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SOMMAIRE

On a repéré une lentille de glace en croissance dans le sol en conditions de laboratoire, par photographie aux rayons X, afin de connaître la température de la face en croissance active par sa position dans le champ du gradient thermique. On peut montrer qu'en général, les températures de changement de phase sont prévues par l'équation de Clapeyron. La structure de la phase solide semble également suivre l'équation du taux de soulèvement proposée par Penner et Ueda (1978). En cas de soulèvement sous de faibles pressions exercées par les terrains, les lentilles de glace ont tendance à être bien délimitées et à ne pas contenir de sol. Quand la pression est plus forte et le gradient thermique semblable, la lentille a tendance à former une bande plus diffuse, sur une gamme de températures beaucoup plus étendue.

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LOCATION OF SEGREGATED ICE IN FROST-SUSCEPTIBLE SOIL

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ABSTRACT

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X-ray photography has been used to locate the position of a growing ice lens in soil under laboratory conditions in order to establish the temperature of the actively growing face by means of its position in the thermal gradient field. It can be shown that in a general way the phase change temperatures are predictable from the Clapeyron equation. The structure of the ice phase also appears to follow the predictions of the heave rate equation proposed by Penner and Ueda (1978). When heaving occurs at low overburden pressures, there is a tendency for the ice lens to be very discrete and essentially soil free; at higher pressures and under similar thermal gradients it tends to develop in a more diffuse band and over a much wider temperature range.

INTRODUCTION

Understanding of the water/ice transformation process, which results in frost heaving in saturated soil, is normally based on the Clapeyron equation. Its applicability has been somewhat tenuous for frost action, however, because in the strictest sense it should only be invoked under equilibrium conditions. In ice segregation processes the ice and water pressures can only be maintained in the presence of a temperature gradient, and the induced heat flow appears to abrogate the application of the equation. Yet it is often used, and present understanding of the thermodynamics of ice formation has to a large extent come about in this way. Now the application of the Clapeyron equation has been extended to actively heaving systems to obtain at least some quantitative information about the relation of the pressure in the ice, the pressure in the water (negative when the water is in tension), and the deviation of the freezing point ΔT from 0°C. Assuming an absence of solutes and small ΔT deviations (Miller, 1972):

$$\Delta T = (P_w/\rho_w - P_i/\rho_i)/(\Delta H_f/T)$$

where P_w is pressure in the water, P_i is pressure in the ice (overburden pressure), ρ_w and ρ_i are density of water and ice, respectively, ΔH_f is latent heat of the water/ice transition, and T is absolute temperature of the water/ice transition.

Hoekstra (1969) used an indirect method to establish the ΔT—P_i relation for various overburden pressures when water pressure is zero. He employed light photography to locate the ice lens in a sample through transparent cell walls. This permitted a real step forward in thermodynamic understanding of the effect of frost heave pressures.

To establish the temperature at the actively growing face under various conditions of heaving and whether such changes can be predicted even semi-quantitatively using the Clapeyron equation, is the main thrust of this paper. A further area of interest is the structure of the segregated ice under various externally-imposed conditions. Evidence has been presented (Penner and Ueda, 1978; Penner and Walton, 1979) that the zone of ice segregation appears to extend over an increasingly greater distance and temperature range from the 0°C-isotherm as overburden pressure is increased. Fig.1 shows the predicted change in rate of ice accumulation as a function of cold-side temperature and overburden pressure. The ice is apparently located near the 0°C-isotherm at low pressures; at high pressures, on the other hand, the interpretation is that it forms in a more diffuse band and over a wider temperature range.

The study method was designed to create the various conditions described below and to locate the ice phase by X-ray photography through the test cell without interrupting the test conditions.

