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MEASURING SNOW WATER EQUIVALENT AND SNOW DENSITY USING TDR MINI-PROBES

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Abstract
Conventionally, the snow water equivalent and snow density are determined by destructive core-

sampling and analysis. This paper presents the results of a series of experiments designed to

evaluate the use of TDR mini-probes in a non-destructive method for measuring snow water equivalent and snow density.

Time Domain Reflectometry (TDR) measures the apparent dielectric constant around a wave guide inserted into a media. Several researchers have demonstrated that there is a polynomial relationship between the apparent dielectric constant and water content of a porous medium. Changes in soil water content have been successfully monitored non-destructively using TDR probes. Initial tests showed that the density of the snow affected the TDR travel time. A series of tests was carried out to relate the changes in snow TDR travel time to the changes in the density of snow and to snow water equivalent.

Calibration equations were developed for using the TDR probes in snow measurements. A mixed reciprocal and quadratic model was suggested for the snow density range of $0.40 - 0.95$ Mg/m^3.

INTRODUCTION

Snow density and water equivalent are important parameters that are measured frequently as part of may investigations. Snow water equivalent determines the amount of snow-melt discharge that is a factor in runoff modeling (Jones et al., 1983) and hence in designing a drainage system. It also has an economic importance if the snow-melt-water is to be used for power generation. As snow-melt water carries pollution from snow dumps, it is also a factor in contaminant transport modeling. Snow density has a direct effect on the mechanical strength of the snow pack and therefore, is a factor in forecasting avalanche occurrence. Therefore, measuring snow density and water equivalent are of great interest. These measurements also are important in validating data obtained using remote sensing systems.

Liquid water content and snow density of a snow pack changes with time and horizontally and vertically. Therefore, a system that can measure quickly with minimum disturbance is

needed. Such a system can be used to log the data continuously and make timely decisions. The direct method of determining snow density and water equivalent is through destructive core-sampling and analysis. This method is tedious and does not permit continuous logging of data from the same location.

Time Domain Reflectometry (TDR) measures the apparent dielectric constant around a wave guide inserted into a media using a Cable Tester. Changes in soil water content have been successfully monitored non-destructively using TDR probes. Topp et al. (1980 1982a,b) demonstrated that there is a polynomial relationship between the apparent dielectric constant and water content of a porous medium. Stein and Kane (1983) are the first to show the feasibility of using TDR technique to monitor water content of snow in the field. The exploratory measurements were mostly done in soil. Lundberg (1997) used an array of long TDR probes to measure liquid water content. TDR-method has the potential to register variations in snow liquid water content down to 1 to 2 % by volume. Stein et al. (1997) monitored snow dry density and liquid water content using three types of horizontal probes. The probe lengths varied between 0.45 – 0.90 m. For the liquid water content measurement, the empirical relationship between the liquid water content and the dielectric content yielded a 1.0% error of estimate by volume. With little liquid water, dry snow density was measured with a mean absolute error of 0.03 Mg/m^3. These studies used long TDR probes. Because snow density changes horizontally and vertically, a longer probe tends to give the average measurement of the snow density. In this study a TDR mini-probe (0.1 m long) was used to monitor the changes in snow density. The objective of this study was to use the mini-TDR probes to establish a relationship between the dielectric constant and the density of the snow. Different empirical models were compared.

MATERIALS AND METHODS

In the laboratory experiment, first of all TDR mini-probes having different lengths have been tested to find the effect of probe length on measurement accuracy. Once the probe length was selected, a series of TDR measurements were made on snow having different densities.

The TDR mini-probes used in this laboratory experiment were fabricated in the Department of Biosystems Engineering, University of Manitoba. The TDR mini-probe consisted of three 1.6 mm diameter stainless steel rods. A two-meter coaxial cable connected the TDR mini-probe to the Cable Tester. A Tektronix 1502B metallic TDR Cable tester was used to obtain the TDR waveforms. The individual waveforms were stored in a computer and a Quick Basic program was used to extract the travel time and convert it into dielectric constant data.

In the first part of the laboratory experiment, probes having lengths of 0.04, 0.08, and 0.12 were tested. A 425 mL plastic container was filled with snow and probes having different lengths were inserted and readings taken. Then the snow was compacted to obtain a higher density snow. More snow was added to bring the volume to the same level. Probes having different lengths were quickly inserted and the readings were taken. The data were analyzed to select a probe length that was used in the second part of the experiment.

