FREEZE-THAW EFFECTS ON SHEAR MODULUS AND DAMPING RATIO OF FROZEN SOILS

X. Yu[(1)], R. Sun[(2)]

[(1)] *Associate professor, School of Civil Engineering and Architecture, Guilin University of Technology, yuxbiem@163.com*
[(2)] *Professor, Institute of Engineering Mechanics, China Earthquake Administration, iemsr@163.com*

Abstract

Seasonal temperature change makes the frozen ground experiences freeze-thaw cycles in some regions in the world. The dynamic modulus and damping ratio are indispensable in engineering design, and they are affected by the freeze-thaw cycles. The previous studies on freeze-thaw effects paid more attention to the unfrozen soil, while the dynamic properties of frozen soil after freeze-thaw cycles were seldom investigated. The previous studies suggested that freeze-thaw cycles increased the pore volume and changed the pore size distribution inside the thawed specimens. Compared to specimens without any freeze-thaw cycles, the thawed specimens had lower shear modulus and shear strength. In this study, a series of freeze-thaw tests were carried out using a resonant column apparatus. Two cohesive and one incohesive soils were selected. The clayey and silty soils in the study were taken from Harbin, China, which are common used in the subgrade construction in Harbin. And the incohesive soil in the study is Chinese Fujian standard sand. Different from commonly freeze-thaw cycles completed in a refrigerator, the soil specimens experienced freeze-thaw cycles in the apparatus directly, and were tested in the frozen state. The test results showed that for the three soils after different numbers of freeze-thaw cycles, the shear moduli decreased with an increase in the strain, which was the same as those before any freeze-thaw cycle. The initial shear modulus (G_{max}) obviously decreased with increasing number of freeze-thaw cycle for the sandy and silty specimens, but decreased and slightly increased for the clayey specimen. For the clayey and silty specimens, G_{max} became stable after the 2nd or 4th freeze-thaw cycles, but that for the sandy specimen kept decreasing. The varying trends of the damping curves followed the trends of the modulus curves, but damping increased with strain, and it increased with an increase in the number of freeze-thaw cycles. The Hardin-Drnevich model has been widely used as the seismic analyses of soil ground, and the test results showed that this model is also available for shear moduli and damping ratio of specimens experiencing freeze-thaw cycles. The trends obtained in this study on the sandy specimen were similar to previous study. The authors could not find test results on frozen silty and clayey soils after freeze-thaw cycles in the literature, although those of thawed specimens were reported by former researchers, which showed that the modulus decreased with an increase in the freeze-thaw cycles for three types of clayey specimens. It appears that freeze-thaw cycles might disturb the soil structure, which might contribute to the decrease of soil modulus and increase of damping ratio. However, the present study is still preliminary, and further studies should be carried out for a comprehensive understanding of the freeze-thaw effects.

Keywords: Frozen soil, Shear modulus, Damping ratio, Freeze-thaw cycle, Hardin-Drnevich model

1. Introduction

In the seismic analysis of ground response, shear modulus (*G*) and damping ratio (*D*) are indispensable mechanical parameters. In an unfrozen state, the *G* and *D* of soils have nonlinear characteristics: with an increase in the shear strain amplitude the shear modulus decreases, while the damping ratios increase [1,2]. In a frozen state, the nonlinear responses of soils can also be observed [3-5]. The factors that influence the *G* and *D* of frozen soils are commonly summarized as soil type, temperature, water content, confining pressure, and loading frequency [4,6,7], while some studies also found that stress history and phase transition history had effects on the two parameters [6,8,9].

In many areas in the world, such as the Northeastern region in China, soil ground experiences freeze-thaw (FT) cycles each year. While extensive studies could be found that investigated the dynamic properties of frozen soils, very limited took into account the FT effect. It is noted that the FT effects on thawed soil specimens have been substantially studied [10-12]. It was found that FT cycles increased the pore volume and changed the pore size distribution inside the thawed specimens [13-15]. Compared to specimens without any FT cycles, the thawed specimens had lower shear modulus and shear strength.

In order to accurately reproduce the seismic responses of grounds that freeze in winter and thaw in spring each year, it is necessary to understand the change of the frozen-soil dynamic properties after FT cycles. This note presents a preliminary experimental study for this purpose.

2. Experiments

2.1 Test apparatus

A resonant column apparatus (RCA) was employed in the study, as shown in Fig.1. The torsional excitation frequency of the apparatus ranges from 5 Hz to 1000 Hz, and the test range of shear strain is $10^{-7} \sim 10^{-4}$. Resonant column test is suitable for the determination of small-strain mechanical parameters, especially the modulus and damping of soils.

