1. Introduction

1.1 Soil freezing

When soil is cooled under 0 °C, soil water solidifies with decreasing temperature. This is known as soil freezing. Large areas of land that undergo soil freezing are found worldwide and frozen soil is harnessed in various fields.

Soils at high altitudes and latitudes can remain frozen for long periods. Soil that remains at or below 0 °C for at least two years is termed permafrost (International Permafrost Association, 1998). Permafrost underlies about 14 per cent of the Earth's land surface (21×10^6 km^2) and the permafrost is over 1-km thick in some regions (e.g. Washburn, 1980). Even at middle latitudes, most of the ground surface is subject to seasonal or short term freezing. In Japan, the ground is frozen seasonally in Hokkaido, Tohoku, and some mountain areas. Short-term frozen ground is even found in the Kanto plains and the western part of Japan, where the temperature is below 0 °C on winter mornings. In this manner, soil freezing is estimated to occur in almost 70 per cent of the Earth's land surface (Kinosita, 1984). Furthermore, soil near highways, bridges, and tunnels sometimes freezes in areas where soil freezing generally does not occur. Soil freezing is not limited to the Earth. Frozen soil water is reported on the Moon (Feldman, 1998) and Mars (Carr and Schaber, 1977). Moreover, most soil in the solar system is in the frozen state.

Soil is sometimes frozen artificially for use, since the mechanical strength of soil increases with freezing and its permeability decreases dramatically. For example, cold storage for farm produce (Tuchiya and Ryoukai, 1996) and barriers against contaminant migration (Mohamed *et al.*, 1995) have been constructed from soil kept frozen using refrigeration pipes. Artificially frozen ground is also utilized for

underground tunnel construction in urban areas and for soft ground construction in caves and underwater (artificial soil freezing method). The soil around LNG (Liquid Natural Gas) storage tanks (Akiyama and Iguno, 1981) and pipelines under construction in cold regions is also kept frozen to maintain a stable construction base (Nixon, 1987). On the other hand, frozen soil is used as a source of cold energy because it contains a large amount of ice. Thus, there are many situations in which soil freezes.

1.2 The importance of studying soil freezing

If soil expands when it freezes, the volume change is called frost heave. Clay particles in soil migrate as a result of frost heaving and thawing. The migration of clay particles can change water paths and micro-pores in soil and damage irrigation and drainage systems in farmland. Disturbance of soil and changes of aggregated structure and hydraulic conductivity due to the action of frost-thaw are also reported (Tuchiya, 1986). The ground surface sometimes expands dozens of centimeters due to frost heaving and the heaving pressure can exceed 10 kPa (Japanese Society of Geotechnical Engineering, 1994). The heaving and subsidence of the surface causes much damage to paved roads (Photograph 1), airports, railways, foundations, and so on.

When heaving occurs, some of the ice formed near the ground surface is present as seams of pure segregated ice; this ice is called an ice lens. The growth of ice lenses induces soil water to flow from the unfrozen zone to the surface zone. In this case, some solutes illuviate to near the ground surface with the water flow, so that salinization occurs. If the ice lenses thaw and water collected near the ground surface runs off, soil loss can occur. Water can collect near the ground surface of farmland and remain until early spring, hindering plowing and seeding (Yakuwa, 1961). The thawing of ice lenses softens the ground. Furthermore, plant roots are sometime cut or extracted by frost heaving and ice lensing, so that plants wither in the field.

Photograph 1. Frost damage to paved roads (Kushiro, 1997).

With artificial soil freezing, unless the freezing is well controlled, frost heaving also occurs and affects the surrounding soil. Frost heave is also reported in concrete (Wang *et al*. 1996) and can damage the bases of dams and bridges. To overcome such frost-action damage, it is important to clarify the mechanism of frost heave.

We can identify various features associated with frost action, such as solifluction and patterned grounds in cold regions, where the ground undergoes repeated freezing and thawing (e.g. Washburn, 1980; Fukuda *et al*., 1992; Mackay, 1993; Sone and Strelin, 1997). Pingos occur in Siberia, Alaska, and northern Canada. These are perennial frost mounds, 10 m or more in height, consisting of surface soil and a core of massive ice (e.g. Yoshikawa and Harada, 1995). Soil freezing and frost heave play important roles in the formation of these landforms.

