Influence of Freeze-Thaw Cycles on Triaxial Shear Strength of Saline Intact Loess

Jian Xu[1,2,3], Yanfeng Li[1], Sai K. Vanapalli[3]
[1]School of Civil Engineering, Xi'an University of Architecture and Technology, Xi'an, Shaanxi, 710055, China
[2]Shaanxi Key Laboratory of Geotechnical and Underground Space Engineering, Xi'an University of Architecture and Technology, Xi'an, Shaanxi, 710055, China
[3]Department of Civil Engineering, University of Ottawa, Ottawa, ON, K1N 6N5, Canada

ABSTRACT
In cold regions, saline loess earthen structures are prone to failures when subjected to cyclic freeze-thaw conditions. This occurs mainly due to the deterioration in soil structure and the reduction in mechanical soil properties arising from salt migration and crystallization. In this paper, an experimental study is carried out to investigate the influence of freeze-thaw cycles and varying salt content on the stress-strain behavior of saline loess. Test specimens prepared from undisturbed loess samples were artificially treated with different amounts of sodium sulfate. The strain-controlled unconsolidated undrained triaxial shear tests were conducted on the prepared test specimens to investigate the mechanical behavior. All specimens exhibited an elastic-plastic strain-hardening response, regardless of the number of freeze-thaw cycles and salt contents. Moreover, the deviatoric stress at failure was found to decrease due to cyclic freeze-thaw and increased salt content. This behavior may be attributed to salt erosion associated with an increase in the salt content. After several freeze-thaw cycles, the rate of reduction in deviatoric stress exhibited a decline. One of the shear strength parameters, cohesion was found to decrease significantly. Whereas, the other shear strength parameter, internal friction angle was hardly influenced. The normalized deterioration factor (ratio of freeze-thaw to salt content induced deterioration) increased nonlinearly with freeze-thaw cycles, which stabilized after several cycles. The normalized deterioration factor decreased with an increase in the salt content; in addition, its attenuation rate also declined. geovirtual2020.ca.

RÉSUMÉ
Dans les régions froides, les structures en terre saline de loess sont sujettes à des défaillances lorsqu'elles sont soumises à un gel-dégel cyclique. Cela se produit principalement en raison de la détérioration de la structure du sol et de la réduction des propriétés mécaniques du sol résultant de la migration et de la cristallisation du sel. Dans cet article, une étude expérimentale est menée pour étudier l'influence du gel-dégel et de la teneur en sel sur le comportement contrainte-déformation du loess salin. Des échantillons d'essai ont été préparés à partir d'échantillons de loess non perturbés et traités artificiellement avec différentes quantités de sulfate de sodium. Les essais de cisaillement triaxial non consolidé non drainé contrôlés par déformation ont ensuite été réalisés. Tous les échantillons ont présenté une réponse de durcissement élastique-plastique, quel que soit le nombre de cycles de gel-dégel et la teneur en sel. De plus, on a constaté que la contrainte déviatorique à la rupture diminuait en raison du gel-dégel cyclique et de l'augmentation de la teneur en sel. Cela peut être attribué à l'érosion saline associée à une augmentation de la teneur en sel. Après plusieurs cycles de gel-dégel, le taux de réduction du stress déviatorique a diminué. En termes de paramètres de résistance au cisaillement, la cohésion a diminué de manière significative. Alors que l'angle de frottement interne n'était guère influencé. Le facteur de détérioration normalisé (rapport entre le gel-dégel et la détérioration induite par la teneur en sel) a augmenté de façon non linéaire avec la congélation et la décongélation et s'est stabilisé après plusieurs cycles. Le facteur de détérioration normalisé diminue avec une augmentation de la teneur en sel; en outre, son taux d'atténuation a également diminué. geovirtual2020.ca.