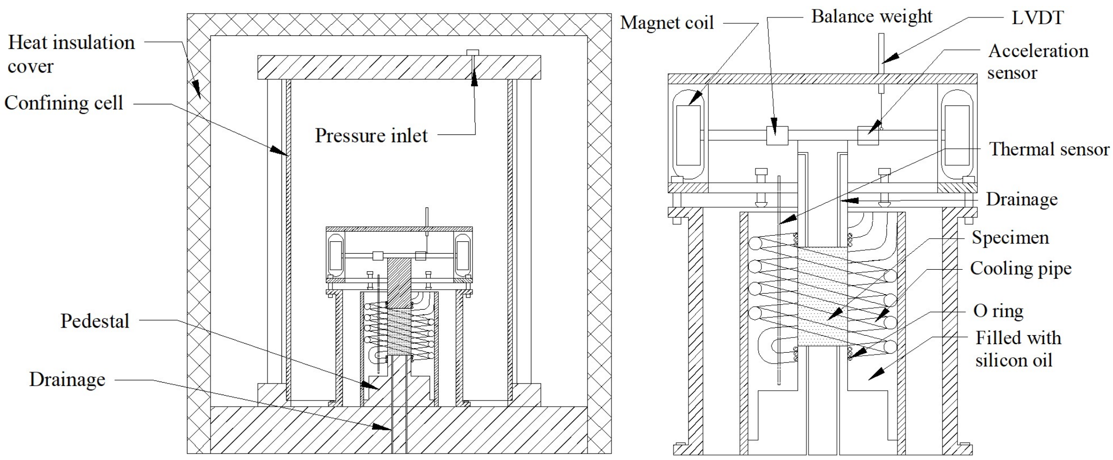

Fig. 1 –Resonant column apparatus sketch

2.2 Properties of soils

The clayey and silty soils in the study were taken from Harbin, China, which are common used in the subgrade construction in Harbin. The soils were buried 2 m below ground surface, and were disturbed during sampling. The cohesionless soil in the study is Chinese Fujian standard sand. Fig.2 shows the grading curves of the soils, and the basic physical properties of the soil specimens are listed in Table 1.

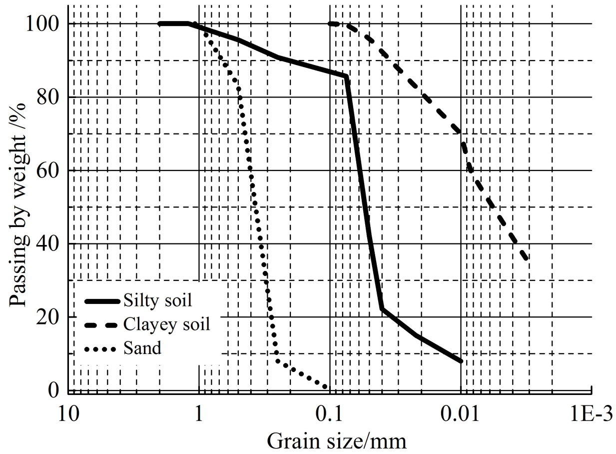

Fig. 2 – Grading curves of soils

Table 1 – Physical properties of soil specimens

Soil type	Dry density (g/cm^3)	Water content (%)	Degree of Saturation	Specific gravity	Plastic limit (%)	Liquid limit (%)
Clayey soil	1.45	28.0	0.82	2.8	21	55
Silty soil	1.75	26.5	1.0	2.7	21.2	30.5
Sand	1.55	20.0	0.73	2.6	/	/

2.3 Specimen preparation

The remolded soil specimens were prepared according to the Chinese Standard for Soil Test Methods (GB/T50123-1999) [16]. The clayey and silty soils were dried in an electric oven for 8 h before specimen preparation. After moisturization with the desired water content shown in Table 1, the clay and silt samples were left undisturbed in a sealed condition for 12 h, so that moisture in the soil diffused uniformly. Then the moist soil was put into a Φ50 mold and compacted. All the clay and silt specimens were preserved in a moisturized chamber before use. For the sand, specimens were prepared directly on the RCA pedestal. The moisturizing procedure was similar to that for the clay and silt. The specimen mold with a rubber membrane attached inside was placed directly on the RCA pedestal. The air between the membrane and mold was eliminated by a vacuum pump. Then the sandy soil was poured into the mold and compacted.

