Monitoring of Phase Transition in Frozen Soil Using the Nonlinear (SPC-1) Ultrasonic Technique

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ABSTRACT

Frozen soils constitute a significant amount of land's surface and are responsible for the (global) energy balances and heat transfer mechanisms affecting both land and atmospheric processes. Characterization and measurement of the properties of frozen soils during phase transition (frozen to unfrozen) is a challenging problem vowing to heterogeneity in ice-lens formation, unfrozen water, and pore structure configuration of soil grains. This study presents a non-linear ultrasonic (NLU) technique called the sideband peak count-index (SPC-I) in combination with the linear ultrasonic (LU) technique to monitor the phase transition (frozen to unfrozen) of frozen soil specimens. Earlier studies using non-destructive testing and evaluation (NDT&E) have demonstrated the use of LU and NLU techniques to detect defects such as micro-cracks, however, there are no studies performed to evaluate the use of this approach to quantify the non-linearity in frozen soils during their phase transitions. The general approach of applying the SPC-I technique is by transmitting and analyzing a single excitation signal that is propagated through the frozen soil specimen. In this study, the clayey sand soils are considered for evaluating the non-linear behavior of the soils during the phase transition process (frozen to unfrozen). These soils can undergo significant frost-heave and thaw-weakening phenomena resulting in infrastructure distress including potholes, differential settlements, slope failures, and thawing-induced landslides. In the United States approximately 2 billion dollars were spent annually to just repair the highway infrastructure distress caused due to freeze-thaw cycles and better characterization approaches are required to understand the behavior of this non-linear geomaterial. The NLU SPC-I technique combined with LU technique could robustly detect the changes in material properties of frozen soil, however, it can be further tuned and improved by exciting a tuned excitation signal.

INTRODUCTION

Climate change has a significant effect on the land surface characteristics, especially in the permafrost and seasonally frozen ground regions where the topography is continuously changing due to changing weather patterns [1]. Due to the increasing occurrence of extreme weather events and seasonal climatic variability, it is crucial to gain a better understanding of the interactions between soil and porous media [2]. This understanding will aid in the assessment of the resilience and vulnerability of earthen infrastructure such as retaining walls, levees, runways, and highways. In cold regions, the interactions between soil and porous media involve intricate phase change processes of water to ice and vice versa.

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These phase changes particularly in frost-susceptible soils can lead to significant frost-heave and thaw-weakening phenomena resulting in infrastructure distresses including potholes, differential settlements, slope failures, and thawing-induced landslides. In the United States approximately 2 billion dollars were spent annually to just repair the highway infrastructure distress caused due to freeze-thaw cycles. Hence, better characterization approaches are required to understand the non-linear behavior of soils, especially in the cold regions.

The frozen ground contains soil particles, unfrozen water, ice, and pore-air where the behavior of these components is non-linear. The current state of art practice does not consider the nonlinearity of the soil's behavior in the field, particularly in frozen and thawing conditions. One way to develop an understanding is by evaluating frozen soil samples through thawing in real time. This can be a useful way to capture phase change i.e. from frozen to unfrozen state. In previous studies, guided acoustic waves were used for non-destructive testing and evaluation (NDT&E) to extract features for detecting properties like unconfined compressive strength and elastic constants of frozen soils. Although the use of linear ultrasonic (LU) techniques (i.e., shift in frequency of propagating wave, change in time-of-flight, attenuation etc.) is very effective for many applications it can fall short sometimes, such as for detecting micro-cracks. Detecting the microcracks due to thawing and uneven frozen condition is extremely challenging, which will be highly beneficial in evaluating the nonlinearity associated with the thawing-induced micro-cracks. It would be difficult to detect micro-cracks with linear acoustic techniques or other non-destructive testing techniques. However, Non-linear ultrasonic (NLU) techniques [4-15] can detect defects such as micro-cracks where LU techniques fall short.

This study will focus on the use of the non-linear ultrasonic (NLU) technique called the sideband peak count index (SPC-I) in combination with linear ultrasonic (LU) technique. NLU SPC-I technique is used to monitor phase transition (frozen to unfrozen) in frozen soil specimens.

MATERIALS AND METHODS

In this study, the SC clayey sand that can undergo significant frost-heave and thaw-weakening phenomena [1,3] is considered for evaluating the non-linear behavior of the soils during the phase transition process (frozen to unfrozen). A summary of basic characterization studies of test soil with respective ASTM standards is presented in Table I. X-ray diffraction (XRD) analysis performed on test soil showed that the sample consists of various minerals including Quartz (33%), Muscovite (18%), Montmorillonite (16%) and others.

