INFLUENCE OF ICE LENS FABRIC ON THE HYDRAULIC CONDUCTIVITY OF THAWING SOIL

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Abstract

Thawing ice lenses in a soil are capable of causing a large increase in hydraulic conductivity. Permeameter tests on samples several hundred times larger than those used in laboratory bench-scale experiments show that values at least two orders of magnitude greater than that given by the same soil in a saturated but normally consolidated condition are possible. In the experiments the high conductivities seem to be concentrated in the zone of ice enrichment in the upper 10 cm or so of the sample thickness. In nature this zone is liable to be thicker, allowing a longer time during which raised hydraulic conductivities are in effect. If a source of water at the top of a slope is available to feed water to the active layer, conductivities may remain elevated throughout the thaw season, allowing considerable discharge and therefore movement of water to take place.

Résumé

Les lentilles de glace qui dégèlent dans le sol peuvent causer une forte augmentation de la conductivité hydraulique. Les essais au perméamètre sur des échantillons plusieurs centaines de fois plus gros que ceux utilisés dans les expériences usuelles de laboratoire révèlent qu'il est possible d'obtenir des valeurs d'au moins deux ordres de grandeur plus élevées que celles obtenues avec le même sol dans un état saturé, mais normalement consolidé. Dans les expériences, les conductivités élevées semblent être concentrées dans la zone d'enrichissement en glace dans les premiers 10 cm environ de l'échantillon. Dans la nature, cette zone peut être plus épaisse, allongeant ainsi la période d'influence des conductivités accrues. Si une source d'eau au sommet d'une pente alimente en eau le mollisol, les conductivités peuvent demeurer élevées pendant toute la saison du dégel, ce qui permet un débit et donc un mouvement considérable de l'eau.

Introduction

As soil rich in ice lenses thaws, the hydraulic conductivity of the thawed portion may be considerably higher than that measured for the same material, never frozen, in a conventional laboratory permeameter. Dyke and Egginton (1988) and Egginton and Dyke (1989) suggest that thawed ice lenses remain as water-filled macropores and increase the bulk hydraulic conductivity of the soil. This phenomenon may be particularly important in permafrost regions where the active layer will contain the enhanced flow.

The fabric of frozen soils is commonly dominated by lenses of ice several centimeters long and several millimeters thick. To include a representative sample of this fabric in a measurement of hydraulic conductivity, permeameters containing about 1 m^3 of soil have been used to measure the influence of thawing ice lenses on hydraulic conductivity. Two tests have been carried out on a well graded soil. Only a brief summary of the first test results are given here as Egginton and Dyke (1989) describe them in detail. The first test showed that the hydraulic conductivity during thaw was as much as four orders of magnitude higher than that determined in a conventional permeameter test on the unfrozen soil. However, the placement of the soil in the large permeameters may have introduced an artificial fabric that contributed to the high values. Although the soil was wetted during compaction, spaces between soil clods may have remained. This paper reports the results from the second permeameter test, after the soil masses were recompacted.

Active layer hydrology: the field

Several workers report evidence of high hydraulic conductivities in thawing soil of the active layer. Lissey (1975) recorded rapid water table fluctuations during thaw of the active layer in clayey silts near Inuvik, suggesting a high hydraulic conductivity. Both Lewkowicz and French (1982) and Woo and Steer (1983) have measured subsurface discharge in the active layer. None of these authors calculated hydraulic conductivity, but their measurements suggest 2 values greater than 10 cm/sec for silty sands. However, as these authors point out, field measurements can suffer from the difficulty of knowing the exact route of groundwater flow. Consequently, the crossectional area accommodating this flow is in doubt.

Dyke and Egginton (1988) infer the hydraulic conductivity of well graded till in District of Keewatin from water level changes in bedrock observation holes and open bedrock cracks. In Keewatin, bedrock outcroppings at the top of slopes lose water by seepage into the till. Water levels in an outcrop lowered at a rate requiring a hydraulic conductivity of 10^{-4} cm/sec for the till if the entire water loss was accomplished by seepage through the till active layer. This is considerably above the 10^{-6} cm/sec measured for the saturated but fully consolidated till in a conventional permeameter. A steady settlement of the till surface over the summer totaling 6 cm suggests the loss of a considerable volume of thawed excess ice. It is concluded that this thawing ice contributed to the hydraulic conductivity.

