Experimental study on rate of frost heave by artificial freezing

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Abstract: The developing characteristics of rate of frost heave of silty clay (undisturbed and disturbed) by artificial freezing are revealed, and different experimental results are compared. The influence of diverse experimental parameters on the rate of frost heave is analyzed and concluded. 12 artificial freezing tests are performed on silty clay samples for this investigation, and the experimental parameters consist of two kinds of cooling temperature models for artificial freezing (sine-varying and constant), three kinds of freezing directions (vertical freezing, lateral freezing and vertical-lateral freezing), and different water contents (23.5%, 28% and 32%), with or without water supply. It is significantly concluded that the existence of seasonal frozen layer will reduce or suppress the second frost heave caused by artificial ground freezing in the engineering projects. This study will provide significant instruction for the construction of artificial ground freezing, especially in seasonally frozen ground.

Key words: rate of frost heave; artificial freezing; sine-varying; temperature models; lateral freezing

CLC number：TU443　　**Document code**：A　　**Article ID**：1000－4548(2009)12－1902－05

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人工冻结冻胀速率试验研究

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摘　要：研究了不同实验条件下原状和扰动粉黏土人工冻胀速率的发展特点，并对试验结果进行了对比分析。同时还分析、总结了各种试验因素对人工冻胀速率的影响。针对粉黏土冻胀速率的研究，共进行了12组人工冻结试验，试验中所采用的各种影响因素如下：两种人工冻结冷端温度模式——正弦变化冻结温度和恒定冻结温度，三个不同人工冻结方向——竖向冻结、侧向冻结以及复合冻结（竖向—侧向冻结），不同含水率——23.5%、28%和32%，不同水分补给条件——开放体系和封闭体系。试验结果表明：季节冻土层的存在将减少或是抑制由人工冻结所引起的二次冻胀的发展。研究结果将为人工冻结实际工程,特别是在季节冻土区的人工冻结工程提供重要的理论指导。

关键词：冻胀速率；人工冻结；正弦变化；温度模式；侧向冻结

0 Introduction

Rate of frost heave, i.e., amount of frost heave of soil developing per unit time, has been studied intensively for many years, and considerable laboratory freezing experiments and field tests have been carried out. The rate of frost heave is one of the most important characteristic parameters for the evaluation criterion of the feasibility and security of artificial ground freezing projects. It is essential to investigate which factor influences the frost-heaving rate most in the artificial freezing process.

Horiguchi presented that as the rate of heat removal from the freezing front increases, the rate of frost heave increases, reaches the maximum, and then decreases[1]. Loch concluded that there exists a maximum heave rate[2]. Konrad and Morgenstern proposed a new parameter, the segregation potential[3]. The segregation potential theory assumed that rate of frost heave is proportional to the overall temperature gradient in the frozen fringe. However, the segregation potential theory of Loch involves the assumption that the heave rate is equal to water intake rate. E. Penner and T. Walton studied the influence of overburden pressure on the relationship between rate of heave and cold-side temperature, and the results showed that the heave rate for various overburden pressures tends to converge as the

Foundation item: National Natural Science Foundation of China（40571032）

Received date: 2008－08－26

cold-side temperature is lowered[4]. Hermansson used data from Loch to show that initially saturated fine-graded soils can heave, at least during the first few days, three times more than water intake[5]. Furthermore, Guthrie and Hermansson reported, for freezing tests on variably saturated specimens, heave-uptake ratios as high as 2.2 for highly frost susceptible soil. Ake Hermansson researched the relationship between the rate of frost heave and the heat extraction by laboratory and field testing[6].

However, for a long period of time, most of the researches on the rate of frost heave only focused on disturbed soil and with simple test conditions. Currently, artificial ground freezing is used in many engineering projects with different geological conditions, which results in the un-applicability of the former test results. Therefore, some new experimental parameters have been considered in this study on the rate of frost heave and the results are analyzed and compared in detail, to provide some references to artificial freezing engineering.

1 Experimental program

1.1 Materials

The experiments were carried out on silty clay Ⅰ (undisturbed silty clay), Ⅱ (undisturbed silty clay) and Ⅲ (disturbed silty clay) from Harbin, in Northeast China. Silty clay Ⅰ and Ⅱ were taken at the same site with depths of 2 m, 5 m, respectively and silty clay Ⅲ was made from silty clay Ⅱ. The physical properties of soil are listed in Table 1.

