

## STRENGTH VARIATIONS WITHIN ARTIFICIALLY FROZEN SOILS

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### ABSTRACT

An artificial radially freezing experiment has been undertaken to investigate the variation of strength characteristics of a frozen sand mass. The artificial freezing experiment was carried out in a 1.5m diameter and 1.0m high cylindrical tank. The unconfined compressive strength of the frozen sand and its influence on factors such as the freezing rate, temperature and pore water salinity are presented. The results show that low freezing rate caused radial solute rejection that consequently provokes the increase in strength of frozen sand, contrasting with values in the literature.

### RÉSUMÉ

Une expérience de congélation artificielle radiale a été conduite pour étudier la variation de la rigidité caractéristique d'un sable gelé. L'expérience de congélation artificielle a été effectuée dans une cuve cylindrique avec un diamètre de 1.5m et une hauteur de 1.0m. La résistance uniaxiale du sable congelé et l'influence des facteurs tels que le taux de congélation, la température et la salinité de l'eau interstitielle sont présentés. Les résultats prouvent que le taux de congélation réduit/bas a induit le rejet radial du sel dissous, provoquant par conséquence l'augmentation de la force du sable congelé, ce qui est en contradiction avec les valeurs présentées dans la littérature.

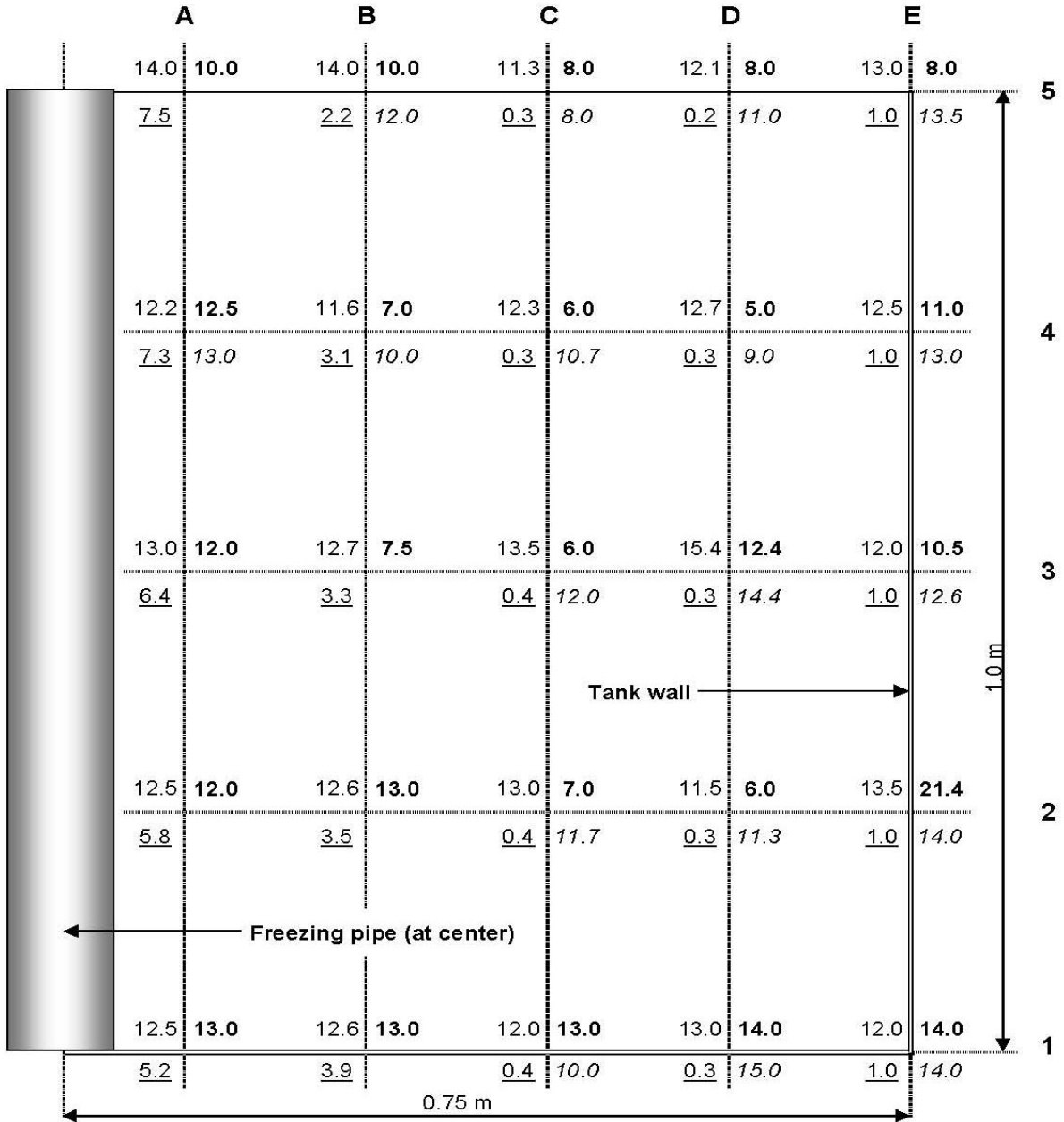
### 1. INTRODUCTION

Artificial ground freezing is a common technique used to temporally improve soil strength in geotechnical engineering. The actual strength and deformation characteristics of the frozen soil structure depend on the applied temperature, the freezing regime, the pore water chemistry, and grain size of the soil being frozen. During the freezing via vertical freeze pipes, the dynamics of the ice formation as the freezing front advances radially, results in a significant variation in the mechanical behaviour of the frozen mass. Temperatures, unfrozen water contents and salinities vary within the radially frozen material. The extent and effect of these variations depends on the above mentioned factors and the solute redistribution is often unknown. As a consequence, a conservative approach is generally chosen to solve this problem by degrading the available strength based on average initial conditions. We present a laboratory investigation of the variation in strength properties within a frozen zone surrounding a freeze pipe. Fine sand with a pore water salinity of approximately 13 g/L (or ppt) was radially frozen from the centre in a 1.5m diameter and 1.0m high cylindrical tank. Temperature, salinities and unfrozen