The influence of freeze-thaw cycles on loess cutting slope in seasonal frozen regions

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ABSTRACT
Denudation, a common disaster existing on loess cutting slope in seasonal frozen regions, will lead to near-surface soil erosion, damage of road landscape, and finally affect the operation of the road. With respect to the disaster, the automatic meteorological stations were setup at three field sites along expressway from Pingliang to Dingxi, northwest of China, and the ground temperatures and volumetric moisture contents on loess cutting slope at different depths, were monitored and measured for about 2 years. The monitoring and measurements indicated that even in winter-time the near-surface ground temperature was below zero all day long, freeze-thaw cycles still took place. Those cycles would result in variations of the moisture content of the near-surface soil, which had been validated by the measurements. Based on the results of field monitoring and measurements above, further laboratory experiments were conducted. The undisturbed soil samples with different moisture content were tested after freeze-thaw cycles. The direct shear tests showed that the freeze-thaw cycles and dry-wet cycles resulted in a considerable decrease of loess strength. The results of field and laboratory experiments showed that freeze-thaw cycle was an important factor, which induce the denudation on the loess cutting slope in seasonal frozen regions.

RÉSUMÉ
Dénudation, une catastrophe communes existantes sur la pente de la coupe de loess dans les regions glacées saisonniers, conduira à l'érosion du sol près de la surface, les dégâts du paysage routier, et enfin d'affecter le fonctionnement de la route. En ce qui concerne la catastrophe, les stations météorologiques automatiques ont été installées à trois sites le long de les voies express de Pingliang à Dingxi, nord-ouest de la Chine. De plus, la température du sol et la teneur en humidité volumétrique sur la pente de la coupe de loess à différentes profondeurs, ont été suivis et mesurés environ 2 ans. Les surveillances et les mesures ont indiqué que les cycles de gel-dégel ont encore lieu lorsque la température du sol près de la surface était encore en dessous de zéro pendant la journée de l’hiver. Ces cycles se traduirait par des variations de la teneur en humidité du sol près de la surface, qui avait été validé par les mesures. Basé sur les résultats ci-dessus, les autres expériences de laboratoire ont été effectuées. Les échantillons de sol non perturbé avec les teneurs en humidité différentes ont été testées après des cycles de gel-dégel. Les essais de cisaillement direct ont montré que les cycles de gel-dégel et les cycles sec-humide a entraîné une diminution considérable de la force de loess. Les résultats ont montré que le cycle de gel-dégel a été un facteur important, qui induisent la dénudation sur sur la pente de la coupe de loess dans les regions glacées saisonniers.

1 INTRODUCTION

In China, the loess covers an area of 640,000 km^2, and most of it lies in seasonal frozen regions. As a kind of special soil, the loess has a uniform particle spatial distribution, but a poor resistance to erosion and will collapse when wetting due to its richness in vertical joint fissure, large pores and calcium. In seasonal frozen regions, after the excavation of loess cutting slope, near-surface soils will loose and the salt will migrate to the slope surface during the period from late autumn to early spring, which will lead to soil erosion, environment pollution and damage of road landscape. Sometimes, soils falling from the cutting slope will block the side ditches, and finally impact the operation of the road. Through the investigations of expressways and secondary roads in Gansu province, northwest of China, it was found that the main disasters of loess cutting slope are denudation and gully erosion as shown in Figure 1.

Denudation is a common disaster on loess cutting slope in seasonal frozen regions, including scaly, lamellar and schistose denudations, and has few proper and effective treatments. The disaster is related to the characteristics of loess including clay and salt content, and also to environmental factors including freeze-thaw cycles and dry-wet cycles (Feng and Zheng, 1980). As a kind of weathering, the freeze-thaw cycles have a strong influence on clay strength. When the void water temperature in the soil descends to subzero, they will freeze and expand in volume. This expansion will destroy the glue function and internal structure of soil, and then undermine the soil strength. (Tsytovich, 1985; Konrad, 1989; Qi et al., 2004; Yong and Boonsinsuk, 1985; Wang et al, 2007)

