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Ice Lensing in Layered Soils

by E. Penner

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Ice lensing in layered soils

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The ice lensing phenomenon in layered soils, a condition that simulates the process of ice growth in varved soils, has been studied experimentally. Under the limited conditions of layer thicknesses, soils used, freezing rates, and moisture conditions, ice lenses formed at the face of the fine-textured (clay) layer when it was encountered by the freezing plane. Only minor heaving occurred in the coarse-textured (silt) layer when its thickness was increased.

Key words: frost action, ice lensing, frost heaving, varved soils, layered soils.

Le phénomène de formation de lentilles de glace a été étudié dans des sols multi-couches, condition qui favorise le processus de croissance de glace dans les sols varvés. Sous les conditions limitées des épaisseurs de couches, des sols utilisés, des vitesses de pénétration de gel, et des conditions d'humidité, des lentilles de glace se sont formées à la surface de la couche de sol à grains fins (argile) lorsqu'elle était traversée par le front de gel. Seulement un soulèvement mineur se produisait dans la couche à grains grossiers (silt) lorsque son épaisseur était augmentée.

Mots clés : action du gel, formation de lentilles de glace, soulèvement dû au gel, sols varvés, sols multi-couches.

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Introduction

During previous permafrost investigations in northern Manitoba, a number of profiles consisting of ice-rich varved sediments were examined (Johnston *et al.* 1963). The conclusion from this study was that "there was no apparent relation between the location of ice lenses and the soil varves." Russian papers reviewed on the subject of varved clays in permafrost regions (Zhestkova 1963; Shpolyanskaya 1965) refer to the extensive horizontal ice lensing between soil layers and the crystal orientation of the ice, but do not give information about any preferred positioning of the ice in relation to the layers.

Soil samples of alternating silt and clay layers were prepared for a laboratory study of ice lens formation in layered soil. The samples were intended to simulate the annual structure of varved clays, a well-known glacial soil deposit found extensively in Canada.

The complexity of the geological history of varved sediments (Eden 1955) and the postdepositional freezing and moisture regime make any attempt at simulation somewhat tenuous. The results of these simulation studies are however, not only of interest in attempting to unravel the ice lensing phenomenon in varved soil deposits but are also helpful in elucidating the behaviour of ice lensing in soils generally. These studies became possible because of recent improvements in equipment and techniques for freezing soils in the laboratory (Penner 1985).

Materials and methods

Soil sample preparation

The two soil types used in the preparation of the layered samples were Leda clay for the clay layers and a 50/50 mix of two samples of Fairbanks silt for the coarser silt layers. The grain size curves are given in Fig. 1. The method of preparation was to add sufficient water to the soil so that the moisture content would be well above the liquid limit—72% for the clay and 52% for the silty soil. The soils were then placed in alternating layers in the frost cell using a large medical syringe. Sample 1 was prepared by using about 60 cm³ of the coarse-grained soil (silt layer) and 27 cm³ of the fine-grained soil (clay layer) for each composite layer. For sample 2 the volume of coarse-grained soil was increased to 142 cm³; the fine-grained soil volume was kept at 27 cm³.

FIG. 1. Grain size analyses of soils used.

Small metal markers (11 mm diameter brass washers, 0.82 mm in thickness) were placed above and below each clay layer so that the layers could be easily identified in the X-ray photographs. In sample 1 a total of 12 composite layers was used, resulting in a height of about 96.0 mm after consolidation under a stress of 500 kPa (in stages). The after-consolidation thickness of the clay layers was about 2.5 mm and of the silt layers, about 5.5 mm. In the second sample the clay layers were the same thickness as in the first sample but the silt layers were made much thicker (after-consolidation thickness of 13 mm). Because of the added thickness of the silt layers, the number of layers of each type was reduced to six, giving a total height of 93.0 mm after consolidation.

