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EFFECTS OF TEMPERATURE AND PRESSURE ON FROST HEAVING

ANALYZED

by E. Penner and T. Walton

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SOMMAIRE

Des études effectuées sur l'influence de la pression de surcharge exercée sur le rapport taux de soulèvement et température du côté froid de l'échantillon ont indiqué que le taux de soulèvement sous diverses pressions de surcharge tend à converger à mesure que la température du côté froid baisse; les études ont aussi démontré que les taux maximaux d'accumulation de glace à de basses pressions sont atteints à des températures plus près de 0°C que ne le sont les taux d'accumulation de glace à de hautes pressions. De plus, on explique qu'une zone de soulèvement plutôt qu'une zone de gel serait associée à l'action du gel. La zone de soulèvement s'étend de plus en plus et selon une gamme de températures de plus en plus élevée à mesure que la pression de surcharge augmente. Le concept de la zone de soulèvement permet d'élaborer une méthode pour le calcul de la courbe de diminution du soulèvement. La période de diminution du soulèvement est caractérisée par la baisse rapide du taux de ségrégation de la glace et par la réduction du taux de pénétration du gel.

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EFFECTS OF TEMPERATURE AND PRESSURE ON FROST HEAVING

E. PENNER¹ and T. WALTON²

¹Head, Geotechnical Section, Division of Building Research, National Research Council of Canada, Ottawa (Canada)

²Head, Gas Pipeline Division, Engineering Group, National Energy Board, Ottawa (Canada)

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ABSTRACT

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Concerning the influence of overburden pressure on the relation between rate of heave and cold-side temperature, studies show that the heave rate for various overburden pressures tends to converge as the cold-side temperature is lowered, and the maximum rates of ice accumulation at low pressures occur at temperatures closer to 0°C than do those at high pressures. Evidence is also presented that a *heaving zone* is involved in frost action rather than a *freezing plane*. This zone extends over an increasingly greater temperature range and distance as the overburden pressure is increased. Using the concept of a heaving zone leads to a method for calculating the heave-decrease curve. The period of heave decrease is marked by a rapidly increasing ice segregation ratio and a reduced frost-penetration rate.

INTRODUCTION

The constant nature of frost heaving in response to a step freezing temperature in frost-susceptible soils for the early stages of frost-line penetration has been well documented for laboratory conditions [1]. There is also evidence that the same behaviour is observed in the field under similar freezing conditions. However, the heave rate is strongly dependent on the overburden pressure and the cold-side freezing temperature for any particular soil. The interrelationship of these three factors has not been considered in any great detail previously, although much is now known about the dependence of heave rate on pressure and temperature separately.

In a paper by Penner and Ueda [2], the ratio of the applied pressure and the cold-side temperature was expressed as an exponential function of the total heave rate as follows:

$$dh/dt = a \exp (b P/T) \quad (1)$$

where:

- dh/dt = total heave rate (mm/min);
 h = heave (mm);
 t = time (min);
 P = overburden pressure (kg/cm²);
 T = cold-side freezing temperature (°C);
 a and b = constants, dependent on soil type.

Heave experiments (Fig.1) were carried out in the open-system mode at various values of T and P for two soils in the saturated state [2]. A constant heave rate was observed in the early stages of freezing which sometimes continued in this way for several days. However, given sufficient time the heave rate started to decrease. One aspect of the present paper is to draw attention to the diminishing heave rate after long periods of time, and to the relationship between heave rate (dh/dt), T and P . Evidence follows from this that points to the existence of a *freezing zone* rather than a *frost line*, which is similar to the frost fringe in the concept used by Miller [3]. A method of calculating the decrease in the heave rate is suggested in this paper based on the existence of a freezing zone.

Ice segregation ratios were found to increase as the rate of frost penetration diminished. This has a direct bearing on the size of the frost bulb and the

Fig.1. Heaving rate versus the overburden pressure/step temperature ratio.

amount of heave predicted around chilled pipelines by numerical modelling methods. For frost-susceptible soils the frost-heaving phenomenon must be included correctly in the heat budget if meaningful results are to be obtained.

The degree of success achieved in predicting heave-rate decay by the proposed method gives credence to the validity of the underlying frost-heave concept.

