Method for Continuous Measurement of Frost Depth in Soil

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Abstract

The objective of this study was to evaluate a method for continuous measurement of frost depth in soil. The measuring device consists of a bucket filled up with a soil-water mixture. The open bucket is placed in a pit with its upper brim at the ground surface, so that frost is formed from the top of the bucket. A pipe is vertically mounted at the centre of the bucket, ending in an oil-filled balloon. The volume expansion of formed frost results in a corresponding oil flow, from the balloon at the bottom of the bucket through the pipe into an expansion bucket above ground. By measuring the volume expansion continuously, the frost depth can be determined at any time. The performance of preliminary laboratory tests confirmed the feasibility of this method.

Background

The methods most commonly used to determine the frost depth in soil (Knutson et al. 1972) are:

Temperature measurements: A number of temperature gauges are evenly spaced along a vertical line from the ground surface to a depth greater than that of the expected maximum frost depth. The temperatures are measured and recorded. The interface between the frost and the soil is defined by the freezing temperature (0°C) of water. This method indicates if the location of the temperature gauge is inside or below the frost. The method gives discrete values of the frost depth, because a certain number of temperature gauges and thus the corresponding number of frost depths are investigated. Sophisticated analysis of densely located temperature gauges makes it possible to interpolate between the gauges, and so a "semi-continuous" frost depth is obtained. The frost front is, however, difficult to evaluate since a fairly big zone around the frost front has a temperature of 0°C. Another problem is that the freezing temperature of water decreases with increasing pressure (Nordell, 1990).

The Gandahl method: In this method a pipe containing a liquid that changes its colour at the freezing point of water (0°C) is placed vertically through the soil layer. The location of the frost depth is determined by taking up the pipe and measuring the distance to the colour change, i.e. the frost depth.

There are also a number of other electrical methods; e.g. the varying electrical resistance in frozen and unfrozen soil can be used to evaluate the frost depth.

None of these methods are continuous in space and time. In many applications reliable frost measurements that are continuous in time would be desired. Such measurements would be useful in hydrological applications, e.g. in infiltration studies (Westerström, 1986). A continuous measurement method would result in a better understanding of the frost process.

Objective

The objective of this study was to evaluate a method for continuous measurement of frost depth in soil by determining the free volume expansion of the freezing water of a soil-water mixture.

Principle

A bucket of volume V (m^3) with the active height z_0 (m), filled up with saturated soil or sand, is placed in a pit with its upper brim at the ground surface. A pipe is vertically mounted at the centre of the bucket, ending in a rubber balloon. The pipe and the balloon are filled up with oil. The upper part of the bucket is open to the air according to Figure 1. In the surrounding cold air the soil-water mixture freezes from the top, and the unfrozen part of the soil-water mixture is confined by the formed ice layer and the walls of the bucket. As a result of the volume expansion of the formed ice, the corresponding volume of oil flows through the pipe to an expansion bucket. The volume of the oil accumulated in the expansion bucket is continuously measured and recorded, and the frost depth can be calculated.

Frost-Depth Calculation

When the frost depth has reached the depth z (m) from the surface, Figure 2, the frozen part ΔV (m^3) of the total volume is:

$$\Delta V=\frac{z}{z_o}V \tag{1}$$

The porosity, p, of the filling material implies that the saturated volume contains $p \bullet V$ (m^3) of water. The soil part of the frozen volume ΔV_s (m^3) is:

$$\Delta V_s=(1-p)\cdot\Delta V \tag{2}$$

and the ice part ΔV_i (m^3), i.e. the pore volume, becomes:

$$\Delta V_i=p\cdot\Delta V \tag{3}$$

Conservation of mass gives the volume of the frozen water ΔV_w (m^3) before freezing:

$$\Delta V_w=\Delta V_i\frac{\rho_i}{\rho_w}=p\cdot\Delta V\frac{\rho_i}{\rho_w} \tag{4}$$

where the densities of ice and water at 0°C are denoted by ρ_i and ρ_w respectively. By inserting the numerical densities of ice and water at 0°C, 917.3 kg/m^3 and 999.84 kg/m^3 respectively, into eq.(4) it is seen that $\Delta V_i > \Delta V_w$ (Hobbs, 1974).

In a confined bucket this would result in a pressure increase. However, the pipe (Figure 1) drains the volume expansion by conducting the corresponding volume of oil from the balloon to the expansion bucket. So the only pressure that occurs in the bucket is the oil pressure from the expansion bucket. If the distance between the expansion bucket and the frost front is small, this pressure will not influence the test. A pressure corresponding to 1 m of water reduces the freezing point of water by 0.000737°C (Nordell, 1990).