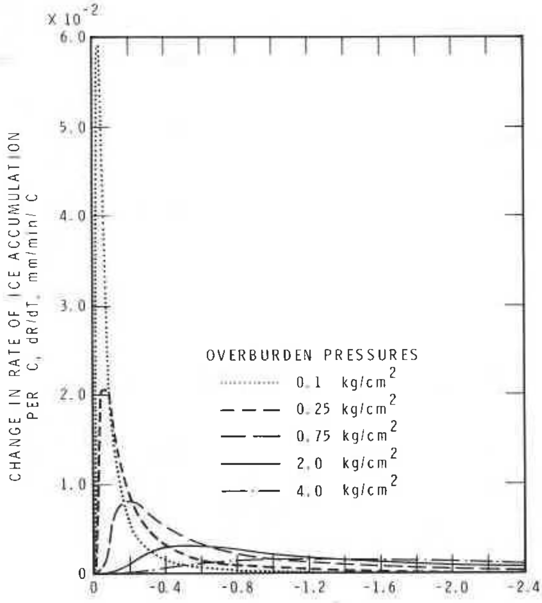


Fig.1. Change in rate of ice accumulation (heave rate) per degree Celsius versus cold-side temperature for Leda clay.

Experimental

The test cell used in these experiments has been described in detail (Penner and Ueda, 1978). It is located in a constant temperature chamber operating at about 4°C controlled to ±0.05°C. The only substantial difference was the replacement of thermocouples by small glass-encased thermistors. These minute sensors, calibrated to ±1/1000°K, were positioned behind a thin teflon sheet at ten different elevations from the cold side: 0, 8.4, 16.8, 25.4, 38.1, 50.8, 63.5, 76.2, 88.9 and 101.6 mm. Temperatures measured after installation were considered to be the true temperatures to at least ±1/100°K.

All specimens tested were prepared from previously water-slurried soils at moisture contents somewhat above the liquid limit. These slurries were placed in the cell and consolidated in stages to an arbitrary pressure of 416.8 kPa, then reduced to freezing test pressure and allowed to equilibrate with an outside water supply. Moisture and dimensional stability of the sample usually took several days to achieve. Before starting experimental runs the water lines were purged with de-aired water to rid the supply system of air bubbles. The surface of the external water source was held level with the porous plate diffuser in contact with the specimen.

Initiation of crystallization was carried out by rapid supercooling. A sudden temperature rise in the sample next to the heat exchanger was used as a phase change initiation indicator. Two or three minutes (usually less than one minute) were always sufficient.

X-rays were taken while heaving was in progress on 20 × 25 cm film. Heave, water influx and expulsion measurements were made with an on-line computerized HP 9835 DAS at time intervals consistent with measurable changes in output readings. Time intervals ranged from 1 min at the beginning to 60 min after several hours. The frequency of data recording was never less than once per hour. The accuracy of heave measurement with a DCDT was ±0.01 mm and of water intake or expulsion with a force transducer, ±0.02 mm.

Soil

Two soils of differing frost-susceptibility characteristics were used in these studies. For both, all the material passed the 200 sieve, but the particle-size distribution differed considerably, as may be seen from the particle-size distribution curves given in Fig.2. The Calgary soil was provided some years ago by W.A. Slusarchuk of Northern Engineering Services from the Calgary pipeline test sites; the Fairbanks soil was provided by Foothills Pipelines (Yukon) Ltd. from the site of the Fairbanks pipeline test.

RESULTS AND DISCUSSION

Soil slurries were consolidated in the test cell and the pressure reduced to that required for the test run. The sample in the cell was preconditioned in the constant temperature chamber to equilibrium with respect to temperature,