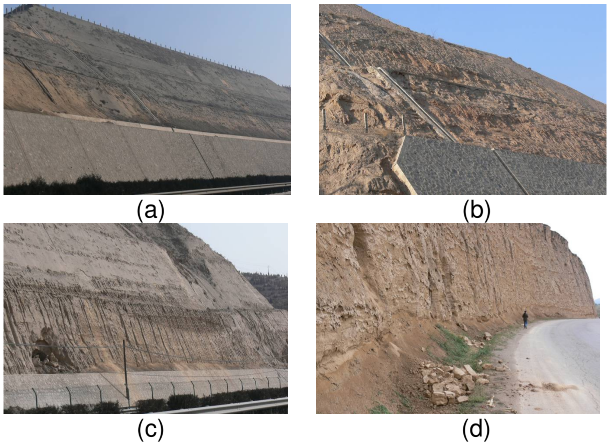


Figure 1. The examples of denudation and gully erosion on loess cutting slopes in Gansu province

At present, many researches about influence of freeze-thaw cycles on loess mainly focus on disturbed soils but little focus on undisturbed soils. However, the disturbed and undisturbed soils differ from their microstructures and consequently from their mechanics properties. So this paper researched the depth of undisturbed loess on cutting slope influenced by freeze-thaw cycles through field observation and measurement. And by laboratory test, the paper researched the impact of freeze-thaw cycles on dry density and shearing strength of undisturbed loess samples.

2 FIELD OBSERVATION AND MEASUREMENT

2.1 Observation instruments and method

Based on many years of observation data from six meteorological stations along expressway from Pingliang to Dingxi, we divide the expressway into two sections: semi-humid section from Jingchuan to Pingliang and semi-arid section from Dingxi to Huining. Then three automatic meteorological stations (Figure 2) were erected at typical loess cutting slopes separately located in Pingliang (semi-humid section), Dingxi (semi-arid section) and Jingning (border of two sections), so that the air temperature, air humidity, radiation, ground temperatures and volumetric water contents at different depths on the slope were measured and collected during the period from 2006 to 2008. The ground temperatures and volumetric water contents were measured at 5 cm, 20 cm, 50 cm and 100 cm depths perpendicularly from the slope surface. Both the ground temperature sensor and the water content sensor are made by ONSET Company (America), and the precision of the two sensors are ± 0.2 ℃ and ± 3%, respectively.

Figure 2. The automatic meteorological station

2.2 The physics properties of loess at observation stations

Undisturbed loess samples were collected near meteorological stations in Pingliang, Dingxi, Jingning, and their physics properties were tested in the laboratory. The test results were described in Table 1, and from these results we found that the three soil samples were all typical clay with lower liquid limit.

Table 1 Physical properties of three loess samples collected from Jingning, Dingxi and Pingliang

Place	Depth (cm)	Wet density (g/cm^3)	Natural moisture content(%)	Specific gravity	LL(%)[1]…. PL(%)[2]	Plasticity index	Cohesion (Kpa)	internal friction angle(º)
Jingning	10～35	1.41	15.5	2.724	32.8 22.2	10.6	1.8～6.2	15.8～20.9
	35～50	1.21	11.2	2.718	33.2 23.9	9.3	0.8～2.5	13.8～18.9
Dingxi	0～25	1.78	11.4	2.74	29.7 20.2	9.5	6.9	20
	25～50	1.83	11.6	2.782	29.3 18.7	10.6	0.4～7.3	13.0～14.2
	50～75	1.78	10.9	2.768	28.8 19.1	9.7	18.0～22.3	8.4～14.0
	75～100	1.69	10.1	2.759	28.5 19.3	9.2	11.5～27.7	12.8～18.9
Pingliang	0～25	1.89	13.8	2.754	30.1 20.1	10	14.8～37.8	13.7～26.0
	25～50	1.74	13	2.76	30.5 20.0	10.5	7.2	17.9
	50～75	1.79	13.5	2.749	31 20.8	10.2	7.3～12.1	16.8～22.0
	75～100	1.8	13.2	2.736	31 19.6	11.4	4.7～7.0	15.6～19.5

