Time Domain Reflectometry for Indirect Measurement Change During Freeze-Thaw Process of Soil Volume

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Abstract. The variation of soil mechanical properties during the freeze-thaw cycles, especially the reduction of air suction in the thaw stages, was investigated in this paper. The reduction of air suction is the major cause of the volume expansion between 20–50 min during the thaw stage. An innovative TDR tube sensor was developed to nondestructively monitor the freeze-thaw process, from which the water content and the degree of freeze-thaw can be accurately determined. Compared with existing technologies for frost measurement, TDR has advantages in that it provides more details on the progresses of freeze-thaw status. With the assistance of this tool, not only the onset of freeze or thaw process, but also the extents of their development can be investigated. From the measured soil mechanical properties, an analysis is given to calculate the change of air suction during the thaw stage. The air suction at complete thaw status can be measured by use of a traditional instrument, such as a tensiometer. As a result, the air suction pressure during the thaw process can be indirectly measured.

Keywords: Time Domain Reflectometry (TDR) · Air suction · Freeze-thaw · Unsaturated soil mechanics

1 Introduction

In cold regions, freeze-thaw cycles induce ground settlement and causes the loss of soil bearing capacity. It also leads to larger pavement deflection and accelerates delamination in pavement structure. In addition to the detrimental effects on soil mechanical properties, freeze-thaw cycles also impact the drainage capability and generate additional soil pressure on underground structures, such as pipes and tunnels.

The frozen soil is a four-phase system including: a. solid mineral particles, b. ideally plastic ice inclusions (cementing ice and interlayer ice), c. bounded water and liquid states, and d. water vapors. During the freezing process of fine grained soils, not

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all the pore water changes to ice at the freezing temperature. With further decrease of the temperature, phase transitions from the water to ice continues at steadily decreasing rates [1],

The dielectric constant of ice which is around 3, is much smaller than that of liquid water (around 81) [2]. Therefore, the change in dielectric constant due to ice formation can be easily detected by use of Time Domain Reflectometry (TDR) technology. This provides the means for distinguishing between frozen and unfrozen soil [3, 4].

In this study, experimental methods are conducted to investigate the effects of freeze-thaw on soil mechanical behaviors. An innovative TDR tube sensor is developed to nondestructively monitor the freeze-thaw process. We improved a new method to determine the accurate degrees of freeze-thaw instead of using the traditional factor dielectric constant (Ka). From the unexpected volume change phenomena, we also explored the analysis procedure to determine the change of air suction during the thaw process.

2 Background of TDR

TDR is a new technology for soil moisture content measurement, which has been used in most field studies on pavement performance. A typical TDR system generally includes a TDR device (pulse generator and sampler), a connection cable, and a measurement probe. The measurement probe is surrounded by materials which are to be measured. TDR works by sending a fast-rising step pulse or impulse to the measurement sensor that measures the reflections due to the change of system geometry or material dielectric permittivity. The fundamental of TDR for moisture measurement lies in the large contrast between the dielectric constant of water (around 81) and that of the air (1) or soil solids (the dielectric constant for dry solids is between 2–7) [5].

Figure 1 shows a typical measured TDR signal. Dielectric constant (denoted by Ka in this paper) and electrical conductivity (denoted ECb in this paper) can be obtained from direct analysis of TDR signal. Dielectric constant is related to the speed of electromagnetic wave in soils and electrical conductivity is related to the rate of attenuation of electromagnetic wave propagation. The dielectric constant is calculated by Eq. (1).

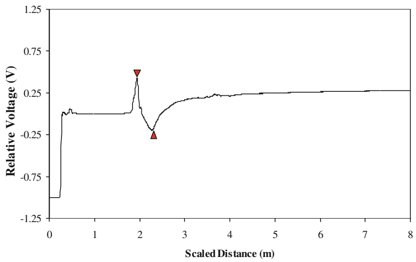

Fig. 1. A typical TDR output signal

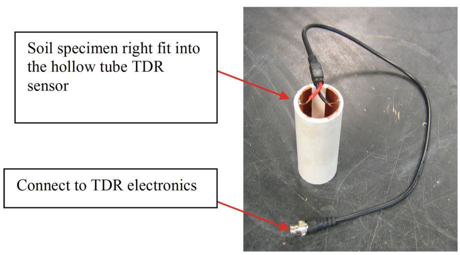

Fig. 2. Photo of PVC TDR sensor

$$K_a = \left(\frac{L_a}{L_p}\right)^2 \tag{1}$$

There are several empirical equations to relate soil moisture content to TDR measured soil dielectric constant. The Siddiqui and Drnevich equation (Eq. 2) is unique in that it accounts for the effects of soil density and soil type.

