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Mechanism of shear strength deterioration of loess during freeze-thaw cycling

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Abstract. Strength of loess that experienced cyclic freeze and thaw is of great significance for evaluating stability of slopes and foundations in loess regions. This paper takes the frequently encountered loess in the Northwestern China as the study object and carried out three kinds of laboratory tests including freeze-thaw test, direct shear test and SEM test to investigate the strength behaviors of loess after cyclic freeze and thaw, and the correlation with meso-level changes in soil structure. Results show that for loess specimens at four dry densities, the cohesion decreases with freeze-thaw cycles until a residual value is reached and thus an exponential equation is proposed. Besides, little change in the angle of internal friction was observed as freeze-thaw proceeds. This may depend on the varying of soil structure, based on which a clue can be found from the surface morphology and mesoscopic scanning of loess specimens. Clearly we observed significant changes in surface morphology of loess and it tends to aggravate at higher water contents or more cycles of freeze and thaw. Moreover, freeze-thaw cycling leads to obvious changes in the meso-structure of loess including lowering the particle aggregates and increasing both the proportion of fine particles and porosity area ratio. A damage variable dependent on the ratio of porosity area is introduced based on the continuum damage mechanics and its correlation with cohesion is discussed.

Keywords: loess; freeze and thaw; strength; cohesion; damage variable

1. Introduction

The Loess Plateau, especially the northern part of Shaanxi province, has the most representative and deepest loess layers. The temperature in this region changed greatly within one year and the shallow soils began to thaw in February and the maximum frozen depth is reached in January. The mean annual precipitation is 552-631 mm, mainly in the summer and autumn seasons, while the snow dominates in spring and winter. Loess is one of the common building materials in Northwestern China, and has been widely used in infrastructures such as earth-filled dams, roadway embankments and artificial slopes that inevitably experience freeze-thaw cycling during operating period (Guo *et al.* 2017). Freeze-thaw effect is generally considered as a strong weathering process, and for cases when soils are exposed, soil structure will be significantly remolded while engineering properties of soils changed (Qi *et al.* 2006). This kind of effect should always be considered in evaluating the deformation of engineering activities (Cheng *et al.* 2008, Kamei *et al.* 2012, Wang *et al.* 2016).

Many experiments have been carried out on the physical properties of a wide range of soils. Viklander (1998) proposed a new concept of residual porosity ratio based on the complex variations in soils after freeze and thaw that loose soils tend to compact while expansion occurs in dense soils. Yao *et al.* (2009) analyzed the stored free energy (SFE) of soils based on dual effects of freeze-thaw cycling and the SFE increases for soils at lower dry unit weights. Angin *et al.* (2016) gives an interesting discussion on the negative effect of freeze-thaw cycling on the aggregate stability by increasing the diatomite application rate. Tian *et al.* (2014) found a hysteresis loop in bond water content during freeze and thaw and three distinct zones were noticed but the bound water content varies insignificantly with temperature in all tested soils.

When thermal and mechanical properties are concerned, little work has been reported yet. An experimental work by Orakoglu *et al.* (2016) indicated that the thermal conductivity of reinforced soils reduced when the number of freeze-thaw cycles increased. Moreover, strength of soils after freeze-thaw cycling has been investigated by many scholars. Experiments by Ghazavi and Roustaei (2013) show that the triaxial strength ratio of reinforced and unreinforced samples decreases with the number of freeze-thaw cycles. This indicates that freeze-thaw cycling is more destructive on ground surface that is in close contact with structures or road pavements. Aldaood *et al.* (2014) found that the unconfined compressive strength of gypseous soil samples lowers and a substantial amount of strength loss occurs within some limited cycles. Hotineanu *et al.* (2015) observed that the lime treatment improves the shear strength against freeze-thaw. Matsumura *et al.* (2015) based on cyclic testing observed that freeze-thawing significantly decreases the liquefaction strength for densely-compacted volcanic soils. Zhang *et al.* (2016) proposed a new freeze-thaw cycles-time analogy method for forecasting long-term strength of frozen soil.

