Probabilistic Estimation of Uplift Resistance for Chilled Gas Pipelines

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ABSTRACT
Pipe-soil interaction in northern climates will have to account for the behaviour of frozen and unfrozen soils, and the transitions between the two as a pipeline traverses discontinuous permafrost regions. Given uncertainties associated with frozen soil properties and the changes in behaviour with time and location, a large variation in pipe uplift resistance is expected. The uplift resistance of a frozen soil is dependent on such properties as tensile strength, creep and the modulus of deformation; it is also dependent on the magnitude and rate of the pipe displacement as well as the pipe dimensions. A series of modeling simulations using Fast Lagrangian Analysis of Continua (FLAC) were completed varying one parameter of the frozen soil with each run to develop a library of peak uplift resistances at different temperatures, soil properties and pipe parameters. A probabilistic analysis of peak uplift resistance of a hypothetical pipe that incorporates a pre-defined distribution of pipe displacement, temperature, and soil properties and allows these to vary with time was completed. The results suggest that the first three months produced the greatest peak pipe uplift resistance because of the completely frozen cover depth, cold temperatures, and highest heave rate of the pipe. By the first summer the resistance was significantly reduced because of the reduced frozen cover depth, lower soil temperatures, and reduced heave rates.

RÉSUMÉ
Les interactions entre le sol et les pipelines dans les climats nordiques doivent tenir compte du comportement des sols gelés et dégelés ainsi que de la zone de transition entre ces deux types de sols quand un pipeline traverse du pergélisol discontinue. Considérant les incertitudes sur les propriétés mécaniques des sols gelés et des changements de comportement dû au temps et aux caractéristiques du site, une grande variation dans la résistance au mouvement du pipeline est anticipée. La résistance d'un sol gelé contre le mouvement vertical d'un pipeline dépend des paramètres tels que la force en tension du sol et du module de déformation; il est aussi dépendant de l'amplitude et du taux de déplacement du pipeline. Des simulations numériques utilisant le 'Fast Lagrangian Analysis of Continua (FLAC)' on été complétés en variant certain paramètres pour calculer les valeurs maximales de résistance au mouvement vertical. Ces valeurs ont ensuite été utilisées dans des analyses probabilistiques. Les résultats des simulations numériques indiquent que la plus grande résistance au mouvement vertical du pipeline arrive pendant les trois premier mois quand le sol est complètement gelé et le taux du mouvement est maximal. Lorsque le dégel avance a l'été suivant, la résistance des sols est considérablement réduite. L'exemple illustré dans cet article montre que les méthodes probabilités présentées sont faisables.

1 INTRODUCTION

A buried pipeline is subject to a variety of forces, both internal and external, including the interaction of the pipe with the surrounding soil. Soil-pipe interaction in permafrost regions has to account for the behaviour of the frozen and unfrozen soils, and the transition between the two as the pipeline traverses in a discontinuous permafrost zone.

The variations in the properties and behaviour of frozen soils are expected to be substantial in three dimensions and with time (seasonal fluctuations and changes with the history of pipeline operation). Given the uncertainties with frozen soil properties and the changes in behaviour with time and location, a large variation in soil-pipe interaction characteristics can exist. The uplift resistance of a pipeline is one of these soil-pipe interactions that can be impacted by the variations in soil condition and state.

The purpose of this paper is to outline the use of a probabilistic analysis of pipe uplift resistance in an attempt to capture the magnitude of these variations and uncertainties of the frozen soils and the impact on the soil-pipe interaction. The probabilistic analysis will allow the designer of a pipeline to consider a range of uplift resistance to a certain confidence level that would represent the likely values that a pipe may be subjected to.

2 UPLIFT RESISTANCE IN FROZEN GROUND

Pipeline uplift occurs when a transition in soil type or behaviour causes differential movement of a pipeline, where one side of the transition attempts to push the pipe upward through the soil cover, while the other side of the transition is resisting the upward pipe movement. The idealized situation for an arctic pipeline is when a cold pipe traverses through a frozen-unfrozen interface in a discontinuous permafrost zone of frost susceptible soil. The cold pipe, in conjunction with the alteration of the pipeline Right of Way (ROW) due to construction, begins to freeze the unfrozen section beneath the pipe causing heave of the frost susceptible soil, forcing the pipe upwards. The frozen section of the ROW does not undergo the same movement and resists the upward movement of the pipe. In a different scenario, forces are exerted on the pipe during thaw settlement due to the separation of the underlying soil from the pipe and the weight of overburden above the pipeline, as shown in Figure 1. In this case, since the surrounding soil is unfrozen, there is less restraint to pipeline movement and the pipe is more likely to achieve its optimum deformed configuration.