Active layer hydrology: the laboratory

Few experimental determinations of hydraulic conductivity of thawing soil have been made, perhaps because of the difficulty of representing the true effect of the thawed ice fabric. On the other hand, a permeameter possesses the advantage of accurately determining the crossection from which discharge issues. Chamberlain and Blouin (1978) report an increase in hydraulic conductivity of about 2 orders of magnitude after thawing a remolded, highly plastic, silty clay. In this case, dessication cracks generated by freezing cause the increase in conductivity. The till encountered by Dyke and Egginton (1988) is non-plastic with a low shrinkage limit. It rarely drys enough to crack, indicating that another fabric element must produce the elevated hydraulic conductivity.

In an attempt to measure the hydraulic conductivity of soil containing a thawing segregated ice fabric, permeameters that contain enough soil to ensure a large sampling of this fabric are used in this study. The permeameters (fig. 1) consist of inclined boxes filled with a saturated, well-graded soil averaging 41 % sand, 31 % silt, and 28 % clay. The soil sample contained was 2.7 m long, 1.2 m wide, and 0.25 m deep, dimensions far larger than those offered by conventional permeameters and that insure a large ratio of sample size to ice lens size. Styrofoam insulation 5 cm thick was placed on the bottom and sides to prevent thaw from these directions. Three different inclinations (gradients of 0.05, 0.10, and 0.17) were used to produce a variation in hydraulic gradient. The boxes were housed in an unheated building near Ottawa, Ontario and allowed to freeze under winter air temperatures. After complete freezing, cores showed abundant interfingering ice

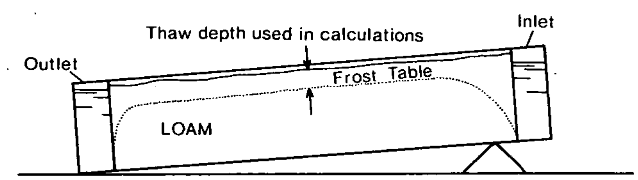

Figure 1. Section through the length of a permeameter. Soil sample length=2.7 m, width=1.2 m, depth=0.25 m. Thaw depth used in the calculation of hydraulic conductivity is averaged from several locations in a a permeameter.

lenses 1 mm or less thick but no other visible voids. The top 10 cm contains about 30 % excess ice as lenses. Excess ice decreases to almost zero at the base of the soil.

When thaw began during the subsequent spring, water was maintained at a constant level in a reservoir at the top end of each permeameter. Similarly, a reservoir was maintained at constant level at the bottom end and overflow was measured as discharge. Discharge was recorded automatically but the mechanism failed on all but one permeameter. However the similarity between continuous and spot readings for one permeameter (fig. 2) show that spot readings accurately represent the discharge. This discharge was interpreted as seepage through the thawed zone and therefore allowed the calculation of an apparent hydraulic conductivity.

Summary of the first test

For the first test (Spring, 1988) the permeameters were operated from the beginning of soil thaw for an interval of 20 days. The soil in the permeameters thawed to the base in 11 to 12 days. During the first 4 days of the thaw interval, the frost table deepened only 4 cm followed by a partial freeze-back. Thereafter, thaw was continuous and accelerating. Although discharge in general increases with inclination of a permeameter, the relationship is not linear. The discharge for the steepest permeameter is disproportionately large throughout the test. Also the discharge from the shallowest permeameter generally increases over the duration of the test, whereas discharge from the other two generally decreases. Hydraulic conductivities were calculated using the inclination of a permeameter as the hydraulic gradient and the depth of thaw to give a crossectional area. A maximum value of about $2*10^{-2}$ cm/sec was found for the steepest permeameter, ultimately decreasing to about 10^{-3} cm/sec. These values contrast with a value of about $2*10^{-5}$ cm/sec measured for the compacted soil masses before freezing and $2*10^{-2}$ cm/sec measured in a permeameter containing a uniform medium sand.

Results from the second test

For the second test, the soil in the permeameters was treated with a motorized compactor utilizing a vibrating steel plate. This device liquified the soil, homogenizing the soil structure and removing artificial voids that may have influenced the hydraulic conductivity of the soil. The soil was maintained saturated and left to freeze as in the previous winter.

From the beginning of thaw, air temperatures remained between 0 and 10 °C for the first four days, stayed within one degree of 0 °C for the next three days, then rose to about 4 °C until the completion of thaw (fig. 2). Thaw to the base of the soil took 10 to 14 days, the most rapid thaw being associated with the steepest permeameter. These rates of thaw are similar to observations from permafrost regions, indicating that the permeameter insulation was sufficeunt to ensure thaw from the soil surface only.