METHODS AND MATERIALS

The experimental apparatus and methods used to obtain the basic data has been described previously [1]. Briefly, the test cell (obtained from Northern Engineering Services Company Ltd., Calgary, Alberta) holds a sample 10 cm long and 10 cm in diameter. Temperature measurements were made with a series of thermocouples placed between the cell wall and the sample at 10 fixed levels. These were used to determine thermal gradients in the specimen and the location of the 0°C isotherm throughout the experiment. Loading for the consolidation phase of sample preparation and during freezing was done by an air-pressurized arrangement mounted externally to the cell. Water-movement measurements, both into and out of the sample, measurements of heave in response to the frost-action process, and temperatures of the chamber, the sample, and the conditioning liquid were recorded as required. In the early experiments an HP2010H DAS was used; recently this was replaced with an HP3052A programmable DAS with both printing and plotting facilities.

The two soils used in these experiments were a Mackenzie Valley soil (MVS 4) with a clay size content of 23%, 72% silt size and 5% sand, and Leda clay consisting of 80% clay size particles and the remainder in the silt size.

For sample preparation, the test cell was filled with saturated remoulded soil aged near the liquid limit. The same consolidation and loading schedule was followed each time for sample preparation to reduce sample variation. The pressure was reduced to the test condition after consolidation was completed, and the sample was allowed to rebound at the test overburden pressure before freezing was started.

The test cell containing the sample was placed inside a Tenney constant-temperature chamber and allowed to establish thermal equilibrium at the warm-side test temperature. The selected step freezing temperature was then imposed at one end of the sample with a temperature-conditioned end plate. The other end of the sample had free access to bubble-free water through a sealed porous plate system. The external free water level was maintained at the level of the porous plate inside the apparatus throughout the experiment. Unidirectional freezing was achieved by heavily insulating the cell walls.

INTERRELATIONSHIP OF OVERBURDEN PRESSURE (P), COLD-SIDE TEMPERATURE (T) AND HEAVING RATE (dh/dt)

Penner and Ueda [2] showed that the warm-side temperature of the sample (at least between 1 and 4°C) had no measurable influence on the heaving rate, i.e., the magnitude of the cold-side temperature appeared to determine heave rate at any particular overburden pressure. In addition, in these experiments the heave rate was independent of the frost penetration rate or final frost depth.

Although some scatter exists in the data, the straight-line pattern (Fig.1) between $\ln$ heave rate and the P/T ratio appears to be reasonably well established. Values for the constants a and b in eq. 1 for Leda clay are 5.7×10^{-3} and 0.507 respectively; the values for a and b are 4.4×10^{-3} and 0.968 for MVS 4 soil. The observed relationship between T , P and dh/dt , in response to a step change in the freezing temperature [1] led the authors of the present paper further to consider the nature of the freezing zone.

Using eq. 1, the heave rates were plotted against cold-side temperatures for different overburden pressures between 0.1 and 4 kg/cm² (Figs.2 and 3). It was immediately evident that the rates at the various pressures appear to converge to a common value as the step freezing temperature is made larger. Maximum heave rates were established close to 0°C for small overburden

Fig.2. Rate of ice accumulation (heave rate) versus cold-side temperature at various overburden pressures for Leda clay (from Fig.1).

Fig.3. Rate of ice accumulation (heave rate) versus cold-side temperature at various overburden pressures for MVS 4 (from Fig.1).

pressures. In contrast to this, at high overburden pressures, the heave rate increases over a larger temperature span. It can be also noted that the freezing temperature at which ice accumulation begins is at an increasingly lower temperature as the overburden pressure is increased.

In the heave-rate equation for Leda clay, R , in millimetres per minute, is:

$$dh/dt = R = 5.7 \times 10^{-3} \exp (0.507 P/T) \quad (2)$$

The heave-rate change per unit temperature in millimetres per minute per degree Celsius is given by:

$$\frac{d (dh/dt)}{dT} = \frac{dR}{dT} = -2.89 \times 10^{-3} P/T^2 \exp (0.507 P/T) \quad (3)$$

In the heave-rate equation for MVS 4, R , in millimetres per minute, is:

$$dh/dt = R = 4.4 \times 10^{-3} \exp (0.968 P/T) \quad (4)$$

The heave-rate change per unit temperature in millimetres per minute per degree Celsius is given by:

$$\frac{d (dh/dt)}{dT} = \frac{dR}{dT} = -4.26 \times 10^{-3} P/T^2 \exp (0.968 P/T) \quad (5)$$

Eqs. 3 and 5 are plotted in Fig.4 as a function of cold-side temperature for a range of overburden pressures.

Fig.4. Change in rate of ice accumulation (heave rate) per degree Celsius versus cold-side temperature for Leda clay.

