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Effects of Freeze–thaw Cycles on Soil Mechanical and Physical Properties in the Qinghai–Tibet Plateau

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Abstract: Extreme freeze-thaw action occurs on the Qinghai-Tibet Plateau due to its unique climate resulting from high elevation and cold temperature. This action causes damage to the surface soil structure, as soil erosion in the Qinghai-Tibet Plateau is dominated by freeze-thaw erosion. In this research, freezing–thawing process of the soil samples collected from the Qinghai–Tibet Plateau was carried out by laboratory experiments to determinate the volume variation of soil as well as physical and mechanical properties, such as porosity, granularity and uniaxial compressive strength, after the soil experiences various freeze–thaw cycles. Results show that cohesion and uniaxial compressive strength decreased as the volume and porosity of the soil increased after experiencing various freeze–thaw cycles, especially in the first six freeze–thaw cycles. Consequently, the physical and mechanical properties of the soil were altered. However, granularity and internal friction angle did not vary significantly with an increase in the freeze–thaw cycle. The structural damage among soil particles due to frozen water expansion was the major cause of changes in soil mechanical behavior in the Qinghai–Tibet Plateau.

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Introduction

Freeze–thaw action refers to the freezing and thawing of water within a certain range in permafrost caused by daily, seasonal, and multi-annual variations of surface temperature in a specific climatic zone (French 2007). This action occurs mostly in cold regions at high latitudes and altitudes, and may occur as surface temperatures fluctuate above and below zero degrees Celsius. The volume of water expands as it freezes in the soil, thereby exerting large pressure on the pore walls in soils and rocks and altering physical and mechanical properties of those soils and rocks (Bing and He 2009; Hazirbaba and Gullu 2010; Gullu and Hazirbaba 2010; Lin et al. 2011; Gullu and Khudir 2014). These properties include aggregates and stability (Oztas and Fayetorbay 2003), permeability (Othman and Benson 1993; Kurylyk and Watanabe 2013), hydraulic conductivity (Konrad 2000), bulk density (Yang et al. 2003), volume (Viklander 1998; Zhang et al. 2007), porosity and particle size (Viklander and Eigenbrod 2000; Chepil 1942), water content (Kim and Daniel 1992), strength (Swan and Greene 1998; Formanek et al. 1984; Kok and Mccool 1990; Qi and Ma 2006), particle arrangement (Konrad 1989; Qi et al. 2003), and elastic modulus (Simonsen et al. 2002). The original structures of soil and rock are destroyed (Chamberlain and Gow 1979; Lai et al. 2008), and composition materials are broken up and disaggregated into loose debris (Mutlutuk et al. 2004). The demolition of freeze–thaw action on soil bodies originates from water migration in the soil, while the temperature gradient from the positive and negative variations of surface temperature drives this phenomenon (Wang et al. 2005). The strength of the destructive action is related to factors such as surface freezing temperature, freezing depth, freezing duration, and winter snowfall. Generally, lower surface temperature (Bai et al. 2012; Wan et al. 2012), deeper freezing depth, longer freezing duration, and larger winter snowfall make the damage more severe (Chang et al. 2014; Chen et al. 2008).

The Qinghai–Tibet Plateau is located in an alpine frost zone with an average elevation exceeding 4000 m. The air temperature is low, the daily temperature range is large (Liu et al. 2008), and the number of days with alternately occurring positive and negative air temperatures varies between 150 and 300 $d \cdot a^{-1}$ in a large part of the plateau, leading to prolonged freeze–thaw alternation (Yang et al. 2007). Intense and frequent freeze–thaw actions alter the physical and mechanical properties of soils, produce loose and clastic materials on the surface, and increase material sources for wind and water erosion (Sharratt et al. 2000). As the most severe freeze-thaw erosion region of China (Liu et al. 2006), the freeze-thaw erosion of Qinghai-Tibet Plateau covers an area of 104×10^4 km^2, accounting for 82% of China’s total freeze-thaw erosion area (126.98×10^4 km^2), and the eroded product is one of the main sediment sources of the Yangtse River, Yellow River, and Lancang River (Fan and Cai 2003). Freeze-thaw erosion is a large eco-environmental problem facing the Qinghai-Tibet Plateau, and investigating these processes is essential for soil and water conservation (Dong et al. 2000). Studies regarding the effect of freeze–thaw action on physical and mechanical properties of soils are available (Ma et al. 1999; Qi et al. 2008; Broms and Yao 1964). However, only a few studies involve the Qinghai–Tibet plateau, and the results show that some physical–mechanical characteristics of investigated soils change after they were subjected to freeze–thaw cycles, such as the height of sample, water content, the resilient modulus and the failure strength (Wang et al. 2005; Wang et al. 2007), there are still other physical and mechanical characteristics of Qinghai–Tibet soils that urgently need to be studied after soils are subjected to freeze–thaw cycles, such as porosity, granularity and uniaxial compressive strength. The potential influence of future climate warming on the number of freeze-thaw cycles and associated geotechnical failures (Harris et al. 2009; Kurylyk et al. 2014) provides the impetus for seeking a better understanding of the influence of freeze-thaw cycles on soil physical and mechanical properties. Therefore, physical and mechanical properties of a variety of soil samples collected from the Qinghai–Tibet Plateau during the freeze–thaw processes were selected as the objects of this research, in order to enhance our understanding of the laws of freeze-thaw erosion, thereby providing the basis for controlling the freezing-thawing hazards of Qinghai-Tibet Plateau.