1 Introduction

Loess is an aeolian (windblown) soil sediment consisting mainly of extensive yellow silts which is often loosely packed in nature. These soils, which can range in thickness from a few centimeters to over 90m, are widely distributed across China. Therefore, areas covered with this type of soil are prone to natural and anthropogenic disasters (i.e., collapse, landslides and mudslides), endangering the safety of people and property within these areas. In cold regions, damages and failures frequently occur during spring, following thawing (Derbyshire 2001; Donald and Chen 1997; Li et al. 2018; Qi et al. 2006). The migration of soluble salts and salt crystallization due to cyclic freezing and thawing are one of the major concerns encountered in loess-formed earthen structures, i.e. slopes and embankments. This process, also known as salt erosion (Roman 1994; Wang et al. 2018), highly influences the soil structure and produces expansion cracks, leading to a considerable deterioration in the engineering behavior of soils (Trusov and Gorodetskii 1993; Zhou et al. 2018). The change in soil structure of loess associated with freezing and thawing conditions has been the focus of several studies (Xu et al. 2020; Koniorczyk, 2010; and Rodriguez-Navarro et al. 2000). In these studies, the development of cracks and the change in soil structure in loess were linked to the presence of sodium sulfate (Na_2SO_4). A significant increase (i.e., about four times) in the volume of Na_2SO_4 crystals was observed, resulting in remarkable change in soil structure. Yet, the influence of freeze-thaw cycles on the shear strength of loess containing sodium sulfate saline has not been investigated comprehensively.

The published research in the literature focused on the mechanical behavior of salt-free soils. Eigenbrod (1996) reported an increase in the volume of specimens after freeze-thaw cycles with the rate of volume expansion decreasing after several cycles. Moreover, the soil properties such as the elastic modulus and the shear strength of soil decreased significantly after cyclic freezing-thawing (Hotineanu et al. 2015; Kamei et al. 2012; Tang et al. 2018; Wang et al. 2007; Xu et al. 2011). More recently, Zhang et al. (2019) investigated the impact of freeze-thaw cycles on the volumetric and low-temperature mechanical behavior of high-salinity soils. The moisture state was regarded as a key factor for the loss of shear strength due to freeze-thaw (Othman and Benson 1993). Steiner (2018) found that the ice lens size in soils consisting of clay mineral, Illite, increased after freeze-thaw cycles, with the failure plane coinciding with the plane of the largest ice lens. In addition, Chen et al. (2007) found that the reduction in shear strength for soils having sodium sulfate was larger than that for soils with identical content of calcium chloride at a given water content. Li et al. (2017) stated that when loess is used as backfill material for roads in cold regions, the influence of freezing and thawing cycles on the engineering soil properties needs to be considered.

The purpose of this study is to investigate the influence of freeze-thaw cycles on the mechanical behavior of loess containing sodium sulfate. The shear strength of undisturbed saline loess samples treated with sodium sulfate contents of 0.0%, 0.5%, 1.0% and 1.5% were measured using unconsolidated undrained strain-controlled triaxial shear tests. The coupled effects of freeze-thaw and salt erosion on the shear strength of saline intact loess were investigated.

The results of this study are of significance in transportation and other infrastructure projects in cold regions that are prone to freeze-thaw cycles. These projects often entail natural or cut slopes and construction of embankments and are susceptible to instability. The findings of the experimental investigation will facilitate in better understanding of the collapse mechanism of loess slopes due to salt erosion and freeze-thaw cyclic loading.

2 Test program

2.1 Material

The soil used in this study can be classified as loess belonging to the Late Pleistocene age (Q_3). The intact soil samples were retrieved from a foundation pit in Xi'an, from a depth of 8 – 10 m. The physical properties of the test soil (summarized in Table 1) were measured according to the GB/T50123-2019 (2019) standards. The ion content of soluble salts in the representative soil sample collected for testing were determined by ion chromatography and titration. As shown in Table 2, the initial ion content of soluble salts is relatively low and its influence on the mechanical behavior of the soil can be ignored.

