PURPOSE

The “engine” that drives the frost heave process and determines heaving pressures is revealed by investigating and analyzing the role of physical chemical factors in the frost heave process.

DEFINITION

Frost heave: upward movement of the ground surface caused by ice lens formation within the soil. (The expansion of water upon freezing is a minor factor.)

ESSENTIAL FACTORS

1. Water
2. Sub-freezing temperatures
3. A frost-susceptible soil
4. Freezing point depression

Factors 1 and 2 are self-evident. Factor 3 will be defined later. Factor 4 provides the starting point for the development of a frost heave model based on the role of physical chemical factors.

FREEZING SOIL

A soil undergoing downward freezing has three zones (Figure 1):

1. A frozen zone, in which ice lenses and pore ice in the soil between the lenses are

present. This zone contains a continuous ice matrix and behaves as an ice-cemented material.

2. An unfrozen zone, into which the freezing front has not yet advanced.

3 A frozen fringe, or partially frozen zone, in which some pore sequences are ice filled and others are ice free.

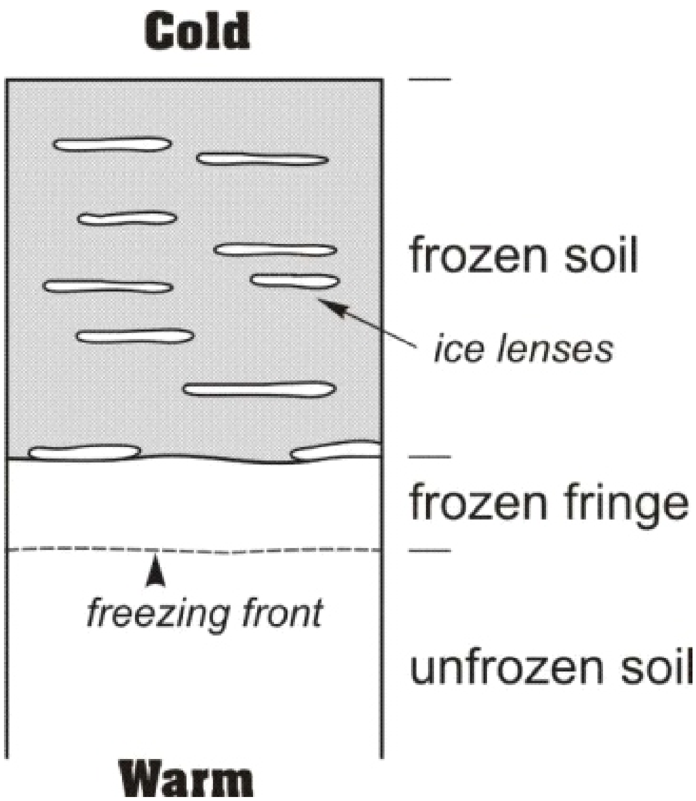

Figure 1: Schematic of freezing soil

FREEZING POINT DEPRESSION (FPD)

FPD occurs for two reasons:

1. Confinement of ice nuclei in small

spaces (pores), increases the pressure within the ice (the ice-water surface pulls inward on it) and thereby lowers it freezing point relative to unconfined ice. This serves to delay penetration of projections from the base of an ice lens through pore necks into underlying pore space.

2. Soluble salts and exchangeable ions that satisfy soil particle surface charge osmotically depress the freezing point of the soil water. Because exchangeable cations are constrained from moving any substantial distance from the surface charge site they satisfy, their presence maintains an unfrozen film of water between soil particle surfaces and ice in the soil.

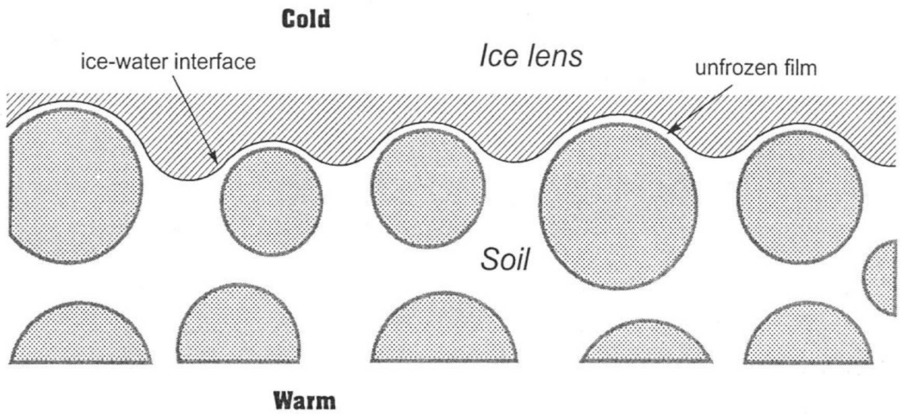

Figure 2. Ice lens base in the absence of a frozen fringe

Figure 2 indicates the situation where an ice body on/in the soil has formed but the ice has not yet penetrated into the pore space below the ice lens. At this time, ice projections extend downward from the ice lens base, but the temperature is not sufficiently low for ice to be stable in the pore neck. The temperature gradient is extracting heat upward, but the ice lens basal surface does not constitute an isotherm, rather, the ice base is colder above the soil particles than on the projection into the pore. The coldest location above the particle is the least accessible place for water delivery in the unfrozen film, and the warmest place on the ice lens base is the tip of the projection into the pore. Ergo, temperature gradients exist between the ice surface over the pore space and that over the particle.