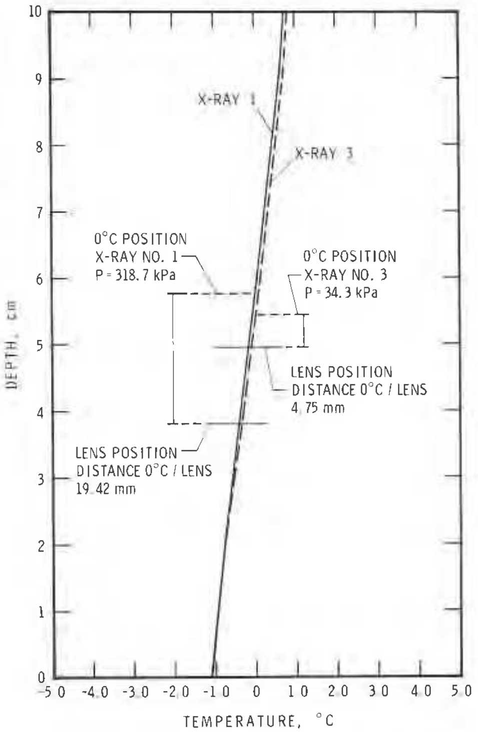


Fig.3. Temperature gradients in sample at time of X-rays 1 and 3 (see Fig.5).

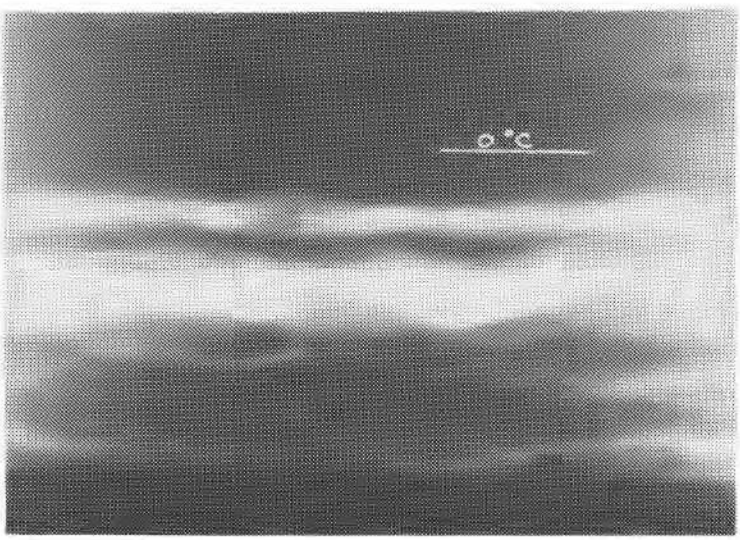


Fig.4. An enlargement of X-ray 3 in Fig.5.

intended direction of heat flow and the lenses in the sample were essentially flat from one side of the cell to the other, it may be assumed that the measured temperatures give a reasonably accurate thermal picture. Straight-line interpolation of temperatures between measured points was considered to be sufficiently accurate for the nature of the study. No discontinuities were noted in the gradients plotted, even when the thermistor lay directly at the position of the growing ice lens.

Table I gives the results of calculations such as interpolated lens temperature, negative temperature due to overburden pressure, temperature drop due to suction force, and calculated suction potential. Given also is the distance between the 0°-isotherm and the ice lens position. The freezing-point depression of the pore water due to dissolved salts was measured separately and is given in Table I. The heaving experiment was started with an overburden pressure of 318.7 kPa. (All heaving pressures include a separately measured component due to friction of the unfrozen soil in the teflon-lined cell that was added to the overburden pressure.) X-rays 1 and 2 (Fig.5) were taken at this pressure and a temperature drop of —0.39° C was calculated from the Clapeyron equation. After allowing for the measured salt effect this left —0.07° C for X-ray 1; translated into suction potential (Clapeyron equation) this is about 83 kPa. The induced flow rate was $27.8 \cdot 10^{-4}$ cm^3/min. Flow at the time of X-ray 2 was somewhat less owing to heave rate drop-off, which is always present following the original straight-line heave condition when using a step freezing cold side temperature.