Table 1. Physical properties of the test soil "loess".

Physical /index properties of the soil	Value
Specific gravity, G_s	2.70
Dry density, ρ_d / g·cm^{-3}	1.42
Void ratio, e	0.92
Liquid limit, ω_L / %	34.3
Plastic limit, ω_P / %	19.6
Plasticity index, I_p	14.7
Particle grading characteristics	
> 0.05 mm	5.0%
0.01-0.05 mm	52.0%
0.005-0.01 mm	24.0%
< 0.005 mm	19.0%

Table 2. Initial ion content of soluble salts.

Initial Ion content (%)	
Anion content (%)	0.0146
CO_3^{2-}	0.0000
HCO_3^{-}	0.0028
Cl^{-}	0.0038
SO_4^{2-}	0.0080
Cation content (%)	0.0106
K^{+}	0.0013
Ca^{2+}	0.0020
Na^{+}	0.0062
Mg^{2+}	0.0011

2.2 Soil specimen preparation

Natural intact samples may not provide a wide range of salt contents to investigate the influence of salt erosion.

It is almost impossible to retrieve samples from the field for the same soil having various desirable Na_2SO_4 contents, for investigation. Therefore, intact samples were artificially treated with predetermined percentages of salt solution under controlled conditions. This was achieved by following a novel infiltration method. The procedure followed in preparing saline intact loess specimens at predetermined Na_2SO_4 contents is outlined herein. First, cylindrical soil specimens having a diameter of 39.1 mm and height of 80 mm were cut from larger intact soil samples retrieved from the pit. Then, the gravimetric water content (w) was controlled at 20%, following the procedure for artificially preparing saline intact loess specimens given in Xu et al. (2020). Four Na_2SO_4 contents (η) were considered (i.e., 0.0%, 0.5%, 1.0%, and 1.5%). A sponge soaked with a certain amount of saline water is wrapped around the soil specimen using a perforated film. Then, the specimen is allowed to rest for a certain time to permit the proper infiltration of Na_2SO_4 solution into the intact loess. During this time, the specimen is continuously weighed to achieve the target value. Throughout the infiltration and weighing process, the salt solution is slowly applied in the form of drops to avoid exceeding the target salt content. Once the infiltration process is complete, the soil specimen is wrapped in a plastic film and placed in a moisturizing tank for 24 h, for achieving equilibration conditions (i.e., even distribution of salt solution across the specimen). It is vital to follow the same steps in specimen preparation in order to minimize errors, and carefully control the infiltration time to ensure the accuracy of the test result. The proposed method was checked and found to provide relatively uniform salt and moisture contents within the specimen (Xu et al. 2020). In addition, the disturbance to the soil structure during solution infiltration was minimal.

2.3 Test Methodology

2.3.1 Freeze-thaw process

The freeze-thaw process was carried out in a temperature-controlled chamber with a working range of -60 ^{o}C – 100 ^{o}C and a precision of ±0.5 ^{o}C. The insitu temperature can be well simulated in the chamber. As discussed previously, specimens prepared following the proposed method had a diameter of 39.1 mm and a height of 80 mm. To reflect the influence of water and salt on the damage caused by freeze-thaw cycling, four levels of sodium sulfate of 0.0%, 0.5%, 1.0% and 1.5% were considered in the test program. Due to the limitation of specimen size, the heat transfer through both ends and side of the specimen is different. To minimize the transport of pore water, the multi-directional rapid freeze-thaw method was applied here with no availability of external water.