$$w = \frac{1}{b}\left(\frac{\rho_w}{\rho_d}\sqrt{K_a} - a\right) \tag{2}$$

where ρ_d is the dry density of soil, ρ_w is the density of water, a and b are soil-dependent calibration constants.

An innovative TDR tube sensor was fabricated to nondestructively measure the change of free water content during the freeze-thaw process. The underlying principles are, during the freeze-thaw process, the transition between liquid water and solid (ice) status causes significant change of their dielectric constant. The TDR waveguide cable was mounted on a PVC tube (Fig. 2). A clean clay sample from DEL-23 site was used in this study. Soil specimens were prepared by a Harvard compactor which will fit into the TDR tube to ensure the accurate measurement.

3 Background of Soil Suction

The concept of soil suction was developed in soil physics in the early 1900's. The soil suction theory was mainly developed for the soil-water-plant system. The importance of soil suction in explaining the mechanical behavior of unsaturated soils relative to engineering problems was introduced at the Road Research Laboratory in England. Researchers provided quantitative definitions of soil suction and its components from a thermodynamic context. These definitions have become accepted concepts in geotechnical engineering.

4 Laboratory Experimental Program

4.1 Sample Preparation

Nine soil samples were prepared at optimal water content (17%) and compacted with a Harvard miniature compactor. The samples were compacted in three layers, each layer with 42 g of soils. The compaction control aimed to develop soil samples with high consistency and quality. Figure 3 shows the process of soil sample preparation including the Harvard miniature compactor and a sample of the specimen.

After the soil specimens were prepared, they were subjected to the freeze-thaw process described in the subsequent context. Destructive strength tests were performed on the soil specimen at different freeze-thaw stages. Specimen S1, S2, S3, S6 and S7 were tested during the thaw process. S4 was used for TDR monitoring and S9 was used as a reference sample for the measurement of axial deformation to determine the freeze

Fig. 3. Preparation of soil specimen

induced volume change. Table 1 summarizes the physical properties and testing program conducted on each specimen.

Table 1. Physical properties of soil specimens and testing program

Specimen no.	Mass (gram)	Water content (%)	Function
S1	117.01	17	0 min Compression test
S2	118.14	17	13 min Compression test
S3	117.68	17	26 min Compression test
S4	117.67	17	TDR test
S5	116.81	17	Volume test
S6	116.56	17	39 min Compression test
S7	117.63	17	52 min Compression test
S8	117.63	17	Back up
S9	115.23	17	Reference sample

4.2 Freeze-Thaw Setup of Clay Sample

One soil sample was prepared for unconfined compression testing under room temperature. The remaining specimens were placed in freezer with a constant temperature of −12 °C. Based on monitoring results by TDR tube sensor, it was estimated that it took about 52 min for the soil sample to be completely melt from Fig. 4.

Compression test on the virgin sample S9 was conducted with loading rate of 0.1 mm/s. From Fig. 5, we could find that the compressive strength of the virgin specimen was 457 kPa. We also performed compressive tests at different thaw stages listed in Table 2, including one for completely frozen, one for completely thaw and the 3-remaining specimens at different thaw stages. The frozen specimens were removed from freezer and sat on a table with room temperature. At different thaw stages, 13 min, 26 min and 39 min, a specimen was tested on the MTS machine. The remaining specimen, S7 was tested after it has completely thawed; S1 was tested at completely frozen.