After the second X-ray (20,584 min) the overburden pressure was reduced to 34.3 kPa. There was some shifting in the 0° C isotherm owing to unloading and rebound, but of greater significance was the formation of the new ice lens much closer to the 0° C-isotherm. The high pressure was reapplied after X-ray 3, i.e., at 24,804 min. During the next period of about 10,000 min the newly formed lens deteriorated and dispersed, as would be expected. A fragment of the second ice lens left at this time can still be seen. No over-all heaving was observed, but there may have been some rearrangement of ice in the sample in addition to the observed dispersal of the lens formed at low pressure. Using the Clapeyron equation it was estimated that the equilibrium ice lens temperature should be —0.29° C at the overburden pressure of 318.7 kPa. The measured temperature of the deteriorating ice lens was estimated from the X-rays and temperature gradients to be —0.26° C (X-ray 4). Had the experi-

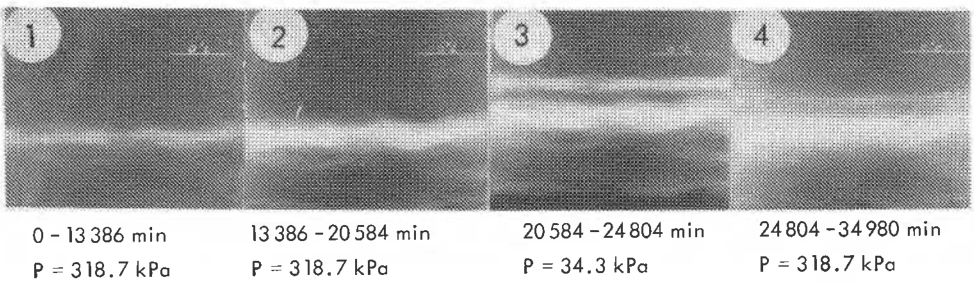


Fig.5. X-ray photographs of Calgary soil sample at various stages of heaving.

TABLE I

Effect of pressure change on heave conditions, Calgary soil*[1]

X-ray	Time period (min)	Imposed cold side T (°C)	Imposed overburden pressure (kPa)	Measured lens T (°C)	Calculated ΔT overburden (°C)	Measured ΔT in pore water (°C)	Calculated ΔT suction (°C)	Calculated suction potential (kPa)	Measured distance from 0°C (mm)	Measured heave rate (mm/min)	Measured water flow rate (cm^3/min)
1	0 to 13386	−1.1	318.7	−0.39	−0.29	−0.03	−0.07	83	19.42	$4.063 \cdot 10^{-4}$	$27.8 \cdot 10^{-4}$
2	13386 to 20584	−1.1	318.7	−0.36	−0.29	−0.03	−0.04	47	17.38	$2.95 \cdot 10^{-4}$	$21.05 \cdot 10^{-4}$
3	20584 to 24904	−1.1	34.3	−0.17	−0.03	−0.03	−0.11	131	4.75	$8.71 \cdot 10^{-4}$	$59.81 \cdot 10^{-4}$
4	24904 to 34980	−1.1	318.7	−0.26	−0.29	−0.03	—	—	11.77	no heave	no flow

*[1]See also Figs.3—5.

ment been continued, it is expected that heaving would have recommenced as soon as the ice lens temperatures were reestablished, judging from previous experience.

The next experiment (Fig.6, Table II) was undertaken with Fairbanks silt to show the influence of increasing overburden pressure on the position of the ice. In this case heaving started at a low pressure of 34.3 kPa and a lens of about 10 mm in thickness was formed by the time of the first X-ray (11,271 min). An overburden pressure of 416.8 kPa was applied at this time, and it may be seen that the lens receded as an expanded ice-rich band into the colder regions of the soil. From X-rays 2 to 6*1 this process continued. It may be seen in Table II that the edge of the broad band of ice had receded to a position 11.92 mm from the 0°C isotherm. The pressure was next reduced in two successive stages (to see whether two ice lenses could be induced), first to 122.6 kPa and then to 73.5 kPa; as a consequence, two ice lenses were formed, both nearer the 0°C isotherm. When the pressure was reduced, water intake and heaving commenced again, although the amount due to rebound could not be separated from that due to heaving and water intake resulting from ice segregation.