Figure 1(a) presents the mean daily minimum surface temperature of two cities in the Loess Plateau during the past ten years, i.e., Yulin and Yan'an. The temperatures for freezing and thawing phases were selected based on the peak and valley of the curve, i.e., -20 ^{o}C for freezing and 20 ^{o}C for thawing, as shown in Figure 1(b). The cycles of freeze-thaw were controlled to be 0, 1, 2, 5 and 10. In a closed system, with the absence of an external water source, the height of the specimen tends to stabilize after cyclic freezing and thawing. Here, a deformation-based standard procedure is used for the determination of freeze-thaw duration. It was observed that the deformation of the specimens, as measured from the displacement transducer, stabilized after 12 hours of thermal loading. Hence, a duration of 12 hours was set for freezing and thawing path, respectively.

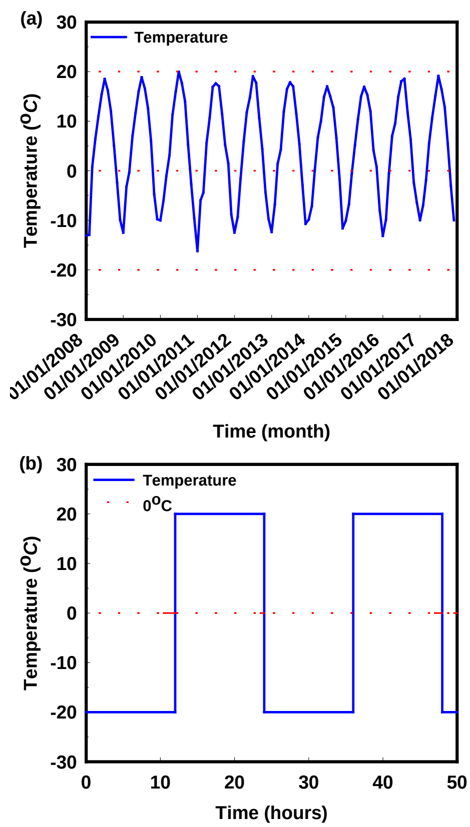


Figure 1. Temperatures used for freeze-thaw: (a) meteorological data; (b) simplified thermal boundary.

2.3.2 Triaxial shear tests

The stress-strain and shear strength behavior of the specimens were determined by conducting strain-controlled triaxial shear tests. The axial load capacity of the apparatus used ranges between zero to 30 kN and the shear rate ranges between 0.002 – 4.5 mm/min. In order to alleviate the influence of consolidation on the soil structure damage during the triaxial test, the tests were conducted under unconsolidated undrained conditions, at a constant strain rate of 0.4 mm/min. Such a testing approach will facilitate in the investigation of the coupling effect of freeze-thaw and salt erosion can be studied, while preventing consolidation. The shear strength parameters were determined using the Mohr-Coulomb failure criterion. To simulate field condition, four levels of confining pressures were used, i.e., 50, 100, 150 and 200 kPa. The mechanical behavior of the specimens at various salt contents were interpreted from the stress-strain relationships and their shear strength behavior.

3 Results and analyses

3.1 Stress-strain curves and strength parameters

Figure 2 illustrates the stress-strain response of the test specimens during triaxial shearing. In general, all tested specimens exhibited an elastic-plastic strain-hardening response, i.e., the shear stress increases rapidly at lower strains and then tends to stabilize gradually upon further deformation. However, specimens tested under the same confining pressure and salt contents that were subjected to freezing and thawing had a higher rate of strain hardening at low strain, i.e. below 3% (Figure 2 (a)).

On the other hand, for the same number of freeze-thaw cycles, the specimens tested at different sodium sulfate contents exhibited a similar strain-hardening response at low strain rate, which is less than 2% (Figure 2 (b)). The influence of salt content appeared to be more pronounced at higher strain rates, i.e. above 2%.

