Protection against frost heave of L-type retaining walls in cold regions

RUI Da-hu[1], SUZUKI Teruyuki[2]
(1. School of Civil Engineering, Henan Polytechnic University, Jiaozuo 454000, China; 2. Department of Civil Engineering, Kitami Institute of Technology, Hokkaido, Japan)

Abstract: In order to investigate protection against the frost heave of seasonal frozen soil behind precast L-type retaining walls in cold regions, test walls are installed in the campus of Kitami Institute of Technology (KIT, Hokkaido, Japan) in two sections. One is incorporated countermeasures against frost heave and the other has no such countermeasures. The freezing front distribution and ground temperature within the backfill are observed, and deflections of the walls are measured over three freeze-thaw seasons. Some understanding of the mechanisms of the build-up of frost heave pressure is gained, and the effectiveness of replacement method is observed. A simulation is performed to predict the shape of the freezing front in the backfill behind L-type walls with various cross sections. These findings are employed to propose a method for determining the appropriate zone for replacement with frost unsusceptible backfill materials in cold regions.

Key words: L-type retaining wall; frost heave; freezing front; numerical simulation; replacement zone

CLC number: TU475 **Document code**: A **Article ID**: 1000－4548(2010)04－0612－07

Biography: RUI Da-hu (1969－), male, Associate professor, he current research interest freezing soil and environmental engineering problems. E-mail: dhrui@hpu.edu.cn.

寒区L型挡土墙的冻胀防治研究

芮大虎[1]，铃木辉之[2]
(1．河南理工大学土木工程学院，河南 焦作 454000；2．日本北见工业大学工学部，日本 北见)

摘 要：为研究寒区（季节冻土）L型挡土墙的冻胀防治措施，在日本国立北见工业大学冻土试验场进行了挡土墙的冻胀试验。挡土墙由无冻胀防治措施和有冻胀防治措施（置换工法）区间构成。通过 3 个冻融循环期的墙后土体温度、冻结面分布及墙体变形等的现场测试，验证了置换工法的有效性，并分析了挡土墙的冻胀破坏机理。另外，结合数值分析对各种挡土墙断面冻结面形状进行推算，提出了利用冻结指数或冻结深度确定墙后土体的置换范围的方法。

关键词：L型挡土墙；冻胀；冻结面；数值分析；置换范围

0 Introduction

Freezing of the ground causes a variety of damages to structures in contact with the ground in cold regions, such as cracking of paved road surfaces and frost heave of buildings. Previous studies on frost damage in civil engineering structures have mainly addressed countermeasures against frost heaving in road subgrades or base course. Few have taken up such measures for retaining walls, canal works, box culverts or other structures. Generally, construction standards have provided inadequate guidance against frost heave[1-3].

The fundamentals of frost heave proofing structures consist of countermeasures against low temperatures, water, or regarding soil, but actual construction procedures vary widely. The most trusted and widely employed procedure is to replace the soil within the zone vulnerable to freezing with a material that does not frost heave, generally, sand or gravel. Thus, the designer must determine the replacement zone and the frost unsusceptible material to be used for backfill[4-5].

The present study focused on precast L-type concrete retaining walls of 1 m to 4 m in height, with the goal of

Foundation item: Supported by Henan Polytechnic University Natural Science Foundation（648349）
Received date: 2008－12－19