Frost cell and freezing technique

The frost cell used (Fig. 2) and the temperature control of the ramp freezing process of the sample, along with the X-ray technique, have been described in detail elsewhere (Penner 1986). The design of the frost cell used in these experiments is similar to the model designed by W. Slusarchuk at Northern Engineering Services in Calgary, Alberta; it has been modified (Penner and Ueda 1977) by a basic change in the application of overburden pressure and by the addition of temperature-

FIG. 2. Schematic of frost cell.

controlled exchangers at both ends of the 10 cm long sample. The external water supply in all cases was held level with the porous plate inside the cell. The vertical stress on the sample was 50 kPa and the frictional component during heaving was estimated at 25 kPa. The initial thermal condition to which the sample was equilibrated overnight was -0.25°C at the cold end (bottom of sample) and $+0.6^{\circ}\text{C}$ at the warm end (top of sample). After crystallization was induced to start the heaving of the sample, the latent heat of freezing increased to some extent the temperature of the cold side but this was quickly brought down to the starting temperature by the circulating fluid. Water intake and heaving measurements were estimated to be accurate to ± 0.01 mm (in terms of heave) and ± 0.002 mm displacement, respectively.

Freezing in all cases was from the bottom of the sample. It is important to appreciate this when interpreting the location of the ice lens formation with respect to the position of the different soil layers in the X-ray photographs. From measured temperature gradients in the sample and the position of the ice lens (determined by X-rays), it was possible to determine the temperature of the growing face of the ice lens as heaving was taking place.

The temperature ramp freezing rate¹ used for sample 1 was reduced from 0.05 to $0.01^{\circ}\text{C}/\text{d}$ midway through the experiment (Fig. 3). For sample 2 the freezing rates were changed more frequently, ranging again from 0.01 to $0.05^{\circ}\text{C}/\text{d}$, but in four equal steps. A final ramping rate of $0.015^{\circ}\text{C}/\text{d}$ completed the freezing program for sample 2 (Fig. 4). The different ramping

FIG. 3. End temperatures during the freezing of sample No. 1, as a function of time.

rates and soil layer thicknesses selected were intended to provide a range of conditions for ice lenses to form in different parts of the system. The frost penetration rates achieved by the imposed ramping rates ranged from 2 to 5 mm/d. The similarity of these rates to actual field conditions would depend on the weather, the depth below ground surface that freezing was taking place, soil type, and geographic location.

Results and discussion

Sample 1

The results of both total heave and water intake heave are

¹The temperature ramp freezing technique involves lowering the temperature at both ends of the sample at a uniform rate.

FIG. 4. End temperatures during the freezing of sample No. 2, as a function of time.

FIG. 5. Total heave and water intake heave as a function of time, sample No. 1.

given in Fig. 5 for sample 1, including the number of the ice lens, the time of its formation, the X-ray number, and the ramping rate. The time associated with each lens formed can be seen from the length of the humps on the heave curves. Figure 6 gives the isotherms in the sample in steps ranging from 0.0 to -0.30°C for the complete run. The time at which each lens started growing is given by the deflection of the isotherm, and its position is indicated on the graph by the assigned number of the lens. Lens initiation caused a temporary deflection in the isotherm curves since there was a short period of rapid latent heat release when a new lens was initiated.

Figure 7 shows the changing total heave rate during the experiment resulting from the lensing phenomenon; these rates correspond to the humps in the curves of Fig. 5 and the deflections in the curves of Fig. 6. Finally, Fig. 8 contains the positive prints of the X-rays taken while heaving was in progress to show the location of the lenses with respect to the soil layers. X-ray No. 1 is a portion of the prefreezing X-ray, where the metal markers were located in the sample to show clearly the location of the layers with respect to the ice features. The ice lens marked No. 2 does not show up well in the positive prints,

FIG. 6. Isotherms between 0 and -0.3°C as a function of time, sample No. 1.

although it can be seen clearly in the X-ray negatives. All the remaining lenses are fairly clear. In the lighter prints, e.g., X-ray Nos. 10–14, the thickness of the clay layers can be clearly seen, although on close examination the clay layers are discernible on all the prints. In all cases, the ice lens formed as the freezing plane encountered the dark (clay) soil layer. As freezing was from the bottom of the sample upwards, the ice lenses are in contact with the bottom of the dark layer. The direction of heat flow is indicated in the figure.

Sample 2

The structural difference between samples 1 and 2 was in the thickness of the silt layers. As stated previously, this difference in thickness plus the additional freezing rates used provided a wider range of conditions for variations in ice lens positioning in the layered soil systems.

