other resource-based activities, which may include drilling rigs, camps, tanks etc. These mats are used as pathways to provide support against unstable and soft ground (low soil bearing capacity). Due to the favourable position on perceptual mapping, the demand for crane mats increased compared to the use of methods of ground preparation. Market research was conducted in 2014 by Golden Environmental Mat Services (GEMS) to assess the size of the mat market in Canada for future company growth. According to their market research, in 2014, the total mat demand (Canada) alone was approximately 450,000–750,000 mats per annum. Annual mat production in North America in 2014 was approximately 300,000–600,000 mats per annum. The number of rig mats produced in Canada in 2014 was approximately 20,000–25,000 mats per annum. Furthermore, in 2004, the industry was small in terms of mats, but the growth was approximately 200% from 2009 to 2014 (Golden Environmental Mat Services 2015) (see Figure 1).
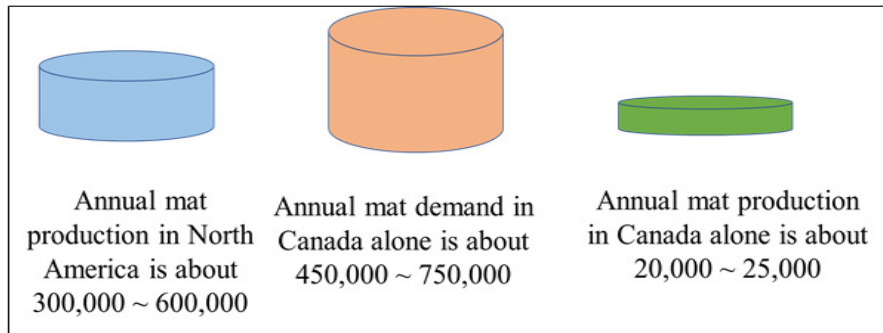

Figure 1: Market Research Conducted by Golden Environmental Mat Services in 2014 (Golden Environmental Mat Services 2015)

The aim of this research is to develop an alternative solution for ground support for heavy lifting, especially for the northwestern region of Canada. Edmonton, Alberta is the largest city in this cold region (Northwestern Canada) with an average temperature of 4° C and an average of 6 months below freezing. The winter of 2017-18 saw 167 days below zero degrees Celsius, breaking the record that was set in the winter of 1975 (Beyer 2018). The research presented in this paper is about the competitive analysis of various mat materials along with ice and frozen silt. The idea of ice as a supporting structure is not new in the construction industry. The tensile and compressive strength of ice is comparable to current construction materials (Andersland and Ladanyi 2004), and it is environmentally friendly. Furthermore, ice has low thermal conductivity when compared to construction metals (i.e., steel), which makes it a good insulator, which is favorable. These characteristics of ice make it a favorable option to be used as construction material in extremely cold weather. In addition to considering ice, soil mixed with water below freezing point results in a frozen soil that has strong mechanical statistics when compared to wood and concrete (Andersland and Ladanyi 2004). Artificial ground freezing is now widely used in the construction industry, especially in tunnel construction to provide temporary earth support and in some cases groundwater containment. Artificial ground freezing became an industry saviour by accomplishing the most problematic jobs in underground construction. Using the same characteristics of ice and frozen silt (a type of soil), a competitive finite element analysis using ANSYS (version 17.1) is carried out on five mat materials (i.e., S355, G40.21, Coastal Douglas-fir, ice, and frozen silt) using five linear and one non-linear mechanical properties. A standard size mat is used for all five materials under similar boundary conditions. The competitive analysis is built on the selection criteria of crane mat, which are deflection of the mat and the compressive stresses transferred to the ground. The required mat surface temperature for frozen silt is considered to be -10 °C, based on the competitive mechanical properties for its practical usage and finite element simulation. To establish a realistic environment for finite element analysis, a crane model is built to map the pressure exerted by the crane on the sample mat, mimicking a real-life lift. However, rather than designing mat support using traditional material, i.e., timber or steel, this work intends to explore the potential of using ice and frozen silt, which are widely available in nature, as the basic building blocks for crane mats. Of course, to be a viable solution for industry, these materials (ice and frozen silt) need to satisfy at least two conditions: (i) have structural properties that can ensure safety; and (ii) the technology needs to be cost effective. This research focuses on the first aspect in the context of which structural

properties of ice and frozen silt were modeled and compared with those of Coastal Douglas-fir. Instead of designing a new mat material, the existing available novel mat materials (ice & frozen silt) in nature are compared with the market mat materials to map their perceptual position. The outcome in the form of stress and deflection maps provided a favourable approach for the use of frozen silt as an alternative to Coastal Douglas-Fir. The results show that the mats made of frozen silt and Coastal Douglas-Fir are similar in behaviour within the constraints of deflection and stress distribution. The findings can be used as a foundation for the usage of frozen silt mat as an alternative to timber mats. Based on the outcome, the bottom-up estimation of capital and operating costs of frozen silt mat can be generated.