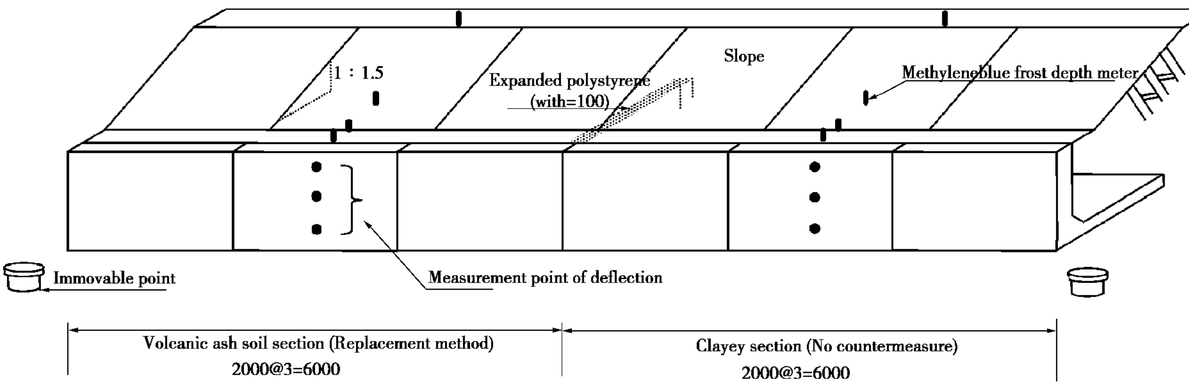

Fig. 1 Schematic diagram of retaining walls

establishing efficient design procedures for replacement method[6]. Concrete L-type walls were installed in a test bed at Kitami Institute of Technology and freezing conditions, wall deformation and other parameters were observed through winters over a period of three years in order to obtain a precise record of the behavior of the wall. This test also compared and assessed different backfills (replacement materials) and the effectiveness of replacement method. A computer simulation was conducted to extend these results to typical conditions by varying wall configurations and freezing fronts, and to develop a method for specifying the replacement zone.

1 Performance of retaining walls

Fig. 1 and Fig. 2 show a schematic representation of the concrete L-type retaining walls, while Fig. 3 shows these in cross section. The walls are 1.5 m high, 2.0 m wide and the base length is 1.7 m. Six such walls are erected. The overall installation is divided into two sections as described below, each differing with respect to the fill conditions behind each wall.

Fig. 2 Photo of test walls in winter season

(1) Volcanic ash soil section: The "refilled zone" is filled with frost unsusceptible volcanic ash soil.

(2) Clayey soil section: The "un-replaced zone" is filled with clayey soil that was prone to frost heaving.

Table 1 Soil properties

Soil type		Clayey soil	Volcanic ash soil
$\rho_s/(g\cdot cm^{-3})$		2.59	2.51
Particle size distribution	Gravel/%	5.80	13.90
	Sand/%	57.00	63.90
	Silt/%	27.50	18.20
	Clay/%	9.70	4.00
	C_u	43.40	21.20
	C_c	1.74	1.37
Compaction	w_{opt}/%	29.40	29.80
	$\rho_{dmax}/(g\cdot cm^{-3})$	1.31	1.15
Frost heave tests	Frost heave ratio/%	21.30	0.82

Table 1 gives the properties of backfill material. The volcanic ash soil is employed as a frost unsusceptible layer for roadways in the Hokkaido region. Conversely, clayey soil is strongly prone to frost heave.

The inclinometers and copper-constant thermo-couples are installed as shown in Fig. 3 to measure the action of walls and the temperatures of the front and back surfaces of the wall. The inclinometer and thermo-couple sensors readings are automatically recorded every 2 hours. The rated capacity of inclinometer is ±5°, and operating temperature is -20～70 ℃ (±0.01°). The copper-constant thermo-couple accuracy control is ±1℃(-40～133℃). The frost depth in the backfill is also measured once a day with a meth yleneblue frost depth meter and recorded.

2 Results and discussions

2.1 Ground freezing condition

The mean daily temperature, frost heave amount, frost depth, frost heave force of three seasons from November, 1999 to April, 2002 in the flat test field is shown in Fig. 4, respectively.