water contents were measured at different radial locations as a function of time as the mass of sand freezes. After freezing was complete, core samples were obtained throughout the frozen sand and unconfined compression strengths were measured on these samples at the same temperature the sample experienced at the end of freezing. The samples were cored using a CRREL core barrel. Salinity and water contents were also determined on these samples after strength testing. This test data assist in understanding the strength and deformation characteristic of the frozen mass as a

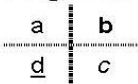
function of both time and location. These initial tests form the base measurements for ongoing research on the variation of strength and factors that influence this strength in the frozen soils to guide more economical design of artificially frozen soils.

### 2. TEST METHOD AND MATERIAL

The freezing pipe was placed in the center of the cylindrical tank. Clean medium sand was saturated with 13g/L sodium chloride solution. Thermistor and Time Domain Reflectometry (TDR) probes were embedded in the sand to measure the temperature, unfrozen water content (Patterson and Smith, 1980; Noborio et al., 1994) and pore water salinity (Dalton et al., 1984; Zegelin et al., 1989). The TDR signals were interpreted after the probes had been calibrated (Nguyen et al., 2006). The TDR unit, Tektronix 1502C Metallic TDR Cable Tester, has an accuracy of 0.1 g/L for the salinity and 0.1% for the determination of the unfrozen water content. The salinity of the pore water in the frozen cored samples was measured after the strength test, using an Accumet pH/Ion/Conductivity Meter 50 from Fisher Scientific with an accuracy of 0.1 g/L. The chilled fluid maintained at -22.5 °C was circulated through the freeze pipe and the room temperature was kept at +5.0 °C. Unconfined compression tests were carried out in a cold room using a constant strain rate of one percent per minute whilst the sample was being maintained at the in-situ temperature obtained from the four-week curve (Fig. 3). During the compression test chilled fluid was circulated in the test cell keeping the sample temperature constant.



**Legend:**



- a: Initial salinity before freezing, g/L (measured by TDR)
  - b: Salinity measured from coring samples after freezing, g/L (TDR, Reflectometer, Solution salinity/pH meter)
  - c: Salinity measured just before freezing-front arrived, g/L, (TDR)
  - d: Daily temperature gradient near freezing point, °C/day, (Thermistor)
- Ambient air temperature: 5 °C

Figure 1. Pore water salinity distribution prior, during and after radial ground freezing (after Nguyen et al., 2006)).

