Thermo-Hydro-Mechanical Characterization and Deformation Behavior of Reconstituted Multi-Couplets of Varved Laminae under Freeze-Thaw Cycle

Deepali Anand[1], Arindam Dey[1*] and Ravi Karangat[1]

Deepali Anand

Research Scholar, Department of Civil Engineering, Indian Institute of Technology Guwahati, Assam, India. ORCID No.: 0000-0002-0072-2236 Email: a.deepali@iitg.ac.in

Arindam Dey*

Associate Professor, Department of Civil Engineering, Indian Institute of Technology Guwahati, Assam, India. ORCID No.:0000-0001-7007-2729 Contact No.: +918011002709 Email: arindamdeyiitg16@gmail.com

* Corresponding author

Ravi Karangat

Associate Professor, Department of Civil Engineering, Indian Institute of Technology Guwahati, Assam, India. ORCID No.: 0000-0002-3152-1533 Email: ravi.civil@iitg.ac.in

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Abstract: This study focuses on the deformation behavior of reconstituted varved clay profiles under freezing and thawing, which is a critical aspect of cold region geotechnical engineering. Varved clays consist of alternating silt-dominated and clay-dominated laminae. Red Soil (RS) and Black Soil (BS) are selected based on extensive geotechnical investigations as representative of these laminae. Seven soil profiles are analyzed, which includes two homogeneous profiles of RS and BS, and five reconstituted varved clay profiles with 2, 4, 8, and 16 alternating layers of RS and BS. In the two-layer profiles, RS overlies BS in one arrangement, while BS overlies RS in the other. In all other reconstituted varved clay profiles, RS forms the topmost layer. Temperature-induced deformation in these profiles is studied using Finite Element (FE) based numerical modeling under initial suction magnitudes ranging from 0 kPa to -20 kPa. The results show that RS exhibits higher heave at lower suctions, while BS shows greater heave at higher suctions. In reconstituted varved clays, the heave magnitude generally increases with the number of layers. The study demonstrates that soil composition, initial suction, hydraulic conductivity, unfrozen water content, lamina arrangement, and temperature gradients all influence frost-induced deformation.

Keywords: Reconstituted Varved Clays, Finite Element Modelling, Temperature Gradient, Soil Water Characteristic Curves, Soil Freezing Characteristic Curves, Frost-Induced Deformation

1. Introduction

The Indian Himalayan region is currently grappling with the impacts of global warming, resulting in a transformation of its permafrost regime. This metamorphosis is evident through the rise in unpredictable and frequent hazards (Gruber et al., 2017; Krishnan et al., 2019; Mukherji et al., 2019; Pandey et al., 2022; Singh, 2022; Ramya et al., 2023; Sharma et al., 2023). Soils in glacial regions undergo seasonal freeze-thaw processes which significantly affects their strength, hydrological profile, and geomorphic characteristics (Huggel et al., 2010; Gariano et al., 2016; Boike et al., 2018; Cao et al., 2019; Thakur et al., 2021; Pandey et al., 2022; Chen et al., 2023).

Freezing and thawing involve the transformation of water to ice and vice-versa, inducing physical and chemical interactions. These interactions deteriorate the soil structure, leading to visible soil cracking and resulting in a loss of strength (Aldaood et al., 2014; Zou et al., 2022). When the soil freezes, it sustains internal stresses; upon thawing, these stresses are released (Edwin and Anthon, 1970). Recognized as a weathering process, freezing and thawing cause considerable changes in soil structure, including density, void ratio, water redistribution, consequently affecting the pore-water pressures and permeability, thereby influencing the microfabric, physical, and mechanical properties of the soils (Andersland and Anderson 1978; Qi et al., 2008; Deprez et al., 2020; Xiang et al., 2022). Thawing periods pose substantial hazards, triggering catastrophic ground subsidence, meltwater-induced landslides, rockfalls, thaw slump activity, and slope failures due to high erodibility and strength loss during thawing (Birhan, 2000; Harris et al., 2009; Yang et al., 2010). In roads, freezing and thawing can cause pit formation which reduces the performance of the roads (Adeli Ghareh Viran, 2018; Sadiq, 2023). The extent of damage depends on soil properties, temperature, the number of freezing-thawing cycles, and water availability (Sadiq, 2023). Therefore, when designing infrastructure projects in cold regions, it is crucial to consider the effects of freezing and thawing on regional soil for safe, stable, and reliable structures (Thevanayagam et al. 2002; Adeli Ghareh Viran and Binal, 2018; Jia et al., 2023).

Expansion of soil volume due to the ice lenses formed at sub-zero temperatures is a well-accepted phenomenon due to frost-heave. Continuous water flow from the vadose zone to growing ice lenses is another significant factor contributing to the heaving (Sadiq, 2023). Thaw settlements, or a decrease in soil volume, occur when these ice lenses melt. Both heaving and settlement are significantly influenced by compactness, temperature, and water content, with the water content demonstrating the strongest correlation (Wan et al., 2019). Air temperature influences the soil temperature that leads to water migration and subsequent phase change (Xu and Wang, 1993). This hydrothermal coupling results in the compression of soil grains in unfrozen areas and frost heave in the frozen area of soil (Niu et al., 2017; Xu et al., 2020; Zhang et al., 2021). Thermal parameters, such as thermal conductivity and specific heat capacity vary with unfrozen water content that influences the geomechanical properties during freezing and thawing (Derk and Unold, 2022). When subjected to sub-zero air temperatures, the soil undergoes a frozen-unfrozen interface, resulting in a change in its geomechanical properties that may lead to frost heave during freezing and subsequent thaw settlement during thawing.

Several researchers have conducted freezing-thawing tests on soils through laboratory experiments, noting a decrease in strength and an increase in porosity (Adeli Ghareh Viran and Binal, 2018). These studies also reported desiccation and hardening of soil samples upon freezing (Aubert and Gasc-Barbier, 2012). For instance, Wang et al. (2007) conducted a freeze-thaw study on clay with different cycles, reporting an increase in volume, a decrease in cohesion, and no changes in the internal angle of friction. Similar findings of changes in cohesion while observing little change in the friction angle have been reported by Aoyama et al. (1985). Simonsen et al. (2002) reported a decrease in the resilient modulus of soil due to freezing-thawing. Throughout the literature, changes in engineering parameters such as shear strength, resilient modulus, and elastic modulus have been reported for various soil classes (Zhao et al., 2020; Wang et al., 2020; Balandin et al., 2020). Sadiq (2023) assessed the climatic conditions on soil with an open and closed system. In an open system, which comprised an external source of water, there was a significantly higher heaving magnitude compared to soils in a closed system. The author further reported significantly higher heave and water intake in silty sand and silty clay compared to low plasticity clay, attributing these differences to their hydraulic conductivities.

Several researchers have investigated freezing and thawing processes using complex numerical modeling techniques. Zhang and Michalowski (2013), Yu et al. (2021) and Park et al. (2022) employed an elastoplastic framework in FE numerical modelling to predict frost heave and thaw settlement in soils. Wang et al. (2016) applied FE numerical modelling in conjunction with the FISH programming language to simulate volume changes in soil due to freezing and thawing. Additionally, some researchers have incorporated the Barcelona Basic Model and the Modified Cam-Clay Model within an elastoplastic framework to predict deformations in soils under freezing and thawing, as demonstrated by Amiri et al. (2016). Chen et al. (2020) implemented double yield surface models in FE modelling to predict frost heave. However, each of these methods involves the need for several complex parameters that are not obtainable through standard soil laboratory tests. Often, advanced computational techniques and specialized laboratory instruments, such as temperature control apparatus, are required to simulate cold environments and capture the deformation behavior of soils under freezing and thawing conditions. The approach demonstrated in this paper requires only minimal input parameters, making it more practical and accessible for routine applications. For example, this study uses the Soil Freezing Characteristic Curve (SFCC) derived from the Soil Water Characteristic Curve (SWCC), which is obtainable in a standard geotechnical laboratory setup. In this study, a simple model approach to predict frost heave and thaw settlement has been employed using the Mohr-Coulomb material model, whose parameters can be easily obtained in the laboratory. The use of the Mohr-Coulomb material model to simulate freezing and thawing has also been employed by Zhu et al. (2021) and found to be satisfactory.

Despite the above discussed research efforts, there is still a lack of understanding regarding frost-heave and thaw-settlements during freezing and thawing. This includes sensitivity of heave-settlement due to temperature changes in different types of soils, different soil profiles, and how the presence of water within the soil or externally plays a vital role. In order to bridge this research gap, the present study is conducted to investigate the freezing-thawing induced deformation response in homogeneous soils and reconstituted varves under different monthly average air temperatures in the cold region of the Indian Himalayas.

In India, very recently, a few studies have been reported to investigate the freeze and thaw effect in the context of Indian soils (Wani et al., 2021; Sardana et al., 2022; Pandey et al., 2022). However, all such studies were conducted on homogeneous soils. For a better understanding of the complex cryospheric responses of soils in glacial regions, researchers have pointed out the requirement for additional studies (Wani et al., 2021). Varved clays are one of the common soil deposits in glacial environments (Way 1977; Anderson and Dean, 1988; Shur and Zhestkova, 2003; Netto et al., 2012; Palmer et al., 2019; Vergnano et al., 2023; Wang et al., 2023) and have been observed in Indian Himalayan glaciatic regions as well (Ahmad and Hashimi, 1974; Pant et al., 1998; Juyal et al., 2009; Bhattacharyya et al., 2011; Beukema et al., 2011). The present study discusses the freezing and thawing behavior of seven different soil profiles, including both homogeneous and layered soil profiles. In this study, two soils, namely the Red Soil (RS) and Black Soil (BS), are chosen based on their similarity with the engineering properties of the actual varved clay laminae. Ground deformation resulting from freezing and thawing effects is computed with the aid of Finite Element (FE) based numerical modeling. The study involves Thermo-Hydro-

Mechanical (THM) coupling. Seven types of soil profiles are considered, including two homogeneous soil profiles consisting solely of RS and BS, and five reconstituted varved clay profiles with different numbers of alternating RS and BS layers. The chosen soils, RS and BS, are placed in sequential layers to represent the laminae of actual varved clays while maintaining the same profile dimensions as that of homogeneous soil specimens. The temperature variation considered herein is a representative of the average monthly temperatures during the winter (freezing period) and summer (thawing period) seasons in Tawang, Arunachal Pradesh, India, based on which the deformation in the varved profiles is assessed.

2. Material Characterization of Constituent Laminae

2.1 Laboratory investigations of the constituent materials

Varved clays are distinctive soil deposits that are typically found in glacial environments (Hang et al., 2003; Ehlers, 2022). These soils are characterized by their composition, which consists of alternating and repeating layers of silt-dominant and clay-dominant laminae (Brodzikowski and Van Loon 1990; Palmer, 2019). These soils exhibit anisotropic properties due to variations in textures and geotechnical properties due to the laminae structure (Lydzba and Tankiewicz, 2012; Tornborg et al., 2023; Philippe et al., 2023). Unlike homogeneous soils, varved clays require special consideration due to their unique characteristics. The representative results obtained from bulk sampling in varved clays may not accurately reflect the behavior of these soils (Metcalf and Townsend, 1961; Bell, 1997). Hence, it is important to determine the properties of the individual soils constituting the laminae of the reconstituted varved clay.