It follows directly from the nature of these plots (Figs.2–5) that the zone of appreciable heaving is associated with an increasingly greater temperature range as the pressure is increased. This appears to substantiate that a *heaving zone* is involved in frost heaving rather than a *freezing plane*. The maximum rate change in ice accumulation per unit degree temperature change takes place at progressively lower temperatures as the overburden pressure is increased. The temperature/pressure relationship at these maxima can be obtained for the two soils by differentiating eqs. 3 and 5 respectively, with respect to temperature, setting these to zero and solving for T . For Leda clay the relationship is given by:

$$T = -0.254 P \quad (6)$$

and for the Mackenzie Valley soil:

$$T = -0.484 P \quad (7)$$

These results are plotted in Fig.6.

In all these step freezing temperature experiments the thermal gradient in the frozen zone was essentially linear at any particular time, and at any cold-

Fig.5. Change in rate of ice accumulation (heave rate) per degree Celsius versus cold-side temperature for MVS 4.

Fig.6. Cold-side temperature/overburden pressure relationship at maximum rate change in ice accumulation per degree Celsius.

side temperature as freezing progressed into the unfrozen sample. The temperature axis in both Figs.4 and 5 may then be also thought of as a measure of the distance from the location of the 0°C isotherm where the heave phenomenon is occurring. It follows from this that the greatest rate change in ice accumulation moves further into the colder zone as the overburden pressure is increased. This is shown graphically in Fig.6. Therefore, ice accumulation at higher overburden pressures is spread out not only over a greater temperature range but also over a greater distance, i.e., we have deduced from these studies that a *zone* of ice accumulation exists and that the size of this zone is pressure dependent. This concept is used below for calculating the heave-decrease curves after long periods.

LONG-TERM HEAVE IN STEP FREEZING EXPERIMENTS

Penner and Ueda [1] showed that the total heave rate remained relatively constant up to periods as long as several days. This appears to be characteristic of step freezing experiments with frost-susceptible soils that heave under a load and can be repeated easily. However, given sufficient time the heave rate tends to decrease and must approach zero when $h/p \rightarrow 1$, where h is the total heave and p the depth of frost penetration.

The basis for the calculation is that the rate of heave is dependent on the fraction of soil contained in the frozen zone, since it has been shown that heaving appears to involve the entire frozen zone to some extent at the temperature and pressure used in these experiments. Making the simplifying assumption that the heaving is uniformly distributed over the frozen zone:

$$dh/dt = R_0 (1 - h/p) \quad (8)$$

where:

R_0 = initial heave rate (mm/min);

h = heave (mm);

p = frost penetration (mm);

t = time (min);

h/p = the ice segregation ratio;

$1 - h/p$ = the soil fraction contained in the frozen zone.

Integrating eq. 8 and rearranging gives the fraction of soil $(1 - h/p)$ contained in the frozen zone in terms of time, t , frost penetration, p and initial heaving rate, R_0 , i.e.:

$$1 - h/p = \exp [-(R_0 t)/p] \quad (9)$$

Solving for heave, h , gives:

$$h = p \{1 - \exp [-(R_0 t)/p]\} \quad (10)$$

To check the correctness of this equation from the known behaviour of frost-heaving soils the following observations can be made:

(1) In eq. 10 when $t = 0$, $\exp [-(R_0 t)/p] = 1$, hence when $t = 0$ there is no heave, i.e., $h = 0$.

(2) In eq. 10 when $t \rightarrow \infty$, $\exp [-(R_0 t)/p] \rightarrow 0$ and $h \rightarrow p$.

(3) In eq. 8 when $h \rightarrow p$, $1 - h/p \rightarrow 0$ and $dh/dt \rightarrow 0$. This is the condition as the final steady state is approached.

Three fairly long-term experiments were undertaken to compare calculated heave values with measured results. As argued earlier, at higher overburden pressures ice accumulation occurs throughout the zone, associated with a relatively large temperature range below 0°C (see Figs. 4 and 5). At low pressures, e.g., 0.1 kg/cm^2 , the zone of ice accumulation is located near the 0° isotherm with only a low degree of ice growth activity at locations further away or at temperatures much below -0.5°C . Agreement between measured and calculated values based on these findings lends support to the concept developed in this paper. Furthermore, it would be expected that with the development of ice lenses near the frost line — as would occur at low pressures — the remainder of the frozen soil would be cut off from the water supply and the calculated results would tend to be an overestimation of the measured values.

Table I gives measured and calculated heave data for the three different overburden pressures. Tables Ia and b show that the measured and calculated heave values compare favourably. The calculated results in Table Ic show a greater deviation from the measured values. The reason for the initially low calculated heave values is not understood, but it is believed that the reason for the calculated values being higher at the end of the experiment is that a solid ice lens prevented water from the still unfrozen part of the soil from contributing to the total heave and to the error introduced by the simplifying assumption in eq. 8.