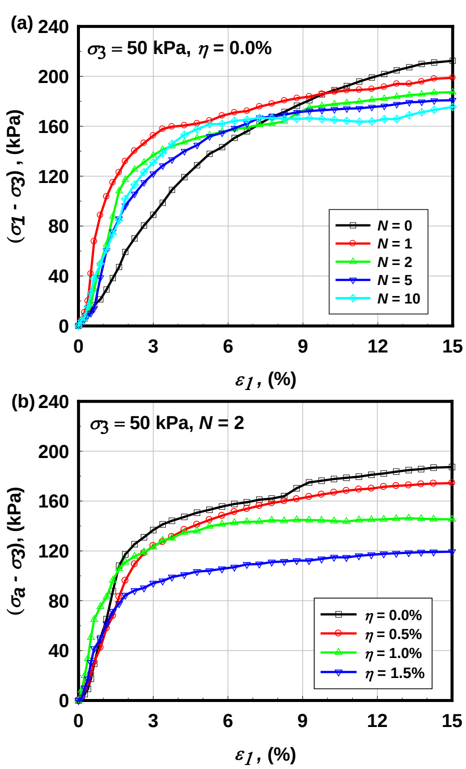


Figure 2. Stress-strain curves of saline intact loess: (a) effect of freeze-thaw cycles; (b) effect of salt content.

The influence of freeze-thaw cycles and salts content on the shear strength behavior is illustrated in Figure 3. Failure was assumed to occur at 15% axial strain. The deviatoric stress at failure, $(\sigma_1\text{-}\sigma_3)_f$ was plotted against the number of freeze thaw cycles (Figure 3 (a)) and salt content (Figure 3 (b). Under the same confining pressure, the deviatoric stress at failure was observed to decrease significantly due to freezing and thawing for all salt contents. The shear strength of specimens with higher salt content deteriorated at a faster rate as compared to specimens tested with lower or no salt content. In other words, the influence of freeze-thaw on the shear strength deterioration increases with an increase in the salt content. In addition, the loss in shear strength mainly occurred after the second freeze-thaw cycle. The deterioration rate in the shear strength was found to decelerate upon further cyclic freezing and thawing. Contrarily, the increase in salt content resulted in an accelerated deterioration rate, irrespective of the number of freeze-thaw cycles, with the shear strength deterioration being highest after the 10^{th} freeze-thaw cycle. This implies that salt erosion tends to intensify the rate of shear strength deterioration.

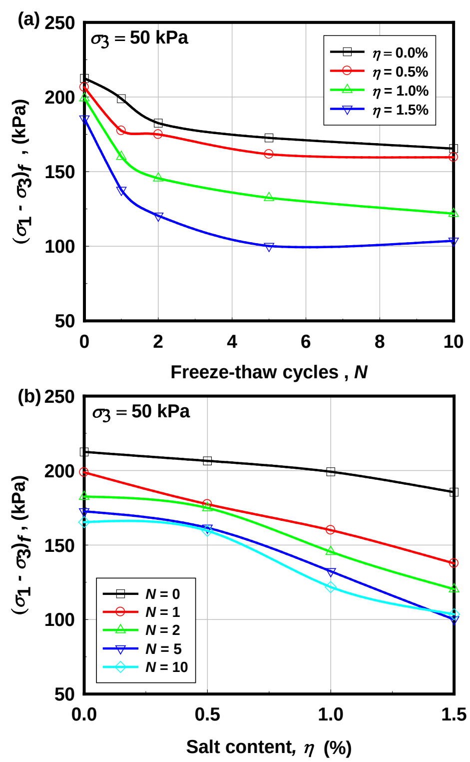
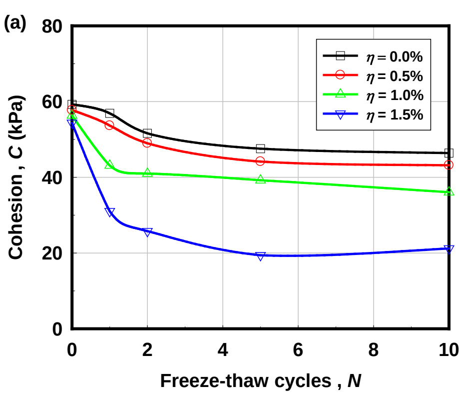


Figure 3. Deviator stress at failure: (a) effect of freeze-thaw cycles; (b) effect of salt content.