1 Study Area

The Honglianghe River, located at 35°03'13"N, 93°01'07"E, was chosen as the sampling place for this work. The site is located in the hinterland of Qinghai–Tibet Plateau and described as a cold and semiarid climate region with an average altitude of 4600 m (Figure 1). The average annual temperature is −4.2°C, the lowest monthly average temperature is −16.9°C, the highest monthly average temperature is 6.3°C, the extreme maximum temperature is 17.0°C, and the extreme minimum temperature is −30.3°C. The annual average relative humidity is 54.2%, the annual average saturation vapor pressure is 306.3 kPa, the average annual number of strong wind days is 136 (Xie et al. 2014), and the annual average rainfall is 266 mm. Landforms of the region are relatively flat

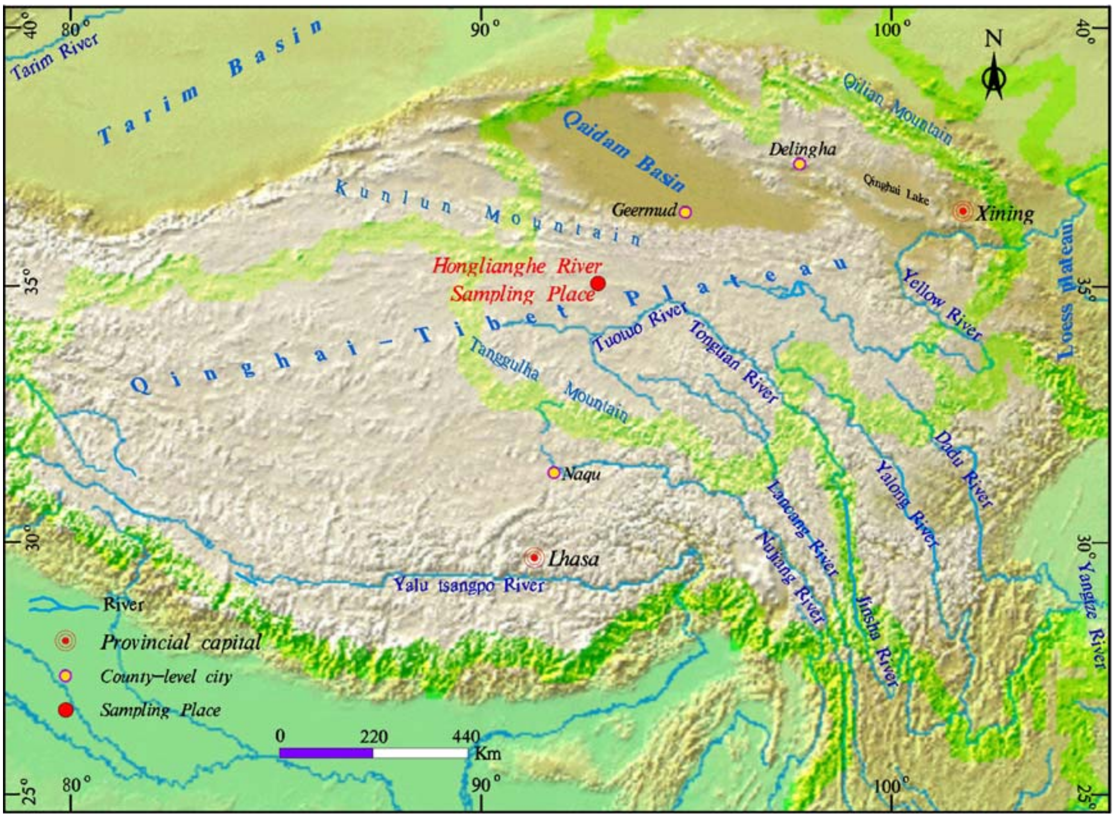


Figure 1 Location map of Honglianghe River of Qinghai-Tibet Plateau.

and vegetation is sparse and dominated by herbaceous plants. Soil samples were collected from the primitive bedrock surface.

2 Materials and Methods

2.1 Sample preparation

The dry density of the soil in the sample preparation was set to 1.8 $g\cdot cm^{-3}$ according to the dry density of soil for road engineering in the sample location. The soil texture of the sample belongs to argillaceous siltstone. The grain size distribution curve of the soil sample is shown in Figure 2 and the Gs (specific gravity), Sr (saturation), Cu (coefficient uniformity), Cc (coefficient of curvature) of the soil sample are 2.69 $g\cdot cm^{3}$, 65.32%, 20%, 3.53%, respectively. Sample preparation by undercompaction was conducted according to related research (Gullu 2014), cylindrical test samples that were 61.8 mm in diameter, 125 mm in height, and possessing moisture content of 12% were passed through a 2 mm circular-hole (diameter) sieve. According to the volume size and water content of sample, soil samples with the target dry density were weighed and molded at one time in the special sampling machine. The soil samples were saturated by using distilled water under vacuum conditions for 4 hours, and then were set in negative temperature conditions for over 48 hours. To ensure stable water content in the freeze–thaw experiment

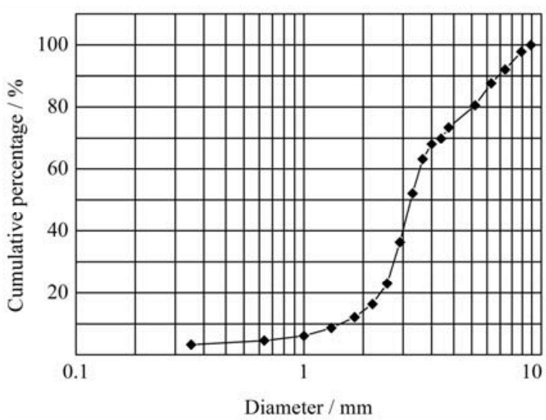


Figure 2 Grain size distribution curve of the soil sample tested.

processes, samples were sealed by double-layer plastic foil and a self-sealing bag, and then placed in a freeze–thaw experiment box to simulate the surface freezing and thawing processes of the Qinghai–Tibet Plateau. With 24 h as a circulation period, both freezing and thawing durations were 12 h. The freeze–thaw temperature difference was from −40°C to 20 °C, and freeze–thaw circulation times were 0, 1, 3, 6, 9, 12, and 15. In addition, some physical parameter variations, such as volume, porosity and granularity of the test samples, were measured during the freeze–thaw processes.

Volumetric strain ε_v was introduced to quantify the relative volume variation of soil samples during the freeze–thaw processes in this research.

$$\varepsilon_v = \frac{\Delta V}{V_0} \times 100\% \quad (1)$$

where ε_v is the volume strain rate, ΔV is the volume after each freeze–thaw cycle (cm^3), and V_0 is the original volume of the tested sample (cm^3).

Porosity was obtained from specific density and dry bulk density, and can be calculated by the following formula:

$$P = (1 - \frac{d}{d_1}) \times 100\% \quad (2)$$

where P is porosity (%), d is dry bulk density ($g \cdot cm^{-3}$), and d_1 is specific density ($g \cdot cm^{-3}$).

Granularity of the soil particles was obtained by sieving analysis.

