International Journal of GEOMATE, June, 2020, Vol.18, Issue 70, pp. 106 - 115
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2020.70.9439
Geotechnique, Construction Materials and Environment

THE INFLUENCE OF TEMPERATURE AND WATER CONTENT ON THE BEHAVIOR OF SOILS

Xingyi Wu[1], Junping Ren[1] and Sai K. Vanapalli[1]

[1]Department of Civil Engineering, University of Ottawa, Ottawa, Ontario, Canada

*Corresponding Author; Received: 21 Sept. 2019, Revised: 20 Nov. 2019, Accepted: 27 Dec. 2019

ABSTRACT: The most widely used construction material for various civil infrastructures is the naturally available, compacted or modified soils. The behavior of these soils is significantly influenced by environmental factors such as the precipitation, evaporation and variations associated with the natural ground water table. The stability and deformation behavior are two key criteria that govern the design of these infrastructures. Soil is a complex material with different phases in unfrozen and frozen conditions. The water content within the unfrozen and frozen soils is influenced by a wide range of negative and positive temperatures. The soil can be in a frozen or thawed, saturated or unsaturated condition or combinations of them due to the variations in temperature and water content. In other words, the hydro-mechanical behavior of soils is significantly influenced by freezing/thawing and wetting/drying processes. In this paper, the influence of variation of temperature and water content on the soil behavior is explained using the soil-water characteristic curve (SWCC) and soil-freezing characteristic curve (SFCC). The SWCC and SFCC are respectively used as tools in the prediction and interpretation of the behavior of unfrozen unsaturated soils and frozen soils. The focus of this paper is directed to understand the influence of wetting/drying, freezing, and freeze-thaw cycles on soil properties such as void ratio, hydraulic conductivity, shear strength, microstructure change and swelling behavior of expansive soils. Finally, the influence of temperature and moisture on the design of pile foundations in expansive soils is succinctly highlighted.

Keywords: Soil, Water content, Temperature, Wetting-Drying, Freezing-Thawing

1. INTRODUCTION

The most widely used material in the construction of various engineered infrastructure is the soil, in its natural, compacted or modified form. For example, soils are compacted to form dams, canals, roads and railway subgrades, and waste containment structures such as soil covers and liners. The infrastructure constructed is typically in a state of the unsaturated condition during their service life. The variation of water content within the soil has a significant influence on the performance of these infrastructures.

The pore water in unfrozen unsaturated soils typically has a lower free energy in comparison to free water due to the interactions between soil particles, pore water and pore air. The soil-water characteristic curve (SWCC) defines the relationship between the free energy of pore water (or soil suction) and its amount in the unsaturated soil. The quantity of pore water can be represented by either gravimetric or volumetric water content or degree of saturation. The SWCC is a conceptual and interpretative tool for understanding the behavior of unsaturated soils [1]. For example, the SWCC has been used for predicting the hydraulic and mechanical properties of unsaturated soils, such as the hydraulic conductivity [2], shear strength [3], and modulus of elasticity [4].

The environmental impacts on soil behavior would be incomplete if only the influence of the variation of water content is considered. This is because phase changes of pore water (from liquid to solid or vice versa), which is the result of freezing and thawing of soils, has a significant impact on various soil properties are not considered. In the permafrost and seasonally frozen regions, frost penetration generally results in the freezing of the top layer of the soil which is close to natural ground level. For example, the frost penetration in northern Ontario, Canada can be deeper than 3 m; however, it is typically around 1 to 2 m in southern Ontario [5]. Frost penetration depths in many cold regions of the world typically extend from 1 to 3 m.

The unfrozen water and pore ice typically coexist within a frozen soil. The relationship between unfrozen water content and the subzero temperature is defined as the soil-freezing characteristic curve (SFCC). Several researchers during the past five decades have investigated the similarity between SWCC and SFCC behavior [6], [7]. This background has provided a foundation for using SFCC as a tool in cold regions engineering applications extending the mechanics of unsaturated soils, which is highlighted and succinctly discussed in later sections of this paper.

There is an urgent need for both the researchers and practicing engineers to better understand the influence of climate change and global warming effects on the engineering properties of unfrozen and frozen soils. Lu et al. [8] estimated the possible variation of water contents within the soils of various regions of the world for the 21st century. Their study suggests significant widespread drying effects in most regions (e.g., Australia, America, Europe, and East Asia), while significant wetting is expected in regions of East Africa, and central and south Asia. They also suggested that drying is related to precipitation reduction and temperature increase. In addition, soils in humid regions may undergo several wetting/drying (W-D) cycles due to high intensity rainfalls followed with periods of high temperature that contribute to significant evaporation. In addition, global warming effects are expected to contribute to widespread temperature variations in cold regions resulting in freeze-thaw (F-T) cycles. The focus of this paper is directed to understand the influence of freezing, F-T, and W-D cycles on soil properties which include void ratio, hydraulic conductivity, shear strength, microstructure change, and swelling behavior of expansive soils. Finally, the influence of variation of temperature and water content on the design of pile foundations in expansive soils is succinctly highlighted.