Table 1 Basic physical properties of silty clay

Type	Composition of grains/%			Liquid limit /%	Plastic limit /%	Dry density /(g·cm^{-3})	Initial water content /%
	<0.005 mm	0.005~0.05 mm	>0.05 mm				
Ⅰ	48.7	43.9	7.4	30.08	20.93	1.55	23.5
Ⅱ	49.8	43.3	6.9	31.33	20.83	1.51	28
Ⅲ	49.9	43.5	7.1	31.50	21.01	1.44	32

1.2 Preparation of specimens and experimental apparatus

Cylindrical specimens nominally with 100 mm in diameter and 120 mm high were prepared by in-situ excavation. In term of experimental requirements, the authors developed a frost heave test apparatus, shown in Fig. 1. In this study, the following apparatuses were also applied, such as advanced Type-ST5405 frost-thaw-cycle device (attainable precision is ±0.1℃), DT615 data taking system, displacement sensor with a precision of ±0.01 mm to measure frost-heaving amount, Type-T thermocouples (precise of ± 0.01 ℃) and water-supplying device.

There are three cooling parts of Type-ST5405 device, i.e., top board, bottom board and test box (air cooling), and all the experimental data were collected by computer continually.

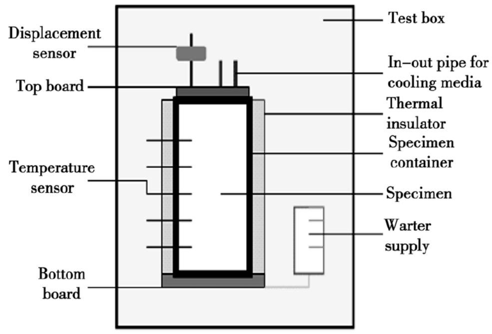

Fig. 1 Sketch of experimental apparatus

1.3 Testing procedures

Twelve freezing experiments were conducted on undisturbed silty clay, and the test schedule is given in Table 2.

Table 2 Test procedures

No.	Soil type (silty clay)	Temperature model	Water supply	Freezing model
1	Disturbed Ⅲ	Constant Ⅰ	Without	Lateral
2	Disturbed Ⅲ	Constant Ⅰ	With	Lateral
3	Disturbed Ⅲ	Sine Ⅰ	Without	Lateral
4	Disturbed Ⅲ	Sine Ⅰ	With	Lateral
5	Undisturbed Ⅰ	Constant Ⅱ	With	Vertical
6	Undisturbed Ⅰ	Sine Ⅱ	With	Vertical
7	Undisturbed Ⅱ	Constant Ⅱ	With	Vertical
8	Undisturbed Ⅱ	Sine Ⅱ	With	Vertical
9	Undisturbed Ⅰ	Constant Ⅲ	With	Vertical-lateral
10	Undisturbed Ⅰ	Sine Ⅲ	With	Vertical-lateral
11	Undisturbed Ⅱ	Constant Ⅲ	With	Vertical-lateral
12	Undisturbed Ⅱ	Sine Ⅲ	With	Vertical-lateral

Note: For sine-freezing, −19℃ was trough value, −5℃ peak value shown in Fig. 2.

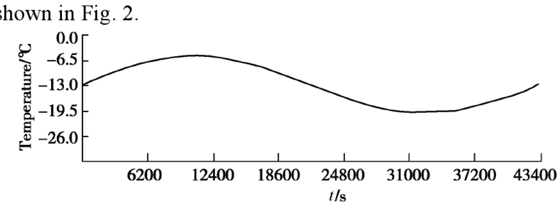

Fig. 2 Sine-freezing temperature of test box

After being taken from pit, undisturbed silty clay block was cut into a cylindrical specimen, nominally with 10 cm in diameter and 12 cm in height, or disturbed silty clay was made into a cylindrical specimen with the same size. Then the specimen was put into the test cell made of synthetic glass. The teflon liners were used to prevent side friction between specimen and the test cell.

Above-mentioned work was followed by: Type-T thermocouples were employed as thermal sensors distributed in the specimen to determine the inner temperature. From the top (12 cm) to the bottom (0 cm) along the height of specimen, thermal sensors were inserted centrally every 1.5 cm to monitor the simulated temperature of seasonal freezing.

Kept for 4 hours (undisturbed silty clay) or 6 hours (disturbed silty clay) in an environment with a constant temperature of 1℃, the specimen was placed into the frost-heave test apparatus, and then an artificial freezing test was started. The temperatures of the three cooling parts could be controlled and adjusted by the set computer program to perform the artificial freezing test, and the set temperatures of the three parts of high-low temperature freezing-thaw cycle test device were presented in Table 3. For sine-freezing, −19℃ was trough value, −5℃ peak value, shown in Fig. 2.