2.2 Test equipment and methods

To investigate the effect of freeze–thaw cycle action on the mechanical properties of soil samples from Qinghai–Tibet Plateau, seven types of soil samples after different freeze–thaw cycles were used in uniaxial and triaxial compression tests at room temperature of 15°C. After a fixed number of freeze–thaw cycles, all the samples were kept at a room temperature of 15°C for 24 h, and then used in two types of tests. Uniaxial compression tests were performed on the seven types of soil samples with a constant loading rate of 1.25 mm/min in the entire test by using a conventional universal material testing machine with a maximum load range of 100 KN (Figure 3, left). After the axial load reached a peak, the load was continued for another 2.5 mm and the test was stopped. The peak stress was taken as the uniaxial strength. Triaxial compression tests were conducted on the seven types of soil samples by using an MTS-810 material testing machine (Figure 3, right) whose axial load range was 100 KN. Axial displacement was in the range of −85 cm to 85 cm, and confining pressure load was in the range of 0 MPa to 20 MPa (Gullu 2014), all triaxial compression tests were conducted under consolidated and drained conditions, and the axial constant loading rate was 1.25 mm/min. The testing temperature was maintained at 20°C in the loading process.

3 Experiment Results

3.1 Effect of freeze–thaw cycle on soil physical parameters

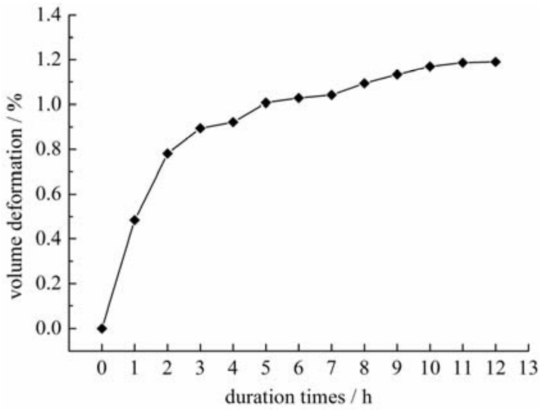
According to Equation (1), sample volume strain can be obtained during the process of freezing, as shown in Figure 4(a). In the freezing

Figure 3 The test equipment.

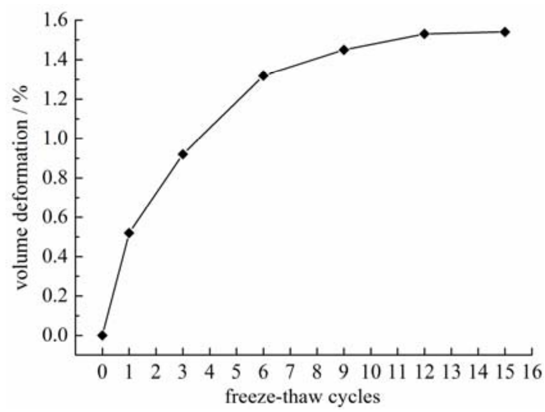
process of a single specimen, volume deformation gradually increased with time due to frost heaving, especially within the first 3 h. The growth rate of volume strain was at maximum at 3 hours, after which the increase had slowed down and generally tended to be stable. Figure 4(b) shows the variation pattern of the volume strain along with the freeze–thaw cycles. During the first six freeze–thaw cycles, the volume strain rate of the specimen was larger. Between the 6th and 15th freeze–thaw cycles, the volume strain was roughly stable between 1.3 and 1.5. Soil porosity is another physical parameter affected by freeze–thaw cycles (Figure 4(c)). Porosity increased significantly from 23% to 32% during the 15 freeze-thaw cycles. Furthermore, the porosity growth rates were the fastest during the first six freeze-thaw cycles. To further analyze the influence of freeze–thaw cycles on soil structure, this research also analyzed the granularity variation characteristics of each particle group of soil samples, as shown in Table 1. The particle mass fraction of each soil granularity did not exhibit obvious variation within 15 freeze–thaw cycles.

3.2 Uniaxial compression test results

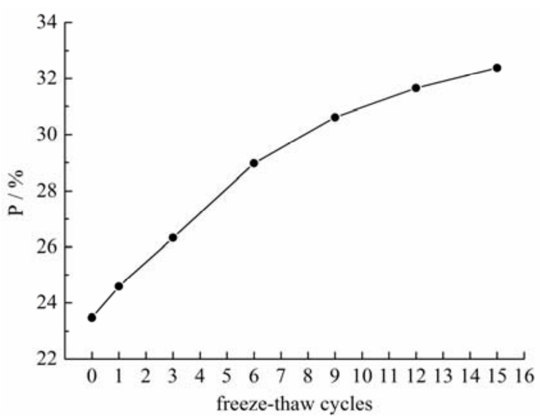
Figure 4(d) shows the variation pattern of uniaxial compression strength of the tested samples after being exposed to freeze–thaw cycles. The uniaxial compressive strength of the test sample that did not undergo freeze–thaw cycles was 252.3 kPa. After one, three, and six freeze–thaw cycles, the strength of the samples were 177.3, 98.7, and 86.4 kPa, respectively. Freeze–thaw cycles significantly reduce the compressive



