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Experimental assessment of the effect of frozen fringe thickness on frost heave

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Abstract. A frozen fringe plays a key role in frost heave development in soils. Previous studies have focused on the physical and mechanical properties of the frozen fringe, such as overall hydraulic conductivity, water content and pore pressure. It has been proposed that the thickness of the frozen fringe controls frost heave behavior, but this effect has not been thoroughly evaluated. This study used a temperature-controllable cell to investigate the impact of frozen fringe thickness on the characteristics of frost heave. A series of laboratory tests was performed with various temperature boundary conditions and specimen heights, revealing that: (1) the amount and rate of development of frost heave are dependent on the frozen fringe thickness; (2) the thicker the frozen fringe, the thinner the resulting ice lens; and (3) care must be taken when using the frost heave ratio to characterize frost heave and evaluate frost susceptibility because the frost heave ratio is not a normalized factor but a specimen height-dependent factor.

Keywords: laboratory analysis; frost heave; frozen fringe; frost heave amount; frost heave rate; frost heave ratio; specimen height

1. Introduction

Many geotechnical structures have been constructed on the frozen ground in cold regions. However, the construction and global climate warming cause huge degradation to the frozen ground (Huang *et al*. 2019), and freeze-thaw causes structure instability due to unexpected soil deformation and reduction of shear strength (Zwissler *et al*. 2014, Heidari *et al*. 2017, Yilmaz and Fidan 2018). Thaw settlement caused by consolidation has been carefully studied until now (Wang and Liu 2015, Wang *et al*. 2019). Frost heave has also been studied after Taber (1929) and Beskow (1947) found the mechanism of ice segregation in freezing soils. A frost heave laboratory test is the most straightforward approach to investigate the characteristics of frost heave, but the effect of the thickness of the frozen fringe and specimen size have not been thoroughly investigated.

The temperature at which pore water freezes is designated as the pore freezing temperature (generally referred to as T_p). The frost front may be very close to the zero isotherm for coarse silts or fine sands, slightly behind the zero isotherm for finer soils and coincides with zero isotherm for Devon silt which contains 30% clay sized particles (Konrad and Morgenstern 1981). The temperature at which migratory water freezes at the base of the growing ice is designated as the segregation-freezing temperature (T_s) which is lower than the T_p (Hoekstra 1969, Penner and Goodrich 1982, Konrad and Morgenstern 1980, 1982, Konrad 2005). The zone between the T_p and T_s isotherms has been referred to as frozen fringe (Miller 1972). The frozen fringe plays a key role in frost heave. Konrad and Morgenstern (1980, 1981) studied the mechanism of ice lens formation in fine-grained soils and established a segregation potential theory, expressed as the water intake rate divided by the temperature gradient in the frozen fringe. Fig. 1 shows that the frozen fringe thickness (L_{ff}) varies with advancing frost front. When a thermal steady-state condition is approached, L_{ff} tends to a maximum (Konrad and Morgenstern, 1980). Since L_{ff} is variable, several studies of frozen fringe behavior have been conducted. Based on the results of experiments, Konrad and Morgenstern (1982) verified that the segregation-freezing temperature (T_s) decreased and L_{ff} increases with increasing applied surcharge load. O'Neill and Miller (1985) found that ice segregation (at the last ice lens) can only occur in the frozen fringe when the capillary force overcomes the applied surcharge load. Using an X-ray radiography technique, Akagawa (1988) discovered that T_s and L_{ff} vary, acting together under constant boundary temperature conditions at the surface. In other words, after ice lens formation becomes visible in X-ray radiographs, T_s and L_{ff} level off simultaneously. These studies showed that L_{ff} can affect frost heave and has a maximum value when the applied surcharge load reaches the shut-off pressure, at

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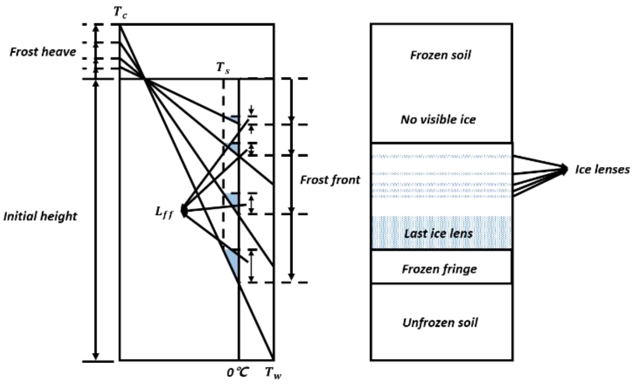


Fig. 1 Schematic diagram of frozen soil under constant temperature condition at the surface (Konrad and Morgenstern 1980) : frozen fringe

which point no further growth of the ice lens occurs.