The uplift resistance is dependent of the soil properties and the magnitude and rate of the pipe displacement, as well as the pipe dimensions and depth of cover. The soil properties that are important to the magnitude of the uplift resistance are:

- soil type;
- grain size distribution;
- thermal state;
- tensile properties;
- creep properties; and
- modulus of deformation.

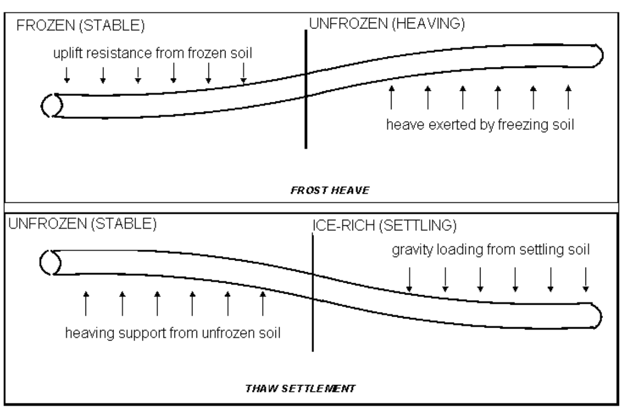

Figure 1. Conceptual Illustration of Freezing Thawing Effects on Pipelines in Discontinuous Permafrost (Nixon, 1994)

The response of the soil resisting the uplift of a pipe depends also upon the magnitude and rate of the loading. Strength and deformation of frozen soils are known to vary substantially depending upon whether the loading rate is high or low. The temperature of the frozen soil also has an important effect on the behavior. The properties of frozen soils are functions of density and ice/water content, which for this analysis are assumed to be constant.

3 OVERVIEW OF PROBABILISTIC MODEL

The primary objective of the pipe-soil interaction analysis is to provide an estimate of the maximum uplift force incurred when a pipe is forced upward through frozen soil. There are uncertainties, however, associated with the proper definition of parameters in the model. The ground temperature, pipe displacement rate, and frozen cover depth for instance may all vary significantly along the pipe due to temperature fluctuations and soil heterogeneity. As a result, it is difficult to define a single value that accurately models soil conditions and displacement state of the pipe at any given location at a specific time.

To overcome these limitations, a probabilistic approach is utilized in which the ground temperature, displacement rate, and effective frozen cover depth are defined in terms of probability distributions that vary seasonally throughout the year. A geothermal analysis conducted by Nixon Geotech Ltd provides the basis for definition of the probability distributions. These parameters are then used together with empirical relationships from the literature and lab test data to define the required soil properties for the probabilistic model. The tensile strain limit, modulus of deformation, and secondary creep parameters are considered key parameters.

A series of 84 numerical simulations are conducted using FLAC to define a function that predicts the peak uplift resistance over the range of potential soil/pipe input parameters. This correlation function is then used to provide a link in the probabilistic model between the stochastic model parameters and the estimated peak uplift resistance.

In summary, the key components of the probabilistic approach are:

i. definition of the ground temperature, displacement rate, and effective frozen cover depth as a distribution of values (from a geothermal analysis);
ii. relating the soil parameters to the input parameters from (i) using empirical relationships and lab fitted curves; and
iii. estimating the peak uplift resistance for a model with parameters defined by (ii) using a correlation function constructed via regression on the results of a series of numerical simulations.

Section 4 discusses the geothermal analysis and implementation of (i) and Section 5 describes the subsequent relation to soil parameters according to (ii). A discussion of the FLAC model and subsequent correlation to peak uplift resistance is then presented in Section 6. The implementation and results of the probabilistic model are then detailed in Section 7.

4 INPUT PARAMETERS

Three input parameters representing the ground and operating conditions of the pipe were used in the probabilistic model to estimate peak uplift resistance: ground temperature, frozen cover depth and displacement rate.

4.1 Seasonal Ground Temperature of the Soil

The seasonal ground temperatures were provided by Nixon Geotech Ltd., who completed a geothermal analysis of the hypothetical 915 mm gas pipeline using their proprietary software GASSIM and THERM2 (Nixon, 1983). The following assumptions were necessary to define a scope for the analysis:

- a 915 mm pipe running south from Norman Wells for a distance of 450 km;
- a gas flow rate of 1.31 bcf and a seasonal flow rate variation of +/- 5.5 % were assumed, with a discharge temperature of -1 ºC.

