8. Summary and conclusions

This study focused on the mechanism of process of ice lensing. The formation of ice lenses is recognized as a necessary condition for frost heave and also occurs in many porous media. The importance of studying soil freezing associated with ice lensing was described in chapter 1.

Numerical studies on ice lensing have been carried out. The main factors involved in soil freezing and ice lensing, and the models and theories for ice lensing were summarized in chapter 2. Then, it presented two main problems for considering ice lensing. One is to clarify the microstructure near the freezing front, which has been dealt with like a black box. The other is to explain the dynamic mechanism of ice lensing, in which the generation and growth of an ice lens is repeated to form intermittent layers.

Soil is heterogeneous in terms of texture, particle shape, electrical charge, and chemical composition. Ice lensing is a complex crystal growth phenomenon that is caused by various water and heat-related factors. Observing the microstructure and clarifying the mechanism are difficult because of the non-uniformity and the complexity. Therefore, we observed ice lensing in actual soil and in porous media consisting of uniform glass particles using an unidirectional freezing apparatus that can control temperature gradient and freezing rate independently. And based on the experimental results, we proposed a model to simulate ice lensing in water-saturated porous media.

The characteristics of the samples we used and the unidirectional detail of freezing apparatus were described in chapter 3. The relationship of temperature, specific surface area, solute type and its concentration to unfrozen water amount in the porous media was also shown in this chapter.

The details of unidirectional freezing experiments were described in chapter 4-6, then, following results were obtained. (1) Ice lensing in soil and porous media consisting of fine particles were microscopically observed. Ideal ice lenses for modeling can be made using uniform sized glass beads. The growth of ice lens is dependent on supercooling of the growth surface. The freezing rate influences the ice lens growth more than temperature gradient. It is suggested that freezing rate, supercooling degree at growth surface of ice lens and particle condition near growing ice lens were important factors for considering ice lensing model. (2) From the observation of ice interface in water with dispersed glass particles, the criteria for exclusion and encapsulation of particles during ice formation with respect to particle size and freezing rate was shown. The relationship between particle size and critical freezing rate was explained by Köber's theory. It is suggested that the critical freezing rate was important for the generation of ice lens. (3) Microstructure in the vicinity of ice lens is observed using Raman spectroscopy. No ice was found in any pore warmer than the warmest ice lens in the porous media and the ice lens grew without penetrating the warmer pores.

Based on the experimental results, a model for simulating the formation of ice lenses during freezing of unconfined uniform porous media was presented in chapter 7. This model is based on the freezing rate, the temperature at the growth surface of the ice lens, and the change in the critical freezing rate due to the change in the number of particles near the growing ice. The simulating location, growth, and formation of an intermittent layer of ice lenses using this model were good agreement with experimental results.

As mentioned above, we clarified the microstructure near the freezing front in water-saturated porous media experimentally and made a model, which can explain the formation of intermittent layers of ice lenses.