2. EFFECT OF FREEZING ON VARIOUS SOIL PROPERTIES

2.1 Hydraulic Conductivity

The hydraulic conductivity of frozen soils near zero temperature is a key property required in water balance calculation in cold regions and is useful information in both engineering applications and agricultural management. It is also an important property in artificial ground freezing techniques. Ice crystals form in the pore spaces of the soil when it is subjected to freezing and block the pathways for water flow. As a result, the hydraulic conductivity of frozen soils is much lower in comparison to unfrozen soils. If the soil temperature falls further below subzero values, more ice will form in the soil pores. Due to this reason, the available unfrozen water films that facilitate free flow of water will substantially decrease. Therefore, hydraulic conductivity decreases further with a decrease in subzero temperature (or unfrozen water content). Fig. 1 summarizes the hydraulic conductivity behavior for various frozen soils.

The hydraulic conductivity of frozen soils is strongly dependent on the soil type. This is because the unfrozen water content, pore size distribution, void ratio, particle size, and surface area are dependent on the type of soil. For example, most water available in sand freezes close to 0 °C. The amount of water in unfrozen sand below 0 °C is small; due to this reason the hydraulic conductivity of sand below 0 °C is significantly lower. On the other hand, an unfrozen clay has a low hydraulic conductivity. However, at temperatures below 0 °C, the hydraulic conductivity of clay is still relatively higher in comparison to its unfrozen value since the clay contains unfrozen water that has continuous paths available for flow of water [9]. These observations can be derived from the experimental results summarized in Fig. 1.

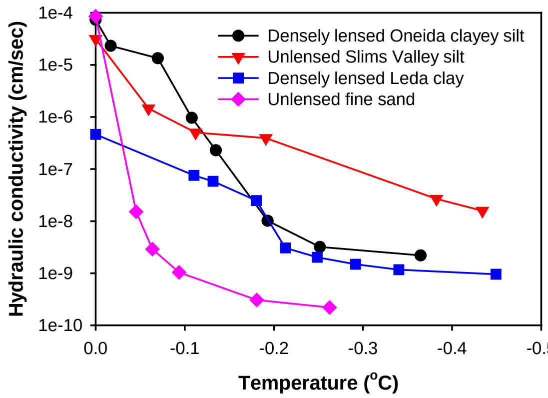

Fig. 1 Hydraulic conductivity of frozen soils [9].

There are limited experimental studies in the literature that focus on the measurement of hydraulic conductivity of frozen soils. This may be attributed to difficulties associated with conducting and obtaining reliable experimental results. For this reason, hydraulic conductivity of frozen soils is estimated using relatively simple yet reliable models. The SFCC can be used as a tool for estimating the relationship between frozen hydraulic conductivity and subzero temperature. For example, Azmatch et al. [10] proposed a permeability function for partially frozen silt using the saturated hydraulic conductivity and SFCC following two steps; which include; (i) the SFCC data points determined from laboratory tests are fitted with the Fredlund and Xing [2] SWCC equation; and, (ii) the fitted curve is then used together with saturated hydraulic conductivity to estimate the hydraulic conductivity function for partially frozen silt by employing the Fredlund et al. [11] equation.

2.2 Resilient Modulus

The resilient modulus (M_R) has been widely used as a key parameter for rational characterization of the resilient behavior of unbound base/subbase and subgrade soils subjected to traffic loading. These unbound soils are porous media and contain a certain amount of water in their pore spaces. The phase change of pore water has a significant impact on the M_R of these soils. When pore water freezes, ice binds adjacent soil particles together, resulting in a dramatic increase in M_R. For example, Bigl and Berg [12] highlight the M_R of subbase and subgrade soils can increase approximately two orders of magnitude for frozen soils. Bosscher and Nelson [13] report a 20-

fold increase in modulus for certain type of frozen sands. Similar increases in moduli for frozen granular base soils were also observed by Cole et al. [14]. The pavement structure has relatively high stiffness and bearing capacity during the freezing process and at frozen state; due to this reason, overloading of the pavement structure is allowable in frozen soils without damages.

The SFCC is used as a tool for estimating the M_R of frozen soils. Ren and Vanapalli [15] proposed a semi-empirical model for predicting $M_{R(\text{frozen})}$ for saturated soils. The model exploits the similarity between SWCC and SFCC and uses cryogenic suction (ψ_{cryo}) and degree of unfrozen water saturation (S_u, which is the ratio of the volume of unfrozen water to the total water volume) for prediction. It is assumed that the rate at which ψ_{cryo} contributes towards frozen M_R can be related to S_u. The value of S_u varies from unity to a small value at large ψ_{cryo}. The semi-empirical model is expressed as:

$$M_{RSAT(\text{frozen})} = M_{RSAT(0℃)}\left(1+\chi\psi_{cryo}S_u^{\ \delta}\right) \tag{1}$$

where $M_{RSAT(0\ °C)}$ is the saturated M_R at 0 °C (MPa); χ and δ are fitting model parameters.