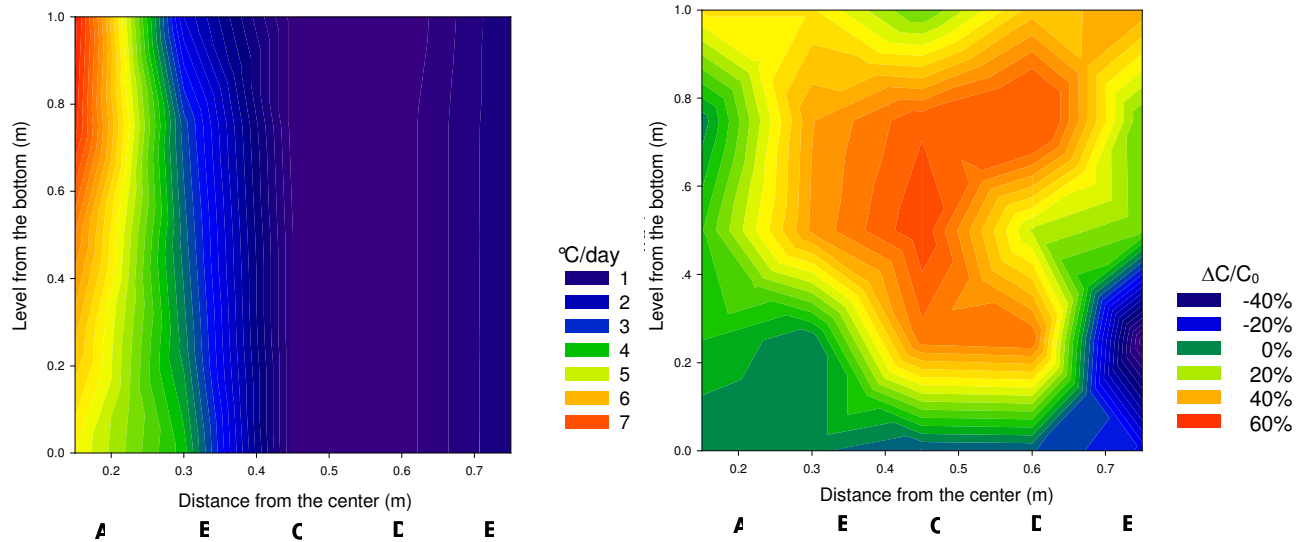


Figure 2. Cooling rates in  $^{\circ}\text{C}/\text{day}$  at the onset of freezing (left) and relative pore water salinity decrease after radial freezing (right).

### 3. SALINITY REDISTRIBUTION

The distributions of pore water salinity and freezing rate are presented in Figures 1 and 2. Cooling rates as low as  $0.3^{\circ}\text{C}/\text{day}$  occurred from vertical axis C to axis D (Fig. 1). In this zone, significant reduction of pore water salinity occurred (up to 60% decrease).

The highest pore water salinity was found in the lower right corner. The authors believe that this was caused by radial salinity rejection in combination with gravity driven downward drainage. This redistribution of salinity influences the strength variation within the frozen sand mass that is discussed in the remainder of this paper.

### 4. STRENGTH AND SALINITY DISTRIBUTION

The temperature distribution three and four weeks after commencement of freezing is shown in Figure 3. Strength experiments were carried out utilizing the temperature from the four-week curve. Figure 4 shows the measured uniaxial compression strengths compared to those reported by Mahar and Stuckert (1985) for frozen sand with similar pore water salinity. The Mahar and Stuckert (1985) data were based on the actual in-situ temperature and the initial salinity (i.e. their data does not account for salinity redistribution during freezing). The results showed a significant increase in strength from this experiment compared with the previous work in the zone of low freezing rate that can be found between axis C and D. This low freezing rate of less than  $0.3^{\circ}\text{C}/\text{day}$  causes the salinity rejection. In consequence, the strength is higher for a particular temperature. Similar solute rejection was also observed with lower freezing rate at or less than  $0.1^{\circ}\text{C}/\text{day}$  (Konrad and McCammon, 1990).