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freeze-thaw primarily originate from the remolding of soil structure. Qi *et al.* (2003) analyzed the mechanism of changes in mechanical properties of soils after freeze-thaw cycling and quantitatively analyzed the SEM image of soils before and after freeze-thaw. Mu *et al.* (2011) from SEM image investigated the relationship between soil structure and mechanical properties. Cui *et al.* (2014) proposed a constitutive model for silty clay that suffered freeze and thaw based on SEM. Aldaood *et al.* (2014) carried out the Mercury porosimetry tests and SEM tests to determine changes at the mesoscopic and mineralogical levels. Mahya Roustaei *et al.* (2015) analyzed the effect of polypropylene fibers on improving the mechanical properties of fine grained soils based on SEM tests. From studies above, it can be found that qualitative interpretations of how freeze-thaw affects soil structure and engineering properties have been frequently given; however, little quantitative work has been reported, and thus required for engineering design.

This paper aims to investigate the strength characteristics of loess after freeze-thaw cycling and takes the frequently encountered loess in Northwestern China as the study object. A series of laboratory tests were carried out including freeze-thaw tests, direct shear tests as well as SEM tests. The strength indexes of loess were presented and based on the surface morphology and SEM image, the mechanism of how freeze-thaw affects the strength will be discussed.

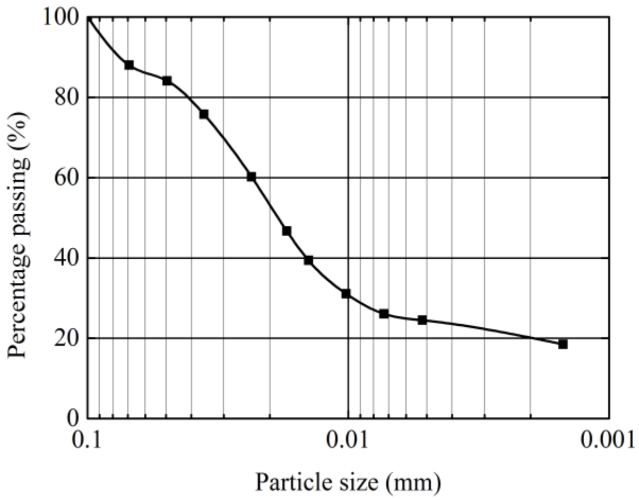


Fig. 1 Grading curve for loess

Table 1 Types of prepared specimen

Dry density / g/cm^3	Water content /%				
1.4	15.0	18.0	21.0	28.0	33.6*
1.5	15.0	18.0	21.0	-	28.9*
1.6	15.0	18.0	21.0	-	24.7*
1.7	15.0	18.0	-	-	21.0*

Note: “-” indicates specimens that are not considered here; “*” represents the saturated water content

2. Materials and method

2.1 Specimen preparation

The loess samples are taken from a foundation pit in Chang’an District, Xi’an, with a depth of 5-6 m below the natural surface, which can be classified as Q_3 loess (Qing *et al.* 2016). The specific gravity for the loess is 2.65. The dry density is 1.7 g/cm^3 and the water content is 17.5%. The liquid and plastic limits for loess are 33.9% and 18.7%, respectively. Fig. 1 presents the grading curves for the loess samples.

The loess samples were crushed and air-dried in laboratory and were then sieved by a 2-mm geotechnical standard sieve. The specimens at five levels of water contents were prepared by sieved loess and distilled water and put into a sealing container for 24 h to ensure the uniformity of water in soils. The cylindrical specimens were produced by slowly compressing slurry weighted, with diameter of 61.8 mm and height of 20 mm. The difference between the dry density for prepared specimens and the target value was controlled to be less than 0.01 g/cm^3 while 0.1% for the water content to minimize the discreteness of experimental results. The specimens used in testing are listed in Table 1. Specimens were produced from the same piece of soil sample, and some specimens are subjected to freeze-thaw tests first, and then used for direct shear tests while the other specimens were directly used in direct shear tests.