In order to simulate the constituent alternate laminae of actual varve clay, two types of soils are collected from the hillslopes at and around IIT Guwahati campus with coordinates 26.2027° N and 91.7004° E. One of the soil is silt-dominated Red Soil, hereby termed as RS, while the other is clay-dominated Black Soil, hereby termed as BS. Figure 1 shows the representative RS and BS collected for the present study. For both the soil samples, the basic geotechnical tests are conducted to identify their particle size distribution (PSD) (IS:2720 (Part 4)-1985), Atterberg limits (IS:2720 (Part V)-1985), and compaction characteristics as per the Standard Proctor test (IS:2720 (Part-7)-1983). Further, the mineralogy and morphology of RS and BS are determined with the aid of X-Ray Diffraction (XRD) powder analysis and Field Emission Scanning Electron Microscopy

(FESEM) techniques. The XRD and FESEM was conducted using Tokyo-based Rigaku Micromax-007HF and Germany based Zeiss Sigma microscope, respectively. For XRD, both RS and BS were scanned for 2θ for a range of 0° to 80°. Other routine laboratory investigations conducted on the selected RS and BS soils included the tests to assess the specific gravity (IS:2720 (Part 3/Sec-2)-1980), saturated hydraulic conductivity using a prefabricated mold, and the data points of suction magnitudes at different water contents using a WP4-T Dewpoint Potentiometer manufactured by Decagon Devices, Inc., Pullman, WA, USA. The working principle of the potentiometer can be found in detail in ASTM D6836 Method D (ASTM 2004). These data points were then further fitted in the van Genuchten model to obtain the SWCC and the corresponding model parameter through which the Hydraulic Conductivity Function (HCF) curve was further derived. Since the RS and BS both had substantial amount of clay, permeability test was very difficult to conduct with the standard permeability mold in the laboratory as even after months, the soil was not getting saturated. Hence, permeability test was carried out with the help of specially prefabricated mold manufactured in workshop, wherein the sample mold has height of 10 cm and diameter of 4.5 cm. The dimensions of the prefabricated mold adhered to the standards outlined in ASTM-D5856-15 (ASTM 2007). Further, for computing stiffness parameters such as Elastic modulus and Poisson's ratio, Unconfined Compressive Strength (UCS) tests were conducted as per ASTM 2166 (ASTM 2006) and shear strength parameters were obtained from the Direct Shear Test (DST) following ASTM D3080/D3080M (ASTM 2012).

2.2 Basic geotechnical characterization of RS and BS

The basic geotechnical characteristics obtained for RS and BS obtained from the laboratory investigations are listed in Table 1. It is to be noted that RS and BS, as being used in the present study, is chosen as a representative of the constituents of the actual varve laminae. Based on a literature survey (Eden, 1955, Penner and Butler, 1961; Soderman and Quigley, 1965; Kazi, 1968; Eigenbrod and Burak, 1991; Marko et al., 2010; Florkiewicz et al., 2014; Lydzba and Tankiewicz, 2012; Tankiewicz, 2016; Krawczyk and Flieger-Szymanska, 2018, Flieger-Szymanska et al., 2019; Nielepkowicz et al., 2023), the geotechnical characteristics of the varve laminae are collated and is presented in Table 2.

Figure 1. Representative sample of (a) RS and (b) BS collected in the vicinity of IIT Guwahati campus

From Table 1, it is observed that the liquid limit of RS and BS is 45% and 95%, respectively. The liquid limit is the moisture at which the soil undergoes a transition from a plastic to a liquid state. A higher liquid limit of BS suggests that it has a greater capacity to retain water and remain in a plastic state at higher moisture content than RS. Liquid limit is also often associated with the clay content in soils; soils with higher clay content tend to have a higher liquid limit. This aligns well with the findings of PSD, wherein BS has a significantly higher clay content of 84.9% compared to RS, which has a lower clay content of 22.4% and a lower liquid limit of 45%. The plastic limit of RS and BS is 19% and 30%, respectively. The plastic limit is the water content at which a soil transitions from a plastic to a semi-solid state. In comparison to RS, the higher plastic limit of BS signifies that it requires a higher moisture content to transition from plastic to a semi-solid state. In practical terms, it means that BS has the capability of retaining more water while maintaining a plastic consistency. This can be attributed to the high clay content in BS (i.e. 84.9%), thereby providing a larger surface area that allows to attract and retain more water. Furthermore, the plasticity index of 26% for RS reflects its moderate plasticity, whereas BS demonstrates a markedly high plasticity with an index of 65%. The plasticity index values provide insight into the range of moisture over which each soil exhibits plastic behavior. In this case, BS exhibits plastic behavior over a wider range of moisture content as compared to RS. Analyzing the grain size distribution (Figure 2), RS is found to have a composition of 23.2% sand, 54.4% silt, and 22.4% clay, while BS is characterized by 8.4% sand, 6.7% silt, and a predominant 84.9% clay content. These variations in grain size distribution and Atterberg limits contribute to the divergent engineering behavior of the soils when placed in layers to form the laminae of varved clays. The dominance of clay in BS and the higher silt content in RS are noteworthy and are self-explanatory of the above-mentioned magnitude of the Atterberg limits. Furthermore, as per the classification system, RS is classified as ML (silt with low to medium plasticity), while BS is classified as CH (clay with high plasticity). Overall, from Table 1, in comparison to RS, the high plasticity of BS is indicative of high potential volume changes and settlement, lesser permeability, which will, in turn, pose challenges in terms of drainage and overall stability of constituting slopes.

Table 2 enlists the basic geotechnical properties of the two soils that constitute the actual varved clays, as reported by different researchers. In the table, the dark varve and light varve signify clay-dominant and silt-dominant lamina, respectively. As mentioned earlier, the relative magnitudes of various parameters in Table 1 were selected based on their alignment with the corresponding magnitudes of basic engineering properties of the two soils present in actual varved clays as highlighted in Table 2. All the earlier observations indicated higher silt and higher clay contents, respectively, in the light-colored and dark-colored lamina, which also holds true for RS and BS (as shown in Table 1). Similarly, the liquid limit, plastic limit, and plasticity index, as reported by various researchers, are higher for dark-colored varve as compared to these values for light-colored varve. This complements the corresponding findings of RS and BS, where BS has a higher liquid limit, plastic limit, and plasticity index than RS. Therefore, it can be deduced that the geotechnical properties of the chosen soils for the present study, i.e. RS and BS, are in reasonable agreement with the characteristics of the constituent laminae. With this noted agreement, it can be asserted that the chosen RS and BS are suitable enough to be considered as material counterparts of the laminae of the actual varve clay found in glaciated regions.

Figure 2. Particle Size Distribution (PSD) curves for RS and BS

2.3 Compaction characteristics of RS and BS

Figure 3 shows the compaction curves of RS and BS. The Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) for RS were found to be 1.77 Mg m^{-3} and 19.5%, respectively, while for BS, the corresponding values were 1.59 Mg m^{-3} and 21.5%, respectively (also listed in Table 1). From Figure 3, it is observed that as compared to the BS, the OMC of RS is lesser. This behaviour in RS is attributed to the silt particles allowing better packing, aiding in achieving the MDD at a lower moisture content. On the contrary, the higher OMC in BS is attributed to its high clay content that requires substantial amount of water for proper compaction. Furthermore, it is observed that the shape of the compaction curve for BS is relatively flatter than that of RS, thereby indicating that the former is relatively lesser affected by the variation in moisture content.

Table 1. Geotechnical properties of RS and BS soils for the present study

Geotechnical Characteristics	Red Soil (RS)	Black Soil (BS)
Specific Gravity	2.7	2.6
Grain Size Distribution (%)		
Sand	23.2	8.4
Silt	54.4	6.7
Clay	22.4	84.9
Soil Classification	ML	CH
Atterberg Limit (%)		
Liquid Limit	45	95
Plastic Limit	19	30
Plasticity Index	26	65
Compaction Characteristics		
Maximum Dry Density (kg/m^3)	1770	1590
Optimum Moisture Content (%)	19.5	21.5

Table 2. Geotechnical properties of the two soils constituting the laminae of actual varved clays as per the literature

Researchers	Varve Type	Sand (%)	Silt (%)	Clay (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
Nielepkowicz et al. (2023)	**Dark Varve**	1	51	48	59.8	25.9	-
	Light Varve	1	74	25	35.9	19.8	-
Flieger et al. (2019)	**Dark Varve**		18-48%	54-85%		30.9	80.6
	Light Varve		54-74%	24-42%		22.6	42.2
Krawczyk and Flieger-Szymanska (2018)	**Dark Varve**	-	-	-	84.67	32.25	52.42
	Light Varve	-	-	-	47.95	21.95	26.00
Lydzba and Tankiewicz (2012) Tankiewicz (2016)	**Dark Varve**	0.2-0.4	36.5-51.2	48.6-63.1	-	-	-
	Light Varve	5.7-22.9	52.5-71.8	18.7-24.6	-	-	-
Florkiewicz et al. (2014)	**Dark Varve**	NA	NA	26-84	46	23	23

	Light Varve	NA	NA	12-40			
Eigenbrod and Burak (1991)	**Dark Varve**	-	-	43	48	21	28
	Light Varve	-	-	27	21	18	3
Soderman and Quigley (1965)	**Dark Varve**	-	-	-	60-85	-	10-50
	Light Varve	-	-	-	35-55	-	2-20
Kazi (19687)	**Dark Varve**	NA	NA	62-72	60	27	33
	Light Varve	NA	NA	35-40	30	14	16
Penner and Butler (1961)	**Dark Varve**	-	-	82	74	-	47
	Light Varve	-	-	22	30	-	8
Eden (1955)	**Dark Varve**			65-95	63.8-95.2	25.5-34	38.3-63.5
	Light Varve			18-35	23.0-26.9	19.3-21.7	3.0-5.4

2.4 Mineralogical and morphological characteristics of RS and BS

To ensure that the soils RS and BS used as two representative soils in reconstituted varved clays are mineralogically similar to the two laminae in actual varved clay, XRD and FESEM were carried out. Figures 4a and 4b illustrate the results of XRD analysis, while Figures 4a and 4b show the outcome of FESEM analysis of RS and BS, respectively. In the XRD technique, the crystal structure of the soil is analysed, whereas in the FESEM technique, the microstructure of the soil is analysed. XRD works by shining X-rays onto the soil samples and measuring the angles and intensities of the X-ray beams scattered by the crystal lattice of the soil particles. On the other hand, FESEM works by creating an image of the sample surface and topography using electrons that interact with the sample. This electron beam is focused on the sample with the help of electromagnetic lenses.