2   RESEARCH METHODOLOGY

2.1   ANSYS Methodology

ANSYS workbench (version 17.1) is used for this research. For mechanical simulation, mechanical workbench "Static Structural" is available in ANSYS, which can simulate the load variation along the slew of the crane superstructure. "Static Structural" is a module in ANSYS that deals with static structural mechanics. For the mat deformation analysis using the mechanical workbench, the whole ANSYS simulation process is divided into 6 steps. Step 1 (Define Material Properties): In step one, the material of the mat and the soil under the mat are defined; only 6 mechanical properties (5 linear and 1 non-linear) are investigated. These properties are defined in section 2.2 of the paper. Step 2 (Geometry Build): In this step, the geometry of the object or structure under investigation is built. The geometry can also be imported from the 3D AutoCAD file of that model. The smaller the number of geometry parts, the faster the ANSYS mechanical solver can analyze and implement the mesh. Step 3 (Generate Mesh): In this step, the model is uploaded in ANSYS Mechanical Solver "Model". Each geometry part is assigned to its respective material. The density of the material is adjusted to achieve the required weight of that particular part in geometry. Also, the contact that is made between the different parts of the model is assigned. This is required in ANSYS to define how the forces will be transferred from one part to another. This step also includes meshing of the model to small elements for FEA. Meshing is defined as the process of dividing the whole component into a number of elements so that whenever the load is applied on the component it distributes the load uniformly. The type and conditions of meshing are described in this section. Step 4 (Apply Boundary Conditions): The next step is to apply the boundary condition. The boundary conditions include (but are not limited to) fixed support, rotation of the joint, gravity, forces, pressure, etc. They also include the rotation of the superstructure of the crane as a function of time. Step 5 (Obtain Solution): The next step is to define the parameters of the solution. These include among other things the number of time steps, iterations per time step, FE connection visibility, linear and non-linear controls, etc. Once all the parameters have been assigned correctly, ANSYS Mechanical APDL is initiated to solve the problem. Step 6 (Display Results): The final step is to display the results. The results can be displayed in many ways, including normal stresses, principal stresses, forces, energy, deformation, etc. The results can also be displayed in the form of a video which shows the changes in values with respect to boundary conditions and time intervals.

2.2   Linear & Non-Linear Mechanical Properties

For the mat strength, the first thing to consider is the material properties. For the purpose of this research, five mat materials (G40.21-44W, S355, Coastal Douglas-fir, ice, and frozen silt) are selected. For each these materials, 5 linear and 1 non-linear mechanical properties are selected for finite element analysis. In a similar way, ice/frozen silt is considered as a material that can be used for the manufacturing of crane mats. The temperature of the frozen silt and ice is considered as –10°C for analysis purposes (Andersland and Ladanyi 2004). The mechanical properties of the frozen silt mat under investigation are taken from the research done by Yang, Still and Ge (2015) on specimens composed of silt from the Campbell Creek Bridge case project in Anchorage, AK (seasonally frozen soil) and the CRREL Permafrost Tunnel in Fox, AK (permafrost, frozen for two consecutive seasons) (Yang, Still and Ge 2015).The values of the mechanical properties of these materials are presented in Table 1. To simplify the analysis, all of the models developed for ANSYS simulation were carried out assuming that the mechanical properties of the five materials at hand are isotropic.