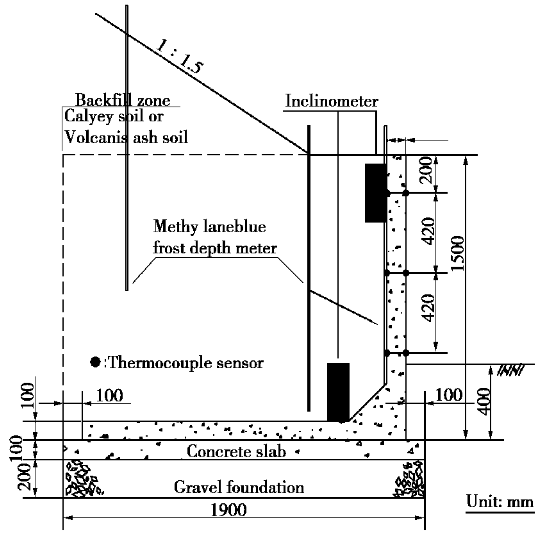

Fig. 3 Cross section of retaining walls

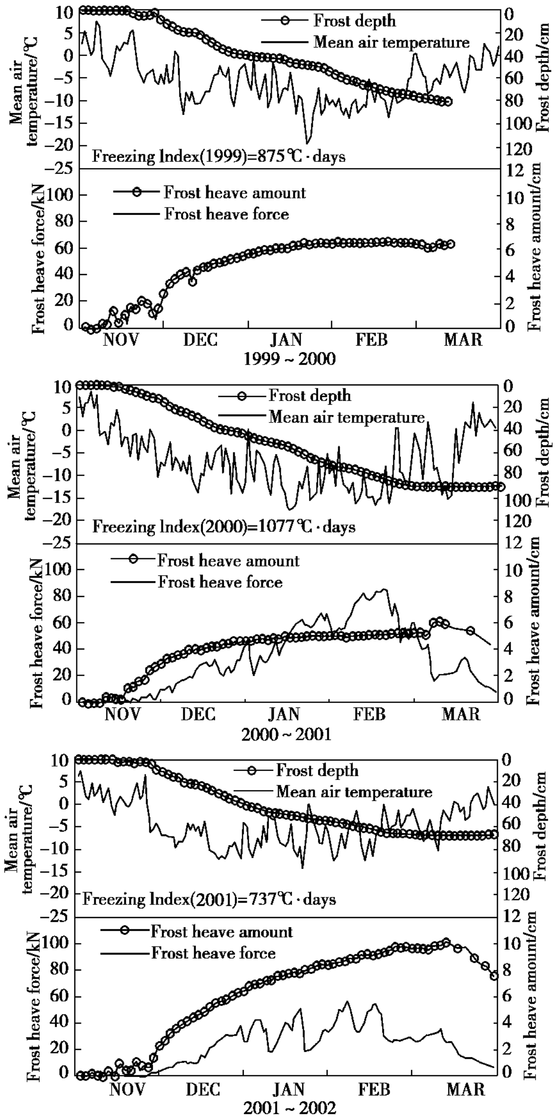

Fig. 4 Ground freezing conditions of experiment season

The freezing index in the first season is 875℃·days, second season is 1077℃·days, third season is 737℃·days. Considering the warm winter tendency in recent years, the three experiment seasons had the comparatively strong cold tendency. The second season shows especially the maximum freezing index in the past ten years. The frost heave pressure is the force acting on a disk with a diameter of 10 cm on the ground surface [7].

2.2 Frost penetration of backfill

The frost heaving pressure acts on the normal direction of freezing front or the direction of heat flow[8]. Therefore, if the freezing front shape can be established, the designer can calculate the size of the fill zone behind the wall where damaging frost heaving occurs and tends to deform the wall. Understanding the freezing front shape in backfill is the primary and one of the most essential tasks of countermeasures for protecting civil engineering structures against frost heaving damage. Fig. 5 shows the backfill freezing front shapes deduced from the methyleneblue frost depth meter data. The following can be inferred from these figures:

(1) The shape of the freezing front is primarily influenced by surface topography (the heat outflow surface). The frost heaving force acts normal to the freezing front. A steep freezing front was associated with the flow of heat out of the volcanic ash soil zone or clayey soil zone through the wall (Fig. 5). When the freezing front has this shape and there is frost heave in the backfill, it increases the horizontal frost heave force tending to push out the front face of the retaining wall.

