Effects of Freeze-Thaw Cycles on Soil Hydraulic Conductivity Normal to the Direction of Freezing[1]

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ABSTRACT

The effect of freeze-thaw cycles on soil hydraulic conductivity normal to the direction of freezing (K_n) was studied. Results showed that freeze-thaw effects on (K_n) are modified by soil water content at freezing, initial soil aggregate size, and freezing temperature. The ratio of final to initial K_n was exponentially related to soil water content at freezing with K_n increasing at low soil water content and decreasing at high soil water content. The effects of freeze-thaw cycles on K_n were qualitatively the same as for vertical conductivity but of a different magnitude, indicating that freezing and thawing may be responsible for the development of anisotropic conditions.

INTRODUCTION

Northern soils are usually anisotropic with respect to hydraulic conductivity. One reason may be that normal fall and spring freeze-thaw action influences soil structure and thus hydraulic conductivity. The fact that natural frost develops anisotropically with ice lenses generally oriented normal to the direction of freezing suggests that freeze-thaw action may promote conditions of anisotropic hydraulic conductivity.

Previous work indicates that multidirectional or unidirectional (vertically down as in nature) freezing and thawing of soils (1, 2, 3) can have a positive or negative effect on vertical hydraulic conductivity (K_v). The type and magnitude of the effect have been shown to be a function of soil water content at freezing, state of soil aggregation, and freezing temperature. Data are needed to show the effect of unidirectional freeze-thaw action on hydraulic conductivity normal to the direction of freezing (K_n) as compared to K_v.

It is the objective of this paper to present data that show the effect of unidirectional freeze-thaw action on K_n, to compare the data to previously reported K_v data (2), and to relate these data to anisotropic field conditions.

PROCEDURE

Surface soil from a Cabot silt loam was dry-sieved into aggregate groups 0.0 to 0.8, 0.8 to 1.2, and 1.2 to 2.0 mm in size. Random samples of each aggregate size were uniformly packed into 7.6 x 7.6 cm aluminum cylinders and set in a pan of water to saturate from below.

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After saturation, an initial hydraulic conductivity value was determined for each core by a standard vertical flow, constant head procedure. Within each aggregate group, half of the cores were selected at random and equilibrated at maximum water-holding capacity. The remaining cores were equilibrated at 0.5 bar of pressure. The equilibrium soil water content of each core was determined.

One half of the cores randomly selected in each aggregate size in both water treatment levels were subjected to 20 freeze-thaw cycles at a freezing temperature of -4C. The remaining cores were subjected to 20 freeze-thaw cycles at a freezing temperature of -4C. The remaining cores were subjected to cyclic freezing and thawing at -18C. All 12 treatments, consisting of all combinations of three aggregate sizes, two soil water levels, and two freezing temperatures, were run in triplicate.

A thin plastic film was placed over the top and bottom of each core to control evaporative water loss. The cores were then insulated with styrofoam on the bottom and top so that freezing and thawing occurred primarily from the sides inward, normal to the direction of water flow during hydraulic conductivity determinations. Alternate freezing and thawing were accomplished by inserting and removing the cores from a freezing chest maintained at the desired temperature. The cores were thawed at ambient room temperatures. A final hydraulic conductivity value was determined after completing the freeze-thaw treatment.

The initial percentage of water-stable aggregates larger than 0.5 mm was determined for each aggregate size group by a standard wet sieving procedure. A final water-stable aggregate value was determined after the last freeze-thaw cycle and before air drying could take place.

A complete analysis of variance (AOV) was run on all data collected. In addition, a regression equation and a correlation coefficient were computed for the relationship between the ratio of final to initial K_n and the soil water content of the aggregates at freezing.

RESULTS AND DISCUSSION

An AOV of the initial equilibrium water levels and hydraulic conductivities of the soil cores (data not shown) indicated uniform initial conditions for the cores within each aggregate group. Differences observed in initial conditions were only those expected as a result either of the imposed water level treatment, or of the natural water-holding differences of the three aggregate size groups. Initial conductivity values varied among all aggregate groups from 0.05 to 0.80 cm per min. The AOV also indicated that the ratios of the final (after 20 freeze-thaw cycles) to initial percentage of water stable aggregates retained on a 0.50-mm screen repeated findings previously reported (2).