Table 1: Linear & Non-Linear mechanical properties

		Units	G40.21-44W	S355	Coastal Douglas-fir	Ice	Frozen Silt
	Linear Mechanical Properties						
1.	Young's Modulus	MPa	200,000[a]	210,000[b]	13,400[c]	9.0[d]	10,000[e, h]
2.	Poisson's Ratio		0.3[a]	0.3[b]	0.449[f]	0.33[d]	0.3[k]
3.	Tensile Yield Strength	MPa	350[a]	355[b]	2.3[c]	3.1[g]	5.1[h]
4.	Compressive Yield Strength	MPa	152[i]	546[j]	5.0[c]	25[d]	5.0[h]
5.	Tensile Ultimate Strength	MPa	450[a]	460[b]	5.0[c]	3.1[d]	5.1[h]
	Non-Linear Mechanical Properties						
1.	Tangent Modulus	MPa	504[a]	504[a]	110[f]	0[l]	0[l]

Sources: Data adapted from
a. CISC. 2017. Handbook of Steel Construction. Canadian Institute of Steel Construction, 11th edition. Accessed 03 16, 2018. http://www.webcivil.com/frmsteelproperty.aspx.
b. MEADinfo. 2015. Material Properties of S355 Steel - An Overview. 08 23. Accessed 03 16, 2018. http://www.meadinfo.org/2015/08/s355-steel-properties.html.
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f. 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.
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k. Andersland, Orlando B., and Branko Ladanyi. 2004. Frozen Ground Engineering. New Jersey: Wiley
l. Assumed brittle in nature

2.3 Mat Sizes

For steel mats (G40.21 44W, S355), the design mat illustrated in Figure 2 is used, which is the most commonly used design by crane rental company NCSG in Alberta. For Coastal Douglas-fir, ice, and frozen silt mats, the conceptual test mat is depicted in Figure 2. For ANSYS analysis, the overall dimensions of these mats are assumed to be the same, except for the ice. The length and the size of the test mat are as below:

Length X Width   = 3.6449 m X 2.4384 m

Height (thickness): G40.21-44W, S355, Coastal Douglas-fir & Frozen Silt   = 0.2032 m

Ice   = 0.8 m

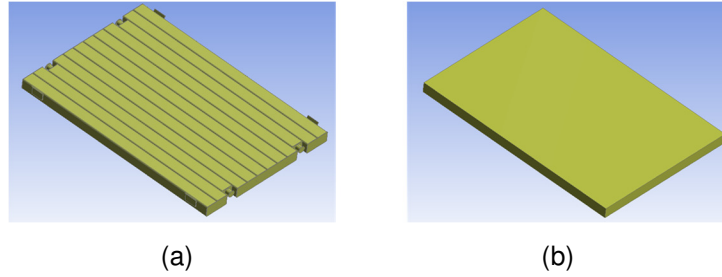<div align="center">(a)   (b)</div>

Figure 2: (a) Real Steel mat (S355 & G40.21-44W) (b) Conceptual Test mat (Coastal Douglas-fir, ice, & frozen silt)

2.4 Soil Properties

The target of this research is to find a better solution for crane matting. These mats are required in heavy industrial projects to provide stable ground support in situations where the soil bearing strength is insufficient. The soil parameters considered for this research are listed in Table 2 (Yang, et al. 2010). The soil under the mats is modelled as per Drucker-Prager theory (Badry and Satyam 2013). The model was first presented by D. C. Drucker in 1952 and is based on the elastic-plastic constitutive relationship. It is a pressure-dependent model to estimate the failure or permanent deformation under loading (Drucker and Prager 1952).

<div align="center">Table 2: Soil properties for mat investigation Source</div>

	Property	Value	Unit
1	Density	1900	Kg/m^3
	Isotropic Elasticity		
	Derive from	Young Modulus	
2	Young Modulus	4×10^7	Pa
3	Poisson's Ratio	0.3	
4	Bulk Modulus	3.33×10^7	Pa
5	Shear Modulus	1.538×10^7	Pa
	Drucker-Prager		
	Drucker-Prager Base		
6	Uniaxial Compressive Strength	1×10^5	Pa
7	Uniaxial Tensile Strength	1×10^{-19}	Pa
8	Biaxial Compressive Strength	1.1×10^5	Pa
	Failure Plane Data Set-1		
9	Inner Friction Angle	0.010656	radian
10	Initial Cohesion	10,000	Pa
11	Dilatancy Angle	0.0015231	radian
12	Residual inner Friction Angle	0.0097478	radian
13	Residual Cohesion	10,000	Pa

Sources: Data adapted from Yang, Xiujuan, Zongxiang Xiu, Lisong Zhang, and Xiangzhen Yan. 2010. "3D simulation of weak foundation for good-sized oil storage tank." Wuhan. 1345-1348. doi:10.1109/MACE.2010.5536276.