In the second part of the laboratory experiment snow was packed in the 425-mL plastic container to the 410 mL mark. The TDR probe was inserted and a reading was taken. The snow was weighed to find the mass of snow. The snow was discarded. Fresh snow was taken and compacted to give a higher snow density. The TDR probe was inserted and a reading was quickly taken. This procedure was repeated to obtain waveforms that represented various snow densities. A computer program was used to extract the travel times and then convert them to dielectric constant values. The snow density data were fitted with dielectric constant data using various general linear models. A comparison of the results is presented.

RESULTS AND DISCUSSION

Figure 1 shows the effect of snow density on the TDR wave forms. The shape of the TDR

waveform obtained at high snow density (e.g) 0.95 Mg/m^3 is similar to that obtained from water.

However, with the decrease of snow density the falling limb of the TDR form disappears and the

remainder of the waveform rises. This phenomenon is similar to the changes in waveform when
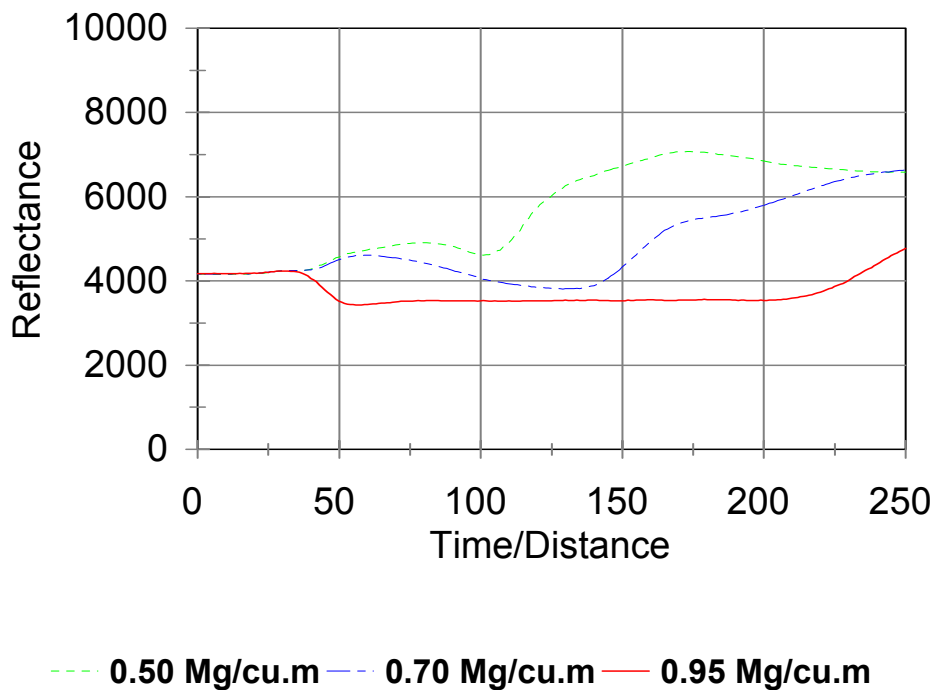
a wet soil becomes a dry soil.

--- **0.50 Mg/cu.m** -- **0.70 Mg/cu.m** —— **0.95 Mg/cu.m**

Fig. 1. TDR waveforms as affected by the changes in snow density..

Figure 2 shows the travel distance calculation between the first peak and the second

reflection from an individual wave form. It was hard to identify the first peak in a waveform.

The first derivative of the waveform showed a prominent peak and for all practical purposes this

peak was considered as the first peak. Second reflection point was located as the intersecting