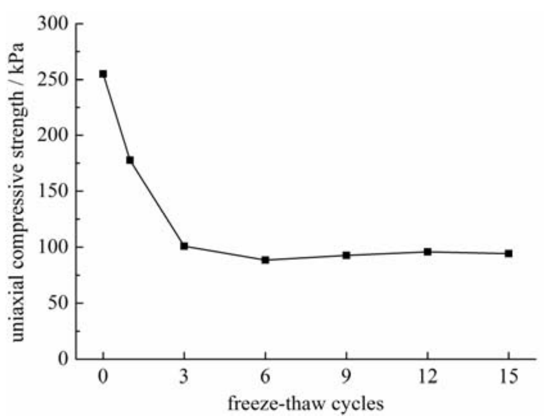
(a) Relation between freezing time and volume variation in the tested sample



(b) Relation between freeze–thaw cycles and volume variation in the tested sample



(c) Relation between freeze–thaw cycles and porosity of the tested sample



(d) Relation between freeze–thaw cycles and uniaxial compressive strength of the tested sample

Figure 4 Relations between freeze–thaw cycles and physical and mechanical properties of the tested sample.

strength. The uniaxial compression strength of the tested sample was relatively unchanged after six freeze-thaw cycles.

3.3 Triaxial compression test results

The triaxial compression test results of different soil samples under four kinds of confining pressure strengths are shown in Table 2. In order to investigate the effect of freeze–thaw cycles in complex stress state of failure points for testing soils, the strength envelope curves of different soil samples in the p-q stress space were plotted.

$$p = \frac{1}{3} I_1 = (\sigma_1 + \sigma_2 + \sigma_3)/3$$

$$q = \sqrt{3J_2} = \frac{1}{\sqrt{2}} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}$$

where p is mean stress (kPa), q is deviatoric stress (kPa), I_1 is the first invariant stress (kPa), and J_2 is the second invariant of stress deviator (kPa), σ is the normal pressure of failure surface (kPa). Under the triaxial stress state, $q = \sigma_1 - \sigma_3$, $p = \frac{1}{3}(\sigma_1 + 2\sigma_3)$.

Table 1 Granularity of the tested sample after experiencing various freeze–thaw cycles (%)

Granularity (mm)	Freeze–thaw times 0	1	3	6	9	12	15
2.00–0.50	8.65	8.82	9.10	8.65	9.50	8.90	9.35
0.50–0.25	9.55	9.38	9.40	9.15	9.25	9.55	9.45
0.25–0.05	64.45	61.46	59.15	59.85	60.30	60.95	59.75
0.05–0.005	11.20	11.90	12.20	14.40	12.80	12.20	11.60
＜0.005	6.15	8.44	10.15	7.95	8.15	8.40	9.85

Table 2 The triaxial test results of the tested sample after experiencing various freeze–thaw cycles

Freeze–thaw times	Sample no.	Confining pressure σ_3 (kPa)	Destruction of axial stress σ_1 (kPa)
0	$C_{0\text{-}1}$	17	175
	$C_{0\text{-}2}$	49	295
	$C_{0\text{-}3}$	80	415
	$C_{0\text{-}4}$	112	535
1	$C_{1\text{-}1}$	21	166
	$C_{1\text{-}2}$	52	293
	$C_{1\text{-}3}$	87	417
	$C_{1\text{-}4}$	115	548
3	$C_{3\text{-}1}$	26	136
	$C_{3\text{-}2}$	56	250
	$C_{3\text{-}3}$	91	340
	$C_{3\text{-}4}$	120	476
6	$C_{6\text{-}1}$	24	159
	$C_{6\text{-}2}$	56	294
	$C_{6\text{-}3}$	85	432
	$C_{6\text{-}4}$	118	566
9	$C_{9\text{-}1}$	26	142
	$C_{9\text{-}2}$	57	266
	$C_{9\text{-}3}$	91	387
	$C_{9\text{-}4}$	119	514
12	$C_{12\text{-}1}$	29	117
	$C_{12\text{-}2}$	61	220
	$C_{12\text{-}3}$	94	323
	$C_{12\text{-}4}$	128	423
15	$C_{15\text{-}1}$	27	126
	$C_{15\text{-}2}$	61	233
	$C_{15\text{-}3}$	94	343
	$C_{15\text{-}4}$	124	454