TABLE I. SUMMARY OF BASIC CHARACTERIZATION OF TEST SOIL [1]

Soil Properties	Test soil	ASTM Standards
Coarse Fraction, %	96	D422-63
Fine Fraction, %	4	D422-63
Specific Gravity, G_s	2.7	D854-00
Liquid Limit (LL), %	22	D4318
Plastic Limit (PL), %	35	D4318
Plasticity Index (PI), %	13	D4318
USCS	SC Clayey sand	D2487-17
Optimum Moisture Content (OMC), %	14	D698
Maximum Dry Density (MDD), gm/cm^3	1.5	D698

SAMPLE PREPARATION

The samples were prepared in the cylindrical split mold (38mm * 84 mm) as shown in Fig. 1(a). The samples consist of a thick layer of ice sandwiched between two soil layers compacted at its optimum moisture content (Fig. 2(b)). Sample preparation involves three steps: firstly, bottom layer of soil was made in the mold compacting the soil at its OMC and the setup was allowed to freeze for 12 hours at a temperature of 20^{o}C. Secondly, a layer of water was placed above that and allowed for freezing for another 12 hours at a temperature of -20^{o}C and finally, top layer of soil was placed compacting the soil at OMC and whole setup was allowed freezing for another 12 hours at -20^{o}C before experimental study was conducted. At the time of freezing, the top of the mold was closed with the lid.

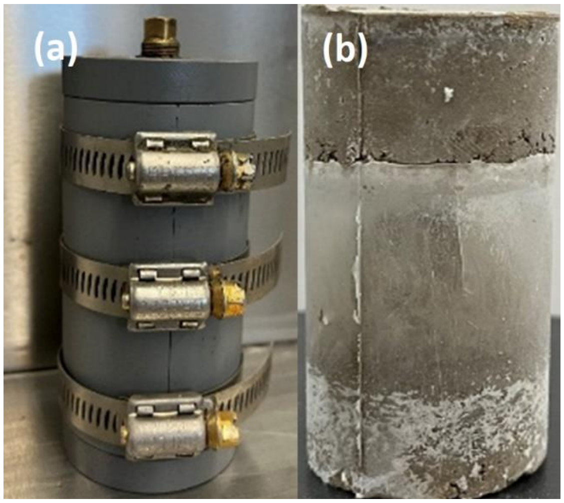


Figure 1. Sample preparation: (a) Split mold; (b) Representative frozen sample

INSTRUMENTATION AND EXPERIMENTAL SETUP

The instrumentation used in this study is shown in Figure 2. A computer controlled arbitrary waveform generator (AWG) produces an electric signal that is converted to an ultrasonic signal by the exciting transducer. The ultrasonic signal then propagates through the frozen soil specimen. At the receiving end, the ultrasonic signal is detected and then converted back to an electric signal by the detecting transducer. The PZT transducers that were used for this study are proprietary transducers that are supplied by Pacific Waves NDT, LLC., Tucson, AZ. A five-cycle excitation signal of 66 kHz was generated and analyzed in this experimental study. All experimental tests were performed in a controlled temperature environment of 23°C.

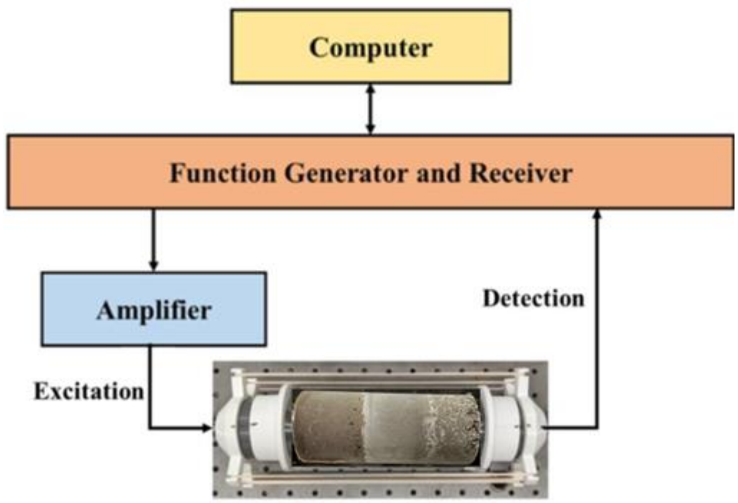


Figure 2: Schematic Diagram of the Experimental Setup

SIDEBAND PEAK COUNT – INDEX (SPC-I) TECHNIQUE

SPC-I technique is a newly developed nonlinear ultrasonic technique. As waves propagate through a nonlinear material, frequencies other than the input wave frequency can be generated due to material nonlinearity. If the generated frequency is an integer multiplier of the input wave frequency, it is called higher harmonics. If the generated frequency is half of the input wave frequency, it is called subharmonics. The frequencies other than higher harmonics and subharmonics can also be generated from frequency modulation between different frequencies of propagating waves. These new frequency peaks recorded by the receiver generally have much lower magnitude than the exciting frequency peaks and are called the sideband peaks or simply sidebands. Several sidebands are generated when a broadband wave is propagated through a nonlinear material. The interaction between several modes of a propagating wave can generate additional modes or frequency peaks resulting in an increase of sideband peaks [4-11]. SPC-I technique counts the peaks of higher harmonics, subharmonics, and other sideband peaks above a threshold line as it moves between two limits (upper and lower limits) to evaluate the nonlinearity of the material.

