The dependence of strength and modulus of frozen saline sand on temperature, strain rate and salinity

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ABSTRACT
A large scale artificial radially freezing experiment was carried out using saturated saline sand. Once frozen, core samples were taken and tested for strength and salinity to study the dependence of uniaxial unconfined compressive (UC) strength and deformation modulus of frozen saline sand (FSS) on strain rate, temperature and salinity. Results showed power-law relationships between UC strength and strain rate, temperature and salinity. These relationships presented in this paper can be used to guide future frozen wall design. This paper will also present how salinity varies in the sand during freezing. The experiment's preparation, setup and procedure will also be presented in this paper.

RÉSUMÉ
Un artificielle à grande échelle l'expérience de congélation radialement a été réalisée en utilisant du sable salines saturées. Une fois congelés, des échantillons de carottes ont été prélevés et testés pour la résistance et de la salinité pour étudier la dépendance de la compression simple uniaxiale (UC) résistance et le module de déformation du sable sale congelés (FSS) sur la vitesse de déformation, la température et la salinité. Les résultats ont montré des relations de pouvoir entre la force de droit UC et la vitesse de déformation, la température et la salinité. Ces relations présentées dans ce document peuvent être utilisés pour guider la future conception du mur gelé. Ce document sera également présent sur la façon dont la salinité varie dans le sable pendant la congélation. Expérience de préparation, l'installation, la procédure sera également présentée dans le présent document.

1 INTRODUCTION

Artificial ground freezing is a common technique used to improve the strength of soils and create a groundwater cut-off especially in sandy soil. A frozen soil mass or structure is usually created by freezing initiated by a single line or several lines of vertical freezing pipes embedded in the ground. This paper studies the dependence of strength of frozen sand on other dependent factors. This soil type is occasionally encountered in saline environment. In cold regions, artificial freezing for strength improvement and groundwater cut-off of this soil type is a very feasible and economic option. Differ from cohesive soils, freezing in sand causes much less soil disturbance due to its permeability. However, ground freezing in a saline environment is challenging in order to get good result. In this environment, the strength of frozen sand is significantly reduced comparing to non-saline because of the salt content. The strength of frozen sand also depends on other factors such as strain rate and temperature.

The dynamic of the freezing process in saline soil is very complex. Salinity depresses freezing. Therefore, the temperature, salinity and unfrozen water content vary greatly while the freezing process takes place. So does the strength of frozen soil. There has not been a study to investigate thoroughly the variation of the UC strength in a frozen sand column created around a freezing pipe. Consequently, a conservative UC strength has been chosen in design, which is estimated from mean values of salinity, temperature and strain rate.

Furthermore, because the simultaneous dependency of the strength of saline frozen sand on salinity (sodium chloride concentration), temperature and strain rate have not been studied thoroughly to date. This study therefore was planned and performed to get a better understanding of how the strength depends on these parameters and how to estimate it based on available parameters.

For these purposes, a radially artificial freezing experiment was carried out. A lab test program was performed where saturated sand was gradually frozen outward within 1.5m diameter and 1.0m high cylindrical tanks. Uniaxial unconfined compressive strengths of the frozen sand were taken for various strain rates, salt concentrations and temperatures.

The result of this test program will provide means for a better estimation of the UC strength used in a design.

In this test program, medium clean uniform sand was saturated with sodium chloride solution at three different concentrations within three cylindrical tanks. The sand was frozen radially from a vertical central freezing pipe. The experimental program also planned to investigate salt migration during the freezing. However, this portion of the result will be presented in another paper. During the freezing process, temperatures and salt concentrations varied within the soil mass. Temperatures, salinities and unfrozen water content within the tanks were measured at different radii and heights periodically as the mass of sand froze. After freezing was complete, core samples were obtained throughout the frozen sand tanks using a CRREL core barrel and unconfined compression strengths were tested on these samples. Uniaxial unconfined compressive strengths for 90 core samples were tested at three different strain rates, four different temperatures and various salinities of pore water. Salinities were determined from these samples after strength testing.