2.2 Test procedure

Three types of tests were performed on remolded loess specimens, i.e., 1) freeze-thaw tests, 2) the direct shear tests determining the strength indexes of loess, and 3) the SEM tests for quantifying the freeze-thaw induced changes in the meso-structure of loess.

1) Freeze-thaw tests

The prepared specimens with preservative film wrapped around were sealed in a temperature and humidity chamber to produce a closed system with no availability of water. Then specimens were mounted on test chamber, with the effective volume of 400 L, and the refrigeration method is compressor cooling, with a range of -60 - 100℃ and an accuracy of ±0.5℃, for fast freeze-thaw testing to ensure minimum migration of soil water. The apparatus for freeze-thaw testing was illustrated in Fig. 2. Here, a three-directional mode for temperature controlling is utilized, instead of the one-dimensional way that was commonly applied. During freezing, the temperature in test chamber was controlled to be -20℃ with a duration of 12 h while +20℃ during thawing for 12 h, which is determined by considering the actual meteorological data of the Northern part of the Shaanxi province. The cycles of freeze and thaw *N* were set to be 0, 2, 5, 7, 10, 14, 17 and 20.

2) Direct shear tests

Specimens that experienced preset cycles of freeze and thaw were mounted on a strain-controlled direct shear apparatus. The maximum shear stress and displacement for shear testing are 1.2 kN and 20 mm, with accuracy of 0.002 kN and 0.01 mm, respectively. The shear rate can be adjusted to be 2.4, 0.8, 0.1 and 0.02 mm/min. The strain rate was adjusted to be 0.8 mm/min for determining strength of loess at quick shear conditions, with normal stresses of 100, 200, 300 and 400 kPa applied. The strength parameters

Fig. 2 Temperature and humidity chamber

Fig. 3 The Quanta 600 FEG Field Emission Scanning Electron Microscope

were obtained based on the Mohr-Coulomb criterion.

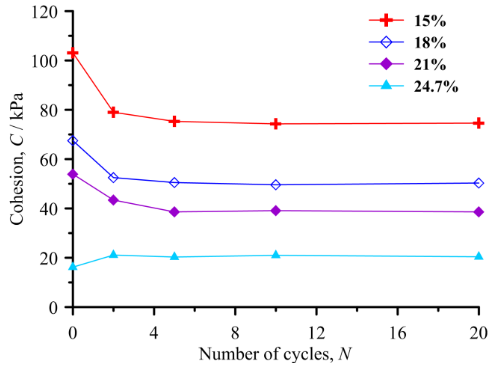
3) SEM tests

Specimens at a water content of 18.0% and a dry density of 1.7 g/cm^3 were taken out and air-dried after preset cycles of freeze and thaw. Then a ring of groove was cut around the central part of the specimen so as to obtain a relatively smooth section and the dimensions for SEM testing in high vacuum conditions are 1.0 cm×1.0 cm×2.0 cm. The Quanta 600 FEG Field Emission Scanning Electron Microscope, as shown in Fig. 3, can be used to provide basic images for further evaluating the particle form and porosity characteristics of prepared samples. The instrument has an acceleration voltage of 200 V-30 kV, and the tests were carried out under a voltage of 30 kV, with a resolution of 1.0 nm. After trial of five levels of factor of magnification, i.e., 100, 500, 1000, 2000 and 5000, the images magnified 2000 times were utilized in order to obtain more meso-level information in soil structure, such as particle form in soil skeleton, particle contact, porosity form as well as the ratio of porosity area.