(2) Comparison of the results within backfill zones indicates that freezing penetrats to a greater depth in the second season (2000-2001). This is consistent with the freezing index, an indicator of the coldness of the winter, which is the greatest during the second winter. Comparing within seasons, the volcanic ash soil section shows penetration of the frozen zone to a greater depth than in the clayey soil section. Discrepancies in frost depth are attributed to discrepancies in water content; generally, the greater the water content, the more shallow the frost depth, because of the higher latent heat of freezing.

2.3 Behavior of retaining walls

Fig. 6(a) is a graph showing the time-dependent change in the inclination of each wall. In the clayey soil section, where no particular frost heave prevention is employed, the wall begins to tilt almost simultaneously with the onset of freezing in every season. The maximum values of this inclination are 3.7º, 5.4º and 6.3º in the

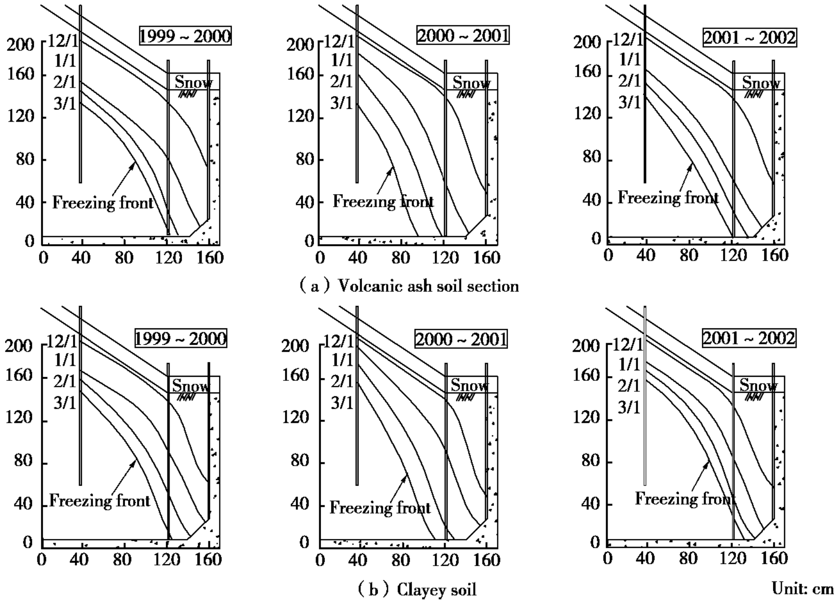

Fig. 5 Freezing front shape of backfill earth

first, second and third seasons, respectively. The maximum deflection of the top of the wall after the beginning of the experiment is approximately 14 cm in the third season. The inclination of the vertical wall rebounds partially after the back fill begins to thaw in late March, but some tilt remains after complete thaw in summer and tilting of the wall is observed to be cumulative. It was apparent that tilting of the vertical wall supporting the clayey soil backfill was due to frost heaving pressure. The tilt and the displacement of the top of the wall clearly exceed the allowable values for concrete, and cracks occur at the foot of the wall (Fig. 7). This is typical for frost heaving pressure-induced cracking in concrete L-type retaining walls.