The strength result of previous studies was obtained with only two variable parameters whereas in this study, three parameters: salt concentration, temperature and strain rate were varied. The strength result obtained by Hivon and Sego (1995) were unconfined compressive strength tested under a constant strain rate (0.012 % per minute), varied temperatures (-5 to -12 ℃) and varied salt concentration of pore fluid (5 to 30 g/L). Sego et al. (1982) showed the uniaxial unconfined compressive strength result obtained under a constant temperature (-7℃), varied strain rates (0.005 to 0.4 % per min.) and varied salt concentrations of pore fluid (0 to 100 g/L). Stuckert and Mahar (1984) presented uniaxial unconfined compressive strength obtained under a constant strain rate (0.51 % per min.), varied temperatures (-3 to -12 ℃) and varied salt concentrations (6 to 38 g/L). The study by Sego and Cherenko (1984) showed uniaxial unconfined compressive strength result under constant temperature (-7℃) and strain rate (0.013 % per min.) with varied salt concentration (10 to 50 g/L).

This study attempts to provide more accurate strength estimation based on the three independent variables: temperature, salinity and strain rate.

2 TEST SETUP AND PROCEDURE

Freezing pipes were placed in the center of the cylindrical tanks (Figure 1), which sat in a temperature-controlled cold room.

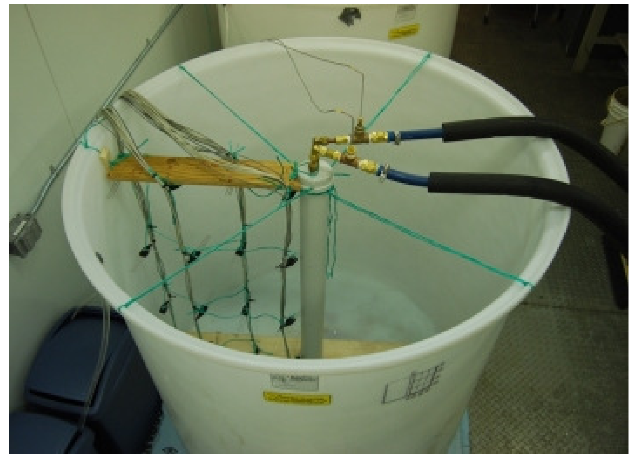

Figure 1. Instrumentation before sand filling

The vertical freeze pipes were connected with a chiller circulating chilling fluid (glycol). Medium clean uniform sand (Figure 2), graded SP in USCS, was saturated with 5, 13 and 20 g/L sodium chloride (NaCl) solutions in two cylindrical tanks having 2.0m diameter and 1.0m height. The sand has average void ratio of 0.587 and porosity of 0.37. Since this “play” sand is clean sand made mostly from quartz, Gs can be accurately estimated to be about 2.65. Volumetric water content in the sand was about 0.37. Sand was mixed with saline solution by cement mixer before being poured into the tanks. After tanks were fully filled, the tanks were kept for 24h before the freezing started. Since the freezing happened in the poorly graded sand, which had high permeability. There was no possibility of soil expansion and ice lenses formation. There was fluid expelled from the sand during freezing. It was collected into buckets for volume and salt mass balance calculation (Two blue buckets showed in lower left corner of Figure 1). The salt content collected was used to confirm the salt rejection. The unit weight of samples varied from 1.86 to 1.99 ton/m^3. Tanks were fully submerged and saturated.

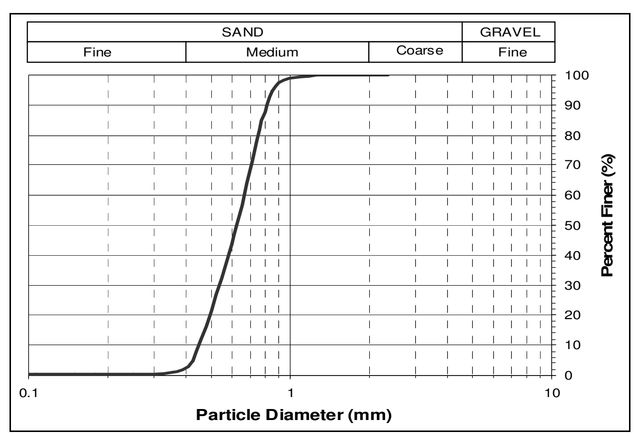

Figure 2. Gain size distribution of tested sand

Thermistors, time domain reflectometer (TDR) probes (Figure 3) were embedded in the sand mass to measure the temperature, salinity and unfrozen water content within the sand mass during the freezing. The sand was mixed with sodium chloride solutions of desired initial concentrations and placed into the tanks.