The volume difference between unfrozen and frozen water gives the volume expansion, i.e. the volume of the oil in the expansion bucket, $\Lambda(m^3)$:

$$\Lambda(z)=\Delta V_i-\Delta V_w=p\cdot\Delta V-p\cdot\Delta V\frac{\rho_i}{\rho_w}=p\cdot\Delta V(1-\frac{\rho_i}{\rho_w}) \quad (5)$$

which after inserting eq.(1) can be expressed as:

$$\frac{z}{z_o}=\frac{\Lambda(z)}{p\cdot V(1-\frac{\rho_i}{\rho_w})} \quad (6)$$

If the volume expansion is measured as the mass m (kg) of the expanded oil volume of density ρ_o (kg/m^3) then this volume can be rewritten as:

$$\Lambda(z)=\frac{m(z)}{\rho_o} \quad (7)$$

After inserting eq.(7) into eq.(6) the frost depth z is given by:

$$\frac{z}{z_o}=\frac{m(z)}{\rho_o\cdot p V(1-\frac{\rho_i}{\rho_w})} \quad (8)$$

The analysis results in a simple linear expression. The properties of ice, water and oil are well defined and constant, at the occurring freezing temperature (0°C) and normal pressure.

Preliminary Test

A preliminary laboratory test was performed, to see if this idea would encounter any unforseen problems.

A heat-insulated glass bucket, 1000 ml, was filled up with water and sand, Figure 3. A glass pipe was placed vertically in the centre of the bucket, and a thin rubber balloon was mounted at the end of the pipe. The pipe and the balloon were filled up with oil to the bottom of the expansion bucket. The equipment was placed inside a freezer. As a result of the heat insulation around the sides of the water-filled bucket, frost formed from the top.

The volume of the oil that accumulated in the expansion bucket was recorded manually. At the same time the frost depth was measured. The frost front was located and measured by temporarily removing the heat insulation. The water was coloured to simplify the location of the frost front. The measurements were in agreement with eq.(6) i.e. there is a linear relation between the volume expansion and the frost depth.

Discussion and Conclusions

This method of continuous measurement of frost depth in soil has only been tested in this preliminary laboratory test. Though manual measurements were made, the basic idea of continuous measurement was shown. An electronic weighing machine, connected to a recording system, could have been used for continuous measurements of the expanded mass.

There are some basic problems to consider. Should the expanded volume be measured as mass or volume? Where should the measuring unit be placed?. The measurement method should work from the initial freezing to the maximum frost penetration. It should also work in thawing situations, i.e. when the frost depth is reduced. In such situations the evacuated oil volume must be refilled.

When these requirements have been decided it is necessary to determine the size and design of the freezing bucket. If the mass of the expanded volume is to be measured, there are numerous systems available.

If a leakage through the frost layer were to occur, e.g. in thawing situations, the volume expansion would cause a water flow through the ice to the surface. This could, however, be avoided by a thin water-tight lid at the top of the bucket.

The material of the freezing bucket should have a lower thermal conductivity than the surrounding soil, to avoid the frost depth penetrating deeper because of the bucket. Plastic is an example of such a material. The soil-water mixture in the bucket should preferably be of the same type as the surrounding soil, but this is not necessary. If the thermal conductivity of the soil-water mixture is close to that of the surrounding soil, the frost front inside and outside the bucket will also be at the same depth. Here it is assumed that the relatively small bucket does not influence the slowly changing temperature field of the surrounding ground. The transient freezing and thawing processes should, however, be analyzed in further studies.

This method will be developed and tested further at the Division of Water Resources Engineering. It should be developed both for field and laboratory tests.

We foresee several feasible applications of this principle. It could for instance be used to prevent frost heave in construction work in frost-hazardous soils. Most often the soil is removed and the pit is refilled with, e.g. sand. The construction is then built on top of the sand-filling. This does not prevent frost heave in deep clays where the unfrozen pressurized water cannot flow from the pit. By considering this sand-filled pit as a large "bucket", a heat-insulated (or heated) pipe could be installed and the drainage water would be conducted to e.g. the sewage system of the building. Even if all of the sand-filling is frozen there will be no frost heave with this system.

Nordell and Westerström (1994) suggested another application, a continuous measurement method to determine ice cover thickness.