The monthly pipe temperatures were calculated using GASSIM, which was then used to estimate the average backfill temperature of the soil above the pipe (in the frozen interval only using THERM2), as illustrated in Figure 2.

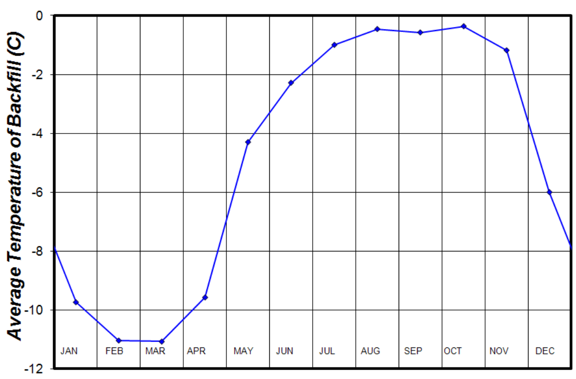

Figure 2. Average Temperature of the Soil Above the Pipe

The normal distribution of soil temperature used in the probabilistic analysis has a mean value which varies in time according to the curve in Figure 2.

4.2 Displacement Rate

The displacement rate of the pipe is an important input parameter affecting the behaviour of frozen soil and the response to loading. It is known from laboratory testing that the strength, both in tension and compression, and creep properties of frozen soil are highly dependent of the rate of the loading (Zhu and Carbee 1987a and b). In the case of pipe uplift resistance model, the displacement rate of the pipe was approximated as one-half of the frost heave as estimated from the geothermal analysis. The estimated frost heave for the 915 mm diameter pipe is illustrated in Figure 3.

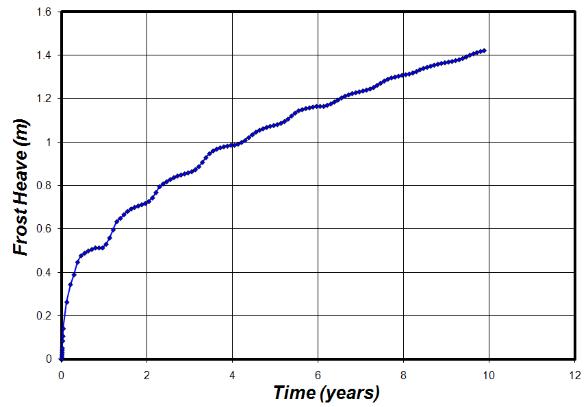

Figure 3. Frost Heave of Hypothetical Pipe with Time

The frost heave curve from the geothermal analysis estimates that there is about 0.5 m of heave in year one. This would be the greatest heave rate experienced in the life of the pipeline since the rate of increase of the curve slows in subsequent years. Therefore, the variation of heave over the first year is converted into a daily displacement rate that can be applied to the pipe as it changes throughout the year.

4.3 Effective Frozen Cover Depth

The THERM2 program was also used to estimate the effective frozen cover depth of the pipe. The frozen cover depth with time is shown in Figure 4.

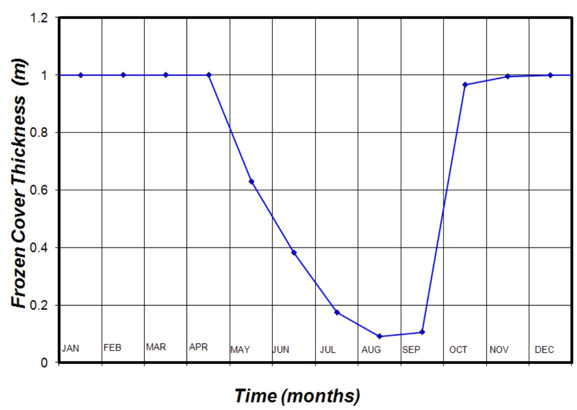

Figure 4. Frozen Cover Depth

5 FROZEN SOIL PARAMETERS

The following sections detail the sources and equations used to estimate the frozen soil parameters from the input parameters outline in Section 4.