Figure 3. Thermistors and TDR probes in the tank

The test program was carried out in two stages. In the early stage, the tank having an initial sodium chloride concentration of 13 g/L was frozen with a freezing regime that the freeze pipe was maintained at -25℃ (Nguyen et al., 2006). In the later stage, two tanks having initial sodium chloride concentration of 5 and 20 g/L was frozen with a freezing regime that the freeze pipe temperature was lowered gradually from 0 to -25℃ so that the cooling rate in freezing front was maintained at less than 0.3℃ per day. The cylindrical freezing front advanced horizontally from the central freezing pipe toward the wall of the tank. After the freezing process was complete (freezing front arrived at the wall of the tank), samples were cored at various radii using CRREL core barrel. Samples were wrapped, labelled, and stored in the freezer at -20℃ until being tested. These samples with a diameter of 6.35 cm (2.5 inches) were cut to the height of 12.7 cm (5 inches). A triaxial compression cell was modified for this specific test (Figure 4).

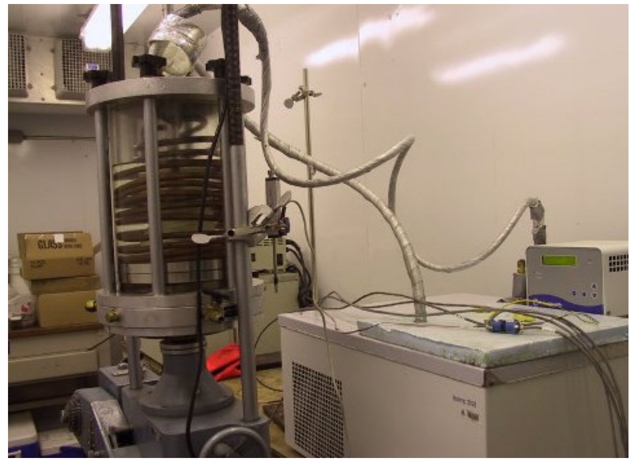

Figure 4. Modified cell used for UC strength test of FSS

Inside the modified triaxial cell used for this UC test, the chilled fluid (glycol) maintained at planned subzero temperatures (- 2℃, - 4℃, - 6℃, - 10℃) was circulated through a coil placed inside the test cell where the frozen sand samples were placed. The temperature of a cold room, where the UC tests took place, was also maintained at these temperatures. The test cell was filled with natural oil and the sample and the coil were submerged in it. The samples were sealed with latex membrane tube to prevent oil infiltration. In order for the whole sample to reach the designed temperature of the strength test, samples had been maintained in intended temperature-control condition for 24 hours before the UC strength test took place. During compression tests, the temperature of both chilled fluid circulated through the coil placed inside the cell and cold room were kept unchanged. Therefore, compression tests could be carried out at relatively unchanged temperatures. Tests were carried out under different strain rates 1.0, 0.1 and 0.01 % per minute and at different temperatures -10, -6, -4 and -2 ℃. These UC strength tests were performed in accordance with ASTM D2166-06. After compression tests were complete, the weight of samples was measured for bulk density calculation. Subsequently, samples sat in +5℃ cold room until thawed. The pore fluid of thawed samples then was extracted to measure sodium chloride concentration using a handheld refractometer in accordance with ASTM D4542-07. After measurement of salt concentration of pore fluid, the samples were oven-dried for water content determination.

3 RESULT AND DISCUSSION

3.1 Dependence of UC Strength on Other Factors

Figure 5 showed a sample after strength test was performed. Uniaxial unconfined compressive strength results of cored samples can be presented in three graphical formats: 3D scatter, 3D surface and 2D contour. Figure 6 to Figure 8 presented test results at -10℃.

