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Reconstruction of Soil Particle Composition During Freeze-Thaw Cycling: A Review

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ABSTRACT

Studies conducted over several decades have shown that the freeze-thaw cycles are a process of energy input and output in soil, which help drive the formation of soil structure, through water expansion by crystallization and the movement of water and salts by thermal gradients. However, most of these studies are published in Russian or Chinese and are less accessible to international researchers. This review brought together a wide range of studies on the effects of freezing and thawing on soil structure. The following findings are summarized: i) soil structure after freeze-thaw cycles changes considerably and the changes are due to the mechanical fragmentation of soil coarse mineral particles and the aggregation of soil fine particles; ii) the particle size of soil becomes homogeneous and the variation in soil structure weakens as the number of freeze-thaw cycles increases; iii) in the freezing process of soil, an important principle in the variation of soil particle bonding is presented as: condensation → aggregation → crystallization; iv) the freeze-thaw cycling process has a strong effect on soil structure by changing the granulometric composition of mineral particles and structures within the soil. The freeze-thaw cycling process strengthens particle bonding, which causes an overall increase in aggregate stability of soil, showing a process from destruction to reconstruction.

Key Words: aggregate stability, aggregation, fragmentation, mineral particle, soil granulometric composition, soil structure

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INTRODUCTION

Due to the periodic changes of atmospheric temperature with seasons, soils in seasonally and permafrost (frozen ground) regions are inevitably subjected to periodic freezing and thawing, with temperatures alternately rising above and falling below 0 °C. Ground surfaces in cold areas may experience over 100 of these freeze-thaw cycles in one year. As a result, much attention has been paid to the long-term influence of freeze-thaw cycles on soil structure and environment in cold regions (Ershov, 1982). Freeze-thaw cycling is a process of energy input and output in soil (Li *et al.*, 2002). During this process, water and salt transfer causes changes in soil structure, with the initial stable state of soil particles being changed through aggregation and fragmentation, causing changes in particle granularity. These changes may result in further variations in soil, including its composition, structure and characteristics, all of which can lead to ecological and engineering problems.

From an ecological viewpoint, the changes in soil will affect its water-retention and nutrient-preservation capabilities, which will result in water loss, grassland degradation, desertification, *etc.* (Zhang and Zhu, 1993; Wu *et al.*, 2003; Wu *et al.*, 2004; Liang *et al.*, 2005; Zhang and Zhao, 2009). From an engineering viewpoint, the changes in soil will impact soil strength, bearing capacity of foundations, capillary water pressure in soil, and soil's plasticity and collapsibility (Gao and Xiong, 1988; Zhang and Wang, 2000; Zhu *et al.*, 2007; Luo *et al.*, 2009; Zhang and Pendin, 2010; Xu *et al.*, 2012). These geological changes in soil directly impact the stability of foundations and upper structures, resulting in the problems such as subsidence or upheaval of foundations and structural damage. Construction of soil structure in cold regions will destroy the natural water and heat balances in frozen soil by changing soil temperature, water and stress fields, resulting in the potential increase in the severity of damage from freeze-thaw cycles (Wu *et al.*, 2002).

The effect of freeze-thaw cycles can significantly change the arrangement and bonding of soil particles and thus soil structure (Chamberlain and Gow, 1979;

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Chamberlain, 1981; Pawluk, 1988; Layton *et al.*, 1993; Bullock *et al.*, 2001; Qi *et al.*, 2003; Qi and Ma, 2006). The freeze-thaw cycle destroys the initial state of soil to generate a new state with updated composition, structure and properties through a complex process that evolves physical and chemical changes. This paper reviews the processes and mechanisms of the micro- and macro-changes in soil structure under freeze-thaw cycles through analyzing soil mineral particles and soil granulometric composition.