As shown in Figure 5, the failure loci of the seven-group testing samples were essentially identical in the p-q stress space. The freeze–thaw cycles had no significant influence on the shape of the failure surface of the soil samples. However, the failure surfaces of the samples which experienced 12-15 freezing-thawing cycles were significantly lower than that experienced other times of freezing-thawing cycles. The main reason for this was that freeze-thaw cycle affected the whole property of testing soils and thus resulted in notable decrease of failure loci. To further analyze the effects of freeze–thaw cycles on soil failure strength, linear failure surfaces of the soil sample were obtained under the $\sigma - \tau$ plane based on the Mohr–Coulomb criterion((Li et al. 2009) (Figure 6):

$$\tau = \sigma \tan\varphi + c$$

where τ represents shear strength of the soil sample (kPa), σ represents normal pressure of failure surface (kPa), φ is the internal friction angle (degrees), and c is cohesion (kPa).

As shown in Figure 6, the cohesion value and the internal friction angle of the soil sample that did not undergo freeze–thaw cycles were 28.18 kPa and 35.69°, respectively. During the initial freeze–thaw cycles (the first six times), the cohesion of the soil samples significantly decreased after one, three, and six freeze–thaw cycles. The cohesion values of the soil samples were 18.58, 12.97, and 10.1 kPa, respectively. After six freeze–thaw cycles, cohesion decreases slowly as the number of freeze–thaw cycles increases. In addition, internal friction angle has no obvious variation within 15 freeze–thaw cycles.

4 Discussion

Freezing and thawing processes are the responses of soil physical characteristics to temperature boundary conditions. In essence, these processes comprise the development of soil samples from an unstable state to a dynamic and steady state (Lee et al. 1995). The steady state of

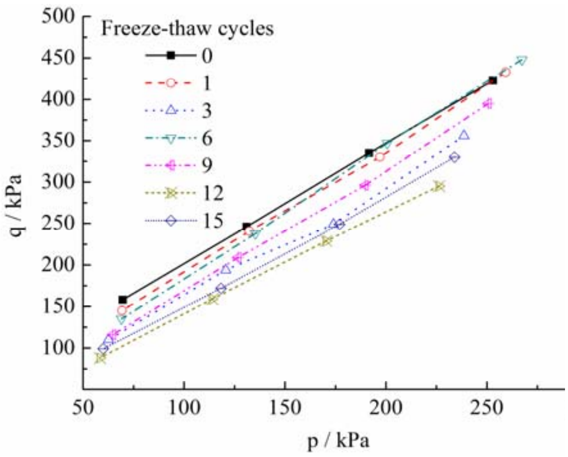


Figure 5 Failure loci of specimens in the p-q space.