2.5 Mat Strength Analysis Methodology

The mat model is placed under the crane. The material properties of the mat material are uploaded to ANSYS mechanical workbench. For the mat material strength simulation, both the linear and non-linear material properties are considered. As for post-simulation analysis, only the normal stresses under the mat are examined. Usually, the normal stresses are similar to minimum principal stresses. The purpose of the analysis is to determine the relationship between different mat materials under similar circumstances. The main normal stress values are not compared with manual calculations, rather, they are compared with each

other to define whether ice or frozen silt mats can replace or perform equally well as traditional materials. Therefore, all 5 materials are tested under similar conditions. Along with normal stresses, the ground deflection is also considered for the comparative analysis. The deflection is low for steel as compared to timber mats and ice/frozen silt mats. For the analysis, only one crane configuration was selected for the crawler crane. The data flowchart for the crane mat strength analysis is presented in Figure 3. The values of normal stresses under the crane mat and the ground deflection for each mat material are obtained for analysis and comparison purposes. The data obtained from this exercise is used to obtain the strength of ice and frozen silt under loading, observing similar circumstances used for timber mats and steel mats.
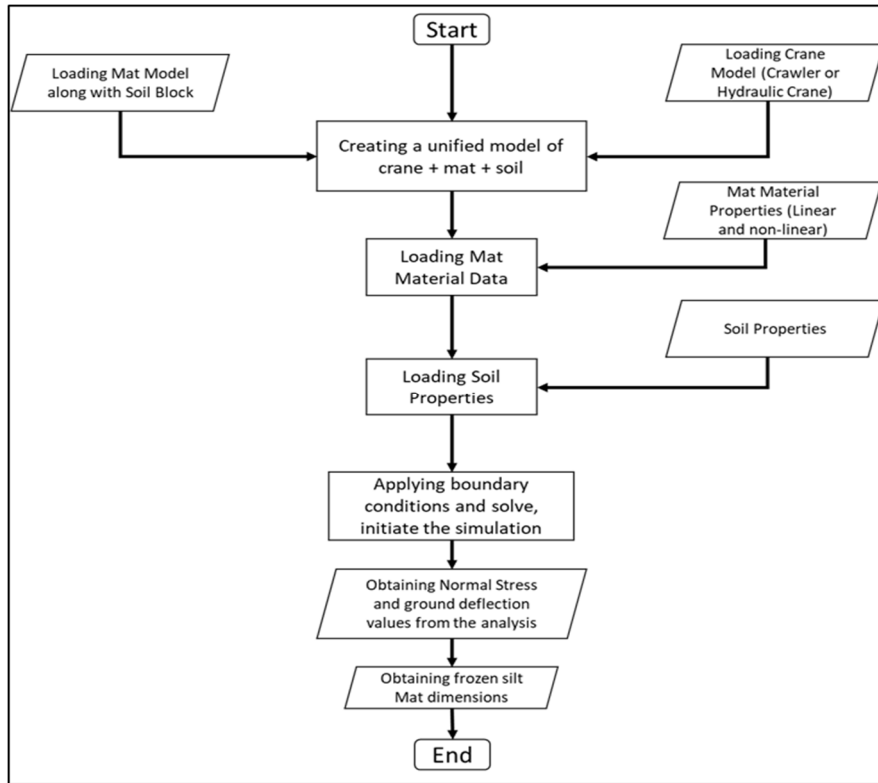

Figure 3: Flowchart for Crane Mat Strength Analysis

3   LINEAR AND NON-LINEAR STRESS ANALYSIS (ANSYS)

For ANSYS, a case example of a Manitowoc 18000 crawler crane with boom slew angles ranging from 0° to 90° from the front to the left side and with a load of 50,000 kg (110,231.13 lbs) at a lifting radius of 25.917 m (85 ft) is considered. The crane configuration is shown in Table 3. Crane steel mats and test mats are placed under the crawler tracks. Figure 4 shows the geometry (crane, load, mat, and soil). A block of soil is placed under the mats as ground support. The properties of soil are incorporated in ANSYS and assigned to this soil block. After loading the geometry with the material properties for mat and soil, the crane superstructure rotation is simulated using Mechanical solver in ANSYS Workbench. During the rotation of the superstructure, the ground bearing pressure under the crawler track varies with the change in boom/superstructure slew angle. Figure 5 shows the minimum normal stress under the left front mat along superstructure slew angle.