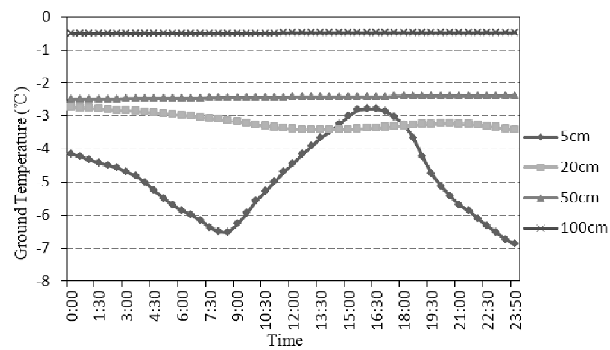
[1] LL: liquid limit
[2] PL: Plastic limit

2.3 Observation results and analysis

In order to research the influence of the freeze-thaw cycles on the loess cutting slope, some daily observation results were chose and analyzed in the following. The soil moisture contents in the following figures were converted to gravimetric moisture contents.

Figure 3 shows the ground temperatures and soil moisture contents at different depths (5 cm, 20 cm, 50 cm and 100 cm) on a loess cutting slope at Pingliang on 26 February 2008. From the figure, it can be found that the ground temperature and soil moisture content at 5 cm depth changed obviously with time. The ground temperature at this depth ranged from -6.6 ℃ (at 4 a.m.) to -3.3 ℃ (at 4 p.m.) with a variation range of 3.3 ℃, and the soil moisture content at the depth ranged from 5.5% to 4.8% with a variation range of 0.7%. While at 20cm depth, the ground temperature and soil moisture content varied slightly and only with ranges of 0.5 ℃ and 0.2%, respectively. At depths of 50 cm and 100 cm, almost no changes occurred both on the ground temperatures and soil moisture contents.

For ground temperature at depth of 5 cm, it began to increase at 8 a.m. and reached maximum value at about 4 p.m. then decreased till midnight. Meanwhile the soil moisture at this depth began to increase at 9 a.m. and reached maximum value between 4 to 6 p.m. then decreased till midnight. The trends of the ground temperature and soil moisture content agreed very well. So it can be concluded that the variation of soil moisture content at depth of 5 cm were induced by ground temperature variation.



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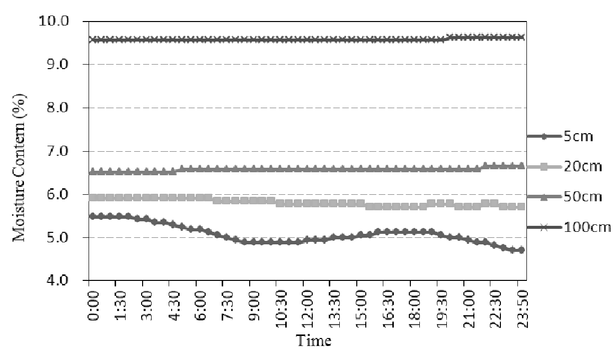
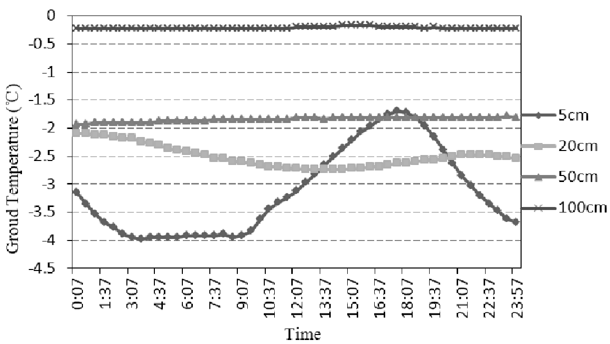


(b)

Figure 3. The ground temperature (a) and moisture contents (b) at different depths on a loess cutting slope at Pingliang on 26 February 2008

Figure 4 shows ground temperatures and soil moisture contents at different depths (5 cm, 20 cm, 50 cm and 100 cm) on a loess cutting slope at Jingning on 25 February 2008. The conditions here were the same as that at Pingliang. The ground temperature at 5 cm depth varied with time markedly; it reached the minimum value of -4 ℃ at 8 a.m. then increase with time till 5 p.m. to -1.6 ℃. And the soil moisture content ranged from 4.0% (at 9 a.m.) to 4.8% (at 4 p.m.). While at depth of 20cm, the variation ranges of the ground temperature and soil moisture content were only 0.5 ℃ and 0.2%, respectively. At depths of 50 cm and 100 cm, almost no changes occurred on the ground temperatures and soil moisture contents.