point of the two regression lines as shown in Fig. 2. The difference between these two points in pixel length was the travel distance.
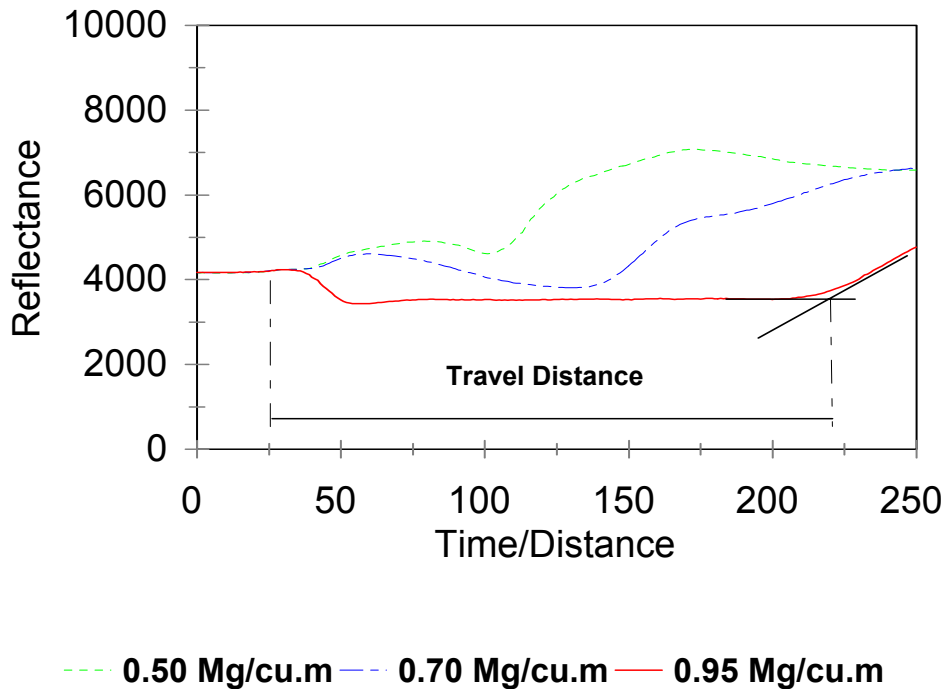

Fig. 2. Travel distance estimation from a TDR waveform.

TDR mini probes of different lengths were tested to find their effect on accuracy of TDR measurements on snow density measurements. For this experiment, TDR probes of lengths 0.04, 0.08, and 0.12 m were tested on snow of two different densities. Figure 3 shows the effect of TDR probe lengths on the measurement accuracy of snow density. With the increase in probe length, TDR wave forms shifted to the right. As the length increased the difference in travel length increased indicating increase in accuracy of measurements for a longer probe. Travel distance differences for the same level of snow density TDR probes of lengths 0.04, 0.08, and 0.12 m were 15, 18, and 41 pixel length, respectively. Although a longer probe may give a better

accuracy, vertical heterogeneity in snow density would negate using a long probe. Because of this limitation, a 0.10 m probe was selected for the rest of the experiments.
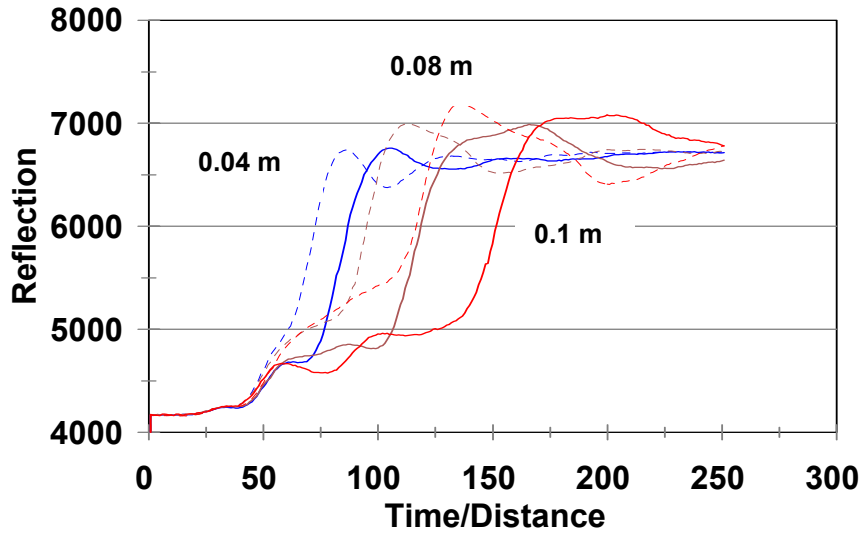

Fig 4. Effect of TDR probe length on measurement accuracy of snow density. Dotted lines refer to a measurement at a lower snow density. Solid lines refer to a measurement in high snow density.