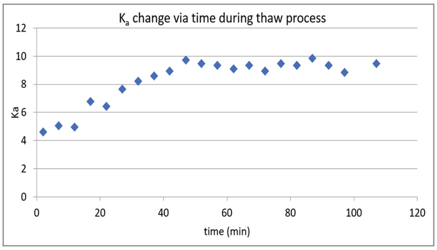

Fig. 4. K_a change during thaw process

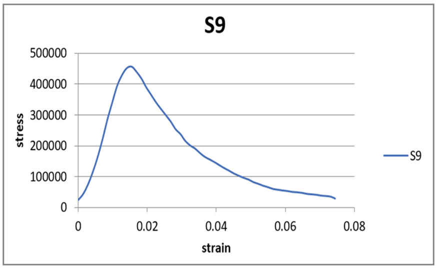

Fig. 5. Unconfined compression test

Table 2. Compressive strength of soil specimens at different freeze-thaw stage

Specimen no.	Mass (g)	Freeze degree	Thaw degree	Compressive strength (kPa)
S1	117.01	100%	0%	6491
S2	118.14	38%	62%	2188
S3	117.68	16%	84%	682
S6	116.56	6%	94%	419
S7	117.63	0%	100%	518
S9	115.23	0%	100%	238

4.3 Discussion 1

From the following charts, we could notice that the compressive strength and modulus of S6 (2^{nd} data) is slightly lower than those of S7 (1^{st} data). This means when a soil sample was frozen for a while, such as 13 min (6% frozen), its compressive strength and modulus would reduce rather than increase. Is it the increase of air suction during the freezing process that initiates these phenomena? (Fig. 6)

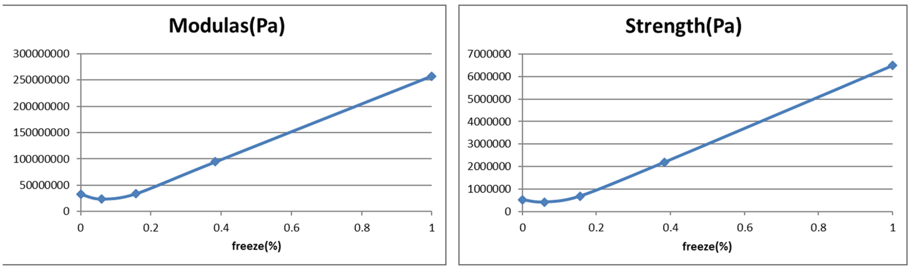

Fig. 6. Physical properties curves of the specimens at different freeze-thaw stage

4.4 Discussion 2

There was a significantly unexpected phenomenon we found in this experiment. Usually when the frozen soil was melting, its volume should reduce because the density of ice is 10% smaller than that of water. However, the volume increased as you could see in Fig. 7. Is it the decrease of air suction during the thaw process that initiates these phenomena?

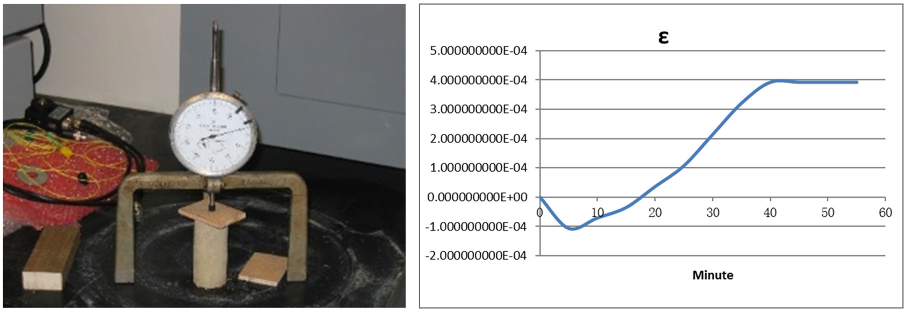

Fig. 7. Volume change of S5 with the displacement gage

To verify and compare this volume increase phenomena, we studied additional five soil specimens listed in Table 3.

Table 3. Physical properties of soil specimens in additional experiment

Specimen no.	Mass (g)	Actual water content (%)
S16	114.98	16.2
S18	123.58	18.1
S20	121.00	20.6
S22	116.16	22.2
S24	123.33	24.0

4.5 Estimation of Soil Air Suction Change

For soil samples with water contents of 18.1% and 20.6%, the volume first decreased and then increased. For soil sample with water content of 24%, the volume continued to decrease except at a certain location where volume expansion appeared in Fig. 8.

