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<td>凍結土層の融解による浸入度</td>
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Infiltration Rate during the Thawing of Frozen Soil Layers

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I. Introduction

The soil freezing is usually accompanied by the occurrence of several physical phenomena, such as heaving, a change in soil structure, the migration of soil moisture, and development of frost pressure. Consequently these phenomena may have a great effect on productive activities in cold regions.

In particular, the migration of soil moisture affected by soil freezing seems to provide greater water storage in the upper frozen layers, and provide such bad supersaturated conditions as the excess surface runoff during early spring and the weak bearing capacity of soil ground. In early spring frozen soil layers may begin to thaw from both top and bottom in the profile, may remain the impervious frozen layer in the intermediate soil zone, and may restrict infiltration caused by snow melting and thawed water accumulated in the upper layer.

In addition, the excess water prevented from infiltration may flood over the surface of agricultural land, may make the land wetter resulting in standing water, and may retard the spring operation of tillage and seeding of crops. Besides in sloped land, soil erosion due to runoff occurs frequently.

Fig. 1 shows the observed results on frost depth and dissipation of the

\[ \text{Fig. 1. Formative duration and dissipation of frost layer at the experimental field of Obihiro Univ. during the winter, 1974 -1975 (after Y. KONDO, 1975).} \]

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frozen layer under a bare experimental field from which snow had been removed. The field was located at Obihiro University of Agriculture and Veterinary Medicine. This soil is classified as volcanic ash soil. This figure indicated that it took about one and a half months till the frozen layer in the profile dissipated perfectly after thawing on the surface.

The rapid drainage of the excess on the surface zone, may contribute to making soils drier and warmer in spring, and may be significant for cold region agriculture.

It is necessary, therefore, to understand how the properties of frozen soils influence infiltration during the thawing process. A laboratory experiment was conducted to determine the relationships between moisture content of frozen soil, bulk density, freezing temperature and infiltration rate during thawing.

II. Experimental Methods

Soil samples were taken out of the subsoil in the experimental field at Obihiro University and were air-dried. Water was added in order to achieve moisture contents by weight of 30, 40 and 50 percent, respectively. Then 10 cm diameter vinyl-chinders 5 cm long were packed with as uniform bulk density as possible, with 0.68 and 0.83 gram per cubic centimeter. These cylinders were frozen at temperatures of −5, −10 and −20 degrees, respectively.

After reaching the desired temperature, the cylinder was attached to another cylinder of the same but unfrozen sample, as shown in Fig. 2. One liter of water of 17°C was poured into the upper hollow cylinder. This soil column apparatus may approximate the condition that there is a frozen soil layer under the soils; this apparatus is regarded as the simplest model.

For the thermal insulator, styrofoam was used in order to prevent frozen soil cylinders from thawing through the side wall, and for water proofing, a semi-dry binding agent was used in order to prevent percolated water from running through the space between the cylinder walls and samples, and from leaking into the conjunct parts of the cylinders. A thermistor was used to measure temperatures of frozen samples in the center and a digital water-level indicator was used to measure water level changes electrically.

III. Results and Discussion

(1) Evaluation of the dissipation of frozen layer

The cumulative infiltration into the soil surface is generally known to change greatly
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Due to the soil texture, bulk density, moisture content etc. with time. In particular, infiltration increases rapidly as the frozen layer thaws because the restraint of infiltration in the frozen zone is reduced and dissipated. Fig. 3 shows these experimental results.

The change of infiltration with time may be generally written as

$$D = CT^n$$

where $D$ is cumulative infiltration (mm), $T$ is time (min.) and both $C$ and $n$ are empirical constants. Thus, since the two linear experimental lines shown in Fig. 4 were plotted in logarithmic scale, the point where the two lines intersected may be thought to be the position giving the remarkable change of infiltration. Also, the temperature in this

position, as recorded by the thermistor, ranged from $-0.4$ to $-0.3^\circ\text{C}$.

Therefore, the remarkable changing point of infiltration, that is, the dissipation of frozen layer during thawing can be considered to be this intersectional point by way of this manner. The cumulative infiltration and time for this point was calculated by the least square method and the consequent values were shown in Table 1.

(2) Definition of the average infiltration rate during thawing $\alpha$, and the properties of frozen soil

Here, $\alpha$ is defined as the average infiltration rate during thawing, that is, the
Table 1. The cumulative infiltration and time at intersectional point.