At the present work, the open system indicates that during the test, the specimen could gain water through a porrferous plate at the bottom board of the frost heave test apparatus, connected with an equipment of water-supply, and the closed system is just the reverse.

2 Results and discussion

The results of lateral freezing specimens are given in the Figs. 3, 4, 5 and 6 with curves of the rate of frost heave (disturbed silty soil, w=32%).

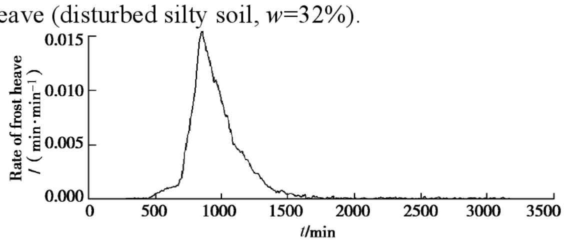

Fig. 3 Relationship between rate of frost heave and time of lateral constant freezing specimen without water supply (32%)

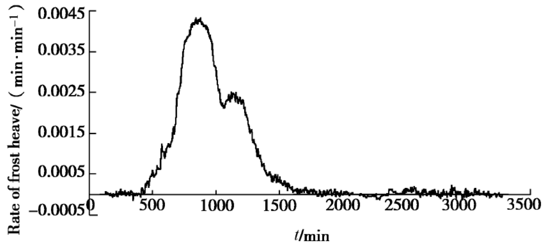

Fig. 4 Relationship between rate of frost heave and time of lateral constant freezing specimen with water supply (32%)

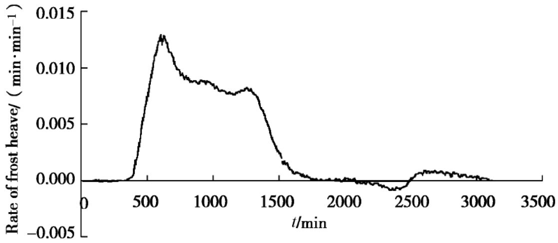

Fig. 5 Relationship between rate of frost heave and time of lateral sine freezing specimen without water supply (32%)

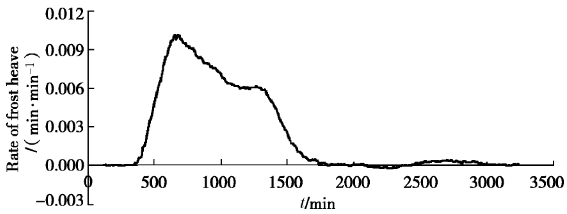

Fig. 6 Relationship between rate of frost heave and time of lateral sine freezing specimen with water supply (32%)

From the process of laterally artificial freezing, it can be seen that there are approximately four phrases: 1) the slow-increasing phase, the rates of frost heave is very small and develops slowly. 2)the fast-increasing phrase, the rates of frost heave rise rapidly and reach the peak. Because of the critical heat, the rates of the specimens without water supply are larger than those with water supply and attain the maximum earlier. With

Table 3 Artificial freezing temperature model

Freezing model		Constant Ⅰ/Ⅱ/Ⅲ								Sine Ⅰ/Ⅱ/Ⅲ							
Freezing side		Top			Body			Bottom		Top			Body			Bottom	
Sequence		i	ii	iii	i	ii	iii	i	ii	i	ii	iii	i	ii	iii	i	ii
Temperature /℃	Ⅰ	1	1		1	−12		1	1	1	1		1	−5~−19		1	1
	Ⅱ	1	−12		1	1		1	1	1	−5~−19		1	1		1	1
	Ⅲ	1	0~−12	−6	1	1	−12	1	1	1	0~−12	−6	1	1	−5~−19	1	1
Total time /h	Ⅰ	6	48		6	48		6	48	6	48		6	48		6	48
	Ⅱ	4	24		4	24		4	24	4	24		4	24		4	24
	Ⅲ	4	12	12	4	12	12	4	24	4	12	12	4	12	12	4	24
Cycle times	Ⅰ	1	1	1	1	1		1	1	1	1		1	2		1	1
	Ⅱ	1	1	1	1	1		1	1	1	2		1	1		1	1
	Ⅲ	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Note: 1. Sequence i was set to make the temperature field of sample homogeneous; Sequence ii was settled to carry out freezing test; Sequence iii was the second experimental stage, but only for freezing temperature model Ⅲ. 2. The temperature variation of 0～−12℃ dropped linearly to make a layer (2 cm) of artificial seasonal frozen soil on the top of specimens. 3.−5 (crest)～−19 (trough)℃ was sine-varying and the initial temperature was −12℃, with the period of 24 hours for Sine Ⅰ, 12 hours for Sine Ⅱ/Ⅲ. 4.