2.4 Freeze-thaw cycles

A negative pressure of 20 kPa was applied to the specimen by a vacuum pump to prevent disturbance on the specimen while installing the RCA, after which 50 kPa confining pressure was applied on the specimen and the negative pressure was removed. The pressure was maintained for 10 min and increased to 100 kPa, followed by 8 h of consolidation for the clay and silt specimens, or 1 h for the sand specimen. Afterwards, keeping the confining pressure the specimens were frozen for 24 h in a closed system without moisture exchange with the freezing environment.

The thawing procedure was started after shutting down the cold bath, and the heat insulation cover outside the pressure cell was removed. The specimen was thawing naturally at room temperature (25ºC) while the confining pressure (100 kPa) was maintained. The thawing procedure lasted for 24 hours. After thawing the specimen was frozen again, the duration of which lasted 24 hours. Fig.3 illustrates the FT cycles on the sandy specimens, the other soils followed similar procedure. All FT cycles and tests for a certain soil type were conducted on one specimen. The resonant column tests were carried out on the frozen specimens before and after the FT cycles.

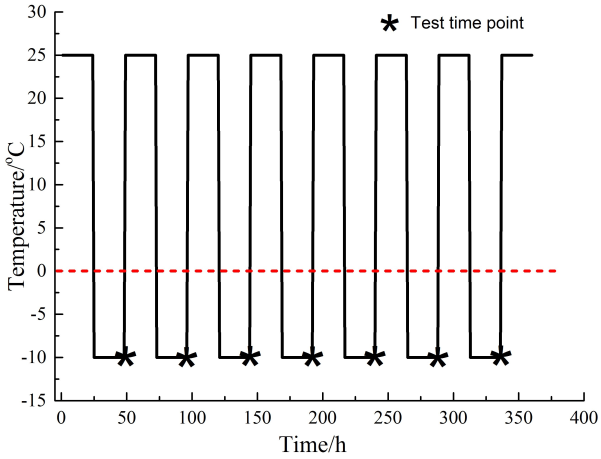

Fig. 3 –Temperature cycles for sand specimens

2.5 Modulus and damping tests

Eq.1 shows the relationship between the resonant frequency and shear wave velocity in a resonant column test. Here f is the tested resonant frequency, L is the height of the specimen, V_s is the shear velocity of the specimen, I is the mass polar moment of the specimen, and I_0 is the mass polar moment of the additive mass. I_0 was acquired by the apparatus calibration. Eq.2 was used to obtain the shear modulus of the specimen, in which G is the shear modulus, and ρ is the density of the specimen.

$$\frac{fL}{V_s}\tan\left(\frac{fL}{V_s}\right) = \frac{I}{I_0} \tag{1}$$

$$G = \rho V_s^2 \tag{2}$$

$$\delta = \ln\left(\frac{X_1}{X_2}\right) = \frac{2\pi D}{\sqrt{1 - D^2}} \approx 2\pi D \tag{3}$$

Damping ratio was obtained with the logarithmic decrement of free vibration of the specimen, as shown in Eq.3. X_1 and X_2 are the adjacent vibrating peaks, and D is the damping ratio.

3. Laboratory test results

Fig. 4 shows the modulus and damping curves of the three soils. Nonlinear responses were very obvious before and after the FT cycles.