Figure 3. Compaction curves for the chosen reconstituted soils RS and BS

For XRD, dry and finely grinded samples of RS and BS were prepared, creating a thin layer of the sample on the flat glass slide surface. The prepared soil samples were placed in a sample holder inside the XRD instrument, which consists of a detector. When the X-ray beams interact with the crystal lattice of the minerals in the soils, diffraction patterns are obtained. The X-ray diffraction patterns are obtained by varying the angle at which X-rays strike the soil samples. Therefore, the intensity of diffracted X-rays at different angles is used to create XRD patterns. The peak positions and intensities of the XRD patterns are compared with reference patterns or a database to identify the mineral composition in the soils RS and BS, as shown in Figure 4(a) and 4(b). The XRD patterns clearly indicate that BS contains a significant amount of the clay mineral montmorillonite compared to RS. A similar observation was reported by Ringberg and Erlström (1999), where researchers performed XRD by separating the summer layer (i.e. lighter lamina) and winter layer (i.e. darker lamina) of the varved clay and reported a major difference between XRD diffractograms of the two soils in the clay mineral peaks, with higher magnitudes of clay mineral peaks in the diffractograms for winter layers. Blondeau (1975) reported that when the dark and light laminae were X-rayed separately, they were found to be mineralogically identical, except for the higher clay content in the darker layer compared to the lighter layer. The author further reported the dominance of Illite in the light-colored layer with minor montmorillonite, whereas the dominance of montmorillonite in the dark-colored layer. This finding also resembles the findings of XRD of RS and BS as obtained from the present study.

Figure 5 displays the microstructure of RS and BS using FESEM. The presented FESEM images for both soils are captured at 1.00 KX magnification. FESEM requires the samples to be carefully prepared, wherein the samples were oven-dried for 24 hours. Ample care was taken to ensure that moisture does not enter the sample during preparation. To avoid any moisture exposure, the samples, after oven-drying, were kept with silica beads. Both samples were mounted on the same stub with the help of sticky carbon tape. To prevent the build-up of charges due to moisture present in the environment, the samples were then coated with gold, and FESEM images were captured. From the captured images, it was observed that particles of RS appeared larger and more rounded compared to BS exhibiting flaky-shaped particles, which is typical in the case of clays. The surface texture of RS appeared smoother, while the same appeared rough for BS. Moreover, as evident from the intricate network of pores between the particles, a higher porosity was observed in BS as compared to RS, which can be attributed to the presence of clay minerals with a highly flocculated structure leading to larger amount of inter-floc voids.

Hence, based on the mineralogical compositions and microstructure of the chosen RS and BS, it can be comprehensibly assessed that the light-colored and dark-colored laminae of the actual varves of the glaciatic regions can be suitably represented by RS and BS, respectively.

Figure 4. X-ray Diffraction spectra of (a) RS (b) BS samples

Figure 5. Field Emission Scanning Electron Microscopy (FE-SEM) showing microstructure of (a) RS (b) BS at 1000X magnification

2.5 Frozen and Unfrozen Soil Characteristics

Thermal conductivity stands as a critical parameter in modeling heat transfer within soils (Tian et al., 2020). In this study, the thermal characteristics of both soils, RS and BS, in frozen and unfrozen states were determined using the KD2 Pro Thermal Properties Analyzer (KD2 Pro, 2008) developed by Decagon Devices (Pullman, Washington). The sensor operates based on the transient line heat source method, offering a relatively faster and reliable method for measuring thermal properties. A dual-needle SH-1 sensor was employed, with the heater and temperature sensor positioned in two separate needles which are capable of measuring volumetric heat capacity, thermal diffusivity, thermal conductivity, and thermal resistivity. The device includes a handheld controller serving as a read-out analyzer for thermal properties. The stainless-steel dual-needle SH-1 sensor features two parallel probes, each 30 mm long, with a diameter of 1.3 mm and a spacing of 6 mm between the needles. During measurements, the controller generates a 30-second heat pulse in the heating needle probe, followed by temperature measurement in the monitoring needle probe during cooling. The sensor employs a dual-needle algorithm (KD2 Pro, 2008), assuming the needles function as infinite line heat sources with a constant heat output and zero mass in an infinite medium, aligning with the model proposed by Carslaw and Jaeger (1959). The specifications followed by KD2 Pro sensors adhere to the ASTM D5334-14 (ASTM 2014). Before commencing the experiment, the calibration of the SH-1 dual-needle sensor was conducted to ensure accurate measurement and check the needle spacing. Figure 6 illustrates an ongoing calibration test for the SH-1 sensor using the Derlin verification block. The needle spacing was deemed satisfactory as the tip spacing of the sensor matched the hole spacing in the Derlin block. To assess the performance of the SH-1 sensor, the needles were fully inserted into the pre-drilled holes in the Delrin block, and the assembly was left to equilibrate for 15 minutes before recording the measurements. The obtained measurements aligned with the Certificate of Quality Assurance provided by the manufacturer. The thermal properties of the RS and BS samples were determined on the prepared soil samples in pre-fabricated cylindrical acrylic mold at MDD and OMC. The mold dimensions were 60 mm in height and 80 mm in diameter, exceeding the recommended minimum distance between the sensor needle probe and the outer boundary of the acrylic cylindrical mold (Campbell et al., 1991). This distance, measuring 5.86 times the needle diameter, was sufficient to prevent boundary effects due to the heating of the sensor needle probe (Cai et al., 2015). Before inserting the sensor probe into the prepared soil sample, a dummy dual hole, smaller in diameter than the probe needle, was created using a pre-fabricated replica of the sensor made of plexiglass material (Figure 6). This dummy dual hole facilitated the easy insertion of the sensor needle probe into the compacted sample. During freezing, prefabricated needles were kept inserted in the soil sample (Figure 7) to simplify the insertion of the thermal sensor into the frozen sample without the risk of breaking the sensor needles. Figure 8 shows the ongoing measurement of thermal properties on the prepared sample using KD2 Pro immediately after taking out the sample from deep freezer. For this study, the thermal conductivity and volumetric heat capacity were recorded at room temperature (unfrozen) and at -10°C (frozen), with the values listed in Table 3.

Table 3. Thermal parameters of RS and BS

Soil type	**Unfrozen thermal conductivity (kJ/sec/m/°C)**	**Frozen thermal conductivity (kJ/sec/m/°C)**	**Unfrozen volumetric heat capacity (kJ/m^3/°C)**	**Frozen volumetric heat capacity (kJ/m^3/°C)**
RS	0.001328	0.001873	3050	4633
BS	0.000989	0.001416	2862	3241

Figure 6. KD2 Pro Thermal Properties Instrument with Data Acquisition System, SH1 Dual-Needle sensors, Delrin calibration block and Dummy needle

Figure 7. Prepared soil sample in mould to measure thermal conductivity with inserted pre-fabricated dummy needle

Figure 8. Ongoing thermal properties measurement on prepared sample using KD2 Pro immediately after taking out the sample from deep freezer

2.6 Hydraulic characteristics of RS and BS

The SWCC of a soil defines the relationship between the water potential of the soil and pore water content, commonly used to study the water retention behavior of unsaturated soils and hence their hydromechanical behavior. As mentioned in Section 2.1, the data points of suction magnitudes at different water contents were obtained using a WP4-T Dewpoint Potentiometer (Figure 9). Subsequently, these data points were fitted into the van Genuchten model to derive the SWCC for both soils. The obtained model parameters were then utilized to compute the HCF for the soils. Similar to SWCC, the SFCC describes the relationship among unfrozen water content and the temperature of the soil at sub-zero temperatures, which has essential applications in cold region engineering (Bittelli et al., 2003; Flerchinger et al., 2004; Wen et al., 2012). Therefore, SFCC is a valuable tool for modeling the coupled THM behavior of the soil. The present study focuses on the deformation behavior of homogeneous and reconstituted varved clays under freezing and thawing effects.

Figure 9. WP4-T Dewpoint Potentiometer with its operating parts, and prepared soil sample in stainless steel cups

In cold weather engineering, as in the present case, the proportion of frozen water or ice plays a significant role in the geotechnical response of the soil. In freezing soils, a certain amount of liquid water exists at subzero temperatures depending on the capillarity and the surface energy of the soil particles (Li et al., 2020; Bi et al., 2023). The existence of water in the soil at subzero temperatures is attributed to the lower energy potential of pore water, which in turn reduces the freezing point of the water (Miller 1966; Spaans and Baker 1996; Watanabe and Wake 2009). The relationship between unfrozen water content in the soil at corresponding subzero temperatures is termed as the Soil Freezing Characteristic Curve. There are several experimental techniques to obtain the SFCC graphical plot, such as Nuclear Magnetic Resonance method, Time Domain Reflectometry method, Frequency Domain Reflectometry method, Calorimetry method, and Dilatometry method (Patterson and Smith, 1985; Konrad, 1994; Watanabe and Wake, 2009; Kozlowski and Nartowska, 2013). The mentioned experimental techniques are costly and time-consuming. Therefore, several unfrozen water content models were developed by combining the SWCC model and Clapeyron equation by various researchers, such as Bittelli et al. (2003), Nishimura et al. (2009), Liu and Yu (2013) and Zhang et al. (2016). In the present study, the empirical formula proposed by Zhang et al. (2016) is used for the determination of SFCC curves, which combines the Clapeyron relationship with the van Genuchten equation and is discussed in detail in the forthcoming section. Based on experimental validation, several researchers have reported an analogy between SWCC and SFCC in their water retention mechanisms during drying and freezing processes, respectively (Wang and Hu, 2023). The SWCC is governed by the soil-water interaction, which is unique for every soil and inherently linked to pore-size distribution and mineral constituents. Therefore, the SWCC serves as a foundation for predicting the SFCC of soils. In the present study, above subzero temperatures, water retention occurs according to the SWCC curves, and the corresponding water movement follows the HCF. During periods of sub-zero temperatures, water converts into ice, and some amount of unfrozen water remains, as per the SFCC curve.

The hydraulic parameters of RS and BS were determined using the van Genuchten formulation, which involved analyzing the data points of suction values corresponding to different moisture contents. Equation 1 represents the SWCC using the van Genuchten functions, offering a mathematical depiction of the relationship between volumetric water content (θ) and soil water potential (φ). In physical terms, it characterizes the capacity of soil to retain water under varying suction conditions, defining the interplay between residual water content (θ_r), saturated water content (θ_s), and the shape parameters (α, n, m).

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{[1 + |\alpha\varphi|^n]^m} \; ; m = 1 - 1/n \tag{1}$$

where θ, θ_r and θ_s are expressed in units of m^3/m^3,

Equation 2 provides the formula for computing the HCF based on the van Genuchten model. In physical terms, it articulates the relationship between the unsaturated hydraulic conductivity, $K(\varphi)$

of the soil and φ. The unsaturated hydraulic conductivity describes the ability of the soil to transmit water in conditions where the soil is not fully saturated.

$$K(\varphi) = \frac{K_s\{1 - (\alpha\varphi)^{mn}[1 + (\alpha\varphi)^n]^{-m}\}^2}{[1 + (\alpha\varphi)^n]^{ml}} \tag{2}$$

where K_s is the saturated hydraulic conductivity.

Table 4 portrays the van Genuchten parameters, water content and saturated permeability of RS and BS.

