Cold Regions Science and Technology 148 (2018) 104–120

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Strength behaviors and meso-structural characters of loess after freeze-thaw

Jian Xu[a], Jianwei Ren[a], Zhangquan Wang[a], Songhe Wang[b,*], Jun Yuan[c]

[a] School of Civil Engineering, Xi'an University of Architecture and Technology, Xi'an, Shaanxi, 710055, China
[b] Institute of Geotechnical Engineering, Xi'an University of Technology, Xi'an, Shaanxi, 710048, China
[c] Northwest Electric Power Design Institute of Co. Ltd. of China Power Engineering Consulting Group, Xi'an, Shaanxi, 710075, China

ARTICLE INFO

Keywords:
Freeze-thaw
Shear strength
Loess
Damage variable
Factor of safety

ABSTRACT

Freeze-thaw induced variations of the shear strength of loess is critical for evaluating the stability of natural and artificial slopes in loess terrains. The frequently encountered loess in Northern China was taken as the study object and two types of specimens were produced for direct shear testing including the undisturbed and the remolded. Strength behaviors of loess that has suffered preset cycles of freeze and thaw were investigated based on the particular correlations with freeze-thaw cycles, water content and dry density. Cohesion of the loess varied with the cycles of freeze and thaw until a residual value was reached while little change can be noted from the angle of internal friction. The apparent surface that was the first to be affected by freeze-thaw was compared with a quantified index of surface cracks determined by image processing. The meso-structural characters for loess after freeze-thaw cycling were explored such as the equivalent diameter, the particle orientation, the degree of circularity and the ratio of porosity area, with a damage variable that depends on the ratio of porosity area proposed. The coefficient of safety for a natural loess slope was calculated by considering the coupled effect of freeze-thaw cycles, frozen depth and the initial water content. This may provide guidance in predicting the stability of slopes in loess terrains when the freeze-thaw is included.

1. Introduction

Loess is characterized by large porosity, vertical joint development and high permeability, leading to weak bonding effect between soil particles and if this particular material is used as the filling material in constructing foundations for highways, railways and other infrastructures, engineering problems such as the flooding accident and instability may arise as a result. In addition, the long and cyclic freeze-thaw in seasonal frozen ground, as a strong weathering process (Hansson et al., 2004), and for cases when soils are exposed, soil structure will be significantly remolded with engineering properties of loess changed (Qi et al., 2006). This frost action should always be considered in evaluating the possible deformation that resulted from the engineering activities (Cheng et al., 2008; Kamei et al., 2012; Wang et al., 2016).

Effect of freeze-thaw cycling on engineering properties of soils was such a traditional issue in frozen soil mechanics that many experimental works have been reported already. One of the classic index concerning the freeze-thaw of soils at various compaction degrees is the residual void ratio proposed by Viklander (1998) that loose soils tend to compact while expansion occurs in dense soils. Similar results have also been found by Qi et al. (2006). Yao et al. (2009) further used the stored free energy (SFE) to describe the possible variations of soils at such a dual effect of freeze and thaw and the lowering of the SFE will be found at lower densities. Even in dynamic conditions, the liquefaction strength for densely-compacted volcanic soil significantly decreases from a typical cyclic testing (Matsumura et al., 2015). The threshold value was also found from an experiment of expansive soils that experienced freeze-thaw, beyond which the strength behaviors of the expansive soils will not be significantly influenced (Tang et al., 2018). 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. Zhang et al. (2016) proposed a new freeze-thaw cycles-time analogy method for forecasting long-term strength of frozen soil. This is closely related to the bi-directional changes of soil structure and a strong dependence of initial densities can be easily noted from previous work (Zhou et al., 2018).

The meso-level interpretation of the complex changes in the above engineering properties were also given based on advanced technology, e.g., SEM. Qi et al. (2003) discussed the mechanism of the changes in the mechanical responses of soils after freeze-thaw cycling and a quantitative analysis was carried out by processing the SEM images of soils before and after freeze-thaw. Mu et al. (2011) from SEM image investigated the correlations of mechanical behaviors versus soil

* Corresponding author.
E-mail address: wangsonghe@xaut.edu.cn (S. Wang).

https://doi.org/10.1016/j.coldregions.2018.01.011
Received 5 April 2017; Received in revised form 26 December 2017; Accepted 23 January 2018
Available online 03 February 2018

Table 1
Basic physical parameters of the loess samples.

Physical index	Data
Specific gravity, G_s	2.69
Dry density, ρ_d/(g/cm^3)	1.70
Natural water content, w_n/%	17.5
The Atterberg limit	
Liquid limit, w_L/%	33.9
Plastic limit, w_P/%	18.7
Soil classification	CL
Particle grading characteristics	
0.075–2.0 mm	10.0%
0.005–0.075 mm	64.7%
< 0.005 mm	25.3%

Table 2
Types of prepared specimen.