EXPERIMENTAL RESULTS AND DISCUSSION

Once the FFTs of all recorded data are calculated, the SPC-I values for all recorded signals are calculated and plotted as shown in Figures 3. The SPC-I values shown in plots are normalized for a comparative study. The horizontal axis represents the data collected in real time (minutes).

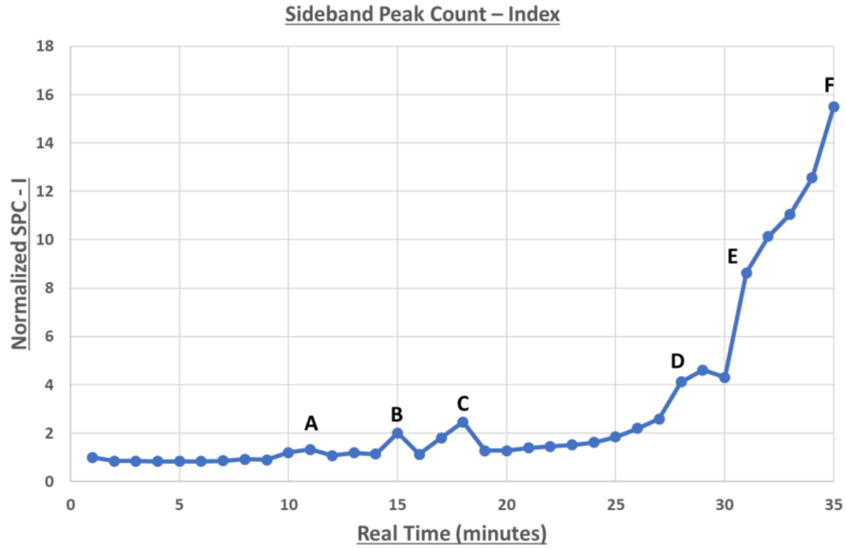


Figure 3: SPC-Index of frozen soil specimen at different stages of thawing

From figure 3, it can be observed that SPC-I values are changing as the frozen samples goes through the thawing process. First, significant change is observed around 11 minutes which is marked as **A** in figure 3. Subsequent changes are observed at 15 minutes marked as **B**, 18 minutes marked as **C**, 28 minutes marked as **D**, 31 minutes marked as **E** and 35 minutes marked as **F.** Similarly, shift in frequencies of propagating waves and change in the time-of-flight of first arrival signals are calculated and presented in figure 4 and 5, respectively.

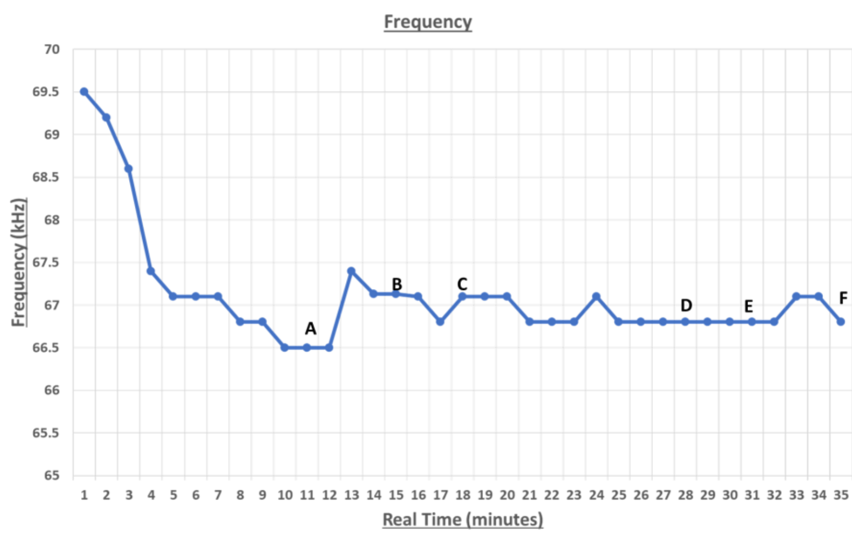


Figure 4: Shift in frequencies in frozen soil Specimen at different stages of thawing