FRAGMENTATION AND AGGREGATION OF SOIL MINERAL PARTICLES UNDER FREEZE-THAW CYCLES

Mechanisms of soil particle fragmentation

The fragmentation of larger soil particles to smaller fractions, a fundamental physical process that may occur naturally or be imposed, can have both beneficial and deleterious effects on the physical functioning of soil (Díaz-Zorita *et al.*, 2002; Gregory *et al.*, 2012). Temperature and moisture variations can cause material dilation (Thomachot *et al.*, 2005). Soil, as a material, is an unstable system under freeze-thaw cycles. Interactions between liquid water, solid ice and water vapor exchange mass and energy with the external environment in a process that, from a geological point of view, is called a weathering process. Freezing is also a weathering process, but it is potentially more severe than common physical weathering because of the high degree of weathering that results from the transformation of water to ice, which involves a change in volume of about 9%. Volumetric expansion of pore water during freezing adds to material cracking (Walder and Hallet 1986), and ice segregation at subzero temperatures is another productive power in cracking rocks as shown by Hallet *et al.* (1991), Murton *et al.* (2006) and Hall and Thorn (2011). Soils with high moisture content will generate more ice with stronger expanding forces, which are likely to break inter-particle bonds, whereas in soils with low moisture content, ice crystals simply grow in soil pores (Nickling and Bennett, 1984; Bullock *et al.*, 1988; Ferrick and Gatto, 2005). Freezing causes fragmentation only in relatively coarse soil particles (including silty and coarser particles). Furthermore, thermal stress alone can drive rock and particle fragmentation in the course of high-amplitude daily or seasonal temperature changes (Hall and André, 2003). However, in soil clay particles, large numbers of water molecules exist in the form of bound water, and no cracking happens because of the greater amount of unfrozen water than that found in coarse particles.

Soil is made up of a variety of mineral components, and each mineral component has its own deformation and stress behaviors under freeze-thaw cycles. The stress depends on the magnitude of temperature variation: the greater the temperature varies, the greater the stress becomes, even reaching a level of KMPa (Chernyakhovsky, 1968) that may cause anisotropy in the thermal and physical characteristics of soil. Many studies have shown that the bonding stress between soil particles in a radius of 1 mm can reach 500 MPa under a vertical compression of 0.2 MPa (Poltev, 1966; Tsytovich, 1973; Ershov *et al.*, 1978). Thus, an external stress of as much as 2 MPa can be generated in the freezing process of soil (Tsytovich, 1973). We can confirmed that under contacting stress, the existing joints in soil coarse particles continue to develop, accompanied by the expansion of closed joints, which leads to the fragmentation of coarse mineral particles.

Poltev (Poltev, 1967) divided the frost weathering process of soil mineral particles into two stages. At the first stage, the phase changes of water (from liquid to solid phase) in soil result in the generation of cracks on the surface of mineral particles driven by the temperature tension (Step 1) (Fig. 1), and pore water becomes ice, thus resulting in increases the volume by about 9% in the freezing process (Li *et al.*, 2015) and development of the micro-cracks of particles sustained into macro-cracks (Step 2) (Fig. 1). At the second stage, the thickness of water film in the crack of soil particles increases (Step 3) (Fig. 1), causing further fragmentation of primary minerals (Step 4) (Fig. 1) (Poltev, 1966, 1967, 1977; Han and Cheng, 2015).

As shown in Fig. 1, the intensity of frost weathering is proportional to the number of freeze-thaw cycles and soil water content. The size of cracked secondary mineral particles is always larger than 0.01 mm, and there are great differences in the degree of fragmentation for primary minerals (Konischev, 1973). Studies on the fragmentation of primary minerals under freeze-thaw cycles showed that soil mineral particles with banded or layered structure, which were fragmented into silt particles, experienced a greater degree of fragmentation than those with skeleton structure, as shown in Fig. 2. In the particles with layered structure, all clay minerals consist of two fundamental units: sheets of silicon (Si)-oxygen (O) tetrahedra and sheets of aluminium (Al) or magnesium (Mg) octahedra, in which each Al^{3+} or Mg^{2+} ion is linked to six hydroxyl (OH^-) anions. The sheets of Si-O tetrahedra (silica sheets) are shown in Fig. 2a, and they are easily penetrated by water. All silicate minerals contain silicate oxyanions (SiO_4^{4-} groups). These oxyanions resemble a tetrahe-