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Aspects of Ice Lens Growth in Soils

by E. Penner

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RÉSUMÉ

Les caractéristiques de croissance de différentes lentilles de glace se trouvant dans des sols naturels ont été étudiées en laboratoire par la méthode du contrôle de température par échelons. Le rythme de croissance augmente rapidement après l'apparition des lentilles de glace, puis il décroît pendant une longue période. La température à l'interface de croissance des lentilles décroît continuellement pendant la formation de celle-ci.

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ASPECTS OF ICE LENS GROWTH IN SOILS

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ABSTRACT

Growth characteristics of individual ice lenses in natural soils have been studied in the laboratory using ramped temperature control. The growth rate rises rapidly after ice lens initiation and this is followed by a protracted period of decreasing growth. The temperature at the growing face of the lens decreases continuously during its formation.

INTRODUCTION

Ice lenses are a common feature of the frost heaving process in soils. It is surprising, therefore, that relatively few attempts have been made to study the details of the nature of the growing ice lens since the early studies of Tabor (1924) and Beskow (1935). Martin (1959) theorized about the rhythmic nature of ice lens growth and compared the lensing process to Liesegang ring formation. Miller proposed two types of ice lens formation, primary and secondary, and described how a frozen fringe plays a major role in secondary heaving; he has contributed two important papers in the field (1977, 1978). Development of the concept culminated in a paper by O'Neill and Miller (1980) that formulated a numerical frost heave model based on the existence of a frozen fringe. The presence of a frozen fringe is also basic to the mechanistic theory of ice lens formation in fine-grained soils (Konrad and Morgenstern, 1980). Although it is generally recognized that formation of ice lenses is fundamental to the frost heaving process, their growth characteristics in soils have not been investigated to an extent consistent with the importance of the phenomenon.

In the course of recent laboratory studies, improvements were made in the temperature control of the freezing process. The freezing technique now being used, a refinement of the "ramped freezing" method introduced by Myrick et al. (1982), makes it possible to measure growth rate and temperature changes in the ice lens during its formation. Such observations form the basis of this paper.

METHODS AND MATERIALS

Frost cell

The 10-cm-diameter frost cell (Fig. 1) used in the experiments is similar to the model designed by W. Slusarchuk while employed by Northern Engineering Services in Calgary, Alta., but modified (Penner and Ueda, 1977) by a basic change in the application of overburden pressure and the addition of temperature-controlled heat exchangers at both ends of the 10-cm-long sample.

The external water supply is, in all cases, held level with the porous plate at the top of the cell. An independent total heave measurement is made with a direct-current displacement transducer (DCDT) mounted between the top of the cell and the heave transfer pipe (Fig. 1). Heave measurements are made to a precision of ± 0.01 mm based on water intake, but independent heave measurements with the displacement transducer have a precision of ± 0.002 mm. Ten thermistors are mounted along the sample walls in contact with the samples. The three nearest the cold end are spaced at 0.85-cm intervals; the rest are 1.27 cm apart. Leads to each thermistor encircle the inside of the cell in shallow grooves at the level of the thermistor beads to reduce lead thermal con-

Fig. 1. (a) Frost cell, (b) Hydrometer analyses of soil No. 1 and 2.

duction errors. All thermistors were calibrated to 0.001°C , based on previously-calibrated platinum thermometers.

Experiments with the cell were carried out inside a constant-temperature chamber held close to the mean of the sample end temperatures. Freezing of the sample was from the bottom upwards, and resistance to movement of the unfrozen portion was reduced by the use of a lubricated teflon film inside the cell.

Temperature control

The temperature baths that supply liquid coolant to heat exchangers at the ends of the sample are located outside the constant-temperature chamber. A dedicated multi-tasking HP 1000, Model 6, mini-computer with the required periphery units running under an RTE-A operating system is used to control the temperature of the liquid coolant, to measure sample temperatures, water intake and heave, and to store and graph results. The computer, in combination with a multiprogrammer unit, is capable of

changing the temperature at each end of the sample at a selected rate. This arrangement allows a mode of freezing known as "ramped temperature" freezing and permits the use of a wide range of frost penetration rates, including those observed under various field conditions.