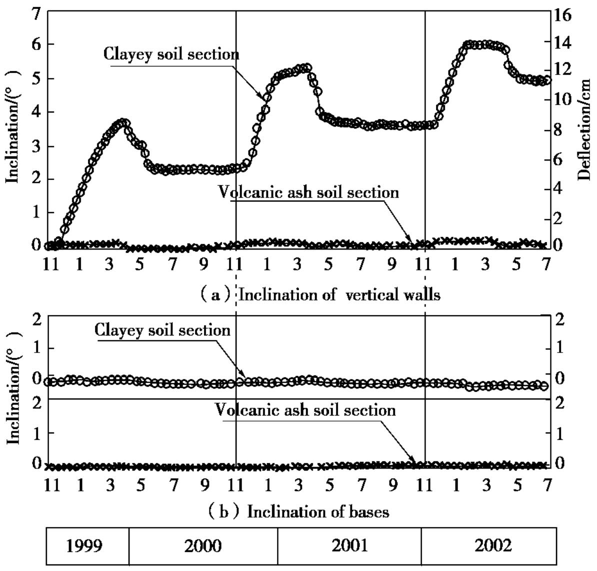

Fig. 6 Inclination of wall over 3 seasons

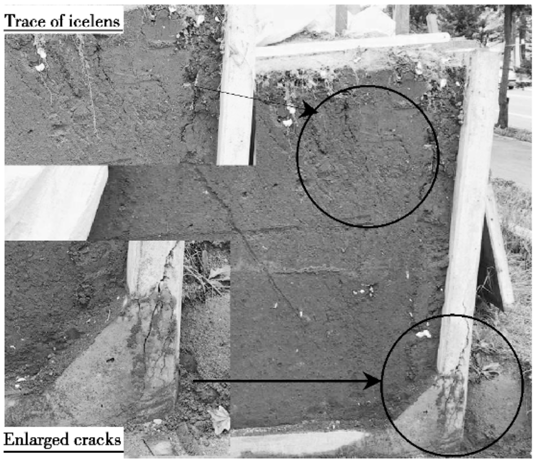

Fig. 7 Typical crack occurred at the foot of concrete L-type retaining walls

Almost no tilting of the vertical wall is observed in the volcanic ash soil section throughout the observation periods. A conspicuous advantage is gained by replacing the soil with the frost unsusceptible volcanic ash soil backfill within the zone most vulnerable to frost damage. No cracking like that shown in Fig. 7 is ever observed, even after the 3 seasons of observations of this section.

Fig. 6 (b) shows the progression in inclination of the base of each wall. Slight but detectable tilting occurs in both sections during the winter seasons. The reason for the absence of further tilting during the third winter is thought to be due to the spreading of the cracks in the lower regions of the vertical walls, which may have reduced transmission of the forces from the vertical walls to their bases. The tilting of the base is markedly less than that of the vertical walls, and the bases return to the horizontal during the unfrozen seasons. There is almost no tilting (rotation) of the wall monoliths ascribable to inadequate support by the underlying bed. The tilting and cracking of the vertical walls is attributed entirely to frost heaving pressure.

3 Design of backfill zones

3.1 Method for determining backfill zone

The previous sections describe (i) the results of observations of dynamic behavior of L-type concrete retaining walls during the freezing season, (ii) the situation of wall failure during backfill freezing, and (iii) the mechanisms of that failure. Here, procedures for the design of countermeasures against frost heaving by replacement are proposed on the basis of those observations.

Fig. 8 shows the proposed method for determining the zone to be replaced with frost unsusceptible backfill material. When the frost depth is Z_f, the zone throughout which frost heaving forces can be considered to act upon the rear face of the vertical wall (plane c-d) is the volume extending back to the (a-b) line. Here, point **a** is referred to as the border point. Thus, it is assumed that replacing the volume represented by the cross section (a-b-c-d-e) is sufficient for preventing push out.