Figure 10(a) shows the SWCC curves obtained by fitting the van Genuchten model through experimental data points for RS and BS, respectively. Through this fitting process, α, n, m has been determined for both the soils. Notably, RS and BS exhibit distinct SWCC curves, indicating variations in water retention capacity, hydraulic conductivity, and, consequently, their responses to changes in moisture content. A key observation is the relative positioning of the SWCC plots, where the curve for BS lies over that of RS. This positioning implies that under similar suction conditions, BS retains more water than RS. The steeper slope of the SWCC curve between the θ_r and θ_s for RS compared to BS suggests a more rapid change in water content occurs in RS with the same change suction for both soils. In contrast, the gentler slope for BS indicates a higher degree of water retention even at lower suction levels. This difference in the slope between θ_r and θ_s has significant geotechnical implications. The steeper slope for RS suggests a more rapid response to changes in suction, potentially leading to quicker drainage and changes in water content under varying environmental conditions. On the other hand, the gentler slope for BS signifies a more gradual response, indicating enhanced water retention and resistance to rapid changes in moisture content.

Figure 10(b) illustrates the estimated HCF curves for RS and BS using van-Genuchten parameters, with the saturated permeability obtained through laboratory experiments as mentioned in the preceding section. The magnitudes of saturated permeability align with the range computed in the literature (Kazi, 1968; Kohv et al., 2009). The saturated permeability of both the soils was carried out in laboratory in pre-fabricated molds as discussed in the previous section. The HCF curve for the soils used in present study reveal notable intersection point known as the breakthrough point.

Towards the higher suction side of this breakthrough point, BS exhibits higher hydraulic conductivity, while RS demonstrates higher hydraulic conductivity on the lower suction side. The breakthrough point holds critical significance, particularly in the context of water infiltration from a layer with lower hydraulic conductivity to one with higher hydraulic conductivity in a layered system. This phenomenon is vital for understanding the behaviour of partially saturated layered systems. The moment at which breakthrough occurs is referred to as the 'breakthrough time' (Hillel, 1987; Li et al., 2022; Chen et al., 2022; Liu et al., 2023; Scarfone et al., 2023). As can be observed from the graph, the breakthrough suction for RS and BS is 160 kPa. This parameter plays a crucial role in governing flow dynamics at the interface of layered systems. Specifically, at the interface, water traverses from a layer with lower hydraulic conductivity to one with higher hydraulic conductivity. To overcome the capillary barrier formed at this interface, water content rises within the low hydraulic conductivity soil layer until the pressure surpasses capillary forces, facilitating movement into the underlying soil with higher hydraulic conductivity (Morris and Stormont, 1997; Stormont and Anderson, 1999; Scarfone et al., 2023). While the breakthrough point is a key aspect, it is important to note that a detailed breakthrough study analysis is not undertaken in the present research due to the inherent complexity involved.

Table 4. van Genuchten parameter, water content and saturated permeability of RS and BS

Soil type	van Genuchten parameters			Saturated water content θ_s (m^3/m^3)	Residual water content θ_r (m^3/m^3)	Saturated permeability K_s (m/s)
	a (kPa)	n	m			
RS	167	2.6	0.615	0.42	0.035	1.10×10^{-7}
BS	1000	1.8	0.444	0.37	0.045	5.18×10^{-9}

2.7 Generation of SFCC curve for numerical modeling

The SFCC for RS and BS, shown in Figure 11, is derived using a numerical expression proposed by Zhang et al. (2016). This expression combines the Clapeyron relationship (Equation 4) with the van Genuchten equation (Equation 1) to establish Equation 3. The generated pore-water pressure at the freezing point temperature is then used to obtain the corresponding unfrozen volumetric water content. The obtained unfrozen volumetric water content is further normalized by the soil porosity and finally cross-plotted against the sub-zero temperatures to obtain function as shown in Figure 11.

$$\theta_{uwc} = \theta_r + (\theta_s - \theta_r)\left[1 + \left(ah_{sf} \ln \frac{T + 273.15}{T_0 + 273.15}\right)^n\right]^{-m} \tag{3}$$

where θ_{uwc} is the unfrozen water content in the soil.

Figure 10(a). Soil Water Characteristic Curve for RS and BS

Figure 10(b). Hydraulic Conductivity Function curve for RS and BS

Figure 11. Soil Freezing Characteristic Curve for RS and BS

The SFCC in Figure 11 for both soils used in the present study represents the constitutive relationship between unfrozen water content and sub-zero temperatures. The curve illustrates the unique response of each soil type to freezing conditions or sub-zero temperatures. As mentioned previously, depending on the soil type, which results in a unique soil-water interaction for every soil, a depression in the freezing point of soil water occurs at sub-zero temperatures due to adsorptive and capillary forces. These forces are responsible for the existence of liquid water during the freezing point (Harrysson Drotz et al., 2009). From the figure, it can be observed that at 0°C, the amount of unfrozen water content in BS is higher than in RS. As the curves move towards the negative temperature side, the unfrozen water content in both soils keeps decreasing, with the rate of decrease in unfrozen water content in RS being higher than in BS until a temperature of -4.4 °C is reached. Since the present study is conducted by averaging temperatures, with the minimum temperature being -4.3 °C throughout the study period, at sub-zero temperatures, the unfrozen water content in BS will be higher than in RS. The higher unfrozen water content in BS is attributed to the high adsorptive and capillary forces in clayey soils compared to silt, which reduces the mobility of water and leads to higher adsorbed water pressure than bulk water pressure, thereby resisting freezing (Chen 2021; Wang 2022; Lu, 2022).

2.8 Stiffness and strength characteristics of RS and BS

The remaining parameters required for the numerical modeling in the present study involves the index properties (unit weight and initial void ratio), the stiffness properties and the strength parameters of RS and BS specimens. The corresponding properties were obtained from relevant laboratory tests, as mentioned earlier, and are listed in Table 5. Since both RS and BS are in a disturbed state in the present study, for standardization, the unit weight corresponds to the MDD of the soil. The void ratio has been calculated using the standard three-phase relationship $\gamma_d = G\gamma_w/(1+e)$, wherein the expression relates dry unit density (γ_d), specific gravity (G), unit weight of water (γ_w) and void ratio (e). The elastic modulus used in this study is the initial elastic modulus, which is estimated from the stress-strain curve obtained from the UCS test. The stress-strain curves for RS and BS, along with the calculation of the elastic modulus, are shown in Figure 12. It can be observed that three trials of UCS tests were conducted. The elastic modulus was calculated for each UCS trial, and then the values were averaged and used in the present numerical analysis. The Poisson's ratio for both soils was calculated from the deformed sample dimensions at the peak stress. The deformed samples of RS and BS after the test are shown in Figure 13.

Table 5. Index, stiffness and shear strength parameters of RS and BS

	Index Parameters		**Stiffness Parameters**		**Shear Strength Parameters**	
Soil Type	**Unit weight (kN/m³)**	**Initial void ratio**	**Initial elastic modulus (kPa)**	**Poisson's ratio**	**Effective cohesion (kPa)**	**Effective friction angle (°)**
RS	17	0.587	24330	0.35	12.4	17.53
BS	16	0.730	5058	0.45	6.1	13.0

Figure 12. (a) Stress-strain curves from UCS test for RS (b) Initial elastic modulus curve for RS (c) Stress-strain curves from UCS test for BS (d) Initial elastic modulus curve for BS

Figure 13. Deformed samples of (a) RS and (b) BS after UCS test

Cohesion and friction angles of both soils were obtained from small Direct Shear box tests conducted at five normal stress levels: 50 kPa, 100 kPa, 150 kPa, 200 kPa, and 250 kPa for each soil. Figures 14(a) and 14(c) show the variation of shear stresses with displacement for RS and BS, respectively. It can be observed from the graphs that BS exhibits a relatively smooth transitional and gradual increase in shear stress with an increase in displacement compared to the curve representing RS. Additionally, the peak stresses achieved at different normal stresses are at higher displacement magnitudes for BS compared to RS. The behavior of BS, undergoing larger deformation under applied normal stresses, is attributed to its higher plasticity compared to RS. The higher plasticity in BS contributes to a transitional and more gradual increase in shear stresses compared to RS. Figures 14(b) and 14(d) depict graphical plots showing the maximum shear stress obtained at corresponding applied normal stresses. From the plot, it is observed that both shear strength parameters – angle of internal friction and cohesion – are higher for RS compared to BS. Therefore, despite exhibiting plastic behavior, the peak shear strength attained by BS is lower than that of RS due to its lower friction angle.

Several researchers have reported the shear strength parameters of varved clays, but only in their bulk form and by placing the sample such that shearing occurs along the plane of the laminae. Giraud et al. (1991) reported average magnitudes of shear strength parameters for varved clays, with the friction angle ranging from 22-23° and the cohesion ranging from 1-5 kPa. Eigenbrod (2003) reported the internal angle of friction to be 31° and the cohesion as 12 kPa. Kohv et al. (2010) tested for strength parameters of two types of varved clays lying over one another along a vertical profile. The lower varved clay section had a higher water content than the upper section. For the lower section varved clay, the authors reported the angle of internal friction and cohesion to be 21° and 8 kPa, respectively, whereas for the upper section varved clays, the corresponding values were reported to be 8.4° and 15.2 kPa. In the present study, all laboratory tests were conducted separately on RS and BS. As shown in Table 5, the internal angle of friction for RS and BS is 17.53° and 13°, respectively, while the corresponding cohesion is 12.4 kPa and 6.1 kPa. If the shear strength parameters are averaged considering the equal proportion of RS and BS in the soil profile, then the internal friction angle would come out to be 18.5° and the cohesion magnitude would be 15.265 kPa. These averaged magnitudes of shear strength parameters closely resemble the corresponding magnitudes reported in the literature.

Figure 14. (a) Shear Stress-Displacement curves of RS at different confining stresses (b) Shear Stress-Normal Stress plot for RS (c) Shear Stress-Displacement curves of BS at different confining stresses (d) Shear Stress-Normal Stress plot for BS

3. Numerical Modeling of the Freezing-Thawing Behavior of Varved Laminae

FE modelling is employed to simulate the ground deformation during subsequent freezing and thawing processes of varved laminae. The numerical modelling is performed using three modules in GeoStudio 2023.1, namely TEMP/W, SEEP/W, and SIGMA/W. The TEMP/W and SEEP/W modules are coupled to account for the free convection of water induced by temperature changes. Negative temperatures cause the freezing of water in soil pores, while thawing occurs as the temperature rises above zero. This phase change of water in soil pores is considered in the analysis by varying the density of water with temperature according to Thiesen's formula (Kell, 1975). The Clapeyron thermodynamic equilibrium equation (Equation 4) is used to calculate the variation in pore-water pressure of the unfrozen liquid water at sub-zero temperatures (Schofield, 1935; Williams and Smith, 1989).

$$\frac{\partial u_w}{\partial T} = \frac{h_{sf}}{v_w T_0} \tag{4}$$

where, ∂u_w represents the variation in water pressure within the unfrozen water in partially frozen soil, ∂T denotes the temperature change below the phase change temperature, h_{sf} is the latent heat of vapourization (334000 kJ/m^3), v_w represents the specific volume of water (1.0 L/kg), and T_0 corresponds to the standard freezing point of water at atmospheric pressure, which is considered as 0°C in this analysis.