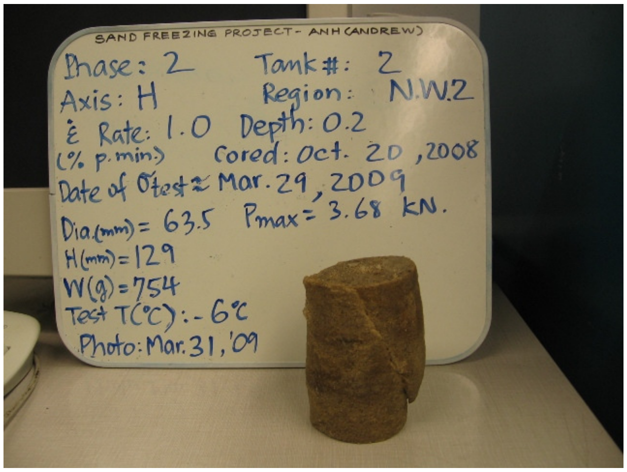

Figure 5. A sample after the strength test

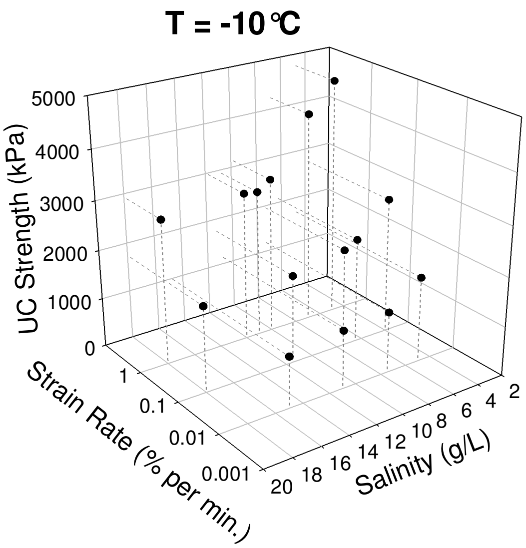

Figure 6. 3D Scatter graph for T= -10℃

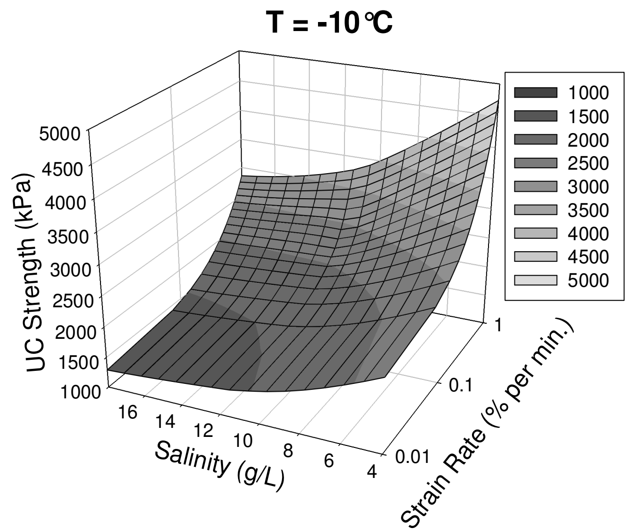

Figure 7. 3D smoothed surface graph for T= -10℃

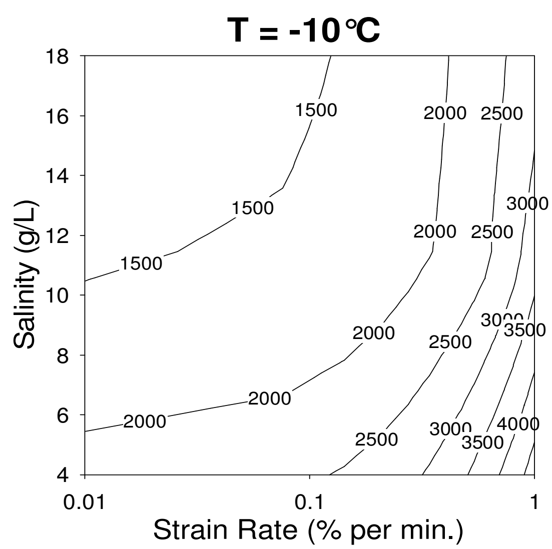

Figure 8. Contour graph for UC strength at T= -10℃

All graphs for strength test results were plotted using SIGMAPLOT program. However, in 3D surface and 2D contour graphs, the strength results were processed and smoothed using "Loess"model before plotted. This technique was defined as "local smoothing technique with tricube weighting and polynomial regression" in SIGMAPLOT. The graphs were constructed with "sampling proportion" and "polynomial degree" of 1. The coefficients of correlation for 3D strength surfaces were 0.924, 0.887, 0.923 and 0.898 for T= -10, -6, -4 and -2℃ respectively.

Using the same techniques, other strength surfaces for T= -6, -4 and -2℃ were established and presented in Figure 9.