Table 3: Crane Configuration for Manitowoc 18000 (Crawler Crane)

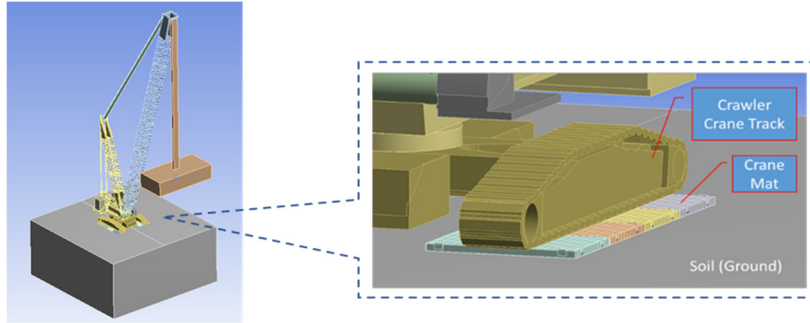|	Description	Configuration
1.	Boom	85.344 m (280 ft) #55 OR #55A
2.	Carboy Counterweight	145,150 kg (320,000 lbs)
3.	Superstructure Counterweight	239,500 kg (528,000 lbs)

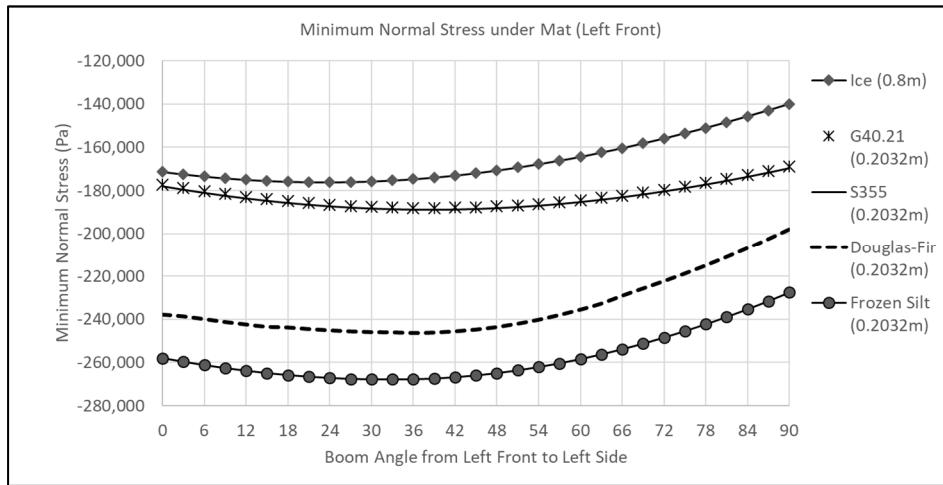Figure 4: Geometry (crane, load, mat and soil) for analysis.

Figure 5: Normal Minimum Stress under Left Front Mat along with boom slew angle of 0° to 90° from left front to left side (Manitowoc 18000)
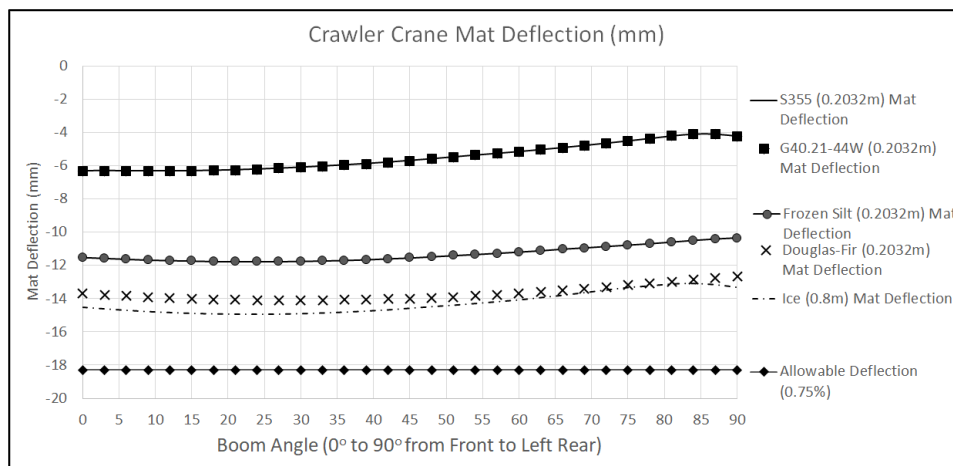