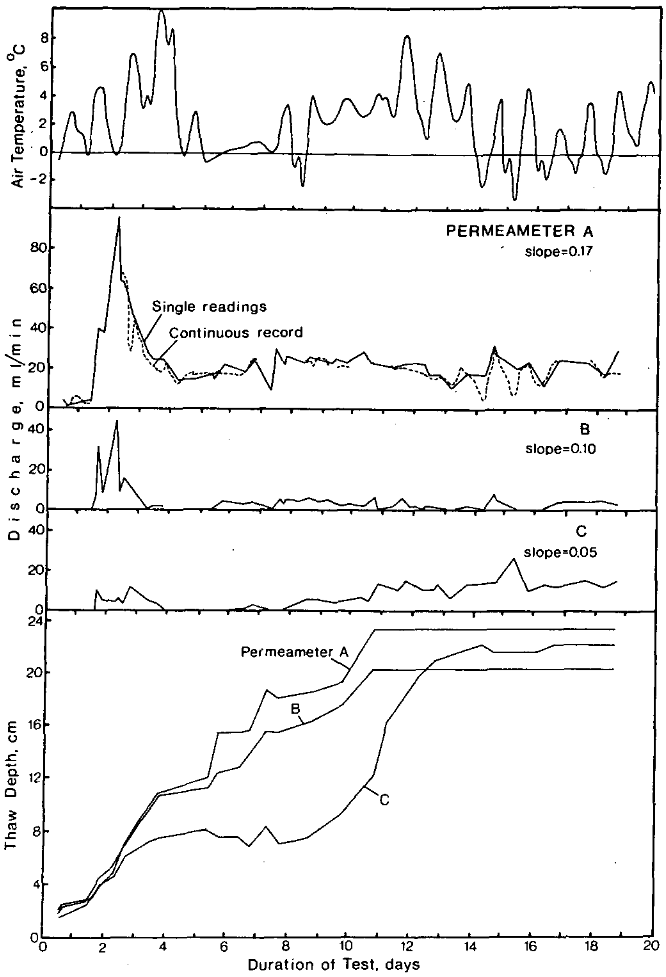

Figure 2. Air temperature, discharge and thaw records for permeameters.

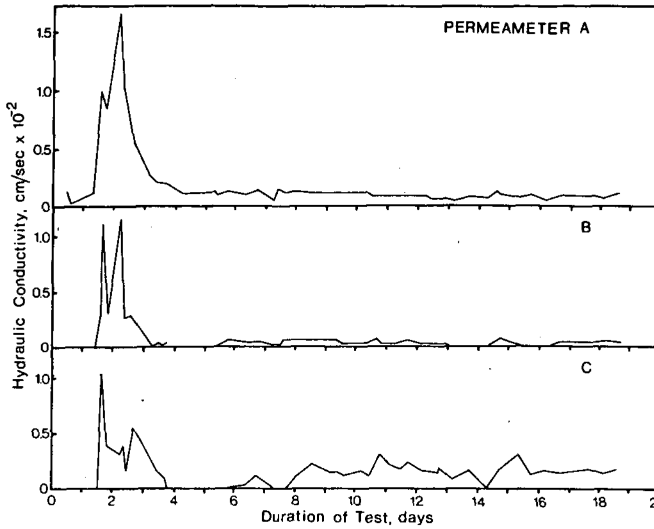

Figure 3. Hydraulic conductivity records for permeameters.

The discharge histories and calculated hydraulic conductivities for the 20 day interval of the test are shown in Figures 2 and 3 respectively. The most steeply inclined permeameter exhibits a distinct peak discharge of almost 100 ml/min during the first interval of thawing temperatures. Subsequently, discharge decreases to stabilize at a more or less constant 20 to 25 ml/min for the remainder of the test. During an interval of daily freeze-thaw cycles from day 14 to 18, the greatest variation in flow after the peak took place. These freezing events probably caused a shallow refreezing of the soil. Uptake of water by ice segregation in the soil would reduce the discharge during a refreezing event, producing the variation seen in the discharge record.

The intermediate permeameter (gradient = 0.10) shows a similar but subdued peak followed immediately by an interval of no flow. Subsequently, discharge is variable but never exceeds 10 ml/min. The shallow permeameter (gradient = 0.05) shows no early high discharge but discharge also stops during the same interval as the intermediate permeameter. Thereafter discharge generally rises, ultimately to about 10 ml/min.