The total heave and water intake heave curves, as a function of time, are shown in Fig. 9 for sample 2. The ramping rate changes, the location of the lenses, and times of the X-rays are all given on the graph. The increases and decreases of heave rate during the formation of the ice lenses are seen as humps on the curves of Fig. 9. Characteristic of the growth rate curves, shown in Fig. 10, are the relatively rapid growth rate increases to a maximum after the lens was initiated and a slow tailing off on the decrease side of the maximum. The small bumps at locations, A, B, and C were induced by ramp rate increases and, of course, coincide as shown with the times of the ramping rate changes.

Finally, Fig. 11 contains the positive prints of the 12 X-rays taken and all verify that the major portion of the heave can be identified with the ice lenses interfacing with the clay layers as in sample 1. Some minute lenses could be observed in the thick layers of silt in the X-ray negatives of sample 2 but the main movement could be attributed to the extensive lenses that developed when the active freezing plane, proceeding from the bottom of the sample upwards, encountered the clay layers.

Ice lensing process in layered samples

The experimental results obtained in this study are not sufficiently encompassing to apply to all the freezing and moisture conditions that might occur in the field for all types of layered deposits. The results do give insight, however, into the nature of ice lensing in simple layered soil systems and, together

FIG. 7. Heave rate as a function of time, sample No. 1.

FIG. 8. Positive prints of X-rays for sample No. 1, containing closely spaced clay layers.

FIG. 9. Total heave and water intake heave as a function of time, sample No. 2.

with other information found in the literature, enable a preliminary scenario to be developed based on experimental evidence.

It is now known that in frost-susceptible soils, when heave is produced by substantial rhythmic ice lens development, there is an ice lens initiation temperature (LIT) and an ice lens

termination temperature (LTT) (Penner 1986). Both these temperatures are known to be freezing rate dependent, i.e., the faster the rate of freezing the lower the temperature for both LIT and LTT. This trend can be seen both in the previous paper (Penner 1986) and in the results shown here for sample 1 at two rates (Table 1). Unfortunately, in experiment 1, the time of the X-ray did not necessarily coincide exactly with lens initiation or termination because the importance of the timing was not realized. The pattern of the temperature changes, however, is well documented in Table 1.

The suction and (or) pressure developed by the lensing process is also dependent on the pore/grain size of the soil at similar moisture and freezing conditions (Everett 1961; Penner 1967); hence the temperature of ice lens growth is also dependent, on the pore/grain size.

To summarize what is known from previous work:

- Comparison of the ice lens LIT and LTT for two layers must be made at the same temperature ramping rate or other external freezing conditions because both are freezing rate dependent. The overburden pressure must also be the same as it was in these experiments.
- Fine-grained soils have lower ice lens growth temperatures (LIT and LTT) than coarse-grained soils.

FIG. 10. Heave rate as a function of time, sample No. 2.

FIG. 11. Positive prints of X-rays for sample No. 2, containing widely spaced clay layers.

A lensing model illustrated in Fig. 12 has been developed on the basis of measured LIT and LTT for Leda clay at the ramping rate of $0.01^\circ\text{C}/\text{d}$ when it is part of a layered system with a coarse-grained soil such as is shown in Fig. 1. The LIT and the LTT are not available for the silty soil but the lens growth temperature has been measured in the one-step freezing mode at about the same overburden pressure as used here (Penner and Goodrich 1981) and found to be around -0.13°C . On this basis a value of -0.10°C has been assigned to it for the LIT and -0.15°C for the LTT.

The LTT for Leda clay in the layered system configuration has been taken from the end of lens Nos. 7 and 8, Table 1, and is about -0.25°C ; the LIT is taken from the start of lens No. 9, at -0.15°C , for illustration purposes.

The temperature gradients, $a-a$, a_1-a_1 , etc. in Fig. 12, are from the experiments. The clay/silt layers are shown in vertical section, as are the ice lens locations. As in the experiments, the ice lenses lie above the dark layer when freezing is from the top downwards.

Starting with the location of the temperature gradient $a-a$, the temperature at the top of the clay layer is -0.15°C . An ice lens grows at this location until the temperature has dropped to -0.25°C , owing to the continual decrease of temperature at both ends of the sample. The gradient is now at the position marked as a_1-a_1 . The heat released as a result of the phase change is not sufficient to hold the temperature at -0.25°C at that ice lens, and hence that temperature becomes the LTT. During the growth of the lens just terminated, the growth rate has risen to a maximum and decreased to a low rate at the end. The decreasing heave rate, which follows the theory of Miller (1977), is due to the continuously decreasing permeability as the temperature drops in the frozen fringe.