Figure 4 shows the variation in cohesion with respect to freeze-thaw cycles and varying salt contents. From Figure 4(a), a steep reduction in cohesion can be observed following the initial cycles of freezing and thawing. After about five cycles, a residual cohesion value is reached and no further reduction in cohesion is observed for additional freeze-thaw cycles. This response is consistent with the deviatoric stress at failure with respect to freeze-thaw cycles (Fig. 3(a)), which suggest a declining deterioration rate associated with freeze-thaw cycles. The behavior of saline loess specimens during triaxial shearing is analogous to the structural disturbance and remolding of clayey soils during the initial freeze-thaw cycles. The soil structure eventually stabilizes and attains constant mechanical soil properties after several cycles of freeze-thaw (Qi et al. 2006). It can be seen from Figure 4(b) that specimens with higher salts content experienced more reduction in cohesion upon freezing and thawing. This also compares well with the variation of deviatoric stress at failure with respect to salt content (Figure 3(b)), where salt erosion was found to increase the rate of deterioration. At higher salt contents, more crystals mainly composed of $Na_2SO_4 \cdot 10H_2O$ precipitate during freezing leading to a greater damage in the soil structure. During thawing, ice crystals melt and dissolve with the salt crystals, creating macropores in soil structure, eventually leading to a rapid decrease in the shear strength. In addition, the cohesion of specimens not subjected to freeze-thaw varies gently, since there is no phase change of sodium sulfate under this condition. From Figure 5, the range of variation in internal friction angle due to freeze-thaw and salt content is relatively narrow, i.e. 1 to 2 degrees only. Most likely, freeze-thaw cycles and salt content have minor influence on the internal friction angle because this parameter is primarily controlled by the contact area and the shape of soil grains rather than the structure.

3.2 Decoupling analysis on dual action of freeze-thaw and salt erosion

The saline intact loess test specimens containing sodium sulfate (Na_2SO_4) is affected by the freeze-thaw cycles induced volume change, as much as it is influenced by the salt erosion caused by the phase change of Na_2SO_4. In order to investigate the deterioration of shear strength of undisturbed saline loess under the dual influence of freeze-thaw and salt erosion, the cohesion-based data was selected to quantitatively estimate the damage caused by freeze-thaw cycles and salt erosion, respectively.



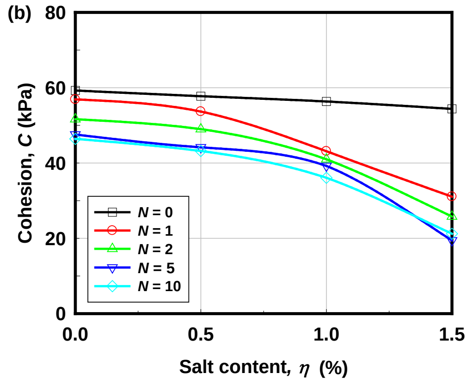


Figure 4. Cohesion of saline loess: (a) freeze-thaw cycle dependence; (b) salt content dependence.

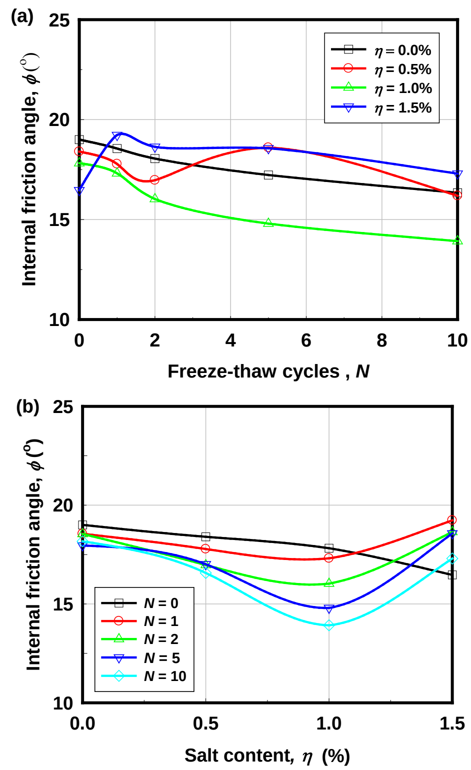


Figure 5. Internal friction angel of saline loess: (a) freeze-thaw cycle dependence; (b) salt content dependence.