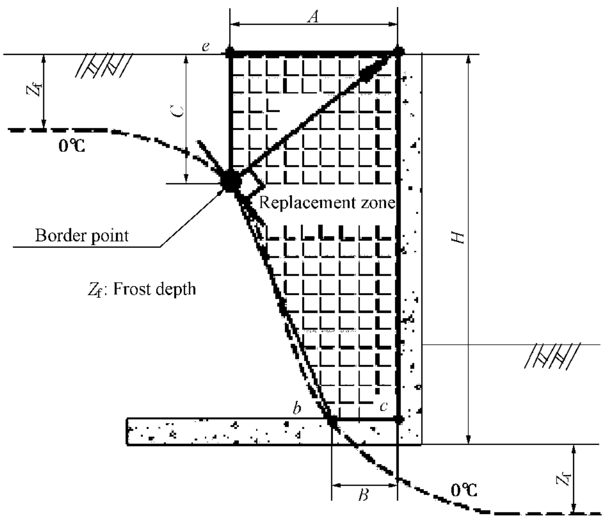

Fig. 8 Proposed replacement zone

The Japanese standards for retaining walls specify that the penetration depth of L-type retaining walls must extend at least 50 cm[9]. There is not assumed to be any penetration depth in the calculations of the freezing distributions in Fig. 8. The penetration depth varies with site, support offered by the underlying soil, and several other conditions, and all should be taken into consideration when designs are to be implemented in critical locations. Fig. 8 also does not consider the influence of drifting snow on the shape of the freezing front. If the heat-insulating effect of drifting snow was considered, the replacement zone could actually be reduced in size, but it is difficult to make any quantitative estimates of this effect. This analysis makes the above assumptions estimate a relationship between the maximum frost depth Z_f and the parameters *A*, *B*, *C*, in order to determine the replacement zone (a-b-c-d-e) in Fig. 8.

3.2 Numerical simulation

Before predicting the extent of the replacement zone in Fig. 8, the shape of the freezing front must be approximated; this is attempted using a numerical simulation. Two-dimensional unsteady thermal conduction incorporating the latent heat associated with freeze-thaw is assumed in developing the fundamental equations for the analysis. User-determined parameters are the cross-sectional shape of the analytical model, the thermophysical properties of the materials, and the meteorological conditions. Data from the meteorological tower on the KIT campus are employed for the latter parameters and the soil temperature at a depth of 5 m is assumed to be constant at 9ºC. The atmospheric temperature data set is from the winter of 2000, which had been the coldest winter in the last 10 years[10].

Fig. 9 presents an example of the results of the simulation. Soil isotherms are indicated by white lines at intervals of 1ºC. This analysis compares different shapes of the retaining wall rear face (presence vs. absence of slope; berm width; and wall height) for their effects on freezing front shape. A draft manual for the design and construction of precast L-type retaining walls covers walls of heights from 1 m to 4 m, so this range is investigated in this simulation. Fig. 9 is an example of the isotherms at an arbitrary time. This group of lines can be considered as change in the freezing front over time. This analysis is carried out for several wall surface configurations and the relationship between freezing depth Z_f and replacement zone parameters *A*, *B* and *C* were elucidated for each freezing front configuration.

3.3 Frost depth Z_f

Parameters *A*, *B* and *C* which describe the replacement zone are determined by the frost depth. Fig. 10 shows the relationship between the freezing index and the frost depth[10]. This figure shows the relationship calculated for a one-dimensional case under level ground. Maximum dry density ρ_{dmax} and optimum water content w_{opt} were also employed as parameters, but these are known to correlate with soil type and thermophysical properties[11-13].