Effect of lowering cold-side temperature

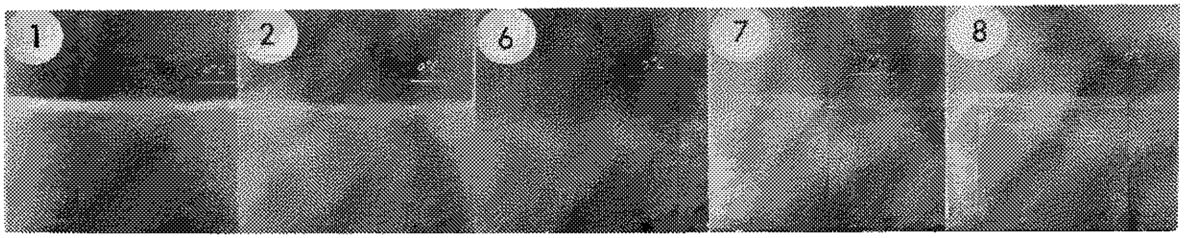
It was of special interest to establish the conditions at the growing face of the ice lens when the cold-side temperature was lowered in successive stages. Previously, Penner and Walton (1979) showed that this increased the flow and heave rate. Although the X-rays are not shown, the technique was the same as that previously described. The results are summarized in Table III.

As the cold-side temperature on the soil was dropped in successive stages, i.e., —0.26, —0.66, —1.05, heave rate and water intake increased dramatically each time. The increased rates of ice growth could only occur as a result of greater suctions developed at the growing ice lens. When the heave rate (at the applied overburden pressure) was $4.81 \cdot 10^{-4}$ mm/min, the measured lens temperature was —0.07°C; when the cold side was dropped to —0.66°C, the lens temperature dropped to —0.13°C and the heave rate increased to $7.08 \cdot 10^{-4}$ mm/min. Finally, at the last stage, the cold-side temperature was —1.05°C, causing the heave rate to increase to $8.85 \cdot 10^{-4}$ mm/min and the lens temperature to drop —0.19°C. These results could perhaps be expected, but it is useful to establish that such conditions actually occur.

Separation distance of ice lens and the 0°C-isotherm at constant P and cold-side temperature

In earlier studies (Penner and Ueda, 1978; Penner and Walton, 1979) it was observed that rate of heave falls off with time, after beginning at a constant rate in response to a step freezing temperature. An attempt was made to show

*1 In order to conserve space X-rays 3, 4 and 5 are not shown in Fig.6.



1	2	6	7	8
0 - 11 271 min P = 34.3 kPa	11 271 - 12 645 min P = 416.8 kPa	24 551 - 28 860 min P = 416.8 kPa	28 860 -34 631 min P = 122.6 kPa/1 day P = 73.5 kPa/3 days	34 631 -38 946 min P = 73.5 kPa

Fig.6. X-ray photographs of Fairbanks soil samples at various stages of heaving.

TABLE II

Effect of pressure change on heave conditions, Fairbanks soil*[1]

X-ray	Time period (min)	Imposed cold side T (°C)	Imposed overburden pressure (kPa)	Measured lens T (°C)	Calculated ΔT overburden (°C)	Measured ΔT in pore water (°C)	Calculated ΔT suction (°C)	Calculated suction potential (kPa)	Measured distance from 0°C (mm)	Measured heave rate (mm/min)	Measured water flow rate (cm³/min)
1	0 to 11271	−1.1	34.3	−0.13	−0.03	−0.02	−0.08	95	5.15	$3.24 \cdot 10^{-4}$	$2.28 \cdot 10^{-3}$
2	11271 to 12645	−1.1	416.8	−0.18					7.27		
3	12645 to 18786	−1.1	416.8	−0.23					9.70		
4	18786 to 21665	−1.1	416.8	−0.24					9.90		
5	21665 to 24551	−1.1	416.8	−0.27					10.63		
6	24551 to 28860	−1.1	416.8	−0.29					11.92		
7	28860 to 34631	−1.1	122.6 for 1 day 73.5 for 3 days	−0.152					6.79 (for lens nearest 0°C)		
8	34631 to 38946	−1.1	73.5						6.19 (for lens nearest 0°C)		

*[1]See also Fig.6.