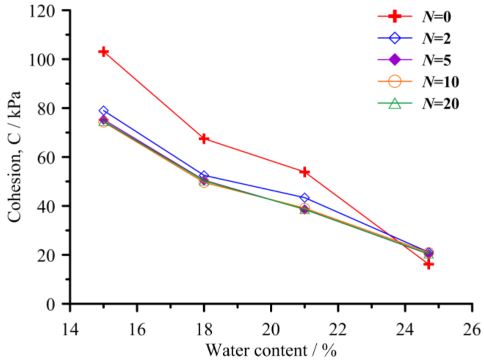
3. Test results

3.1 Strength indexes vs. cycles of freeze and thaw

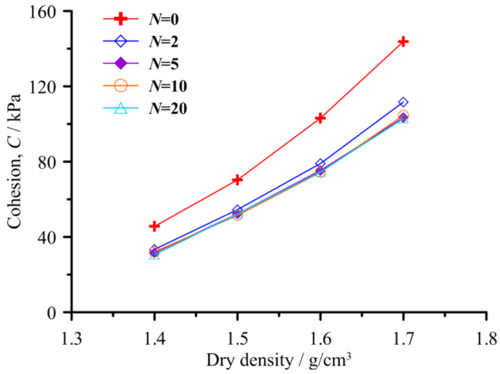
Fig. 4(a)-4(c) illustrate the freeze-thaw induced changes in the cohesion of loess with cycles of freeze and thaw, water content and dry density. For saturated specimen, the cohesion shows a slight increase but stabilizes in the initial two cycles while the specimens at water contents of 15.0%, 18.0% and 21.0% all show an approximately exponentially



(a) freeze-thaw cycles dependence (ρ_d=1.6 g/cm^3)



(b) water content dependence (ρ_d=1.6 g/cm^3)



(c) dry density dependence (w=15.0%)

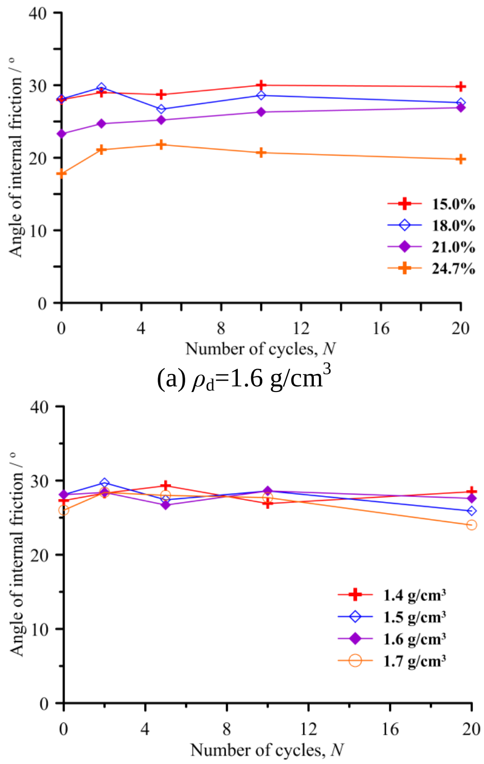
Fig. 4 Freeze-thaw induced changes in cohesion of loess

decrease in the cohesion within five freeze-thaw cycles, and followed by a relatively constant residual value. We can also see from Fig. 4(b) that the cohesion approximately decreases linearly with water content, which may be attributed to the thicker bound water between soil particles, intensifying the damage in soil structure under load. Moreover, the curves for loess specimens which experienced more than five cycles of freeze and thaw overlapped, indicating that even the water contents of soils change, the cohesion will approach to a constant. Fig. 4(c) shows that the cohesion of loess grows linearly with dry densities. However, after about five cycles, the cohesion of loess shows little change. The variation of the angle of internal friction with freeze-thaw cycles, illustrated in Fig. 5(a) and 5(b), shows that the angle of internal friction shows complex changes but the magnitude has always been varying within a small range, with a maximum difference of 5°. This may simplify the procedure for analyzing freeze-thaw induced deformation of soils by assuming that the angle of internal friction is irrelevant with freeze-thaw cycling.