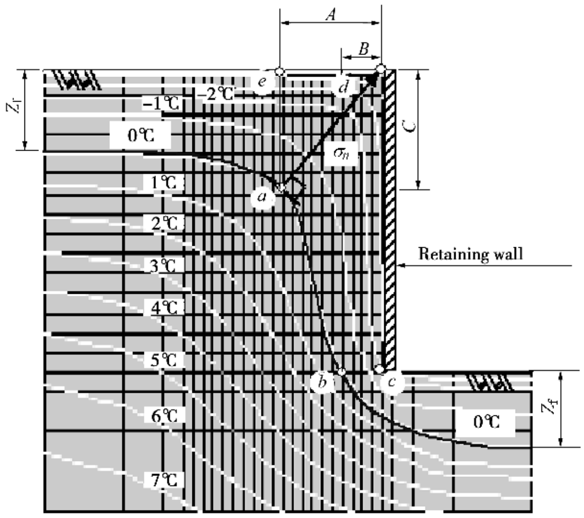

Fig. 9 An example of simulation result

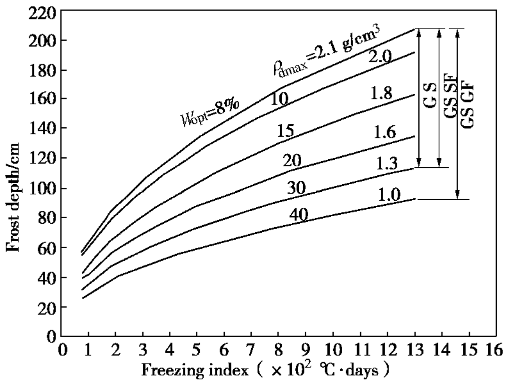

Fig. 10 Relationship between frost depth and freezing index

3.4 Determining *A*, *B*, *C*

Fig. 11 is a plot of the relationship between *A* and Z_f for different wall heights. The curve predicted for a wall height of 100 cm resembles those for the higher walls up to a frost depth of about 40 cm. Behind a low, 100 cm wall, when Z_f is 80 cm, the upper face of the step matches the depth of the border point (point *a* in Fig. 7). In this case, if the frost depth is increased further, the calculations show that *A* tends to decrease. For the purpose of designing actual structures, however, *A* is fixed at a constant 80 cm in freezing depth deeper than 80 cm behind 100 cm walls, as shown Fig. 11.

Fig. 12 presents the relationship between parameter *B* and Z_f for the four wall heights. There are minor differences between wall heights because *B* is determined by the shape freezing front at the lowest portion of the wall, which is itself only slightly influenced by wall height or berm width. B was fixed at 80 cm for frost depths exceeding 80 cm behind 100 cm walls; for the same reason *A* is fixed as described above. Thus, for 100 cm walls in locations where freezing is expected to reach depths of at least 80 cm, a comparison of Fig. 11 and Fig. 12 shows that *A* = *B*. This means that the soil replacement zone is rectangular in cross section.

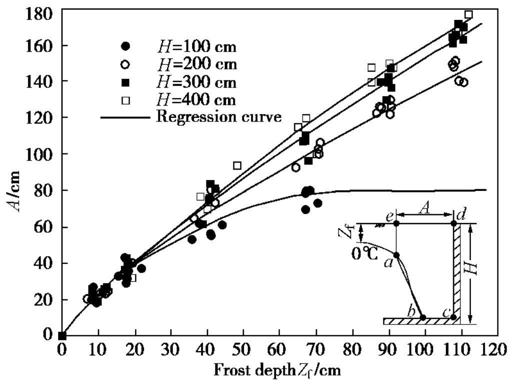

Fig. 11 Relationship between frost depth and *A* for different wall heights

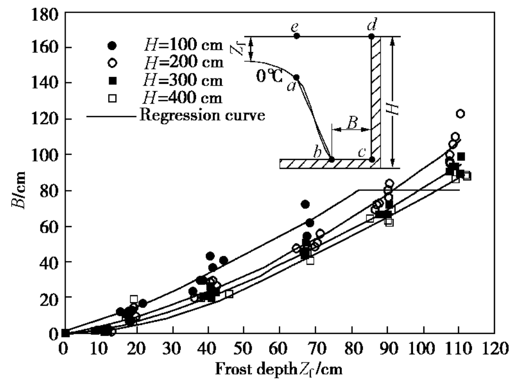

Fig. 12 Relationship between freezing depth and *B* for different wall heights

Fig. 13 depicts the relationship between depth parameter *C* and Z_f for differing berm widths *D*. The freezing front shape is dominated by the topography of the surface, but the narrower the berm, the more closely the freezing front parallels and approaches the vertical wall, so that the border point approaches the top of the wall. Over longer berm widths, conversely, the freezing front in the backfill approaches a wedge shape, due to heat flow out of the ground surface behind the wall, and the border point recedes from the top of the wall. Similar to the limiting approximations of parameters *A* (Fig. 11) and *B* (Fig. 12), *C* is set to 100 cm for the 100 cm wall and $Z_f \geq 80$ cm, calling for a rectangular cross-section backfill.