Although frost heave is commonly examined in the laboratory (Konrad 1987, 2005, Seto and Konrad 1994) with the application of various boundary conditions, there has been no discussion on the effect of frozen fringe thickness on frost heave. Prior studies have only considered changes in the physical and mechanical properties of frozen fringes, including overall hydraulic conductivity, water content, heat transfer and pore pressure.

This paper presents the results of laboratory tests on frost heave and evaluates the influence of L_{ff} on the frost heave amount, rate and ratio (ξ) for specimen heights with carefully controlled initial and boundary temperature conditions. In particular, the L_{ff} in thermal steady state was controlled.

2. Transparent temperature-controllable cell

Jin *et al.* (2019) developed and validated a frost heave testing system including transparent temperature-controllable cell in which the temperature can be controlled at the top, bottom and around the periphery of a soil specimen. Three temperature-control pumps are used, connected to the top and bottom pedestals, and the cell periphery. The cell comprises an acrylic double-tube system, and anti-freeze liquid is circulated between the tubes to block the soil specimen from the outside temperature and freeze unidirectionally.

Unidirectional freezing and reliability of the transparent temperature-controllable cell have been confirmed by following 3 steps. 1) The temperature profile of the soil specimen can be predicted by the top and bottom temperature. 2) Zero isotherm can be predicted by the temperature profile of the soil specimen. 3) 9% volume expansion of pore water in sandy soils (heave by pore water in soils which generate ice segregation) can be calculated from the zero isotherm. The verification tests of unidirectional freezing have shown that the discrepancy between calculated and measured heave by pore water is less than 10% (Jin *et al*. 2019), which means that unidirectional freezing is guaranteed.

Using this apparatus, a freezing chamber is not necessary for frost heave tests, and the development of ice segregation can be observed with the naked eye. Vertical displacement over time is measured using a linear voltage displacement transducer (LVDT) positioned on the top pedestal. The top and bottom temperatures are measured using thermocouples installed on the top and bottom pedestals. In this study, laboratory frost heave tests were performed from the bottom upwards within a fully saturated soil specimen to eliminate the effect of lateral friction. The soil specimen was submerged throughout the frost heave testing to maintain a continuous supply of distilled water (Konrad and Morgenstern 1982, Jin *et al*. 2019).

3. Soil properties and testing conditions

Frost heave tests were performed using a frost-susceptible soil classified as SC by USCS (Unified Soil Classification System) (ASTM 2017) and obtained from Halden, Norway. The grain size distribution curve of Halden soil is shown in Fig. 2 and its mechanical characteristics are presented in Table 1.

A dry soil was used in preparing the soil specimens, which were reconstituted to heights of approximately 100