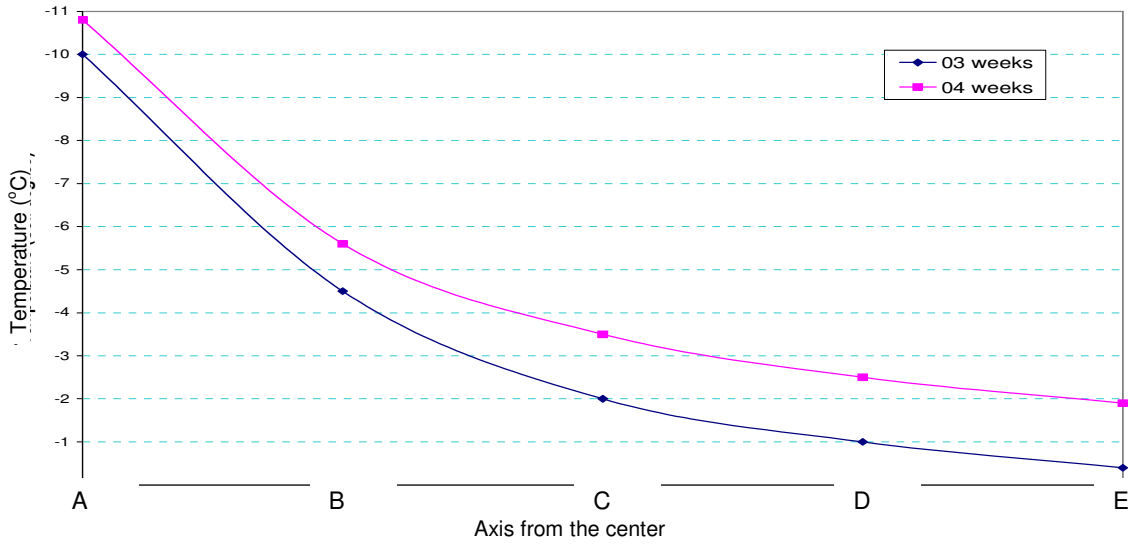


Figure 3. Temperature distribution within frozen zone.

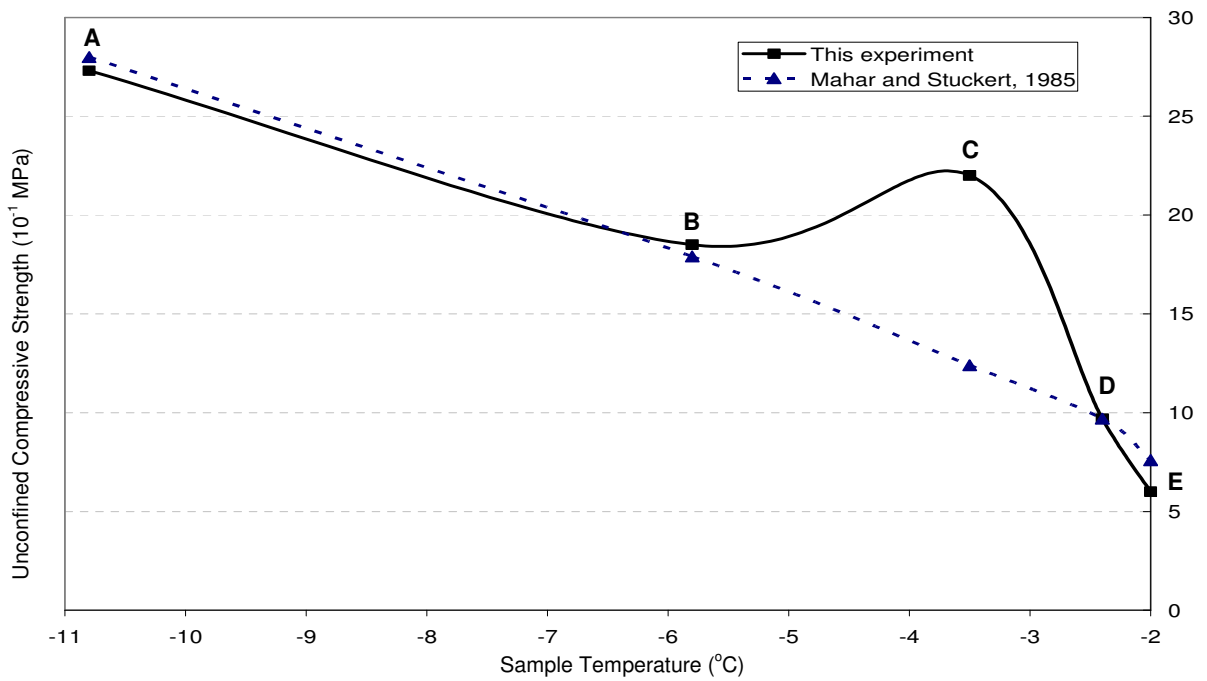


Figure 4. Unconfined compressive strength distribution at a tank height of 0.5m from the bottom (week four temperatures).