the same experimental conditions, the peaks of constant-freezing specimens are higher than those of sine-freezing ones. 3) the decreasing phrase, the rates of frost heave almost decline to 0 mm/min, and the slope is a lot gentler than that in increasing phrase. As shown in Figs. 5 and 6, for the sine variation of temperatures, the descending slopes of the rates of frost heave present the corresponding changes. 4) the stable or relatively stable phrase (the last one), the rates of frost heave reach 0 mm/min and last to the end of the experiments with constant-temperature freezing. For the sine-temperature freezing specimens, the rates of frost heave reach a relatively stable phrase: although there are still slightly changes till the end, they vary within quite narrow limits than those in phrase 2) and 3), and the rates of frost heave without water supply change a bit harder than the one with water supply. From the minus values of the rates of sine freezing specimens, it can be suggested that a very small quantity of thaw occurs in the frozen part of the specimens, and at its minimum, the freezing temperature arrives at the maximum (−5℃) at the same time, and it is evident that the changes of the rates of frost heave and sine temperatures are reverse.

It can be found in Figs. 7, 8, 9 and 10 that just like the rates of frost heave obtained in the lateral freezing experiments on disturbed silty clay, there are also four phrases in the development process of the rates of frost heave in the vertical freezing experiments with undisturbed silty clay. The rate peaks of the specimens with 28% water content are higher than those with 23.5% under the same conditions, because the higher initial water content causes the frost heave easily in the starting stage. The developing time of the rate of frost heave with 23.5% water content lasts longer than the one with 28%, in that more water (from the exterior water-supplying device) comes to the specimens with 23.5% water content in the rear part of the whole process. In comparison with the lateral freezing, the sine-varying temperature has less or almost no influence on the rate

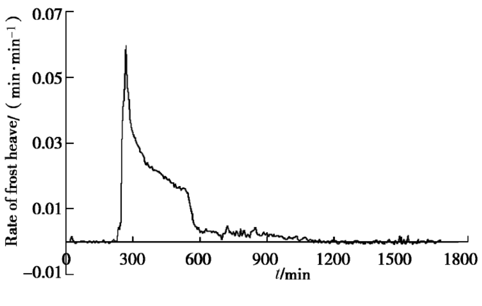

Fig. 7 Relationship between rate of frost heave and time of vertical constant freezing specimen with water supply (23.5%)

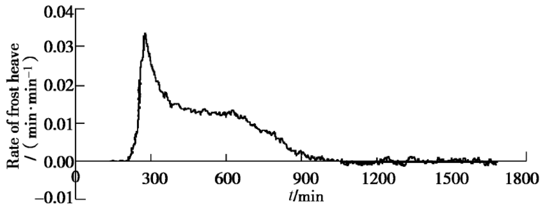

Fig. 8 Relationship between rate of frost heave and time of vertical sine freezing specimen with water supply (23.5%)

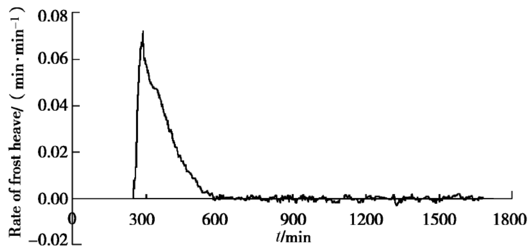

Fig. 9 Relationship between rate of frost heave and time of vertical constant freezing specimen with water supply (28%)

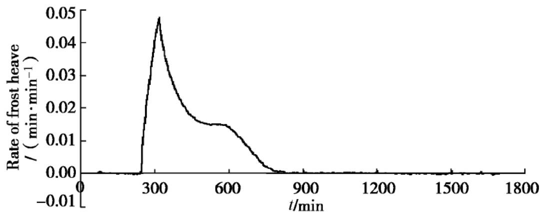

Fig. 10 Relationship between rate of frost heave and time of vertical sine freezing specimen with water supply (28%)

of frost heave in the 4) phrase, for the lateral freezing area (376 cm^2) is larger than the vertical area (78.5 cm^2).