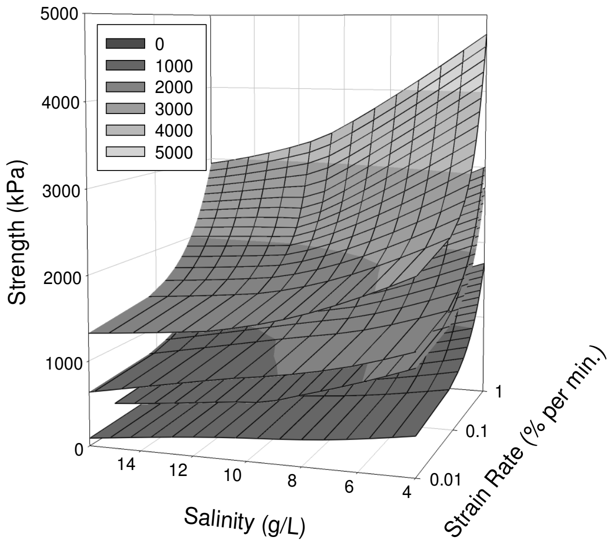

Figure 9. 3D surface plots for UC strengths at T= -10°C, -6°C, -4°C and -2°C from top down respectively

The dependence of uniaxial UC strength on the salt concentration of the pore solution can be observed in these Figures. Several relationship types were tried and the power-law relation had the highest correlation coefficient. The exponent of salt concentration in this relation varied but was in a range from -0.4 to -0.5.

Similarly, the dependence of the strength on strain rate was also noted in these Figures (Figure 6 to Figure 9). Several relationships were tried to fit the data and the power-law relationship had the highest correlation coefficient. The exponent of strain rate in this relationship was in a range from 0.2 to 0.3. From these figures, one can observe that as temperature increases, the influence of salinity and strain rate on strength reduces.

Regarding the dependence of strength on temperature, several relationship types were tried and power-law relationship had the highest correlation coefficient. The exponent of absolute value of temperature in degree Celsius in correlation with strength mostly ranged from 0.6 to 0.9.

"Solver" function in MS Excel was used to analyze the correlation between uniaxial unconfined compressive strength and other testing parameters (temperature, strain rate and salt concentration. Exponents were tried with various values in an iteration performed by "Solver" function to obtain maximum possible value of correlation coefficient R for the following relationship:

$$\sigma = A(-T)^m \times \dot{\varepsilon}^n \times \left(\frac{1}{S}\right)^p + B \qquad [1]$$

Where:

σ is uniaxial unconfined compressive strength in kPa,

T: sub-zero temperature in ºC,

$\dot{\varepsilon}$: strain rate in % min.$^{-1}$ or 10^{-2} × min.$^{-1}$, and

S: salt concentration of pore solution in g/L.

Running "Solver" function in MS Excel, exponents in this equation have been found to create an empirical equation determining uniaxial unconfined compressive strength based upon other independent parameters (salt concentration, strain rate and temperature). The empirical equation showed a well-fitted relationship (Figure 10) between strength and quantity $(-T)^m \times \dot{\varepsilon}^n \times \left(\frac{1}{S}\right)^p$.

Details of this analysis will be presented in a separate paper submitted to the Canadian Geotechnical Journal and the first author's doctoral thesis. Obtained empirical equation confirmed results obtained from previous studies by Hivon and Sego (1995), Stuckert and Mahar (1984), Sego et al. (1982) and Sego and Cherenko (1984), in which the strength was studied with only two independent variables.

The result from previous studies showed a good agreement with this study's found empirical equation.