The coupling of thermal and hydrological processes through the integration of SEEP/W and TEMP/W leads to changes in the hydraulic conductivity of the soil due to freezing and thawing. In this analysis, the TEMP/W module predominantly controls the simulation, with information exchanged iteratively between TEMP/W and SEEP/W as the solution progresses. SEEP/W applies Darcy's Law for unsaturated soils to compute water flow within the soil, treating hydraulic conductivity as a variable dependent on the thermal and hydraulic data exchanged between TEMP/W and SEEP/W, which, in turn, depends on several variables discussed in Section 3.1.

In the subsequent stages of numerical modelling, the SEEP/W and SIGMA/W modules are combined. The water pressure generated during the thermo-hydro coupling is captured in SEEP/W and then used by SIGMA/W to compute the deformations. It should be note that it is not possible to directly couple or link the TEMP/W and SIGMA/W modules. The integration of SEEP/W and SIGMA/W enables simulation of ground movement caused by variations in water pressure and density of water during freezing and thawing. Ground displacement resulting from water movement and phase change is the specific focus of the SIGMA/W module. In this study, the in-situ gravity activation method in SIGMA/W is used to analyze ground deformations. This method of analysis accounts for the effect of self-weight of the soil. The Mohr-Coulomb material model is used to relate the generated stresses to the resulting strains. Displacement is then calculated based on the strain increments obtained in the current numerical modeling. The parameters employed in the Mohr-Coulomb model are provided in Table 5. Equation 5 provides Mohr-coulumb yield criterion used in SIGMA/W.

$$F_y = \sqrt{J_2}\sin(\theta + \frac{\pi}{3}) - \sqrt{\frac{J_2}{3}}\cos\left(\theta + \frac{\pi}{3}\right)\sin\varphi - \frac{I_1}{3}\sin\varphi - c\ \cos\varphi \qquad (5)$$

where F_y is the yield function, c is the cohesion, and φ is the angle of internal friction. I_1 is the first stress invariant, J_2 is the second stress invariant, θ is the Lode angle.

The coupling of SEEP/W and SIGMA/W can be expressed as Equation 6.

$$\begin{bmatrix} [K]_s & [L] \\ [L]^t & [K]_w \end{bmatrix} \begin{Bmatrix} \Delta d \\ \Delta u \end{Bmatrix} = \begin{Bmatrix} F_e \\ Q \end{Bmatrix} \qquad (6)$$

where $[K]_s$ is the soil stiffness matrix, $[L]$ is the coupling matrix that represents the interaction between the displacement and pore-pressure change, $[L]^t$ is the transpose of the coupling matrix, $[K]_w$ is the hydraulic conductivity matrix, Δd is the incremental displacement, Δu is the incremental pore-pressure change, F_e is the external force applied to the system, Q is the seepage or water flux.

The numerical modeling was performed on representative two-dimensional (2D) soil profiles with dimensions of 400 cm in height and 100 cm in width. This thickness of the varve deposit considered in the present study is adopted on the basis of the findings from several researchers who have identified 4 m varve thickness as optimal for a maximal infiltration, water storage, and moisture fluctuation (Zou et al., 2001; Dongli et al., 2013; Mei et al., 2018; Luo et al., 2023; Ya et al., 2023). The primary objective of the present study is to investigate the response of homogeneous and laminated soils when subjected to freezing and thawing conditions, particularly examining the influence of laminae on these responses. In the literature, governed by the depositional recurrences, thick varve formations of up to 760 mm have been reported (Palmer et al., 2019), with exceptional circumstances possibly leading to even greater depths. Therefore, considering both the active zone of soil depth and the maximum reported varve thickness, 400 cm depth of soil is chosen for the modelling approach. This choice of soil depth is aimed at encompassing sufficient stratigraphic complexity while maintaining computational feasibility. The variability in varve thicknesses and geological formations is acknowledged, and the modelling approach in the paper reflects a balance between practical constraints and the need to capture crucial aspects of homogenous and laminated soil behaviour under freezing and thawing conditions.

The sequence of boundary conditions applied during different stages of the modeling process is depicted in Figure 15. The analysis consists of four stages for all considered soil profiles, namely the initial stage, freezing stage, thawing stage, and ground deformation assessment stage. In the initial stage (Figure 15a), temperature boundary condition of 4°C is applied to both the top and bottom of the soil profiles. This is done to establish a steady-state temperature distribution throughout the profile. For simulating the freezing-thawing cycle, the air temperature data for Tawang in Arunachal Pradesh, India is considered over a period from 2005 to 2015. The data for the same was obtained from 'Time and Date' (https://www.timeanddate.com/weather/), an online climate data collector. During this period, Tawang experienced an average air temperature below 0°C for five months, which is considered the freezing period for the analysis. For the remaining seven months, the average air temperature was above 0°C, which is considered the thawing period in this study. To establish a uniform initial temperature condition across the soil depth in the numerical modelling, the average temperature between these extremes is used, and the phase change temperature is considered as zero. Hence, during the freezing stage (Figure 15b), freezing temperature (negative temperatures) is assigned to the top surface of the soil. Additionally, this transient analysis also incorporates a water table at the bottom of the soil profile. In the thawing stage (Figure 15c), the temperature at the top surface of the soil is set to thawing temperatures (positive temperatures). The hydraulic and temperature conditions from the final time step of the freezing analysis are carried over as initial conditions for the thawing analysis across the entire soil profile. In GeoStudio, this is achieved using the parent-child concept, where the freezing analysis serves as the parent, and the thawing analysis is the child. This approach ensures continuity between the freezing and thawing stages. Finally, in the last stage, to capture ground deformation resulting from convection and the freezing-thawing phenomenon, restraints are imposed on the boundaries of soil profile. The bottom boundary of the soil is fixed in both horizontal and vertical directions, the sides are fixed in the horizontal direction only, and the topmost boundary is free to move (Figure 15d).

Figure 15. Applied boundary conditions in the numerical analysis: (a) Initial stage (b) Freezing stage (c) Thawing stage (d) Ground deformation assessment stage

In the present study, seven types of soil profiles are considered (Figure 16). Two of these profiles consist of homogeneous soils, wherein one profile comprises only RS and the other profile comprises only BS. The remaining five soil profiles are reconstituted multi-layered couplets of varved laminae. The multi-laminae profiles considered in this study are likely to replicate the layered structure observed in natural varved clays. These profiles are created by sequentially placing alternate laminae of RS and BS, with the number of couplets varying among the five varved clay profiles. The chosen profiles comprise 2 layered single couplet, 4 layered dual couplet, 8 layered quadruple couplets and 16 layered octuplet couplets. In reality, there can be any numbers of couplets depending on the depositional recurrences. However, the object of the current study is to analyze the typical influence of number of laminae on the frost heave and thaw settlement of a varve deposit. Accordingly, the cross-section of the soil profiles for both the homogeneous soils and the varved laminae is considered identical. This ensures a consistent comparison of the behavior and characteristics of the different soil types within the unified geometrical framework. The input parameters for the initial stress conditions in the various soil profiles are according to the findings from the DST, Standard Proctor Compaction Tests, and UCS tests, the details of which are already mentioned in the earlier parts of the manuscript.

Figure 16. Different homogenous and reconstituted varved clay profiles

3.1 Theory of heat transfer in TEMP/W module

Free convection of water refers to the movement of water caused by temperature gradients (Schenk and Schenkels, 1968). Temperature gradients across soil boundaries result in changes in water density. This means that upon heating, water moves due to the decrease in density. For example, heated water rises to replace the denser and cooler water in the system. In this study, the 'Full Thermal' material model is selected to characterize heat transmission across the soil profiles. This material model assumes a constant volumetric water content throughout the analysis, allowing thermal conductivity to vary with temperature while maintaining constant volume heat capacities in frozen and unfrozen states. The functional relationship between material thermal conductivity and temperature in the considered material model is estimated as given in Equation 7.

$$k = k_u + (MF)(k_f - k_u) \tag{7}$$

where k_u is the unfrozen thermal conductivity; k_f is frozen thermal conductivity; and MF is a modifier function which is uniquely defined for a range of freezing point temperatures.

The first law of thermodynamics, based on the law of conservation of energy, governs the rate of change of thermal energy stored in a control volume and it describes the modality of the change in energy in a system (Tolhoek and De Groot, 1952). According to this law, the rate of change of thermal energy must equal the energy entering the control volume minus the energy leaving it, plus the energy generated within it.

The rate of change of thermal energy stored in soil containing water within the control volume $(dx.dy.dz)$ is given by

$$\dot{E_{st}} = \dot{U_{sens}} + \dot{U_{lat}} = \dot{U_{sen}} + \dot{U_{sf}} + \dot{U_{fg}} \tag{8}$$

where $\dot{E_{st}}$ represents the rate of change of the stored thermal energy; $\dot{U_{sens}}$ represents the rate of change of thermal energy associated with sensible heat; $\dot{U_{lat}}$ represents the rate of change of thermal energy associated with latent heat; $\dot{U_{sf}}$ accounts for the change in latent energy within the soil, encompassing both freezing and melting case i.e when conversion takes place from liquid to solid and vice-versa; and $\dot{U_{fg}}$ represents the change in latent heat due to vapourization, which is not considered in the present analysis $(\dot{U_{fg}} = 0)$.

The rate of change of thermal energy associated with sensible heat ($\dot{U_{sens}}$) is

$$\dot{U_{sens}} = C_p \frac{\partial T}{\partial t} dx\, dy\, dz \tag{9}$$

where C_p represents volumetric heat capacity parameter.

The rate of change of thermal energy associated with fusion of water ($\dot{U_{sf}}$) is represented by

$$\dot{U_{sf}} = -h_{sf} \frac{\partial M_{ice}}{\partial t} = -\rho_{ice} h_{sf} \frac{\partial \theta_{ice}}{\partial t} dx\, dy\, dz \tag{10}$$

where M_{ice} and ρ_{ice} represent the mass and density of the ice, respectively and θ_{ice} represents the volumetric ice content in the soil mass.

For free convection, the volumetric heat capacity (C_{ap}) is given by

$$C_{ap} \frac{\partial T}{\partial t} = \frac{\partial}{\partial y} (k \frac{\partial T}{\partial y}) \tag{11}$$

where k represents the thermal conductivity of the soil. C_{ap} is further defined as

$$C_{ap} = C_p + \rho_w h_{sf} \frac{\partial \theta_{uwc}}{\partial T} \tag{12}$$

where ρ_w represents the density of water and θ_{uwc} represents the unfrozen water content in the soil.