A similar trend was observed between ground temperature changes and soil moisture content changes; that was both the ground temperature and soil moisture content increase from about 9 a.m. till 4 p.m., and then both of them decreased till midnight.



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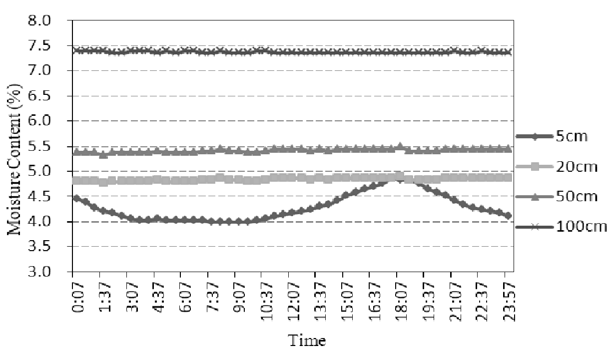
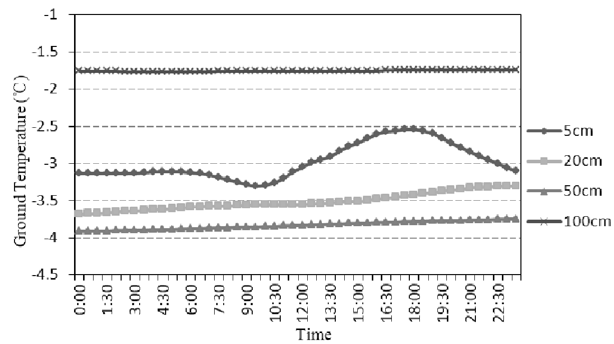


(b)

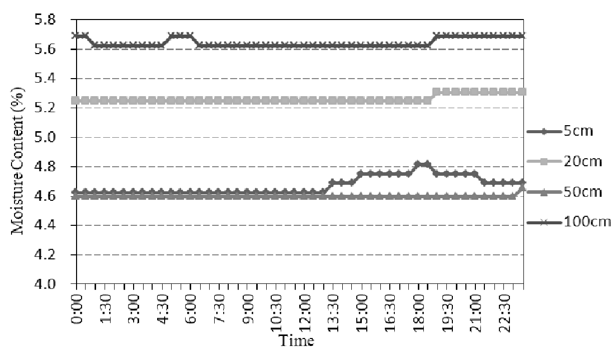
Figure 4. The ground temperatures (a) and moisture contents (b) at different depths on a loess cutting slope at Jingning on 25 February 2008

Figure 5 shows the ground temperatures and soil moisture contents at different depths on a loess cutting slope at Dingxi on 26 February 2008. The figure indicates that the ground temperature and soil moisture content changed obviously at 5cm depth but slightly at 20 cm depth, and almost had no changes at depths of 50 cm and 100 cm, which was same as the conditions at Pingliang and Jingning. Also, same change trends existed between the ground temperature and soil moisture content at depth of 5 cm.

From the above measurements and analysis, some conclusion can be driven: (1) the ground temperature and soil moisture content changed obviously near loess cutting slope surface (5 cm depth), but at 20 cm depth the change were slightly and then almost no changes occurred at depths of 50 cm and 100 cm, implying that the depth of loess on the cutting slope influenced by freeze-thaw cycles was less than 20 cm; (2) although the ground temperature were below 0 ℃ all day long, the soil moisture content still changed appreciably with ground temperature, so there were still freeze-thaw cycles occurred near the loess cutting slope surface.