The snow density and dielectric constant data obtained from the laboratory experiment were fitted with different general linear models to find the relationship between the. Simple linear model fitting gave a R^2 of 0.52 and was discarded. Figure 5 shows a reciprocal curve fitting between snow density and dielectric constant. The model had a R^2 of 0.86. Although the curve fitted well for snow densities below 0.70 Mg/m^3, it did not fit well for higher snow densities. Therefore, this model was discarded
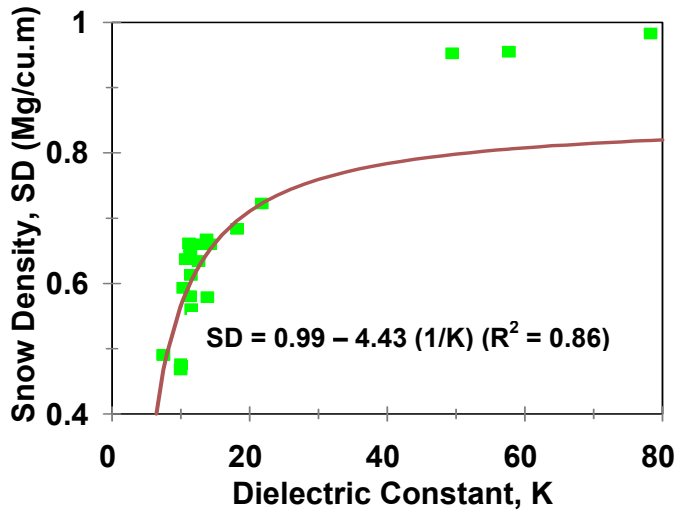
Fig. 5. A reciprocal curve fitting between snow density and dielectric constant.

Figure 6 shows a quadratic curve fitting between snow density and dielectric constant. The model R^2 improved to 0.89. The curve fitted well for snow densities above 0.70 Mg/m^3. However, it did not fit well below this level of snow density. Fitting cubic or higher order models did not improve R^2 or fitting and therefore were not considered. It is worth recalling the relationship between water content and dielectric constant in soils is a higher order one.
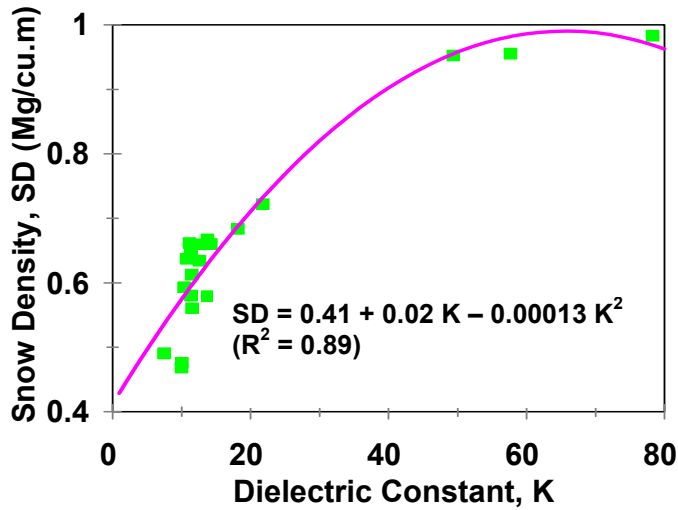
Fig. 6. A quadratic curve fitting between snow density and dielectric constant.

In the reciprocal model (Fig. 5) ($R^2 = 0.86$), the dielectric component was added to see if the model predicted better than the reciprocal model. The R^2 increased to 0.90. Figure 7 shows the curve fitting. The lack of fit, as shown in Fig. 5, for snow densities above 0.70 Mg/m^3, improved.
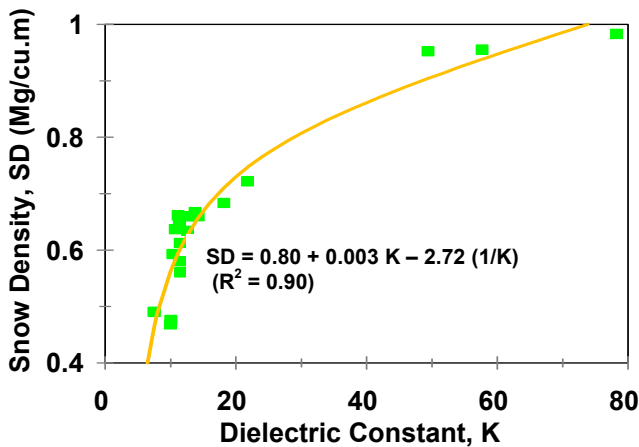

Fig. 7. Improvement in curve fitting by incorporating dielectric component in the reciprocal model.