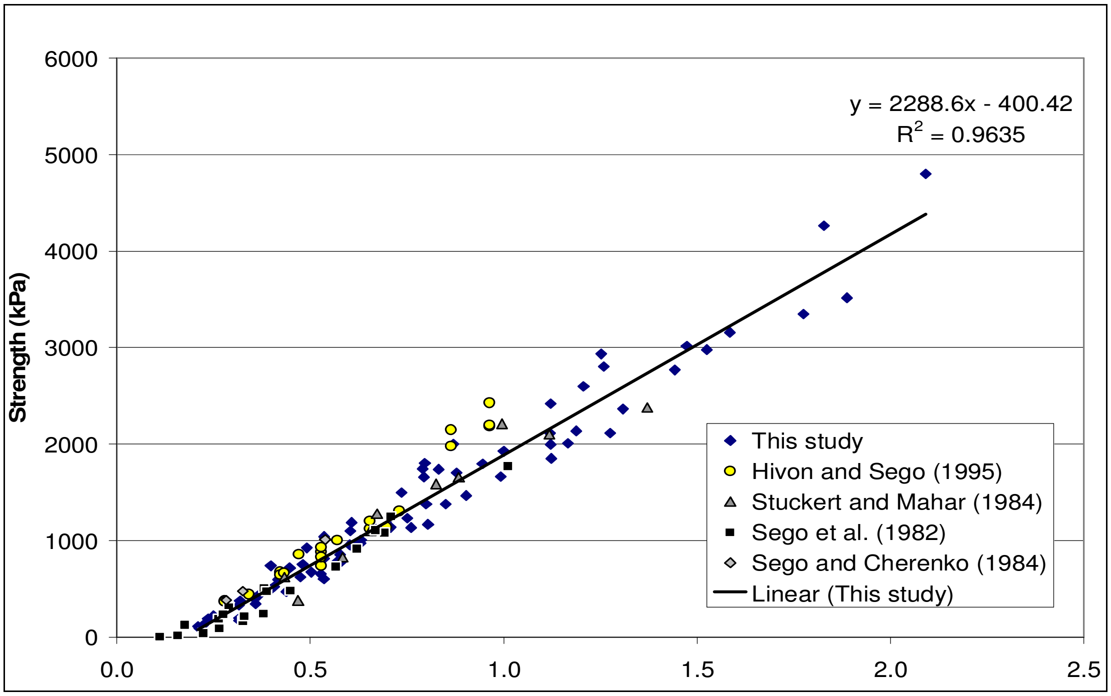

Figure 10. Correlation of compressive strength σ (kPa) versus $(-T)^m \times \dot{\varepsilon}^n \times \left(\frac{1}{S}\right)^p$

3.2 Dependence of Modulus on Other Factors

An effort was made to find an empirical relationship between secant young modulus and three independent parameters of interest. This relationship was assumed to be a form as shown in following equation:

$$E_S = A \times \left[S^{-a} \times \dot{\varepsilon}^b \times (-T)^c\right] - B \qquad [2]$$

Where: E_S is secant modulus (kPa)
T is sub-zero temperature (ºC)
$\dot{\varepsilon}$ is strain rate (% min.$^{-1}$ or 10^{-2} × min.$^{-1}$)
S: Salt concentration of sand's solution (g/L)
A, B: Constants

In order to find out exponents in this equation, test results were applied to exponents a, b and c. Subsequently the exponents were found when the correlation coefficient of linear relationship between the secant modulus E_s and quantity $S^{-a} \times \dot{\varepsilon}^b \times (T)^c$ reached maximum value when running "Solver" Excel function similar to previous section.

Results from previous studies were processed with found exponents and included in the same Figure (Figure 11) with this study data to show how well they agree with one another. It showed that the results from previous studies confirmed well with this study and the empirical equation. Details of this analysis will be presented in a separate paper submitted to the Canadian Geotechnical Journal and the first author's doctoral thesis. Resulting maximum R^2 values was 0.8826 (Figure 12) showed a well-fitted relationship between these quantities with all data.

This analysis indicated that there is a power-law correlation between secant modulus and other three independent variables, which are salinity, strain rate and temperature.

