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Short communication

Fractal analysis of cracking in a clayey soil under freeze–thaw cycles

Yang Lu [a], Sihong Liu [a,*], Liping Weng [b], Liujiang Wang [a], Zhuo Li [c], Lei Xu [a]

[a] College of Water Conservancy and Hydropower, Hohai University, No.1, Xikang Road, Nanjing 210098, China
[b] Business School of Hohai University, No.1, Xikang Road, Nanjing 210098, China
[c] Nanjing Hydraulic Research Institute, No.223, Guangzhou Road, Nanjing 210029, China

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ABSTRACT

Under extreme climate conditions, clayey soils experience not only seasonal drying and wetting but also frequent freezing and thawing. Cracking would also occur in clayey soils under freeze–thaw cycles, but now less academic attention has been paid on this issue. In this study, a series of laboratory tests were conducted on a clayey soil to investigate the cracking behaviors under freeze–thaw cycles. Water loss, surface crack initiation and propagation processes were monitored after each freeze–thaw cycle. By using the image processing technique, the crack patterns were described and then quantitatively analyzed on the basis of the fractal dimension concept. It was found that for the tested clayey soil subjected to freeze–thaw cycles, the surface crack pattern slowly evolves from an irregularly rectilinear pattern towards a polygonal or quasi-hexagonal one; and the water loss, closely related to the sample thickness, plays a significant role in the process of the clay cracking; Upon cyclic freezing–thawing, the fractal dimension is well correlated to the surface crack ratio in a logarithmic equation. Fractal dimension concept can offer a new perspective on the quantitative understanding of cracking initiation and propagation in clayey soils under freeze–thaw cycles.

1. Introduction

Cracking is a common natural phenomenon that occurred in clayey soils and significantly impacts the mechanical and hydraulic behaviors of soils. In practical engineering applications, clay-rich soils are widely used for the construction of lining and covering systems because of their low permeability and high cation exchange capacity. The development of cracks in liners and covers will provide preferential flow paths for water infiltration and dramatically increase the hydraulic conductivity, resulting in the failure of anti-seepage systems. In addition, cracks will induce zones of weakness in a soil mass, leading to the reduction of the soil shear strength and the increase of the soil compressibility (Saada et al. 1994). Moreover, cracks will probably cause the instability of slopes (Gao et al. 2015), foundations (Lozada et al. 2015), embankments (Spencer 1968; Dyer et al., 2009) and other structures related to clayey soils. Therefore, better understanding of soil cracking formation and development can facilitate the analysis of a wide spectrum of geotechnical, environmental and geological problems.

Development of cracks may be attributed to various processes including desiccation and shrinkage (Yesiller et al. 2000; Tang et al. 2008), drying and wetting (Tang et al. 2011a; Asahina et al. 2014), freezing and thawing (Chamberlain and Gow 1979), syneresis (Pratt 1998), differential settlement (Viswanadham and Rajesh 2009), and penetration by vegetation roots (Whiteley and Dexter 1983; Sinnathamby et al. 2013; Li et al. 2016). Among them, cracks induced by the first three processes are mainly related to atmospheric conditions, which significantly influence the long-term behaviors of earthworks. Many laboratory experiments, field tests and numerical simulations have been conducted to investigate the phenomenon of desiccation cracking of clayey soil (Morris et al. 1992; Konrad and Ayad 1997; Péron et al. 2009; Li and Zhang 2011; Amarasiri and Kodikara 2013; Costa et al. 2013; DeCarlo and Shokri 2014a, 2014b). Desiccation cracks, induced by sustained water loss to the atmosphere from a drying material, often occur on the surface of clayey soils. Drying results in shrinkage and subsequent cracking of the soil. When a clayey soil is subjected to repeated wetting and drying, the crack surface becomes more irregular and coarse, and the segments of short and narrow cracks increase prominently (Tang et al. 2008).

In cold and arid regions, clayey soils are subjected to not only desiccation and seasonal wetting–drying, but also frequent freezing–thawing. Damages due to cyclic freezing–thawing can present various forms, in which the most common ones are cracking and spalling (Andersland and Al-Moussawi 1987; Czurda and Hohmann 1997; Yarbaşı et al., 2007). It has been found that the permeability of fine-grained soils changes under freezing and thawing (Chamberlain and Gow 1979). A network of cracks resulting from the ice lenses during freeze–thaw cycles appeared to be the primary causes of the larger hydraulic conductivities of soils (Benson and Othman 1993). The mobilization of colloid and colloid-associated contaminants could also increase under frequent freeze–thaw cycles in a fractured soil, where preferential flow paths are prevalent

* Corresponding author.
E-mail addresses: luy@hhu.edu.cn (Y. Lu), 15161461318@163.com, sihongliu@hhu.edu.cn (S. Liu).

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(Mohanty et al. 2014). According to the study by Pardini et al. (1996), the ice lenses formed during the freezing period tend to segregate the soils and the segregating forces cause the breakage of the micro-fissures existing in the soils, which are transformed into a great number of irregular and rounded pores and the soil structures are readjusted in micro- and macro-scales. Akagawa and Nishisato (2009) proposed that fractures or cracks would take place in a soil when the ice pressure exceeds the tensile strength of the frozen soil and such rupture of the pore-ice framework in the soil is necessary for the initiation of the ice lenses. Bhreasail et al. (2012) applied the synchrotron micro-computed tomography (CT) to study the microstructures of frozen soils and found that the micro-cracks and longer cracks were orientated parallel to the freezing front, affecting both the frozen soil's mechanical properties and permeability. During the thawing period, the fissures and cracks still exist due to the previously frost-induced plastic deformation, although part of the porosity is affected by the slaking of aggregates (Hohmann-Porebska 2002).