From the above curve fitting analysis, it became apparent that the relationship between snow density and dielectric constant at lower snow densities (<0.70 Mg/m^3) was governed by a reciprocal model and at higher snow densities (>0.70 Mg/m^3) it was governed by a quadratic model. Therefore, a mixed model between these two was envisaged. Figure 8 shows the curve fitting of a mixed model of reciprocal and quadratic. Although the R^2 marginally increased, the curve fitting improved for the entire data range. Figure 9 shows the residuals plot for the mixed model. Authors suggest using this mixed model if one works in the snow density range of 0.40 – 0.95 Mg/m^3. A simpler reciprocal model may be selected if one works in the snow density range of 0.40 – 0.70 Mg/m^3. Above snow densities 0.70 Mg/m^3 a quadratic model is suggested.
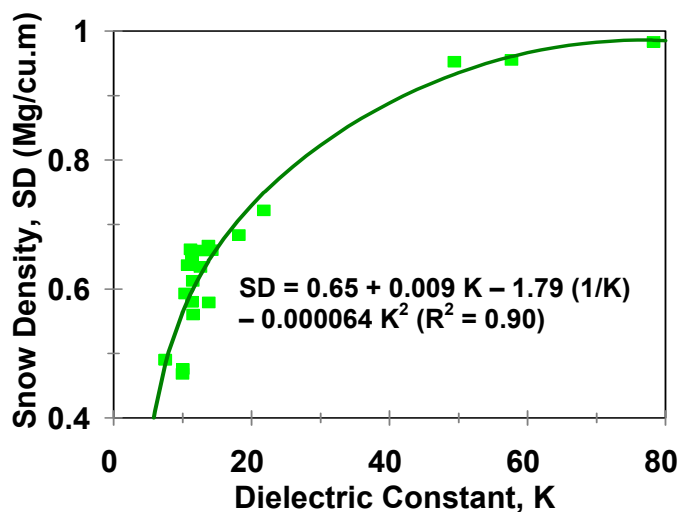

Fig. 7. A mixed reciprocal and quadratic model curve fitting showing better fit.
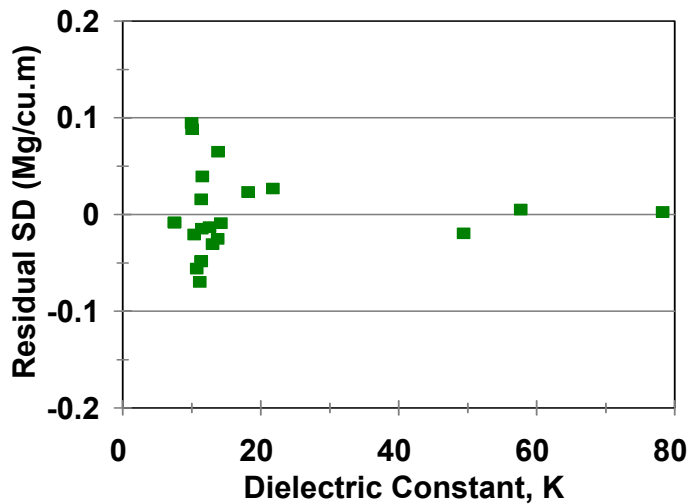
Fig 9. Residuals plot of the reciprocal and quadratic mixed model.

CONCLUSIONS

The curve fitting data analysis between snow density and dielectric constant as measured by the TDR indicated that the model for the prediction to be used is dependent on the range of snow density one works with. At a snow density between 0.40 and 0.70 Mg/m^3, a reciprocal model fitted the data well. At snow densities above 0.70 Mg/m^3, a quadratic model fitted well. For the snow density range 0.4 – 0.95 Mg/m^3, a mixed model of reciprocal and quadratic is recommended.

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