From test data illustrated in Fig. 4, the following exponential equation can be obtained by fitting

$$C = ae^{bN} + c \quad (1)$$

where C is the cohesion of loess; N is the freeze-thaw cycles; a, b and c are fitted parameters that depends on the water content, as listed in Table 2. Comparison of calculated and measured data, presented in Fig. 6, shows that most of points lie on or close to the line of $y=x$, indicating that the calculated data agrees well with test data, which proves a good accuracy of the empirical equation. We have found the relevant data from literatures for verification, as shown in Fig. 7 and it shows that the predicted values are close to the measured, indicating that the empirical equation is feasible for describing the relationship between cohesion and freeze-thaw cycles.



(a) ρ_d=1.6 g/cm^3

(b) w=18.0%

Fig. 5 Angle of internal friction after cyclic freeze and thaw

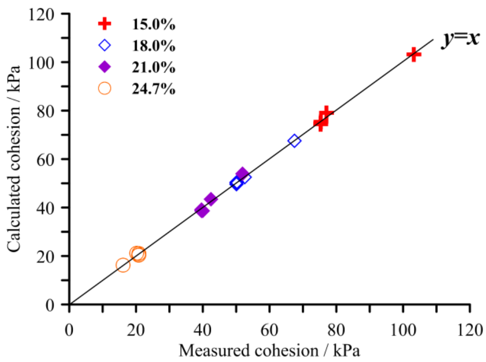


Fig. 6 Comparison between calculated and measured data

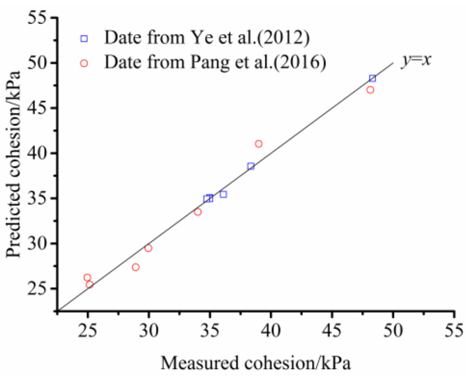


Fig. 7 Comparison between predicted and measured data

Table 2 Fitted parameters

w/%	15.0	18.0	21.0	24.7
a	27.88	17.42	12.30	-4.71
b	-1.40	-0.98	-0.73	-1.00
c	75.34	50.08	39.63	20.82
R^2	0.99	0.98	0.95	0.94

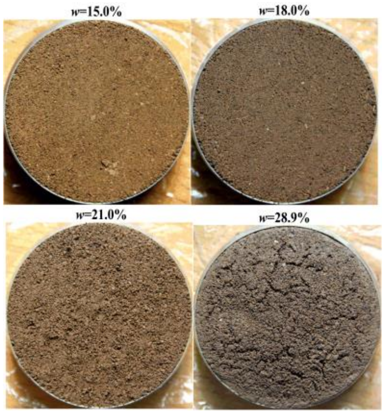
3.2 Surface morphology

Freeze-thaw cycling is regarded as one of the strong weathering effects, significantly remolding soil structure that we can observe a hint from the surface feature of specimens. Fig. 8(a) gives the close-up shot for specimens at a dry density of 1.5 g/cm^3. After seventeen cycles of freeze and thaw, specimens at lower water contents, i.e., 15% and 18%, the surface feature shows little change while for those at higher contents of water, soil surface tends to be looser with larger porosity that can be easily noticed and even some fragments emerged. For saturated soils, large cracks were formed in the surface. Fig. 8(b) presents the surface feature of unsaturated loess at various cycles of freeze and thaw. A few flocculent fragments firstly appeared in soil surface and after more than seven cycles of freeze-thaw, more flocculent fragments emerged and short cracks tends to grow and extend.