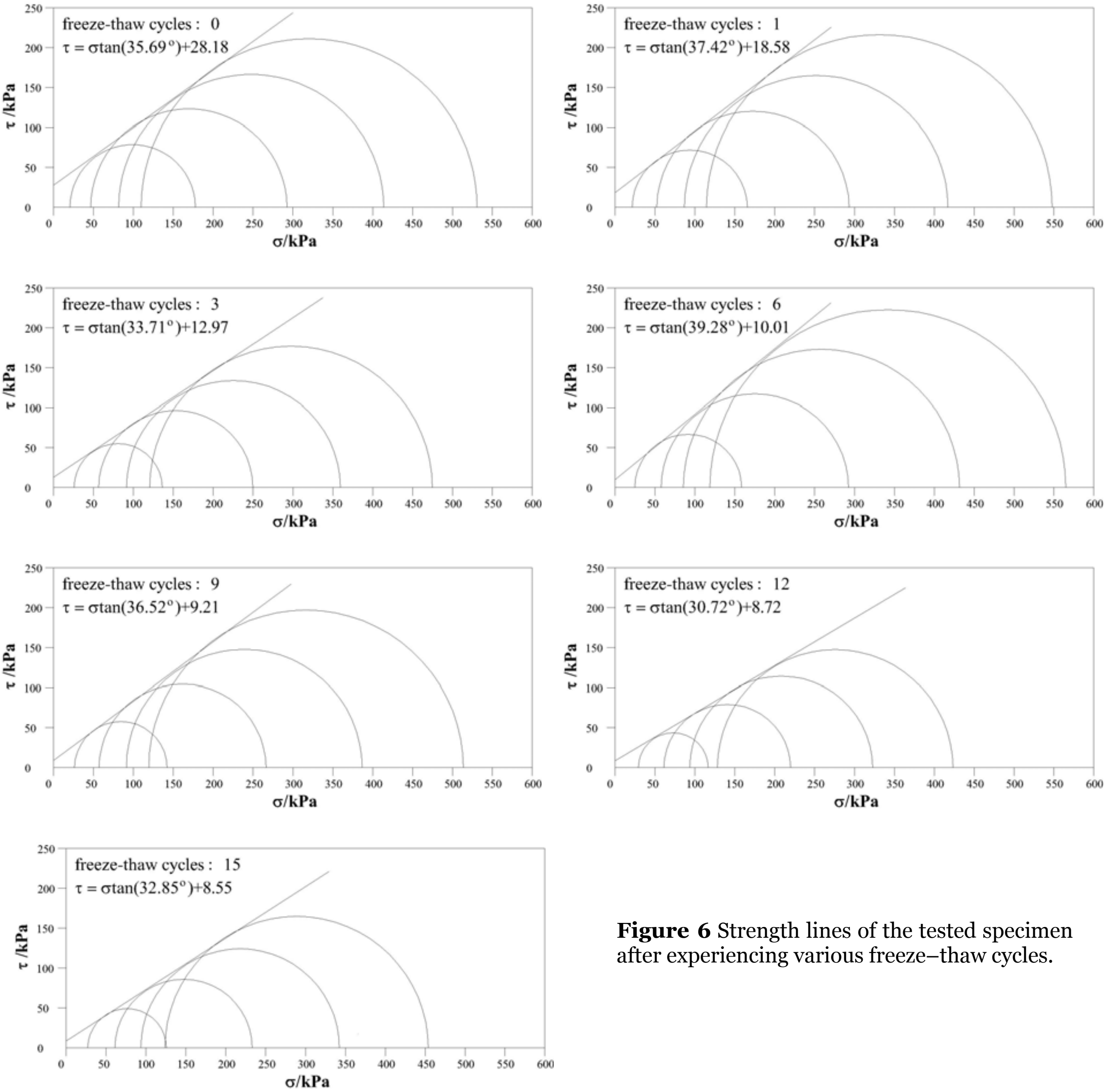


Figure 6 Strength lines of the tested specimen after experiencing various freeze–thaw cycles.

testing soil is achieved when the gap in the soil particles caused by a rearrangement of the soil particles is constant. Multiple freeze–thaw cycles cause irreversible alterations in some physical characteristics and further change the physical and mechanical characteristics of soil. During the freezing process, water in the soil samples increases the pressure in the soil pore wall due to volume expansion. Thus, the gap between the soil particles increases, which causes a rearrangement of the soil particles. In the melting process, particle gaps produced in the frost heave cannot be fully recovered, directly leading to an irreversible porosity increase due to the process of freezing and thawing. The particle mass fraction of each soil granularity did not exhibit obvious variation within 15 freeze–thaw cycles as the freeze-thaw cycles were not sufficiently long enough to induce the soil particles to fail.

Soil strength is mainly determined by the interactions between particles rather than the strength of particle minerals themselves. The main failure mode of soil is shear failure, and its strength is directly affected by cohesion and the internal friction angle. During the initial freeze–thaw cycles (fewer than six times), volume strain and porosity of the tested sample increased significantly, causing soil particle gaps and altered arrangement. The original connection between soil particles failed and cementation strength decreased, affecting soil cohesiveness and inducing a decrease in uniaxial destruction strength. With the increase in number of freeze–thaw cycles (6 times to 15 times), the uniaxial compression strength of the tested sample tended to become stable due to stabilizing of the volume strain and porosity. However, it can be clearly concluded that the volume strain and porosity are two primary factors for uniaxial strength for testing soil, which are both strongly sensitive to freeze–thaw cycle exposure.