5.1 Modulus of Deformation

An equation for the dependence of the modulus of deformation, E, on displacement rate and temperature was developed using laboratory testing data found in the literature. Zhu and Carbee (1987a) completed a suite of laboratory tests on frozen Fairbanks silt where they undertook compressive strength testing at various temperatures, loading rates and densities. Zhu and Carbee concluded that the modulus of deformation can be approximated as:

$$E=a(\dot{\varepsilon}/\dot{\varepsilon}_1)^b(T/T_o)^n \quad (1)$$

where E is in MPa, a = 745 MPa for medium density Fairbanks silt, b = 0.122, n = 0.624, $\dot{\varepsilon}$ is the strain rate, T is the temperature in ºC, $\dot{\varepsilon}_1$ is a reference strain, and T_o is a reference temperature.

The reference strain rate is 1% per second and the reference temperature is -1°C. Therefore, the equation becomes:

$$E=745\left(\dot{\varepsilon}/(86400*365)\right)^{0.122}(-T)^{0.624} \quad (2)$$

5.2 Tensile Strain Limit (TSL)

In a separate study, Zhu and Carbee (1987b) completed tensile testing of frozen Fairbanks silt at various temperatures and strain rates to identify the effect on the failure strain in tension. A plot of this failure strain versus strain rate, at various temperatures, identified that the failure strain was not greatly dependant of the temperature of the test. Given this data set and the apparent small dependency of temperature, it was decided to estimate the tensile strain limit as a function of the strain rate only.

Figure 6 shows that there is an abrupt change in tensile failure strain at a strain rate of 10^{-3} %/second. The TSL is therefore approximated by the linear piecewise-continuous function:

$$For\ Strain\ Rate < 100\ \frac{\%}{day};\ TSL = 0.0088\dot{\varepsilon}^{\,0.1609} \quad (3)$$

$$For\ Strain\ Rate > 100\ \frac{\%}{day};\ \ TSL = 0.074\dot{\varepsilon}^{-0.346} \quad (4)$$

where TSL is the tensile strain limit and $\dot{\varepsilon}$ is the strain rate, in percent per day.

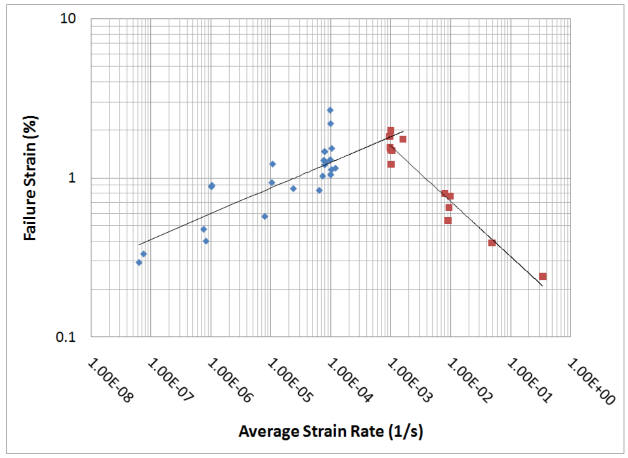

Figure 6. Variation of Failure Strain with Strain Rate in Tension for Fairbanks Silt

5.3 Secondary Creep

Secondary creep of frozen soils can be approximated as:

$$\dot{\varepsilon}_c = B\sigma^n \quad (5)$$

where $\dot{\varepsilon}_c$ is the secondary creep rate, B is the temperature dependent creep coefficient (kPa^{-3} * $year^{-1}$), σ is the applied stress in kPa, and n is the slope of the strain rate versus stress on a log-log plot. The slope is approximately n = 3 for ice rich soils (McRoberts et al. 1978, Morgenstern et al. 1980). The empirical formula developed by Morgenstern et al., (1980) for fresh water ice and icy soils was used to estimate the secondary creep parameter B. The equation for B in terms of temperature, T in ºC, is:

$$B = \frac{6.1X10^{-8}}{(1-T)} \quad (6)$$

6 FLAC SIMULATIONS

The work discussed in this section draws upon work completed by Liu et al. (2004). A FLAC model was developed to analyze the effects of varying tensile strain limit, modulus of deformation, and creep on peak uplift resistance. Key features of the model are:

- the geometry incorporated in the model corresponds to a two dimensional plane strain section taken perpendicular to the pipeline axis;
- the pipeline is represented as a series of steel beams comprising a continuous rigid cylindrical opening attached to the surrounding soil continuum by means of interface elements; and parameters describing the constitutive creep relationship and failure criteria are derived from the laboratory geo-mechanical tests and appropriate values from the technical literature (Liu et al., 2004).