Figure 6 presents the damage of shear strength parameters caused by freeze-thaw cycles and salt erosion of undisturbed loess. After five freeze-thaw cycles, four typical paths can be identified from the curve, i.e., i) the path *a-b* denotes the damage solely caused by freeze-thaw cycles, ii) *b-c* can be considered as the damage induced by salt erosion at an incremental salt content of 0.5%, iii) *b-d* represents the salt erosion induced damage at an incremental salt content of 1.0%, and iv) *b-e* denotes the damage at an incremental salt content of 1.5%.

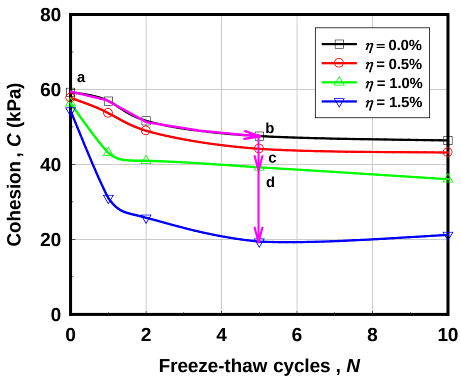


Figure 6. Schematic diagram for the cohesion-based decoupling pathway.

In order to quantitatively investigate the deterioration induced by freeze-thaw cycles and salt erosion respectively, a normalization process was implemented to define freeze-thaw and salt erosion induced deterioration factors, which can be described as follows:

$$D_1 = \frac{C_0 - C_{i0}}{C_0 - C_{ij}} \quad [1]$$

$$D_2 = \frac{C_{i0} - C_{ij}}{C_0 - C_{ij}} \quad [2]$$

where D_1 and D_2 are the deterioration factors due to freeze-thaw cycles and salt erosion, respectively; C is the cohesion, with the subscripts i and j denote, respectively, the freeze-thaw cycle and salt content; C_0 is the cohesion for salt-free loess before freeze-thaw cycles. Here, i is taken as 1, 2, 5 and 10 while j is 0.5, 1.0 and 1.5. By combining Eq. (1) and Eq. (2), we get:

$$D_1 + D_2 = 1 \quad [3]$$

The above Eq. (3) indicates that after normalizing the damage process, D_1 and D_2 represent the proportion for freeze-thaw and salt erosion induced damages respectively, both of which have a definite physical meaning.

The normalized freeze-thaw cycles to salt erosion induced deterioration factor, i.e. D_1/D_2, is plotted against the number of freeze-thaw cycles in Figure 7(a). Generally, the normalized factor is found to increase nonlinearly as the number of cycles increases. This indicates that the soil structure disturbance associated with cyclic freeze-thaw is higher compared to that arising from salt erosion. After several freeze-thaw cycles, the rate of increase in the normalized deterioration factor diminishes until it reaches a constant value after about 5 cycles. Regardless of this, it is observed that at higher salt contents (i.e., 1.5%), the ratio is constantly lower than 1 irrespective of the number of freeze-thaw cycles, indicating that the damage of soil structure mainly results from the salt erosion in this case. This can be explained by the fact that, for specimens at higher salt contents, the salt erosion induced deterioration factor D_2 increases dramatically, as calculated using Eq. (2). Consequently, the ratio of the two factors, D_1/D_2, decreases significantly.