For this test the discharge records show that peak discharges are again not proportional to gradient. Also the steepest permeameter shows the highest hydraulic conductivity, $1.5*10^{-2}$ cm/sec. For all permeameters the discharge histories after the peaks match the general character of the histories from the first test. The loss of discharge for the two shallower permeameters is most easily explained by diversion of flow to growing ice lenses as this loss occurred when the air temperature was varying between -1 and 1 °C. The steepest permeameter maintains flow through this interval. In this permeameter enough heat to prevent ice segregation may have been introduced by the greater water flow.

Discussion

In using measured discharge to calculate hydraulic conductivity, it is implicit that this discharge originates from the inlet of a permeameter. However, evaporation and consolidation may subtract from or add to the flow through the soil. Less than 1 mm/day of evaporation is expected because the permeameters were protected from wind and sunshine and temperatures were never above 10 °C. This estimated evaporation is derived from pan evaporation measurements made during the summer in District of Keewatin. It would be equivalent to less than 2 ml/min discharge. Ice segregation during the tests occurred but can easily be distinguished on the discharge records where discharge decreases during freeze or increases during thaw. Consolidation contributes to discharge by producing flow over the soil surface. The most rapid settlement was 1 cm over about 1 day, occurring in the permeameter with the highest discharge. Expressed as an equivalent loss of water, this would amount to about 20 ml/min. If this value is subtracted from the discharge peak, flow through the soil still accounts for most of the discharge. Temporary immobilization of water by rewetting of a horizon desiccated by shallower ice segregation (Mackay, 1980) is a further possibility for reducing discharge. Once replacement of water was complete, discharge would increase. An increase during thaw is only seen for the shallow permeameter but this is attributed to an increasing crossectional area of thawed soil. Because all components of the water budget were not rigorously measured, the calculated hydraulic conductivities are referred to as apparent conductivities.

The high hydraulic conductivity measured in these tests can be attributed to the existence of large pores that remain after the thaw of ice lenses. If lenses are arranged end to end, then a route preferential to water movement is available. For an inclined layer of thawing soil, in-line lenses are at different elevations and therefore the water contained is at different total hydraulic heads. If it can be assumed that little head loss takes place in water flowing through a macropore, then the head loss takes place over that part of the flow path between macropores. For flow directly from one macropore to the next, the hydraulic gradient will be locally raised above what would exist if no macropores were present. This hydraulic gradient will be greatest where the ends of macropores are most closely spaced. The relationship between this spacing and hydraulic gradient is shown in Figure 4. If rows of macropores are closely spaced one above the other, discharge through the entire crossection of thawed soil will be increased. The result is an increase in hydraulic conductivity of the bulk soil over what would be measured for the same soil that had never hosted ice lenses.

The maximum discharges in the steeper permeameters early in the thaw are disproportionately large compared with the shallowest permeameter. The discharges should be in proportion to the slope assuming that the thaw fabric of the soils is similar between permeameters. An explanation for this discrepancy rests with the behavior of a macropore as the slope is increased. On an incline the increasing pressure head toward the downslope end of a macropore acts to prevent the collapse of the pore. As the inclination is increased, so is the pressure head in the downslope part of the pore. This effect prolongs the life of the pore, allowing a greater thickness of thawed soil containing macropores to develop. However, it must reach a limit when the pressure head becomes too large to be maintained by the overlying pressure of soil. A shear failure parallel to the soil surface would be favoured. This limiting slope was not reached in these tests as no evidence of failure was seen. Once the slope becomes very shallow, the pressure head effect disappears. Instead, macropores do not survive as long and discharge increases proportionaly to thaw depth. This happened in the most shallowly inclined permeameter after the initial peak discharge.

The highest hydraulic conductivities only lasted a few days but the subsequent values are still considerably higher than would be measured on the same normally consolidated but non-frozen material. Even after emptying the inlets and outlets and refilling them 3 days later, discharges matching the previous values were measured in the shallower permeameters. The steepest permeameter showed a ten-fold decrease, perhaps because the steeper inclination promoted drainage and therefore additional consolidation occurred during the empty reservoir interval.