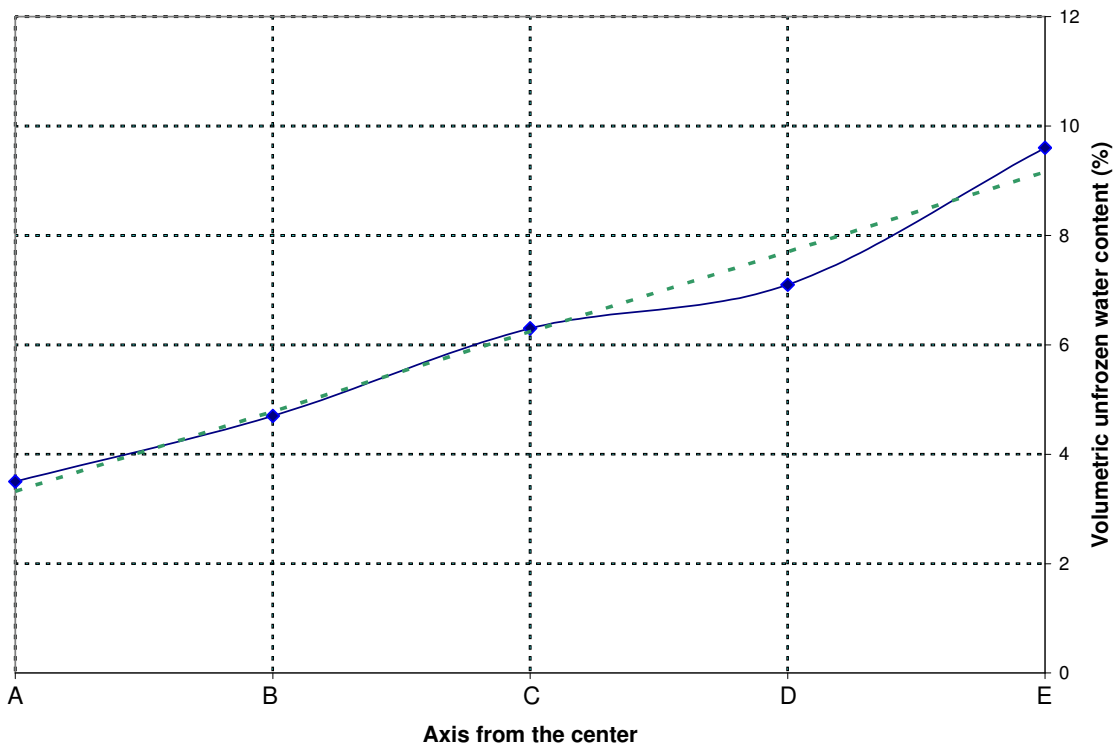


Figure 5. Volumetric unfrozen water content versus radial distance from freeze pipe for the height of 0.5m.

On the other hand, lower strengths were measured within the high salinity zone found in the lower part of axis E (grid arrangement is shown in Fig. 1). With cooling rates greater than 0.33 °C/day, the strengths obtained are similar to those reported in the literature.

The unfrozen water content distribution along the radial axis is presented in Figure 5. The dashed line in this figure is the linear referral trend found in the zone of high freezing rate of this experiment, between axis A and B (detailed data are not presented), in which there is no significant change in salinity before and after freezing, i.e. the salinity of pore water remained at approximately 13 g/L. The solid line was experimentally obtained at different radial distances, and samples where the change in unfrozen water content results from different pore water salinities. The trends in unconfined compressive strength and unfrozen water content are in agreement with each other as shown when comparing Figure 4 and Figure 5 where a lower unfrozen water content occurred, and an increase in the unconfined compressive strength was obtained and vice versa.

## 5. CONCLUSION

An artificial freezing experiment has been carried out to measure the variation of unconfined compressive strength radially around a freeze pipe. The result shows that the strength of a frozen sand increased due to radial solute rejection, which results when low radial freezing rates

occur. During this experiment, the solute rejection in the pore water occurred at freezing rates that was less than 0.3 °C/day.

An inverse relationship between the measured strength and the unfrozen water content, which is affected by the solute redistribution, was further observed during this experiment.

The strength behavior of a saline frozen soil can be expected to be improved in zones where the cooling rate is less than the aforementioned threshold. Additional experiments are currently being carried out to closer investigate this threshold and different original salinities.

## 6. ACKNOWLEDGEMENTS

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