The results of the rates of frost heave of the vertical-lateral artificial freezing experiments on undisturbed specimens with 23% water content and 28% water content indicate that the majority of the frost heave occurs in the vertical freezing stage, as presented in Figs. 11, 12, 13 and 14. In the vertical stage (the temperature linearly descending from 0℃ to −12℃, 240～960 min), the rates of frost heave arise at about 450 min and ends at 960 min or so. After vertical freezing comes with lateral freezing, in which stage the second development of rate of frost heave happens and by reason of the difference between the lateral freezing temperature models, the second development of constant freezing specimens occurs earlier than that of sine freezing specimen. In the last phrase, the rates of all the four specimens are stable at 0 mm/min. It is obvious that the value of rate caused by lateral freezing is far less than that caused by vertical freezing, because the temperature goes down very slowly, which provides enough time for most water migrating to the freezing area to form a simulative seasonal frozen layer with 3～4 cm in thickness. Thus, the frost heave in the lateral freezing stage is quite little. Based on the above results, it can be concluded that if there is a seasonal frozen area in the artificial ground freezing area, the frost heave caused by artificial freezing will be rather less than that without seasonal freezing, especially for the area with a deep ground water level, which offers a certain reference to artificial projects.

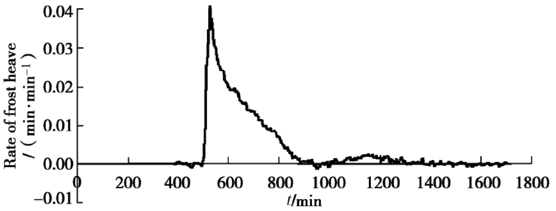

Fig. 11 Relationship between rate of frost heave and time of vertical-lateral constant freezing specimen with water supply (23.5%)

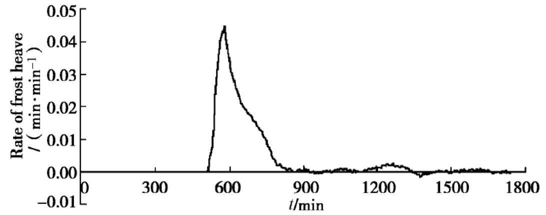

Fig. 12 Relationship between rate of frost heave and time of vertical-lateral sine freezing specimen with water supply (23.5%)

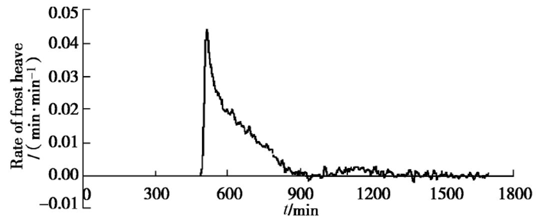

Fig. 13 Relationship between rate of frost heave and time of vertical-lateral constant freezing specimen with water supply (28%)

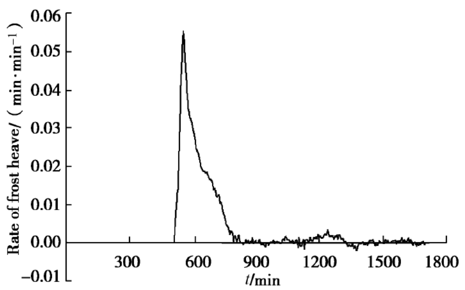

Fig. 14 Relationship between rate of frost heave and time of vertical-lateral sine freezing specimen with water supply (28%)

3 Conclusions

(1) There are four phrases in the process of the development of the rate of frost heave. The sine-varying freezing temperature model has a significant impact on the rate of frost heave in the freezing process and frozen soil, especially with powerful freezing energy. With the same experimental conditions, the rate of frost heave with water supply is easily subjected to the influence caused by sine-temperature (disturbed silty clay, water content of 32%).

(2) For the vertical freezing experiments, the heave rate peaks of the specimens with water content of 28% are higher than those with 23.5% under the same conditions. The developing time of the rate (23.5%) lasts longer than the one (28%) (undisturbed silty clay).

(3) According to the developing analysis of the rates of frost heave in the vertical-lateral freezing experiments, the existence of seasonal frozen layer will reduce or suppress the second frost heave caused by artificial ground freezing in the engineering projects, especially in seasonally frozen ground.

Acknowledgement: This research was supported by the National Natural Science Foundation of China(NNSFC) (40571032). The authors would like to express especial thanks to the reviewers for their helpful comments.

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