Figure 6: Left-Front Mat deformation under loading, along boom slew angle of 0° to 90° from left front to left side (Manitowoc 18000)

According to Figure 6, under loading condition, the maximum deflection occurs with the ice mat. As expected, the best performers are found to be S355 and G40.21 steel. The allowable deflection is taken as 0.75% of the original length, less than the industry standard (1%) (ISO 1991). The analysis shows that all

the different material mats fall within an acceptable range according to industry standards. In this mat deflection analysis, the frozen silt (0.2032 m) and Coastal Douglas-fir (0.2032 m) are comparable to each other. Figure 7 shows the normal stress variation under the mat of interest on the left front. For steel (S355 & G40.21), the variation is less as compared to other materials, and the stress is uniform throughout the length of the steel mat under crawler track pressure. The compressive strength and the value of the Young's modulus of steel is higher as compared to those of Coastal Douglas-fir, ice, and frozen silt.
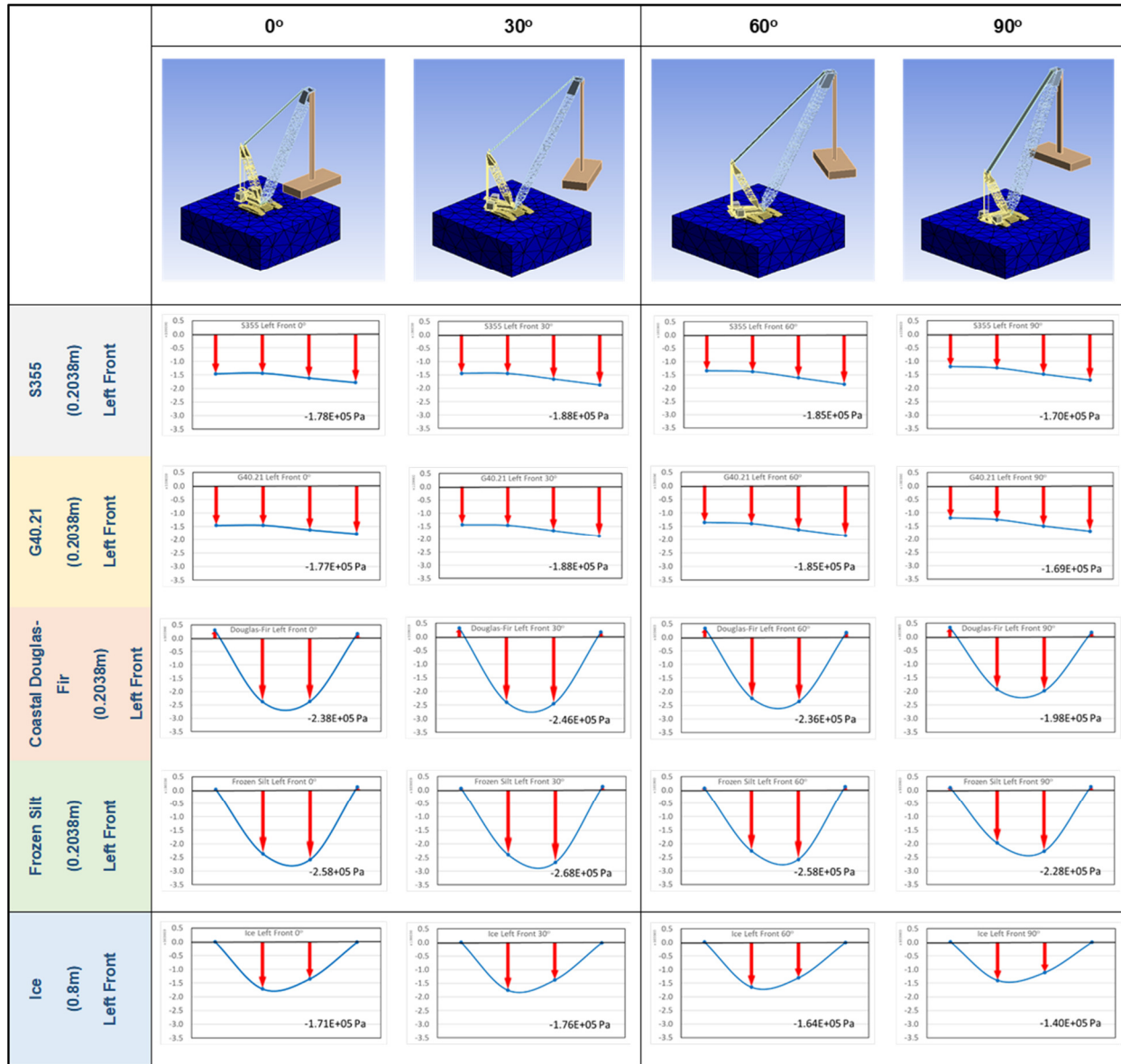