The above model works well for different types of saturated soils (e.g., see Fig. 2) and has a theoretical basis. However, the model is only applicable for saturated soils.

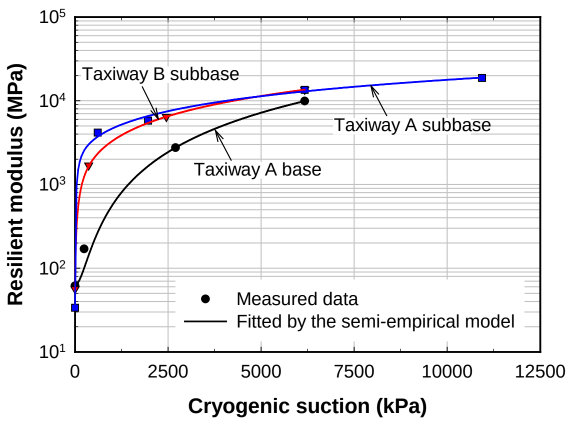

Fig. 2 Prediction of M_R of frozen saturated soils using the SFCC [15].

3. EFFECT OF F-T CYCLES ON VARIOUS SOIL PROPERTIES

The effect of F-T cycles can be compared to the natural weathering process that has a significant influence on the behavior of various infrastructures that include the pavements, railroads, pipelines, and building constructions. The F-T cycles considerably change the soil void ratio (density) and hydro-mechanical properties of soils; namely, hydraulic conductivity, shear strength, and stiffness.

3.1 Void Ratio (Density)

Previous studies show that F-T cycles have a dual influence on soil density, i.e. loose soils tend to densify and dense soils become looser after F-T cycles [16]. Viklander [17] proposed a new term residual void ratio to explain this behavior associated with F-T cycles. The void ratios of different specimens show significant change after one F-T cycle; however, there is little or no change in void ratio for later F-T cycles. The initially loose soil experiences volume increase during freezing (due to ice-lensing) and decrease during thawing (due to the consolidation of soil matrix). The soil density will increase as soil particles are getting closer during this process. On the other hand, the void ratio of an initially dense soil increases due to F-T, since particles of the soil cannot fall back to the same position after thawing, resulting in a net volume increase. Therefore, the soil structure is slightly looser in comparison to soil prior to soil freezing. The void ratios of the specimens reach a residual value after a certain number of F-T cycles, as shown in Fig. 3.

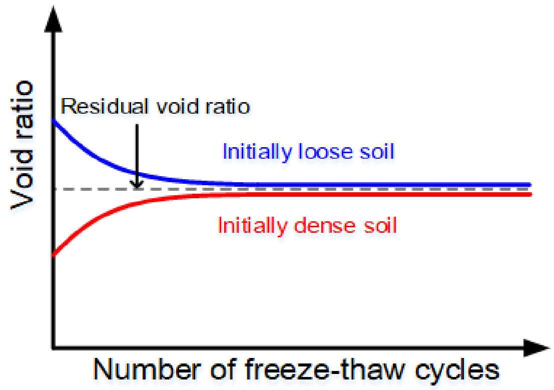

Fig. 3 Effect of F-T cycles on void ratio.

3.2 Hydraulic Conductivity

The F-T cycles typically weaken soil structure and contribute to more cracks and fissures. This leads to higher hydraulic conductivity after the soil is subjected to several F-T cycles. Fig. 4 highlights the effect of one- and three-dimensional F-T cycles on the hydraulic conductivity of three Wisconsin soils. The hydraulic conductivity test indicated that there was an increase in vertical hydraulic conductivity of different types of fine-grained soils [18]. The increase in the hydraulic conductivity was attributed to the formation of polygonal shrinkage cracks and/or the reduction in the fine content in the pores of coarse fraction. The cracks and other structural changes can be observed using the scanning electron microscope (SEM). At low magnification, distinct cracks spaced at 0.5 mm were observed. However, at higher magnifications, voids of 0.005 mm were observed within the aggregates formed during the freezing process [19]. These results suggest F-T cycles can cause changes in both the macro- and micro-structure of fine-grained soils.

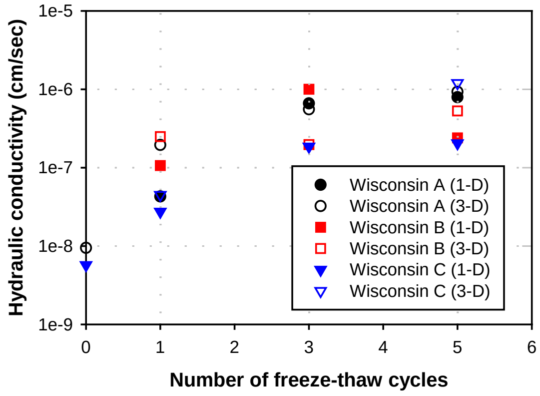

Fig. 4 Effect of F-T cycles on hydraulic conductivity [20].