(a)



(b)

Figure 5. The ground temperature (a) and moisture contents (b) at different depths on a loess cutting slope at Dingxi on 26 February 2008

3 LABORATORY EXPERIMENT

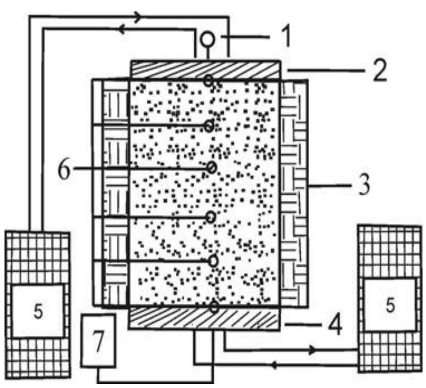
3.1 Experimental methods and conditions

From the field measurement, it was found that freeze-thaw cycles still took place on the loess cutting slope surface. So in order to study the influence of the cycles on the mechanics properties of undisturbed loess, some laboratory experiments were carried out. The loess samples were collected at 50-75 cm depth on cutting slopes, and then their dry densities and strengths were tested after freeze-thaw cycles. The initial physics properties of these samples were described in Table 1.

3.1.1 Experimental system for freeze-thaw test on loess samples

The freeze-thaw cycles tests on loess samples were carried out on a system made by State Key Laboratory of Freezing soil Engineering, Chinese Academy of Sciences. Figure 6 shows the system, and in the system the undisturbed sample was cut as a cylinder with a height of 13 cm and a diameter of 10 cm. In order to better research the influence of freeze-thaw cycles on undisturbed loess, the temperature controlling did not follow the field measurement but carried out as followings: the temperature at bottom of sample was kept at +1 ℃ while the temperature at the top of sample varied with time. When the freezing began, the temperature at top of sample was -10 ℃ and would last for 12 hours, then the thawing began, the temperature was set to +10℃ till another 12 hours. So in one day, the sample would experience a freeze-thaw cycle, and during the cycle there was no water supply on sample from outside. After the cycles, the dry density of loess sample was tested at three layers (upper, middle and lower layers).

(a)



(b)

Figure 6. Schematic drawing of experimental system for freezing and thawing

Notes: (a) Photo of freeze-thaw experiment system; and (b) Simplified model of components in the experimental system. 1-Deformation sensor, 2-Top plate, 3-Insulation layer, 4-Bottom plate, 5-Cooling bath, 6-Temperature sensors, and 7-Water reservoir

3.1.2 Strength test after freezing and thawing cycles

Enclose the loess samples with the preservative film and put them into a freezer which can keep a constant temperature of -10 ℃, 12 hours later get the samples out and let them thaw in the indoor for 12 hours. So a freeze-thaw cycle will be completed in 24 hours. After the cycles, strength test was carried out on a direct shear apparatus. In order to ensure the accuracy of test results, a parallel test (Group1 and Group2) was conducted on every sample.

3.2 Experiment results and analysis

3.2.1 Influence of freeze-thaw cycles on dry density of undisturbed loess

The natural dry density of loess samples from Pingliang and Dingxi are 1.61 g/cm^3 and 1.54 g/cm^3, respectively. After the freeze-thaw cycles, the dry densities of samples were measured at three layers and the results were showed in the figures 7 and 8.

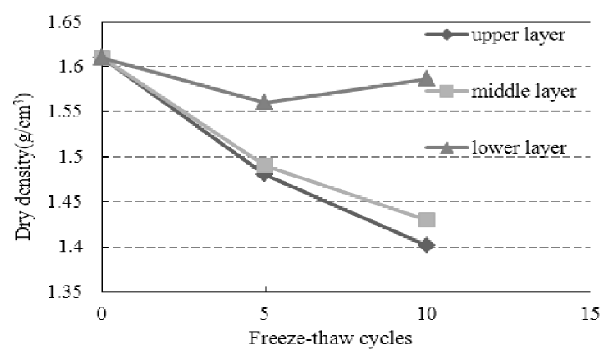


Figure 7. The changes of dry density at three layers of the samples from Pingliang after freeze-thaw cycles

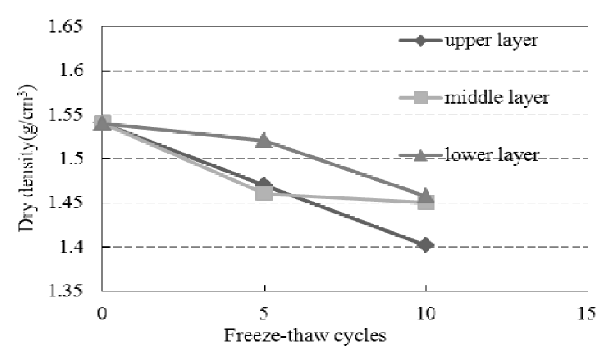


Figure 8. The changes of dry density at three layers of the sample from Dingxi after freeze-thaw cycles