The normalized freeze-thaw to salt erosion induced deterioration factor, i.e. D_1/D_2 is plotted against the salt contents in Figure 7(b). The normalized factor is found to decrease significantly as the salt content increases, indicating that the damage to soil structure associated with salt erosion is more significant at higher salt contents. In addition, the declining rate of the ratio attenuates to a constant value. It is worth noting that for specimens subjected only to one freeze-thaw cycle, the normalized factor is always less than 1, irrespective of the salt content, indicating that salt erosion induced damage is more significant in this case. This behavior is due to a remarkable decrease in the freeze-thaw induced deterioration factor D_1 for the test specimens subjected only to one cycle of freeze-thaw cycle, as calculated from Eq. (1).

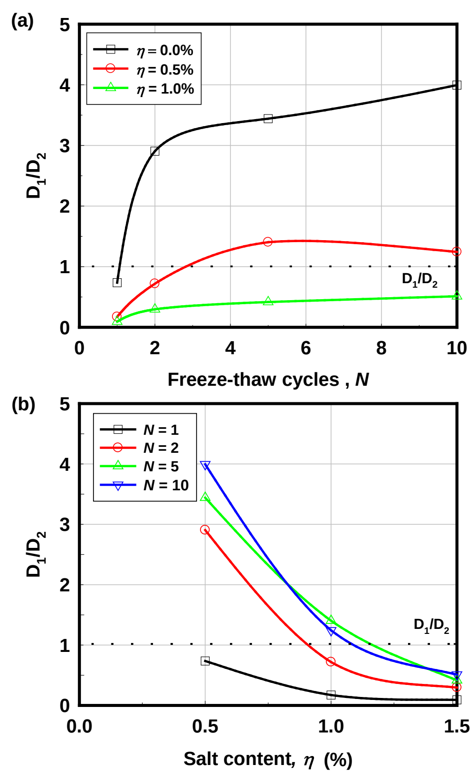


Figure 7. The deterioration factor based on cohesion: (a) freeze-thaw cycle; (b) salt content.

4 Conclusions

Natural saline loess slopes and embankments in cold regions are prone to failures when subject to freeze thaw cycles. This may be attributed to the deterioration in soil structure and the reduction in mechanical soil properties arising from salt migration and crystallization of sodium sulfate present in the soil. This paper provides insights into the change in mechanical properties of saline loess soils, as affected by the deterioration in the soil structure, induced by freeze-thaw cycle. An experimental study involving triaxial shear testing on artificially treated sodium sulfate saline intact loess specimens is carried out to examine the change in soil structure and the associated reduction in soil shear strength due to freeze-thaw cycles. Particularly, the influence of freeze-thaw cycles and salt contents on the stress-strain curves and shear strength parameters (cohesion and internal friction angle) were investigated. The main conclusions drawn from this study are outlined below:

(1) A non-linear elastic plastic stress-strain response indicating strain-hardening was observed for all tested specimens, regardless of freeze-thaw cycles and sodium sulfate content. Cyclic freezing and thawing as well as salt content both resulted in a gradual reduction in deviatoric stress at failure. However, the rate at which the deviatoric stress decreased was observed to diminish following several cycles. Contrarily, the increase in salt content intensified the deterioration rate, irrespective of the number of freeze-thaw cycles.

(2) Similar to the deviatoric stress, cohesion also exhibited a deterioration associated with freeze-thaw cycles and salt content. Whereas, the internal friction angle was hardly altered.

(3) Examination of the normalized factor for cohesion revealed that the ratio of freeze-thaw induced deterioration factor to salt erosion increased nonlinearly following several freeze-thaw cycles. In addition, the ratio decreased with respect to salt content and its attenuation rate declined as the salt content exceeded 1.0%.

The results of this experimental study are of interest to practicing engineers involved in the design of infrastructure projects founded on saline loess in cold regions that are prone to freeze-thaw cycles.

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