3.2 Verification of the Numerical Model

The numerical modelling approach in the present study was verified using the work of Konrad and Morgenstern (1981) and Amiri et al. (2021). Amiri et al. (2021) modelled frost heave using extended FE numerical modelling and verified it with the work of Konrad and Morgenstern (1981), who studied frost heaving of Devon silt. Some parameter values such as heat capacity, thermal conductivity, and stiffness were not originally reported by Konrad and Morgenstern (1981), which were later used by Amiri et al. (2021) from other literature sources on the same soil. The numerical approach used in present study has been validated using the collated parameters provided by

Konrad and Morgenstern (1981) and Amiri et al. (2021). The original experimental test was conducted on a soil column with a length of 78 mm. The initial temperature across the soil profile was +3°C, and freezing was initiated by reducing the top surface temperature to -5.5°C. The hydraulic conductivity of the sample used was 1×10^{-7} cm/s. The heat capacity of frozen and unfrozen soil was 4190 J/kg·K and 2095 J/kg·K, respectively. The thermal conductivity of frozen and unfrozen soil was 2.2 J/m·s·K and 3 J/m·s·K, respectively. The Young's modulus and Poisson's ratio used were 5 MPa and 0.25 respectively. Since no information on the shear strength parameters of the soil (cohesion and angle of internal friction) was available, an isotropic elastic material model was used. Figure 17 shows the heave magnitude obtained through present modelling approach with that of Amiri et al. (2021). A reasonable agreement is obtained between the reported results obtained through both the approaches, with a maximum difference being less than 2 mm. Hence, the numerical model developed for the present study can be considered reliable and hence, is used for further studies.

Figure 17. Verification of the numerical model developed in the present study

4. Results and Discussions

The freezing and thawing analysis in the present study involve seven soil samples, with two being homogeneous and the remaining five consisting of reconstituted varve clays. All the soil profiles have dimensions 4 m along the depth and 1 m along the width, with the water table at the bottom of the soil profiles. The homogeneous soil profiles comprise two separate profiles, one comprising only of RS and the other comprising only of BS. In the reconstituted varved arrangement, RS and BS are arranged in alternate layers of varying thickness along a 4-meter soil depth profile. This study aims to analyse and compare the soil profile under two conditions. Firstly, it studies the impact of the sequential arrangement of RS and BS on freezing and thawing. Secondly, it explores the influence of the number of laminae in the varved soil structure under the effect of freezing and thawing. To investigate how the arrangement of laminae affects the displacement of a soil profile during freezing and thawing, two cases of sequential arrangements of 2-layered soil profiles are studied with RS and BS. In one scenario, RS overlies BS which is denoted as 2L-RS-BS, and in the other arrangement, BS overlies RS which is denoted as 2L-BS-RS. Further, to examine the effect of the number of laminae along the soil profile (4 m), RS and BS are arranged in alternating sequential layers, forming reconstituted varved clays with 4, 8, and 16 layers. In all these arrangements, RS laminae occupy the uppermost layer, while BS laminae occupy the bottommost position.

The study includes seven soil specimens analyzed at seven initial suction magnitudes of 0 kPa, -2.5 kPa, -5 kPa, -7.5 kPa, -10 kPa, -15 kPa, and -20 kPa. The initial suction pressure of 0 kPa represents the soil in a fully saturated state, whereas negative suction magnitudes represent unsaturated states of soil. The aim of considering different initial suction across soil profiles is to understand how the initial suction, which corresponds to the initial water content in the soil, affects the deformation rate in different soil profiles. These suction values are chosen because frost-heaving in the soil can only be initiated if sufficient water is present in the soil along with some external source of water. Therefore, for the present analysis, the numerical simulation begins with an initial suction value of 0 kPa (fully saturated soil condition), and further simulations are carried out by increasing the suction values to -2.5 kPa, -5 kPa, -7.5 kPa, -10 kPa, -15 kPa, and -20 kPa, respectively, with an available external source of water as the groundwater table, which lies at the bottom of the soil profile.

Figures 18 and 20 clearly demonstrate that the applied initial suction pressure significantly affects the deformation in all the soil profiles. It is observed that the higher the initial suction, the lower is the frost-heave in all the soil profiles. For applied initial pressure beyond -10 kPa, there is not much deformation observed in the soil profiles after the initial heave in the first month; therefore, the present study is carried out with the stated initial suction values up to -20 kPa. In the present study, all the soil profiles under different initial pressure conditions are analyzed for a period of 365 days. The analysis begins from November, when the freezing period starts. The freezing period is when the atmospheric temperature remains at or below 0°C, whereas during the thawing period, the atmospheric temperature remains above 0°C. For the study area considered in this study, the freezing period is typically from November to March (0 to 151 days), whereas the thawing period is from April to October (152 to 365 days).

In cold regions, where temperatures drop below 0°C during the freezing period, a gradual freezing front traverses from the soil surface exposed to the atmosphere to the inner depth of the soil profile.

This results in a temperature gradient between the top and bottom sections of the soil. When there is water present in the soil under this temperature gradient, water migration occurs from regions of higher potential (higher temperature) to lower potential (lower temperature). The analysis considers an initial temperature of 4°C across all soil profiles. This choice aligns with the average monthly temperature of October, just before the commencement of the freezing period in November. As the freezing starts, the available water in the soil at a given initial pressure migrates from the bottom of the soil profile to the upper soil profile, moving from the bottom towards the freezing front at the top. The temperature gradient plays a crucial role in driving this water migration. The amount of secondary heave the soil experiences upon freezing, under a given initial pressure, depends on the net resultant force. This force is influenced by water migration within the soil profile under gravity and the upward movement (against gravity) of water due to convection. The interplay between gravity-driven water movement and convection-induced upward water flow contributes to the overall deformation and frost-heave observed in the soil profiles during the freezing period.

The deformation profiles of RS, BS, and the 2L varve couplet (2L-RS-BS and 2L-BS-RS) at different initial pressures are illustrated in Figures 18a to Figure 18n under freezing and thawing conditions. These graphs provide insights into the sequencing effects on these soil profiles. In the homogeneous soil profiles of RS and BS at an initial suction pressure of 0 kPa and -2.5 kPa, the rate of heaving and the heave magnitudes at the end of each month during the freezing period up to 151 days are notably higher for RS than for BS (Figure 18a and 18c). For instance, at an initial pressure of 0 kPa, RS exhibits heave magnitudes at the end of November, December, January, February, and March as 8.4 mm, 15.5 mm, 21.6 mm, 27.25 mm, and 32.1 mm, respectively, while the corresponding values for BS are 3.1 mm, 5.7 mm, 7.9 mm, 9.9 mm, and 11.6 mm. This trend is consistent with higher initial suction pressure of -2.5 kPa wherein higher frost-heave is higher in homogenous RS as compared to BS for the entire freezing period (Figure 18c). The higher heave in RS compared to BS can be attributed to multiple factors which includes higher permeability, high thermal conductivity, and lower unfrozen water content in RS than BS for the same freezing temperature. Higher permeability of RS facilitates a greater water flow towards the freezing front during the convection process. The higher thermal conductivity in RS leads to quicker flow of temperature under the established temperature gradient. As a result, the freezing front temperature traverses faster in RS than in BS. Additionally, at a given freezing temperature, the amount of unfrozen water in RS is lesser than BS. This means that at the same temperature, the volume of water converting to ice will be higher for RS than for BS. These factors contribute to the high ultimate heaving at the end of each freezing month, followed by a higher rate of heaving in RS compared to BS. During the thawing period (day 151-365), although the rate of settlement in RS is greater than in BS, the settlement magnitudes at the end of each month are lower for BS than for RS. This can be attributed to higher thermal conductivity of RS, resulting in a quicker temperature change in the soil and a higher melting rate. Additionally, RS also has higher hydraulic conductivity, leading to the rapid dissipation of meltwater. Since the final heave magnitude in RS is significantly higher than in BS by the end of the freezing period (i.e., by the end of March), even though the rate of settlement is higher in RS, the ultimate settlement values at the end of each month still remain higher for RS. For example, considering the final thawing magnitudes at the end of April, May, June, July, August, September, and October at an initial pressure of 0 kPa, the values for RS are 22.8 mm, 19.8 mm, 16.8 mm, 14.6 mm, 12.8 mm, and 2.8 mm, respectively, while for BS, the corresponding values for the given months are 8.5 mm, 7.6 mm, 7.1 mm, 6.0 mm, 4.9 mm, and 1.0 mm (Figure 18a and 18b). A similar trend of lesser settlement magnitudes for RS and BS is observed for the soil profiles with an initial pressure of -2.5 kPa.

As the initial suction pressure in the soil profile is increased to -5 kPa, -7.5 kPa, and -10 kPa, a significant observation is made where heaving in BS surpasses RS after a certain duration of freezing. The heave in BS is higher than RS at the end of January for an initial pressure of -5 kPa (Figure 18e). For an initial suction of -7.5 kPa and -10 kPa (Figure 18g and Figure 18i), the heave in BS is higher than in RS after December and January, respectively. The behaviour of RS and BS can be attributed to the net resultant flow of water, as mentioned briefly in the previous section, explaining how water movement under convection and gravity acts during freezing. The permeability of RS is higher than the permeability of BS. Therefore, as soon as the analysis begins at the stated suction values of -5 kPa, -7.5 kPa, and -10 kPa, water from the upper soil section starts permeating to the lower soil profile. Due to high permeability of RS, water percolates into lower soil profiles at higher velocity under the effect of gravity. This creates even higher negative suction at the upper soil profiles than the initially applied suction, even though the temperature at the soil surface is negative (freezing temperature). This mechanism is observed in BS soil as well, but due to its low permeability, water movement in lower soil profiles is restricted. Therefore, at the same freezing temperature at the surface of RS and BS profiles, BS has a comparatively higher amount of water in its upper layers to move under convection and contribute to solidification of water under freezing. Consequently, this results in higher heave in BS than RS after a few months of freezing at initial suction magnitudes of -5 kPa, -7.5 kPa, and -10 kPa. The initial heaving in RS at the stated initial suction is greater than that in BS due to the initial freezing of water in the top surface layer. For a clearer understanding, Figures 19a to 19l are shown in the paper to illustrate the distribution of water pressure profiles at different initial pressures and freezing times for RS and BS profiles. Figures 19a and 19b show the pressure profile across RS and BS, respectively, after 91 days (end of January) for the considered initial pressure in the soil profile of 0 kPa. It can be observed from both the figures that pore water pressure built up is higher in RS compared to BS throughout the soil profiles. When the initial pressure is set at -5 kPa in both of these homogeneous soils, the pressure profile across RS is much lower compared to that of BS at the corresponding soil profile depths (Figure 19c and 19d). Similar behavior can be observed in the RS and BS soil profiles after 120 days of analysis (end of February), where the soil profiles with initial pressures of 0 kPa and -7.5 kPa are compared (Figure 19e to 19h). After 120 days of analysis (end of February), the water pressure generated in the RS soil profile is higher when the initial pressure is set at 0 kPa for both RS (Figure 19e) and BS (Figure 19f), whereas the reverse trend is observed when the initial pressure is increased to -7.5 kPa for RS (Figure 19g) and BS (Figure 19h). Similar observations of the changed pressure trend for RS and BS are found after 151 days (end of March) when the initial pressure across the soil profile is changed from 0 kPa to -10 kPa (Figure 19i to 19l). Additionally, it can be observed from the figures that the days on which this behavior is observed are delayed as the initial suction in the soil profiles increases (Figure 19a to 19l). Such behaviors are not observed in the previous cases where the initial pressure in the soil was 0 kPa (fully saturated) and -2.5 kPa (near saturation). In both cases, there is no scope for water to infiltrate to lower depths of the soils, as the soil voids are already filled with water, and at the bottom, there is a water table. Therefore, as soon as the initial pressure is increased in the soil to allow sufficient voids for water to move downwards under gravity, the above-discussed mechanism comes into play.