3.3 Shear Strength

The soil particles are forced to separate from each other when water within the soil pore changes its phase to ice. This characteristic contributes to an increase in pore volume which results in swelling of frozen soils. The soil particles have a tendency to re-position to their original locations when the pore ice melts. However, this is not possible in dense soils. As a result, the original soil structure is typically weakened. In other words, the mechanical properties of soils are significantly influenced by F-T cycles.

From their studies, Formanek et al. [21] highlighted the reduction of more than half of its original shear strength after the first F-T cycle for a silt loam. The second and third cycles contributed to a further loss, however, reduction of shear strength was not as significant as in the first cycle. Aoyama et al. [22] found the reduction in soil cohesion increased with a decrease in temperature, whereas little change was observed in friction angle after F-T cycles. Lerouil et al. [23] conducted shear strength tests on nine Champlain Sea clays after one F-T cycle. Results showed that freezing typically led to a drastic decrease in the undrained shear strength, and the frozen-thawed specimens presented a dilatant behavior similar to granular soils. Graham and Au [24] found that the F-T cycles produced increased compressibility and pore water pressure, and reduced strength at low stresses compared with the behavior of undisturbed Winnipeg clay. Kamei et al. [25] found that the unconfined compressive strength and durability decreased with an increase in the number of F-T cycles. The greatest reductions in both strength and durability were observed during the second F-T cycle; however, later F-T cycles only had a limited influence.

Wang et al. [26] investigated the mechanical properties of Qinghai-Tibet clay subjected to a maximum of 21 closed-system F-T cycles. The experimental results suggest a strong relationship between the failure shear strength and the number of F-T cycles. Figure 5 shows variations in cohesion and friction angle of the soil with respect to F-T cycles. These results suggest that the cohesion decreases dramatically with an increase in the number of F-T cycles, from 0.55 MPa to about 0.25 MPa after 15 cycles. On the other hand, the friction angle shows a dramatic increase. Similar trends of results were also reported by Ogata et al. [27].

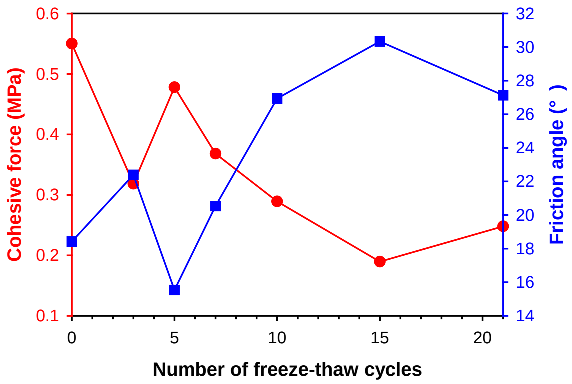

Fig. 5 Effect of F-T cycles on shear strength [27].

3.4 Resilient Modulus

The resilient response of compacted soils under cyclic loading is significantly influenced by soil structure. The M_R of soil typically decreases as F-T cycles weaken the soil structure. Culley [28] investigated the resilient strains and M_R of till specimens subjected to F-T cycles in a one-dimensional closed-system. The specimens were compacted to various densities and water contents. At water contents lower than the optimum water content, the decrease in M_R resulting from F-T cycles decreased as density increased. However, at water contents of optimum and higher, the detrimental F-T effect increased with an increase in the density. The water content at which the maximum F-T effect occurred increased as density increased, ranging from 1.5% less than optimum at 93% density to 1.5% greater than optimum at 100% density. These trends were also consistent for resilient strain.

Lee et al. [29] concluded from the M_R tests performed on five cohesive soils samples collected from in-service subgrades that the stress at 1% strain in the unconfined compression test ($S_{u1.0\%}$) was a good indicator of M_R, and proposed an empirical relationship between M_R and $S_{u1.0\%}$. The proposed relationship is applicable to both as-compacted and in-service subgrade soils. There was a negligible effect of F-T on M_R, when there was no ice lens formation, for soils having values of $S_{u1.0\%}$ less than approximately 55 kPa. The effect of F-T increased as the value of $S_{u1.0\%}$ increased. It was observed that a single cycle of F-T caused a 30 to 50% reduction in M_R. The M_R of various coarse- and fine-grained subgrade soils subjected to F-T cycles were presented by Simonsen et al. [30], the results indicated that all the soils exhibited a substantial reduction in M_R (approximately 20 to 60% depending on soil type) after F-T cycles.

Wang et al. [26] studies suggest decreases of 18 to 27% for unfrozen soil M_R depending on confining pressure. The greatest changes in M_R in all the four soils studied with various confining pressures (i.e., 200, 400, 600, and 800 kPa) were obtained after the first F-T cycle (as shown in Fig. 6), suggesting significant disturbance during the first F-T cycle.