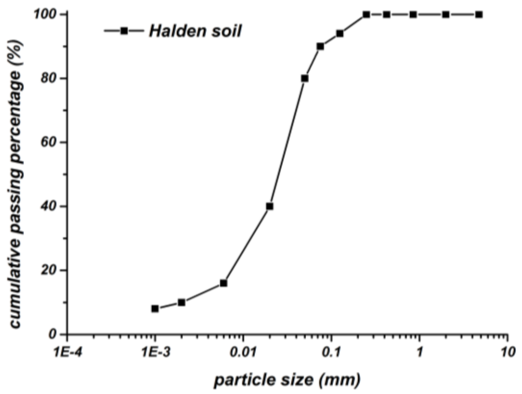


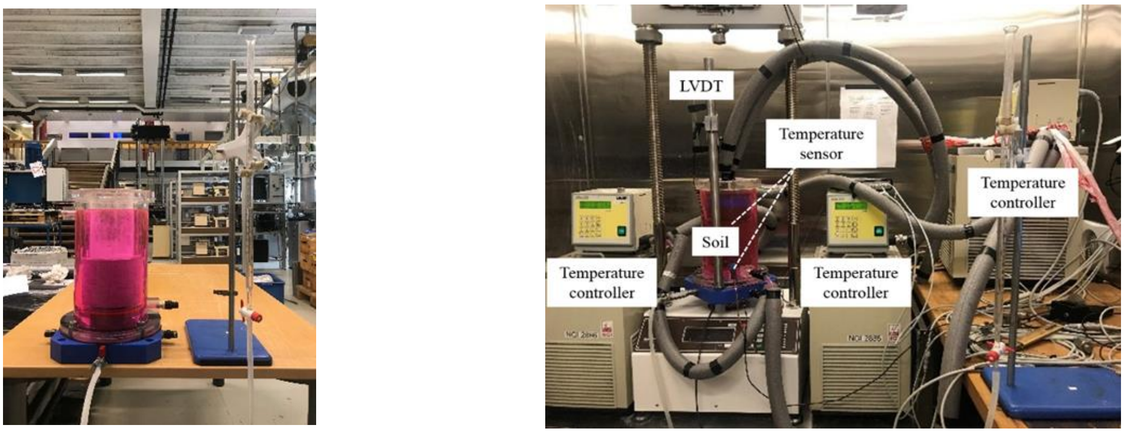
Fig. 2 Grain size distribution curve of Halden soil

Table 1 Particle grading characteristics and soil classification of Halden soil

D_{10}	D_{30}	D_{60}	Uniformity coefficient, C_u	Coefficient of curvature, C_c	Specific gravity, G_s	USCS
0.002	0.01	0.032	16	1.56	2.65	SC

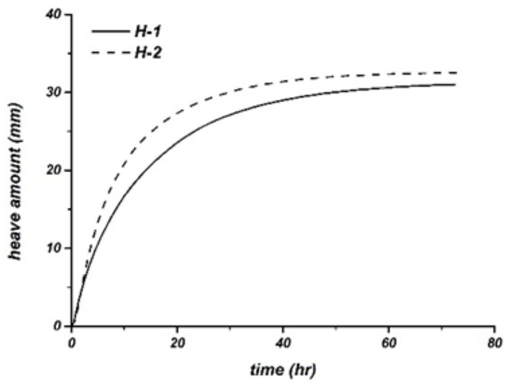
Table 2 Boundary conditions of frost heave tests

No.	Initial height (mm)	Dry unit weight (kN/m^3)	Temperature gradient (°C/mm)	Temperature (°C)			
				Setting	Measured		conditioning (initial)
				Peripheral	Top	Bottom	
H-1	99.59	14.51	0.118	1.0	2.7	-9.1	3.0
H-2	97.94	14.75	0.240		2.7	-20.8	3.0
H-3	52.20	13.84	0.117		1.5	-4.6	1.5
H-4	50.54	14.30	0.241		1.6	-10.6	1.5
H-5	29.22	14.84	0.137		0.7	-3.3	0.9
H-6	29.07	14.91	0.255		0.7	-6.7	0.9

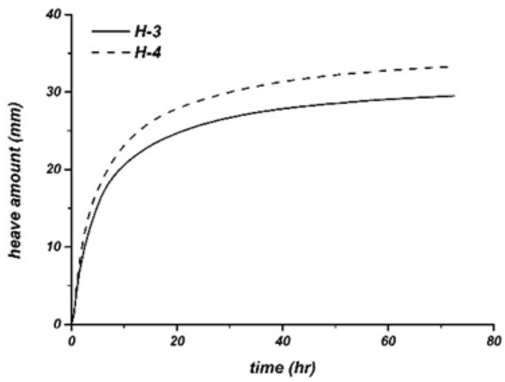


(a) Specimen saturation (b) Temperature conditioning

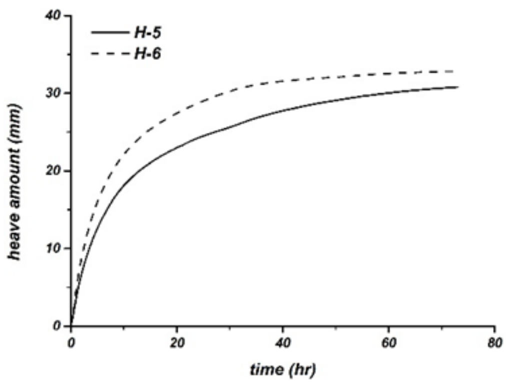
Fig. 3 Specimen saturation and temperature conditioning



(a) H-1 & H-2 (Group I)



(b) H-3 & H-4 (Group II)



(c) H-5 & H-6 (Group III)