Acknowledgements

We invite all readers to communicate to us any comments they might wish to make on this method for continuous measurement of frost depth. We acknowledge Tech. Rolf Engström for his constructive work with the laboratory tests and Dr. Sven Knutsson for his assistance in improving this paper.

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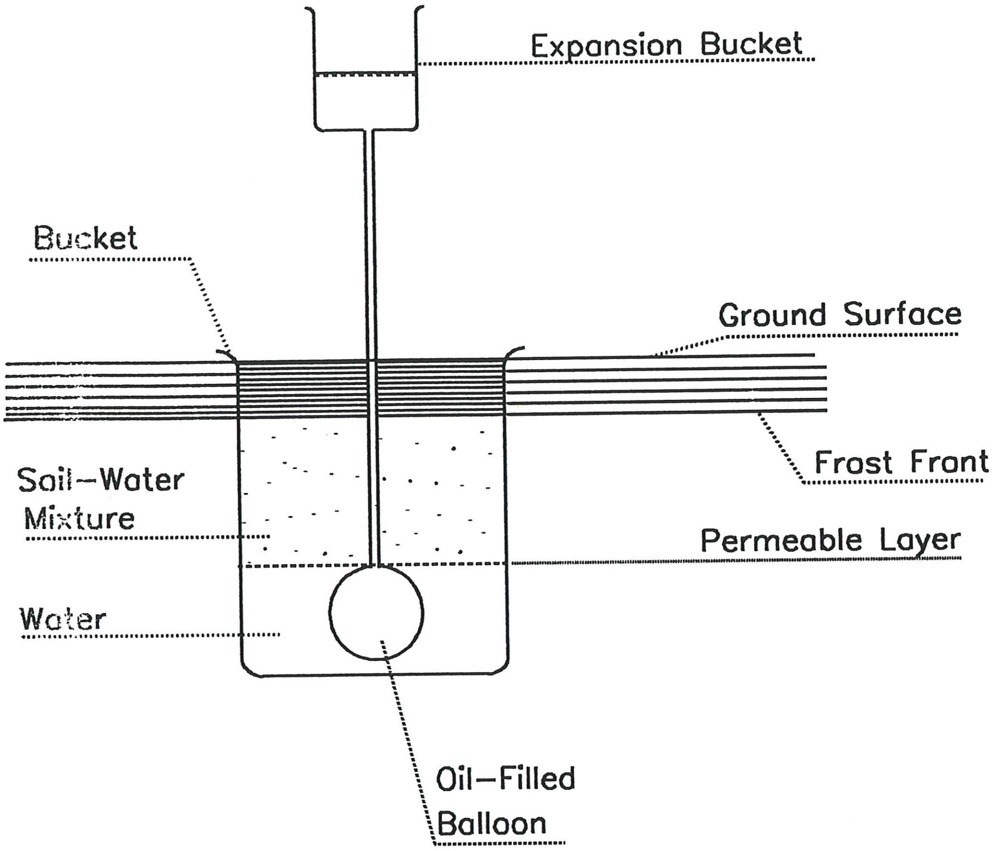

Figure 1. Outline of frost depth measurement device with a closed oil system to evacuate the volume expansion.