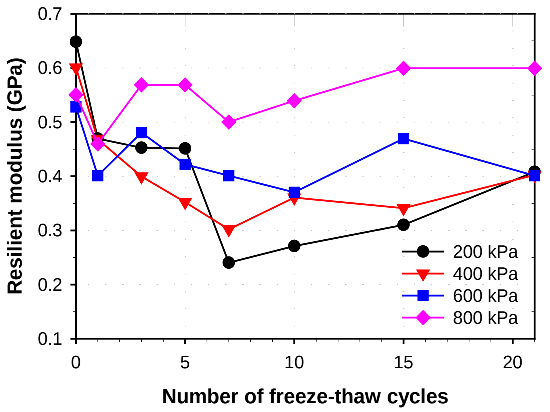

Fig. 6 Effect of F-T cycles on resilient modulus [26].

4. EFFECTS OF TEMPERATURE AND WATER CONTENT VARIATIONS ON THE BEHAVIOR OF EXPANSIVE SOILS

4.1 Structure of Expansive Soils

The structure of expansive soil has a significant influence on its mechanical behavior. Tang et al. [31] studied pore size distribution (PSD) of an expansive soil from mercury intrusion porosimetry (MIP) tests. The results of this study summarized in Fig. 7 shows two peaks of pores suggesting it is bimodal in nature. The two peaks are around 30 μm and 7 nm, respectively. These two sizes of pores can be considered as macropores and micropores, respectively. Studies on different types of expansive soils showed similar results [32]–[34]. The soil structure with micro and macropores is typically referred to as the double structure in the literature.

The double structure can typically be attributed to the aggregation of elementary soil particles. For fine-grained soils, several factors including the water content and interparticle forces can facilitate particle aggregation. The soil particles get closer to each other during the drying stage due to an increase in suction associated with a decrease in water content. The positive ions of water (i.e., hydrogen ions) can be attracted to the negatively charged soil particle's surface when the distance between adjacent soil particles is relatively small. In addition, the interparticle forces (e.g., van der Waals attraction and electrical double repulsion) contribute to the formation of aggregates. During the drying process, the water content decreases and the air content increases, resulting in an increase in the van der Waals attraction and reduction of the electrical double repulsion. This results in the aggregation of clay particles [35]. On the contrary, during the wetting process, soil suction and van der Waals attraction between soil particles will decrease, and the electrical double layer repulsion will increase. In other words, the wetting process will destroy soil aggregates.

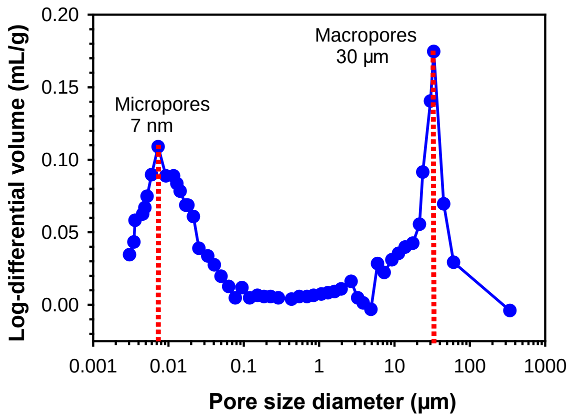

Fig. 7 Pore size distribution of an expansive soil [31].

As shown in Fig. 8, the micropores are defined as pores in aggregates or intra-aggregates pores. The pores between aggregates (inter-aggregates) are the macropores. The double structure concept has been widely accepted to describe the behavior of expansive soils [36]–[38]. The micropores and macropores sizes are not unique values. Many factors including the soil type and the specimen preparation method may contribute to the different pore sizes.

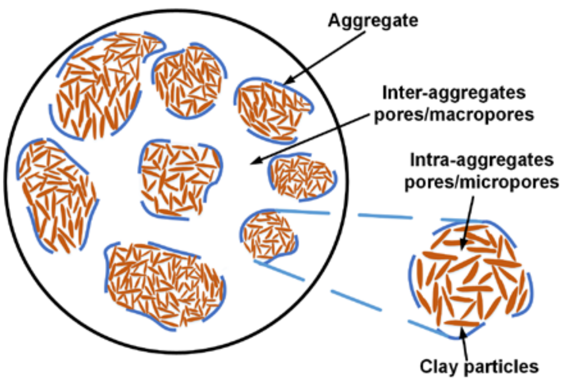

Fig. 8 The structure of aggregated soil [39].

4.2 Volume Change Behavior of Expansive Soil

4.2.1 Effect of high temperature

The effects of high temperature (from 20 to several hundred °C) on the deformation behavior of expansive soils have been studied by several researchers [40]–[42]. These studies suggest the influence of temperature on volume change behavior of expansive soils is affected by confining pressure and suction.

Romero et al. [40] used Boom clay to study the volume change behavior by subjecting it to different stresses and temperature paths. The non-isotropic tests at constant suction and confining pressure were performed. The volume change of soil specimens under different thermal cycles is shown in Fig. 9. It can be seen that significant dilation occurs when temperature increases from 20 °C to 80 °C under both the values of suction investigated. However, when the temperature decreases from 80 °C to 20 °C, shrinkage was observed in the two specimens for both the suction values. It is of interest to note that the shrinkage is less in comparison to dilation.

