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# Comparison of soil frost and thaw depths measured using frost tubes and other methods

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ABSTRACT

Frost tubes filled with methylene blue solution are commonly used tools for measuring soil frost and thaw depths in the field. To quantify the accuracy of this method, soil frost depths were measured in agricultural fields in the Tokachi district of the northernmost of Japan's main islands. The frost depths measured using frost tubes coincided with those determined from direct observations of the soil profile. The root mean square error (RMSE) between these two methods (i.e. frost tubes and direct observations) was ±0.035 m, which is expected for frost tubes in this region. The soil temperature profile was characterized over four winters using thermocouples to estimate soil frost depths in an experimental field in central Tokachi. Frost depths were also measured using frost tubes during this period. A scatter diagram of the frost depths obtained using these two methods showed a concentration of points along a 1:1 line. The RMSE between these two methods was ±0.028 m, suggesting that frost depth can be accurately estimated from the soil temperature profile. Unlike soil frost depth, soil thaw depths measured using frost tubes were consistently deeper than those determined through direct observation of the profile of soil hardness. This might be true because the frozen soil around the frost tube thawed earlier because of the greater insolation and heat conduction from atmosphere resulting from the decrease in snow cover as a result of snowmelt around the frost tube. However, because a scatter diagram of the thaw depths obtained using these two methods showed an approximately linear relation, the thaw depths measured using frost tubes can be calibrated using this relation.


## 1. Introduction

Soil frost and thaw depth is an important parameter used to ascertain field conditions in cold regions. For example, frost heaving sometimes induces severe damage to construction (Phukan, 1985) and plants in the agricultural field (Sharratt and McCool, 2005). Soil frost depth influences the amount of snowmelt infiltration (Iwata et al., 2010a). Soil thaw depth is important to know the timing of the cultivation and seeding in early spring (Harada et al., 2009). Therefore, it is important to measure the frost and thaw depth accurately in the field.

A frost tube is a common instrument for monitoring soil frost and thaw depths (Phukan, 1985), defined as the distance from the ground surface to the freezing front in winter, and from the ground surface to the thawing front in the spring, respectively. A primitive frost tube is constructed with an outer guide of polyvinyl chloride (PVC) pipe and an inner acrylic tube filled with a solution of methylene blue dye (Gandahl, 1957; Kinosita et al., 1967; Rickard and Brown, 1972; Sharratt and McCool, 2005). To avoid damage to the inner acrylic tube that might be induced by the increase in the solution's volume caused by freezing, a soft rubber tube is sometimes installed inside the inner tube. Methylene blue solution changes from blue to colorless when it freezes. Measurements are taken by pulling the inner tube upwards from the outer guide and recording the length of the clear section as the frozen layer thickness (Fig. 1).

Soil frost and thaw depths can be determined from the soil temperature profile (Gray and Granger, 1986; Riseborough, 2008; Stadler et al., 1996). Because clean water such as the tap water or water from a well generally freezes at 0 °C, the frost and thaw depths measured using this method appear to be equal to those measured using the frost tube. However, because pure water does not freeze below 0 °C under supercooling conditions (e.g., Bigg, 1953), no soil water or the solutions in the frost tube subjected to supercooling conditions would freeze at subzero soil temperatures. For that reason, the frost depth measured using the temperature profile method is expected to be deeper than that recorded using the frost tube.

The difference in heat capacity between water and soil might also show difference in the measured frost depths among these different

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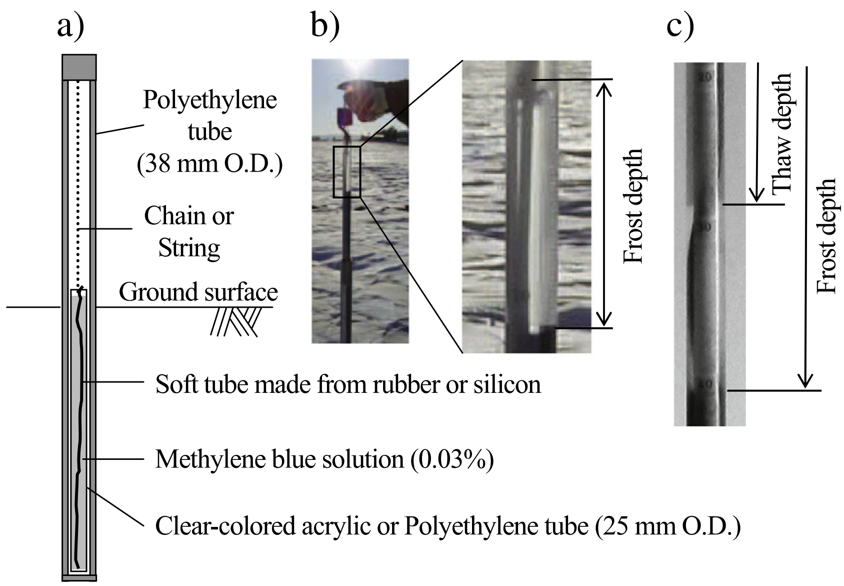