However, previous researchers mainly focused on the detrimental effects and the frost mechanism of clayey soils under freeze–thaw cycles. Few attempts have been made to investigate the evolution of cracks induced by freeze–thaw cycles, especially the quantitative assessment of such cracking behaviors. Owing to climate change and extreme weather events, the phenomenon of freezing–thawing has become as common as the wetting–drying, and its detrimental effects on earthworks have gradually aroused public concerns.

In this study, a series of laboratory cyclic freezing–thawing tests were conducted on a clayey soil to investigate the evolution of the surface cracks. The variation of the water contents, the initiation and propagation of the cracks were monitored during the freeze–thaw cycles. A quantitative method to characterize the crack patterns by combining the image processing with the fractal dimension concept was developed, which was then applied to quantitatively investigate the evolution of the cracks together with the water loss and the number of freeze–thaw cycles.

2. Laboratory freezing–thawing tests

2.1. Preparation of clay samples

As swelling/expansive soils contain active clay minerals like montmorillonite and illite, they have quite high swell-shrink potentials and are more prominent in cracking. Compacted expansive soils are often used as impervious liners in canals and cover materials in waste disposal landfills (El-Sohby et al. 1995; Kayabali 1997; Kaya and Durukan 2004). The cracking in expansive soils resulting from freeze–thaw cycles in cold regions has aroused attentions by some researchers (e.g., Andersland and Al-Moussawi 1987). In this study, the clay samples were prepared with an expansive soil, which was taken from the construction field of a water transfer project in North China. The physical properties of the tested expansive soil are listed in Table 1.

The clay samples were prepared in three procedures. First, the expansive soils were air-dried, lightly crushed by use of a rubber hammer and sieved through a 2.0 mm mesh. Water was added into the sieved soil and mixed thoroughly by hand until the soil has the water content close to its liquid limit (62.0%). The mixed soil was cured for about 24 h in order to make the moisture in the soil as uniform as possible. Then, the mixed soil was poured into three open-faced rectangle containers with a length of 360 mm and a width of 270 mm. The three containers were designed to have different depths of 5 mm, 10 mm and 20 mm so that the effect of soil layer thicknesses on the cracking behavior may be investigated. A thin layer of petroleum jelly (Vaseline) was pasted on the inner walls of the containers to reduce the boundary friction. To eliminate the air bubbles within the clay samples, the containers were slightly vibrated for about 3 min. Finally, the clay sample surfaces were smoothed lightly with a grafter to obtain a uniform thickness.

Table 1
Physical properties of the tested clayey soil.

Soil property	Value
Specific gravity, G_s	2.59
Liquid limit, L_L (%)	62.0
Plastic limit, L_P (%)	39.0
Shrinkage limit, L_S (%)	13.8
Plasticity index, P_I	23
USCS classification	CH

2.2. Freezing–thawing tests

Fig. 1 shows the experimental set-up for the cyclic freezing–thawing tests, which was developed by Li et al. (2013). The tests were performed in a closed system where drainage was closed and no additional water was permitted to enter into the sample during the tests, as done by Dirksen and Miller (1966). In a closed system, the freezing front cannot achieve continuous water supply during freezing because the rate of the downward frost penetration is generally faster than that of the upward moisture transportation (Wong and Haug 1991). In this study, the cyclic freezing–thawing test was performed by freezing the clay sample for 12 h at a temperature of −20 °C and then thawing the clay sample for 12 h at room temperature of about 25 °C. That is to say, one freeze–thaw cycle lasted for 24 h. As the surface of each clay sample was open to air during the test, the moisture evaporation from the sample was permissible. After every freeze–thaw cycle, each clay sample was weighted by using an electronic scale with a precision of 0.5 g and the corresponding water content of the sample was calculated. The freezing–thawing test for each sample was ended until the change of its water content was very small (less than 0.1%). Changes in humidity were not measured during the testing process.

2.3. Observation of crack patterns

During the tests, cracks that occurred in the sample surfaces were observed by using a simple image acquisition technique, which has also been used to observe clay cracking under desiccation and cyclic wetting–drying by some researchers (e.g., Tang et al. 2010, 2011a, 2011b; Xue et al. 2014). At the end of each freeze–thaw cycle, the surface of each sample was pictured by using digital camera to capture the crack patterns. The camera lens was fixed parallel to the sample surface with a suitable distance to ensure the sample totally within the shooting range. It is noted that the interval between the weighting of the sample and its picturing should be as short as possible (less

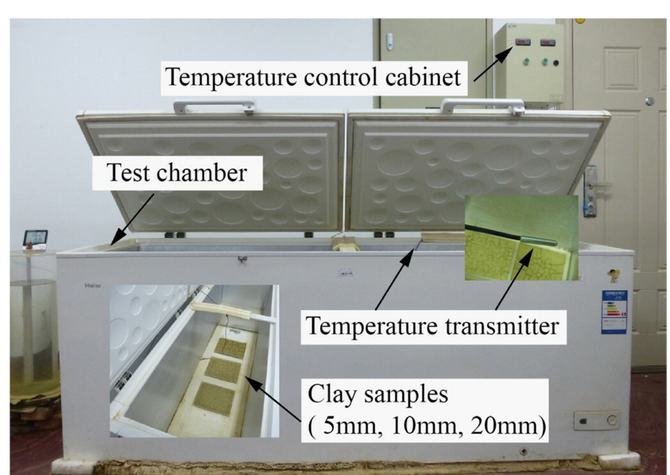

Fig. 1. Image of experimental set-up for the freezing–thawing tests.