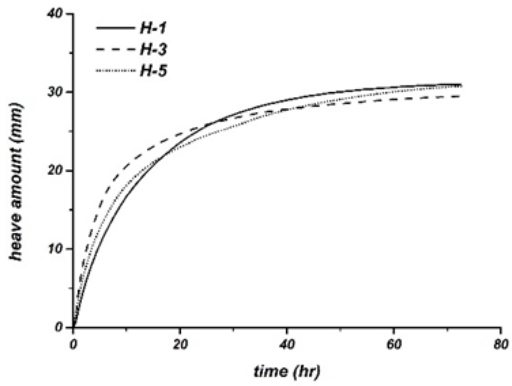
Fig. 4 Frost heave test results with similar specimen heights and different frozen fringe thickness (L_{ff})

mm, 50 mm and 30 mm, and a dry unit weight of 14 kN/m^3 by applying dry tamping, vibration and air pluviation techniques. To saturate the soil specimen, distilled water was injected through the drainage line connected to the bottom pedestal (Fig. 3(a)). A vacuum pump was used to saturate the specimen and to remove any remaining or trapped air inside the specimen. A surcharge load of 1.62 kPa was applied, induced by the top pedestal, which was filled with anti-freeze coolant. The specimens were kept under hydrostatic conditions for 24 hours with the temperature controlled by operating all pumps (Fig. 3b). The conditioning temperature was kept constant according to the specimen height (Table 2), and frost heave tests were performed.

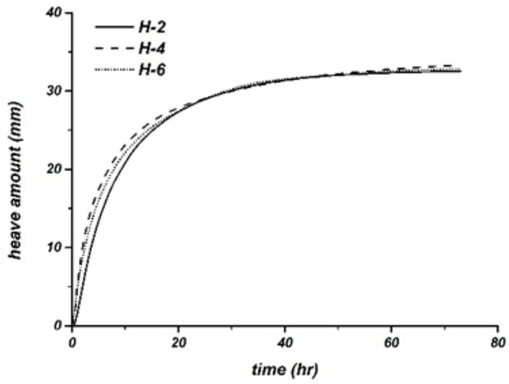
The values of L_{ff} used in this study, which is a key parameter for determining frost heave behaviour, are summarized in Table 2. L_{ff} remains constant after the temperature gradient reaches a steady-state condition. The L_{ff} values of heave tests H-1, H-3 and H-5 (Table 2) are similar, as are those of H-2, H-4 and H-6. The L_{ff} values of H-1, H-3 and H-5 are greater than that of H-2, H-4 and H-6, respectively.

4. Test results

Fig. 4 shows the results of frost heave tests classified



(a) H-1, H-3, H-5 (Group IV)

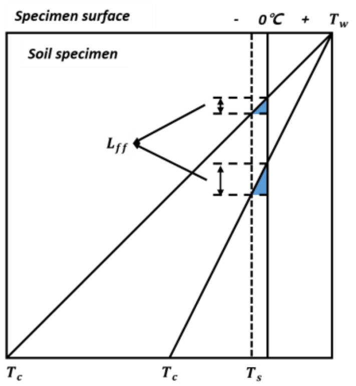


(b) H-2, H-4, H-6 (Group V)

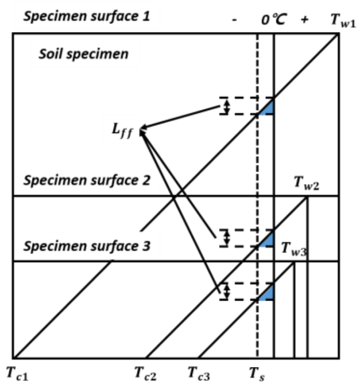
Fig. 5 Frost heave test results with similar frozen fringe thickness (L_{ff}) and different specimen heights

Table 3 Frost heave test results with respect to frost heave ratio (ξ)

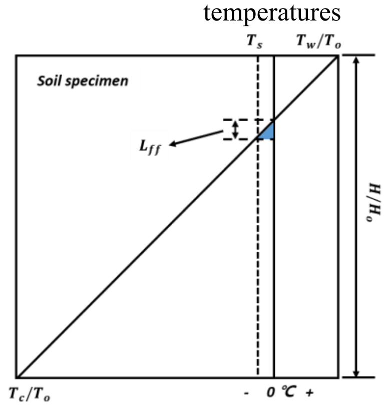
No.	Initial height (mm)	Frozen depth (mm)	Final frost heave amount (mm, t=72 hr)	Frost heave ratio (ξ, %)	
				$\frac{frost\ heave\ amount}{initial\ height}$	$\frac{frost\ heave\ amount}{frozen\ depth}$
H-1	99.59	76.80	31.01	31.1	40.4
H-2	97.94	86.69	32.55	33.2	37.6
H-3	52.2	39.37	29.49	56.5	74.9
H-4	50.54	43.91	33.26	65.8	75.7
H-5	29.22	24.10	30.75	105.2	127.8
H-6	29.07	26.32	32.80	112.8	124.7