As the temperature decreases, the "freezing front" passes through the silt since the temperature is now well below the LTT of the silt; hence only the *in situ* water freezes. As the position of the temperature gradient a_1-a_1 is established, the temperature at the clay/ice front is at -0.15°C once more; this is the LIT for the clay layer, and lens L_2 starts to grow at an increasing rate

TABLE 1. Ice lens data, sample No. 1

X-ray No.	Lens No. and stage	Lens temperature (°C)	0°C depth (mm)	Lens depth (mm)	Lens/0°C separation (mm)	Time (h)
1	Before freezing					
2	Middle of No. 2	-0.288	44.3	14.5	29.8	45.8
3	Near beginning of No. 3	-0.274	55.7	25.4	30.3	93.6
4	Middle of No. 5	-0.273	71.9	42.7	29.2	165.3
5	Near middle of No. 6	-0.247	78.0	50.8	27.2	189.6
6	Near end of No. 6	-0.285	82.9	51.7	31.2	213.5
Decreased ramping rate from 0.05 to 0.01°C/d						213.5
7	Near beginning of No. 7	-0.221	83.5	58.9	24.6	220.9
8	Middle of No. 7	-0.223	85.1	61.0	24.1	237.5
9	Near end of No. 7	-0.237	86.6	61.9	24.7	262.9
10	Before middle of No. 8	-0.194	89.2	69.6	19.6	313.0
11	Middle of No. 8	-0.209	91.2	69.9	21.3	336.2
12	After middle of No. 8	-0.214	92.5	70.5	22.0	357.6
13	Near end of No. 8	-0.230	94.0	70.7	23.3	381.5
14	At beginning of No. 9	-0.148	94.8	79.2	15.6	405.5
15	Toward middle of No. 9	-0.151	96.7	79.9	16.8	430.9
16	Toward middle of No. 9	-0.156	97.6	80.6	17.0	457.0
17	Near middle of No. 9	-0.162	98.5	80.8	17.7	479.0
18	Near middle of No. 9	-0.169	100.1	81.3	18.8	501.4

FIG. 12. Ice lensing process in two-layered sample of different grain sizes.

until a maximum is reached. In this way the pattern of growth and temperature changes is repeated for each lens as each clay layer is encountered. In the scenario presented here, after the ice lens starts to grow at the surface of the clay layer there is a period when temperatures in the silt layer are favourable for ice lenses to form (between -0.10 and -0.15°C). During this period, however, the silt layer is not only a part of the frozen fringe but also is in the active moisture transmission zone and at a high moisture suction level. This combination of conditions apparently impedes any significant ice lensing in the silt layers while the ice lens is actively growing on the clay layer. When the clay/ice interface temperature drops to -0.25°C , the complete silt layer is below the LTT for this particular silt. As shown previously (Penner 1986), when interlens water freezes this rapid heat release can be seen in the isotherm plot (Fig. 6). Ice crystals are assumed to be present at the initiation of ice lenses (i.e. in the frozen fringe), and hence there is no need for spontaneous nucleation. Ice crystals will not exist all the way down to 0°C , for a number of reasons, the most important being the electrolyte content in the soil pore water.

Summary and conclusions

The ice lensing phenomenon has been simulated in layered soils such as varved soils. Under the limited conditions in the investigation (structure of varved soils, materials used, moisture regime, and rate of freezing), ice lenses formed at the face of the clay layer as the freezing plane approached the interface. Some minor heaving occurred in the silt when its thickness was increased.

Growth rates of the lenses formed rose to a maximum quickly and tailed off slowly to a much lower rate before the next lens was initiated. This pattern was repeated at the slower ramp rates used. At higher ramp freezing rates, and with more closely spaced soil layers, there was a similar rise to maximum but a more rapid falloff as heaving rates decreased.

A model showing the ice lensing process in layered soil has been put forward but the extent of its applicability to the wide range of conditions possible in the field is not known.

The experimental studies reported here were very consistent with respect to the location of the growing ice lens. Ice lensing

was always initiated as the freezing plane approached the clay layer. Field observations carried out by Johnson *et al.* (1963) do not support this consistency; the simple laboratory conditions may not properly simulate the complex conditions that occur in nature.

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