<table>
<thead>
<tr>
<th></th>
<th>$T_d$</th>
<th>0.68</th>
<th>0.83</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\tau$</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>F. T.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$-5^\circ C$</td>
<td>$t_m$</td>
<td>6.3</td>
<td>10.9</td>
</tr>
<tr>
<td></td>
<td>$D_m$</td>
<td>26.7</td>
<td>26.7</td>
</tr>
<tr>
<td>$-10^\circ C$</td>
<td>$t_m$</td>
<td>10.5</td>
<td>19.1</td>
</tr>
<tr>
<td></td>
<td>$D_m$</td>
<td>18.5</td>
<td>19.8</td>
</tr>
<tr>
<td>$-20^\circ C$</td>
<td>$t_m$</td>
<td>20.2</td>
<td>33.9</td>
</tr>
<tr>
<td></td>
<td>$D_m$</td>
<td>22.9</td>
<td>18.1</td>
</tr>
</tbody>
</table>

$r_d$ (g/cm²), $\tau$ (%), $D_m$ (mm), $t_m$ (min).

value dividing the cumulative infiltration at the dissipation of frozen layer with its time and is expressed as

$$\alpha = \frac{D_m}{t_m}$$  \[2\]

Where $D_m$ is the cumulative infiltration and $t_m$ is the time at the dissipation.

The increment of the value-$\alpha$ may means the increment of the infiltration rate during thawing and may result in more rapid drainage of the surface water.

The relationship between this value-$\alpha$, water content of soil, bulk density and freezing temperature is shown in Fig. 5. This figure indicated that the increment of water content tended to decrease the value-$\alpha$ clearly and soil conditions with higher freezing temperature and smaller bulk density tended to have larger value-$\alpha$. The value-$\alpha$ may tend to increase with decreasing water content in the same bulk density sample and with decreasing dry bulk density at the same freezing temperature.

From these results, decreasing soil moisture content and bulk density of soils may be found to increase the infiltration rate during thawing. Therefore in actual agricultural land it would be necessary to drain firmly or to loosen the upper soil layer.

(3) The theoretical evaluation of the average infiltration rate during thawing

Since the relationship between cumulative infiltration and time is generally expressed as Eq. [1], infiltration rate with time is given as

$$I = \frac{dD}{dt} = c \ln t^{n-1}$$ \[3\]

where $I$ is infiltration rate.
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And from Eq. [2], Eq. [3] is assumed to be equal approximately as follows

\[ \frac{dD}{dt} = \frac{AD}{t_m} = \frac{D_m}{t_m} = \alpha \]  \hspace{1cm} [4]

On the other hand, the thawing depth equation is given by STEFAN (in ALDRICH\textsuperscript{3}), as follows.

\[ K_u \frac{T_u}{X} = \frac{dx}{dt} \]  \hspace{1cm} [5]

where \( K_u \) is thermal conductivity of the thawed soil (cal/cm sec °C), \( T_u \) is the surface temperature, \( L \) is the latent heat of ice, and \( X \) is the depth of thaw. His equation ignored the thermal gradient in the un frozen soil profile, and regarded soil temperature as 0°C in the un frozen soils. Here, the water volume of infiltration in the cross sectional area of the soil cylinder \( A \) (cm), with porosity \( f \), may be expressed per time as follows

\[ A \cdot dD = A \cdot f \cdot dx \]  \hspace{1cm} [6]

That is, in the small change of time,

\[ \frac{1}{f} \frac{dx}{dt} = \frac{dx}{dt} \]  \hspace{1cm} [7]

The assumption here is that since frozen soil cannot permit percolation of water, thawing the soil leads to entry of water.

Upon placing Eq. [4] and Eq. [7] in Eq. [5], the following equation is given,

\[ K_u \frac{T_u}{X} = \frac{L}{f} \frac{dD}{dt} = \frac{L}{f} \cdot \alpha \]  \hspace{1cm} [8]

Consequently, the value-\( \alpha \) becomes

\[ \alpha = \frac{K_u \cdot T_u \cdot f}{X \cdot L} \]  \hspace{1cm} [9]

Hence, the value-\( \alpha \) is found to be directly proportional to thermal conductivity, surface temperature and porosity and to be inversely proportional to the depth of thawing and the latent heat. Here it is necessary to consider the determination of each factor. Since it is known that the thermal conductivity of soils changes with water content, soil texture, etc., KERSTEN’s data (in NIXON\textsuperscript{2}) are applied to the thermal conductivity of unfrozen soil in this paper. The surface temperature \( T_u \) is applied for convenience as the water temperature used in this experiment. The porosity of samples is given as

\[ f = \left(1 - \frac{\gamma_d}{G_d \cdot \gamma_w}\right) \]  \hspace{1cm} [10]

where \( \gamma_d \) is dry bulk density (g/cm\(^3\)), \( G_d \) is specific gravity of soil particles, and \( \gamma_w \) is unit weight of water. The \( X \) is the depth of thaw and the final restricted position for infiltration since the thawing of samples occurs both upward, and downward and though it is difficult to determine \( X \), \( X \) was found about the middle of the depth of frozen samples experimentally (\( X = 2.5 \) cm). Fig. 6 shows how the frozen layer dissipated with increment of time and where this final thawed depth was located in the profile. Latent heat of samples is given as

\[ L = 0.80 \cdot \omega \cdot \gamma_d \]  \hspace{1cm} [11]
after 80 min.

after 100 min.

after 140 min.

after 150 min.