Figure 7 illustrates an example of the FLAC uplift model mesh.

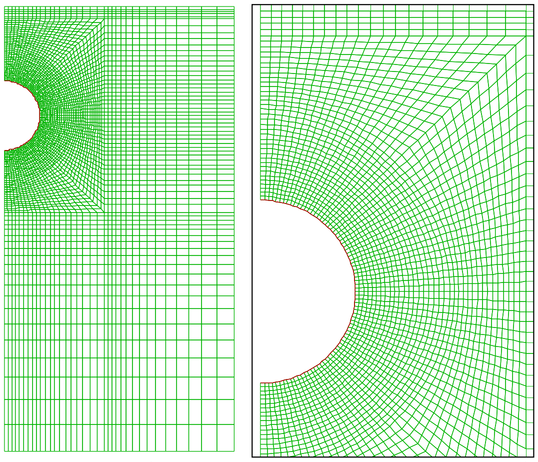

Figure 7. FLAC Model Mesh, Full View (left) and Close Up (right) (Liu et. al 2004)

6.1 Correlation of Peak Uplift Resistance

This FLAC model was used to conduct a series of 84 simulations that varied the following parameters:

- displacement rate, $\dot{d}$ = 0.1, 0.5, 1 mm/day;
- modulus of deformation, E = 100, 200, 300 MPa;
- tensile strain limit, TSL = 0.5, 1.0, 1.5%; and
- secondary creep parameter, B = 10^{-5}, 10^{-7}, 10^{-9} kPa ^{3}yr $^{-1}$

Several functional forms were tested to find a regression equation that adhered to the data. It was identified that secondary creep was a non-linear variable and each attempt to generate a global fit correlation with B produced significant variability. At each value of B, however, the multi-linear regression correlation

$$f(\mathrm{E}, \dot{d}, \mathrm{TSL}, \ln \mathrm{B}) = a\,\mathrm{E} + b\,\dot{d} + c\,\mathrm{TSL} \quad (7)$$

gave an excellent fit. The uplift resistance results were therefore grouped into three data sets, which permitted correlation of the unknown coefficients to B as:

$$a(B) = 0.0091\,\mathrm{B}^{-0.268} \quad (8)$$

$$b(B) = -5.855 \ln(B) + 9.34 \quad (9)$$

$$c(B) = 2.15\,\mathrm{B}^{-0.253} \quad (10)$$

The peak uplift resistance predicted by the correlation function is plotted against the peak uplift data values predicted by FLAC in Figure 8. The match is better at lower values of the peak uplift resistance and deviates for larger values. However, since the predicted values are smaller towards the upper end, utilizing this correlation function will result in a more conservative approximation of the peak uplift resistance and was therefore accepted as reasonable for the purpose of the current analysis.

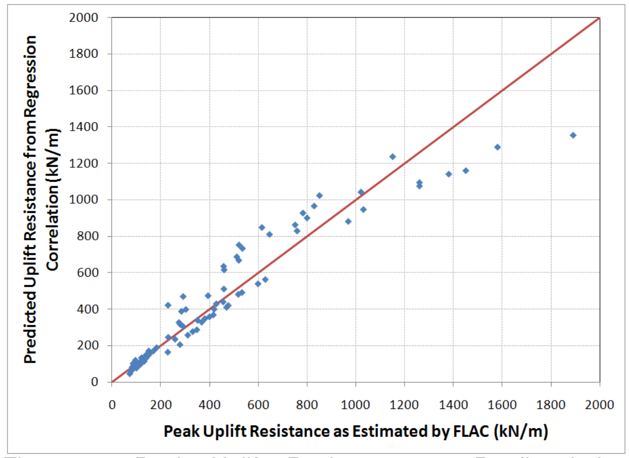

Figure 8. Peak Uplift Resistance as Predicted by Regression Correlation versus Peak Uplift Resistance as Estimated from FLAC modelling.

6.2 Cover Depth Intensity Factor

The variation of cover depth above a pipeline was accounted for by using an intensity factor that is applied to the predicted peak uplift resistance correlation. The intensity factor was used to simplify the correlation regression. Four FLAC simulations were completed using four different cover depths utilizing constant soil parameters of 1 mm/day displacement rate, 200 MPa modulus of deformation, 1% tensile strain limit, and a creep parameter B = 10^{-7} kPa^{3} yr^{-1}. The variation of peak uplift resistance as predicted by FLAC with different cover depths is shown in Table 1.