TABLE III

Effect of lowering cold side temperature on heaving conditions, Calgary soil (P = 34.3 kPa)

X-ray	Time period (min)	Imposed cold side T (°C)	Measured lens T (°C)	Calculated ΔT overburden (°C)	Measured ΔT in pore water (°C)	Calculated ΔT suction (°C)	Calculated suction potential (kPa)	Measured distance from 0°C (mm)	Measured heave rate (mm/min)	Measured water flow rate (cm^3/min)
1	0 to 11713	−0.26	−0.07	−0.03	−0.03	−0.01	12	4.2	$4.81 \cdot 10^{-4}$	$3.59 \cdot 10^{-3}$
2	11713 to 20135	−0.66	−0.13	−0.03	−0.03	−0.07	83	6.0	$7.08 \cdot 10^{-4}$	$5.13 \cdot 10^{-3}$
3	20135 to 27441	−1.05	−0.19	−0.03	−0.03	−0.13	154	8.9	$8.85 \cdot 10^{-4}$	$6.43 \cdot 10^{-3}$

how this fall-off can be predicted. The constant heave rate period is longer at higher pressures than it is at lower pressures. An experiment was initiated in which, at a relatively fixed cold-side temperature (between 8,706 and 17,788 min), unimpeded heave was allowed to proceed. The lens temperature was again estimated from temperature gradients and X-ray photographs, as previously described. Fig.7 shows X-ray results of the position of the ice at various times, with the position of the 0°C isotherm marked. The increase in ice lens temperature (hence reduced suction), which may be observed in Table IV, is consistent with the drop-off of heave rate and water intake rate with time.

CONCLUDING REMARKS

Although the Clapeyron equation should be applied in the strict thermodynamic sense only to equilibrium conditions, the studies discussed in this paper give evidence that it permits prediction of the conditions surrounding ice segregation in soil even under non-equilibrium conditions. These conclusions are based on X-rays taken under various conditions and temperatures during the ice segregation process. The Penner and Ueda (1978) equation for frost heave rate predicts the structure of the segregated ice at various below-zero temperatures and overburden pressures. Investigation of this phenomenon has shown that the results are reasonably consistent with predictions. In general, such studies merely hint at the potential of X-ray photography in the fundamental study of ice segregation in particulate systems.

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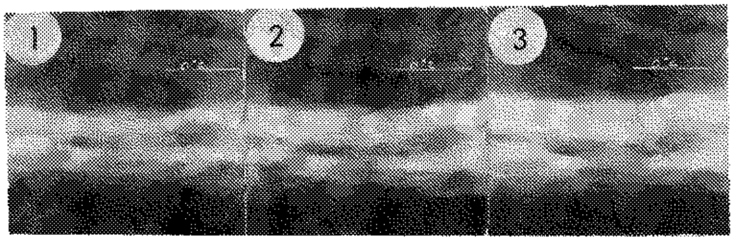

0 - 8 706 min	8 706 - 13 026 min	13 026 - 18 788 min
P = 34.3 kPa	P = 34.3 kPa	P = 34.3 kPa

Fig.7. X-ray photographs of Calgary soil, various times, constant cold-side temperature.

TABLE IV

Heaving results at one step temperature over long period, Calgary soil (P = 34.3 kPa)

X-ray	Time period (min)	Imposed cold side T (°C)	Measured lens T (°C)	Calculated ΔT overburden (°C)	Measured ΔT in pore water (°C)	Calculated ΔT suction (°C)	Calculated suction potential (kPa)	Measured distance from 0°C (mm)	Measured heavy rate (mm/min)	Measured water flow rate (cm^3/min)
1	0 to 8706	−1.10	−0.19	−0.03	−0.03	−0.13	154.3	6.75	$11.96 \cdot 10^{-4}$	$8.10 \cdot 10^{-3}$
2	8706 to 12966	−1.10	−0.16	−0.03	−0.03	−0.10	118.7	5.26	$6.20 \cdot 10^{-4}$	$4.16 \cdot 10^{-3}$
3	12966 to 18728	−1.10	−0.10	−0.03	−0.03	−0.04	47.1	2.82	$3.96 \cdot 10^{-4}$	$2.33 \cdot 10^{-3}$

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