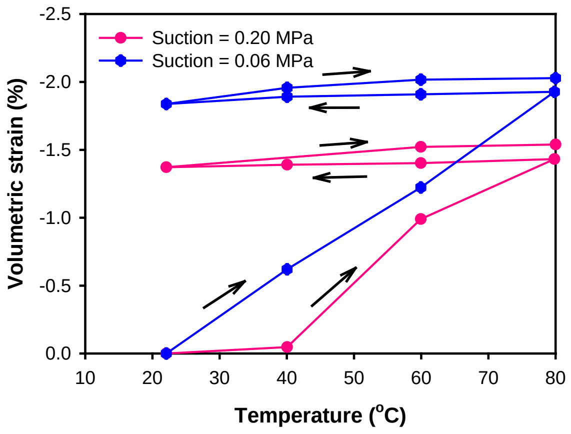

Fig. 9 Volumetric strain due to thermal cycling [40].

Variation in temperature can contribute to significant changes in the soil structure. The clay minerals in the expansive soil typically expand and the adsorbed water could also enhance due to an increase in the temperature [43]. Romero attributed the irreversible strain to the possible rearrangements of particles at the macrostructural scale [40]. However, Tang et al. [42] found the effect of temperature depends on the stress state in the soil (e.g., confining stress and suction). The dilation phenomenon occurs under high suction and low confining pressure, and the associated volumetric strains are reversible. On the other hand, under low suction and high confining pressure condition, the test specimen contracts due to the influence of thermal cycles. The volumetric strain associated with this phenomenon is also irreversible.

Saturated soils with a low overconsolidation ratio typically contract when they are subjected to heating. However, saturated soils with a high overconsolidation ratio will expand due to heating [43]. This effect is similar to that of the confining pressure on a typical unsaturated expansive soil. Tang et al. [42] suggested that soil aggregates weaken when soil is tested at low suction value; such a behavior may be attributed to an increase in water content.

An increase in temperature can result in expansion when the confining pressure is low and the suction is high. On the contrary, a typical unsaturated expansive soil can be compressed under high confining pressure at low suction values.

4.2.2 Effect of wetting-drying (W-D) cycling

The volume change behavior of expansive soils resulting from W-D cycles is influenced by the number of W-D cycles, and W-D cycling pattern [44].

Tripathy and Subba Rao [44] conducted different swelling-shrinkage tests on a highly plastic expansive soil by controlling the height of specimens. Specimens were allowed to fully swell to the saturation and allowed to shrink to initial height or partially shrink to several predetermined heights that were larger than the initial heights of specimens in each cycle. The height of specimens after equilibrium condition was allowed to change from a smaller to a larger value (less shrinkage) or from a larger to a smaller value (greater shrinkage). From these studies, they found that if the greater shrinkage was applied to a soil specimen, a new swelling potential would establish, which means more swelling strains occurred along the first swelling path after the change. The swelling strains along the first swelling path were irreversible. The irreversible strains were reduced with an increase in the number of swell-shrink cycles. Only reversible strains occurred after five cycles. However, if the less shrinkage applied to the specimens, only reversible strain would immediately occur, without any irreversible strains.

The differences in the behavior of expansive soils can be attributed to changes in microstructure associated with the W-D cycles. Water was progressively absorbed by the soil aggregates during the wetting process. The aggregates expanded due to an increase in water content, which closed the macropores. Therefore, during the wetting process, the volume of macropores decreased. However, volume of micropores did not change significantly. Therefore, during the hydration, the soil structure tends to be homogenous [32], [45].

The soil structure change that occurs due to hydration during W-D cycles may be considered as permanent. Therefore, the volumetric strain was reversible or elastic at each of the W-D cycles after equilibrium [46]. Seiphoori et al. [46] used MIP to test the microstructure of an expansive soil at several different stages of W-D cycles. The results summarized in Fig. 10 suggest that during wetting, volume of the macropores decrease rapidly. However, micropores were not affected by the hydration. The micropores in the soil were increased when it was close to the saturation condition. In the subsequent W-D cycles, three curves, C, D, and E were close to each other, which means the soil structure of the test specimen did not change significantly. In other words, the structure of the expansive soil was homogenous during W-D cycles. Only reversible volumetric strain that occurred after W-D cycles can be attributed to the homogenous nature of the soil structure.

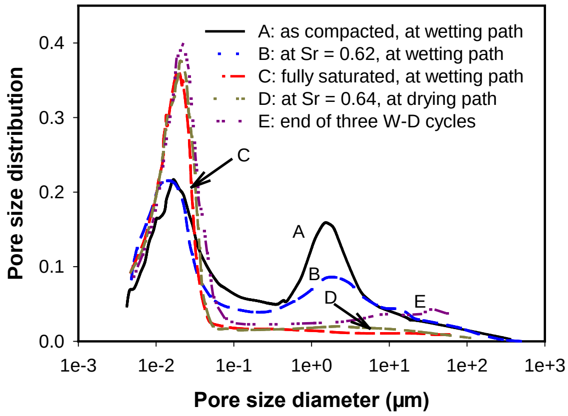

Fig. 10 Evolution of microstructure due to W-D cycles [46].