The total volume change could be viewed as being composed of two major components, i.e., **(1)** the volume change due to the phase change of ice into water, $\boldsymbol{\varepsilon_1}$. As water has a larger density than ice, the volume reduces as ice melts; **(2)** the volume change due to the reduction of the negative air pressure, $\boldsymbol{\varepsilon_2}$. This results in a net

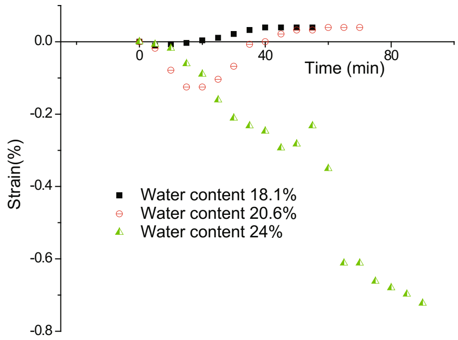

Fig. 8. Measured volume change during thaw process (− stands for volume contraction, + stands for volume expansion)

decrease of the effective stress on soil skeleton and thus causes the volume expansion. The mathematic representation of the terms can be written as following:

$$\varepsilon_v = \varepsilon_1 + \varepsilon_2 \tag{3}$$

The effective stress principle for unsaturated soils is written as follows,

$$\sigma = \sigma' + (1 - x)u_a + xu_w \tag{4}$$

where σ' is the effective stress, σ is the total stress, u_a is the pore air pressure, u_w is the pore water pressure, x is the percentage of cross section by water, which is related to the degree of saturation but affected by soil structure (Bishop et al. 1969) (Fig. 9).

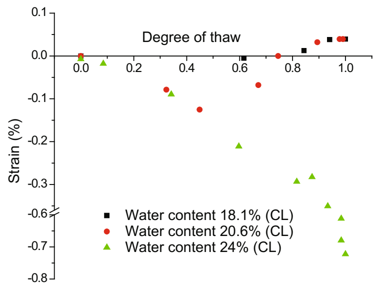

Fig. 9. Volume change versus Degree of thaw

Applying the effective stress principle for frozen soil in the thaw stage, there is,

$$\sigma = \sigma' + (1 - x)u_a + (x - x_1)u_w + x_1 u_{ice} \tag{5}$$

where x_1 is the relative volume of ice in soil skeleton (ranges from 0 to x). u_{ice} is the pressure carried by ice components. The other terms are defined as previously (Fig. 10).

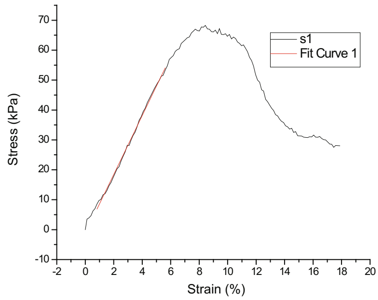

Fig. 10. Example of stress-strain curve of soil under compression

The pressure acting on the solid components, i.e., soil solids and ice, can be represented by an equivalent stress, let

$$\overline{\sigma'} = \sigma' + x_1 u_{ice} \tag{6}$$

Equation (5) can be rewritten as,

$$\sigma = \overline{\sigma'} + (1 - x)u_a + (x - x_1)u_w \tag{7}$$

The change of the volume of soil skeleton is caused by the change in the effective stress. During the melting process, the total stress and the pore water pressure can be

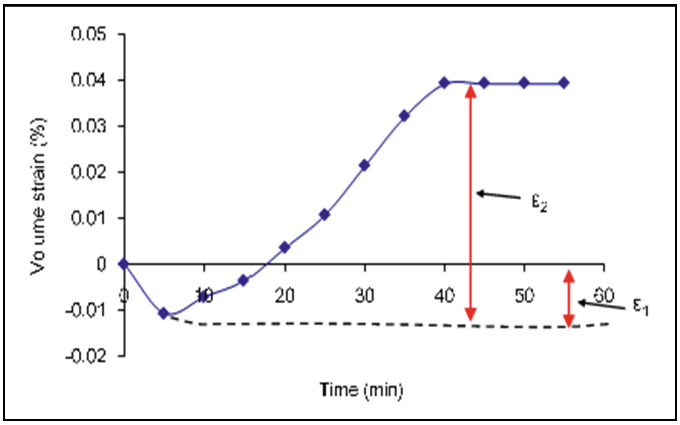

Fig. 11. Components of volumetric strain during thaw process

assumed to be unchanged. The change of effective stress can then be expressed as (Fig. 11)