At each location along the ice lens surface, the osmotic concentration of the solution in contact with the ice is controlled by the local temperature. If the solution is too dilute to be in equilibrium with the ice at that temperature, ice forms; the maximum solution concentration is that which represents equilibrium for the local temperature. Thus the temperature gradient creates an osmotic gradient along which water flows to re-supply the unfrozen film. This lifts the overlying ice lens (i.e. heave occurs). Along with the lifting of the ice lens, ice will grow onto the tip of the projection so that the curvature appropriate to the local temperature is retained.

FROZEN FRINGE DEVELOPMENT

If the heat flow to the ice lens base above the particle (by conduction, sensible heat flow and latent heat of fusion) is insufficient to meet the heat extraction capabilities of the temperature gradient, the temperature all along the ice base will decrease, and at some time, the temperature at the projection tip will become sufficient for the projection to penetrate through the pore neck and grow into the pore space below. The projection, now called an ‘ice finger’, grows through the pores until it reaches pore necks that it cannot penetrate through under the local temperature conditions (Figure 3).

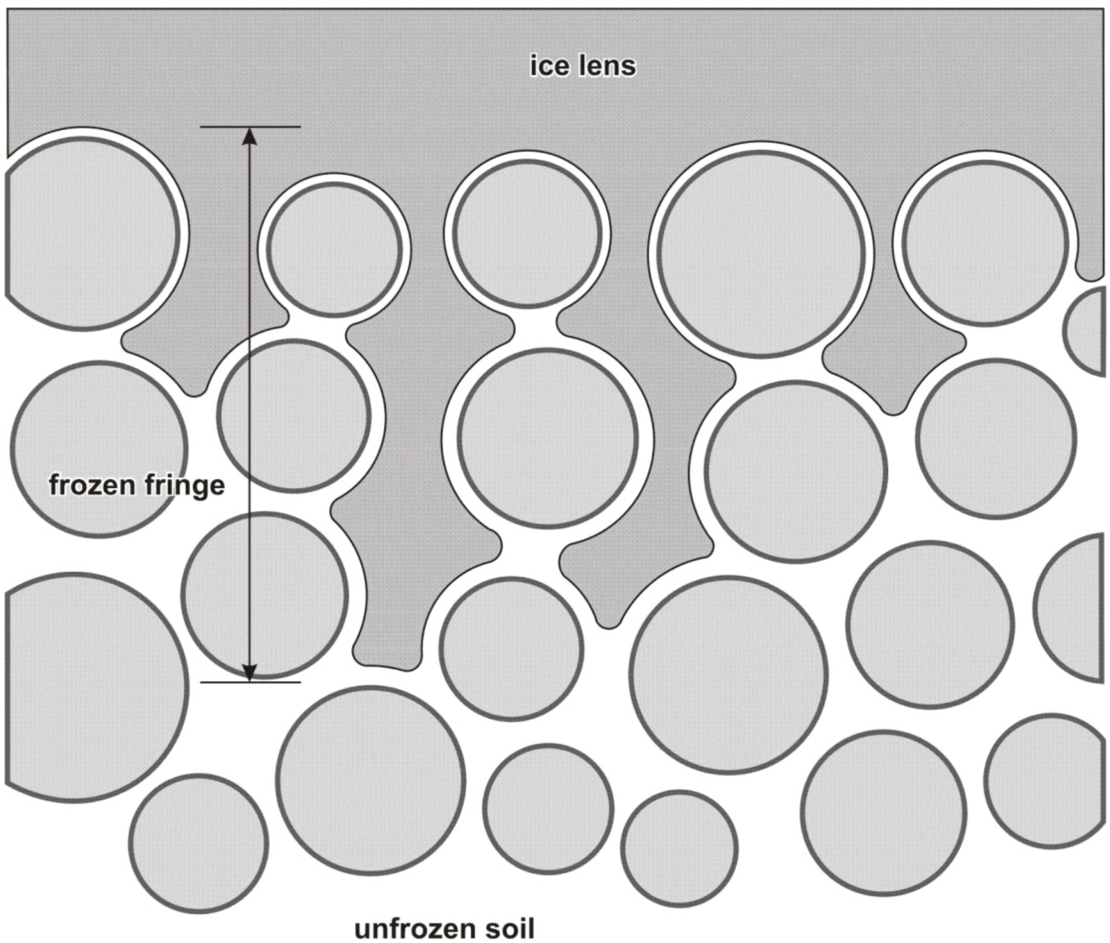

Figure 3. The frozen fringe, with ice fingers in pores below the ice lens

The occurrence of ice fingering into the pore space does not stop the ice lens from experiencing further growth. A temperature gradient, and hence an osmotic gradient, exists along the ice fingers from the unfrozen film above the particle at the ice lens base to the tips of the ice fingers. Water moves along this gradient and continues to re-supply the films above the particles. Continuing heave of the lens above the particles drags the ice fingers upward through the pores. This induces melting, upward movement and re-freezing (regelation flow) of water of those parts of the ice fingers not directly in line with the pore necks. Water also moves upward in pore sequences in the frozen fringe zone in which ice has not formed.