Table 1. Variation of Peak Uplift Resistance with Cover Depth

Cover Depth (mm)	Peak Uplift (kN/m)
228.75	200
457.5	315
915	469
1830	681

The intensity factor was derived by plotting the normalized peak uplift resistance for the cases in Table 1, versus the normalized cover depth. Each case is normalized to a cover depth of 915 mm and a peak uplift resistance of 469 kN/m, and the resulting curve is plotted on Figure 9.

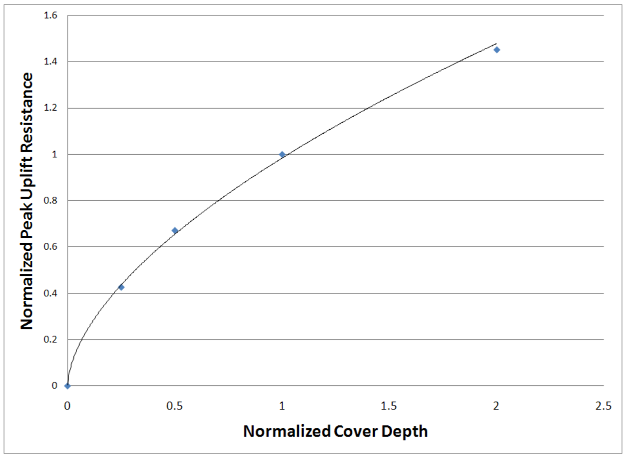

Figure 9. Normalized Peak Uplift Resistance Versus Normalized Cover Depth

The cover depth intensity factor that is applied to the peak uplift resistance is therefore given by:

$$I_f = 0.9878(H/915)^{0.587} \quad (11)$$

where H is cover depth in millimetres. It should be noted that the intensity factor provided here may not be suitable for pipelines of diameters different than 915 mm. A sensitivity analysis to determine how the cover depth intensity factor depends on the soil parameters was not conducted.

7 PROBABILISTIC MODEL

The probabilistic model was constructed using a commercially available software package GoldSim, produced by the GoldSim Technology Group LLC. GoldSim is a visual, object oriented software application for carrying out dynamic, probabilistic simulations (GoldSim, 2009). GoldSim simulates a system by creating a model quantitatively described using equations or rules as supplied by the user. It allows for the definition of input parameters (ground temperature, displacement rate, cover depth) using a distribution of probable values. The resultant variation of soil and pipe parameters is then coupled with the correlation functions, as discussed in Section 6, to perform a probabilistic analysis of peak uplift resistance over the period of one year. The end result is a distribution of uplift resistances over time that allows the user to identify most probable values at given levels of confidence. The analysis generates 100 instances of the input parameters for each day of the year. The 100 instances for the soil temperature, displacement rate, and frozen cover depth, each follow the normal distribution as estimated from the geothermal analysis. The variations of the soil temperature and displacement rate with time are illustrated in Figures 10 and 11. The frozen cover depth is calculated from the curve in Figure 4.