Knowledge of soil freezing is also required in the field of climate change and global warming. The surface layer of ground above the permafrost thaws in summer and freezes again in winter (active layer). When soil water in this layer melts, the melting water is not drained by infiltration because of the high hydraulic conductivity of permafrost (Bridges, 1978). Consequently, wetlands are a major feature in permafrost areas. Wetlands are a major source of atmospheric greenhouse gasses (Nakayama. 1995). The surface soil of permafrost contains large quantities of stored carbon. If the permafrost soil thaws, this carbon may be released as carbon dioxide and methane (Kane, 1997).

Recent research suggests that water and heat circulation in the permafrost area play important roles since the physical environment of the permafrost undergoes large seasonal swings in temperature, duration and intensity of solar radiation, surface albedo, and surface energy balance (e.g. Kane, 1997). Ground surface conditions and soil freezing/thawing in permafrost areas affect water and heat circulation and the climate system (Kanae *et al*., 1998).

Recently, to observe, understand, and model the hydrological cycle and energy fluxes in the atmosphere, at the land surface, and in the upper oceans, an international program, the Global Energy and Water Cycle Experiment (GEWEX), was instituted. Cold region phenomena and the role of frozen ground are major topics of this program. In order to predict global climate change and its impact on permafrost, it is important to clarify the mechanism of soil freezing and to understand the nature of frozen ground.

Natural gas hydrate is found in the ground buried under the permafrost (e.g. Uchida, 1999). Knowledge of soil freezing is also important for exploiting this resource and investigating its distribution and amount (Matumoto, 1996).

In space, the Mars Pathfinder mission is part of the long-term Mars exploration program being conducted by NASA. In July 1997, Sojourner, the rover carried on Pathfinder, investigated the Martian surface (Kerr, 1997). Lunar Prospector, launched in 1998, has brought about many new insights into soil freezing on the moon (Feldman, 1998). The construction of the International Space Station (ISS), which is a huge manned construction, located about 400 km above the Earth, is just beginning. Extraterrestrial soil will be utilized for engineering and agriculture in the near future, and knowledge of soil freezing will be of great importance.

1.3 Ice lensing and the purpose of this study

When water freezes *in situ* during soil freezing, the expansion of soil volume is less than 9 per cent of the volume of soil pores. When soil freezes, however, water is sometimes induced to flow through the unfrozen zone, towards a freezing front, and form regions of ice that are almost devoid of soil particles (Figure 1). This raises the ground surface and causes a great amount of frost heave. The region of ice is called an ice lens because of its shape. Photograph 2 shows ice lenses observed in natural soil and Figure 2 shows artificial ice lenses made in our laboratory in both soil and a porous

medium consisting of glass particles (Watanabe *et al*., 1997; Muto *et al*., 1998). As shown in these figures, a feature of ice lensing is the formation of intermittent layers, which results from the repeated generation, growth, and jumping of the ice lens near the freezing front.

The major factor producing frost heave is ice lensing, which changes the microstructure, water, and heat regimes of soil. Ice lenses form intermittent impermeable layers in soil. Ice lensing complicates water and heat migration, making the process difficult to understand and predict. To clarify the mechanism of ice lensing is not only the main theme of soil freezing science, but also an important theme in various fields, such as agriculture, engineering, geology, hydrology, meteorology, and space science.

Ice lensing is not a phenomenon limited to soil. It has also been observed in tuff (Miyata and Akagawa, 1996, 1997), tofu (Fuchigami, 1996), living cells (Mazur, 1970), sawdust and Bengala (Japanese Society of Geotechnical Engineering, 1994), and in some fine particles and powders. Recent progress in science and technology has increased the opportunities to handle porous media and micro particles under freezing conditions. Knowledge of the mechanism of ice lensing will be applied to fields that involve these frozen materials, including physical chemistry, biology (Mazur, 1970; Wisniewski *et al*., 1997), material science (Tada, 1996), food processing (Thyholt and Isaksson, 1997), and medicine.

In this study, we perform unidirectional freezing experiments to clarify the mechanism of ice lensing, and propose a model of ice lensing.