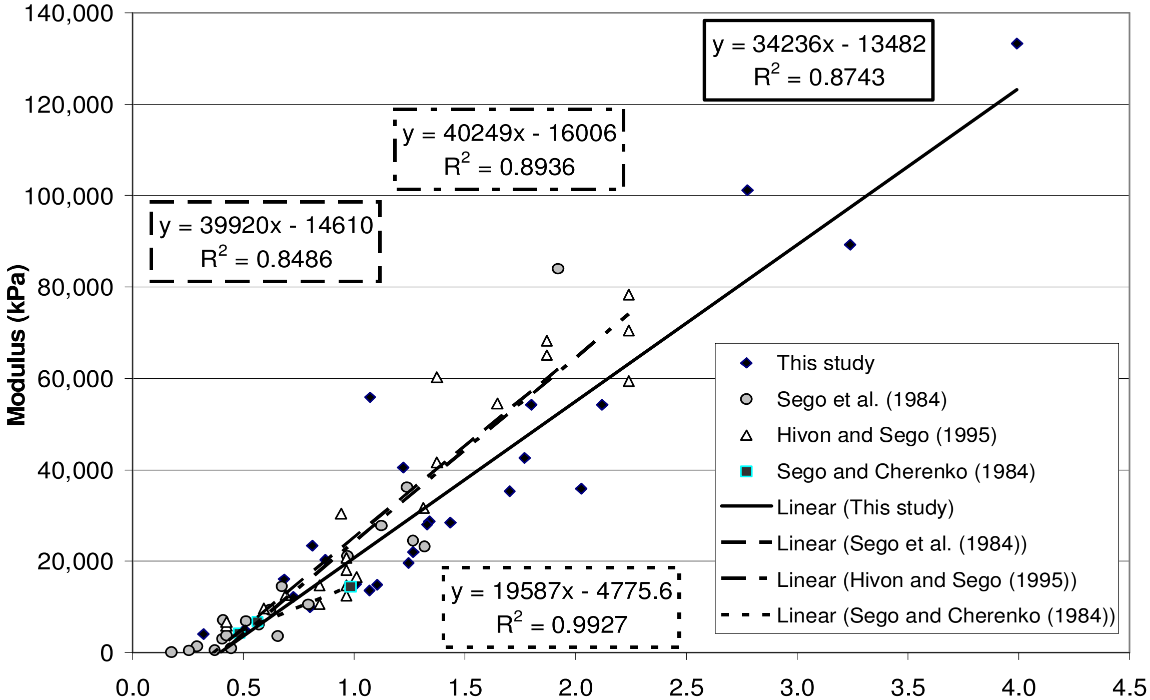

Figure 11. Correlation of modulus Es versus $\left[S^{-a} \times \dot{\varepsilon}^{b} \times (-T)^{c}\right]$ presented in separate sets of data

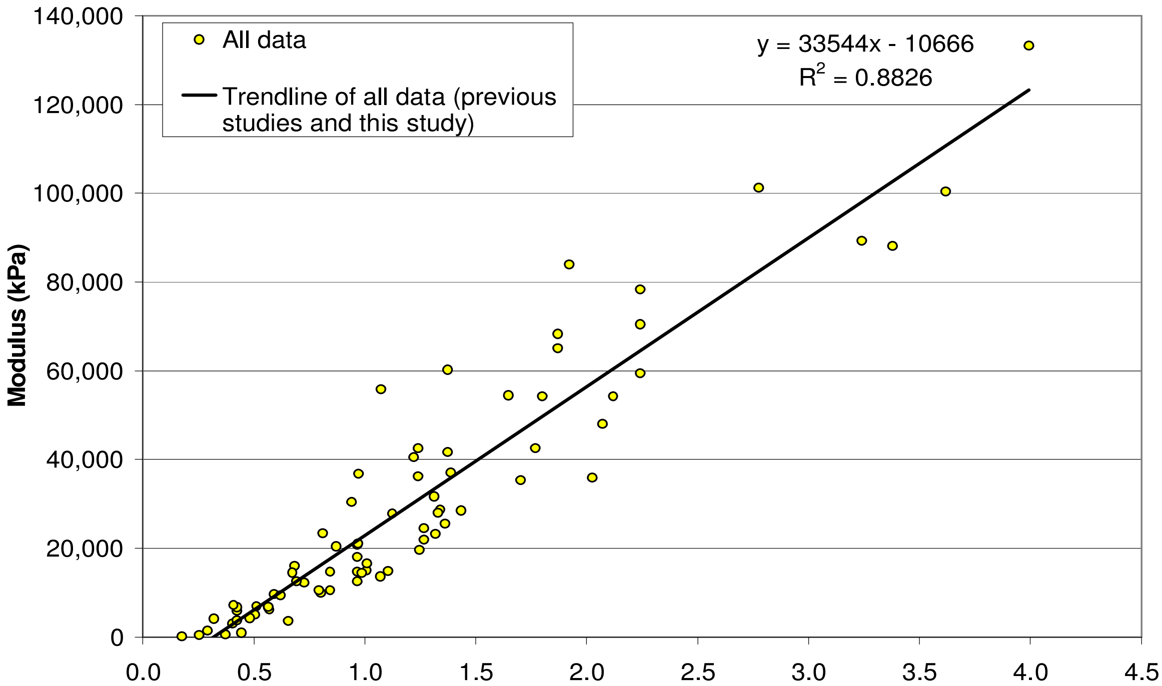

Figure 12. Correlation of modulus Es versus $\left[S^{-a} \times \dot{\varepsilon}^{b} \times (-T)^{c}\right]$ presented with all sets of data