**Fig. 1.** a) Schematic diagram of a frost tube, b) Frost tube during the soil freezing period, and c) Frost tube during the soil thawing period.

methods. The heat capacity of water ($C_w$) at 0 °C is 4217 J kg$^{-1}$ K$^{-1}$ (Dorsey, 1940), whereas the heat capacity of soil particles ($C_s$) is estimated as 837 J kg$^{-1}$ K$^{-1}$ (Kasubuchi, 1977). Because soil contains water, the volumetric heat capacity ($C$) of soil is given as

$$C = C_s\rho_b + C_w f_w \rho_w, \tag{1}$$

where $\rho_b$ stands for the dry bulk density of soil, $f_w$ signifies the volumetric fraction of water, and $\rho_w$ denotes the water density. Assuming that $\rho_b = 820$ kg m$^{-3}$, $f_w = 0.4$, and $\rho_w = 1000$ kg m$^{-3}$, which are the values at the surface soil layer measured by Iwata et al. (2010a), $C$ was calculated as $2.4\times10^6$ J m$^{-3}$ K$^{-1}$. The volumetric heat capacity of water in the frost tube is $4.2\times10^6$ J m$^{-3}$ K$^{-1}$ (=4217 J kg$^{-1}$ K$^{-1}$ × 1000 kg m$^{-3}$), which is twice that of soil.

Lower soil water content or higher concentration of salinity in the soil water decreases the soil water potential, thereby depressing the freezing point (e.g., Miller, 1980). Frozen soil is defined as soil which contains ice. Therefore, this might also induce an estimation error in the frost depth using a frost tube. Alternatively, frost depth should be determined through direct observation of the soil profile, where the boundary between frozen and unfrozen soil is determined according to the soil hardness or the existence (or absence) of visible ice (e.g., Araki, 1989; Phukan, 1985). However, few researchers (e.g., Sartz, 1967; Smith et al., 2009) have compared soil frost or thaw depths determined through direct observation and the methods mentioned above.

Despite possible disparities in the frost depths measured using different methods, these methods are sometimes regarded as equivalent. Hardy et al. (2001) recorded frost depth using the temperature profile method in their first observation year, but they changed to frost tubes in the subsequent 2 years of their observations. Nemoto et al. (2008) calculated soil frost depths using a numerical model to estimate the soil temperature profile, and conducted a sensitivity analysis with frost depths measured using a frost tube. DeGaetano et al. (2001) and Thorsen et al. (2010) also developed numerical models to estimate frost depth from the heat budget of the soil, and confirmed their calculated results obtained using frost depths measured using a frost tube. To confirm the accuracy of these studies, a quantitative comparison of the soil frost and thaw depths measured using different methods is necessary. Knowledge of the differences in measured values using different methods might also be useful to compare results obtained from numerous earlier studies.

To evaluate the differences of the frost and thaw depths measured using frost tubes and other methods, field observations were conducted in the Tokachi district of Japan (Fig. 2). Frost tubes filled with methylene blue solution were installed at each study site. The frost and thaw depths measured using this instrument were compared with those determined from the hardness of the soil and the soil temperature profile. The objective of this study was to reveal the accuracy of the soil frost tube measurements obtained in the field.

## 2. Site descriptions and methods

Locations of the study sites are presented in Fig. 2. Annual mean air temperature and annual precipitation during 1997–2010 were 5.9 °C and 970 mm, respectively, at the meteorological station of the National Agricultural Research Center for Hokkaido Region (NARCH), located in the central part of the Tokachi district (Fig. 2). The mean air temperature in January, the coldest month, was −9.7 °C. The precipitation during winter (from December–March) was 200 mm, on average, during that period.

Soil frost depths were monitored at all sites. Frost tubes (Fig. 1) using a 0.03% methylene blue solution, based on previous research in this region (Tsuchiya, 1985), were installed using a soil sampling auger, which can dig a hole of the same diameter as the outer PVC pipe of the frost tube (38 mm; Fig. 1). At the sites, soil started to freeze in late November and daily mean air temperature rose above 0 °C from early March; so we defined the period from December through February as the soil freezing period. Soil hardens considerably when soil freezes in our study sites. Therefore, we surveyed the soil profiles several times and determined the soil frost depths from the hardness of the soils. Soil pits, approximately 1 m$^2$ for the pit area, were dug using a rock drill during the soil freezing period of 2001–2002 at NARCH. From December 2002, we drove a soil sampler (inner diameter approximately 30 mm) (Eijkelkamp, 04.04.00.30.C and 01.10.11.C) into the frozen ground using a hammer, sampled the frozen and lower unfrozen soils, and determined the soil frost depth from the hardness of the soil profile. These frost depths were compared with those measured using the frost tube simultaneously. To minimize the influence of the spatial variation on the measured