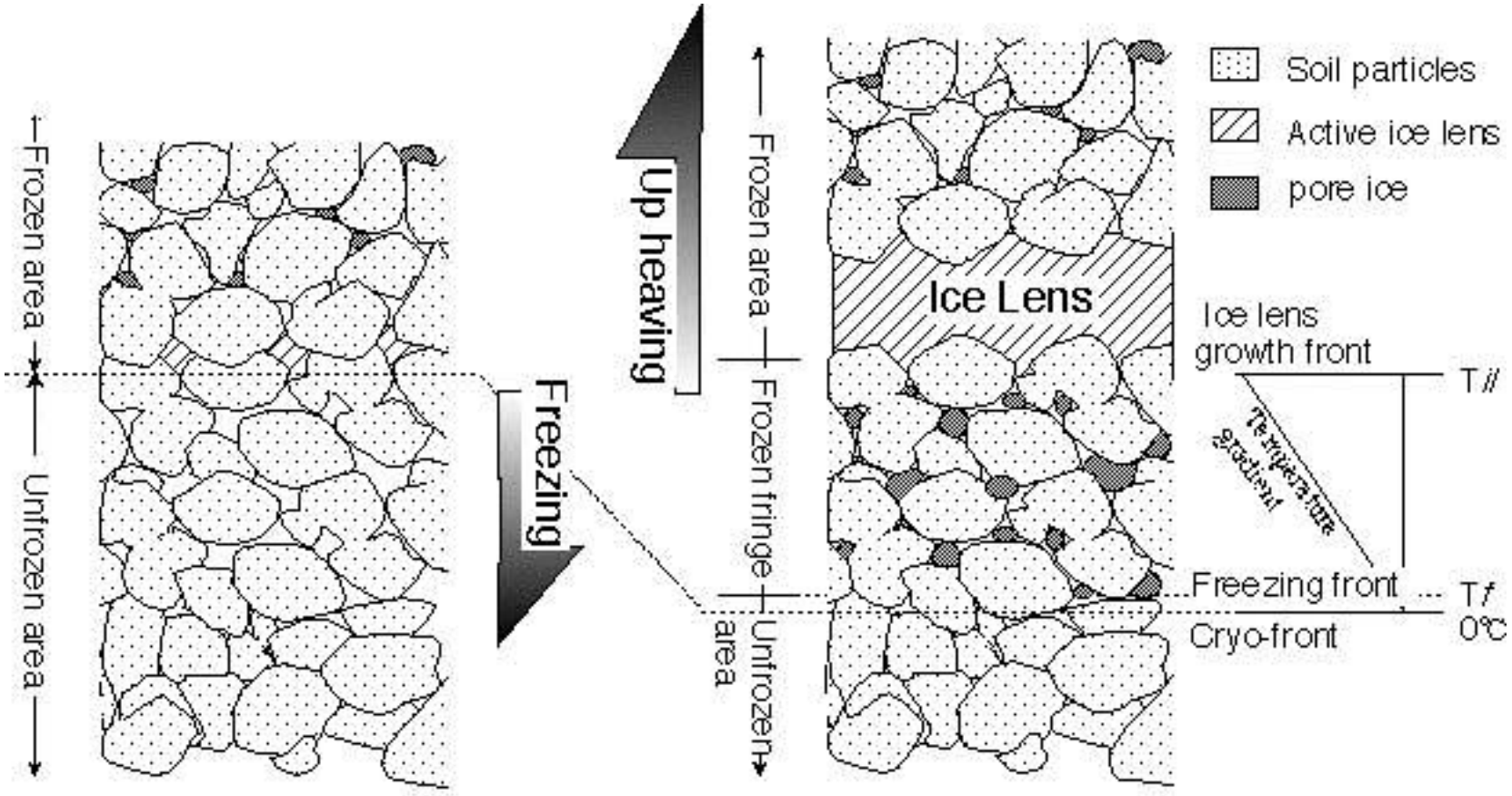

Fig.1. Schematic diagram of soil freezing and ice lensing.
When soil is frozen unidirectionally, water is sometimes induced to flow toward the freezing front and forms region of ice that is almost devoid of soil particles. The region is called ice lens because of its shape. The ground is heaved upward cased by the ice lensing (frost heave).