Type of specimen	Dry density/g/cm^3	Water content/%				
Intact	1.3	16.5	20.5	24.0	29.0	32.5*
Remolded	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*

"–" indicates specimens that are not considered here; "*" represents the saturated water content.

structure. Cui et al. (2014) proposed a constitutive model for silty clay that suffered freeze and thaw based on a quantitative analysis of SEM image. Mahya Roustaei et al. (2015) investigated the effect of polypropylene fibers on improving the mechanical properties of fine grained soils based on SEM tests. The interpretations of how freeze-thaw affects soil structure and engineering properties have been frequently presented; however, little quantitative work has been reported, and thus required for engineering design.

In addition, some engineering measures were proposed to improve the engineering performance of soils that were easily affected by this particular weathering effect. Hotineanu et al. (2015) observed that the lime treatment improves the shear strength against freeze-thaw cycles. Orakoglu et al. (2016) observed that thermal conductivity of reinforced soil reduced when freeze-thaw cycles increased. And further the dynamic behaviors of this kind of materials were experimentally studied with the freeze-thaw cycling considered (Orakoglu et al., 2017). The tensile strength of fiber reinforced soil was also investigated based on a new method for preparing soil specimens (Li et al., 2018). Experiments by Ghazavi and Roustaei (2013) show that the triaxial strength ratio of reinforced and unreinforced samples decrease with the number of freeze–thaw cycles. This indicate that freeze–thaw cycling is more destructive on the ground surface that is in close contact with infrastructures or road pavements.

Since massive infrastructures will be constructed in loess terrains as the Belt and Road proceeds, this paper takes the frequently encountered loess in Northern China as the object and strength tests in direct shear stress state were carried out on remolded and undisturbed specimens. Besides, the SEM technology was also included to represent the specific variations of soil structure as the freeze and thaw was applied on specimens. The mechanism of how freeze-thaw affects the shear strength will be discussed.

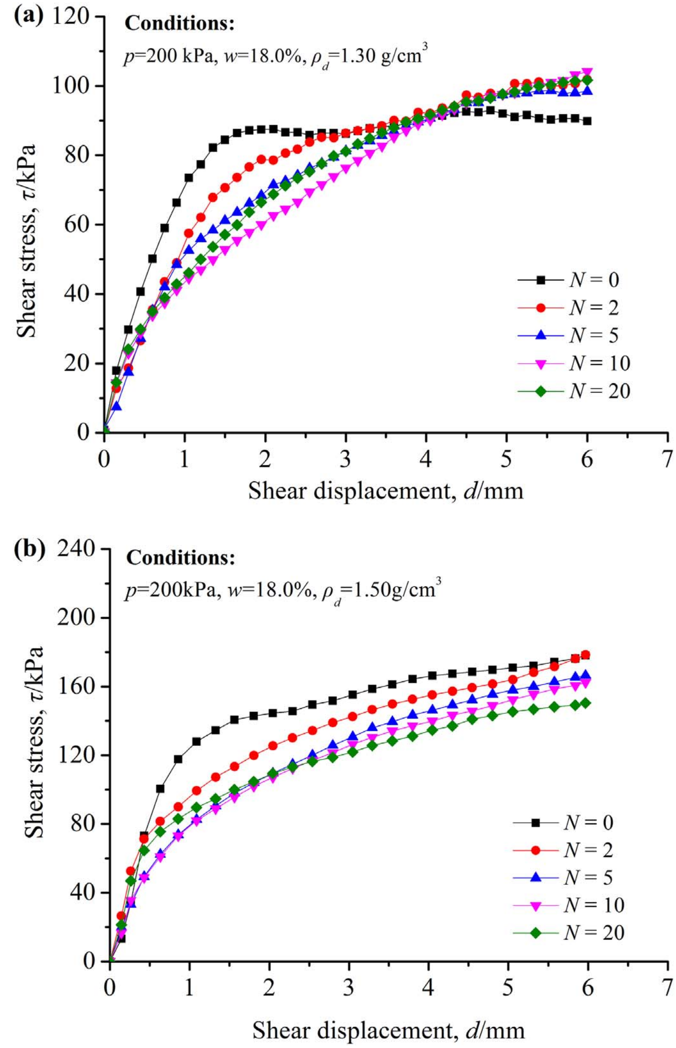

Fig. 1. Shear stress versus shear displacement curves for loess: (a) intact loess; (b) disturbed loess.

2. Test procedure

2.1. Materials

Soil samples were taken from a foundation pit in Xi'an, with the depth of 5–6 m below the natural surface, and can be classified as Q_3 loess (Liu et al., 2016). The basic physical parameters for the taken samples are listed in Table 1. Two types of loess specimens were produced in laboratory including the remolded and the undisturbed. For the former, the crushed soil samples were sieved by a 2-mm geotechnical standard sieve and the distilled water was mixed in air-dried soils. Then specimens were compressed by the above soils, and kept in a sealing container for 24 h to ensure the uniformity of water in soils. For the latter, the specimens at a specific size were cut from a large undisturbed sample and the water content was controlled by adding the distilled water. The diameter and height of the above two types of specimens were 61.8 mm and 20 mm, respectively. The difference between the dry density for prepared specimens and the target value was controlled to be < 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 2.