The significant feature of the computerized sample-end temperature control is that the external liquid baths serve as slaves to the temperature needs of the heat exchangers at each end of the sample. This method of control has most of the features of a proportional controller and is capable of maintaining the sample end temperatures to within $\pm 0.004^{\circ}\text{C}$. The system is also capable of changing the end temperatures of the sample according to a pre-selected rate in the ramped temperature mode.

Sample preparation

Samples for the frost cell were prepared from sieved, air-dry soils by adding sufficient water to bring the moisture content to just above the predetermined liquid limit. The wet soil was then stored in

a closed container for several days to equilibrate. It was placed in layers in the cell and consolidated, in steps, to a final pressure of 500 kPa. The pressure was then reduced to 50 kPa and the sample was allowed to expand to its equilibrium volume before the freezing run was initiated.

Initiating freezing

The loaded cell was allowed to temper in the constant-temperature chamber overnight, with the external water supply connected and the starting temperatures at each end in the control mode. A double-valve system at the cold-end heat exchanger permitted coolant to be circulated temporarily at -10°C to begin a test. Initiation of crystallization within the sample caused a sudden rise in temperature at the cold end owing to release of latent heat, and this was the signal to circulate the cold-side coolant at the test temperature. At this point, computer control of the sample cold-side temperature was reinstated in the selected mode, i.e., either ramped temperature freezing or one-step.

Soil sample X-ray photographs

A portable 200-kV X-ray generator was used to produce X-ray photographs pinpointing the location of the growing ice lens while heaving was in progress. This, together with a temperature profile taken at the same time, allowed an estimate of temperature at the growing face of the lens. An 8-min exposure time at full power was sufficient to provide the photograph detail required, using Industrix AA film sandwiched between one set of fluorometallic and another set of 0.254-mm lead intensifying screens. During exposure, the loaded film holder was mounted directly behind the frost cell inside the test chamber. The X-ray beam was collimated so that the image of the whole cell would cover the $20 \times 25\text{-cm}$ film at a distance of about 2 m.

EXPERIMENTAL RESULTS

Effect of freezing rate on ice lens thickness and frequency

It was shown previously by Czeratzki and Frese (1958) and by McGaw (1977) that both thickness

and frequency of ice lenses are dependent on the frost penetration rate. A preliminary set of freezing experiments was carried out, therefore, to establish the freezing rates (ramped temperature rates) required to grow ice lenses of manageable size for studying ice lens temperature/growth rate relations.

The soil passed the 100 sieve, had a clay-size content of 29% by weight, and is referred to as soil mix No. 1 (Fig. 1b). The sample was placed in the cell at a moisture content of 43% by dry weight. Consolidation to 500 kPa reduced the moisture content to about 20%.

The ramped temperature rates in this investigation were 0.01, 0.02, 0.05, $0.1^{\circ}\text{C}/\text{day}$, giving nominal 0°C isotherm penetration rates of 1.1, 2.2, 5.5 and 11 mm/day, respectively. In addition, a one-step temperature-heaving experiment was carried out for comparison. X-rays of the ice lenses developed at the various frost penetration rates are shown in Fig. 2. Based on these results it was decided that the lower rates of frost penetration, 1.1 and 2.2 mm/day, would provide ice lenses of a suitable size to permit several X-rays to be taken of one ice lens over a period of a day to follow the growth temperature pattern.

Fig. 2. Comparison of lens size and frequency at different freezing rates.