Fig. 6. The typical thawing profile of frozen soils at different times. (−20°C)

Table 2. The thermal conductivity and latent heat in this samples.

<table>
<thead>
<tr>
<th>ω</th>
<th>$K_u$</th>
<th>$r_d=0.68$</th>
<th>$f=0.734$</th>
<th>$r_d=0.83$</th>
<th>$f=0.676$</th>
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<tr>
<td>30</td>
<td>0.198</td>
<td>16.3</td>
<td>19.9</td>
<td>21.8</td>
<td>26.6</td>
</tr>
<tr>
<td>40</td>
<td>0.162</td>
<td>21.8</td>
<td>26.6</td>
<td>27.2</td>
<td>33.2</td>
</tr>
<tr>
<td>50</td>
<td>0.138</td>
<td>27.2</td>
<td>33.2</td>
<td></td>
<td></td>
</tr>
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</table>

$ω$ (%), $K_u$ (cal/cm min °C), $L$ (cal/cm³).

Table 3. The measured value and the calculative value of the average infiltration rate during thawing process.

<table>
<thead>
<tr>
<th>F. T.</th>
<th>$T_d$</th>
<th>0.68</th>
<th>0.83</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>−5°C</td>
<td>4.23</td>
<td>2.45</td>
<td>0.40</td>
</tr>
<tr>
<td>the measured</td>
<td>1.96</td>
<td>1.04</td>
<td>0.31</td>
</tr>
<tr>
<td>−10°C</td>
<td>1.14</td>
<td>0.53</td>
<td>0.24</td>
</tr>
<tr>
<td>−20°C</td>
<td>0.61</td>
<td>0.37</td>
<td>0.25</td>
</tr>
</tbody>
</table>

$α$ (mm/min), $r_d$ (g/cm³), $ω$ (%).

Each factor was shown in Table 2, respectively.

In this way, the calculative value-$α$ with equation [9] and the measured value-$α$ are shown in Table 3. In comparison with both values, the calculative value was approximated to the measured value in the range factor from 0.5 to 2, when water content was 50 percent and freezing temperature was −20°C. When dry density was smaller or water content was lower or when both conditions, the measured value exceeded the calculative value on a large scale. This large difference may be attributed to the previous assumption that frozen soil can not permit percolation. This assumption is received only in with high water content or lower freezing soil temperature, or when both conditions exist. Therefore, it may be thought that the frozen soil layer might not necessarily be impervious. Some studies report that there remains some pores in frozen soils that can permit percolation³,⁸,⁹.
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and that there is much unfrozen water in frozen soils when the freezing temperature is higher\(^5\).

Hereafter, in order to approximate the calculative value to the observed value more exactly, the consideration of the attempt to combine with Eq. [1] with either BERGGREN’s or NEUMANN’s equation containing thermal gradient to evaluate the exact experimental values of each factor (such as thermal conductivity, the depth of thaw, etc.).

Summary

In order to consider how the properties of frozen soil that remain in the soil profile during thawing in early spring, may influence the infiltration rate through the soil surface, a laboratory experiment was conducted with a simple soil column. Also, an equation on the average infiltration rate during thawing was devised using an infiltration rate equation and a thawing depth equation. The results were summarized as follows.

1. The infiltration rate during thawing becomes larger with lowering water content of frozen soils.

2. The infiltration rate becomes larger with decreasing dry bulk density of soils in the same water content.

3. In the same water content and bulk density, the infiltration rate becomes larger with higher freezing temperature.

4. In comparison with the measured values and the calculative values using the derived equation, calculative values approximated the measured values only in higher water content and lower freezing temperatures.

Hereafter, a new combination equation with a thawing depth equation that considers the thermal gradients on the frozen profile, may be necessary. It may also be necessary to evaluate each factor exactly with various experiments.

References


要

凍結土壌が春期融解するとき、土壌中に残存する凍結土層の性質が、融解時の浸入度を与える影響を検討するために、単純な土柱モデルを用いて室内実験を行った。また浸入式と融解
式との結合によって融解平均浸入度の式が誘導された。得られた結果を要約すると、
(1) 凍結土の含水量が少ないほど浸入度は大きい。
(2) 同一状態の水分量のときは、密度の小さいものほど浸入度は大きい。
(3) 水分量、密度が同一状態のときは、凍結温度が高いほど浸入度は大きい。
(4) 融解平均浸入度の式で計算した結果、含水量が多く凍結温度が低いほど、実測値に比較的近い値となった。
今後は、温度勾配を考慮した結合式を誘導する必要があるとともに、各因子のより正確な実測値を求める必要がある。