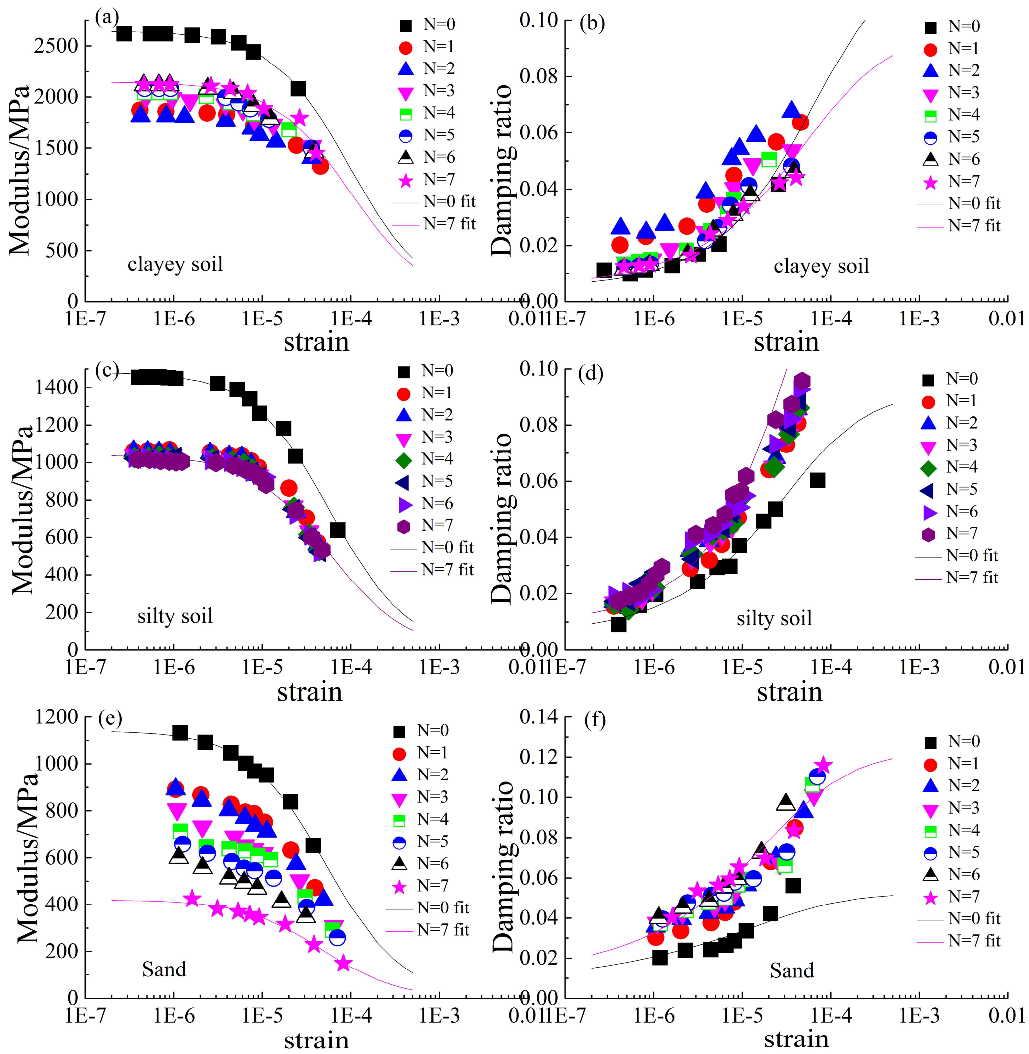

Fig. 4 –Modulus and damping ratio results of different soils

For the three soils after different numbers of FT cycles, the shear moduli decreased with an increase in the strain, which was the same as those before any FT cycle. The shear modulus at a strain of 10^{-6} is considered as the initial shear modulus (G_{max}) in this study, which obviously decreased with increasing number of FT cycle for the sand and silt specimens, but decreased and slightly increased for the clay specimen. For the clay and silt specimens, G_{max} became stable after the 2nd or 4th FT cycles, but that for the sand specimen kept decreasing. The varying trends of the damping curves followed the trends of the modulus curves, but damping increased with strain, and it increased with an increase in the number of FT cycles.

The Hardin-Drnevich model has been widly used as the seismic analyses of soil ground. The relationship between shear modulus and shear strain by this model is shown in Eq.4. Here γ_r refers to the shear strain corresponding to half of the G_{max}. Eq. (4) can still represent the damping curves of the soil specimens after FT cycles, as shown in Fig. 4.

$$G = \frac{G_{\max}}{1 + \dfrac{\gamma}{\gamma_r}} \tag{4}$$

$$D = D_{\min} + D_{\max}(1 - \frac{G}{G_{\max}})^n \tag{5}$$

Previous studies [4,6] also showed that logarithmic linear relationship existed between the modulus ratio and damping ratio of soils. For the test results in this study, this relationship still existed, as shown in Fig.5 and Eq.5. Here D_{min} is the lower limit of the damping ratio, D_{max} is the upper limit, and n is a curve-fitting factor.