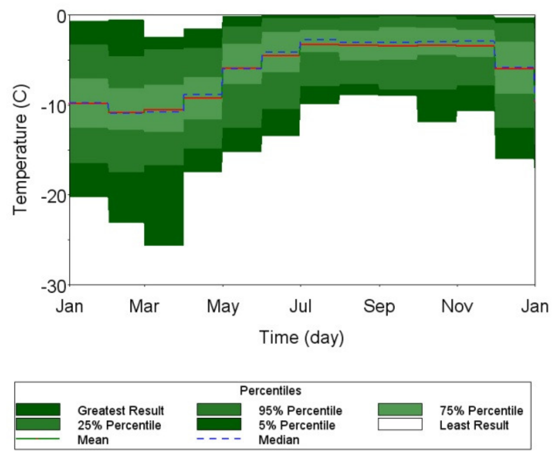

Figure 10. Variation of Soil Temperature with Time

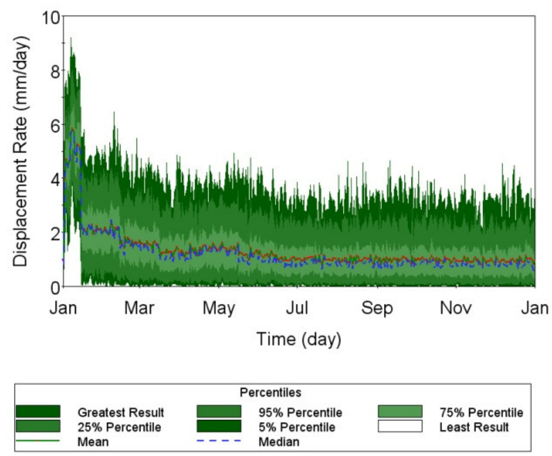

Figure 11. Variation of Displacement Rate with Time

The displacement rate is converted into a strain rate that is applied to the frozen soil above the pipe by dividing the displacement rate by the cover depth. The frozen soil parameters are then estimated by using the equations presented in Section 6. The variation of the frozen soil parameters, namely modulus of deformation, TSL, and creep parameter B, for the first year of the pipeline life are illustrated in Figures 12 to 14, respectively.

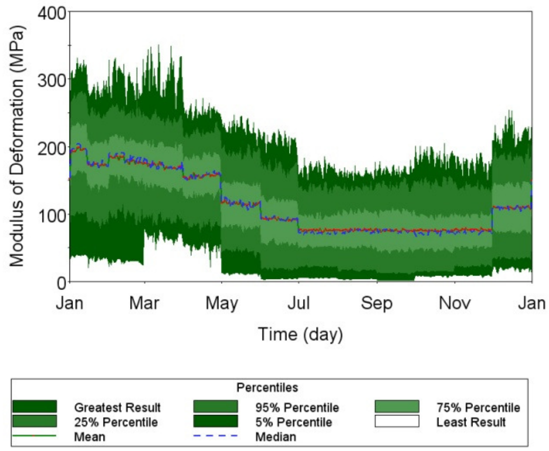

Figure 12. Variation of the Modulus of Deformation with Time

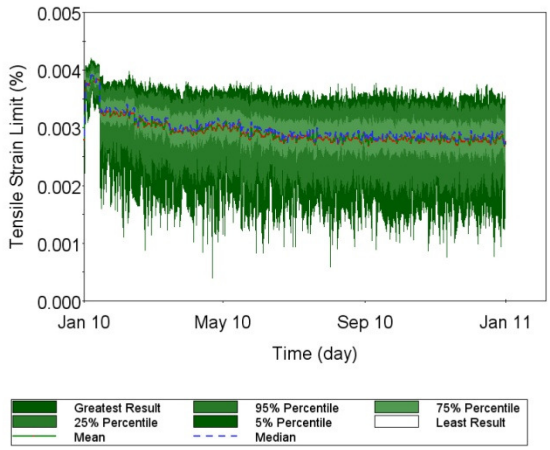

Figure 13. Variation of Tensile Strain Limit with Time

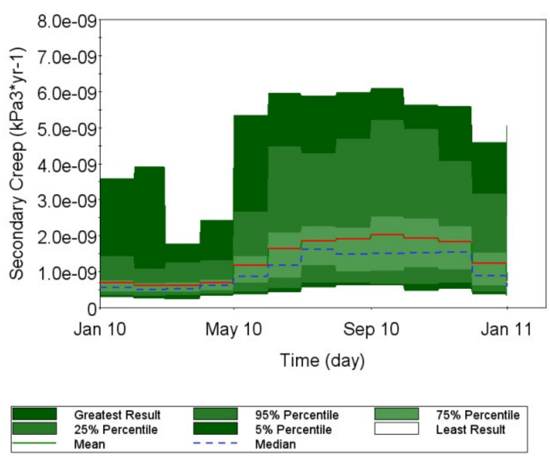

Figure 14. Variation of Creep Parameter B with Time.

The correlation of peak uplift resistance developed from the FLAC simulations in Section 7 was then used to estimate the peak uplift resistance. The cover depth intensity factors were applied based on the frozen cover depth. The result is a probability of occurrence of peak uplift resistance that varies with time, temperature, displacement rate, and cover depth. Figure 15 illustrates the variation of peak uplift resistance as estimated from the probabilistic model over the first year of the pipeline life.