$$\Delta\sigma' = \Delta\sigma - \Delta((1-x)u_a) - \Delta((x-x_1)u_w) \approx -\Delta((1-x)u_a) \qquad (8)$$

where the terms are as defined in the previous equations.

As thaw progresses, the degree of saturation increases. In addition, the magnitude of pore air pressure decreases. The total effect is the reduction in the soil effective stress, which causes the volume expansion. As the amount of volume change is small, the

$$\Delta\sigma' = E\varepsilon_2 \qquad (9)$$

where E is the deformation modulus of soil

Combining Eqs. (8) and (9), there is,

$$-\Delta((1-x)u_a) = E\varepsilon_s \qquad (10)$$

Or

$$\Delta u_a = -\frac{E\varepsilon_s}{1-x} \qquad (11)$$

Equation (11) provides a way to estimate the relative change of the pore air pressure during the thaw process. This can be estimated by measuring the deformation modulus E, volume expansion due to pore air pressure reduction, and the corresponding degree of thaw.

Figure 12 shows the volume expansion due to air suction, reduction, and the change of air suction estimate by Eq. (11) for thawing soil with different water contents.

Figure 12 shows that there are gradual drops in the magnitude of the air suction pressure as the thaw process progresses. Such change is small at the beginning of thaw process. There are, however, a stage that corresponds to around 80% degree of thaw, where there is a significant drop in the magnitude of pore air pressure. This is possibly due to the formation of complete percolation path for air.

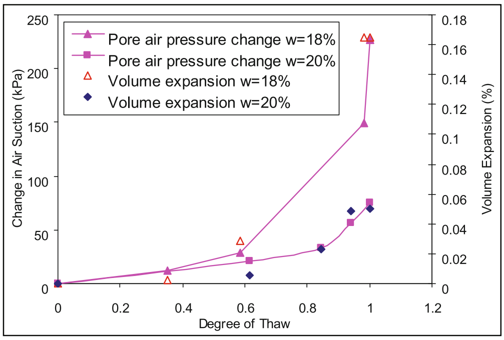

Fig. 12. Estimated change of pore air pressure during the thaw process.

It needs to be pointed out, the estimated values of air suction pressure are the net change of soil air suction. The exact values of air suction pressure are dependent upon the air suction in the complete thaw status.

$$u_{a,thaw} = u_{a,ini} - \Delta u_{a,t} \tag{12}$$

Where $u_{a,thaw}$ is the air suction pressure at certain thaw status, $u_{a,ini}$ is the air suction pressure when soil is completely thawed, and Δu is the change of the air suction pressure as the thaw status changes.

The air suction at complete thaw status can be measured by use of a traditional instrument, such as tensiometer. From what is described above, the air suction pressure during the thaw process can be indirectly measured with the use of procedures described above and Eqs. (11) and (12).

5 Conclusion

In conclusion, when water content was low, i.e. 18.1%, the decrease of the air suction was the main reason which enlarged the volume change of soil. Also, for time factor, the volume change decreased initially and then increased as time elapses. The reason is when the water content is relatively low, ε_2 will dominate the overall volume change. However, when we carried out some experiments with higher water content, the volume of the specimen kept falling while there was a little pop up peak jump during the thaw process. Apparently, the decrease of air suction (ε_2) was the reason for the peak. Also, when the water content was high enough, i.e., more than 20% for this type of CH soil, ε_1 will dominate the overall volume change which caused the volume decrease.

In addition, compared with existing technologies for frost measurement, TDR is an innovative non-destructive testing tool which provided an alternative way to predict soil water content, elastic modulus, freeze-thaw degree and even air suction pressure etc.

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