After six freeze–thaw cycles, cohesion decreases slowly as the number of freeze–thaw cycles increases. The main cause of soil cohesion weakening is particle structure rearrangement in the soil samples. This finding is consistent with the results of the uniaxial test. The internal friction mechanisms of soil samples are mainly categorized into two categories: occlusal friction and sliding friction. The two kinds of mechanisms are affected by soil particle arrangement, particle composition, particle fragmentation, and the particle mass fraction of each granularity of soil sample that did not exhibit obvious variation within 15 freeze–thaw cycles. The number of freeze–thaw cycles did not cause the soil particles to fail. The triaxial constant confining pressure test was adopted by using low confining pressure (less than 130 kPa). The increase in confining pressure did not significantly influence the arrangements and gaps of particles in the soil samples, and failed to further influence occlusal friction between particles.

Similar to previous studies (Yang et al. 2003; Wang et al. 2005; Wang et al. 2007), the present study considered the influence of freeze-thaw cycles on the physical and mechanical properties of soil samples from the Qinghai-Tibet plateau. However, the present study is unique in several aspects. Firstly, the soil textures are different. The soil texture of the samples in previous studies were clays and sandy loam, but the soil texture of the samples in the present study were argillaccous siltstone. Secondly, the test results are different. In previous studies, the internal friction angle exhibited an increasing trend as the times of freeze–thaw cycles increased, but the internal friction angle maintained a fluctuation between 30° and 40° and showed no evident regular variation in the present study. Finally, the perspectives are different, the previous studies investigated this issue from the perspective of mechanics, which covered the effects of freeze–thaw on physical–mechanical properties of soil such as dry density, sample height, water content, stress–strain behavior, failure strength, elastic modulus, cohesive modulus and internal friction angle. However, in the present study, the same issue was investigated from the perspective of environment, the aim of which was to explain the environmental impacts of the physical–mechanical property changes of soil resulting from freeze–thaw cycles.

5 Conclusions

With the rapid development of infrastructure in cold regions (Ma et al. 2011; Lai et al. 2012; Zhang et al. 2012), the effects of freeze–thaw cycles on the physical and mechanical properties of soil requires more attention from the engineering and academic communities. The potential influence of future climate warming on the number of freeze-thaw cycles and associated geotechnical failures (Harris et al. 2009; Kurylyk et al. 2014) provides the impetus for seeking a better understanding of the influence of freeze-thaw cycles on soil physical and mechanical properties. With this premise, a series of freeze–thaw cycle tests, uniaxial compression tests, and triaxial constant confining pressure tests were carried out in soil samples collected from the Qinghai–Tibet Plateau. Some conclusions drawn from the test results are summarized below.

1. In the single freezing process, the growth rate of volume strain attained its maximum within the first 3 h. The volume strain of the soil sample increased as the freeze–thaw cycles increased, and the growth rate of volume strain was maximal within the first six freeze–thaw cycles. The variation pattern of porosity and freeze–thaw cycle was similar to that of volume strain. Granularity did not exhibit obvious variation within 15 freeze–thaw cycles.

2. The variation in the uniaxial compression strength of the soil sample was great within six freeze–thaw cycles. Consequently, the uniaxial compression strength of the soil sample after six freeze–thaw cycles was only 34.7% of the soil sample that did not undergo freeze–thaw cycles. The uniaxial compressive strength remained approximately stable after six freeze-thaw cycles.

3. Freeze–thaw cycles had no significant influence on the shape of soil sample failure locus under the p-q stress space. The failure surfaces of the soil sample after 12 and 15 freeze–thaw cycles were significantly lower relative to those of other soil samples. The soil sample cohesion decreased gradually as the number of freeze–thaw cycles increased, and the decreased rate of cohesion was maximal within six freeze–thaw cycles. In addition, the internal friction angle was barely affected by freeze–thaw cycles. During the entire experiment, internal friction angle fluctuated between 30° and 40° and showed no evident regular variation.

The three groups of experiment results demonstrate that freeze–thaw cycles influence the physical and mechanical behavior of soil samples from the Qinghai–Tibet Plateau. The initial freeze–thaw action, the variation of particle gaps, and the arrangement in the soil sample affect physical and mechanical behaviors directly. Six freeze–thaw cycles were found to critically influence the properties of soil in the scope of this research.

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