The high hydraulic conductivities measured in these tests are horizontal conductivities and are promoted by rapid thaw of ice-rich soil. The velocity with which the thaw front penetrates the soil must outstrip the velocity with which the top of a lens collapses if a macropore is the survive. The collapse is regulated by the vertical hydraulic conductivity. In the case of these experiments this can be taken as the value determined before the soil was first frozen ($2*10^{-5}$ cm/sec). Figure 5 shows the relationship between the progress of thaw and the thickness of soil that would drain

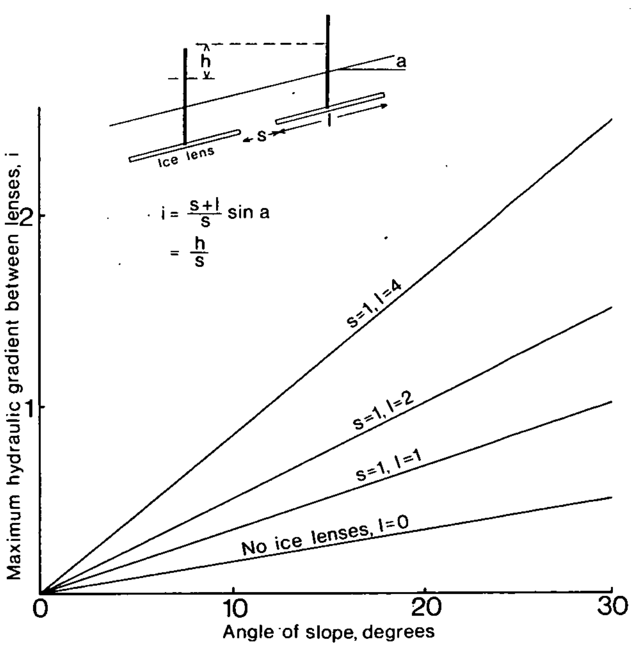

Figure 4. The influence of slope on the hydraulic gradient between evenly spaced, thawing ice lenses. a=angle of slope in degrees, h=the loss in total hydraulic head between lenses, l=length of lens, s= distance between lenses.

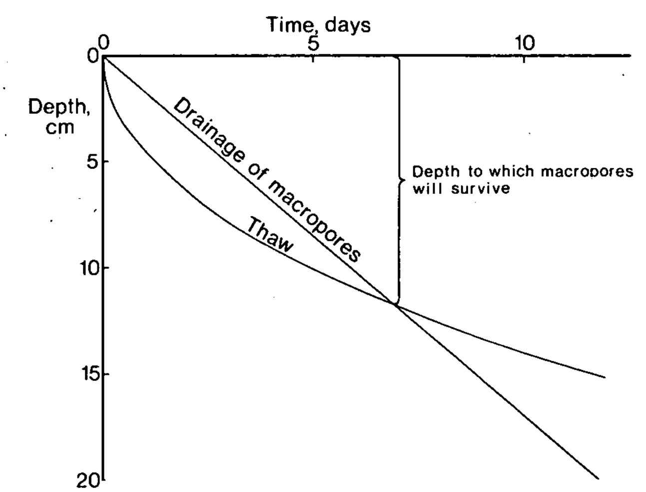

Figure 5. Relationship between the progress of thaw and collapse of macropores. The straight line represents the depth to which collapse of macropores can extend in a given time, assuming the soil drains vertically with a hydraulic conductivity of $2*10^{-5}$ cm/sec. Thaw is for 30% excess ice content and an air temperature of 2 °C.

for given times. If thaw progresses to a depth greater than could be drained, then macropores survive. The thaw curve in Figure 5 is calculated for a thawing temperature of 2°C and an excess ice content (as ice lenses) of 30%. Of course, temperatures and ice contents will vary, resulting in different durations of high conductivities. In nature, the zone of near-surface ice enrichment will probably be thicker than that in the permeameters, allowing a longer time during which peak hydraulic conductivities will be in effect.

In the tests, thaw is probably hastened by the influx of water warmer than 0°C. This effect will be most pronounced for the steepest permeameter because the most heat will be transported into the soil. In nature this effect will be less significant if the water source is from melting ice or snow.

Conclusions

1. The hydraulic conductivity of a well graded soil containing about 30% clay can be raised 3 or 4 orders of magnitude to about 10^{-2} cm/sec by thawing ice lenses. This conductivity is measured parallel to the alignment of the lenses.

2. Disturbance and artificial compaction of this soil does not seem to introduce any fabric that adds to the hydraulic conductivity of the soil. Complete homogenization of the soil for a second test resulted in the same range of conductivities as seen for the first.

3. The duration of highest hydraulic conductivity will be determined by the thickness of the zone of excess ice and the rate at which this zone thaws.

Acknowledgements

This work was supported by a National Science and Engineering Research Council operating grant and by fabricating services of the Geological Survey of Canada. The authors wish to thank S.R. Dallimore, Geological Survey of Canada and C.C. Mathewson, Director, Center for Engineering Geosciences, Texas A&M University, for reviews which considerably clarified the manuscript. The authors are also indebted to two reviewers appointed by the organizing committee of the Fifth Canadian Conference on Permafrost.

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