Photograph 2. Ice lenses in actual soil (James Ross Island, 1998).

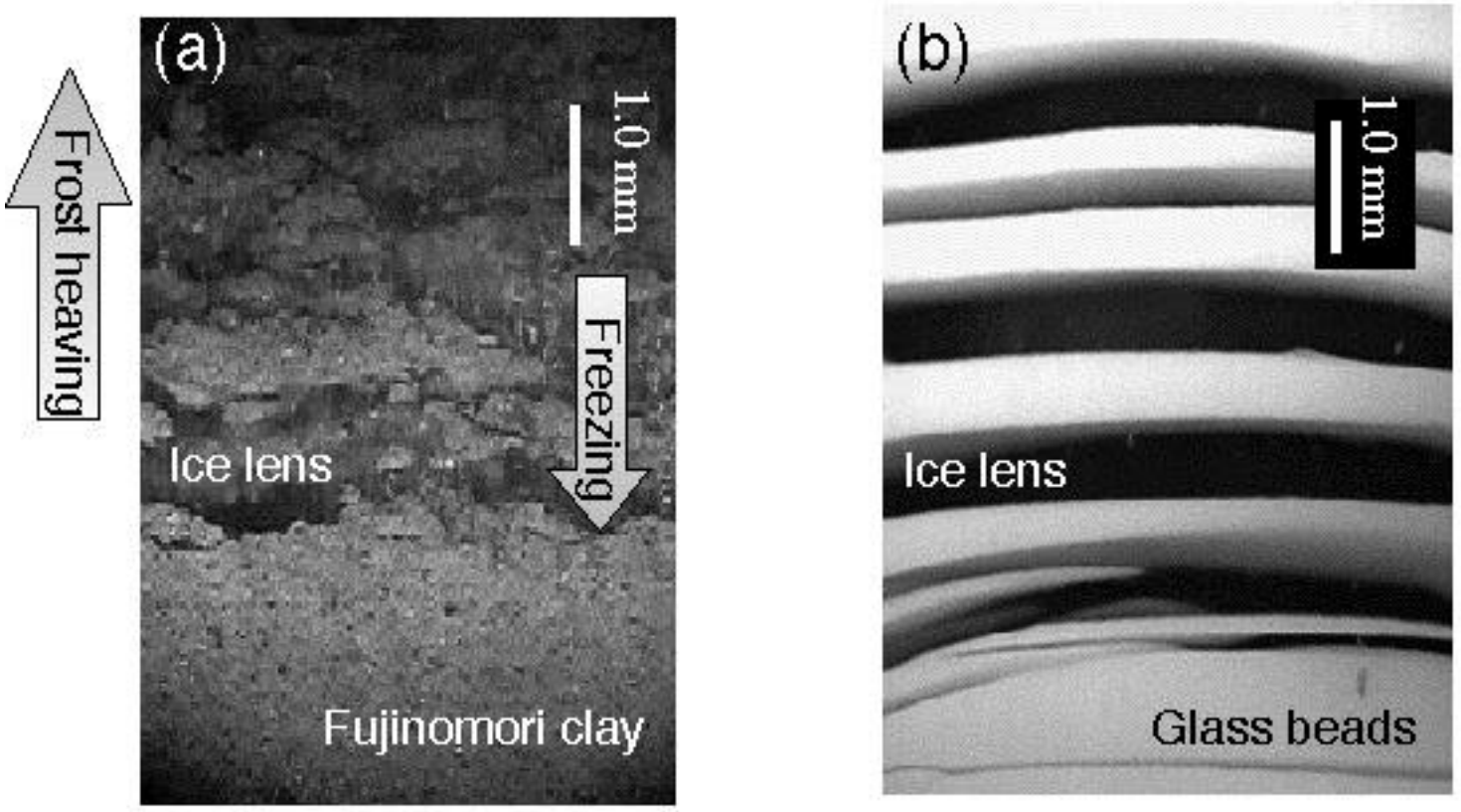

Fig. 2. Ice lensing observed in soil (a) and in porous medium consisting uniform sized glass particles (b) (from Watanabe *et al.*, 1997; Muto *et al.*, 1998). Intermittent layers are shown in the frozen region.