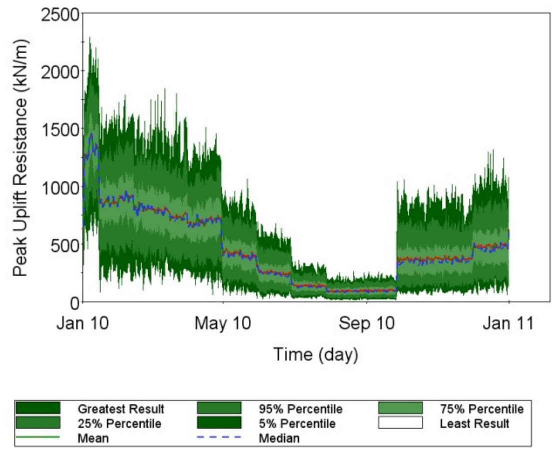

Figure 15. Variation of Peak Uplift Resistance with Time

The result suggests the following:

- the peak uplift resistance can vary from 200 kN/m to 2,200 kN/m in winter months with a mean of 1200 kN/m to 1400 kN/m. In summer, it may range from 50 kN/m to 800 kN/m with a mean of 100 kN/m to 400 kN/m;
- cold temperatures and large displacement in the first three months of the life of the pipeline will produce the highest magnitude, and largest range, of uplift resistance;
- the first month of the life of the pipeline causes the greatest upward displacement due to largest heave. Once the soil becomes frozen the heave and resulting displacement is reduced as is the uplift resistance;
- the reduction in the uplift resistance in the summer months is a result of the reduced effective cover depth and reduced displacement rate; and
- there is a difference between the heave at the end of the first year of the pipelines life and the beginning of the second due to the decrease in the displacement rate of the pipeline that is directly related to the reduced heave rate at the end of the first year.

Assumptions and/or limitations of the model that could be improved upon in future work are discussed below. It was identified that the model shown here is highly dependent of the temperature of the soil above the pipe as the correlation of peak uplift resistance was developed to accommodate the non-linear behaviour of creep. The equation to estimate the creep parameter that is input into the correlation is a conservative value, which is solely a function of the soil temperature.

The model does not attempt to approximate any relaxation of the pipe that may occur during the summer months. Currently the model assumes an upwards movement of the pipe throughout the entire year. This may not be the actual case since downward, or no, movement of the pipe may exist during this period.

The model assumes that the displacement rate of the pipe is approximately equal to half of the heave rate of the soil below the pipe as estimated from the geothermal analysis. This value could be refined based on a specific soil type and frost heave test and analysis.

There is currently no complete set of lab data to quantify the variations of the peak uplift resistance of a single soil type. The FLAC model used parameters based on the behaviour of Calgary Silt and two of the three soil parameter in the equations, the modulus of deformation and tensile strain limit, are based on laboratory results on Fairbanks silt. The creep soil parameter equation is based on ice rich soil and pure ice.

8 SUMMARY

A probabilistic analysis of pipeline uplift resistance was completed using GoldSim and input variables from laboratory testing and the literature review. The example illustrated in this paper demonstrates that the methodology for a probabilistic analysis of pipeline uplift resistance is feasible. The elements associated with the probabilistic analysis are summarised as follows:

- The model draws on the currently available knowledge and understanding of frozen soil behaviour under the loading scenario of pipe uplift. The probabilistic model requires a geothermal analysis of a proposed pipeline to establish the likely range of soil temperatures and frozen cover depth, which can be completed knowing the pipeline operating parameters.
- The model requires that the frozen soil properties be correlated to the operating conditions of the pipeline, which can be established using geo-mechanical testing completed in a geotechnical laboratory. The distribution of each soil parameter was approximated in the example using existing correlations, dependent of the ground and operating conditions of the pipeline, including heaving rate and soil temperature. The ground and operating conditions were varied based on a normal distribution and standard deviation from the geothermal analysis. For an actual design case, typical soils along a pipeline ROW could be tested in the laboratory to generate project specific soil correlations. Also, it should be mentioned that if sufficient data is provided for multiple soils the model could be developed to incorporate soil types that change along the pipeline ROW.
- The correlation between peak uplift resistance and frozen soil parameters can be generated for any soil type using FLAC simulations of pipe uplift. The information required to complete the correlation is the geometry of the proposed pipeline design, and a range of reasonable soil parameters that are established from the geo-mechanical testing.
- The output from the probabilistic model is a distribution of peak uplift parameters that vary with time, pipeline operating parameters, and seasonal variations. The distribution of peak uplift can be used in a reliability based design to bound the stresses that a pipeline may be subjected given uncertainties in pipeline operating parameters, geometry and frozen soil behaviour.

9 ACKNOWLEDGEMENT

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