SUMMARY

Water, heat and salt transport and the interaction among them have been experimentally studied in freezing unsaturated soils, and numerically analyzed by considering unfrozen water content related to both temperature and soluble salt concentration. Although the movement of water and heat during soil freezing has been generally examined in previous studies, the simultaneous transport of water, heat and salt is investigated in this study. This thesis describes the theory, experiment, and physical property, and provides a computer simulation analysis concerning the transport phenomena in soils.

The first chapter of the thesis reviews recent studies of both experiment and theory on soil freezing. Emphasis is given to the necessities of a theoretical study on unfrozen water and an experimental study on the simultaneous movement of water, heat and salt in freezing soils. Thus the purpose of this thesis is established.

The second chapter discusses an unfrozen water property, playing an important role in the transport in freezing soils, based on the theory of chemical thermodynamics. Matric potential of the unfrozen water is defined from the equilibrium between unfrozen water and ice in a frozen soil. The driving force for the movement of unfrozen water in a saline soil is approximately expressed as a linear function of temperature, ice pressure and osmotic pressure gradients. Consequently, the suction is expected to be 1.23 (MPa/^{o}C) for a salt free frozen unsaturated soil, and the suction is proven to be lower for a saline frozen soil under nonheaving conditions.

The third chapter describes several experiments of water, heat and salt transport in freezing unsaturated soils. In section 3.1, the several saturated mixtures, such as methyl orange solution, agar, glass beads, bentonite, and sand, were frozen downward using a specially designed freezing apparatus to grasp the characteristics of freezing phenomena. Consequently, exclusion of a solute by an advancing freezing front was observed in the methyl orange solution, but nevertheless it is not observed in columns of both agar and sand. Comparison of the temperature profiles, measured in each freezing sample, showed that water convection took place in the methyl orange solution and that it might be ignored in the columns of agar, clay, and sand.

In section 3.2, the redistributions of water, solute and temperature were measured in an unsaturated Kanagawa sandy loam, frozen downward from the open surface by cold air. Consequently, the redistributions were found to be dependent on the initial water content and the temperature of cold air. The following characteristics were observed: (1) Soil water migrates from unfrozen to frozen area. The amount of migration is high at high initial water content and it is also high at low temperature of air. (2) Salt also migrates from unfrozen to frozen areas at the high water content. (3) The shape of the temperature profiles could be divided into three regions. The temperature is constant in the region nearest the freezing front, which can be explained in terms of the freezing point depression related to the water

content and the salt content. The unique profiles of temperature are formed by heat transfer during the supercooling period and heat balance in the frozen fringe.

In section 3.3, the redistributions of water, solute and temperature, were measured in an unsaturated Kanagawa sandy loam frozen downward by contacting the closed surface beneath the cold plate. The following results were obtained: (1) The water content after freezing was more constant in the frozen soil and the amount of water migration was smaller than that of the non-contact air freezing conditions. (2) The constant temperature region, which appears only at the air freezing condition, was not observed. (3) Although salt moved together with water from unfrozen to frozen areas, "apparent" solute concentration was found to be at the minimum at the freezing front. This result can be attributed to the migration of unfrozen water along with the solute concentration gradient against the unfrozen water content gradient.

In section 3.4, the influence of salinity on the water movement is conducted experimentally and the results are discussed. The redistribution of water content was measured in a freezing unsaturated Mie sandy loam with three different salinities. The following results were obtained: (1) Water osmosis occurs at the narrow region near the freezing front under a condition of low salinity, whereas it occurs at the wide region near the freezing front under a condition of high salinity. (2) Existence of salt in soils reduced the amount of water migration. These results can be explained in terms of the freezing point depression of unfrozen saline water.

In section 3.5, heat and water transfers were estimated in a discontinuous freezing Mie sandy loam, which was separated by using glass bead thus cutting the continuity of liquid flow. The following results were obtained: (1) The freezing rate of the discontinuous soil was lower than that of the continuous soil. (2) Liquid water flow was dominant and vapor flow was negligible, in a freezing soil. The vapor flow by a temperature gradient was estimated to be less than one percent of the liquid flow during soil freezing conditions.

The fourth chapter gives the equations of water, heat and salt transport in freezing soils, which were derived based on the experimental results in the previous chapter. These equations are expressed as simultaneous partial differential equations containing the physical properties, such as water retention, hydraulic conductivity, thermal conductivity, heat capacity, and the dispersion coefficient of solute. Although the respective equations are independent of each other in an unfrozen soil, the three equations are coupled mathematically through an equation which expresses the amount of unfrozen water as a function of both temperature and solute concentration.

The fifth chapter presents the physical properties, which are significant for the analysis of transport in freezing soils. The section of 5.1 gives the fundamental properties of materials used in this study, Kanagawa sandy loam and Mie sandy loam. In section 5.2, unfrozen water retention and the hydraulic conductivity of a frozen soil are discussed. The amount of unfrozen water in a saline frozen soil is expressed as a function of temperature and osmotic pressure using the water retention curve of an unfrozen soil and the matric potential of the frozen soil. The amount of unfrozen water which was measured by the freezing point depression method, agreed with the expected amount in a salt free frozen soil. The modified hydraulic conductivity is expressed in terms of water viscosity as a function of temperature. In section 5.3, the thermal properties of frozen soils, such as heat capacity, thermal diffusivity and thermal conductivity, are discussed. The apparent thermal diffusivity, which is derived from the heat equation with phase change, was determined for Kanagawa sandy loam using the repeat calculation method. Thermal conductivities of a frozen soil at -20 °C was ascertained from the relationship between the thermal diffusivity and the volumetric heat capacity of the frozen soil. The thermal conductivity of the frozen soils were estimated as a function of water content and temperature, by a newly developed concept. In section 5.4, the dispersion coefficient of solute is presented.

The sixth chapter gives a numerical analysis of water, heat and salt transport during soil freezing by using the finite difference method. In the analysis, first, water content, temperature and salinity are assessed without considering the phase change in the frozen soil. And then the values are modified by the freezing amount determined from the relationship of water content, temperature and solute concentration. The prerequisite physical properties of the soil materials are listed in the fifth chapter. Certain parameters, for example, fitting coefficient of the thermal conductivity, the heat transfer coefficient, the mass transfer coefficient and the empirical coefficient of solute dispersion, were impossible to measure, so that they have been approximated. For the direct freezing conditions described in section 3.3, the simulated results of water content, temperature and salinity, except for the apparent solute concentration, were in good agreement with the observed values. For the air freezing conditions in section 3.2, the simulated results with both evaporation and supercooling, predicted the property of the constant temperature region and the transport phenomena in a general bared soil. In addition, this chapter simulated the influences of initial water content, surface boundary temperature and initial salinity, on both the freezing rate and the water movement. These simulations cause us to conclude that the increase of salinity in soils reduces both the freezing rate and the amount of water movement.

In this thesis, water, heat, salt transport, and the interaction among them, have been experimentally studied in freezing homogeneous soil columns. The results were numerically analyzed using the concept of the matric potential of unfrozen water. Considering that the arable land is vast and heterogeneous, there are many problems still to be solved. However, owing to this study we will be able to understand the essential transport phenomena in freezing soils. I think this study will contribute to the establishment of a general movement theory of mass and energy in soils. Application of this study to an actual field test will enable us to predict the frost heave and the movement of water, heat, and salt in cold regions. And I believe this study can finally be helpful for understanding the mechanism of mass and energy circulation from a standpoint of the global environment.