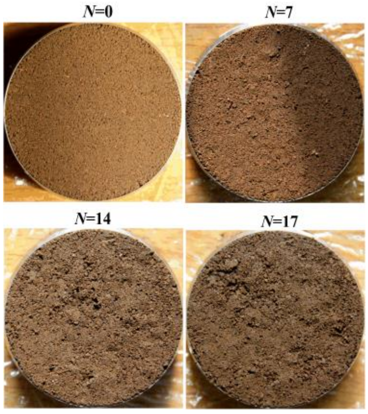
Also, from the close-up view of surface feature at various dry densities, as shown in Fig. 8(c), specimens that experienced seventeen cycles obviously exhibit large joint cracks in the surface at a dry density of 1.4 g/cm^3, while as dry density grows, i.e., 1.5, 1.6 and 1.7 g/cm^3, a few fine cracks can be observed. From the above, freeze-thaw cycling obviously affects the surface feature of loess specimen, especially at higher water contents or more freeze-thaw cycles. This may be related to the collection and evaporation of migrated water towards soil surface during freeze-thaw cycling, especially for specimens at higher water contents. In this case, larger deformation and continuous damage in the surface morphology will occur.

3.3 Mesoscopic characteristics of soil structure

Fig. 9 illustrates the SEM images of loess before and after freeze-thaw tests. It shows that before testing, the particles in soil skeleton mainly consist of two types of



(a) water content dependence (ρ_d=1.5 g/cm^3)



(b) freeze-thaw dependence (w=21.0%, ρ_d=1.6 g/cm^3)

(c) dry density dependence (N=17, saturated specimen)

Fig. 8 Surface feature of specimen

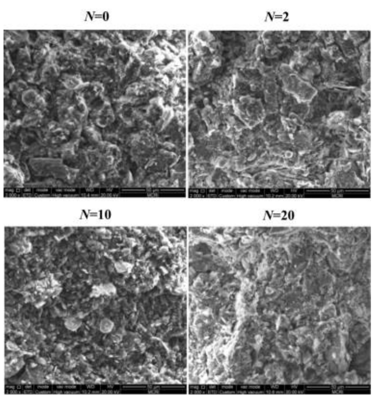


Fig. 9 Mesoscopic image of soil structure after freeze and thaw

particle form manifesting as mono minerals with a proportion of platy-shape particles and cemented aggregates that were closely packed. During freezing and thawing, the ice crystal growth and melting in pores of soils led to the complex glomeration of surrounding aggregates. Visually, soils cracks were produced in soil surface where no external load was applied, as shown in Fig. 8. Moreover, the proportion of large pores that occupy in the considered domain increases with the cycles of freeze and thaw, which may be attributed to the transformation of fine pores into the large.

Here, three typical indexes were applied in further analysis including the equivalent diameter of soil particles, particle orientation, degree of circularity. The first denotes the diameter of equivalent circle that covers the same area as soil particle. Particle orientation is actually an azimuthal angle of the longest string of soil particle, ranging from 0° to 180°. The degree of circularity describes the degree of closeness between soil particle and a perfect circle, with a range of 0-1 and a larger degree of circularity gives a more standard circle. Among the indexes above, the particle orientation is a geometric variable that can be directly measured from the image while the others can be calculated as follows

$$d = (4S/\pi)^{1/2} \tag{2}$$

$$R = 4\pi S / L^2 \tag{3}$$

where d is the equivalent diameter, S is the particle area; R is the degree of circularity, L is the perimeter of soil particles.

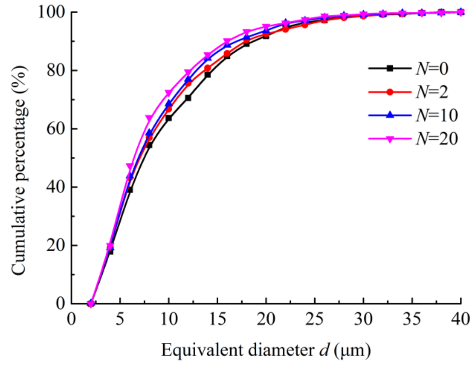
It can be noted from Fig. 10(a) that variation of equivalent diameter that can be easily observed in the population distribution of the diameter demonstrates that crack of soil particles occurs after freeze-thaw cycling and thus the proportion of finer particles in soil skeleton grows. Besides, it shows little changes in both degree of circularity and particle orientation from Fig. 10(b) and (c), indicating that freeze-thaw cycling rarely affects the particle form as well as the orientation. This also gives a meso-level explanation of why the angle of internal friction of loess that strongly depends on both form and contact of soil particles varies within a small range after cyclic freeze and thaw.