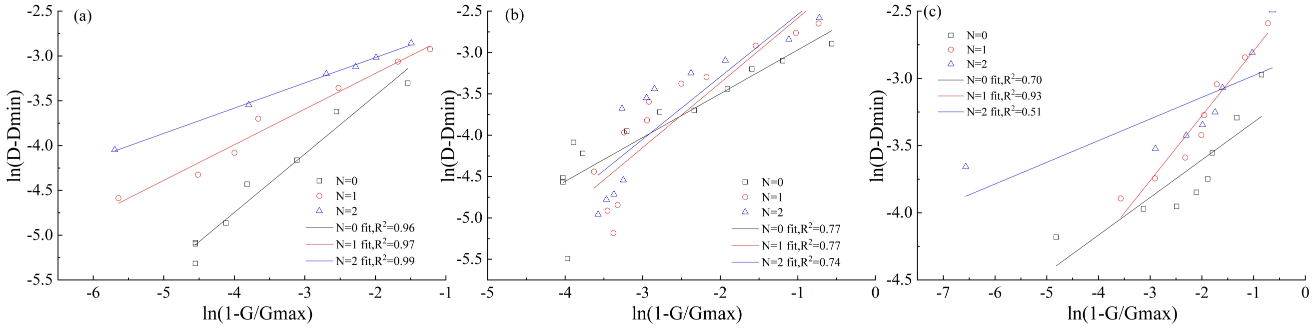

Fig. 5 –Logarithmic linear relationship between G/G_{max} and D, (a) clayey, (b) sity, (c)sandy soil

4. Discussions

Very limited results can be found on the effects of FT cycles on the dynamic modulus and damping ratio of frozen soil. The test results of this study showed that the modulus basically decreased with an increase in the FT cycles, and it stabilized after certain number of cycles for the clay and silt specimen, while the decrease was more obvious for the sandy specimen. The trend basically reversed for the damping ratio.

The trends obtained in this study on the sand specimen were similar to those reported in Zhang et al. [17]. The authors could not find test results on frozen silty and clayey soils after FT cycles in the literature, although those of thawed specimens were reported in [18], which shows that the modulus decreased with an increase in the FT cycles for three types of clayey specimens.

At this stage it is not clear what caused the decrease of modulus and the increase of damping ratio after FT cycles. It appears that for saturated soil specimens or unsaturated soil specimens with high degree of saturation, like the ones investigated in this study, the freeze-thaw cycle caused disturbance to the soil fabric and soil structure, which contributed to the changes. The disturbance might be more severe in the sand specimen. Further study is necessary to fully understand these properties.

5. Conclusions

In this preliminary study, the freeze-thaw effects on the dynamic shear modulus and damping ratio of frozen soil were investigated. Resonant column tests were carried on three types of frozen soils. It was found that freeze-thaw cycle had obvious influences on the dynamic shear modulus and damping ratio of frozen soils. The dynamic shear modulus basically decreased with the FT cycles, while the damping ratio increased. The change was more obvious for the sand specimen, while it ceased to develop after some cycles for the silt and clay specimens. The Hardin-Drnevich model was able to describe the dynamic shear modulus and damping ratio of frozen soils after FT cycles. It appears that freeze-thaw cycles might disturb the soil structure, which might contribute to the decrease of soil modulus and increase of damping ratio. However, more investigations should be conducted for a comprehensive understanding of the FT effects.

Acknowledgements

The research was supported by the Foundation of Guilin University of Technology (GUTQDJJ2019043), and the China Postdoctoral Science Foundation funded project (2018M632865).

References

[1] Chen G, Zhou Z, Sun T, Wu Q, Xu L, Khoshnevisan S, Ling D (2019): Shear modulus and damping ratio of sand-gravel mixtures over a wide strain range. *Journal of Earthquake Engineering*, 23(8), 1407-1440. https://doi.org/10.1080/13632469.2017.1387200

[2] Mayoral JM, Castañon E, Alcantara L, Tepalcapa S (2016): Seismic response characterization of high plasticity clays. *Soil Dynamics & Earthquake Engineering*, 84, 174-189. https://doi.org/10.1016/j.soildyn.2016.02.012

[3] Yu X, Sun R, Yuan X, Chen Z, Zhang J (2017): Resonant Column Test on the Frozen Silt Soil Modulus and Damping at Different Temperatures. *Periodica Polytechnica Civil Engineering*, 61(4), 762–769. 2017. https://doi.org/10.3311/PPci.10349

[4] Zhu Z, Ling X, Wang Z, Lu Q, Chen S, Zou Z, Guo Z (2011): Experimental investigation of the dynamic behavior of frozen clay from the Beiluhe subgrade along the QTR. *Cold Regions Science & Technology*, 69(1), 91-97. https://doi.org/10.1016/j.coldregions.2011.07.007

[5] Kim D, Kwon Y, Kim Y (2017): Dynamic Soil Properties of Frozen and Unfrozen Soils from Terra Nova Bay in Eastern Antarctica. *Journal of the Korean Geotechnical Society*, 33(3), 37-47. https://doi.org/10.1016/10.7843/kgs.2017.33.3.37