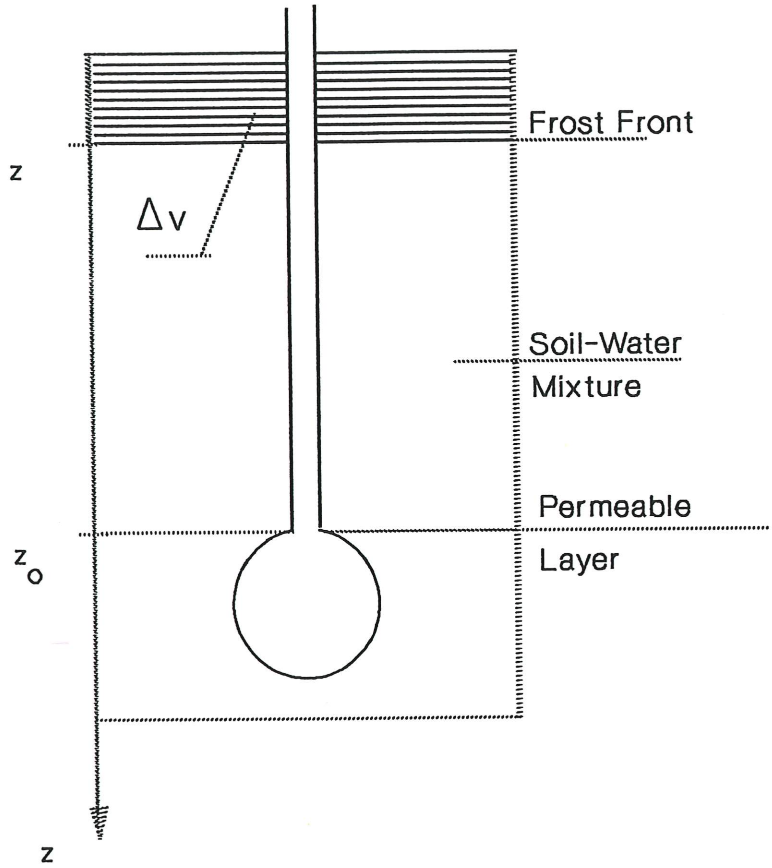

Figure 2. The active part of the bucket, i.e. the maximum frost depth, is z_o from the surface of the bucket.

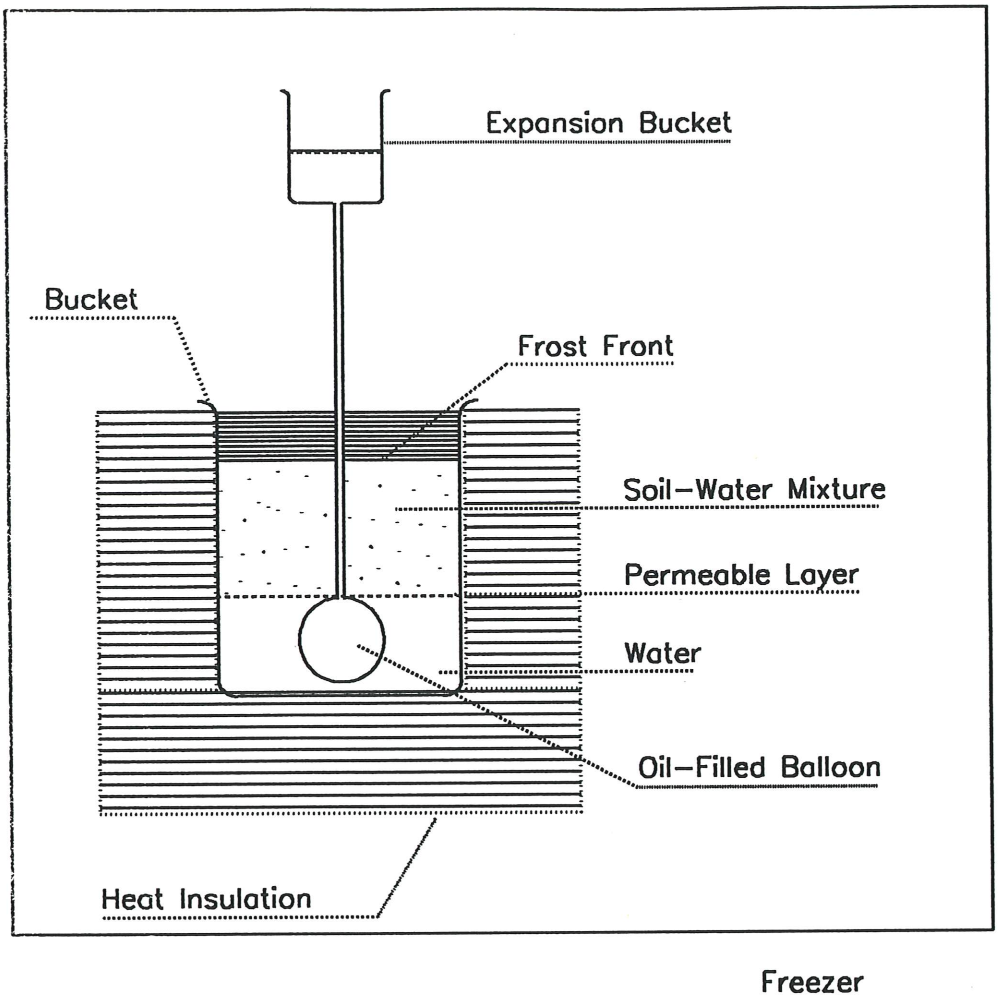

Figure 3. The test equipment. The heat-insulated sand-water-filled bucket is placed in a freezer. The volume expansion of the formed fost drives the oil from the balloon to the expansion bucket.