Freezing run to determine ice lens growth rates and temperature

Details are given for one freezing run to familiarize the reader with the nature of the experiment, particularly the methods used to determine ice lens growth temperatures and rates. Freezing was carried out by ramping both end temperatures at precisely $0.02^{\circ}\text{C}/$

Fig. 3. (a) Ramp freezing method. Record of sample end temperatures ramped at $0.02^{\circ}\text{C}/\text{day}$, soil No. 1, run No. 1. (b) Record of 0°C isotherm penetration, ramped temperature rate $0.02^{\circ}\text{C}/\text{day}$, soil No. 1, run No. 1. (c) Record of total heave and water intake heave, ramped temperature rate $0.02^{\circ}\text{C}/\text{day}$, soil No. 1, run No. 1. (d) Temperature gradient in sample during X-ray No. 5, ramped temperature rate $0.02^{\circ}\text{C}/\text{day}$, average temperature gradient approximately $0.1^{\circ}\text{C}/\text{cm}$, soil No. 1, run No. 1. (e) Positive prints of X-rays taken during run No. 1, soil No. 1, ramped temperature rate $0.02^{\circ}\text{C}/\text{day}$. (f) Increase in heave rate during growth history of ice lenses, run No. 1, soil No. 1, ramped temperature rate $0.02^{\circ}\text{C}/\text{day}$.

day, giving a 0°C isotherm penetration of roughly 2.2 mm/day. The pattern of end temperatures for the complete period of the experiment is given in Fig. 3(a). Note that the starting end temperatures were -0.35°C and 0.55°C . The movement of the 0°C isotherm is shown in Fig. 3(b), and the heave-time curve in Fig. 3(c). The observed deviations in the heave-time curve are the result of ice growth rate changes during ice lens formation. The growth period for each lens as well as the times at which X-ray photographs were taken are indicated in Fig. 3(c).

Figure 3(d) shows the temperature distribution in the sample when the last X-ray, No. 5, was taken. As each X-ray photograph shows both the ice lens and the position of the thermistor beads, the temperature of the growing face of the ice lens can be estimated by interpolation between temperatures above and below the position selected. Positive prints of all five X-rays are given in Fig. 3(e). Figure 3(f) shows the heave rate plotted for the second, third, and fourth ice lenses as a function of time. The rapid increase when a new lens is initiated, followed by a slower decrease rate in heave rate after the maximum was attained, are the main features of the heave rate curve.

TABLE 2

Ice lens data. Soil No. 1, run No. 2, ramped temperature $0.02^{\circ}\text{C}/\text{day}$

X-ray no.	Lens no.	Lens temp* (0°C)	0°C depth (mm)	Lens depth (mm)	Lens 0°C separation (mm)	Time (min)
1	Well into 3	-0.197	43.4	14.3	29.1	3020
2	Well into 4	-0.191	49.8	21.4	28.4	7168
3	Near middle of 4	-0.197	50.3	21.4	28.9	7533
4	Past middle of 4	-0.215	52.4	21.6	30.8	8604
5	Near end of 4	-0.212	53.2	22.4	30.8	9066
6	Near start of 5	-0.177	54.4	26.9	27.5	10052
7	Near middle of 5	-0.185	55.2	27.0	28.2	10507
8	Past middle of 5	-0.193	57.1	27.6	29.5	11484
9	Past of middle 5	-0.200	58.0	27.7	30.3	11951
10	Near end of 5	-0.211	59.6	27.9	31.7	12933
11	End of 5	-0.217	60.6	28.1	32.5	13388
12	Near start of 6	-0.177	66.1	38.1	28.0	17255
13	Before middle of 6	-0.184	66.9	38.1	28.8	17709
14	Middle of 6	-0.190	68.4	39.3	29.1	18691
15	Near end of 6	-0.192	69.0	39.5	29.5	19143
16	Start of 7	-0.169	69.8	42.7	27.1	20126
17	Before middle of 7	-0.175	70.5	43.0	27.5	20583
18	Before middle of 7	-0.178	72.0	45.3	26.7	21570

*Corrected by -0.068°C for combined overburden P and friction component of 75.4 kPa using the Clapeyron equation.

