

FROST HEAVE OF SALINE SOILS

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Theories of ice segregation and frost heave processes in saline soils are briefly examined and modified to explain observations made on clay and sand soils frozen under laboratory conditions. Seawater was observed to reduce the rate of frost heave by more than 50% for both soil types and to dramatically reduce the size of ice lenses. The effect of seawater is to cause the formation of a thick active freezing zone with many ice lens growth sites, each with its own brine concentration. Unbonded brine-rich soil zones between ice lenses are identified as potential zones of low shear strength.

An understanding of the frost-heave and ice-segregation behavior of soils that contain saline pore water is important to the development of off-shore petroleum resources in the Beaufort Sea. Understanding the freezing behavior of saline soils is also important to the artificial ground freezing industry. Unfortunately, little is known of ice segregation processes in saline soils that would allow design for frost heave and for changes in physical and mechanical properties.

Mahar et al. (1982) reported a modified form of the Berggren equation to predict frost penetration in saline soils where little or no frost heave occurs. This is important for determining where potential failure planes may occur in artificial islands. If significant amounts of ice segregation and frost heave occur, however, this method may overpredict the depth of freezing. In addition, the potential failure plane may not be forced below the region of freezing as commonly assumed. Partially frozen brine-rich zones within frozen layers may occur and they must also be considered as potential failure zones. A good example of this type of problem was recently observed at a ground freezing site (Maishman, personal communication) where, after excavation, a brine-rich clay layer was observed to slough back to the freezing pipes. Inspection of the site showed that the soil between ice lenses had little ice bonding and thus provided little strength for supporting the excavation.

Inspection of borehole logs obtained by Osterkamp and Harrison (1979) on Reindeer Island in the Beaufort Sea reveals that the occurrence of ice and ice bonding is sporadic and unpredictable, even though temperatures were below the freezing point of seawater.

This paper presents the results of a series of laboratory freezing tests on two soil types saturated with seawater. The freezing behavior is compared with freezing tests on the same soil types saturated with distilled water. Finally, an explanation for the unique freezing behavior of saline soils is offered.

FREEZING PROCESSES IN SALINE SOILS

The freezing of soils that contain saline pore water solutions is a complex process, due to the

soluble salts in the pore water fluid. The effects of salts on freezing behavior extend well beyond simply lowering the freezing point. Salts are excluded from growing ice crystals and are concentrated in the adjacent pore fluids, so that ice segregation temperatures are lowered and additional sites for ice nucleation form at or near the original ice segregation temperature.

Hallet (1978) suggested that ice tentacles reach out from a morphologically complicated interface. Domains of solute-rich solutions can become isolated from the unfrozen pore-water solutions and eventually become trapped in solidly ice-bonded material. He suggested that significant solute partitioning will accompany frost penetration in frozen ground, with lower bulk concentrations occurring in ice-bonded layers, and increased concentrations of salt occurring in unfrozen soils beneath a growing ice lens. He further stated that constitutional supercooling in soils will lead to a situation where ice will nucleate and grow in a zone ahead of and separate from the freezing front.

Sheeran and Yong (1975) suggested that ice growth in pores that contain salt solutions requires progressively reduced temperatures because the increased salt concentration due to brine exclusion lowers the freezing temperature of the remaining adjacent pore water. Only partial freezing occurs at the freezing front. Substantial phase change may occur up to a meter behind the frost front as cooling continues, depending on the magnitude of the thermal gradient.

Mahar et al. (1982) concluded that the freezing front progressing through saline saturated soil is characterized by a transition zone of partially frozen soil grading from isolated ice crystals to ice-bonded soil. Continued ice growth requires progressively reduced temperatures. Because of the irregular shape of soil grain boundaries and the complex heat transfer pattern in a pore space, isolated brine pockets develop that may not freeze.

The situation in freezing saline soils is somewhat analogous to the frozen fringe concepts of Miller (1978) and Konrad and Morgenstern (1981). The hydraulic conductivity of the frozen fringe controls the availability of water to growing ice lenses. In the case of saline soils, however, the frozen fringe can be very thick, and ice accumulation probably occurs throughout the zone.