There may be other reasons for the poor agreement, since some difficulty was encountered with the temperature control at the beginning and hence the R_0 value is not thought to be particularly reliable. Furthermore, this sample had been frozen several times and hence its heave characteristics may have changed due to structural changes in the soil caused by several freeze-thaw cycles.

The frozen part of the sample (test results given in Table Ic) was photographed after termination of the experiment (Fig. 7). The ice lens thickness and the thickness of the frozen portion are in approximate agreement with the values in the last line of Table Ic, i.e., thickness of frozen layer 19–20 mm, lens thickness 13–14 mm. The cone of soil above the ice lens in Fig. 7 is a portion of the unfrozen soil.

CONCLUSION

Frost heaving considered in this paper is in response to a step change in freezing temperatures applied to one end of a saturated frost-susceptible soil in the open-system mode. Penner and Ueda [1] expressed the frost-heaving rate as an exponential function of temperature and pressure. The heaving rate sometimes remains constant up to several days. The nature of the complex interrelationship of P , T and dh/dt was investigated in this current study.

TABLE I

Calculated heave values of measured decrease curves for different overburden pressures

(a) $R_0 = 1.13 \times 10^{-3}$ mm/min, $t_0 = 1050$ min, $P = 4$ kg/cm², chamber $T = 3.88^\circ\text{C}$, cold-side $T = -1.10^\circ\text{C}$

Time, t (min)	Penetration, p (mm)	Heave, h (mm)		Segregation ratio, h/p
		measured	calculated	
5×10^3	43.5	4.55	4.24	0.10
6×10^3	45.0	5.60	5.30	0.12
7×10^3	45.5	6.60	6.26	0.15
8×10^3	46.0	7.50	7.21	0.16
9×10^3	47.0	8.35	8.18	0.18
1×10^4	47.5	9.20	9.00	0.19
1.1×10^4	48.0	10.03	10.02	0.21

(b) $R_0 = 3.92 \times 10^{-3}$ mm/min, $t_0 = 0$ min, $P = 1$ kg/cm², chamber $T = 4.0^\circ\text{C}$, cold-side $T = -1.10^\circ\text{C}$

1.5×10^3	37.5	5.52	5.44	0.15
2.5×10^3	39.0	8.61	8.66	0.22
3.5×10^3	40.0	11.43	11.61	0.29
4.5×10^3	40.5	14.05	14.30	0.35
5.5×10^3	41.0	16.45	16.71	0.40
6.5×10^3	44.0	18.60	19.34	0.42

(c) $R_0 = 1.8 \times 10^{-3}$ mm/min, $t_0 = 0$ min, $P = 0.5$ kg/cm², chamber $T = 14^\circ\text{C}$, cold-side $T = 1.09^\circ\text{C}$

5×10^3	16.5	8.20	6.93	0.50
6×10^3	17.5	9.25	8.06	0.53
7×10^3	18.0	10.15	9.06	0.56
8×10^3	18.5	10.90	10.00	0.60
9×10^3	18.5	11.50	10.79	0.62
1×10^4	19.0	12.00	11.63	0.63
1.1×10^4	19.0	12.45	12.29	0.66
1.2×10^4	19.0	12.75	12.90	0.67
1.3×10^4	19.0	13.00	13.45	0.68
1.4×10^4	19.0	13.25	13.95	0.70
1.5×10^4	19.5	13.40	14.60	0.69
1.6×10^4	19.5	13.55	15.04	0.69
1.8×10^4	19.5	13.80	15.80	0.71

Results show that ice accumulation rates at various overburden pressures tend to converge with decreasing cold-side temperature. Furthermore, the zone of maximum heave rate and the heave-rate change with temperature occur closer to the 0°C isotherm for low pressures than those frozen at high pressures. The zone of significant heaving at high pressures also exists over a larger temperature range, i.e., the zone of heave extends into colder regions and also begins at increasingly lower temperatures with higher overburden

Fig.7. Frost penetration and ice lens measurements to compare with recorded results in Table Ic.

pressures. This heaving-zone concept as distinct from a freezing plane has been referred to in the literature by others as the *frost fringe*. These studies have further supported its existence by the close agreement obtained between experimental and calculated values for the time dependence of the total heave beyond the initial linear portion. The decreasing nature of the heave rates is consistent with reduced frost penetration rates and higher ice segregation ratios.

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