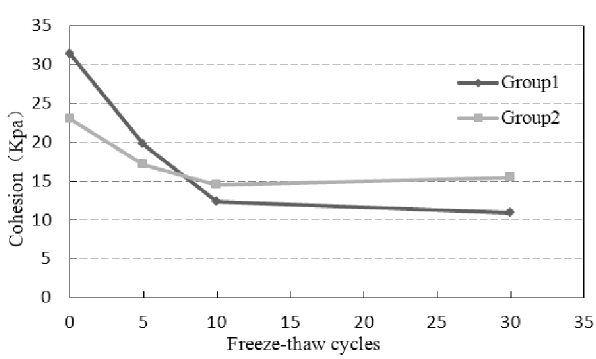
From the figure 7, it can be found that: (1) after 5 freeze-thaw cycles, the dry density of upper layer of loess sample collected from Pingliang decreased from 1.61 g/cm^3 to 1.48 g/cm^3, and after 10 cycles decreased to 1.40 g/cm^3; (2) after 5 freeze-thaw cycles, the dry density of middle layer of loess sample decreased from 1.61 g/cm^3 to 1.49 g/cm^3, and after 10 freeze-thawing cycles decreased to 1.43 g/cm^3 and (3) after 5 freeze-thawing cycles, the dry density of lower layer of loess sample decreased from 1.61 g/cm^3 to 1.56 g/cm^3, and after 10 freeze-thaw cycles decreased to 1.59 g/cm^3.

From the figure 8, it can be found that: (1) after 5 freeze-thaw cycles, the dry density of upper layer of loess sample collected from Dingxi decreased from 1.54 g/cm^3 to 1.47 g/cm^3, and after 10 freeze-thaw cycles decreased to 1.40 g/cm^3; (2) after 5 freeze-thaw cycles, the dry density of middle layer of loess sample decreased from 1.54 g/cm^3 to 1.46 g/cm^3, and after 10 freeze-thaw cycles decreased to 1.45 g/cm^3 and (3) after 5 freeze-thaw cycles, the dry density of lower layer of loess sample decreased from 1.54 g/cm^3 to 1.52 g/cm^3, and after 10 freeze-thaw cycles decreased to 1.46 g/cm^3.

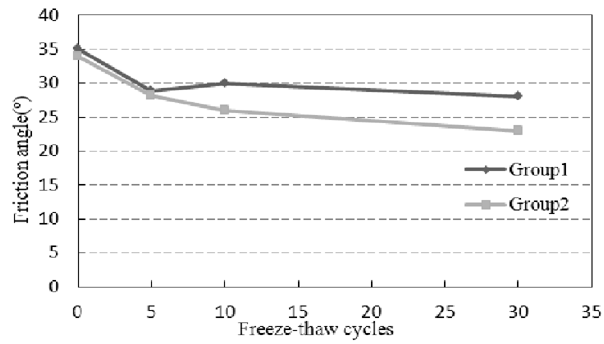
The results above indicated that: (1) after freeze-thaw cycles, the dry density of loess samples from Pingliang and Dingxi decreased with the cycles; (2) the decreases of dry density of loess samples were obviously at upper layer and then middle layer but slightly at lower layer, indicating stronger freeze-thaw actions at upper layer and (3) except the lower layer of the loess samples from Dingxi, the dry density decreased sharply during the early freeze-thaw cycles but slightly with the increase of the cycles.

3.2.2 Influence of freezing and thawing cycles on strength of loess

Figures 9 and 10 show the results of direct shear test on loess samples from Pingliang and Dingxi after the freeze-thaw cycles.