4.3 Shear Strength of Expansive Soil

4.3.1 Effect of high temperature

The effect of high temperature on the shear strength of expansive soil is predominantly dependent on the degree of saturation and dry density [47], [48].

Wiebe et al. [48] conducted undrained triaxial shear strength tests on sand-bentonite mixtures with different degrees of saturation (i.e. 50%, 65%, 80%, and 98%) and under different temperatures (i.e. 26°C, 65°C, and 100°C). Experimental results of this study are summarized in Fig. 11. The shear strength reduced with an increase in temperature when the soil was in a state of unsaturated condition. The effect of temperature on the shear strength can be considered negligible when the soil is close to saturated condition.

Gu et al. [47] used micropenetrometer that was equipped with a series of penetration probes of different diameters ranging from 0.3mm to 1.0mm to test the resistance of a high liquid-limit clayey soil. The resistance can be used as an indicator of the structural strength of the soil. The penetration resistance reduced with an increase in the temperature for soils with a high dry density. The difference in resistance was negligible due to temperature variation for low dry density soils. Therefore, it can be concluded that the structural strength of dense soil decreases due to an increase in the temperature; however, temperature has no influence on loose soils.

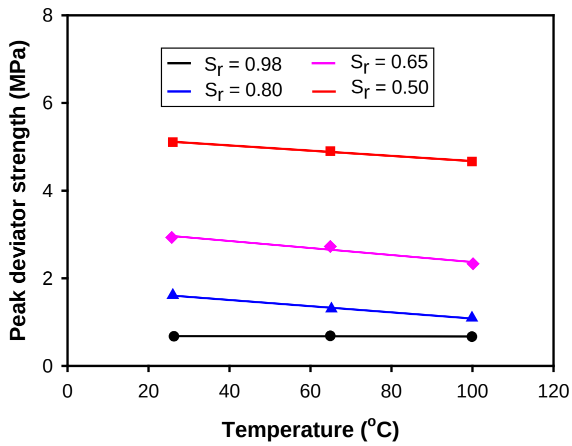

Fig. 11 Strength reduction due to temperature [48].

The soil strength originates from the strength of soil aggregates and forces between soil aggregates. Gu et al. [47] pointed out that soil aggregates will soften as a result of expansion and increase the intra-aggregate pore water pressure due to heating. This translates into a reduction in the shear strength of the soil which can be attributed to the reduction in soil suction due to an increase in the temperature.

Wiebe et al. [48] suggest that soil pores and aggregates are small when the degree of saturation is relatively low; for this reason, suction in intra-aggregate pores will be high. The high suction is sensitive to changes in temperature, which means it can be reduced more than the low suction as the temperature increase. Therefore, a more evident relative reduction in shear strength of the soil can occur at low degrees of saturation.

For dense soils, interparticle forces are significant due to the closer distance between soil particles. The effects of temperature on the interparticle forces will be more evident in dense soils in comparison to loose soils. Therefore, the shear strength of soil specimens at high dry density decreases significantly with an increase in temperature. However, the shear strength of soil specimens at low dry density is not significantly influenced by temperature [47].

4.3.2 Effect of W-D cycles

Yang et al. [49] found that the shear strength of expansive soils reduces due to the influence of W-D cycles. Zeng et al. [50] showed that soil cohesion decreases due to W-D, while the friction angle is relatively constant. They concluded that soil particles aggregate during the W-D cycles; due to this reason, the bonding between soil particles reduces and the shear strength decreases.

Goh et al. [51] measured the shear strength of sand-kaolinite mixtures at several different stages of W-D cycles. Some of the key results are summarized in Fig. 12. The peak soil strength after the first drying cycle is much higher in comparison to that after the first wetting. Although shear strength of soil during the drying stage for subsequent cycles that follow is higher than that during the wetting stage, the differences are not as significant as in the first cycle. The drying strengths of the second and third cycles are lower than that of the first cycle. On the other hand, wetting shear strengths for the second and third cycles are higher than that of the first cycle. Tse and Ng [52] reported similar trends of results from their studies.

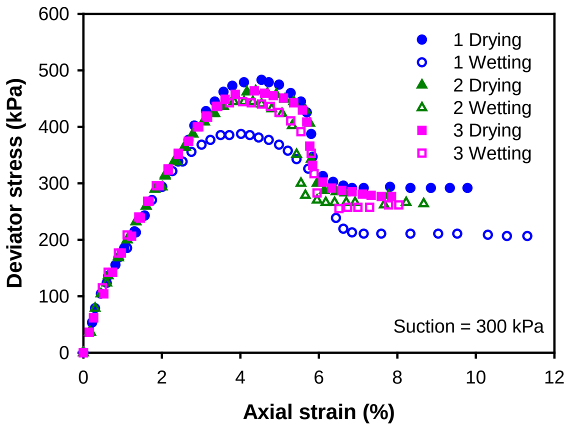

Fig. 12 Stress-strain relations during three W-D cycles [51].