TABLE 1

Ice lens data. Soil No. 1, run No. 1, ramped temperature rate $0.02^{\circ}\text{C}/\text{day}$

X-ray no.	Lens no.	Lens temp* (0°)	Lens/ 0°C separation (mm)	Time (min)
1	Start of 3	-0.172	26.08	7,115
2	Midway through 3	-0.190	27.84	8,619
3	Near end of 3	-0.202	29.72	10,009
4	Start of 4	-0.170	26.55	11,382
5	Middle of 4	-0.182	27.92	12,816

*Corrected by -0.068°C for both overburden P and friction component of 75.4 kPa using the Clapeyron equation.

Table 1 gives the lens growth temperature at the time of the X-ray, the distance between the lens face and the 0°C isotherm, the time, and the state of development of the ice lens.

The results obtained in the study on changing conditions at the growing face of the ice lens stimulated interest in a program to determine more closely the growth characteristics of individual lenses. Many ex-

(b)

Fig. 4. (a) Record of total heave and water intake heave, ramped temperature rate $0.02^{\circ}\text{C}/\text{day}$, soil No. 1, run No. 2. (b) Positive prints of X-rays of soil No. 1, run No. 2, ramped temperature rate $0.02^{\circ}\text{C}/\text{day}$.

(a)

(b)

Fig. 5 (a) Record of total heave and water intake heave, soil No. 2, ramped temperature rate $0.01^{\circ}\text{C}/\text{day}$. (b) Positive prints of X-rays, soil No. 2, run No. 3, ramped temperature rate $0.01^{\circ}\text{C}/\text{day}$.

TABLE 3

Ice lens data. Soil No. 2, run No. 3, ramped temperature rate $-0.01^{\circ}\text{C}/\text{day}$

X-ray no.	Lens no. and stage	Lens temp* ($^{\circ}\text{C}$)	Lens/ 0°C separation (mm)	Time (min)
1	Start of 1	-0.143	24.43	3,513
2	Towards end of 1	-0.163	26.94	7,206
3	Middle of 2	-0.141	24.99	11,435
4	Start of 3	-0.152	25.87	15,771
5	Towards end of 3	-0.173	27.70	18,149
6	Start of 4	-0.151	24.75	21,831
7	Towards end of 4	-0.174	26.53	26,276
8	End of 4	-0.178	26.94	29,150
9	Start of 5	-0.163	24.73	31,700
10	Towards end of 5	-0.183	27.82	36,119
11	Start of 6	-0.167	24.96	37,742
12	Middle of 6	-0.183	26.68	40,685
13	Start of 7	-0.164	23.65	46,052

*Corrected by -0.068°C for both overburden P and wall friction components of 75.4 kPa using the Clapeyron equation.

perimental freezing runs followed, but space permits only a few containing the main features to be reported.

For the experiment designated Run 2, sample preparation, starting end temperatures, and the freezing mode were as given for Run 1. Figure 4(a) shows the total heave and water intake heave curve for the ice lens growth period; the time of X-rays is also indicated. Figure 4(b) contains the positive prints of all the X-rays; as many as six were taken during the growth history of a single lens. As before, the lens growth temperature at the time of the X-ray, the distance between the lens faces and the location of the 0°C isotherm, the time, and the state of development of the ice are all given in Table 2.

The soil sample was prepared, as described previously, to permit determination of lens growth characteristics in soils of higher clay content. Again, all the material passed the 100-mesh sieve, but the clay-size content was 41%. This material was designated soil No. 2, (Fig. 1b). Consolidation to 500 kPa, in stages, reduced the initial moisture content to about 26% by dry weight. The ramped temperature rate used

was $0.01^{\circ}\text{C}/\text{day}$, giving an approximate 0°C isotherm penetration rate of about 1.1 mm/day.

The results for Run 3 with soil of higher clay content are given in Fig. 5 and Table 3. Figure 5(a) gives the heave-time relation for both total heave and water intake heave again, the growth period of each lens is indicated as well as the time of X-ray. Figure 5(b) shows positive prints of the X-rays taken, and Table 3 contains estimates of ice lens temperature, time of X-ray, and stage of development of the lens.