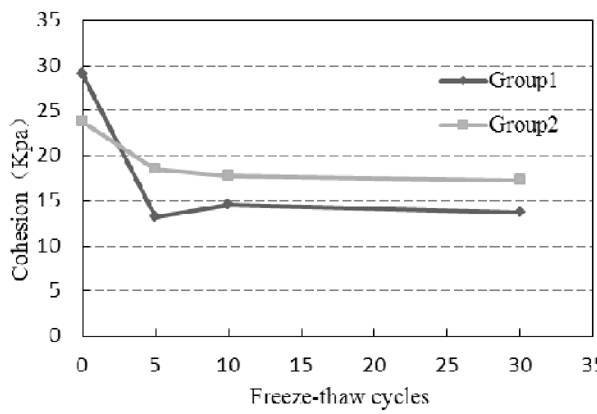


(a)



(b)

Figure 9. Cohesion (a) and friction angle (b) changes of the loess from Pingliang with freeze-thaw cycles



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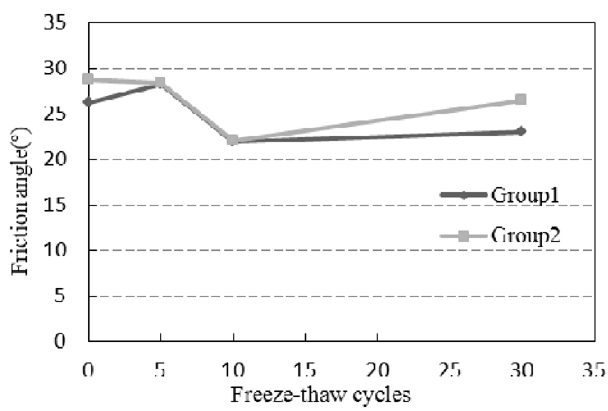

(b)

Figure 10. Cohesion (a) and friction angle (b) changes of loess from Dingxi with freeze-thaw cycles

From figures 9 and 10, it can be found that the cohesion of the four loess samples decreased with the freeze-thaw cycles. After 5 cycles, the cohesion decreased about 22% to 55% of the initial value. Then the cohesion decreased slowly with the cycles, about a decrease of 4.3% to 37.4% occurred after another 5 cycles. After 30 cycles, the cohesion only had a decrease of 2.3% to 12.1% of the value after 10 freeze-thaw cycles. This indicated that the early freeze-thaw cycles impacted the cohesion intensively, but with the increase of the cycles the cohesion decreased slowly and finally kept constant after 10 cycles. The impact of freeze-thaw cycles on fraction angles of the loess samples is not obvious and irregular; for samples from Pingliang, the fraction angles decreased slowly with freeze-thaw cycles but for samples from Dingxi, the fraction angles fluctuated between 23º and 29º.

4 FIELD APPLICATION

The expressway from Pingliang to Dingxi is a major artery connecting northwest and east of China, and plays an important role in National freeway net. The road, with a total length of 232 km is located on the Loess Plateau of China which has very serious soil erosion and geological disasters. It stretches the Liupan Mountain areas where the valleys, ridges, hills and slopes widely spread and with special geography features and complicated climatic conditions. As an easy structure to be constructed and of lower-cost, the slope protection with vegetation can reduce the denudation and gully erosion on loess cutting slopes. The application of this technique on the loess cutting slope along the expressway from Pingliang to Dingxi works well, and almost no denudation and gully erosion occurred. The conditions of vegetation and slope protection effect are showed in Figure 11.

(a) (b)

Figure 11. Field application of the slope protection with vegetation along the expressway from Pingliang to Dingxi.
(a) slope before protection; and (b) slope after protection

5 CONCLUSIONS

The ground temperatures and soil moisture contents of the loess on the cutting slope varied appreciably at 5 cm depth, but slightly at 20 cm depth and almost had no changes at depth more deep. Although the ground temperature at 5 cm depth was below 0 ℃ all day long, the soil moisture content still changed with ground temperature, indicating freeze-thaw cycles still occurred.

The dry density of the loess samples decreased with freeze-thaw cycles, and during the early cycles the decrease was sharply and then slowly. And the decreases at top layer of samples were greater than the middle and lower layers.

The cohesion of the loess samples decreased with freeze-thaw cycles, and the decreases were sharply during the early cycles. After 10 cycles, the cohesion decreased slightly. The fraction angle changes irregularly with freeze-thaw cycles.

The slope protection with vegetation can increase the vegetation coverage promptly and protect the slope from rainfall splashing and washing. So this technique can reduce the denudation and gully erosion on the slope effectively and keep the stability and beauty of the slope.

ACKNOWLEDGEMENTS

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