[6] Ling X, Zhang F, Li Q, An L, Wang J (2015): Dynamic shear modulus and damping ratio of frozen compacted sand subjected to freeze–thaw cycle under multi-stage cyclic loading. *Soil Dynamics & Earthquake Engineering*, 76, https://doi.org/111-121. 10.1016/j.soildyn.2015.02.007

[7] Bosscher P, Nelson D (1987): Resonant column testing of frozen Ottawa sand. *Geotechnical Testing Journal*, 10(3), 123-134. https://doi.org/10.1520/GTJ10944J

[8] Tatsuoka F, Iwasaki T, Fukushima S, Sudo H (1979): Stress Conditions and Stress Histories Affecting Shear Modulus and Damping of Sand under Cyclic Loading. *Soils & Foundations*, 19(2), 29-43. https://doi.org/10.3208/sandf1972.19.2_29

[9] Teachavorasinskun S, Thongchim P, Lukkunaprasit P (2002): Shear modulus and damping of soft Bangkok clays. *Canadian Geotechnical Journal*, 39(5), 1201-1208. https://doi.org/10.1139/t02-048

[10] Orakoglu M, Liu J, Niu F (2017): Dynamic behavior of fiber-reinforced soil under freeze-thaw cycles. *Soil Dynamics & Earthquake Engineering*, 101, 269-284. https://doi.org/10.1016/j.soildyn.2017.07.022

[11] Zhang Y, Hulsey JL (2014): Temperature and Freeze-Thaw Effects on Dynamic Properties of Fine-Grained Soils. *Journal of Cold Regions Engineering*, 29(2), 04014012. https://doi.org/10.1061/(ASCE)CR.1943-5495.0000077

[12] Zhang F, Yang Z, Wang J, Li H, Still B (2017): Shear properties of thawed natural permafrost by bender elements. *Sciences in Cold and Arid Regions*, 9(4), 343-351. https://doi.org/10.3724/SP.J.1226.2017.00343

[13] Makusa G, Mácsik J, Holm G, Knutsson S (2016): A laboratory test study on effect of freeze–thaw cycling on strength and hydraulic conductivity of high water content stabilized dredged sediments. *Canadian Geotechnical Journal*, 53(6), 1038-1045. https://doi.org/10.1139/cgj-2015-0295

[14] Shoop SA, Bigl SR (1997): Moisture migration during freeze and thaw of unsaturated soils: modeling and large scale experiments. *Cold Regions Science & Technology*, 25(1), 33-45. https://doi.org/10.1016/S0165-232X(96)00015-8

[15] Lin B, Zhang F, Feng D, Tang K, Feng X (2018): Dynamic shear modulus and damping ratio of thawed saturated clay under long-term cyclic loading. *Cold Regions Science & Technology*, 145, 93-105. https://doi.org/10.1016/j.coldregions.2017.10.003

[16] Chinese Ministry of Water Resources (1999): *Standard for soil test methods, GB/T50123-1999*. China Water&Power Press, 1st edition. (in Chinese)

[17] Zhang F (2011): Dynamic response and permanent deformation of subgrade induced by heavy truck load in deep seasonally frozen region, Ph.D. dissertation, Harbin Institute of Technology, Harbin, China. (in Chinese) URL:http://kns.cnki.net/KCMS/detail/detail.aspx?dbcode=CDFD&dbname=CDFD1214&filename=1012024332.nh&v=MjE2MzkxRnJDVVJMS2ZaT1Z2Rnl6a1VMM0JWRjI2SExPNkd0TFByWkViUElSOGVYMUx1eFlTN0RoMVQzcVRyV00=

[18] Wang J (2012): Research on the mechanical properties of subgrade soil after several freeze-thaw cycles in seasonally frozen soil region and microscopic mechanism analysis, Ph.D. dissertation, Jilin University, Changchun, China. (in Chinese) URL:http://kns.cnki.net/KCMS/detail/detail.aspx?dbcode=CDFD&dbname=CDFD1214&filename=1012365726.nh&uid=WEEvREcwSlJHSldRa1FhdXNXa0hHRWh5cmZoWnlHdmxjeEs0bEF5SnZiQT0=$9A4hF_YAuvQ5obgVAqNKPCYcEjKensW4ggI8Fm4gTkoUKaID8j8gFw!!&v=MjUxMTMzcVRyV00xRnJDVVJMS2ZaT1Z2RnlqZ1ZyN0xWRjI2SExDK0c5Yk9xWkViUElSOGVYMUx1eFlTN0RoMVQ=