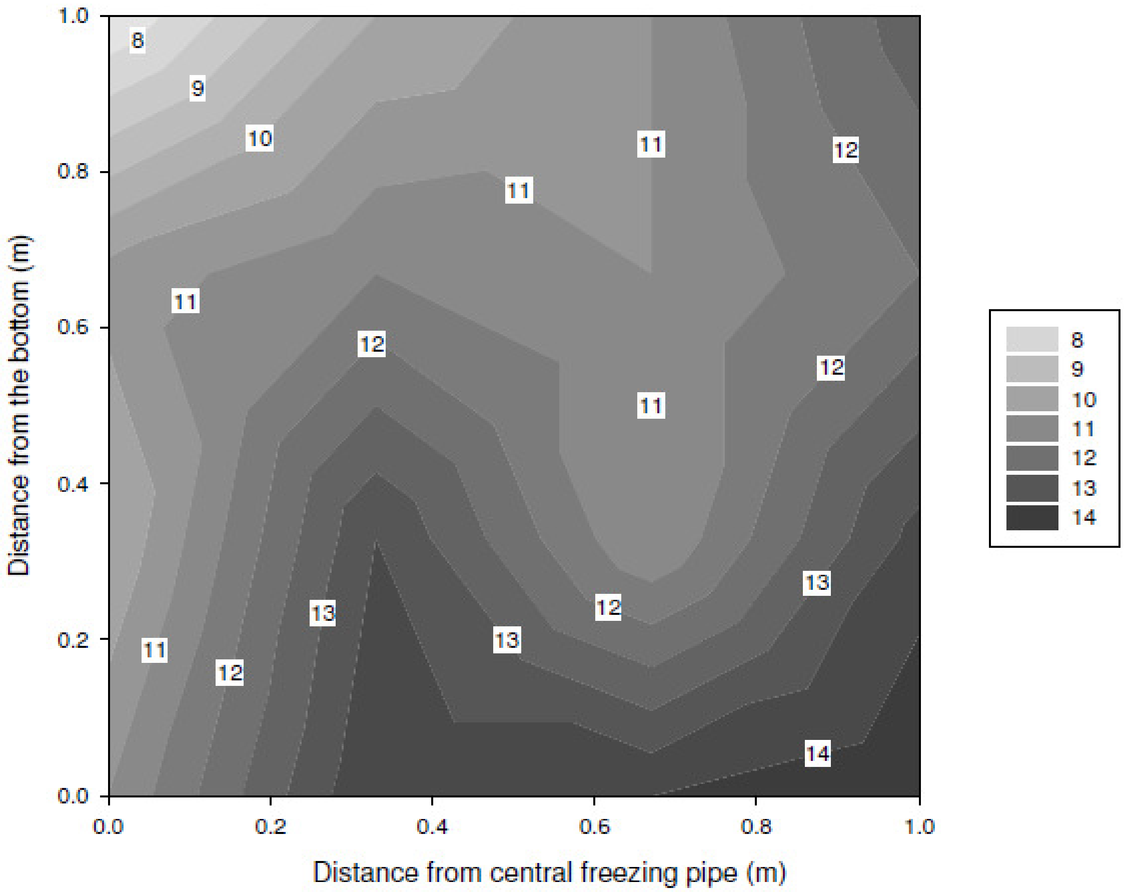

Figure 13. Final salinity distribution in a tank having initial salinity of 20 g/L (left side is the central freezing pipe)

3.3 Other Engineering Aspects

The sand was poorly graded (uniform) sand. If classified, it can be rated as a frost unsusceptible soil due to its high permeability. The coring of samples confirmed that there was no ice lenses were formed in the frozen sand body.

Figure 13 showed final salinity distribution of a tank that had initial salinity of 20 g/L. The cooling rate equal or less than 0.3 C/day generated a rejection of 40-50 % in the most part of sand frozen body. The detailed analysis of cooling rate versus salinity rejection will be presented in a separate paper and in the first author's doctoral dissertation.

4 CONCLUSION

Key findings of this study can be summarized as follows:

- there is a power-law relationship between uniaxial unconfined compressive strength of frozen saline sand and other independent variables of salinity, strain rate and temperature. This power-law relationship can be presented in a power law empirical equation that can be used in estimating UC strength, and
- there is a power-law relationship between secant modulus of frozen saline sand and other independent variables: salinity, strain rate and temperature. This power-law relationship can be presented in a power law empirical equation that can be used in estimating this modulus, and
- horizontal freezing in clean uniform sand with cooling rate equal or less than 0.3 C/day expelled 40-50% salt content from frozen sand body.

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