When the initial suction pressure is further increased to -15 kPa and -20 kPa in the homogeneous RS and BS profiles, the heaving magnitudes for all months again become less for BS as compared to RS for the entire freezing period (Figure 18k and 18m). However, as observed for initial suctions of -7.5 kPa and -10 kPa, the heave in RS occurs only during the initial freezing month of January, and for the remaining freezing period (Figure 18g and 18i), there is negligible change in heaving. Similar observations of initial heave are also made for when the initial pressure profile is -15 kPa and -20 kPa (Figure 18k and 18m). The heaving magnitudes during the entire freezing period become less for BS as compared to RS at initial suction pressures of -15 kPa and -20 kPa. This is likely because, at these initial suctions, the water content in both soil profiles is significantly low, and the lower hydraulic conductivity of BS (compared to RS) is unable to compensate for this low initial moisture content. RS, with its low unfrozen water content, exhibits initial heave during the first month, which remains almost constant for the remaining freezing time. In contrast, in BS, the heaving rate is very slow due to the high initial suction in the soil. As a result, the ultimate heave magnitude throughout the freezing periods remains less than RS at initial suction pressures of -15 kPa and -20 kPa.

The settlement curves of homogeneous profiles of RS and BS when an initial pressure of 0 kPa and -2.5 kPa (Figure 18b and 18d) is considered have already been discussed in the above section. The rate of settlement is higher in RS due to its greater thermal conductivity which results in quicker ice melting compared to BS. Additionally, RS has higher hydraulic conductivity which aids in faster dissipation of pore water pressure than BS. However, the ultimate settlement magnitudes of RS being higher than BS can be attributed to the higher heave magnitude of RS than BS at the end of the freezing period. For instance, the initial suction of 0 kPa, the heave at the end of the freezing period, i.e., at the 151th day, is 32.1 mm for RS and 11.6 mm for BS (Figure 18b). Therefore, the ultimate heave at the end of the freezing period in RS is 2.8 times the heaving in BS. For the initial pressure of -2.5 kPa, the heaving at the 151th day for RS and BS is 28.5 mm and 10.8 mm, respectively (Figure 18d), meaning the heave in RS is 2.6 times that of BS.
The frost-heave and thaw-settlement graphical plots for the considered initial pressure of -5 kPa indicate a transition pressure (Figure 18e and 18f). This pressure seems to affect the behavior of RS and BS, altering their heave behavior after a certain duration of freezing, which subsequently impacts their settlement behavior as well. From the heaving curves of RS and BS when the initial

suction pressure is -5 kPa, between December to February, BS shows higher heave than RS (Figure 18e). The corresponding effect can also be seen in its thawing behavior when the settlement magnitude of BS is higher than the settlement magnitude of RS between April to September (Figure 18f).

As discussed in the above section, when considering the initial suction pressures of -7.5 kPa, -10 kPa, -15 kPa, and -20 kPa, only initial heaving during the first month (November) is observed, and for the remaining period, negligible change in heave is noticed (Figure 18g, 18i, 18k, and 18m). At these initial pressures, as the thawing period begins, a very small magnitude of settlement is observed throughout the thawing period (Figure 18h, 18j, 18l, and 18n). It must be noted that in all soil profiles at the end of the thawing period (i.e., the 365^{th} day), the settlement magnitude is not 0, unlike before the beginning of the analysis. This is because the study employs Thiesen's formula, which considers the variable density of water at different temperatures. Therefore, during the thawing period, the temperature distribution in RS and BS governs the melting and migration of water in the soil profile. Consequently, the density at these temperatures dictates the settlement. The higher thermal conductivity of RS facilitates a faster transfer of positive temperatures throughout the soil profile during the thawing period. At higher temperatures, the density of liquid water is comparatively lower, resulting in a higher volume. As a result, the ultimate settlement at the 365^{th} day is consistently higher in the case of BS compared to RS at all the considered initial pressures. Since in RS, heave occurs during the initial month of November at the stated pressures, it is evident that there is no significant pull of water from the groundwater table; therefore, very less magnitude of settlement is observed.

At initial suction of -5kPa, -7.5 kPa, and -10 kPa, BS shows continuous heave, surpassing RS for the reasons discussed in the above section. Since the heaving at the end of the freezing period is higher for BS, this means there's a higher amount of frozen water. When the thawing begins, initially the settlement magnitude is higher in BS compared to RS at these pressures (Figure 18f, 18h, and 18j). As the water dissipates, the settlement continues, and eventually, the settlement magnitudes fall below those of RS. This transition occurs at the end of September, end of June, and end of May for the initial suction profiles of -5 kPa, -7.5 kPa, and -10 kPa, respectively, during the thawing period. The reasons for transitions are explained in the above section.

The settlement magnitude of RS remains higher than that of BS when the initial pressure in the soil is considered as -15 kPa and -20 kPa (Figure 18l and 18n). This is attributed to the lower heaving in the BS profiles due to the reasons discussed above, which, in turn, results in a lower magnitude of settlement compared to RS. Additionally, for initial pressures ranging from -5 kPa to -20 kPa, both the rate of heaving and the rate of thawing are high in the case of BS. This is in contrast to RS, where such high rates are observed at lower initial suction ranges of 0 kPa and -2.5 kPa. This phenomenon may be attributed to the high pull of water from the groundwater table under the effect of convection at higher initial suction pressure (> -2.5 kPa). This leads to a higher heaving rate in BS. Consequently, this higher heaving rate is associated with a higher rate of thawing observed for high initial pressures in the BS profiles.

To investigate the effect of laminae arrangement on frost-heave and thaw-settlement behavior in the soil, RS and BS are arranged in two different sequences along the vertical profile (Figure 17). In one case, RS lamina overlies BS lamina (2L-RS-BS), while in the other arrangement, BS lamina overlies RS lamina (2L-BS-RS). Observations from the graphs indicate that for initial suctions of 0 kPa, -2.5 kPa, -5 kPa, and -7.5 kPa, the rate of heaving and heaving in 2L-BS-RS is consistently higher at all freezing times compared to the heaving in 2L-RS-BS (Figure 18b, 18d, 18f, and 18h). For example, at the end of the 151-day freezing period (March end), the ultimate heave for 2L-RS-BS is 17.3 mm, 15.7 mm, 9.34 mm, and 1.4 mm at initial pressures of 0 kPa, -2.5 kPa, -5 kPa, and -7.5 kPa, respectively. Conversely, the corresponding values for 2L-BS-RS at these pressures are 24.5 mm, 22.2 mm, 13.8 mm, and 2.3 mm. This behavior can be mainly attributed to the supply of water from the underlying soil. In the case of 2L-BS-RS, where RS underlies BS, its high hydraulic conductivity enables it to supply more water to the BS lamina under convection compared to 2L-RS-BS. In the latter case, the underlying lamina is BS, which has lower hydraulic conductivity than RS. As discussed earlier in the paper, soil heave results from the combined effect of water migration towards the freezing front and the freezing of water to ice. In layered soil systems, water migration appears to play a major role in heaving. During thawing at these stated initial pressures, the initial rate of thawing (up to the end of May) in 2L-BS-RS is higher than 2L-BS-RS, which can be attributed to the higher hydraulic conductivity of the lower laminae RS. However, after the end of May, the rate of thawing in 2L-RS-BS is higher than 2L-BS-RS, which may be attributed to the rapid melting of frozen water in 2L-RS-BS. However, with these initial pressures, the settlement magnitudes remain higher for the 2L-BS-RS profile than the 2L-RS-BS profile. Additionally, the variation in settlement becomes almost negligible for the 2L-RS-BS soil profile after July, June, and May when the initial pressure of -5 kPa, -7.5 kPa, and -10 kPa, respectively, is considered. This indicates that the overlying soil predominantly determines the settlement behavior in the 2-layered varved system.

At an initial suction pressure of -10 kPa, both two-layered soil profiles, 2L-RS-BS and 2L-BS-RS, undergo show complex deformation under freezing and thawing (Figure 18i and 18j). Up to the end of January, 2L-RS-BS shows slightly higher heave compared to 2L-BS-RS. However, for the remaining freezing period, heave for 2L-BS-RS surpasses that of 2L-RS-BS. This difference is because, in 2L-RS-BS, there is negligible deformation in the soil profile after the first month of freezing duration. In contrast, for 2L-BS-RS, both gradual heave during the freezing period and gradual settlement during the thawing period are observed. In 2L-RS-BS, heaving becomes negligible after the end of November, meaning the heave magnitude after November end remains constant for the remaining freezing period, up to March end. A similar trend is observed for both soil profiles during the thawing period. The reason for these behaviors lies in the fact that in 2L-RS-BS, since the applied negative suction is sufficiently high, whatever water is present in RS at this suction infiltrates from upper layers to lower layers (in RS lamina). Therefore, there is not sufficient water available near the freezing front of 2L-RS-BS to freeze and contribute to heaving. On the other hand, for 2L-BS-RS, since the freezing front lies in the BS lamina, and BS has low hydraulic conductivity, there is an availability of moisture near the freezing front of 2L-BS-RS, which can participate in the heaving. During thawing, the settlement magnitude of 2L-RS-BS shows negligible change throughout the entire thawing period, whereas 2L-BS-RS shows a slightly higher rate of heaving compared to the 2L-RS-BS soil profile.

When the initial suction profile in the soil is further increased to -15 kPa and -20 kPa (Figure 18l and 18n), the heaving in 2L-RS-BS remains higher throughout the freezing period compared to the 2L-BS-RS case. This is due to the similar reason discussed for higher heave in RS than BS at higher suction magnitudes of -15 kPa and -20 kPa. Therefore, at higher suction values, the moisture content falls to significantly low values, and this water traverses downwards due to gravity. In RS and 2L-RS-BS, only a small initial heave up to November end can be observed, which remains almost constant for the remaining freezing period. For BS and 2L-BS-RS, the low permeability of BS leads to slightly higher water content near the freezing front even at higher suction magnitudes. Consequently, both BS and 2L-BS-RS still experience slight heave during the freezing period followed by changing settlements during the thawing period. From these observations also, it can be stated that the overlying soil dominantly determines the settlement behavior in the 2-layered varved system, as stated previously for other initial suctions.