Such a behavior may be attributed to hysteresis effects of the SWCC. The water content during the wetting stage is lower than that at the drying stage at the same suction. In other words, the area of water menisci that are in contact with soil particles or aggregates at the wetting stage is less than that at the drying stage. Therefore, the contribution of suction to soil strength during the wetting stage is lower in comparison to the drying path.

The boundary drying and wetting SWCCs were obtained respectively by draining the initially saturated specimen to a totally dry condition and the initially dry specimen was then wetted to saturation condition. The scanning curves lie between the boundary drying and wetting curves. The curves were obtained by wetting or drying at different initial values of suction. At a known value of suction, soil water content on the scanning curves is higher and lower than that on the boundary wetting and drying curve, respectively [53]. The soil specimen followed the boundary curves under the first W-D cycle, while the scanning curves were below the subsequent W-D cycles. As discussed earlier, more water menisci (or larger suction) contribute to an increase in soil shear strength. Therefore, strength during the subsequent W-D cycles was higher than that at the wetting path of the first cycle but lower than that at the drying path of the first cycle.

However, some other researchers suggest shear strength of soil increases with W-D cycles [54], [55]. Liu and Sun [55] studied the influence of W-D cycles on the loading and unloading behavior of a silty clay. It is found that the cyclic shear strength of the specimens subjected to W-D cycles is higher than that of the specimens at the initial state. Khoury and Miller [54] observed that the strength of the specimens that were subjected to W-D cycles is greater than that of specimens only subjected to drying at the same net normal stress and matric suction. Liu and Sun [55] suggested that the irreversible compaction due to W-D cycles increases as the interparticle forces contribute to higher shear strength. They also suggest that the shear strength may reduce due to an increase in water content; however, the influence of irreversible compaction outweighs effects of water content. Therefore, the shear strength was reinforced by W-D cycles.

In summary, there is no consensus about the influence of W-D cycles on the soil shear strength behavior. Further studies are necessary for a better understanding of the influence of W-D cycles on the microstructure and shear strength of expansive soils.

5. DESIGN OF PILE FOUNDATIONS IN EXPANSIVE SOILS CONSIDERING TEMPERATURE AND MOISTURE CHANGES

Energy piles are being used in several engineering applications in recent years. These piles use the thermal properties of the ground soils to exchange heat or cold energy between the ground soils and the superstructure. There is evidence from experimental studies that there will be thermal expansion or contraction of energy piles and surrounding soils due to the changes in temperature. This volume change can result in relative deformation along the soil-pile interface, which contributes to modifying the stress between piles and the surrounding soils. When soil expands due to an increase in temperature, positive friction typically occurs along the surface of the piles, resulting in the uplift of the pile foundations and damage the superstructure. These practical problems should be properly addressed when designing energy pile foundations [56].

Expansive soils expand with an increase in water content and contribute to an increase in the external lateral earth pressure, positive friction and pile uplift. Liu and Vanapalli [57], [58] proposed a simple constitutive framework for rational design piles in expansive soils taking account of the variation of water content induced by infiltration. However, to date, the change in the behavior of soil and soil-pile interface due to W-D cycles has not been considered in the design of pile foundations in expansive soils extending unsaturated soil mechanics framework. The hysteresis of SWCC should also be considered to analyze the shear strength of soil and soil-pile interface. Although the hysteresis of SWCC has been considered in interpreting the strength of expansive soils [51], the strength of soil-pile interface considering different stages of SWCC has not been studied. Reliable behavior of pile foundations in expansive soils is possible by taking account of the influence of W-D history considering the hysteresis effects of SWCC.

6. SUMMARY

Infrastructures constructed in soils or with soils are exposed to the influence of various environmental factors such as precipitation, evaporation, and temperature change. Due to this reason, freezing/thawing (F-T) and wetting/drying (W-D) cycles are likely to affect the various engineering properties of the soils, which include the hydraulic conductivity, volume change and the shear strength. It is anticipated that there will be more frequent F-T and W-D cycles due to climate change and global warming effects in the near future on our planet. In this paper, the influences of temperature and water content variations on the soil behavior are succinctly reviewed. It is necessary to consider these influences for the rational design of infrastructures such as the pile foundations. In addition, constitutive models that take into account climate change and global warming effects should be proposed to facilitate reliable analysis of the behavior of soils and the geotechnical infrastructures.

The freezing process, W-D, and F-T cycles significantly influence the frozen and unfrozen soil properties. For example, frozen soils have low hydraulic conductivity, and high strength and stiffness, due to the formation of ice in soil pore spaces. The F-T cycles typically weaken soil structure and contribute to the formation of cracks and fissures within the soil mass. As a result, frozen-thawed soils typically have higher hydraulic conductivity and lower stiffness and bearing capacity. The temperature and W-D cycling have a significant influence on the behavior of expansive soils (e.g., swelling and shrinkage characteristics), and therefore on the design of pile foundations in expansive soils.

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