Except those mentioned above, the porosity of soils also implies the evolution of soil structure. Here, the ratio of porosity area, a ratio that the projected area of pores occupies the whole area of soil particles, can be written as

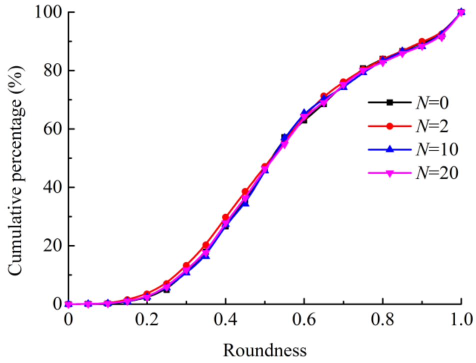
$$\lambda = A_V / A_S \tag{4}$$

where λ is the porosity area ratio, A_v and A_s are the projected areas of pores and soil particles in the considered domain, respectively.

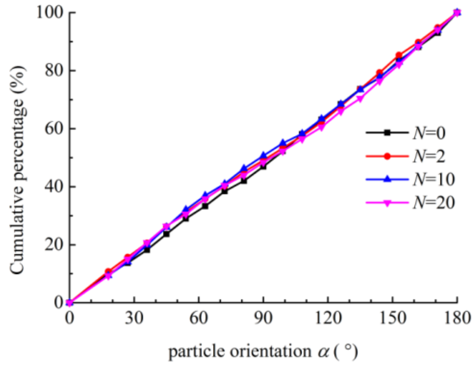
The ratio of porosity area after freeze-thaw cycling illustrated in Fig. 11 increases. This may be related to fact that as the ice crystal grows in soil structure, i.e., the cryogenic structure, the porous area expands and leads to significant changes. The freeze-thaw cycling obviously lowers the content of aggregates and loosens the particle contact which possibly induces a weak bonding between particles and more fine pores. In this case, the potential fracture in soil skeleton develops, as revealed by the surface morphology of loess specimens.