The data presented in Table 1 show the effect of 20 freeze-thaw cycles on K_n and simulate the relationship between natural freezing action and lateral soil water flow. The data are presented as a ratio of final to initial hydraulic conductivity. Values less than and greater than one indicate decreasing and increasing conductivity respectively. The ratio approach normalizes the data and allows for an evaluation of the effect of freezing and thawing on conductivity.

Table 1. Ratio of final to initial hydraulic conductivity of prepared soil cores after 20 freeze-thaw cycles.

	Water treatment level				
	Maximum water holding capacity		0.5 bar pressure		
Aggregate size group (mm)	Freezing temp. °C -18	-4	Freezing temp. °C -18	-4	Avg.
0.0-0 8	0.24[Δ]	0.44	0.91	1.01	0.65[+]
0.8-1.2	0.03	0.24	1.07	1.33	0.67
1.2-2.0	0.05	0.75	1.41	3.03	1.31
Avg.	0.11	0.48	1.13	1.79	

Average ratio for high and low water levels respectively* = 0.30 and 1.46.

Average ratio for -18C and -4C temperature levels respectively* = 0.62 and 1.12.

Δ Each value is the average of six observations composed of duplicate determinations run on each of three cores

+ $LSD_{.01}$ between overall aggregate level means = 0.26.

* $LSD_{.01}$ between overall water level and temperature treatment means = 0.21.

Table 2. Analysis of variance summary of ratio of final to initial hydraulic conductivity.

Source of error	Degrees of freedom	Mean square	F value	$F_{.005}$ level
Total	35			
Aggregates (A)	2	1.706	33.45	6.66
Temperature (T)	1	2.387	46.80	9.55
Water (W)	1	12.308	241.33	9.55
A x T	2	0.951	18.65	6.66
A x W	2	1.101	21.59	6.66
W x T	1	0.195	3.82	4.26^{Δ}
A x W x T	2	0.225	4.41	3.40^{Δ}
Error	24	0.051		

Δ F value needed for significance at the 0.05 level.

A complete AOV of the data used for constructing Table 1 indicates that freezing temperature, aggregate size, and soil water content (Table 2) have a highly significant influence on the way freezing and thawing affect hydraulic conductivity. Highly significant aggregate by temperature and aggregate by water interactions and a significant aggregate by water by temperature interaction are shown. No temperature by water interaction is evident.

The data in Table 1 and the comparative F values shown in the AOV summary (Table 2) indicate that water content effects overshadow the effects of the other main treatments or of the interactions. Basically, freezing and thawing the soil cause a decrease in conductivity at maximum water holding capacity and an increase at the 0.5 bar equilibrium point.

Within each water treatment group, different aggregate size and freezing temperature effects are apparent. At maximum water holding capacity, the -18C freezing temperature caused a greater decrease in hydraulic conductivity than did the -4C temperature; the greatest decrease occurred with the larger aggregate sizes. The -4C freezing temperature effects are inconsistent across aggregate sizes.

At the 0.5 bar water equilibrium point, there was an increase in hydraulic conductivity for increasing aggregate size groups for both freezing temperatures. The increase was greatest for the -4C freezing temperature where all aggregate sizes showed either no change (0.0-0.8 mm size aggregates) or an increase. The 0.0 to 0.8 mm aggregates frozen at -18C showed a slight decrease in hydraulic conductivity.

A photograph (Fig. 1) of those cores equilibrated at maximum water-holding capacity and 0.5 bar of pressure that were frozen at -18C shows the physical appearance of the cores after repeated freezing and thawing. The freeze-thaw process did cause large ice lenses to develop normal to the direction of freezing in those cores with the larger aggregates and maximum water-holding capacity.