Figure 18(a). Frost-heave in RS, BS and single couplets at initial pressure of 0 kPa

Figure 18(b). Thaw-settlement RS, BS and single couplets at initial pressure of 0 kPa

Figure 18(c). Frost-heave in RS, BS and single couplets at initial pressure of -2.5 kPa

Figure 18(d). Thaw-settlement in RS, BS and single couplets at initial pressure of -2.5 kPa

Figure 18(e). Frost-heave in RS, BS and single couplets at initial pressure of -5 kPa

Figure 18(f). Thaw-settlement in RS, BS and single couplets at initial pressure of -5 kPa

Figure 18(g). Frost-heave in RS, BS and single couplets at initial pressure of -7.5 kPa

Figure 18(h). Thaw-settlement in RS, BS and single couplets at initial pressure of -7.5 kPa

Figure 18(i). Frost-heave in RS, BS and single couplets at initial pressure of -10 kPa

Figure 18(j). Thaw-settlement in RS, BS and single couplets at initial pressure of -10 kPa

Figure 18(k). Frost-heave in RS, BS and single couplets at initial pressure of -15 kPa

Figure 18(l). Thaw-settlement in RS, BS and single couplets at initial pressure of -15 kPa

Figure 18(m). Frost-heave in RS, BS and single couplets at initial pressure of -20 kPa

Figure 18(n). Thaw-settlement in RS, BS and single couplets at initial pressure of -20 kPa

Figure 19 (a). Water Pressure distribution along RS profile after 91 days (At initial pressure = 0 kPa)

Figure 19 (b). Water Pressure distribution along BS profile after 91 days (At initial pressure = 0 kPa)

Figure 19 (c). Water Pressure distribution along RS profile after 91 days (At initial pressure = -5 kPa)

Figure 19 (d). Water Pressure distribution along BS profile after 91 days (At initial pressure = -5 kPa)

Figure 19 (e). Water Pressure distribution along RS profile after 120 days (At initial pressure = 0 kPa)

Figure 19 (f). Water Pressure distribution along BS profile after 120 days (At initial pressure = 0 kPa)

Figure 19 (g). Water Pressure distribution along RS profile after 120 days (At initial pressure = -7.5 kPa)

Figure 19 (h). Water Pressure distribution along BS profile after 120 days (At initial pressure = -7.5 kPa)

Figure 19 (i). Water Pressure distribution along RS profile after 151 days (At initial pressure = 0 kPa)

Figure 19 (j). Water Pressure distribution along BS profile after 151 days (At initial pressure = 0 kPa)

Figure 19 (k). Water Pressure distribution along RS profile after 151 days (At initial pressure = -10 kPa)

Figure 19 (l). Water Pressure distribution along BS profile after 151 days (At initial pressure = -10 kPa)

Figures 20(a) to 20(n) depict the frost-heave and thaw-settlement profiles of RS, BS, and reconstituted varved clay profiles with different numbers of layers (2L, 4L, 8L, and 16L). In all layered soil systems, including 2L, lamina made of RS occupies the topmost position in the soil (exposed to the atmosphere), while BS holds the bottommost position (in contact with the water table). Therefore, when comparing displacements in the soil profiles, 2L-RS-BS is simply referred to as 2L in this section. From the graphical plots of frost-heave and thaw-settlement of the layered soil profiles, it is observed that these displacement values mostly lie between the corresponding values of homogeneous profiles of RS and BS.

When the soil is fully saturated (at an initial pressure of 0 kPa) and near saturated (at an initial pressure of -2.5 kPa), all the soil profiles show heaving and settlement throughout the freezing and thawing periods, respectively (Figure 20a to 20d). At an initial pressure of -5 kPa (Figure 20f), homogeneous RS shows some initial heave during the first freezing month (November), after which the heave magnitude remains constant for the remaining two months of December and January. The heave is observed again from January end to the end of the freezing period (up to March end). This initial heave is attributed to the freezing of surface water. After this, not enough water is available in the soil profile to contribute to convection due to drainage of water from upper RS layers to bottom portions under gravity, as discussed in the previous section. However, for BS, heaving occurs for the entire freezing period due to the reasons discussed above. For the reconstituted varved couplet, these mechanisms occur due to the unique effects of both RS and BS. The displacements observed in reconstituted varved clay profiles occur at an intermediate level between the displacements observed in individual RS and BS profiles. The initial heaving stops after the first month for these reconstituted varved clays, as observed in the case of RS. However, the heaving begins again in December, unlike in the case of RS, whose heaving resumes during January. Further, when the initial pressure is further increased to -7.5 kPa, -10 kPa, -15 kPa, and -20 kPa, negligible change in the displacement (both heaving and settlement) is observed after the initial heave during November for all soil profiles, except for BS (Figure 20g to 20n).

Among the layered soil profiles, 2L consistently exhibits the minimum heave throughout the freezing duration, regardless of the considered initial pressures in the study (0 kPa, -2.5 kPa, -5 kPa, -7.5 kPa, -10 kPa, -15 kPa, and -20 kPa) (Figure 20a to 20n). Additionally, the settlement magnitude is also lower for 2L compared to all other considered reconstituted varved clay profiles at the specified suction pressures. Slightly higher heaving than 2L is observed for the 4L varve profile at initial pressures of 0 kPa, -2.5 kPa, -5 kPa, -7.5 kPa, and -10 kPa. At an initial suction pressure of -15 kPa, the heaving in all layered soil profiles (4L, 8L, and 16L) is nearly the same. For the -20 kPa initial pressure across the soil profile, 2L shows the highest heave among all the reconstituted varved clay profiles. A careful analysis reveals that at near-saturation pressures (0 kPa, -2.5 kPa, and -5 kPa), the 2L profile exhibits the highest final heave, with the 4L, 8L, and 16L profiles following in decreasing order of deformation. When the initial pressure is -7.5 kPa and -10 kPa, 2L still exhibits the lowest heave among reconstituted varved clays with the heaving curves for 8L and 16L are almost overlapping. After an increase in initial pressure to -15 kPa, 2L maintains the lowest heave among reconstituted varved profiles, while the heaving curves for 4L, 8L, and 16L almost overlap. At an initial pressure of -20 kPa, 2L continues to exhibit the minimum heave throughout the entire freezing period. However, among the 4L, 8L, and 16L varved profiles, 4L demonstrates the highest heave, followed by 8L and 16L at -20 kPa initial pressure.

In previous settlement cases of RS, BS, and 2L varved couplets, it is observed that during the thawing period (365th day, October end), the ground does not completely return to its original position, with the ultimate settlement still registering a magnitude above 0. Similar observations are made for reconstituted varved arrangements. When the rate of heaving is high, the settlement magnitude is also high at all considered initial pressures. Conversely, soils with a lower heaving rate exhibit a lower settlement rate. However, the final settlement magnitude remains higher for soils that initially show a higher heaving rate. This settlement trend aligns with the observations for the reconstituted layered soil structure. Among reconstituted varved clays, the settlement magnitude is consistently minimum for 2L across all considered initial pressures (0 kPa, -2.5 kPa, -5 kPa, -7.5 kPa, -10 kPa, -15 kPa, and -20 kPa). A slightly higher settlement magnitude than in the case of 2L is observed for 4L reconstituted varved clay at 0 kPa, -2.5 kPa, -5 kPa, -7.5 kPa, and -10 kPa, whereas at -20 kPa, the settlement magnitude for 4L becomes the highest. For settlement magnitudes in 8L and 16L, the curves are almost overlapping. Upon close observation, it is noted that the settlement magnitude is higher in 16L than in 8L for initial suctions of 0 kPa, -2.5 kPa, -5 kPa, and -7.5 kPa. At -10 kPa and -20 kPa initial pressures, the settlement magnitudes become equal, and at -20 kPa, the settlement magnitude is observed to be higher for 8L compared to 16L.

Figure 20(a). Frost-heave in RS, BS and varved soils at initial pressure of 0 kPa

Figure 20(b). Thaw-settlement in RS, BS and varved soils at initial pressure of 0 kPa

Figure 20(c). Frost-heave in RS, BS and varved soils at initial pressure of -2.5 kPa

Figure 20(d). Thaw-settlement in RS, BS and varved soils at initial pressure of -2.5 kPa

Figure 20(e). Frost-heave in RS, BS and varved soils at initial pressure of -5 kPa

Figure 20(f). Thaw-settlement in RS, BS and varved soils at initial pressure of -5 kPa

Figure 20(g). Frost-heave in RS, BS and varved soils at initial pressure of -7.5 kPa

Figure 20(h). Thaw-settlement in RS, BS and varved soils at initial pressure of -7.5 kPa

Figure 20(i). Frost-heave in RS, BS and varved soils at initial pressure of -10 kPa

Figure 20(j). Thaw-settlement in RS, BS and varved soils at initial pressure of -10 kPa

Figure 20(k). Frost-heave in RS, BS and varved soils at initial pressure of -15 kPa

Figure 20(l). Thaw-settlement in RS, BS and varved soils at initial pressure of -15 kPa

Figure 20(m). Frost-heave in RS, BS and varved soils at initial pressure of -20 kPa

Figure 20(n). Thaw-settlement in RS, BS and varved soils at initial pressure of -20 kPa

5. Conclusions

The present study conducts an in-depth analysis of freezing and thawing behavior in homogeneous and reconstituted varved clay profiles, focusing on the influence of soil type, laminae arrangement, the number of laminae, and initial suction pressures. Based on the present study, observations and inferences, the following are the key conclusions drawn:

1. The investigation covers a range of initial suction values from 0 kPa (fully saturated) to -20 kPa, revealing that the initial water content significantly influences deformation during freezing and thawing. Higher initial suction pressures result in lower frost-heaving and subsequently lower settlement magnitudes in all soil profiles.
2. The study underscores the crucial role of the temperature gradient in driving water migration within the soil profile during freezing. The resulting deformation and frost-heave are attributed to the interplay between gravity-driven water movement and convection-induced upward water flow.
3. Among homogeneous soil profiles of RS and BS, RS consistently exhibits higher frost-heave than BS at saturated and near-saturated states (initial pressures of 0 kPa and -2.5 kPa). This is attributed to higher permeability, high thermal conductivity, and lower unfrozen water content of RS which contributes to greater water flow, faster temperature transfer, and more substantial ice formation. At initial pressures of -5 kPa, -7.5 kPa, and -10 kPa, despite both RS and BS experiencing freezing temperatures, BS retains a comparatively higher amount of water near its freezing front due to its low permeability. This results in higher heave in BS compared to RS. At initial suction pressures of -15 kPa and -20 kPa, RS displays an initial heave during the first month, persisting at a nearly

constant rate throughout the remaining freezing period, while the high initial suction in BS impedes the heaving rate, resulting in consistently lower ultimate heave magnitudes.

4. The frost-heave in reconstituted varved clay profiles at different suction pressures is influenced by the hydraulic and temperature characteristics of both RS and BS. The number of laminae in varved structures (2L, 4L, 8L, 16L) affects frost-heave and thaw-settlement, with the 2L varve consistently exhibiting the minimum heave. As the number of layers increase, the deformation generally follows the order 2L < 4L < 8L≈16L.
5. Settlement magnitudes during the thawing period are influenced by the initial heaving rate, with higher initial heave resulting in greater final settlement magnitudes. The settlement trend suggests that soils with higher initial heave rates experience more significant final settlement magnitudes.

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Compliance with Ethical Standards

Conflict of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical Approval: This article does not contain any studies with human participants or animals performed by any of the authors.

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