DISCUSSION

The main growth characteristics of the ice lenses observed in studies with two different soil gradations were:

(a) varying growth rates — both heave rate (as measured by the DCDT mounted on the cell between the heat transfer pipe and the body of the cell) and water-intake (supplied from a source external to the frost cell) changed during the growth period of a lens, as shown by the curve in Fig. 3(f) and the results in Figs. 3(c), 4(a) and 5(a).

(b) varying growth temperatures — temperatures as measured at the growing ice face of the active ice lens varied as indicated in Tables 1–3. (Soil No. 1 range, -0.170° to -0.215°C ; soil No. 2 range, -0.141° to 0.183°C .)

Growth rate characteristics

Changing growth rates during ice lens formation are evident in the three main experiments and are examples of many such heave experiments carried out in the ramped temperature mode. The phenomenon has not been reported previously, nor has it been observed before by the author in using the one-step freezing mode. To observe the behaviour pattern of ice lenses by the present technique the lens must extend across the entire sample and, of course, a succession of lenses must develop, i.e., there must be rhythmic lensing (Martin, 1959).

Ice lenses extending across the entire sample have not been previously observed in soils with a high clay content ($\geq 50\%$), with one exception. In the one-step freezing mode the final lens in heavy clays did extend

over the entire area of the sample, perhaps an indication that the rate of freezing was much lower than has been used for the ramping temperature mode. Previous papers (Penner and Goodrich, 1981; Penner, 1982) have described the temperature pattern with time, rate of freezing, and pressure associated with the final ice lens.

The change observed in the growth rate of an ice lens by means of the present technique, under conditions not unlike those occurring in the field under natural conditions, has a distinctive pattern and was a common feature of all the heave-time curves. With the initiation of a new lens, the heave rate rises rapidly to a maximum, then tails off gradually to a minimum just before initiation of the next lens. These characteristics are illustrated in Fig. 3(f), which was calculated from the results of Run 1, Fig. 3(c). The magnitude of the heave rate increases ranged from 35% to 42% for this particular run when compared with a minimum heave rate of 0.78 mm/day.

Growth temperature characteristics

In his treatise on rhythmic ice banding in soils, Martin (1959) predicted falling ice front temperatures during lens formation. More recently, Konrad and Morgenstern (1980) also predicted a temperature decrease, although their theory of lens initiation and growth is radically different. Both predict a steadily reducing water supply to the growing ice lens, but there is a major disagreement about the cause of the decreased water flow. From measurements of temperature at the face of the developing ice lens a clear temperature pattern emerges (Tables 1–3). It is most evident in Table 3, column 3, because of the frequency of the X-rays. The ice lens temperature falls progressively after lens initiation and is at its lowest prior to the initiation of a new lens. Undoubtedly, lower temperatures are being forced on the ice lens, owing to the temperature ramping process, but growth continues at the same location for some time at a decreasing rate.

One would also expect that the Miller frozen fringe is growing in thickness, since the distance between the lens and 0°C isotherm is increasing. Based on the concept of a frozen fringe the reduced rate of lens growth could be attributed to the longer path the water must traverse as a result of the thickening

frozen fringe. The rise in temperature when lens growth jumps to a new location is probably due, in part, to increased rate of latent heat release as the remaining liquid water within the “frozen fringe” freezes. In addition, the new lens forms on the warm side of the old lens within the confines of the frozen fringe and at this stage is increasing in growth rate.

Table 2 gives the depth of the growing face of the ice lens and the depth of the 0°C isotherm at the time of each X-ray. At the frost penetration rates used a new ice lens is initiated somewhere between 4 and 10 mm from the growing face of the last ice lens, although the distance from the previous ice lens to the 0°C isotherm is some 30 mm. These measurements support the concept that the new ice lens is not initiated by spontaneous nucleation but more likely by the ice crystals in the frozen fringe.