The core designated by the arrow most dramatically displays residual cracks associated with ice-lens development. No cracks are evident in those cores having the lower initial equilibrium water content (0.5 bar). We expected these residual cracks to provide open channels through which water could flow. Such was not the case. Soil material sloughed into the cracks and sealed them during the process of determining final hydraulic conductivity values.

A correlation analysis of previous data (2) has shown a highly significant exponential relationship between the soil water content at freezing and K_y. A similar evaluation of the present data also shows a highly significant relationship between K_n and the soil water content at freezing (Fig. 2). A least squares fit of these data yields the regression equation

$$y = 14.25e^{-0.080X}$$

where y = ratio of final to initial hydraulic conductivity,
and X = soil water content at freezing.
The correlation coefficient 0.817 is much greater than the 0.424 value required for significance from zero at the 0.01 level of significance.

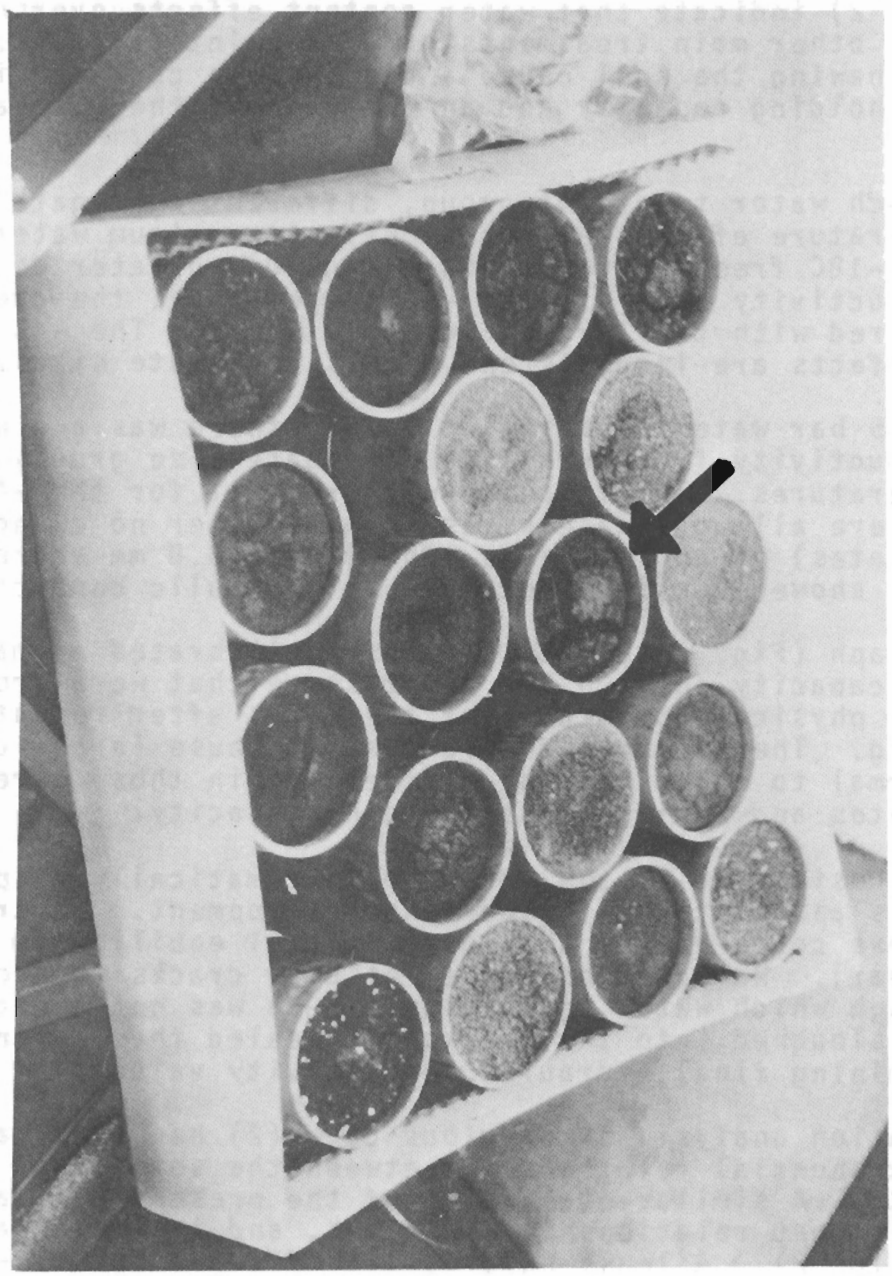

Figure 1. Soil cores with initial water equilibrium values of maximum water-holding capacity and 0.5 bar of pressure just after the -18C freeze-thaw treatment.