Figure 7: Minimum Normal Stresses under left front crane mat along superstructure rotation (0° to 90° from Left Front to Left Side)

The figures/statistics in Figure 7 show that the strength of ice is greater when compared to S355 or G40.21. The main reason for this is the mat thickness. For all other specimens, the mat thickness is 0.2032 m, but to make ice compatible, the ice mat thickness is taken as 0.8 m (see Section 2.3). If the thickness of ice were 0.2032 m, the normal stress would be higher (towards negative) than that of frozen silt mat (0.2032 m). It is also observed that the stresses at the edge of the Coastal Douglas-fir, frozen silt, and ice

mats (lengthwise) are positive, showing that the stress is not fully distributed over the length of the mat. The area bearing the pressure is less than the surface area of the mat. The edges of the mat leave the ground and show as positive instead of negative, indicating that the edges are not under compression and are not bearing the crane load.

4   CONCLUSION

- From the mechanical property analysis, it is inferred that frozen silt mat can be used as an alternative to the timber mat for crane support provided that the load is fully distributed (see Figure 5, Figure 6 & Figure 7).

- Ice can also be used as an alternative to timber mat, but, due to low Young's Modulus, it requires more thickness to compete with Coastal Douglas-fir or frozen silt (see Figure 5, Figure 6 & Figure 7).

- Mats made of frozen silt can sustain the Ground Bearing Pressure (GBP) if the mat temperature is below –10°C. The mechanical properties of the frozen silt mat under investigation, are taken from the research done by Yang, Still, and Ge (2015), and by Wilson (1982).

- From the analysis, the load distribution under the matting is not uniform; in fact, the load distribution is non-uniform in nature. The maximum load is right under the crawler and it decreases to the minimum value moving away from the crawler edge (see Figure 7).

- If the mat is not thick enough, the GBP values (negative due to compression) on the edge of the mats could be zero or more than zero (positive) due to bending, meaning that the edges of the mat are not taking any load (see Figure 7).

5   RECOMMENDATIONS AND FUTURE ASPECTS OF THE RESEARCH

- This research contribution can provide a starting point for the estimation of practical usage of frozen silt mat for crane support. For practical usage, the freezing process needs to be investigated with actual industrial numbers and procedures.

- This research is done considering –10°C as the mat surface temperature, taking frozen silt mat properties closer to Coastal Douglas-fir. But in actuality, the properties change with fluctuations in mat surface temperature. Research is required to define the changes in mat properties with respect to mat surface temperature.

- The load distribution under the mat is non-uniform in nature. This phenomenon warrants further study to estimate the bending and stability of crane mats made of frozen silt.

- Only a few physical properties are compared. Future research can incorporate additional physical properties. In the case of frozen silt, cracking and fracking must be investigated with actual lab tests to get the real and complete picture before 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 strength, soil composition, water content, and mat temperature. These projected number further need to be verified by lab and site testing.

- The variation of Young's modulus on the strength of frozen silt mat warrants a detailed investigation. The dry density of frozen silt varies from 320 kg/m3 to 940 kg/m3 (Yang, Still and Ge 2015). The impact of density on the strength of mat needs to be investigated. The water content varies from 62% to 225% (Yang, Still and Ge 2015). The impact of density change on frozen silt mat strength needs to be investigated.

- Density anomalies of water with respect to ambient temperature are not incorporated in this research. These anomalies and their impact on the strength of an ice/frozen silt mat can be investigated in future research.

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