That there is a sudden rise in temperature in the vicinity of the newly initiated ice lens is evident from the temperature sensed by the thermistors. This can best be illustrated by plotting the isotherms at various temperatures in the vicinity where the ice/water phase change is occurring. A particularly good example of this is given in Fig. 6. The effect of the latent heat dissipates rather slowly over many hours. It may be seen that the heat release is most pronounced in the -0.20° , -0.25° and -0.30°C isotherms, which are in the vicinity of lens formation. The isotherms above and below these values are less affected. The extent of this effect is not fully understood at the time of writing.

Fig. 6. Record of isotherms for soil No. 1, run No. 2, ramped temperature rate 0.02°C/day , see Fig. 4(b) and Table 2.

FURTHER ASPECTS OF LENS INITIATION AND GROWTH

A theoretical basis for the water-to-ice transition process in frost heaving soils is the Clapeyron equation, although its applicability has been questioned. The equation is

$$-\Delta H_f \frac{\Delta T}{T} = \frac{P_i}{\rho_i} - \frac{P_w}{\rho_w} \quad (1)$$

where P_w is pressure in the water, P_i is pressure in the ice (overburden pressure), ρ_w and ρ_i are densities of water and ice, respectively, ΔH_f is latent heat of the water/ice transition, T is absolute temperature of the water/ice transition and ΔT is the difference between the temperature of freezing and 0°C . In the strictest sense, this equation should be invoked only under equilibrium conditions. As the ice and water pressures in the ice segregation process can only be maintained in the presence of a temperature gradient and the concomitant heat flow, such a process should probably not be considered to be at equilibrium thermodynamically.

A further assumption in using the equation is that the particulate material is solute free, but in natural soils there are always some dissolved solutes in the pore water. In the present case the pore water salt content was $0.8^\circ/\text{oo}$.* Added to this is the problem of solute concentration at ice/water interfaces, resulting from solute rejection during ice formation. Assuming that solute rejection causes solute concentration in the pore water, there is a question about the location of rejection, i.e. at the ice lens or in front of the frozen fringe.

Calculations made for Run 1 show that if lenses reject all the solutes contained in the pore water at the freezing plane, the solute content in the pores of the frozen portion of the sample at the end of the experiments will be increased from the original value by about 68%. Hallet's (1978) paper on solute redistribution in freezing ground presents a schematic diagram of the influence of solutes at the ice/water interface, but more information is required before such a complicated scenario can be described thermo-

dynamically as far as ice lens rejection of solutes is concerned.

In a previous paper, Penner and Goodrich (1981) made tentative calculations of the suction induced in the pore water, using the temperatures measured at the growing face of the ice lens after allowing a freezing point depression for the average salt content in the pore water. In the light of the present studies the validity of such calculations must remain highly speculative until the influence and location of rejected solutes can be resolved at the ice/water interface during heaving in soils.

SUMMARY

Frost heave experimental results show growth characteristics of individual ice lenses in natural soils. The growth rate rises rapidly after a lens has been initiated, followed by a protracted period of decreasing growth. The measured temperature of the growing face of the ice lens decreases continuously until the next lens starts to form. The rapid increase in latent heat release in the period following lens initiation can be seen on plots of isotherms, and is thought to be partly due to intra-lens freezing combined with much higher rate of growth during the early period of lens growth.

The initiation of a new lens may not result from spontaneous crystallization but rather from ice in the frozen fringe. It is to be noted that the cold end of the sample was equilibrated at -0.35°C overnight before the heaving experiments were initiated, and that no spontaneous crystallization occurred at this temperature. During the runs the temperature of a new lens was in the regime of -0.20° to -0.25°C ; new lenses are therefore thought to develop within the ice-rich frozen fringe. The nature of the lensing phenomenon did not change when specimens consisted of soils with higher clay content.

Observations of a rapid increase in heat release during lens initiation, determination of the changing temperature at the growing face of the developing lens, and variable growth during the history of lens formation were made possible by the greater accuracy of the computer-controlled, ramped-temperature freezing mode and computer-aided measurements of moisture flow and frost heave.

*Parts per thousand.

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