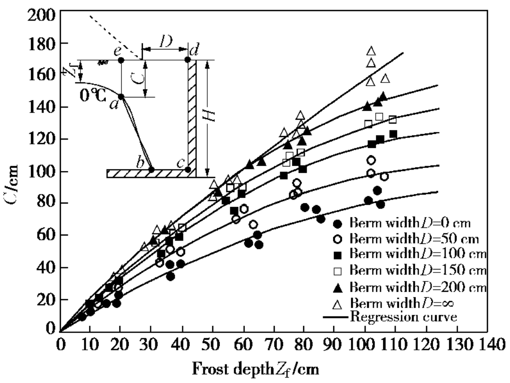

Fig. 13 Relationship between freezing depth and *C* for different berm widths

4 Summary

This study combines the results of outdoor experiments with ground freezing at concrete retaining walls installed in the KIT campus with the results of simulations of ground freezing. The study proposes a method for determining the zone of soil to be replaced in order to minimize the deleterious effects associated with freezing. The conclusions can be summarized as follows:

（1）If the backfill behind a concrete wall is allowed to frost heaving, this causes an accumulating deformation of the wall monolith, which eventually causes the wall to fail.

（2）Beneficial effects are associated with using frost unsusceptible backfill behind concrete retaining walls.

（3）The shape of the freezing front in the backfill varies with frost depth, as well as wall height, wall rear face configuration and berm width.

（4）If the frost depth Z_f in the installation site is known, the fill volume parameters *A*, *B*, and *C* can be found using Fig. 11, Fig. 12 and Fig. 13, respectively, and used to determine the zone of soil replacement necessary for an effective counter- measure against frost heave pressure.

References:

[1] SUZUKI T, UENO K, HAYASHI K. Preventing measure of frost heaving damage on small sized U-trough using gravel backfill[J]. Journal of Geotechnical Engineering, JSCE, 1991, **439**(III-17): 89－96. (in Japanese)

[2] LIANG B, WANG J D，GE J J, CAO Y P. Testing and analysis of earth pressure about L type retaining wall in Qinghai—Tibet Railway[J]. Chinese Journal of Geotechnical Engineering, 2004, **26**(5): 627－631. (in Chinese)

[3] LAI Y M, LIU S Y, WU Z W. Nonlinear analyses for retaining walls in frigid zone a coupled problem of temperature, seepage, and stress fields[J]. China Civil Engineering Journal, 2003, **36**(6): 88－95. (in Chinese)

[4] SUZUKI T, UNO H, SAWADA S, ADACHI K. Freezing front and frost heaving pressure in multi anchored retaining [J]. Journal of Geotechnical Engineering, JSCE, 2000, **645** (III-50): 281－290. (in Japanese)

[5] RUI D H, SUZUKI T, YAMASHITA S, HYASHI K. Countermeasure for frost heave of concrete L-type retaining wall backfill with granular wastes[J]. Journal of Geotechnical Engineering for JSCE, 2006, **62**(3): 562－572. (in Japanese)

[6] SUZUKI T, SAWADA S. Full-scale model test on frost heaving pressure in a reinforce retaining wall [C]// Proc 7th Int Symp on Ground Freezing, A.A.Balkema, 1994: 311－316.

[7] RUI D H, SUZUKI T, KIM YONGSU. Frost heave force of natural ground and countermeasure for damage of structures[J]. Journal of the Korean Geotechnical Society, 2007, **23**(5): 43－51. (in Korean)

[8] PHUKAN A. Frozen ground engineering[M]. Englewood Cliffs, N J: Prentice Hall Inc, 1985: 139－169.

[9] Guidance for earth worker & retaining wall worker[M]. Tokyo: Japan Road Association, 1999. (in Japanese)

[10] UNO H, SUZUKI T, SAWADA S. A countermeasure to frost heave of multi-anchored retaining wall in cold region [J]. Journal of Geotechnical Engineering, JSCE, 2002, **701**(III-58): 243－252. (in Japanese)

[11] SAWADA S, OHNO T. Laboratory studies on thermal-conductivity of clay, silt and sand in frozen and unfrozen states [C]// Proc 4th Int Symp on Ground Freezing, Sapporo, 1985: 53－58.

[12] WOODSIDE W，MESSER J H. Thermal conductivity of porous media I[J]. Journal of Applied Physics, 1961, **32**: 1688－1699.

[13] PENNER G H. JOHNSTON, GOODRICH L E. Thermal conductivity laboratory studies of some Mackenzie Highway Soils[J]. Canadian Geotechnical Journal，1975, **12**(3): 271－288.