Eventually, the flow of water through the frozen fringe to the base of the lens is insufficient to meet the demands of heat extraction by the temperature gradient. The temperature in the frozen fringe decreases and a new ice lens will be initiated at a lower position. The initiation of the new lens ends the stage of the upper lens being the primary location of frost heave. Growth of colder lenses will continue slowly, because water flow continues, along the temperature gradient, through unfrozen films between the top of a newer lens and the base of the older, colder lens above.

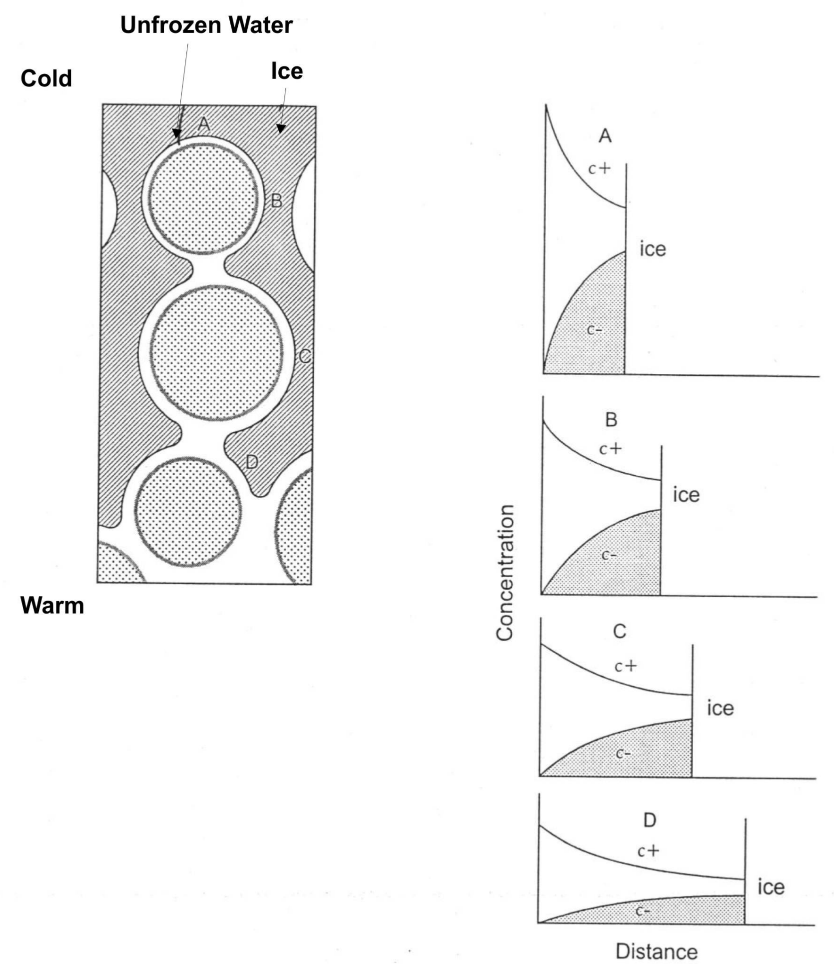

Figure 4. Left: an ice finger in the frozen fringe. Right: thickness of unfrozen films, ion concentrations in unfrozen films, and relative solution concentrations at the film/ice finger interface, for locations A, B, C and D in

the frozen fringe.

FROST HEAVE SUSCEPTIBILITY

The susceptibility of a soil to frost heave is determined by its ability to support ice lens growth, as determined by the ability of ice to propagate through the pore space, the ability to supply water to the portions of the ice lenses situated above soil particles, and the ability to transmit water through the unfrozen soil to the freezing front.

In **coarse soils** (sands) ready propagation of ice into large pores and difficulty of transmitting water to feed the ice lens above the soil particles effectively prevents frost heave. Even the expansion of water on freezing is accommodated by the expulsion of water to the unfrozen zone below.

In **medium textured soils**, ice penetration of pores is delayed, and water is easily supplied to both the ice lens base above the particles, and to the freezing front. In **clay-rich soils**, ice lens growth is restricted by the ability to supply water to the freezing front.

Consequently, clean sands are not frost susceptible, although a relatively small amount of silt and clay in sands renders them frost susceptible; silts and loams tend to be very frost susceptible; clays have limited (but still problematic) frost susceptibility.

HEAVING PRESSURES

In the short term, heaving pressure is limited by the temperature and osmotic pressure at the base of warmest growing ice lens. Over a long term of steady state conditions of heaving (eg. arenas with artificial ice, sub-0C buried pipelines), maximum heaving pressure is determined by the temperature at the base of the slowly growing, coldest ice lens.

For references and further detail see: Torrance and Schellekens, 2006, Polar Record, 42: 33-42