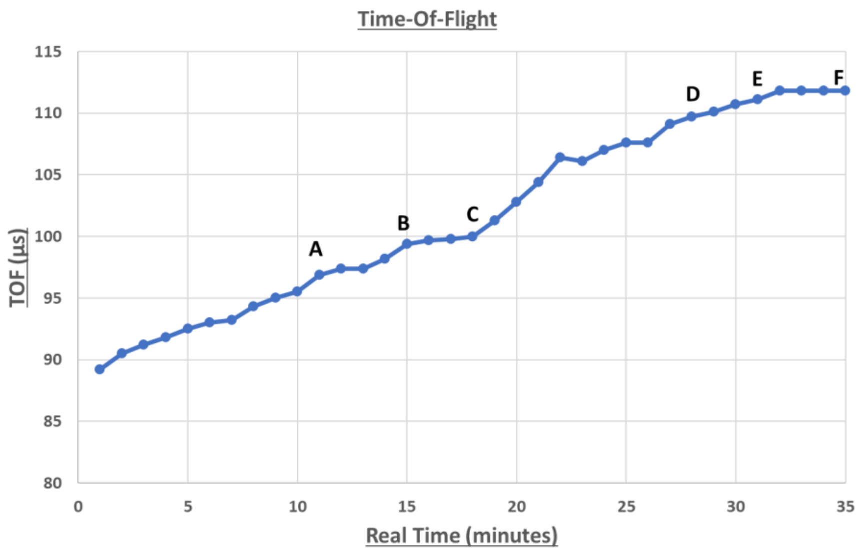
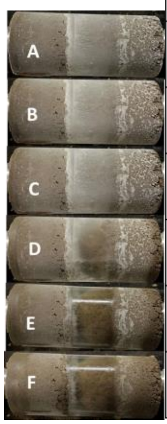


Figure 5: TOF in frozen soil specimen at different stages of thawing

In figure 6, photographs of frozen soil sample are presented on the left at different stages of thawing. On the right, the quantitative values of the real time when the photographs are taken, the SPC-I, the frequency and the time-of-flight values are presented corresponding to the six photographs shown on the left.



	Real Time measurement (minutes)	SPC-I	Frequency (kHz)	TOF (µs)
A	11	1.32	66.5	96.9
B	15	2.01	67.13	99.4
C	18	2.46	67.1	100
D	28	4.11	66.8	109.7
E	31	8.63	66.8	111.1
F	35	15.48	66.8	111.8

Figure 6: On the left, pictures of soil specimen at different stages of thawing. On the right, data is presented in tabulated form with respect to different stages of thawing.

As mentioned earlier, thawing in soil is a nonlinear process and this nonlinear change can be monitored by the SPC-I technique. Significance of using the SPC-I technique is that we were able to detect micro-crack initiation earlier in the thawing process (in figure 3, at 11 minutes mark). A small rise marked as "**A**" in figure 3 indicates formation of micro-cracks causing an increase in material nonlinearity and hence an increase in SPC-I value. Then as these microcracks coalesce to form macro-cracks the material nonlinearity goes down, and thus the peak "**A**" is formed. As a consequence of the macro-crack formation, new micro-cracks are formed which then again coalesce to form more macro-cracks and thus two more peaks **B** and **C** are formed as shown in figure 3. At 28 minutes mark another noticeable peak **D** is observed in figure 3. In the photos presented in figure 6, it can be clearly observed that the sample is in partial frozen state. After 28 minutes the SPC-I values almost doubled every 3 to 4 minutes indicating that the rapid thawing of soil specimen causing significant increase in micro-crack formation.

Linear parameters TOF and frequency shift also exhibited some changes. Change in TOF data corresponds well with the SPC-I data. However, the rate of change of TOF didn't show rapid increase after 27- and 30-minutes marks when thawing progressed rapidly which SPC-I showed. A slightly higher rate of change of TOF was observed between 18- and 22-minutes marks (figure 6, see mark **C**). Shift in frequency did not show much consistency. By using the experimentally determined frequency range coupled with the SPC-I technique and TOF it is possible to detect the initiation of thawing process and monitor the progression of thawing process through micro-crack detection in a robust manner.

CONCLUSION

The main objective of this paper is to evaluate the feasibility of acoustic waves and SPC-I approach to determine the non-linearity of the geomaterial during thawing process. The SC soils considered in this study were frozen and the tests were conducted on several duplicate specimens to evaluate the reliability of the proposed approach. Based on the preliminary results, it can be stated that by examining a frozen soil specimen at different stages of thawing at excitation signal of 66kHz it is possible to detect and monitor thawing process of frozen soil specimens. The combination of non-linear and linear ultrasonic parameters such as SPC-I and TOF can be used for robust and reliable detection of phase change in soil i.e. frozen to unfrozen soil. Furthermore, this technique can be applied to other soil types and geometries to monitor their thawing process.

ACKNOWLEDGMENTS

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