(a) Different frozen fringe thicknesses (L_{ff}) at steady state temperatures



(b) Same frozen fringe thicknesses (L_{ff}) at steady state temperatures



(c) Normalized temperature profile

Fig. 6 Frozen fringe thickness (L_{ff}) at steady state temperatures under various boundary conditions : frozen fringe into three groups based on specimen height: Group I (H-1 & H-2), Group II (H-3 & H-4) and Group III (H-5 & H-6). Frost heave curves with similar specimen heights are dependent on L_{ff}. Group V (in Fig. 5(a)) specimens, with relatively small L_{ff}, show a larger frost heave at a faster rate compared with Group IV (in Fig. 5(b)) specimens.

Fig. 5 shows the results of the frost heave tests classified into two groups based on L_{ff}: Group IV (H-1, H-3 and H-5) and Group V (H-2, H-4 and H-6). Frost heave curves with similar L_{ff} were found to be consistent with one another regardless of specimen height.

The frost heave ratio (ξ) is used to characterize frost heave and to evaluate frost susceptibility, and is defined as the frost heave amount divided by the initial height (JGS, 2009) or the frozen depth (ГОST 2012). The frozen depth is defined as the distance from the surface to the frost front (at 0.0°C) of a specimen and can be inferred by assuming a linear temperature profile between the top and bottom temperatures (Jin *et al*. 2019). The value of the absolute frost heave ratio (ξ) depends on the definition employed, but the overall trend is independent of the definition. For similar L_{ff} values, the shorter the initial height, the larger the generated ξ value (Table 3), regardless of the divisor used (i.e., initial height or frozen depth).

5. Discussion

Tests were carried out to investigate the effect of L_{ff} on frost heave. The main focus of this study is to assess the impact of boundary conditions on L_{ff}. T_s is assumed to be constant when a constant overburden pressure (of only 1.62 kPa, induced by the top pedestal when filled with anti-freeze coolant) is applied (Konrad and Morgenstern, 1982).

Fig. 6(a) shows simplified temperature profiles through soil specimens with different L_{ff} (blue area) and the same height. Thinner L_{ff} results in larger frost heave, generated at a faster rate. This finding is consistent with the results of frost heave tests (Fig. 4). Fig. 6b shows simplified temperature profiles through soil specimens with different heights and the same L_{ff}. For constant L_{ff} and varying specimen height, the same frost heave amount and rate of development are observed in frost heave tests (Fig. 5). Since the frost heave amount and rate vary significantly between specimens with the same heights and different L_{ff}, it can be concluded that L_{ff} determines the frost heave amount and rate of development.

For a given soil profile, ξ is expected to be independent of specimen height (or frozen depth). Fig. 6(b) shows temperature boundary conditions with respect to specimen height and Fig. 6(c) presents normalized height and temperature boundary conditions. Even though the frozen-unfrozen ratio and L_{ff} in Fig. 6(c) are exactly same regardless of height, the test results show that ξ varies significantly with specimen height (or frozen depth). To characterize frost heave and evaluate frost susceptibility using ξ, the specimen height (or frozen depth) should be predefined (Table 3).

6. Conclusions

This study experimentally evaluated the influence of frozen fringe thickness (L_{ff}) on frost heave by using the newly developed transparent temperature-controllable cell. Fully saturated frost-susceptible soil specimens were frozen from the bottom upwards to eliminate lateral friction (Konrad and Morgenstern 1982, Jin *et al*. 2019). Frost heave tests were performed with different L_{ff} and specimen heights, and the following conclusions were drawn.

- The frost heave amount and rate are strongly dependent on L_{ff}, regardless of specimen height.
- When L_{ff} is similar among specimens, frost heave amount and rate are consistent regardless of specimen height. The thicker the frozen fringe, the smaller the frost heave amount and lower the rate of development, and the thinner the final ice lens.
- This study has demonstrated that frost heave amount and rate are reliable metrics with which to determine frost susceptibility because they are influenced by the pre-defined temperature gradient rather than specimen height (or frozen depth). Care must be taken when using the frost heave ratio (ξ) to determine frost susceptibility because it is not a normalized factor but a specimen height (or frozen depth) dependent factor.

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Appendix A: Photos of frozen soil samples