(a) Equivalent diameter



(b) Degree of circularity



(c) Particle orientation

Fig. 10 Three meso-level indexes for soil particles

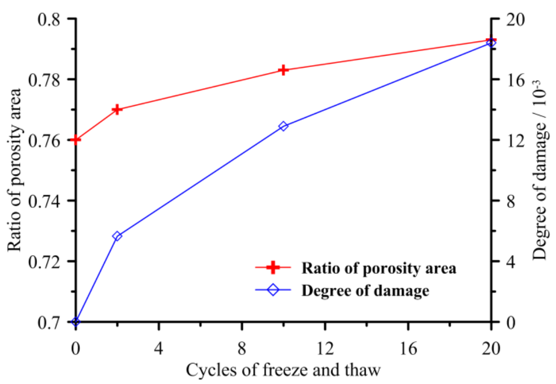


Fig. 11 Correlation of porosity area ratio and damage degree

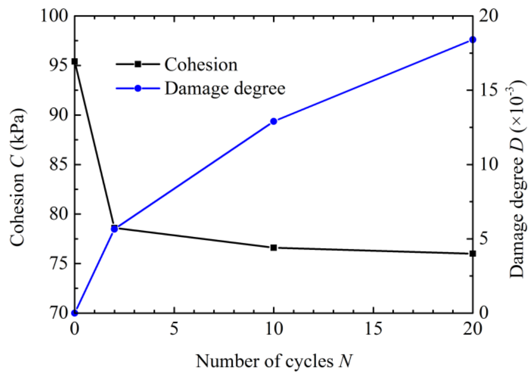


Fig. 12 Correlation of cohesion and damage degree after freeze-thaw cycling

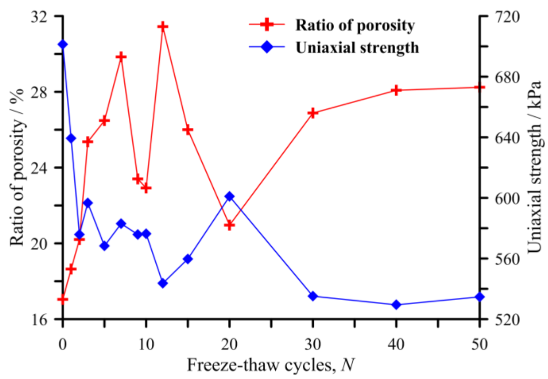


Fig. 13 Variation of porosity and uniaxial strength with freeze-thaw cycles (Zhang *et al.* 2015)

Based on the continuum damage mechanics, the deterioration of material mainly results from the reduction of the effective bearing area, so the following degree of continuity φ can be utilized

$$\varphi = \tilde{A} / A \tag{5}$$

where, A and $\tilde{A}$ are the effective bearing areas before and after freeze-thaw cycling, respectively.

Then, a new degree of damage D based on the degree of continuity φ can be obtained as follows

$$D = 1 - \varphi \tag{6}$$

where D is a scalar parameter, with D=0 representing the non-destructive state of material while D=1 for completely damaged state.

Substitute Eqs. (4) and (5) into Eq. (6), we get

$$D = \frac{\lambda - \lambda_0}{1 + \lambda} \tag{7}$$

where λ_0 and λ denote the ratios of porosity area in a section before and after freeze and thaw, respectively. From Fig. 10, similar changes of degree of damage can also be observed, compared with that of the ratio of porosity area.

Fig. 12 gives the correlation of cohesion and damage degree at various freeze-thaw cycles. This may indicate that the freeze-thaw cycling affects the cohesion by changing the structure of loess, i.e., fracture due to both ice crystal growth in porous area and cryostructure formation, thus weakening soil structure and lowering the cohesion. For saturated soils, part of soil water was migrated to the surface, and as a result, the water content in the shear plane lowers and indirectly increases the cohesion after freeze and thaw. Similar decrease in the cohesion at various dry densities can also be found, especially for those at larger dry densities. An investigation by Zhang *et al.* (2015) reveals that the ratio of porosity tends to grow in general but the uniaxial strength of silty clay decreases, presented as a negative correlation, as shown in Fig. 13. This agrees well with the conclusions drawn from SEM tests, i.e., strength of silty clay after freeze-thaw is closely related to the porosity, rather than the particle form.

4. Conclusions

This paper carried out experiments on loess that experienced cyclic freeze and thaw and the strength characteristics including two indexes, i.e., cohesion and angle of internal friction, were investigated based on analyzing both surface morphology and SEM images. The following conclusions can be drawn from test data:

• The cohesion of loess decreases with cyclic freeze and thaw and can be fitted as an exponential equation. Besides, the cohesion strongly depends on both water content and dry density, and for specimens which experienced more than five cycles of freeze and thaw, the cohesion will approach to a constant. The angle of internal friction shows complex changes but the magnitude has always been varying within a small range.

• The surface feature of loess obviously changes after freeze and thaw. At higher water contents, or experiencing more freeze-thaw cycles, the surface of loess specimen shows more disturbances.

• The meso-level changes in soil structure can be quantitatively determined by four typical indexes including equivalent diameter, orientation of particles, degree of circularity and ratio of porosity area. Results show that little changes can be noted for the former three while the ratio of porosity area obviously increases with freeze-thaw cycles. And variation of cohesion with freeze and thaw has close relationship with damage degree.

• Reducing soil moisture content is an effective measure to reduce freez-thaw induced disasters. For loess slopes, the infiltration of rainwater can be reduced by lining or drainage ditch. A layer of thermal insulation material can be laid on the soil surface to reduce the number of freeze-thaw cycles.

Acknowledgments

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