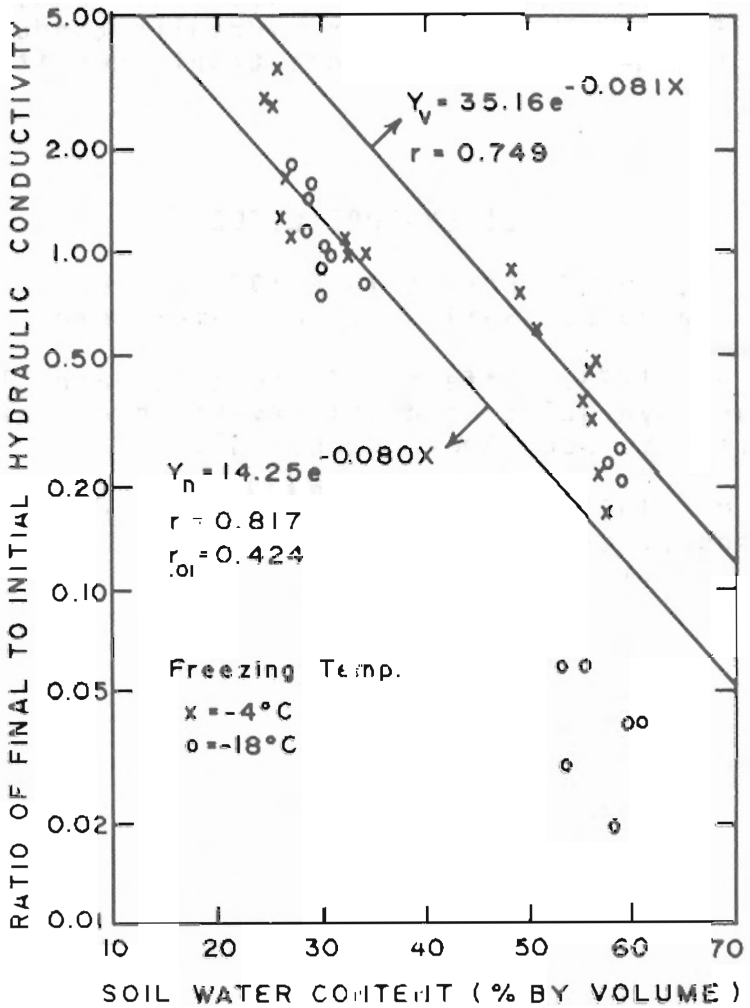

Figure 2 Semilog plot of the relative change in soil hydraulic conductivity normal to the direction of freezing after freezing and thawing soil cores at different soil water contents.

Included in Figure 2 is the regression line and equation ($y = 35.16e^{-0.081X}$) computed for K_v in a previous study (2). A statistical F test evaluation of these two equations shows that their slopes are nearly identical but that they have highly significant differences in intercepts (F value of 17.45 with a value of 8.49 required at the 0.005 level).

Obviously the effect of freeze-thaw action on K_h is similar to the effect on K_v (regression equations have nearly equal slopes). In each case freezing and thawing decrease the soil hydraulic conductivity at high water content and increase it at low water content. However, at a given water content the magnitude of the effect is not the same for conductivity in the two directions (regression equation with significantly different intercepts). This fact tends to verify the hypothesis that freeze-thaw effect on hydraulic conductivity is partly responsible for the development of anisotropic conditions of conductivity

LITERATURE CITED

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